CONTENTS

CHAPTER 43

Learning Objectives

ELECTRIC TRACTION

In electric traction, driving force (or tractive force) is generated by electricity, using electric motors. Electric trains, trams, trolley, buses and battery run cars are some examples where electric traction is employed.

CONTENTS

43.1. General

By electric traction is meant locomotion in which the driving (or tractive) force is obtained from electric motors. It is used in electric trains, tramcars, trolley buses and diesel-electric vehicles etc. Electric traction has many advantages as compared to other non-electrical systems of traction including steam traction.

43.2. Traction Systems

Broadly speaking, all traction systems may be classified into two categories :

(a) non-electric traction systems

They do not involve the use of electrical energy at ***any stage***. Examples are : steam engine drive used in railways and internal-combustion-engine drive used for road transport.

The above picture shows a diesel train engine. These engines are now being rapidly replaced by electric engines

(b) electric traction systems

They involve the use of electric energy at some stage or the other. They may be further subdivided into two groups :

1. First group consists of self-contained vehicles or locomotives. Examples are : battery-electric drive and diesel-electric drive etc.
2. Second group consists of vehicles which receive electric power from a distribution network fed at suitable points from either central power stations or suitably-spaced sub-stations. Examples are : railway electric locomotive fed from overhead ac supply and tramways and trolly buses supplied with dc supply.

43.3. Direct Steam Engine Drive

Though losing ground gradually due to various reasons, steam locomotive is still the most widely-adopted means of propulsion for railway work. Invariably, the reciprocating engine is employed because

1. it is inherently simple.
2. connection between its cylinders and the driving wheels is simple.
3. its speed can be controlled very easily.

However, the steam locomotive suffers from the following disadvantages :

1. since it is difficult to install a condenser on a locomotive, the steam engine runs non-condensing and, therefore, has a very low thermal efficiency of about 6-8 percent.
2. it has strictly limited overload capacity.
3. it is available for hauling work for about 60% of its working days, the remaining 40% being spent in preparing for service, in maintenance and overhaul.

43.4. Diesel-electric Drive

It is a self-contained motive power unit which employs a diesel engine for direct drive of a dc generator. This generator supplies current to traction motors which are geared to the driving axles.

In India, diesel locomotives were introduced in 1945 for shunting service on broad-guage (BG) sections and in 1956 for high-speed main-line operations on metre-guage (MG) sections. It was only in 1958 that Indian Railways went in for extensive main-line dieselisation.*

Diesel-electric traction has the following advantages :

1. no modification of existing tracks is required while converting from steam to diesel-electric traction.
2. it provides greater tractive effort as compared to steam engine which results in higher starting acceleration.
3. it is available for hauling for about 90% of its working days.
4. diesel-electric locomotive is more efficient than a steam locomotive (though less efficient than an electric locomotive).

Disadvantages

1. for same power, diesel-electric locomotive is costlier than either the steam or electric locomotive.
2. overload capacity is limited because diesel engine is a constant-kW output prime mover.
3. life of a diesel engine is comparatively shorter.
4. diesel-electric locomotive is heavier than plain electric locomotive because it carries the main engine, generator and traction motors etc.
5. regenerative braking cannot be employed though rheostatic braking can be.

43.5. Battery-electric Drive

In this case, the vehicle carries secondary batteries which supply current to dc motors used for driving the vehicle. Such a drive is well-suited for shunting in railway yards, for traction in mines, for local delivery of goods in large towns and large industrial plants. They have low maintenance cost and are free from smoke. However, the scope of such vehicles is limited because of the small capacity of the batteries and the necessity of charging them frequently.

The above picture shows a battery run car. Battery run vehicles are seen as alternatives for future transport due to their pollution-free locomotion

43.6. Advantages of Electric Traction

As compared to steam traction, electric trac-

* The Diesel Locomotive Works at Varanasi turns out 140 locomotives of 2700 hp (2015 kW) annually. Soon it will be producing new generation diesel engines of 4000 hp (2985 kW).

tion has the following advantages :

1. Cleanliness. Since it does not produce any smoke or corrosive fumes, electric traction is most suited for underground and tube railways. Also, it causes no damage to the buildings and other apparatus due to the absence of smoke and flue gases.

2. Maintenance Cost. The maintenance cost of an electric locomotive is nearly 50% of that for a steam locomotive. Moreover, the maintenance time is also much less.

3. Starting Time. An electric locomotive can be started at a moment's notice whereas a steam locomotive requires about two hours to heat up.

4. High Starting Torque. The motors used in electric traction have a very high starting torque. Hence, it is possible to achieve higher accelerations of 1.5 to 2.5 km/h/s as against 0.6 to 0.8 km/h/s in steam traction. As a result, we are able to get the following additional advantages:

(*i*) high schedule speed

(*ii*) increased traffic handling capacity

(*iii*) because of (*i*) and (*ii*) above, less terminal space is required—a factor of great importance in urban areas.

5. Braking. It is possible to use regenerative braking in electric traction system. It leads to the following advantages :

(*i*) about 80% of the energy taken from the supply during ascent is returned to it during descent.

(*ii*) goods traffic on gradients becomes safer and speedier.

(*iii*) since mechanical brakes are used to a very small extent, maintenance of brake shoes, wheels, tyres and track rails is considerably reduced because of less wear and tear.

6. Saving in High Grade Coal. Steam locomotives use costly high-grade coal which is not so abundant. But electric locomotives can be fed either from hydroelectric stations or pit-head thermal power stations which use cheap low-grade coal. In this way, high-grade coal can be saved for metallurgical purposes.

7. Lower Centre of Gravity. Since height of an electric locomotive is much less than that of a steam locomotive, its centre of gravity is comparatively low. This fact enables an electric locomotive to negotiate curves at higher speeds quite safely.

8. Absence of Unbalanced Forces. Electric traction has higher coefficient of adhesion since there are no unbalanced forces produced by reciprocating masses as is the case in steam traction. It not only reduces the weight/kW ratio of an electric locomotive but also improves its riding quality in addition to reducing the wear and tear of the track rails.

43.7. Disadvantages of Electric Traction

1. The most vital factor against electric traction is the initial high cost of laying out overhead electric supply system. Unless the traffic to be handled is heavy, electric traction becomes uneconomical.

2. Power failure for few minutes can cause traffic dislocation for hours.

3. Communication lines which usually run parallel to the power supply lines suffer from electrical interference. Hence, these communication lines have either to be removed away from the rail track or else underground cables have to be used for the purpose which makes the entire system still more expensive.

4. Electric traction can be used only on those routes which have been electrified. Obviously, this restriction does not apply to steam traction.

5. Provision of a negative booster is essential in the case of electric traction. By avoiding the flow of return currents through earth, it curtails corrosion of underground pipe work and interference with telegraph and telephone circuits.

43.8. Systems of Railway Electrification

Presently, following four types of track electrification systems are available :

1. Direct current system—600 V, 750 V, 1500 V, 3000 V
2. Single-phase ac system—15-25 kV, $16\frac{2}{3}$, 25 and 50 Hz
3. Three-phase ac system—3000-3500 V at $16\frac{2}{3}$ Hz
4. Composite system—involving conversion of single-phase ac into 3-phase ac or dc.

43.9. Direct Current System

Direct current at 600-750 V is universally employed for tramways in urban areas and for many suburban railways while 1500-3000 V dc is used for main line railways. The current collection is from third rail (or conductor rail) up to 750 V, where large currents are involved and from overhead wire for 1500 V and 3000 V, where small currents are involved. Since in majority of cases, track (or running) rails are used as the return conductor, only one conductor rail is required. Both of these contact systems are fed from substations which are spaced 3 to 5 km for heavy suburban traffic and 40-50 km for main lines operating at higher voltages of 1500 V to 3000 V. These sub-stations themselves receive power from 110/132 kV, 3-phase network (or grid). At these substations, this high-voltage 3-phase supply is converted into low-voltage 1-phase supply with the help of Scott-connected or V-connected 3-phase transformers (Art. 31.9). Next, this low ac voltage is converted into the required dc voltage by using suitable rectifiers or converters (like rotary converter, mercury-arc, metal or semiconductor rectifiers). These substations are usually automatic and are remote-controlled.

The dc supply so obtained is fed via suitable contact system to the traction motors which are either dc series motors for electric locomotive or compound motors for tramway and trolley buses where regenerative braking is desired.

It may be noted that for ***heavy suburban service***, low voltage dc system is undoubtedly superior to 1-phase ac system due to the following reasons :

1. dc motors are better suited for frequent and rapid acceleration of heavy trains than ac motors.
2. dc train equipment is lighter, less costly and more efficient than similar ac equipment.
3. when operating under similar service conditions, dc train consumes less energy than a 1-phase ac train.
4. the conductor rail for dc distribution system is less costly, both initially and in maintenance than the high-voltage overhead ac distribution system.
5. dc system causes no electrical interference with overhead communication lines.

The only disadvantage of dc system is the necessity of locating ac/dc conversion sub-stations at relatively short distances apart.

43.10. Single-Phase Low-frequency AC System

In this system, ac voltages from 11 to 15 kV at $16\frac{2}{3}$ or 25 Hz are used. If supply is from a generating station exclusively meant for the traction system, there is no difficulty in getting the electric supply of $16\frac{2}{3}$ or 25 Hz. If, however, electric supply is taken from the high voltage transmission lines at 50 Hz, then in addition to step-down transformer, the substation is provided with a frequency converter. The frequency converter equipment consists of a 3-phase synchronous motor which drives a I-phase alternator having or 25 Hz frequency.

The 15 kV $16\frac{2}{3}$ or 25 Hz supply is fed to the electric locomotor via a single over-head wire (running rail providing the return path).

A step-down transformer carried by the locomotive reduces the 15-kV voltage to 300-400 V for feeding the ac series motors. Speed regulation of ac series motors is achieved by applying variable voltage from the tapped secondary of the above transformer.

Low-frequency ac supply is used because apart from improving the commutation properties of ac motors, it increases their efficiency and power factor. Moreover, at low frequency, line reactance is less so that line impedance drop and hence line voltage drop is reduced. Because of this reduced line drop, it is feasible to space the substations 50 to 80 km apart. Another advantage of employing low frequency is that it reduces telephonic interference.

41.11. Three-phase Low-frequency AC System

It uses 3-phase induction motors which work on a 3.3 kV, $16\frac{2}{3}$ Hz supply. Sub-stations receive power at a very high voltage from 3-phase transmission lines at the usual industrial frequency of 50 Hz. This high voltage is stepped down to 3.3 kV by transformers whereas frequency is reduced from 50 Hz to $16\frac{2}{3}$ Hz by frequency converters installed at the sub-stations. Obviously, this system employs *two* overhead contact wires, the track rail forming the third phase (of course, this leads to insulation difficulties at the junctions).

Induction motors used in the system are quite simple and robust and give trouble-free operation. They possess the merits of high efficiency and of operating as a generator when driven at speeds above the synchronous speed. Hence, they have the property of automatic regenerative braking during the descent on gradients. However, it may be noted that despite all its advantages, this system has not found much favour and has, in fact, become obsolete because of its certain inherent limitations given below :

1. the overhead contact wire system becomes complicated at crossings and junctions.
2. constant-speed characteristics of induction motors are not suitable for traction work.
3. induction motors have speed/torque characteristics similar to dc shunt motors. Hence, they are not suitable for parallel operation because, even with little difference in rotational speeds caused by unequal diameters of the wheels, motors will becomes loaded very unevenly.

43.12. Composite System

Such a system incorporates good points of two systems while ignoring their bad points. Two such composite systems presently in use are :

1. 1-phase to 3-phase system also called Kando system
2. 1-phase to dc system.

43.13. Kando System

In this system, single-phase 16-kV, 50 Hz supply from the sub-station is picked up by the locomotive through the single overhead contact wire. It is then converted into 3-phase ac supply at the same frequency by means of phase converter equipment carried on the locomotives. This 3-phase supply is then fed to the 3-phase induction motors.

As seen, the complicated overhead two contact wire arrangement of ordinary 3-phase system is replaced by a single wire system. By using silicon controlled rectifier as inverter, it is possible to get variable-frequency 3-phase supply at 1/2 to 9 Hz frequency. At this low frequency, 3-phase motors develop high starting torque without taking excessive current. In view of the above, Kando system is likely to be developed further.

43.14. Single-phase AC to DC System

This system combines the advantages of high-voltage ac distribution at industrial frequency with the dc series motors traction. It employs overhead 25-kV, 50-Hz supply which is stepped down by the transformer installed in the locomotive itself. The low-voltage ac supply is then converted into dc supply by the rectifier which is also carried on the locomotive. This dc supply is finally fed to dc series traction motor fitted between the wheels. The system of traction employing 25-kV, 50-Hz, 1-phase ac supply has been adopted for all future track electrification in India.

43.15. Advantages of 25-kV, 50-Hz AC System

Advantages of this system of track electrification over other systems particularly the dc system are as under :

1. Light Overhead Catenary

Since voltage is high (25 kV), line current for a given traction demand is less. Hence, cross-section of the overhead conductors is reduced. Since these small-sized conductors are light, supporting structures and foundations are also light and simple. Of course, high voltage needs higher insulation which increases the cost of overhead equipment (OHE) but the reduction in the size of conductors has an overriding effect.

2. Less Number of Substations

Since in the 25-kV system, line current is less, line voltage drop which is mainly due to the resistance of the line is correspondingly less. It improves the voltage regulation of the line which fact makes larger spacing of 50-80 km between sub-stations possible as against 5-15 km with 1500 V dc system and 15-30 km with 3000 V dc sysem. Since the required number of substations along the track is considerably reduced, it leads to substantial saving in the capital expenditure on track electrification.

3. Flexibility in the Location of Substations

Larger spacing of substations leads to greater flexibility in the selection of site for their proper location. These substations can be located near the national high-voltage grid which, in our country, fortunately runs close to the main railway routes. The substations are fed from this grid thereby saving the railway administration lot of expenditure for erecting special transmission lines for their substations. On the other hand, in view of closer spacing of dc substations and their far away location, railway administration has to erect its own transmission lines for taking feed from the national grid to the substations which consequently increases the initial cost of electrification.

4. Simplicity of Substation Design

In ac systems, the substations are simple in design and layout because they do not have to install and maintain rotary converters or rectifiers as in dc systems. They only consist of static transformers alongwith their associated switchgear and take their power directly from the high-voltage national grid running over the length and breadth of our country. Since such sub-stations are remotely controlled, they have few attending personnel or even may be unattended.

5. Lower Cost of Fixed Installations

The cost of fixed installations is much less for 25 kV ac system as compared to dc system. In fact, cost is in ascending order for 25 kV ac, 3000 V dc and 1500 V dc systems. Consequently, traffic densities for which these systems are economical are also in the ascending order.

6. Higher Coefficient of Adhesion

The straight dc locomotive has a coefficient of adhesion of about 27% whereas its value for ac rectifier locomotive is nearly 45%. For this reason, a lighter ac locomotive can haul the same load as a heavier straight dc locomotive. Consequently, ac locomotives are capable of achieving higher speeds in coping with heavier traffic.

7. Higher Starting Efficiency

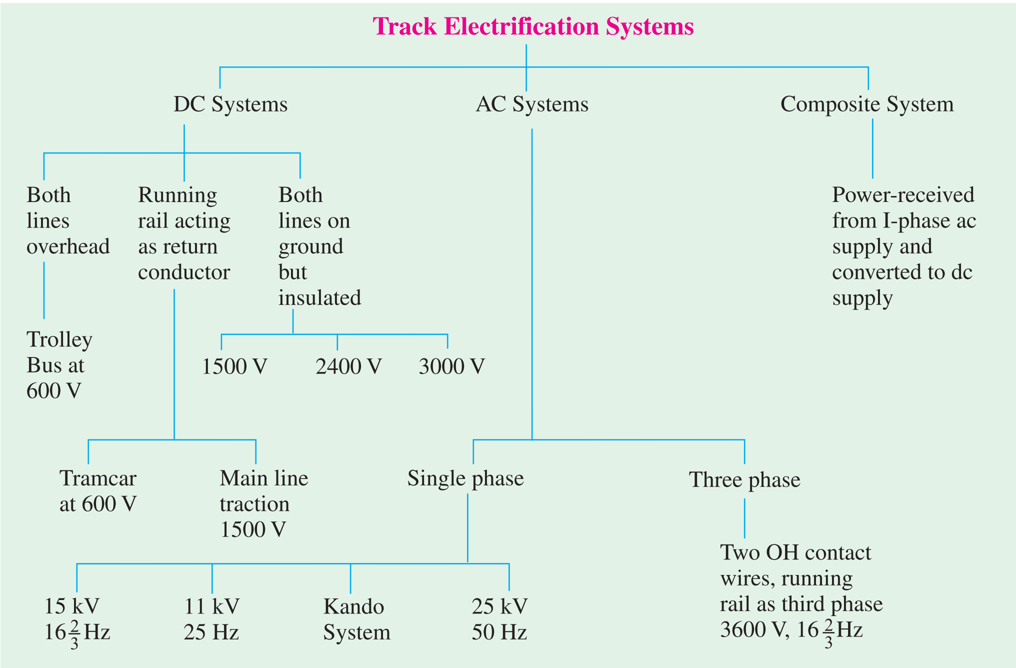
An ac locomotive has higher starting efficiency than a straight dc locomotive. In dc locomotive supply voltage at starting is reduced by means of ohmic resistors but by on-load primary or secondary tap-changer in ac locomotives.

43.16. Disadvantages of 25-kV AC System

1. Single-phase ac system produces both current and voltage unbalancing effect on the supply.

2. It produces interference in telecommunication circuits. Fortunately, it is possible at least to minimize both these undesirable effects.

Different track electrification systems are summarised below :



43.17. Block Diagram of an AC Locomotive

The various components of an ac locomotive running on single-phase 25-kV, 50-Hz ac supply are numbered in Fig. 43.1.

1. OH contact wire

2. pantograph
3. circuit breakers
4. on-load tap-changers
5. transformer
6. rectifier
7. smoothing choke
8. dc traction motors.

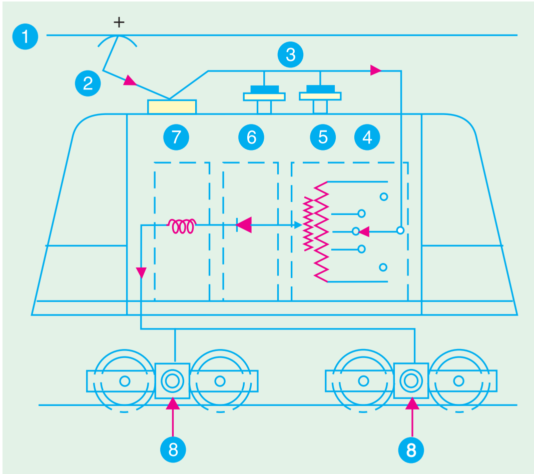


Fig. 43.1

As seen, power at 25 kV is taken via a pantograph from the overhead contact wire and fed to the step-down transformer in the locomotive. The low ac voltage so obtained is converted into pulsating dc voltage by means of the rectifier. The pulsations in the dc voltage are then removed by the smoothing choke before it is fed to dc series traction motors which are mounted between the wheels.

The function of circuit breakers is to immediately disconnect the locomotive from the overhead supply in case of any fault in its electrical system. The on-load tap-changer is used to change the voltage across the motors and hence regulate their speed.

43.18. The Tramways

It is the most economical means of transport for very dense traffic in the congested streets of large cities. It receives power through a bow collector or a grooved wheel from an overhead conductor at about 600 V dc, the running rail forming the return conductor. It is provided with at least two driving axles in order to *(i)* secure necessary adhesion *(ii)* start it from either end and *(iii)* use two motors with series-parallel control. Two drum-type controllers, one at each end, are used for controlling the tramcar. Though these controllers are connected in parallel, they have suitable interlocking arrangement meant to prevent their being used simultaneously.

Tramcars are being replaced by trolley-buses and internal-combustion-engined omnibuses because of the following reasons :

1. tramcars lack flexibility of operation in congested areas.
2. the track constitutes a source of danger to other road users.


Trolley Bus

43.19. The Trolleybus

It is an electrically-operated pneumatic-tyred vehicle which needs ***no track in the roadway***. It receives its power at 600 V dc from two overhead contact wires. Since adhesion between a rubber-tyred wheel and ground is sufficiently high, only a single driving axle and, hence, a single motor is used. The trolleybus can manoeuvre through traffic a metre or two on each side of the centre line of the trolley wires.

43.20. Overhead Equipment (OHE)

Broadly speaking, there are two systems of current collection by a traction unit :

(*i*) third rail system and (*ii*) overhead wire system.

It has been found that current collection from overhead wire is far superior to that from the third rail. Moreover, insulation of third rail at high voltage becomes an impracticable proposition and endangers the safety of the working personnel.

The simplest type of OHE consists of a single contact wire of hard drawn copper or silico-bronze supported either by bracket or an overhead span. To facilitate connection to the supports, the wire is grooved as shown in Fig. 43.2. Because there is appreciable sag of the wire between supports, it limits the speed of the traction unit to about 30 km/h. Hence, single contact wire system is suitable for tramways and in complicated yards and terminal stations where speeds are low and simplicity of layout is desirable.

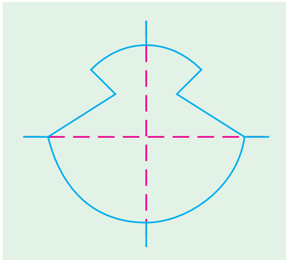


Fig. 43.2

For collection of current by high-speed trains, the contact (or trolley) wire has to be kept level without any abrupt changes in its height between the supporting structures. It can be done by using the single catenary system which consists of one catenary or messenger wire of steel with high sag and the trolley (or contact) wire supported from messenger wire by means of droppers clipped to both wires as shown in Fig. 43.3.

43.21. Collector Gear for OHE

The most essential requirement of a collector is that it should keep continuous contact with trolley wire at all speeds. Three types of gear are in common use :

1. trolley collector **2.** bow collector and **3.** pantograph collector.

To ensure even pressure on OHE, the gear equipment must, be flexible in order to follow variations in the sag of the contact wire. Also, reasonable precautions must be taken to prevent the collector from leaving the overhead wire at points and crossings.

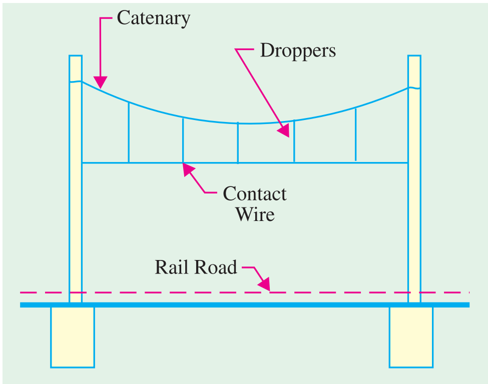


Fig. 43.3

43.22. The Trolley Collector

This collector is employed on tramways and trolley buses and is mounted on the roof of the vehicle. Contact with the OH wire is made by means of either a grooved wheel or a sliding shoe carried at the end of a light trolley pole attached to the top of the vehicle and held in contact with OH wire by means of a spring. The pole is hinged to a swivelling base so that it may be reversed for reverse running thereby making it unnecessary for the trolley wire to be accurately maintained above the centre of the track. Trolley collectors always operate in the trailing position.

The trolley collector is suitable for low speeds upto 32 km/h beyond which there is a risk of its jumping off the OH contact wire particularly at points and crossing.

43.23. The Bow Collector

It can be used for higher speeds. As shown in Fig. 43.4, it consists of two roof-mounted trolley poles at the ends of which is placed a light metal strip (or bow) about one metre long for current collection. The collection strip is purposely made of soft material (copper, aluminium or carbon) in order that most of the wear may occur on it rather than on the trolley wire. The bow collector also operates in the trailing position. Hence, it requires provision of either duplicate bows or an arrangement for reversing the bow for running in the reverse direction. Bow collector is not suitable for railway work where speeds up to 120 km/h and currents up to 3000 A are encountered. It is so because the inertia of the bow collector is too high to ensure satisfactory current collection.

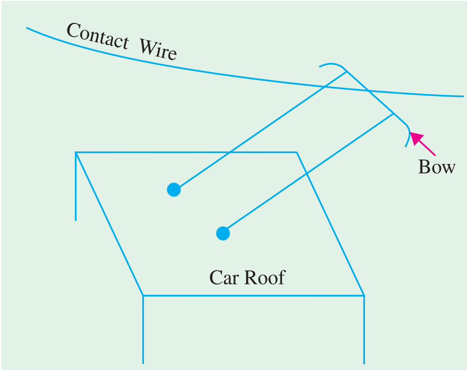


Fig. 43.4

43.24. The Pantograph Collector

Its function is to maintain link between overhead contact wire and power circuit of the electric locomotive at different speeds under all wind conditions and stiffness of OHE. It means that positive pressure has to be maintained at all times to avoid loss of contact and sparking but the pressure must be as low as possible in order to minimize wear of OH contact wire.

A 'diamond' type single-pan pantograph is shown in Fig. 43.5. It consists of a pentagonal framework of high-tensile alloy-steel tubing. The contact portion consists of a pressed steel pan fitted with renewable copper wearing strips which are forced against the OH contact wire by the upward action of pantograph springs. The pantograph can be raised or lowered from cabin by air cylinders.

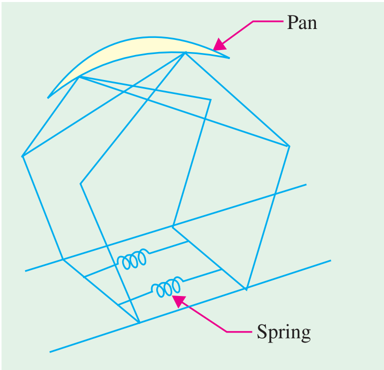


Fig. 43.5

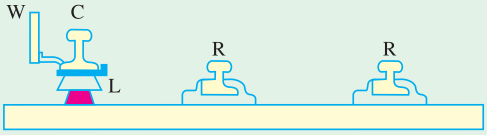
43.25. Conductor Rail Equipment

The conductor rails may be divided into three classes depending on the position of the contact surface which may be located at the top, bottom or side of the rail. The top contact rail is adopted universally for 600 V dc electrification. The side contact rail is used for 1200 V dc supply. The under contact rail has the advantage of being protected from snow, sleet and ice.

Fig. 43.6 shows the case when electric supply is collected from the top of an insulated conductor rail C (of special high-conductivity steel) running parallel to the track at a distance of 0.3 to 0.4 m from the running rail (R) which forms the return path. L is the insulator and W is the wooden protection used at stations and crossings.


The pantograph mechanism helps to maintain a link between the overhead contact wire and power circuit of the electric locomotive

The current is collected from top surface of the rail by flat steel shoes (200 mm · 75 mm), the necessary contact pressure being obtained by gravity. Since it is not always possible to provide conductor rail on the same side of the track, shoes are provided on both sides of the locomotive or train. Moreover two shoes are provided on each side in order to avoid current interruption at points and crossings where there are gaps in the running rail.



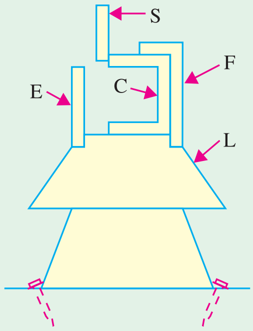


Fig. 43.6 **Fig. 43.7**

Fig. 43.7 shows the side contact rail and the method of the mounting. The conductor rail (*C*) rests upon a wooden block recessed into the top of the procelain insulator *L*. Current is collected by steel shoes (*S*) which are kept pressed on the contact rail by springs. *E* and *F* are the guards which rest upon ledges on the insulator.

43.26. Types of Railway Services

There are three types of passenger services offered by the railways :

1. City or Urban Service. In this case, there are frequent stops, the distance between stops being nearly 1 km or less. Hence, high acceleration and retardation are essential to achieve moderately high schedule speed between the stations.

2. Suburban Service. In this case, the distance between stops averages from 3 to 5 km over a distance of 25 to 30 km from the city terminus. Here, also, high rates of acceleration and retardation are necessary.

3. Main Line Service. It involves operation over long routes where stops are infrequent. Here, operating speed is high and accelerating and braking periods are relatively unimportant.

On goods traffic side also, there are three types of services ***(i)*** main-line freight service ***(ii)*** local or pick-up freight service and ***(iii)*** shunting service.

43.27. Train Movement

The movement of trains and their energy consumption can be conveniently studied by means of speed/time and speed/distance curves. As their names indicate, former gives speed of the train at various ***times*** after the start of the run and the later gives speed at various ***distances*** from the starting point. Out of the two, speed/time curve is more important because

1. its slope gives acceleration or retardation as the case may be.
2. area between it and the horizontal (*i.e.* time) axis represents the distance travelled.
3. energy required for propulsion can be calculated if resistance to the motion of train is known.

43.28. Typical Speed/Time Curve

Typical speed/time curve for electric trains operating on passenger services is shown in Fig. 43.8. It may be divided into the following **five** parts :

1. Constant Acceleration Period (0 to t_1)

It is also called notching-up or starting period because during this period, starting resistance of the motors is gradually cut out so that the motor current (and hence, tractive effort) is maintained nearly constant which produces constant acceleration alternatively called ‘rheostatic acceleration’ or ‘acceleration while notching’.

2. Acceleration on Speed Curve (t_1 to t_2)

This acceleration commences after the starting resistance has been all cut-out at point t_1 and full supply voltage has been applied to the motors. During this period, the motor current and torque decrease as train speed increases. Hence, acceleration gradually ***decreases*** till torque developed by motors exactly balances that due to resistance to the train motion. The shape of the portion *AB* of the speed/time curve depends primarily on the torque/speed characteristics of the traction motors.

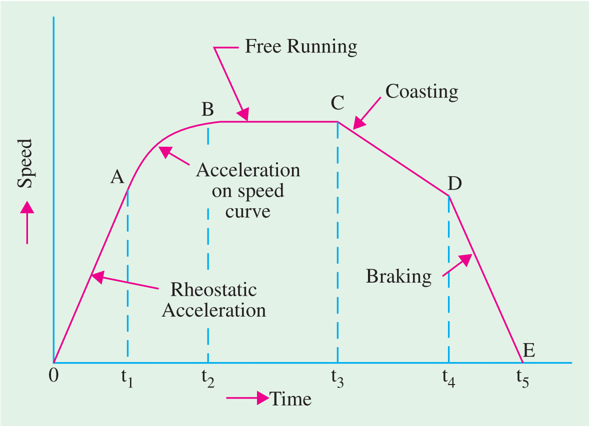


Fig. 43.8

3. Free-running Period (t_2 to t_3)

The train continues to run at the speed reached at point t_2. It is represented by portion *BC* in Fig. 43.8 and is a constant-speed period which occurs on level tracks.

4. Coasting (t_3 to t_4)

Power to the motors is cut off at point t_3 so that the train runs under its momentum, the speed gradually falling due to friction, windage etc. (portion *CD*). During this period, retardation remains practically constant. Coasting is desirable because it utilizes some of the kinetic energy of the train which would, otherwise, be wasted during braking. Hence, it helps to reduce the energy consumption of the train.

5. Braking (t_4 to t_5)

At point t_4, brakes are applied and the train is brought to rest at point t_5.

It may be noted that coasting and braking are governed by train resistance and allowable retardation respectively.

43.29. Speed/Time Curves for Different Services

Fig. 43.9 (*a*) is representative of city service where relative values of acceleration and retardation are high in order to achieve moderately high average speed between stops. Due to short

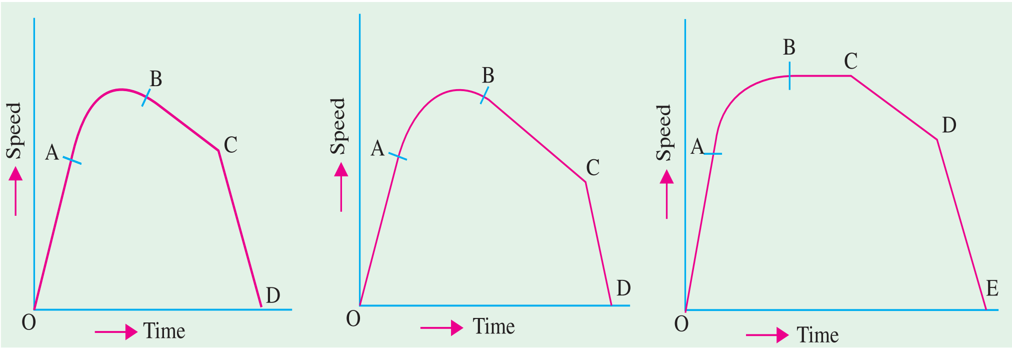


Fig. 43.9

distances between stops, there is no possibility of free-running period though a short coasting period is included to save on energy consumption.

In suburban services [Fig. 43.9 (*b*)], again there is no free-running period but there is comparatively ***longer*** coasting period because of longer distances between stops. In this case also, relatively high values of acceleration and retardation are required in order to make the service as attractive as possible.

For main-line service [Fig. 43.9 (c)], there are long periods of free-running at high speeds. The accelerating and retardation periods are relatively unimportant.

43.30. Simplified Speed/Time Curve

For the purpose of comparative performance for a given service, the actual speed/time curve of Fig. 43.8 is replaced by a simplified speed/time curve which does not involve the knowledge of motor characteristics. Such a curve has simple geometric shape so that simple mathematics can be used to find the relation between acceleration, retradation, average speed and distance etc. The simple curve would be fairly accurate provided it ***(i) retains the same acceleration and retardation and (ii) has the same area as the actual speed/time curve***. The simplified speed/time curve can have either of the two shapes :

(i) trapezoidal shape OA_1B_1C of Fig. 43.10 where speed-curve running and coasting periods of the actual speed/time curve have been replaced by a constant-speed period.

(ii) quadrilateral shape OA_2B_2C where the same two periods are replaced by the extensions of initial constnat acceleration and coasting periods.

It is found that trapezodial diagram OA_1B_1C gives simpler relationships between the principal quantities involved in train movement and also gives closer approximation of actual energy consumed during ***main-line service on level track***. On the other hand, quadrilateral diagram approximates more closely to the actual conditions in ***city and suburban services***.

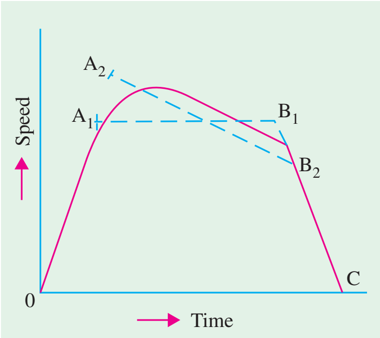


Fig. 43.10

43.31. Average and Schedule Speed

While considering train movement, the following three speeds are of importance :

1. **Crest Speed.** It is the maximum speed (V_m) attained by a train during the run.

2. **Average Speed** $= \dfrac{\text{distance between stops}}{\text{actual time of run}}$

In this case, only running time is considered but *not the stop time*.

3. **Schedule Speed** $= \dfrac{\text{distance between stops}}{\text{actual time of run + stop time}}$

Obviously, schedule speed can be obtained from average speed by including the duration of stops. For a given distance between stations, higher values of acceleration and retardation will mean lesser running time and, consequently, higher schedule speed. Similarly, for a given distance between stations and for fixed values of acceleration and retardation, higher crest speed will result in higher schedule speed. For the same value of average speed, increase in duration of stops decreases the schedule speed.

43.32. SI Units in Traction Mechanics

In describing various quantities involved in the mechanics of train movement, only the latest SI system will be used. Since SI system is an 'absolute system', only absolute units will be used while gravitational units (used hitherto) will be discarded.

1. **Force.** It is measured in newton (N)
2. **Mass.** Its unit is kilogram (kg). Commonly used bigger units is tonne (*t*), 1 tonne = 1000 kg

3. Energy. Its basic unit is joule (J). Other units often employed are watt-hour (Wh) and kilowatt-hour (kWh).

$$1\ \text{Wh} = 1\frac{\text{J}}{\text{s}} \times 3600\ \text{s} = 3600\ \text{J} = 3.6\ \text{kJ}$$

$$1\text{kWh} = 1000 \times 1\frac{\text{J}}{\text{s}} \times 3600\ \text{s} = 36 \times 10^5\ \text{J} = 3.6\ \text{MJ}$$

4. Work. Its unit is the same as that of energy.

5. Power. Its unit is watt (W) which equals 1 J/s. Other units are kilowatt (kW) and megawatt (MW).

6. Distance. Its unit is metre. Other unit often used is kilometre (km).

7. Velocity. Its absolute unit is metre per second (m/s). If velocity is given in km/h (or km.ph), it can be easily converted into the SI unit of m/s by multiplying it with a factor of (1000/3600) = 5/18 = 0.2778. For example, 72 km.ph = $72 \times 5/18 = 72 \times 0.2778 = 20$ m/s.

8. Acceleration. Its unit is metre/second^2 (m/s^2). If acceleration is given in km/h/s (or km-ph.ps), then it can be converted into m/s^2 by simply multiplying it by the factor (1000/3600) = 5/18 = 0.2778 *i.e.* the same factor as for velocity.

For example, 1.8 km.ph.ps = $1.8 \times 5/18 = 1.8 \times 0.2778 = 0.5$ m/s^2

43.33. Confusion Regarding Weight and Mass of a Train

Many students often get confused regarding the correct meaning of the terms 'weight' and 'mass' and their units while solving numericals on train movement particularly when they are not expressed clearly and consistently in their absolute units. It is primarily due to the mixing up of absolute units with gravitational units. There would be no confusion at all if ***we are consistent in using only absolute units*** as required by the SI system of units which disallows the use of gravitational units.

Though this topic was briefly discussed earlier, it is worth repeating here.

1. Mass (M). It is the quantity of matter contained in a body.

Its absolute unit is kilogram (kg). Other multiple in common use is tonne.

2. Weight (W). It is the **force** with which earth pulls a body downwards.

The weight of a body can be expressed in (*i*) the ***absolute*** unit of newton (N) or (*ii*) the ***gravitational*** unit of kilogram-weight (kg. wt) which is often writing as 'kgf' in engineering literature.

Another still bigger ***gravitational*** unit commonly used in traction work is tonne-weight (t-wt)

$$1\ \text{t-wt} = 1000\ \text{kg-wt} = 1000 \times 9.8\ \text{N} = 9800\ \text{N}$$

(*i*) Absolute Unit of Weight

It is called newton (N) whose definition may be obtained from Newton's Second Law of Motion.

Commonly used multiple is kilo-newton (kN). Obviously, 1 kN = 1000 N = 10^3 N.

For example, if a mass of 200 kg has to be given an acceleration of 2.5 m/s^2, force required is $F = 200 \times 2.5 = 500$ N.

If a train of mass 500 tonne has to be given an acceleration of 0.6 m/s^2, force required is

$$F = ma = (500 \times 1000) \times 0.6 = 300{,}000\ \text{N} = 300\ \text{kN}$$

(*ii*) Gravitational Unit of Weight

It is 'g' times bigger than newton. It is called kilogram-weight (kg.wt.)

$$1\ \text{kg.wt} = g\ \text{newton} = 9.81\ \text{N} \cong 9.8\ \text{N}$$

Unfortunately, the word 'wt' is usually omitted from kg-wt when expressing the weight of the body on the assumption that it can be understood or inferred from the language used.

Take the statement "a body has a *weight* of 100 kg". It looks as if the weight of the body has been expressed in terms of the mass unit 'kg'. To avoid this confusion, statement should be 'a body has a weight of 100 kg. wt.' But the first statement is justified by the writers on the ground that since the word 'weight' has already been used in the statement, it should be automatically understood by the readers that 'kg' is not the 'kg' of mass but is kg-wt. It would be mass kg if the statement is 'a body has a mass of 100 kg'. Often kg-wt is written as 'kgf' where 'f' is the first letter of the word force and is added to distinguish it from kg of mass.

Now, consider the statement "a body *weighing* 500 kg travels with a speed of 36 km/h.........."

Now, weight of the body W = 500 kg.wt. = 500 $\cdot$ 9.8 N

Since we know the weight of the body, we can find its mass from the relation $W = mg$. But while using this equation, it is essential that we must ***consistently* use** the ***absolute*** units only. In this equation, W must be in newton (not in kg. wt), m in kg and g in m/s^2.

$\therefore \quad 500 \cdot 9.8 = m \cdot 9.8 \; ; \qquad \therefore \quad m = 500$ kg

It means that a body which *weighs* 500 kg (wt) has a *mass* of 500 kg.

As a practical rule, weight of a body in **gravitational** units is numerically equal to its mass in **absolute** units. This simple fact must be clearly understood to avoid any confusion between weight and mass of a body.

A train which weighs 500 tonne has a mass of 500 tonne as proved below :

train weight, W = 500 tonne-wt = 500 $\cdot$ 1000 kg-wt = 500 $\cdot$ 1000 $\cdot$ 9.8 N

Now, $W = mg$; $\quad \therefore \quad 500 \cdot 1000 \cdot 9.8 = m \cdot 9.8$

$\therefore \quad m$ = 500 $\cdot$ 1000 kg = 500 $\cdot$ 1000/1000 = 500 tonne

To avoid this unfortunate confusion, it would be helpful to change our terminology. For example, instead of saying "a train weighing 500 tonne is........" it is better to say "a 500-t train is ...." or "a train having a mass of 500 t is ...."

In order to remove this confusion, SI system of units has disallowed the use of gravitational units. There will be no confusion if ***we consistently use only absolute units***.

43.34. Quantities Involved in Traction Mechanics

Following principal quantities are involved in train movement :

D	=	distance between stops	M	=	dead mass of the train
M_e	=	effective mass of the train	W	=	dead weight of the train
W_e	=	effective weight of the train	α	=	accelaration during starting period
β_c	=	retardation during coasting	β	=	retardation during braking
V_a	=	average speed	V_m	=	maximum (or crest) speed.
t	=	total time for the run	t_1	=	time of acceleration
t_2	=	time of free running = $t - (t_1 + t_3)$	t_3	=	time of braking
F_t	=	tractive effort	T	=	torque

43.35. Relationship Between Principal Quantities in Trapezoidal Diagram

As seen from Fig. 43.11.

$$\alpha = V_m / t_1 \quad \text{or} \quad t_1 = V_m / \alpha$$

$$\beta = V_m / t_3 \quad \text{or} \quad t_3 = V_m / \beta$$

As we know, total distance D between the two stops is given by the area of trapezium $OABC$.

$$\therefore \quad D = \text{area } OABC$$

$$= \text{area } OAD + \text{area } ABED + \text{area } BCE$$

$$= \frac{1}{2} V_m t_1 + V_m t_2 + \frac{1}{2} V_m t_3$$

$$= \frac{1}{2}V_m t_1 + V_m[t-(t_1+t_3)] + \frac{1}{2}V_m t_3$$

$$= V_m\left[\frac{t_1}{2}+t-t_1-t_3+\frac{t_3}{2}\right]$$

$$= V_m\left[t-\frac{1}{2}(t_1+t_3)\right]$$

$$= V_m\left[t-\frac{V_m}{2}\left(\frac{1}{\alpha}+\frac{1}{\beta}\right)\right]$$

Let, $K = \frac{1}{2}\left(\frac{1}{\alpha}+\frac{1}{\beta}\right)$. Substituting this value of K in the above equation, we get

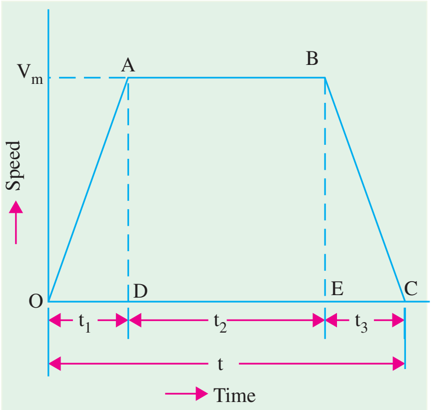


Fig. 43.11

$$D = V_m(t-KV_m)$$

or $KV_m^2 - V_m t + D = 0$ ...(*i*)

$$\therefore \quad V_m = \frac{t \pm \sqrt{t^2-4KD}}{2K}$$

Rejecting the positive sign which gives impracticable value, we get

$$V_m = \frac{t \pm \sqrt{t^2-4KD}}{2K}$$

From Eq. (*i*) above, we get

$$KV_m^2 = V_m t - D \quad \text{or} \quad K = \frac{t}{V_m}-\frac{D}{V_m^2} = \frac{D}{V_m^2}\left(V_m\cdot\frac{t}{D}-1\right)$$

Now, $\boxed{V_a = \frac{D}{t}}$ $\quad\therefore\quad$ $\boxed{K = \frac{D}{V_m^2}\left(\frac{V_m}{V_a}-1\right)}$

Obviously, if V_m, V_a and D are given, then value of K and hence of α and β can be found (Ex. 43.2).

43.36. Relationship Between Principal Quantities in Quadrilateral Diagram

The diagram is shown in Fig. 43.12. Let β_c represent the retardation during coasting period. As before,

$$t_1 = V_1/\alpha,\ t_2 = (V_2-V_1)/\beta_c \text{ and } t_3 = V_2/\beta$$

$$D = \text{area } OABC$$

$$= \text{area } OAD + \text{area } ABED + \text{area } BCE$$

$$= \frac{1}{2}V_1 t_1 + t_2\left(\frac{V_1+V_2}{2}\right)+\frac{1}{2}V_2 t_3$$

$$= \frac{1}{2}V_1(t_1+t_2)+\frac{1}{2}V_2(t_2+t_3)$$

$$= \frac{1}{2}V_1(t-t_3)+\frac{1}{2}V_2(t-t_1)$$

$$= \frac{1}{2}t(V_1+V_2)-\frac{V_1 t_1}{2}-\frac{V_1 t_3}{2}$$

$$= \frac{1}{2}t(V_1+V_2)-\frac{1}{2}V_1V_2\left(\frac{1}{\alpha}+\frac{1}{\beta}\right)$$

$$= \frac{1}{2}t(V_1+V_2)-KV_1V_2$$

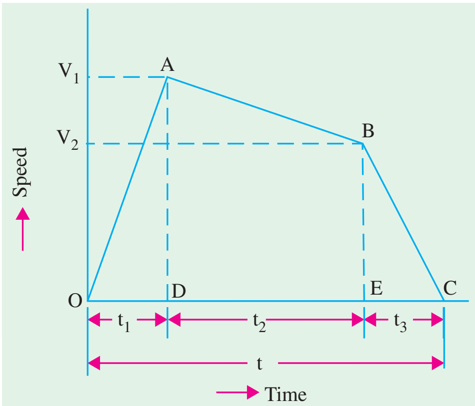


Fig. 43.12

where $K = \frac{1}{2}\left(\frac{1}{\alpha}+\frac{1}{\beta}\right) = \frac{\alpha+\beta}{2\alpha\beta}$ Also, $\beta_c = \frac{(V_1 - V_2)}{t_2}$

$$\therefore \quad V_2 = V_1 - \beta_c t_2 = V_1 - \beta_c (t - t_1 - t_3)$$

$$= V_1 - \beta_c\left(t - \frac{V_1}{\alpha} - \frac{V_2}{\beta}\right) = V_1 \beta_c\left(t - \frac{V_1}{\alpha}\right) + \beta_c \frac{V_2}{\beta}$$

$$\text{or} \quad V_2\left(1 - \frac{\beta_c}{\beta}\right) = V_1 - \beta_c\left(t - \frac{V_1}{\alpha}\right) \qquad \therefore \quad V_2 = \frac{V_1 - \beta_c (t - V_1/\alpha)}{(1 - \beta_c/\beta)}$$

Example 43.1. *A suburban train runs with an average speed of 36 km/h between two stations 2 km apart. Values of acceleration and retardation are 1.8 km/h/s and 3.6 km/h/s.*

Compute the maximum speed of the train assuming trapezoidal speed/time curve.

(Electric Traction, Punjab Univ. 1994)

Solution. Now, $V_a = 36$ km/h $= 36 \times 5/18 = 10$ m/s

$$\alpha = 1.8 \text{ km/h/s} = 1.8 \times 5/18 = 0.5 \text{ m/s}^2,\ \beta = 3.6 \text{ km/h/s} = 3.6 \times 5/18 = 1.0 \text{ m/s}^2$$

$$t = D/V_a = 2000/10 = 200 \text{ s} ;\ K = (\alpha + \beta)/2\alpha\beta = (0.5 + 1.0)/2 \times 0.5 \times 1 = 1.5$$

$$V_m = \frac{t - \sqrt{t^2 - 4KD}}{2K} = \frac{200 - \sqrt{200^2 - 4 \times 1.5 \times 2000}}{2 \times 1.5}$$

$$= 11 \text{ m/s} = 11 \times 18/5$$

$$= \mathbf{39.6\ km/h}$$

Electric traction provides high starting torque and low maintenance costs making it the best choice for trains

Example 43.2. *A train is required to run between two stations 1.5 km apart at a schedule speed of 36 km/h, the duration of stops being 25 seconds. The braking retardation is 3 km/h/s. Assuming a trapezoidal speed/time curve, calculate the acceleration if the ratio of maximum speed to average speed is to be 1.25*

(Elect. Power, Bombay Univ. 1980)

Solution. Here, $D = 1500$ m ; schedule speed $= 36$ km/h $= 36 \times 5/18 = 10$ m/s

$$\beta = 3 \text{ km/h/s} = 3 \times 5/18 = 5/6 \text{ m/s}^2$$

Schedule time of run $= 1500/10 = 150$ s ; Actual time of run $= 150 - 25 = 125$ s

$$\therefore \quad V_a = 1500/125 = 12 \text{ m/s} ; \quad V_m = 1.25 \cdot 12 = 15 \text{ m/s}$$

$$\text{Now,} \quad K = \frac{D}{V_m^2}\left(\frac{V_m}{V_a} - 1\right) = \frac{1500}{15^2}(1.25 - 1) = \frac{5}{3}$$

$$\text{Also,} \quad K = \frac{1}{2}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right) \quad \text{or} \quad \frac{5}{3} = \frac{1}{2}\left(\frac{1}{\alpha} + \frac{6}{5}\right)$$

$$\therefore \quad \alpha = 0.47 \text{ m/s}^2 = 0.47 \cdot 18/5 = \mathbf{1.7\ km/h/s}$$

Example 43.3. *Find the schedule speed of an electric train for a run of 1.5 km if the ratio of its maximum to average speed is 1.25. It has a braking retardation of 3.6 km/h/s, acceleration of 1.8 km/h/s and stop time of 21 second. Assume trapezoidal speed/time curve.*

Solution. $\alpha = 1.8 \times 5/18 = 0.5 \text{ m/s}^2$, $\beta = 3.6 \times 5/18 = 1.0 \text{ m/s}^2$

$D = 1.5 \text{ km} = 1500 \text{ m}$

$$K = \frac{1}{2}\left(\frac{1}{0.5}+\frac{1}{1}\right) = \frac{3}{2} \qquad \text{Now,} \quad K = \frac{D}{V_m^2}\left(\frac{V_m}{V_a}-1\right)$$

or
$$V_m^2 = \frac{D}{K}\left(\frac{V_m}{V_a}-1\right) \qquad \therefore \quad V_m^2 = \frac{1500}{3/2}(1.25-1) = 250 \text{ ; } V_m = 15.8 \text{ m/s}$$

$V_a = V_m/1.25 = 15.8/1.25 = 12.6$ m/s

Actual time of run = 1500/12.6 = 119 seconds

Schedule time = 119 + 21 = 140 second

∴ Schedule speed = 1500/140 = 10.7 m/s = **38.5 km/h**

Example 43.4. *A train runs between two stations 1.6 km apart at an average speed of 36 km/h. If the maximum speed is to be limited to 72 km/h, acceleration to 2.7 km/h/s, coasting retardation to 0.18 km/h/s and braking retardation to 3.2 km/h/s, compute the duration of acceleration, coasting and braking periods.*

Assume a simplified speed/time curve.

Solution. Given : $D = 1.6 \text{ km} = 1600 \text{ m}$, $V_a = 36 \text{ km/h} = 10 \text{ m/s}$

$V_1 = 72 \text{ km/h} = 20 \text{ m/s}$; $\alpha = 2.7 \text{ km/h/s} = 0.75 \text{ m/s}^2$

$\beta_c = 0.18 \text{ km/h/s} = 0.05 \text{ m/s}^2$; $\beta = 3.6 \text{ km/h/s} = 1.0 \text{ m/s}^2$

With reference to Fig. 43.12, we have

Duration of acceleration, $t_1 = V_1/\alpha = 20/0.75 = 27$ s

Actual time of run, t = 1600/10 = **160 s**

Duration of braking, $t_3 = V_2/1.0 = V_2$ second

Duration of coasting, $t_2 = (V_1 - V_2)/\beta_c = (20 - V_2)/0.05 = (400 - 20\,V_2)$ second

Now, $t = t_1 + t_2 + t_3$ or $160 = 27 + (400 - 20\,V_2) + V_2$ $\therefore$ $V_2 = 14$ m/s

∴ $t_2 = (20 - 14)/0.05 = 120$ s ; $t_3 = 14/1.0 =$ **14 s**

43.37. Tractive Effort for Propulsion of a Train

The tractive effort (F_t) is the force developed by the traction unit at the rim of the driving wheels for moving the unit itself and its train (trailing load). The tractive effort required for train propulsion on a *level track* is

$$F_t = F_a + F_r$$

If gradients are involved, the above expression becomes

$$F_t = F_a + F_g + F_r \qquad \text{— for ascending gradient}$$
$$= F_a - F_g + F_r \qquad \text{— for descending gradient}$$

where
F_a = force required for giving linear acceleration to the train
F_g = force required to overcome the effect of gravity
F_r = force required to overcome resistance to train motion.

(*a*) Value of F_a

If M is the dead (or stationary) mass of the train and a its linear acceleration, then

$$F_a = Ma$$

Since a train has rotating parts like wheels, axles, motor armatures and gearing etc., its *effective* (or accelerating) mass M_e is more (about 8 – 15%) than its stationary mass. These parts have to be given angular acceleration at the same time as the whole train is accelerated in the linear direction. Hence, $F_e = M_e a$

(*i*) If M_e is in kg and α in m/s^2, then $F_a = M_e\, a$ newton

(*ii*) If M_e is in tonne and α in km/h/s, then converting them into absolute units, we have

$$F_a = (1000\, M_e) \times (1000/3600)\, a = 277.8\, M_e\, a \text{ newton}$$

(*b*) Value of F_g

As seen from Fig. 43.13, $F_g = W \sin\theta = Mg \sin\theta$

In railway practice, gradient is expressed as the rise (in metres) a track distance of 100 m and is called percentage gradient.

$$\therefore \quad \% G = \frac{BC}{AC/100} = 100\frac{BC}{AC} = 100 \sin\theta$$

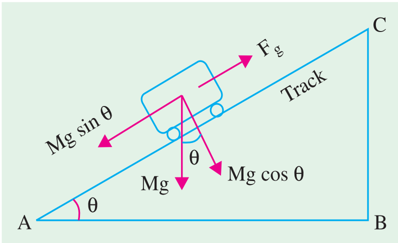


Fig. 43.13

Substituting the value of sin θ in the above equation, we get

$$F_g = Mg\, G/100 = 9.8 \times 10^{-2}\, MG$$

(*i*) When M is in kg, $F_g = 9.8 \times 10^{-2}\, MG$ newton

(*ii*) When M is given in tonne, then

$$F_g = 9.8 \times 10^{-2}\,(1000\, M)\, G = 98\, MG \text{ newton}$$

(*c*) Value of F_r

Train resistance comprises all those forces which oppose its motion. It consists of mechanical resistance and wind resistance. Mechanical resistance itself is made up of internal and external resistances. The internal resistance comprises friction at journals, axles, guides and buffers etc. The external resistance consists of friction between wheels and rails and flange friction etc. Mechanical resistance is almost independent of train speed but depends on its weight. The wind friction varies directly as the square of the train speed.

If r is specific resistance of the train *i.e.* resistance offered per unit mass of the train, then $F_r = M.r$.

(*i*) If r is in newton per kg of train mass and M is the train mass in kg, then

$$F_r = M.r \text{ newton}$$

(*ii*) If r is in newton per tonne train mass (N/t) and M is in tonne (t), then

$$F_r = M \text{ tonne} \times r = M_r \text{ newton*}$$

Hence, expression for total tractive effort becomes

$$F_t = F_a \pm F_g + F_r = (277.8\, \alpha\, M_e \pm 98\, MG + Mr) \text{ newton}$$

Please remember that here M is in tonne, α in km/h/s, G is in metres per 100 m of track length (*i.e.* % G) and r is in newton/tonne (*N/t*) of train mass.

The positive sign for F_g is taken when motion is along an ascending gradient and negative sign when motion is along a descending gradient.

43.38. Power Output from Driving Axles

If F_t is the tractive effort and ν is the train velocity, then

$$\text{output power} = F_t \times \nu$$

(*i*) If F_t is in newton and ν in m/s, then

$$\text{output power} = F_t \times \nu \text{ watt}$$

(*ii*) If F_t is in newton and ν is in km/h , then converting ν into m/s, we have

* If r is in kg (wt) per tonne train mass and M is in tonne, then $F_r = M$ tonne × (r × 9.8) newton/tonne = 9.8 Mr newton.

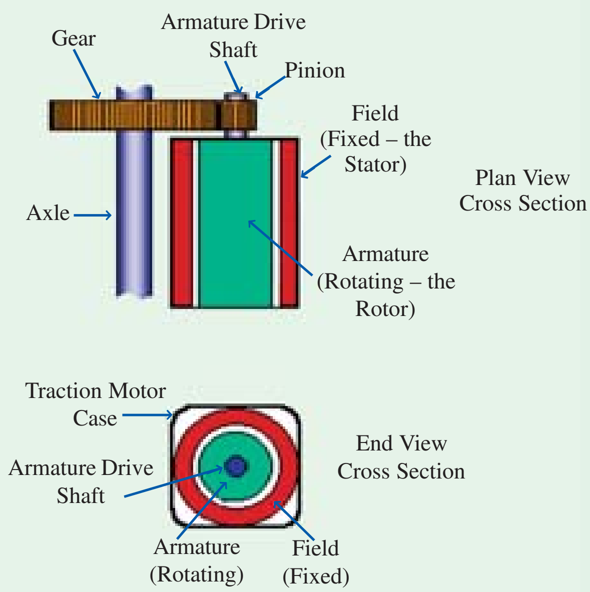


Diagram Shows how a DC motor drives the axle through a pinion and gearwheel

Traction motor schematic diagram

$$\text{output power} = F_t \times \left(\frac{1000}{3600}\right) \nu \text{ watt} = \frac{F_t\, \nu}{3600} \text{ kW}$$

If η is the efficiency of transmission gear, then power output of motors is

$$= F_t \,.\, \nu/\eta \text{ watt} \qquad \text{— } \nu \text{ in m/s}$$

$$= \frac{F_t\, \nu}{3600\, \eta} \text{ kW} \qquad \text{— } \nu \text{ in km/h}$$

43.39. Energy Output from Driving Axles

Energy (like work) is given by the product of power and time.

$$E = (F_t \times \nu) \times t = F_t \times (\nu \times t) = F_t \times D$$

where D is the distance travelled in the direction of tractive effort.

Total energy output from driving axles for the run is

$$E = \text{energy during acceleration} + \text{energy during free run}$$

As seen from Fig. 43.11

$$E = F_t \times \text{area } OAD + F_t' \times \text{area } ABED = F_t \times \frac{1}{2} V_m t_1 + F_t' \times \frac{1}{2} V_m t_2$$

where F_t is the tractive effort during accelerating period and F_t' that during free-running period. Incidentally, F_t will consist of all the three components given in Art. 43.37 whereas F_t' will consist of (98 $MG + Mr$) provided there is an ascending gradient.

43.40. Specific Energy Output

It is the energy output of the driving wheel expressed in watt-hour (Wh) per tonne-km (t-km) of the train. It can be found by first converting the energy output into Wh and then dividing it by the mass of the train in tonne and route distance in km.

Hence, unit of specific energy output generally used in railway work is : Wh/tonne-km (Wh/t-km).

43.41. Evaluation of Specific Energy Output

We will first calculate the total energy output of the driving axles and then divide it by train mass in tonne and route length in km to find the specific energy output. It will be presumed that :

(*i*) there is a gradient of G throughout the run and

(*ii*) power remains ON upto the end of free run in the case of trapezoidal curve (Fig. 43.11) and upto the accelerating period in the case of quadrilateral curve (Fig. 43.12).

Now, output of the driving axles is used for the following purposes :

1. for accelerating the train **2.** for overcoming the gradient

3. for overcoming train resistance.

(*a*) Energy required for train acceleration (E_a)

As seen from trapezoidal diagram of Fig. 43.11,

$$E_a = F_a \cdot \text{ distance } OAD = 277.8\,\alpha\,M_e \times \frac{1}{2}\,V_m.t_1 \text{ joules}$$

$$= 277.8\,\alpha\,M_e \times \frac{1}{2}\,V_m \times \frac{V_m}{\alpha} \text{ joules} \qquad \left(\text{फ}t_1 = \frac{V_m}{\alpha}\right)$$

$$= 277.8\,\alpha\,M_e \times \left[\frac{1}{2}.\frac{V_m \times 1000}{3600} \times \frac{V_m}{\alpha}\right] \text{ joules}$$

It will be seen that since V_m is in km/h, it has been converted into m/s by multiplying it with the conversion factor of (1000/3600). In the case of (V_m /*t*), conversion factors for V_m and a being the same, they cancel out. Since 1 Wh = 3600 J.

$$\therefore \qquad E_a = 277.8\,\alpha\,M_e \left[\frac{1}{2}.\frac{V_m \times 1000}{3600} \times \frac{V_m}{\alpha}\right] \text{Wh} = 0.01072\,\frac{V_m^2}{M_e} \text{ Wh}$$

(*b*) Energy required for over coming gradient (E_g)

$$E_g = F_g \times D'$$

where '*D*′' is the ***total distance over which power remains*** ON. Its maximum value equals the distance represented by the area *OABE* in Fig. 43.11 *i.e.* from the start to the end of free-running period in the case of trapezoidal curve [as per assumption (*i*) above].

Substituting the value of F_g from Art. 43.37, we get

$$E_g = 98\,MG.\,(1000\,D') \text{ joules} = 98{,}000\,MGD' \text{ joules}$$

It has been assumed that *D*′ is in km.

When expressed in Wh, it becomes

$$E_g = 98{,}000\,MGD'\,\frac{1}{3600} \text{ Wh} = 27.25\,MGD' \text{ Wh}$$

(*c*) Energy required for overcoming resistance (E_r)

$$E_r = F_r \times D' = M\,.\,r \times (1000\,D') \text{ joules} \qquad \text{— } D' \text{ in km}$$

$$= \frac{1000\,Mr\,D'}{3600} \text{ Wh} = 0.2778\,Mr\,D' \text{ Wh} \qquad \text{— } D' \text{ in km}$$

∴ total energy output of the driving axles is

$$E = E_a + E_g + E_r$$
$$= (0.01072\ V_m^2/M_e + 27.25\ MGD' + 0.2778\ Mr\ D'\ \text{Wh}$$

Specific energy output

$$E_{spo} = \frac{E}{M \times D} \qquad \text{— } D \text{ is the } \textit{total} \text{ run length}$$
$$= \left(0.01072 \frac{V_m^2}{D} \cdot \frac{M_e}{M} + 27.25\ G\ \frac{D'}{D} + 0.2778\ r\ \frac{D'}{D}\right) \text{Wh/t-km}$$

It may be noted that *if there is no gradient*, then

$$E_{spo} = \left(0.01072 \frac{V_m^2}{D} \cdot \frac{M_e}{M} + 0.2778\ r\ \frac{D'}{D}\right) \text{Wh/t-km}$$

Alternative Method

As before, we will consider the trapezoidal speed/time curve. Now, we will calculate energy output not **force-wise** but **period-wise**.

(*i*) Energy output during accelerating period

$$E_a = F_t \times \text{distance travelled during accelerating period}$$
$$= F_t \times \text{area } OAD \qquad \text{—Fig. 43.11}$$
$$= F_t \times \frac{1}{2} V_m\ t_1 = \frac{1}{2} F_t . V_m . \frac{V_m}{\alpha}$$
$$= \frac{1}{2} . F_t \left(\frac{1000}{3600} . V_m\right) . \frac{V_m}{\alpha} \text{ joules}$$
$$= \frac{1}{2} . F_t \left(\frac{1000}{3600} . V_m\right) . \frac{V_m}{\alpha} . \frac{1}{3600} \text{ Wh}$$

Substituting the value of F_t, we get

$$E_a = \frac{1000}{(3600)^2} . \frac{V_m^2}{2\alpha} (277.8\ \alpha\ M_e + 98\ MG + Mr) \text{ Wh}$$

It must be remembered that during this period, ***all the three forces are at work*** (Art. 43.37)

(*ii*) Energy output during free-running period

Here, work is required only against two forces *i.e.* gravity and resistance (as mentioned earlier).

Energy $E_{fr} = F_t' \times \text{area } ABED$ —Fig. 43.11

$$= F_t' \times (V_m \times t_2) = F_t' \times \left(\frac{1000}{3600} V_m\right) . t_2 \text{ joules}$$
$$= F_t' \times \left(\frac{1000}{3600} V_m\right) \times t_2 \times \frac{1}{3600} \text{ Wh} = \left(\frac{1000}{3600}\right) F_t' \times V_m\ t_2 . \frac{1}{3600} \text{ Wh}$$
$$= \left(\frac{1000}{3600}\right) . F_t' \times D_{fr} \text{ Wh} = \left(\frac{1000}{3600}\right) (98\ MG + Mr)\ D_{fr} \text{ Wh}$$

where D_{fr} is the distance in km travelled during the free-running period*

Total energy required is the sum of the above two energies.

$$\therefore\ E = E_a + E_{fr}$$
$$= \frac{1000}{(3600)^2} \frac{V_m^2}{2\alpha} (277.8\ \alpha . M_e + 98\ MG + Mr) + \frac{1000}{3600} (98\ MG + Mr)\ D_{fr} \text{ Wh}$$

---

* D_{fr} = velocity in km/h × time in hours
= $V_m \times (t_2/3600)$ because times are always taken in seconds.

$$= \frac{1000}{(3600)^2}\frac{V_m^2}{2\,\alpha}\,277.8\,\alpha\,M_e + \frac{1000}{(3600)^2}\cdot\frac{V_m^2}{2\,\alpha}\,(98\,MG + Mr) + \frac{1000}{3600}\,(98\,MG + Mr)\,.\,D_{fr}\ \text{Wh}$$

$$= 0.01072\ V_m^2\,.\,M_e + \frac{1000}{3600}\,(98\ MG + Mr)\left(\frac{V_m^2}{2\alpha\times 3600} + D_{fr}\right)\text{Wh}$$

Now, $$\frac{V_m^2}{2\alpha\times 3600} = \frac{1}{2}\left(\frac{V_m}{3600}\right)\cdot\frac{V_m}{\alpha} = \frac{1}{2}\left(\frac{V_m}{3600}\right)\cdot t_1$$

$=$ distance travelled during accelerating period *i.e.* D_a

$$\therefore \quad E = 0.01072\ V_m^2\,.\,M_e + \frac{1000}{3600}\ (98\ MG + Mr)\ (D_a + D_{fr})\ \text{Wh}$$

$$= 0.01072\ V_m^2\,.\,M_e + (27.25\ MG + 0.2778\ Mr)\ D'\ \text{Wh}$$

It is the same expression as found above.

43.42. Energy Consumption

It equals the total energy input to the traction motors from the supply. It is usually expressed in Wh which equals 3600 J. It can be found by dividing the energy output of the driving wheels with the combined efficiency of transmission gear and motor.

$$\therefore \quad \text{energy consumption} = \frac{\text{output of driving axles}}{\eta_{motor}\times\eta_{gear}}$$

43.43. Specific Energy Consumption

It is the energy consumed (in Wh) per tonne mass of the train per km length of the run.

Specific energy consumption,

$$E_{spc} = \frac{\text{total energy consumed in Wh}}{\text{train mass in tonne}\times\text{run length in km}} = \frac{\text{specific energy output}}{\eta}$$

where η = overall efficiency of transmission gear and motor = $\eta_{gear}\times\eta_{motor}$

As seen from Art. 43.41, specific energy consumption is

$$E_{spc} = \left(0.01072\,.\,\frac{V_{m^2}}{\eta D}\,.\,\frac{M_e}{M} + 27.25\,\frac{G}{\eta}\,.\,\frac{D'}{D} + 0.2778\,\frac{r}{\eta}\,.\,\frac{D'}{D}\right)\text{Wh/t-km}$$

If no gradient is involved, then specific enrgy consumption is

$$E_{spc} = \left(0.01072\,.\,\frac{V_{m^2}}{\eta D}\,.\,\frac{M_e}{M} + 0.2778\,\frac{r}{\eta}\,.\,\frac{D'}{D}\right)\text{Wh/t-km}$$

The specific energy consumption of a train running at a given schedule speed is influenced by **1.** Distance between stops **2.** Acceleration **3.** Retardation **4.** Maximum speed **5.** Type of train and equipment **6.** Track configuration.

43.44. Adhesive Weight

It is given by the total weight carried on the driving wheels. Its value is $W_a = x\ W$, where W is dead weight and x is a fraction varying from 0.6 to 0.8.

43.45. Coefficient of Adhesion

Adhesion between two bodies is due to interlocking of the irregularities of their surfaces in contact. The adhesive weight of a train is ***equal to the total weight to be carried on the driving***

wheels. It is less than the dead weight by about 20 to 40%.

If $x = \dfrac{\text{adhesive weight, } W_a}{\text{dead weight } W}$, then, $W_a = x\,W$

Let, F_t = tractive effort to slip the wheels

or

= maximum tractive effort possible without wheel slip

Coefficient of adhesion, $\mu_a = F_t / W_a$

$\therefore$ $F_t = \mu_a W_a = \mu_a xW = \mu_a x\,Mg$

If M is in tonne, then

$$F_t = 1000 \cdot 9.8\,x\,\mu_a M = 9800\,\mu_a\,x\,M \text{ newton}$$

It has been found that tractive effort can be increased by increasing the motor torque but only upto a certain point. Beyond this point, any increase in motor torque does not increase the tractive effort but merely causes the driving wheels to slip. It is seen from the above relation that for increasing F_t, it is not enough to increase the kW rating of the traction motors alone but the weight on the driving wheels has also to be increased.

Adhesion also plays an important role in braking. If braking effort exceeds the adhesive weight of the vehicle, skidding takes place.

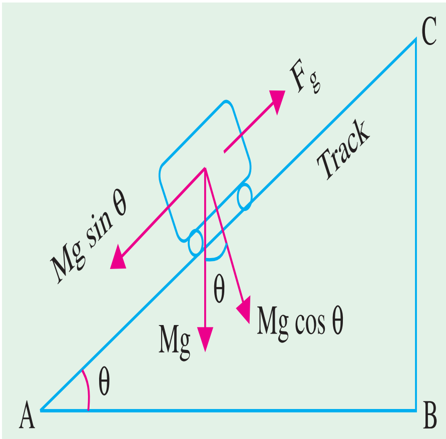


Fig. 43.14

43.46. Mechanism of Train Movement

The essentials of driving mechanism in an electric vehicle are illustrated in Fig. 43.14. The armature of the driving motor has a pinion which meshes with the gear wheel keyed to the axle of the driving wheel. In this way, motor torque is transferred to the wheel through the gear.

Let, T = torque exerted by the motor

F_1 = tractive effort at the pinion

F_t = tractive effort at the wheel

γ = gear ratio

Here, d_1, d_2 = diameters of the pinion and gear wheel respectively

D = diameter of the driving wheel

η = efficiency of power transmission from the motor to driving axle

Now, $T = F_1 \times d_1/2$ or $F_1 = 2T/d_1$

Tractive effort transferred to the driving wheel is

$$F_t = \eta F_1 \left(\frac{d_2}{D}\right) = \eta \cdot \frac{2T}{d_1}\left(\frac{d_2}{D}\right) = \eta\,T\left(\frac{2}{D}\right)\left(\frac{d_2}{d_1}\right) = 2\,\gamma\eta\,\frac{T}{D}$$

For obtaining motion of the train without slipping, $F_t \le \mu_a W_a$ where μ_a is the coefficient of adhesion (Art. 43.45) and W_a is the adhesive weight.

Example 43.5. *The peripheral speed of a railway traction motor cannot be allowed to exceed 44 m/s. If gear ratio is 18/75, motor armature diameter 42 cm and wheel diameter 91 cm, calculate the limiting value of the train speed.*

Solution. Maximum number of revolutions per second made by armature

$$= \frac{\text{armature velocity}}{\text{armature circumference}} = \frac{44}{0.42\,\pi} = \frac{100}{3}\text{ rps.}$$

Maximum number of revolutions per second made by the driving wheel

$$= \frac{100}{3} \cdot \frac{18}{75} = 8 \text{ rps.}$$

Maximum distance travelled by the driving wheel in one second

$$= 8 \cdot 0.91\,\pi \text{ m/s} = 22.88 \text{ m/s}$$

Hence, limiting value of train speed

$$= 22.88 \text{ m/s} = 22.88 \cdot 18/5 = \mathbf{82\ km/h}$$

Example 43.6. *A 250-tonne motor coach driven by four motors takes 20 seconds to attain a speed of 42 km/h, starting from rest on an ascending gradient of 1 in 80. The gear ratio is 3.5, gear efficiency 92%, wheel diameter 92 cm train resistance 40 N/t and rotational inertia 10 percent of the dead weight. Find the torque developed by each motor.*

Solution. $F_t = (277.8 \cdot M_e a + 98\text{ MG} + \text{Mr})$ newton

Now, $\alpha = V_m/t_1 = 42/20 = 2.1$ km/h/s Since gradient is 1 in 80, it becomes 1.25 in 100. Hence, percentage gradient $G = 1.25$. Also, $M_e = 1.1\ M$. The tractive effort at the driving wheel is

$$F_t = 277.8 \times (1.1 \times 250) \times 2.1 + 98 \times 250 \times 1.25 + 250 \times 40$$

$$= 160{,}430 + 30{,}625 + 10{,}000 = 201{,}055 \text{ N}$$

Now, $F_t = 2\gamma\eta T/D$ or $201{,}055 = 2 \times 3.5 \times 0.92 \times T/0.92$ $\therefore T = 28{,}744$ N–m

Torque developed by each motor = 28,744/4 = **7,186 N–m**

Example 43.7. *A 250-tonne motor coach having 4 motors, each developing a torque of 8000 N-m during acceleration, starts from rest. If up-gradient is 30 in 1000, gear ratio 3.5, gear transmission efficiency 90%, wheel diameter 90 cm, train resistance 50 N/t, rotational inertia effect 10%, compute the time taken by the coach to attain a speed of 80 km/h.*

If supply voltage is 3000 V and motor efficiency 85%, calculate the current taken during the acceleration period.

Solution. Tractive effort (Art. 43.46) at the wheel

$$= 2\gamma\eta T/D = 2 \times 3.5 \times 0.9 \times (8000 \times 4)/0.9 = 224{,}000 \text{ N}$$

Also, $F_t = (277.8\ a\ M_e + 98\ MG + Mr)$ newton

$$= (277.8 \times (1.1 \times 250) \times a + 98 \times 250 \times 3 + 250 \times 50 \text{ N}$$

$$= (76{,}395\ a + 86{,}000) \text{ N}$$

Equating the two expression for tractive effort, we get

$$224{,}000 = 76{,}395\ a + 86{,}000\ ;\ a = 1.8 \text{ km/h/s}$$

Time taken to achieve a speed of 80 km/h is

$$t_1 = V_m/a = 80/1.8 = \mathbf{44.4\ second}$$

Power taken by motors (Art. 41.36) is

$$= \frac{F_t \times v}{\eta} = \frac{F_t \times V_m}{\eta} = F_t \cdot \left(\frac{1000}{3600}\right) \cdot \frac{V_m}{\eta} \text{ watt}$$

$$= 22{,}000 \times 0.2778 \times 80/0.85 = 58.56 \times 10^5 \text{ W}$$

Total current drawn $= 55.56 \times 10^5/3000 = 1952$ A

Current drawn/motor $= 1952/4 = $ **488 A.**

Example 43.8. *A goods train weighing 500 tonne is to be hauled by a locomotive up an ascending gradient of 2% with an acceleration of 1 km/h/s. If coefficient of adhesion is 0.25, train resistance 40 N/t and effect of rotational inertia 10%, find the weight of locomotive and number of axles if load is not to increase beyond 21 tonne/axle.*

Solution. It should be clearly understood that a train weighing 500 tonne has a mass of 500 (Art. 43.33).

Tractive effort required is

$$F_t = (277.8\,a\,M_e + 98\,MG + Mr) \text{ newton} = M\left(277.8\,a \,.\, \frac{M_e}{M} + 98\,G + r\right) \text{ newton}$$

$$= M\,(277.8 \times 1 \times 1.1 + 98 \times 2 + 40) = 541.6\,M \text{ newton}$$

If M_L is the mass of the locomotive, then

$$F_t = 541.6\,(M + M_L) = 541.6\,(500 + M_L) \text{ newton}$$

Maximum tractive effort (Art. 43.45) is given by

$$F_t = 1000\,\mu_a\,M_L\,.\,g = 1000 \times 0.25\,M_L \times 9.8 \qquad \text{— } x = 1$$

$\therefore \quad 541.6\,(500 + M_L) = 1000 \cdot 0.25\,M_L \cdot 9.8 \qquad \therefore \quad M_L =$ **142 tonne**

Hence, weight of the locomotive is 142 tonne. Since, weight per axle is not to exceed 21 tonne, the number of axles required is = 142/21 = 7.

Example 43.9. *An electric locomotive weighing 100 tonne can just accelerate a train of 500 tonne (trailing weight) with an acceleration of 1 km/h/s on an up-gradient of 0.1%. Train resistance is 45 N/t and rotational inertia is 10%. If this locomotive is helped by another locomotive of weight 120 tonne, find :*

(*i*) *the trailing weight that can now be hauled up the same gradient under the same conditions.*

(*ii*) *the maximum gradient, if the trailing hauled load remains unchanged.*

Assume adhesive weight expressed as percentage of total dead weight as 0.8 for both locomotives. **(Utilization of Elect. Power ; AMIE, Summer)**

Solution. Dead weight of the train and locomotive combined = (100 + 500) = 600 tonne. Same is the value of the dead mass.

$$\therefore \quad F_t = (277.8a\,M_e + 98\,MG + Mr) \text{ newton}$$

$$= 277.8 \cdot 1 \cdot (1.1 \cdot 600) + 98 \cdot 600 \cdot 0.1 + 600 \cdot 45 = 216{,}228 \text{ N}$$

Maximum tractive effort (Art. 43.45) of the first locomotive

$$= 9800x\,\mu_a M_L = 9800 \cdot 0.8 \cdot \mu_a \cdot 1000 = 784{,}000\,\mu_a$$

$$\therefore \quad 784{,}000\mu_a = 216{,}288\,; \qquad \mu_a = 0.276$$

With two locomotive, $M_L' = (100 + 120) = 220$ tonne

$$\therefore \quad F_t = 9800\,x\,\mu_a M_L' = 9800 \times 0.8 \times 0.276 \times 220 = 476{,}045 \text{ N}$$

(*i*) Let trailing load which the two combined locomotives can haul be M tonne. In that case, total dead mass becomes $M = (100 + 120 + M) = (220 + M)$ tonne. Tractive effort required is

$$= (277.8\,M_e' + 98\,M'G + M'r) \text{ newton}$$

$$= M'\,(277.8 \times 1 \times 1.1 + 98 \times 0.1 + 45) = 360.4\,M' \text{ newton}$$

$\therefore \quad 360.4\,M' = 476{,}045;\ M' = 1321$ tonne $\quad \therefore$ trailing load, $M = 1321 - 220 =$ **1101 tonne**

(*ii*) Total hauled load = 500 + 100 + 120 = 720 tonne

Let G be the value of maximum percentage gradient. Then

$$F_t = (277.8\,a\,M_e + 98MG + Mr) \text{ newton} = M\left(277.8\,a\,\frac{M_e}{M} + 98G + r\right) \text{ newton}$$

$= 720\,(277.8 \times 1 \times 1.1 + 98G + 45)$ newton $= (252{,}418 + 70{,}560\,G)$ newton

Equating it with the combined tractive effort of the two locomotive as calculated above, we have,

$476{,}045 = 252{,}418 + 70{,}560\,G \qquad \therefore \quad G =$ **3.17 percent**

Example 43.10. *The average distance between stops on a level section of a railway is 1.25 km. Motor-coach train weighing 200 tonne has a schedule speed of 30 km/h, the duration of stops being 30 seconds. The acceleration is 1.9 km/h/s and the braking retardation is 3.2 km/h/s. Train resistance to traction is 45 N/t. Allowance for rotational inertia is 10%. Calculate the specific energy output in Wh/t-km. Assume a trapezoidal speed/time curve.* **(Elect. Power, Bombay Univ.)**

Solution. $\alpha = 1.9 \times 5/18 = 9.5/18 \text{ m/s}^2$: $\beta = 3.2 \times 5/18 = 8/9 \text{ m/s}^2$

$K = (\alpha + \beta)/2\alpha\beta = 1.5$; $D = 1.25 \text{ km} = 1250 \text{ m}$

Schedule time $= 1.25 \times 3600/30 = 150$ s. Running time $= 150 - 30 = 120$ s

$$V_m = \frac{t - \sqrt{t^2 - 4KD}}{2K} = \frac{120 - \sqrt{120^2 - 4 \times 1.5 \times 1250}}{2 \times 1.5} = 10.4 \text{ m/s} = \mathbf{37.4 \text{ km/h}}$$

Braking distance $D = V_m^2/2\beta = 10.42/2 \times (8/9) = 0.06$ km

$\therefore \quad D' = D -$ braking distance $= 1.25 - 0.06 = 1.19$ km

$$\text{Specific energy output} = 0.01072\,\frac{V_m^2}{D}\cdot\frac{M_e}{M} + 0.2778\,r\,\frac{D'}{D}$$

$$= 0.01072 \times \frac{37.4^2}{1.25} \times 1.1 + 0.2778 \times 50 \times \frac{1.19}{1.25} \text{ Wh/t-km}$$

$$= 16.5 + 13.2 = \mathbf{29.7 \text{ Wh/t-km}}$$

Example. 43.11. *A 300-tonne EMU is started with a uniform acceleration and reaches a speed of 40 km/h in 24 seconds on a level track. Assuming trapezoidal speed/time curve, find specific energy consumption if rotational inertia is 8%, retardation is 3 km/h/s, distance between stops is 3 km, motor efficiency is 0.9 and train resistance is 40 N/tonne.*

(Elect. Traction, AMIE Summer)

Solution. First of all, let us find D' – the distance upto which energy is consumed from the supply. It is the distance travelled upto the end of free-running period. It is equal to the total distance minus the distance travelled during braking.

Braking time, $t_2 = V_m/\beta = 40/3 = 13.33$ second

Distance travelled during braking period

$$= \frac{1}{2} V_m t_3 = \frac{1}{2} \times 40 \times \left(\frac{13.33}{3600}\right) = 0.074 \text{ km}$$

$\therefore \quad D' = D -$ braking distance $= 3 - 0.074 = 2.926$ km

Since, $M_e/M = 1.08$, using the relation derived in Art. 43.43, we get the value of specific energy consumption as

$$= \left(0.01072\,\frac{V_m^2}{\eta D}\cdot\frac{M_e}{M} + 0.2778\,\frac{r}{\eta}\,\frac{D'}{D}\right) \text{Wh/t-km}$$

$$= \left(0.01072 \times \frac{40^2}{0.9 \times 3} \times 1.08 + 0.2778 \times \frac{49}{0.9} \times \frac{2.926}{3}\right) = \mathbf{21.6 \text{ Wh/t-km.}}$$

Example 43.12. *An electric train accelerates uniformly from rest to a speed of 50 km/h in 25 seconds. It then coasts for 70 seconds against a constant resistance of 60 N/t and is then braked to rest with uniform retardation of 3.0 km/h/s in 12 seconds. Compute*

(i) uniform acceleration *(ii) coasting retardation*

(iii) *schedule speed if station stops are of 20-second duration*

Allow 10% for rotational inertia. How will the schedule speed be affected if duration of stops is reduced to 15 seconds, other factors remaining the same ?

Solution. *(i)* As seen from Fig. 43.15, $\alpha = V_1/t_1 = 50/25 =$ **2 km/h/s**

(ii) The speeds at points *B* and *C* are connected by the relation

$$0 = V_2 + \beta t_3 \quad \text{or} \quad 0 = V_2 + (-3) \times 12 \qquad \therefore \quad V_2 = 36 \text{ km/h}$$

Coasting retardation, $\beta_c = (V_2 - V_1)/t_2 = (36 - 50)/70 = -$ **0.2 km/h/s**

(iii) Distance travelled during acceleration

$$= \frac{1}{2} V_1 t_1 = \frac{1}{2} \times 50 \frac{\text{km}}{\text{h}} \times \frac{25}{3600} \text{ h}$$

$$= 0.174 \text{ km}$$

Distance travelled during coasting can be found from the relation

$$V_{22} - V_{12} = 2 \ \beta_c D \qquad \text{or}$$

$$D = (362 - 502)/2 \times -0.2 \times 3600$$

$$= 0.836 \text{ km}$$

Distance covered during braking

$$= \frac{1}{2} V_2 t_3 = \frac{1}{2} \times 36 \frac{\text{km}}{\text{h}} \times \frac{12}{3600} \text{ h}$$

$$= 0.06 \text{ km}$$

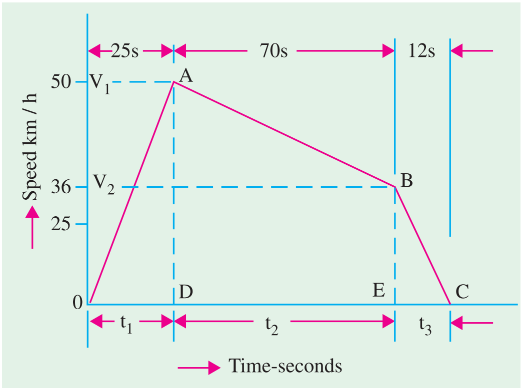


Fig. 43.15

Total distance travelled from start to stop

$$= 0.174 + 0.836 + 0.06 = 1.07 \text{ km}$$

Total time taken including stop time

$$= 25 + 70 + 12 + 20 = 127 \text{ second}$$

Schedule speed $= 1.07 \times 3600/127 =$ **30.3 km/s**

Schedule speed with a stop of 15 s is $= 1.07 \times 3600/122 =$ **31.6 km/h**

Example 43.13. *A 350-tonne electric train runs up an ascending gradient of 1% with the following speed/time curves :*

1. *uniform acceleration of 1.6 km/h/s for 25 seconds*
2. *constant speed for 50 seconds*
3. *coasting for 30 seconds*
4. *braking at 2.56 km/h/s to rest.*

Compute the specific energy consumption if train resistance is 50 N/t, effect of rotational inertia 10%, overall efficiency of transmission gear and motor, 75%.

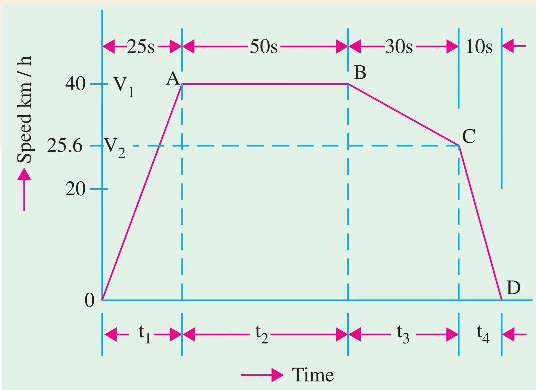


Fig. 43.16

Solution. As seen from Fig. 43.16, $V_1 = \alpha \,.\, t_1 = 1.6 \times 25 = 40$ km/h

Tractive force during coasting is

$$F_t = (98 \, MG + M.r)$$

$$= M \, (98 \times 1 + 50)$$

$$= 148 \, M \text{ newton}$$

Also, $F_t = 277.8 \, M_e \, \beta_c$ during coasting. Equating the two expressions, we get $277.8 \, M_e$

$. \beta_c = 148\, M$

$$\therefore \beta_c = \frac{148}{277.8} \cdot \frac{M}{M_e} = \frac{148}{277.8} \quad \frac{1}{1.1} ;$$

$$\beta_c = 0.48 \text{ km/h/s}$$

Now, $V_2 = V_1 + \beta_c t_3$

$= 40 + (-0.48) \cdot 30$

$= 25.6$ km/h

$t_4 = V_2 / \beta = 25.6/2.56 = 10$ second

Distance travelled during acceleration period $= \frac{1}{2} \cdot 40 \frac{\text{km}}{\text{h}} \quad \frac{25}{3600} \text{ h} = 0.139$ km

Distance travelled during constant speed period is $= V_1 \cdot t_2 = 40 \cdot 50/3600 = 0.555$ km

Distance travelled during coasting $= \left(\frac{V_1 + V_2}{2}\right) \cdot t_3 = \frac{40 + 25.6}{2} \cdot \frac{30}{3600} = 0.273$ km

Distance travelled during braking $= \frac{1}{2} V_2 t_4 = \frac{1}{2} \cdot 25.6 \cdot \frac{10}{3600} = 0.035$ km

Total distance between stops = 0.139 + 0.555 + 0.273 + 0.035 = 1.002 km

Distance travelled during acceleration and free-running period is

$$D' = 0.139 + 0.555 = 0.694 \text{ km}$$

Specific energy consumption (Art. 43.43) is

$$= \left(0.01072 \frac{V_m^2}{\eta D} \cdot \frac{M_e}{M} + 27.25 \frac{G}{\eta} \cdot \frac{D'}{D} + 0.2778 \frac{r}{\eta} \cdot \frac{D'}{D}\right) \text{Wh/t-km}$$

$$= \left(0.01072 \cdot \frac{40^2}{0.75 \cdot 1.002} \quad 1.1 + 27.25 \cdot \frac{1}{0.75} \cdot \frac{0.694}{1.002} + 0.2778 \cdot \frac{50}{0.75} \cdot \frac{0.694}{1.002}\right)$$

$= 25.1 + 25.2 + 12.8 =$ **63.1 Wh/t-km**

Example 43.14. *An ore-carrying train weighing 5000 tonne is to be hauled down a gradient of 1 : 50 at a maximum speed of 30 km/h and started on a level track at an acceleration of 0.29 km/h/s. How many locomotives, each weighing 75 tonne, will have to be employed ?*

Train resistance during starting = 29.4 N/t, Train resistance at 30 km/h = 49 N/t

Coefficient of adhesion = 0.3, Rotational inertia = 10%

(Utilization of Elect. Power, AMIE)

Solution. Downward force due to gravity

$= Mg \sin\theta = (5000 \cdot 1000) \cdot 9.8 \cdot 1/50 = 980{,}000$ N

Train resistance $= 49 \cdot 5000 = 245{,}000$ N

Braking force to be supplied by brakes = 980,000 – 245,000 = 735,000 N

Max. braking force which one locomotive can provide

$= 1000\ \mu_a Mg$ newton —M in tonne

$= 1000 \cdot 0.3 \cdot 75 \cdot 9.8 = 220{,}500$ N

No. of locomotives required for braking = 735,000/220,500 = 3.33

Since fraction is meaningless, it means that 4 locomotives are needed.

Tractive effort required to haul the train on level track

$= (277.8\ \alpha\ M_e + Mr)$ newton

$= 277.8 \times (5000 \times 1.1) \times 0.29 + 5000 \times 29.4 = 590{,}090$ N

No. of locomotives required = 590,090/220,500 = 2.68 ≅ **3**

It means that **4 locomotives** are enough to look after braking as well as starting.

Example 43.15. *A 200-tonne electric train runs according to the following quadrilateral speed/time curve:*

1. *uniform acceleration from rest at 2 km/h/s for 30 seconds*

2. *coasting for 50 seconds*

3. *duration of braking : 15 seconds*

If up-gradient is = 1%, train resistance = 40 N/t, rotational inertia effect = 10%, duration of stops = 15 s and overall efficiency of gear and motor = 75%, find

(i) schedule speed (ii) specific energy consumption (iii) how will the value of specific energy consumption change if there is a down-gradient of 1% rather than the up-gradient ?

(Electric Traction Punjab Univ. 1993)

Solution. $V_1 = \alpha . t_1 = 2 \times 30 = 60$ km/h/s

During coasting, gravity component and train resistance will cause coasting retardation β_c.

Retarding force = $(98\ MG + Mr)$ newton = $(98 \times 200 \times 1.0 + 200 \times 40) = 27{,}600$ N

As per Art, 43.37, $277.8\ M_e . \beta_c = 27{,}600$ or $277.8 \times (200 \times 1.1) \times \beta_c = 27{,}600$

$\therefore \qquad \beta_c = 0.45$ km/h/s

Now, $\qquad V_2 = V_1 + \beta_c t_2$ or $V_2 = 60 + (-0.45) \times 50 = 37.5$ km/h

Braking retardation $\beta = V_2/t_3 = 37.5/15 = 2.5$ km/h/s

Distance travelled during acceleration (area *OAD* in Fig. 43.17)

$$= \frac{1}{2} V_1 t_1 = \frac{1}{2} \times 60 \times \left(\frac{30}{3600}\right) = 0.25 \text{ km}$$

Distance travelled during coasting

$$= \text{area } ABED = \left(\frac{V_1 + V_2}{2}\right) \times t_2 = \left(\frac{60 + 37.5}{2}\right) \times \frac{50}{3600} = 0.677 \text{ km}$$

Distance travelled during braking

$$= \text{area } BCE = \frac{1}{2} V_2 t_3 = \frac{1}{2} \times 37.5 \times \frac{15}{3600} = 0.078 \text{ km}$$

Total distance travelled, $D = 0.25 + 0.677 + 0.078 = 1.005$ km

Total schedule time $= 30 + 50 + 15 + 15 = 110$ s

(i) $\therefore$ Schedule speed $= \dfrac{1.005}{110/3600}$ = **32.9 km/h**

(ii) As per Art. 43.43, specific energy consumption

$$= \left(0.01072 \frac{V_m^2}{\eta D} . \frac{M_e}{M} + 27.25 \frac{G}{\eta} . \frac{D'}{D} + 0.2778 . \frac{r}{\eta} . \frac{D'}{D}\right) \text{Wh/t-km}$$

$$= \left(0.01072 \times \frac{60^2}{0.75 \times 1.005} \times 1.1 + 27.25 \times \frac{1}{0.75} \times \frac{0.25}{1.005} + 0.2778 \times \frac{40}{0.75} \times \frac{0.25}{1.005}\right) \text{Wh/t-km}$$

(iii) the speed/time curve for this case is shown in Fig. 43.18. As before, $V_1 = 60$ km/h. Here, we will take $G = -1\%$

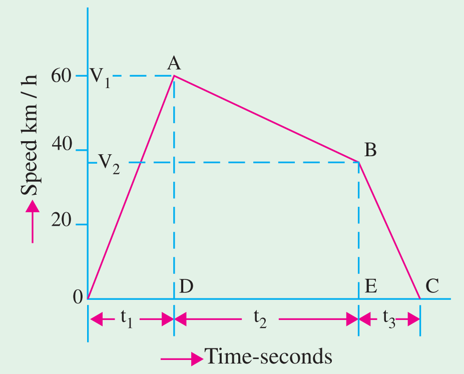


Fig. 43.17

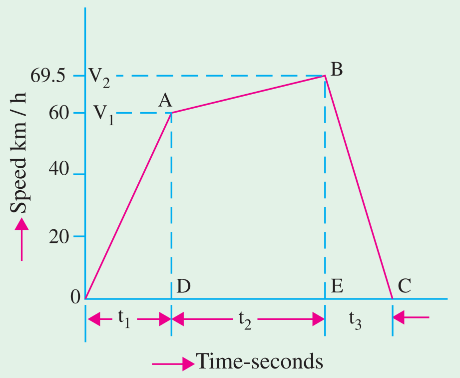


Fig. 43.18

$\therefore$ Retarding force = $(98\,MG + Mr)$ newton = $98 \cdot 200 \cdot (-1.0) + 200 \cdot 40 = -11{,}600$ N

The negative sign indicates that instead of being a retarding force, it is, in fact, an accelerating force. If α_c is the acceleration produced, then

$$11{,}600 = 277.8 \times (200 \times 1.1) \times \alpha_c$$

$$\alpha_c = 0.19 \text{ km/h/s}$$

Also, $$V_2 = V_1 + \alpha_c t_2 = 60 + 0.19 \times 50 = 69.5 \text{ km/h}$$

$$\beta = V_2 / t_3 = 69.5/15 = 4.63 \text{ km/h/s}$$

Distance travelled during acceleration = 0.25 km —as before

Distance travelled during coasting $= \dfrac{60 + 69.5}{2} \times \dfrac{50}{3600} = 0.9$ km

Distance travelled during braking $= \dfrac{1}{2} \times 69.5 \times \dfrac{15}{3600} = 0.145$ km

$\therefore$ $$D = 0.25 + 0.9 + 0.145 = 1.295 \text{ km}$$

Hence, specific energy consumption is

$$= \left(0.01072 \times \frac{60^2}{0.75 \times 1.295} \times 1.1 - 27.25 \times \frac{1}{0.75} \times \frac{0.25}{1.295} + 0.2778 \times \frac{40}{0.75} \times \frac{0.25}{1.295}\right) \text{Wh/t-km}$$

$= 43.7 - 7.01 + 2.86 =$ **39.55 Wh/t-km**

As seen, energy consumption has decreased from 69 to 39.55 Wh/t-km.

Example 43.16. *An electric train has an average speed of 45 kmph on a level track between stops 1500 m apart. It is accelerated at 1.8 kmphps and is braked at 3 kmphps. Draw the speed - time curve for the run.*

Solution.

Acceleration $\alpha = 1.8$ kmphps

Retardation $\beta = 3.0$ kmphps

Distance of run $S = 1.5$ km

Average speed $V_a = 45$ kmph

Time of run, $$T = \frac{S}{V_a} \times 3600 = \frac{1.5}{45} \times 3600 = 120 \text{ seconds.}$$

Using equation $$V_m = \frac{T}{2K} - \sqrt{\frac{T^2}{4K^2} - \frac{3600\,S}{K}}$$

Where $K = \frac{1}{2\alpha} + \frac{1}{2\beta} = \frac{1}{2 \cdot 1.8} + \frac{1}{2 \cdot 3.0} = 0.4444$

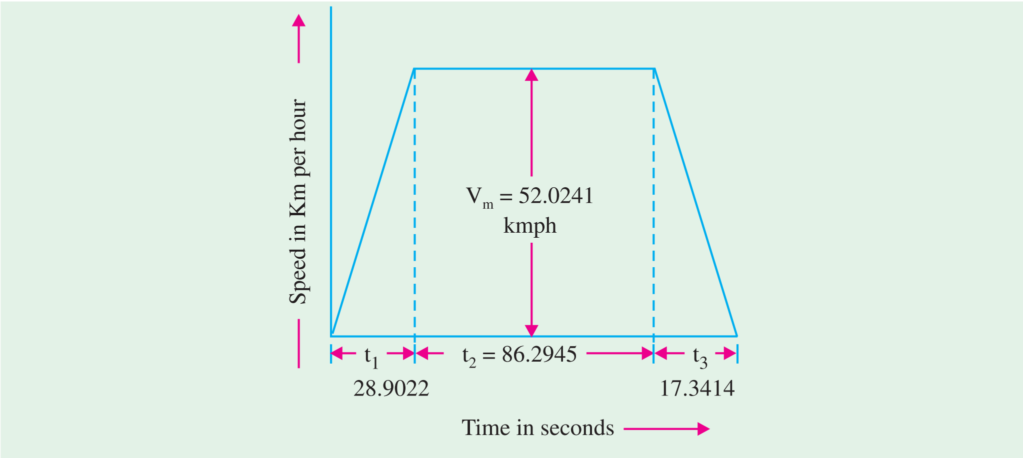


Fig. 43.19

$\therefore$ Maximum speed, $V_m = \frac{120}{2 \cdot 0.4444} - \sqrt{\frac{(120)^2}{(2 \cdot 0.4444)^2} - \frac{3600 \cdot 1.5}{0.4444}}$

$\therefore$ $V_m = 52.0241$ kmph

Acceleration period, $t_1 = \frac{V_m}{\alpha} = \frac{52.0241}{1.8} = 28.9022$ seconds

Braking period, $t_3 = \frac{V_m}{\beta} = \frac{52.0241}{3.0} = 17.3414$ seconds

Free running period, $t_2 = T - (t_1 + t_3) = 120 - (28.9622 + 17.3414) = 86.2945$ seconds

Example 43.17. *A train has schedule speed of 60 km per hour between the stops which are 9 km apart. Determine the crest speed over the run, assuming trapezoidal speed – time curve. The train accelerates at 3 kmphps and retards at 4.5 kmphps. Duration of stops is 75 seconds.*

Solution.

Acceleration α = 3 kmphps

Retardation β = 4.5 kmphps

Distance of run, S = 9 km

Schedule speed, V_s = 60 kmph

Schedule time, $T_s = \frac{S}{V_s} \times 3{,}600 \text{ seconds} = \frac{9}{60} \times 3{,}600 = 540$ seconds

Actual time of run, $T = T_s -$ Time of stop $= 540 - 75 = 465$ seconds

Using the equation

$$V_m = \frac{T}{2K} - \sqrt{\frac{T^2}{4K^2} - \frac{3{,}600\ S}{K}}$$

where $K = \frac{1}{2\alpha} + \frac{1}{2\beta} = \frac{1}{6} + \frac{1}{9} = 0.2777$

$\therefore$ Maximum speed, $V_m = \frac{465}{2 \cdot 0.2777} - \sqrt{\frac{(465)^2}{4 \cdot (0.2777)^2} - \frac{3{,}600 \cdot 9}{0.2777}}$

$$V_m = 837 - \sqrt{700569 - 116640}$$

$$\therefore \quad V_m = \textbf{72.8475 kmph}$$

Example 43.18. *An electric train is to have acceleration and braking retardation of 1.2 km/hour/sec and 4.8 km/hour/sec respectively. If the ratio of maximum to average speed is 1.6 and time for stops 35 seconds, find schedule speed for a run of 3 km. Assume simplified trapezoidal speed-time curve.*

Solution.

Acceleration $\alpha = 1.2$ kmphps

Retardation $\beta = 4.8$ kmphps

Distance of run, $S = 3$ km

Let the actual time of run be T seconds

Average speed, $V_a = \frac{3,600\text{ S}}{T} = \frac{3,600 \times 3}{T} = \frac{10800}{T}$ kmph

Maximum speed, $V_m = 1.6 \times \frac{10800}{T} = \frac{17280}{T}$ kmph

Since $V_m^2 \left(\frac{1}{2\alpha} + \frac{1}{2\beta}\right) - V_m T + 3,600\text{ S} = 0$

$$\therefore \quad V_m^2 = \frac{V_m T - 3,600\text{ S}}{\frac{1}{2\alpha} + \frac{1}{2\beta}} = \frac{\frac{17280}{T} T - 3600 \cdot 3}{\frac{1}{2 \times 1.2} + \frac{1}{2 \times 4.8}}$$

or $V_m = 111.5419$ kmph

and $V_a = \frac{V_m}{1.5} = \frac{111.5419}{1.5} = 74.3613$ kmph

Actual time of run $T = \frac{3,600\text{ S}}{V_a} = \frac{3600 \times 3}{74.3613} = 145.2369$ seconds

Schedule time, T_s = Actual time of run + Time of stop = 145.2369 + 35 ј 180 seconds

$\therefore$ Schedule speed, $V_s = \frac{S \cdot 3,600}{T_s} = \frac{3 \quad 3600}{180} = \textbf{60 kmph}$

Example 43.19. *An electric train has a schedule speed of 25 kmph between stations 800 m apart. The duration of stop is 20 seconds, the maximum speed is 20 percent higher than the average running speed and the braking retardation is 3 kmphps. Calculate the rate of acceleration required to operate this service.*

Solution.

Schedule speed, $V_s = 25$ kmph

Distance of run, $S = 800$ metres $= 0.8$ km

Retardation, $\beta = 3$ kmphps

Schedule time of run, $T_s = \frac{3,600 \times S}{T} = \frac{3600 \times 0.8}{25} = 115.2$ seconds

Actual time of run, $T = T_s -$ duration of stop $= 115.2 - 20 = 95.2$ seconds

Average speed, $V_a = \frac{3,600 \times S}{T} = \frac{3600 \times 0.8}{95.2} = 30.25$ kmphs

Maximum speed, $V_m = 1.2\ V_a = 1.2 \times 30.25 = 36.3$ kmph

Since $V_m^2\left(\frac{1}{2\alpha}+\frac{1}{2\beta}\right) - V_m\,T + 3{,}600\,S = 0$

$$\therefore \quad \frac{1}{2\alpha}+\frac{1}{2\beta} = \frac{V_m\,T - 3{,}600\,S}{V_m^2}$$

$$\text{or} \quad \frac{1}{2\alpha}+\frac{1}{2\times 3} = \frac{36.3\times 95.2 - 3{,}600\times 0.8}{(36.3)^2} = \mathbf{0.4369}$$

$$\text{or} \quad \alpha = 1.85 \text{ kmphps}$$

Example 43.20. *A suburban electric train has a maximum speed of 80 kmph. The schedule speed including a station stop of 35 seconds is 50 kmph. If the acceleration is 1.5 kmphps, find the value of retardation when the average distance between stops is 5 km.*

Solution.

Schedule speed, V_s = 50 kmph

Distance of run, S = 5 km

Acceleration, α = 1.5 kmphps

Maximum speed, V_m = 80 kmph

Duration of stop = 35 seconds

$$\text{Schedule time of run,} \quad T_s = \frac{3{,}600\times S}{V_s} = \frac{3{,}600\times 5}{50} = 360 \text{ seconds}$$

$$\text{Actual time of run,} \quad T = \frac{T_s - \text{duration of stop}}{V_m^2} = 360 - 30 = 330 \text{ seconds}$$

Since $V_m^2\left(\frac{1}{2\alpha}+\frac{1}{2\beta}\right) - V_m\,T + 3{,}600\,S = 0$

$$\text{or} \quad \frac{1}{2\alpha}+\frac{1}{2\beta} = V_m\,T - 3{,}600\,S = \frac{80\times 330 - 3{,}600\times 5}{(80)^2} = 1.3125$$

$$\text{or} \quad \frac{1}{2\beta} = 1.3125 - \frac{1}{2\alpha} = 1.3125 - \frac{1}{2\times 1.5} = 0.9792$$

$$\text{or} \quad \beta = \frac{1}{2\times 0.9792} = \mathbf{0.51064 \text{ kmphps}}$$

Example 43.21. *A train is required to run between two stations 1.6 km apart at the average speed of 40 kmph. The run is to be made to a simplified quadrilateral speed-time curve. If the maximum speed is to be limited to 64 kmph, acceleration to 2.0 kmphps and coasting and braking retardation to 0.16 kmphps and 3.2 kmphps respectively, determine the duration of acceleration, coasting and braking periods.*

Solution.

Distance of run, S = 1.6 km

Average speed, V_a = 40 kmph

Maximum speed, V_m = 64 kmph

Acceleration, α = 2.0 kmphps

Coasting retardation, β_C = 0.16 kmphps

Braking retardation, β = 3.2 kmphps

$$\text{Duration of acceleration,} \quad t_1 = \frac{V_m}{\alpha} = \frac{64}{2.0} = \mathbf{32 \text{ seconds}}$$

Actual time of run, $T = \frac{3{,}600\ S}{V_a} = \frac{3{,}600 \times 1.6}{40} = 144$ seconds

Let the speed before applying brakes be V_2

then duration of coasting, $t_2 = \frac{V_m - V_2}{\beta_c} = \frac{64 - V_2}{0.16}$ seconds

Duration of braking, $t_3 = \frac{V_2}{\beta} = \frac{V_2}{3.2}$ seconds

Since actual time of run, $T = t_1 + t_2 + t_3$

$\therefore \quad 144 = 32 + \frac{64 - V_2}{0.16} + \frac{V_2}{3.2}$

or $\quad V_2\left(\frac{1}{0.16} - \frac{1}{3.2}\right) = 32 + 400 - 144$

or $\quad V_2 = \frac{288}{6.25 - 0.3125} = 48.5$ kmph

Duration of coasting, $t_2 = \frac{V_m - V_2}{\beta_c} = \frac{64 - 48.5}{0.16} =$ **96.85 seconds**

Duration of braking, $t_3 = \frac{V_2}{\beta} = \frac{48.5}{3.2} =$ **15.15 seconds**

43.47. General Features of Traction Motor

Electric Features

- High starting torque
- Series Speed - Torque characteristic
- Simple speed control
- Possibility of dynamic/ regenerative braking
- Good commutation under rapid fluctuations of supply voltage.

Mechanical Features

- Robustness and ability to withstand continuous vibrations.
- Minimum weight and overall dimensions
- Protection against dirt and dust

No type of motor completely fulfills all these requirements. Motors, which have been found satisfactory are D.C. series for D.C. systems and A.C. series for A.C. systems. While using A.C. three phase motors are used. With the advent of Power Electronics it is very easy to convert single phase A.C. supply drawn from pantograph to three phase A.C.

43.48. Speed - Torque Characteristic of D.C. Motor

$$V = E_b + I_a R_a$$
$$V \cdot I_a = E_b \cdot I_a + I_a^2 R_a$$

where $E_b I_a$ = Power input to armature = Electrical power converted into mechanical power at the shaft of motor.

Mechanical Power $= T \cdot \omega = T \times \frac{2\pi N}{60}$

$\therefore \quad \frac{2\pi NT}{60} = E_b \cdot I_a \quad \therefore \quad T = \frac{60\ E_b\ I_a}{2\ \pi\ N} = 9.55\ \frac{E_b\ I_a}{N}$

But $\quad E_b = \frac{\phi\ ZNP}{60\ A}$

$$\therefore \quad T = 9.55\frac{\phi\, ZNP}{60\,A}\frac{I_a}{N} = 9.55\frac{\phi\, ZP}{60}\frac{I_a}{A}$$

$$= 0.1592 \cdot \phi \cdot \left[Z\frac{I_a}{A}\right] P \text{ Nw-m}$$

$\therefore$ Torque T = 0.1592 · flux per pole · armature amp. conductors · Number of poles

Also speed 'N' can be calculated as:

$$E_b = \frac{\phi\, ZNP}{60\,A} \qquad \therefore \quad N = \frac{(E_b)}{\phi\, ZP}60\,A$$

$$N = \frac{(V - I_a R_a)\, 60\,A}{\phi\, ZP} \qquad \therefore \quad N \propto \frac{V - I_a R_a}{\phi}$$

But $T = 9.55\dfrac{\phi\, ZP}{60}\dfrac{I_a}{A}$ from the equation of torque

$\therefore \quad \dfrac{T}{I_a} = \dfrac{9.55\,\phi\, ZP}{60\,A} \Rightarrow \dfrac{9.55\, I_a}{T} = \dfrac{60\,A}{\phi\, ZP}$ Put this value in the above equation of N

$$\therefore \quad N = \frac{(V - I_a R_a)\cdot 9.55\, I_a}{T}$$

Speed
$$N = \frac{9.55\,(V - I_a R_a)}{T / I_a}$$

The torque - current and speed - torque curves for D.C. motors are shown in Fig. 43.20 (*a*) and (*b*) respectively.

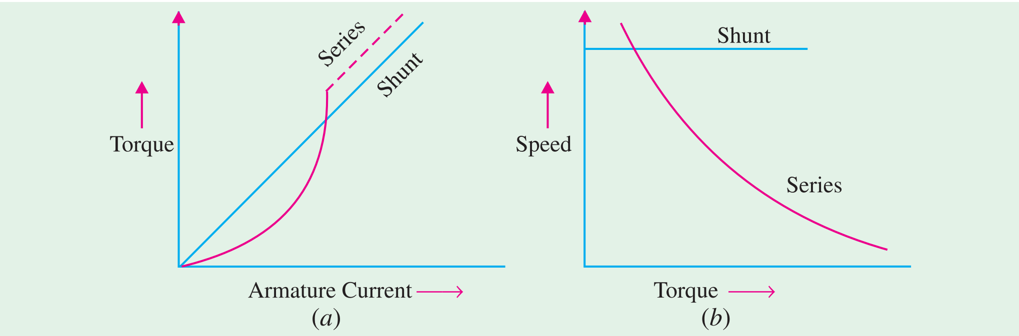


Fig. 43.20

43.49. Parallel Operation of Series Motors with Unequal Wheel Diameter

An electric locomotive uses more than one motor. Each motor drives different set of axles and wheels. Due to wear and tear the diameter of wheels become different, after a long service. But the linear speed of locomotive and wheels will be the same. Therefore, motor speeds will be different due to difference in diameter of wheels driven by them as shown in Fig. 43.21. Therefore, when the motors are connected in parallel they will not share the torques equally, as the current shared by them will be different.

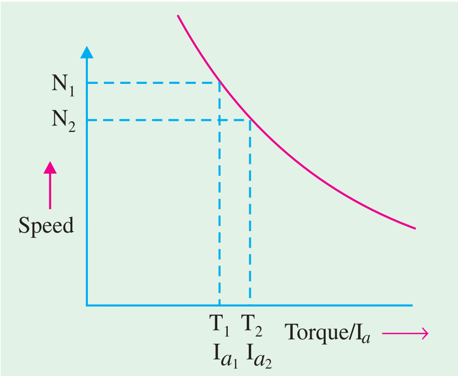


Fig. 43.21

Let the motor wheels ratio is 1.04 : 1 *i.e.* speed of rotation of motor-1 is 1.04 times that of motor-2, as shown in Fig. 43.21.

Let motor 1 drives wheel with 100 c.m. dia. and motor 2 drives wheel with 104 c.m. dia. Then speed of rotation of motor -1 will be $\frac{104}{100} = 1.04$ times that of 2 *i.e.* $N_2 = 1.04\,N_1$, for a given speed of locomotive.

43.50. Series operation of Series Motor with unequal wheel diameter

Let the motors '*A*' and '*B*' be identical having armature resistance *R* in series, as shown in Fig. 43.22.

Since they are in series, the same current '*I*' will flow through both. But due to unequal wheel diameter; they deliver different loads *i.e.* voltage across each will be different

$$V = V_A + V_B \qquad \text{and} \qquad N \propto V - IR$$

$$\therefore \quad \frac{N_A}{N_B} = \frac{V_A - IR}{V_B - IR}$$

$$\therefore \quad V_A - IR = \frac{N_A}{N_B}(V_B - IR)$$

$$V_A = \frac{N_A}{N_B}(V_B - IR) + IR$$

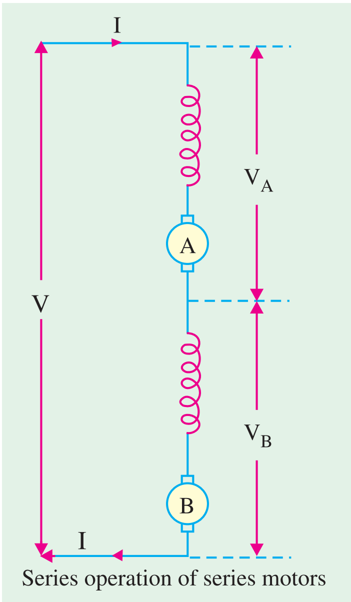
$$V_A = \frac{N_A}{N_B}(V - V_A - IR) + IR$$

$$V_A = \frac{N_A}{N_B}(V - IR) + IR - \frac{N_A}{N_B}V_A$$

$$V_A + \frac{N_A}{N_B}V_A = \frac{N_A}{N_B}(V - IR) + IR$$

$$V_A\left(1 + \frac{N_A}{N_B}\right) = \frac{N_A}{N_B}(V - IR) + IR$$

$$V_A = \frac{\frac{N_A}{N_B}(V - IR) + IR}{1 + \frac{N_A}{N_B}}$$



Series operation of series motors

Fig. 43.22

Similarly,

$$V_B = \frac{\frac{N_B}{N_A}(V - IR) + IR}{1 + \frac{N_B}{N_A}}$$

43.51. Series Operation of Shunt Motors with Unequal Wheel Diameter

It is similar to the case of series operation of series motors, and hence the same equation holds good.

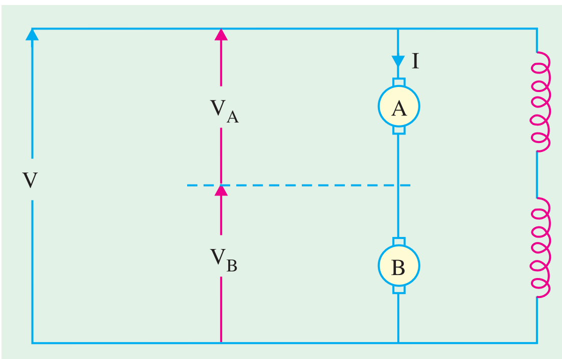


Fig. 43.23

43.52. Parallel Operation of Shunt Motors with Unequal Wheel Diameter

As seen from the Fig. 43.24, a small difference in speeds of two motors, causes motors to be loaded very unequally due to flat speed current curve of D.C. shunt motor.

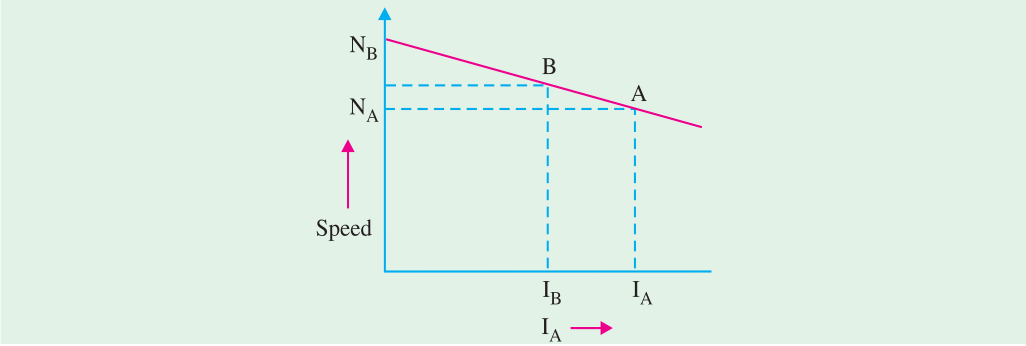


Fig. 43.24

Example 43.22. *The torque-armature current characteristics of a series traction motor are given as:*

Armature Current (amp) :	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*
Torque (N-m) :	*20*	*50*	*100*	*155*	*215*	*290*	*360*	*430*

The motor resistance is 0.3Ω. If this motor is connected across 230 V, deduce the speed armature current characteristics.

Solution.

Supply voltage, $V = 230$ V.

Total Resistance of series motor $R_m = R_a + R_{se} = 0.3\ \Omega$.

Armature current, I_a in amperes	5	10	15	20	25	30	35	40
Torque, T in N-m	20	50	100	155	215	290	360	430
Back e.m.f., $E_b =$ $(V - I_a R_m)$ in volts	228.5	227.0	225.5	224.0	222.5	221.0	219.5	218.0
Speed, N_a ९फ5 (ट − ट. ट उ) / ज ट. in R.P.M.	545	434	323	276	247	218	204	194

The deduced speed-armature current characteristic is shown in Fig. 43.25.

Example 43.23. *The following figures give the magnetization curve of d.c. series motor when working as a separately excited generator at 600 rpm.:*

Field Current (amperes) :	*20*	*40*	*60*	*80*
E.M.F. (volts) :	*215*	*381*	*485*	*550*

The total resistance of the motor is 0.8 ohm. Deduce the speed – torque curve for this motor when operating at a constant voltage of 600 volts.

Solution.

Voltage applied across the motor, $V = 600$ volts

Resistance of the motor, $R_m = (R_a + R_{se}) = 0.8\ \Omega$

Speed, $N_1 = 600$ r.p.m.

Field Current (amperes)	20	40	60	80
Back e.m.f., E_1 (Volts) at speed N_1 (600 r.p.m.) = e.m.f. generated by the armature (given)	215	381	485	550
Back e.m.f., E (Volts) at speed N (to be determined) = $V - I_a R_m$	584	568	552	536
Speed, N (to be determined in r.p.m.) = $N_1/E_1 \cdot (V - I_a R_m)$	1,630	895	683	585
Torque, $T = \dfrac{9.55\,(V - I_a R_m)\,I_a}{N}$ N-m	68.4	240	462	700

The deduced speed-torque curve for the motor is shown in Fig. 43.26.

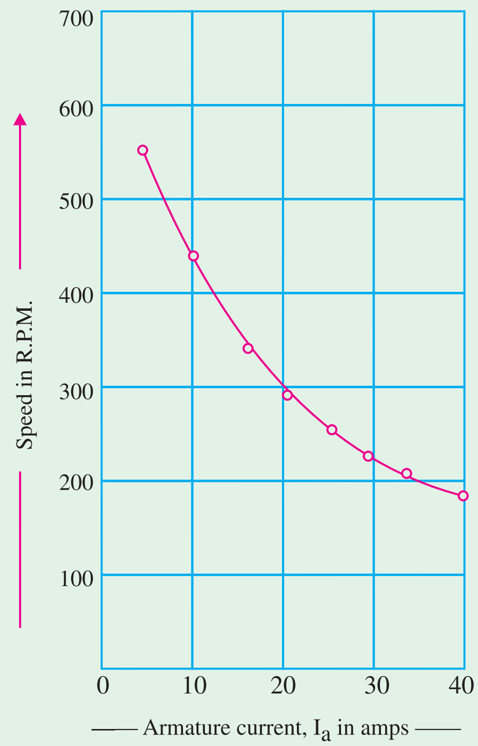


Fig. 43.25

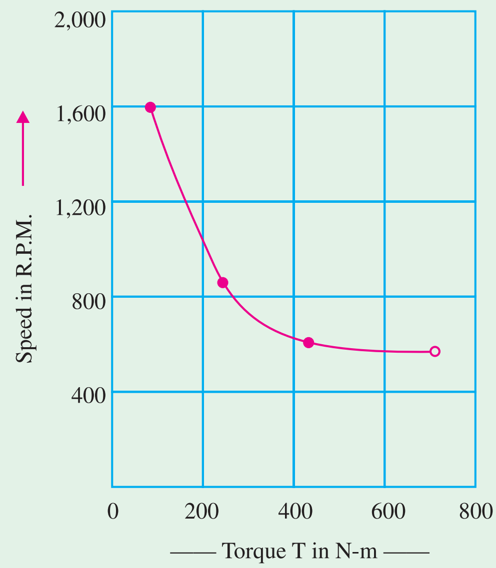


Fig. 43.26

Example 43.24. *Two d.c. traction motors run at a speed of 900 r.p.m. and 950 r.p.m. respectively when each takes a current of 50 A from 500 V mains. Each motor has an effective resistance of 0.3 W. Calculate the speed and voltage across each machine when mechanically coupled and electrically connected in series and taking a current of 50 A from 500 V mains, the resistance of each motor being unchanged.*

Solution.

Let the two motors be A and B of speed N_A = 900 rpm. And N_B = 950 r.p.m. respectively.

Resistance of each motor R_m = 0.3 Ω

Applied voltage across each motor, $V = 500$ V.

Back e.m.f. of motor A when taking a current of 50 A

$$E_{b_A} = V - I R_m = 500 - 50 \cdot 0.3 = 485 \text{ V}$$

Back e.m.f. of motor B when taking a current of 50 A

$$E_{b_B} = V - I R_m = 500 - 50 \cdot 0.3 = 485 \text{ V}$$

When the machines are mechanically coupled and connected in series, the speed of each motor will be same, say N, current will be same and equal to 50 A (given) and the sum of voltage across the two motors will be equal to 500 V.

Let the voltage across motors A and B be V_A and V_B respectively

Now $$V_A + V_B = 500 \quad \text{...}(i)$$

Back e.m.f. of motor A, $$E_{b'_A} = E_{b_A} \times \frac{N}{N_A} = \frac{485}{900} \times N$$

Voltage across motor A, $$V_A = E_{b'_A} + I R_m = \frac{485}{900} \times N + 50 \times 0.3 = \frac{485}{900} \times N + 15$$

Back e.m.f. of motor B, $$E_{b'_B} = E_{b_B} \times \frac{N}{N_B} = \frac{485}{950} N$$

Voltage across motor B, $$V_B = E_{b'_B} + I R_m = \frac{485}{950} N + 15$$

Substituting $V_A = \frac{485}{900} N + 15$ and $V_B = \frac{485}{950} N + 15$ in expression (i) we get

$$\frac{485}{900} N + 15 + \frac{485}{950} N + 15 = 500$$

or $$\left(\frac{485}{900} + \frac{485}{950}\right) N = 470$$

or $$N \left(\frac{1}{900} + \frac{1}{950}\right) = \frac{470}{485}$$

$\therefore$ $$N = \mathbf{447.87 \text{ r.p.m.}}$$

P.D. across machine A, $$V_A = \frac{485\,N}{900} + 15 = \mathbf{256.35 \text{ V}}$$

P.D. across machine B, $$V_B = \frac{485\,N}{950} + 15 = \mathbf{243.65 \text{ V}}$$

Example 43.25. *A tram car is equipped with two motors which are operating in parallel. Calculate the current drawn from the supply main at 500 volts when the car is running at a steady speed of 50 kmph and each motor is developing a tractive effort of 2100 N. The resistance of each motor is 0.4 ohm. The friction, windage and other losses may be assumed as 3500 watts per motor.*

Solution.

Voltage across each motor, $V = 500$ volts

Maximum speed, $V_m = 50$ kmph

Tractive effort, $F_t = 2100$ Newtons

Motor resistance, $R_m = 0.4$ W

Losses per motor = 3500 watts

$$\text{Power output of each motor} = \frac{F_t \cdot V_m \cdot 1000}{3600} \text{ watts}$$

$$= \frac{2100 \cdot 50 \quad 1000}{3600} \text{ watts} = 29166.67 \text{ watts.}$$

Constant losses $=$ 3500 watts

Copper losses $= I^2 R_m = 0.4\, I^2$

Where I is the current drawn from supply mains

$$\text{Input to motor} = \text{Motor output} + \text{constant losses} + \text{copper losses}$$

$$VI = 29166.67 + 3500 + 0.4\, I^2$$

$$0.4\, I^2 - 500\, I + 32666.67 = 0$$

$$I = \frac{500 \pm \sqrt{(500)^2 - 4 \cdot 0.4 \cdot 32666.67}}{2 \cdot 0.4}$$

$$I = 69.16 \text{ A} \qquad \text{or} \qquad 1180.84 \text{ A}$$

Current drawn by each motor $=$ 69.16A

Œ 1180.84 A being unreasonably high can not be accepted

Total current drawn from supply mains $= 69.16 \cdot 2 =$ **138.32 A**

Example 43.26. *A motor coach is being driven by two identical d.c. series motors. First motor is geared to driving wheel having diameter of 90 cm and other motor to driving wheel having diameter of 86 cm. The speed of the first motor is 500 r.p.m. when connected in parallel with the other across 600 V supply. Find the motor speeds when connected in series across the same supply. Assume armature current to remain same and armature voltage drop of 10% at this current.*

Solution.

Speed of first motor, $N_1 = 500$ r.p.m.

Back e.m.f., $E_{b_1} = 600 - \frac{10}{100} \cdot 600$

$= 540$ volts.

When the motors are connected in series across 600 V supply, as shown in Fig. 43.27.

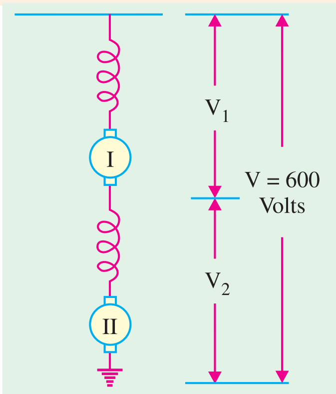


Fig. 43.27

Let the supply voltage across motors I and II be V_1 and V_2 volts and speed N_1' and N_2' respectively.

Since speed, $N \propto \frac{V - IR}{\phi}$

Current through the motors remains the same, therefore flux produced by it also remains the same and $N \propto (V - IR)$

$$\therefore \quad \frac{N_1'}{N_2'} = \frac{V_1 - I\,R}{V_2 - I\,R} = \frac{V_1 - \frac{10}{100} \times 600}{V_2 - \frac{10}{100} \times 600} = \frac{V_1 - 60}{V_2 - 60} \quad ...(i)$$

And also $N'_1\, D_1 = N'_2 D_1 = N'_2\, D_2$

$$\therefore \quad \frac{N_1'}{N_2'} = \frac{D_2}{D_1} = \frac{86}{90}$$

$$\frac{V_1 - 60}{V_2 - 60} = \frac{86}{90} \qquad (ii) \text{ Since peripheral speed is equal}$$

or $90\, V_1 - 5{,}400 = 86\, V_2 - 5{,}160$

or $90\, V_1 - 86\, V_2 = 5{,}400 - 5{,}160 = 240$ ...(*iii*)

and also $V_1 + V_2 = 600$ V ...(*iv*)

Solving expressions (*iii*) and (*iv*)

$$V_1 = 294.55 \text{ V}$$

And $$V_2 = 305.45 \text{ V}$$

Now the speeds of the motors can be calculated as follows :

$$\frac{N_1'}{N_2'} = \frac{E_{b_1}'}{E_b}$$

or $$N'_1 = N_1 \times \frac{E_{b_1}'}{E_b} = 500 \times \frac{294.55 - 60}{600 - 60} = 217 \text{ r.p.m}$$

and $$N'_2 = N_1' \times \frac{D_1}{D_2} = 217 \times \frac{90}{86} = \mathbf{277 \text{ r.p.m}}$$

Example 43.27. *Two similar series type motors are used to drive a locomotive. The supply fed to their parallel connection is 650 V. If the first motor 'A' is geared to drive wheels of radius 45 cms. and other motor 'B' to 43 cms. And if the speed of first motor 'A' when connected in parallel to 2^{nd} motor 'B' across the main supply lines is 400 rpm., find voltages and speeds of motors when connected in series. Assume I_a to be constant and armature voltage drop of 10% at this current.*

Solution.

$N \propto V - IR$ as flux ϕ is constant, since I_a is constant

$N_A = V_A - IR$ $\quad N_B = V_B - IR$ $\quad$ Also $V = V_A + V_B$

Assume $$\frac{N_A}{N_B} = \rho$$

$$V_A = \frac{\rho\,(V - IR) + IR}{1 + \rho}$$

Armature voltage drop = 10% of 650 V $\quad \therefore \quad IR = 65$

But $$\frac{N_A}{N_B} = \frac{r_B}{r_A} = \frac{43}{45} = \rho$$

$$V_A = \frac{43/45\,(650 - 65) + 65}{1 + 43/45} = 320 \text{ V}$$

$$V_B = V - V_A = 650 - 320 = 330 \text{ V}$$

Speed N_A of motor A is 400 rpm with a supply of 650 V.

$\therefore$ Speed N'_A of motor A with supply voltage of 320 V will be

$$\frac{N_A'}{N_A} = \frac{320 - IR}{650 - IR} = \frac{320 - 65}{650 - 65} = \frac{255}{585}$$

$\therefore$ $$N'_A = \frac{255}{585} N_A = \frac{255}{585} \times 400 = \mathbf{175 \text{ r.p.m.}}$$

$$\frac{N_A}{N_B} = \frac{r_B}{r_A} = \frac{N_A'}{N_B'} = \frac{43}{45}$$

$$N'_B = \frac{45}{43} N'_A = \frac{45}{43} \times 175 = \mathbf{184 \text{ r.p.m.}}$$

43.53. Control of D.C. Motors

The starting current of motor is limited to its normal rated current by starter during starting. At the instant of switching on the motor, back e.m.f. $E_b = 0$

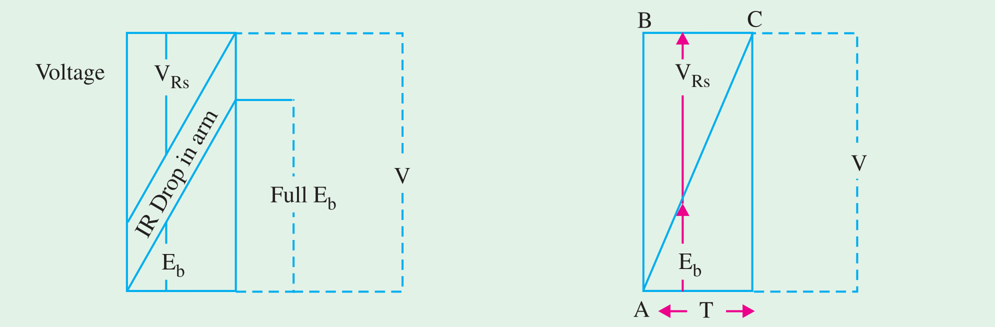
$\therefore$ Supply voltage = V = IR + Voltage drop across R_s.

At any other instant during starting

$$V = IR + \text{Voltage across } R_s + E_b$$

At the end of accelerating period, when total R_s is cut-off

$$\boxed{V = E_b + IR}$$



(*a*) Voltage during starting of D.C. motor (*b*) Voltage during starting neglecting IR drop

Fig. 43.28

If T is the time in sec. for starting and neglecting IR drop, total energy supplied = $V.I.T.$ watt-sec

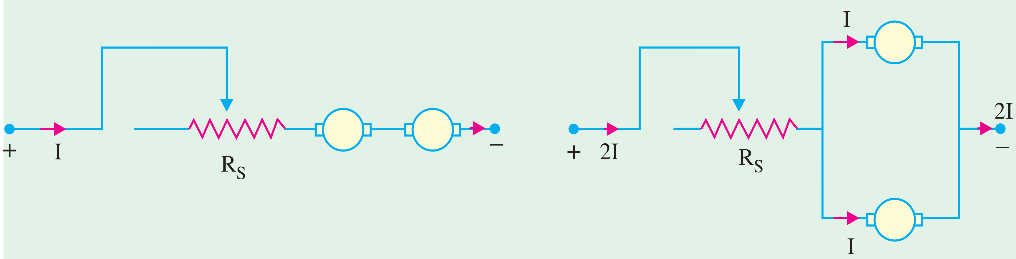
From Fig. 43.28 (*b*) Energy wasted in R_s = Area of triangle $ABC \cdot I$ = ½. $T.V.I.$ watt - sec. = ½ VIT watt - sec. But total energy supplied = $V.I.T$ watt - sec.

$\therefore$ Half the energy is wasted in starting

$\therefore$ $\eta_{starting} = 50\%$

43.54. Series - Parallel Starting

With a 2 motor equipment ½ the normal voltage will be applied to each motor at starting as shown in Fig. 43.29 (*a*) (Series connection) and they will run upto approximate ½ speed, at which instant they are switched on to parallel and full voltage is applied to each motor. R_s is gradually cut-out, with motors in series connection and then reinserted when the motors are connected in parallel, and again gradually cut-out.



(*a*) Motors in series (*b*) Motors in parallel

Fig. 43.29

In traction work, 2 or more similar motors are employed. Consider 2 series motors started by series parallel method, which results in saving of energy.

(*a*) Series operation. The 2 motors, are started in series with the help of R_s. The current during starting is limited to normal rated current 'I' per motor. During series operation, current 'I' is drawn from supply. At the instant of starting $OA = AB = IR$ drop in each motor. OK = Supply voltage 'V'. The back e.m.fs. of 2 motors jointly develop along OM as shown in Fig. 43.30 (*a*). At point. E, supply voltage V = Back e.m.fs of 2 motors + IR drops of 2 motor. Any point on the line BC represents the sum of Back e.m.fs. of 2 motors + IR drops of 2 motors + Voltage across resistance R_s of 2 motors

$$OE = \text{time taken for series running.}$$

At pt 'E' at the end of series running period, each motor has developed a back e.m.f.

$$= \frac{V}{2} - IR$$

$$EL = ED - LD$$

(*b*) Parallel operation. The motors are switched on in parallel at the instant 'E', with R_s reinserted as shown in Fig. 43.29 (*b*). Current drawn is $2I$ from supply. Back e.m.f. across each motor = EL. So the back e.m.f. now develops along LG. At point 'H' when the motors are in full parallel, (R_s = 0 and both the motors are running at rated speed)

$$\text{Supply voltage} = V = HF = HG + GF$$

$$= \text{Normal Back e.m.f. of each motor} + IR \text{ drop in each motor.}$$

43.55. To find t_s, t_p and η of starting

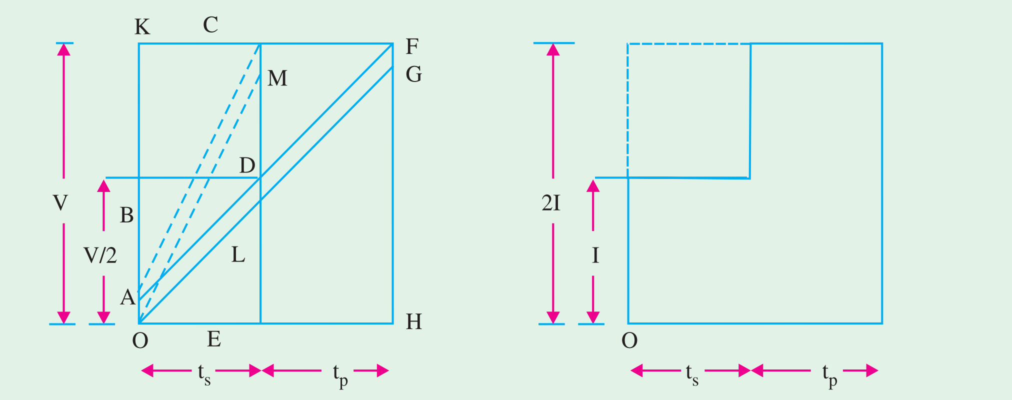
The values of time t_s during which the motors remain in series and t_p during which they are in parallel can be determined from Fig. 43.30 (*a*), (*c*). From Fig. 43.30 (*a*), triangles OLE and OGH are similar

$$\therefore \quad \frac{OE}{OH} = \frac{LE}{GH} \quad \therefore \frac{t_s}{T} = \frac{DE - DL}{FH - FG} = \frac{V/2 - IR}{V - IR}$$

$$\therefore \quad \boxed{t_s = \frac{1}{2}\left(\frac{V - 2IR}{V - IR}\right)T}$$

$$t_p = T - t_s = T - \left\{\frac{1}{2}\left(\frac{V - 2IR}{V - IR}\right)T\right\}$$

$$\boxed{t_p = T\left\{1 - \frac{1}{2}\left(\frac{V - 2IR}{V - IR}\right)T\right\}}$$



(*a*) Voltage built-up in series-parallel starting (*b*) Variation of current in series-parallel starting

Fig. 43.30

To calculate η of starting, neglect IR drop in armature circuit.

This modifies Fig. 43.30 (a) to Fig. 43.30 (c). 'D' is midpoint of CE and back e.m.f. develops along DF in parallel combination. $KC = CF$ *i.e.* time for series combination = time for parallel combination

i.e. $t_s = t_p = t$ and average starting current = I per motor.

Energy lost in R_s = Area under triangle OKC + Area under triangle CDF

$$= \left(\frac{1}{2}V\,I\right)\times t + \left(\frac{1}{2}\frac{V}{2}2I\right)\times t = VIt$$

But total energy supplied

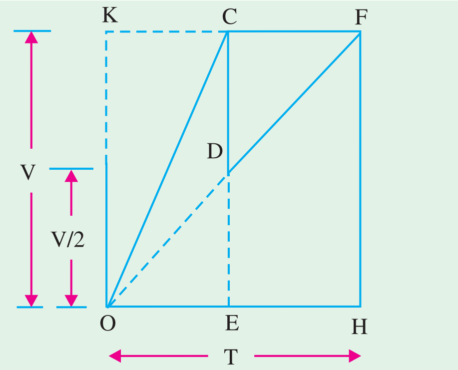
$$= \underset{\text{(Series)}}{I\,V\,t} + \underset{\text{(Parallel)}}{2\,I\,V\,t}$$

$$= 3\,V\,I\,t$$

$$\therefore \eta \text{ of starting} = \frac{3VIt - VIt}{3VIt}$$

$$= \frac{2}{3} = 66.6\%$$

∴ η is increased by 16.66% as compared to pervious case. If there are 4 motors then η_{starting} = 73%. So there is saving of energy lost in R_s, during starting period as compared with starting by both motors in parallel.



(c) Efficiency of starting by series-parallel method

Fig. 43.30

Example 43.28. *Two motors of a motor coach are started on series - parallel system, the current per motor being 350 A (Considered as being maintained constant) during the starting period which is 18 sec. If the acceleration during starting period is uniform, the line voltage is 600 V and resistance of each motor is 0.1 W. Find **(a)** the time during which the motors are operated in series. **(b)** the energy loss in the rheostat during starting period.* **[Nagpur University, Summer 2002]**

Solution.

Time during which motors are in series is given by

$$t_s = \frac{1}{2}\left(\frac{V - 2\,I\,R}{V - I\,R}\right)T = \frac{1}{2}\left(\frac{600 - 2\cdot\ 350\cdot\ 0.1}{600 - 350\cdot\ 0.1}\right)18$$

$$t_s = \textbf{8.44 sec.}$$

Time during which motors are in parallel.

$$t_p = T - T_s = 18 - 8.44 = 9.56 \text{ sec.}$$

Back e.m.f. E_b of each motor, in series operation (from Fig. 43.30a)

$$E_{b_s} = \frac{V}{2} - I\,R = \frac{600}{2} - 350\ (0.1) = 265 \text{ V.}$$

When 2 motors are in series,

Total E_b = 265 + 265 = 530 V

$$E_{b_p} = V - IR = 600 - 350\ (0.1) = 565 \text{ V}$$

Energy lost when motors are connected in series

$$= \frac{1}{2}E_b\ I\ t_s = \frac{1}{2}\cdot\ 530\cdot\ 350\cdot\ \frac{8.44}{3600} = 217 \text{ watt - hours}$$

Energy lost when motors are connected in parallel

$$\frac{1}{2}\frac{E_b}{2}\,2\,I\,t_P = \frac{1}{2}\cdot\frac{565}{2}\cdot 2\cdot\ 350\cdot\ \frac{9.56}{3600} = 262.5 \text{ watt - hour}$$

$$\simeq 263 \text{ watt - hours}$$

$\therefore$ Total energy lost = (217 + 263) watt - hours = **480 watt - hours**

43.56. Series Parallel Control by Shunt Transition Method

The various stages involved in this method of series – parallel control are shown in Fig. 43.31

In steps 1, 2, 3, 4 the motors are in series and are accelerated by cutting out the R_s in steps. In step 4, motors are in full series. During transition from series to parallel, R_s is reinserted in circuit– step 5. One of the motors is bypassed -step 6 and disconnected from main circuit – step 7. It is then connected in parallel with other motor -step 8, giving 1st parallel position. R_s is again cut-out in steps completely and the motors are placed in full parallel.

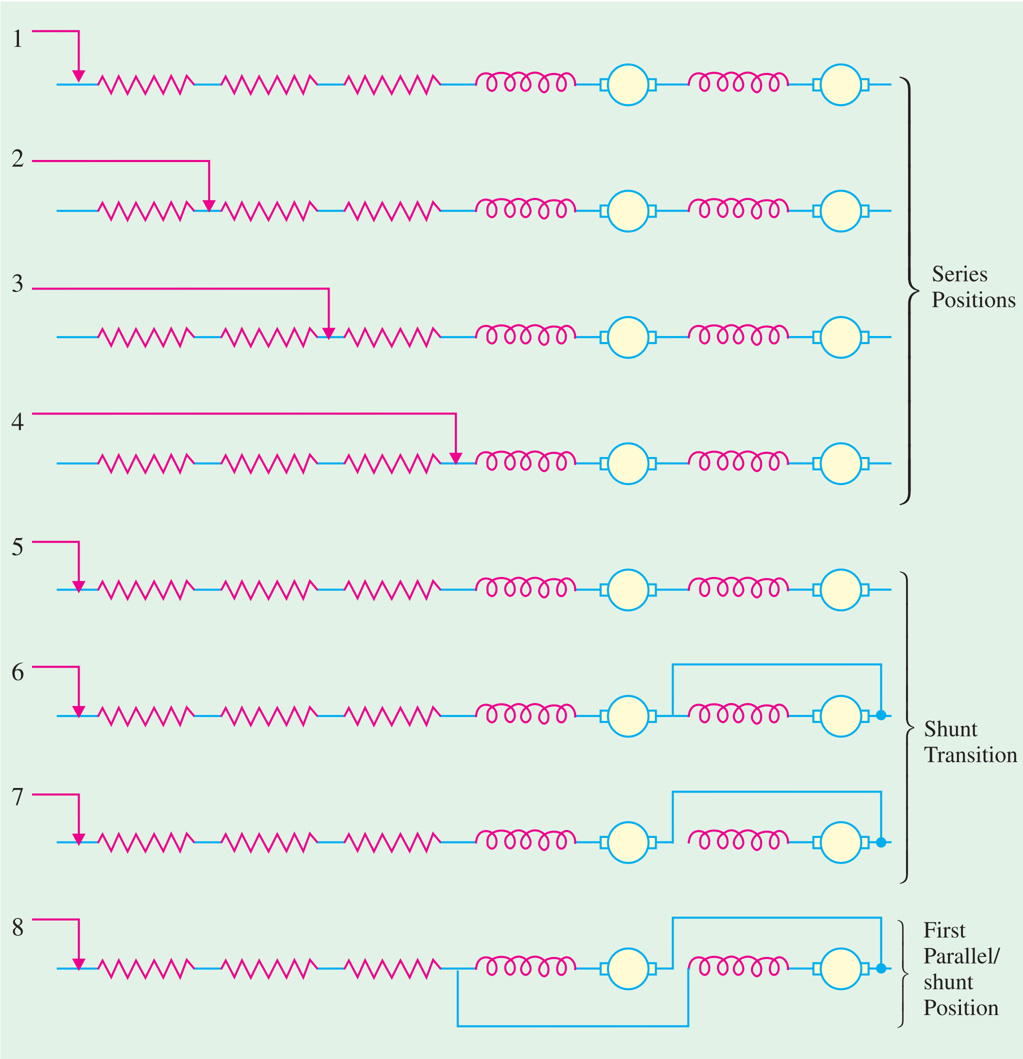


Fig. 43.31

The main difficulty with series parallel control is to obtain a satisfactory method of transition from series to parallel without interrupting the torque or allowing any heavy rushes of current.

In shunt transition method, one motor is short circuited and the total torque is reduced by about 50% during transition period, causing a noticeable jerk in the motion of vehicle.

The Bridge transition is more complicated, but the resistances which are connected in parallel with or 'bridged' across the motors are of such a value that current through the motors is not altered in magnitude and the total torque is therefore held constant and hence it is normally used for railways. So in this method it is seen that, both motors remain in circuit through-out the transition. Thus the jerks will not be experienced if this method is employed.

43.57. Series Parallel Control by Bridge Transition

(*a*) At starting, motors are in series with R_s *i.e.* link *P* in position = *AA′*

(*b*) Motors in full series with link *P* in position = *BB′* (No R_s in the circuit)

The motor and R_s are connected in the form of Wheatstone Bridge. Initially motors are in series with full R_s as shown in Fig. 43.32 (*a*). *A* and *A′* are moved in direction of arrow heads. In position *BB′* motors are in full series, as shown in Fig. 43.32 (*b*), with no R_s present in the circuit.

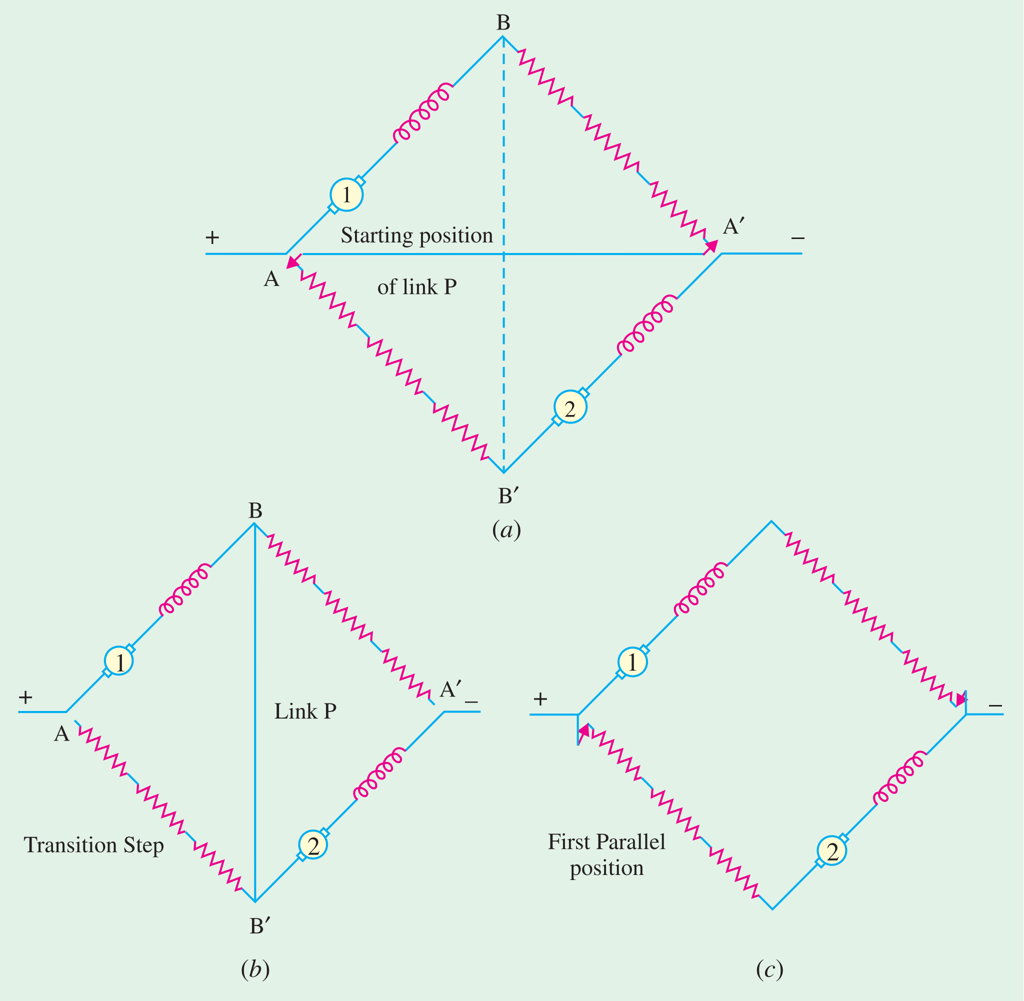


Fig. 43.32

In transition step the R_s is reinserted.

In Ist parallel step, link P is removed and motors are connected in parallel with full R_s as shown in Fig. 43.32 (*c*). Advantage of this method is that the normal acceleration torque is available from both the motors, through - out starting period. Therefore acceleration is smoother, without any jerks, which is very much desirable for traction motors.

43.58. Braking in Traction

Both electrical and mechanical braking is used. Mechanical braking provides holding torque. Electric Braking reduces wear on mechanical brakes, provides higher retardation, thus bringing a vehicle quickly to rest. Different types of electrical braking used in traction are discussed.

43.59. Rheostatic Braking

(*a*) Equalizer Connection (*b*) Cross Connection

(*a*) Equalizer Connection

For traction work, where 2 or more motors are employed, these are connected in parallel for braking, because series connection would produce too high voltage. K.E. of the vehicle is utilized in driving the machines as generators, which is dissipated in braking resistance in the form of heat.

To ensure that the 2 machines share the load equally, an equalizer connection is used as shown in Fig. 43.33 (*a*). If it is not used, the machine whose acceleration builts-up first would send a current through the 2nd machine in opposite direction, causing it to excite with reverse voltage. So that the 2 machines would be short circuited on themselves. The current would be dangerously high. Equalizer prevents such conditions. Hence Equalizer connection is important during braking in traction.

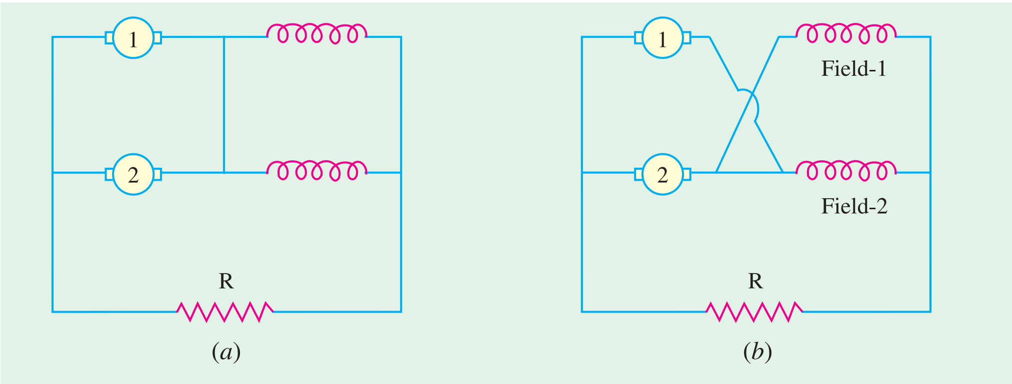


Fig. 43.33

(*b*) Cross Connection

In cross connection the field of machine 2 is connected in series with armature of machine 1 and the field of machine 1 is connected in series with armature of machine 2 as shown in Fig. 43.33 (*b*). Suppose the voltage of machine 1 is greater than that of 2. So it will send greater current through field of machine 2, causing it to excite to higher voltage. At the same time machine 1 excitation is low, because of lower voltage of machine 2. Hence machine 2 will produce more voltage and machine 1 voltage will be reduced. Thus automatic compensation is provided and the 2 machines operate satisfactorily.

Because of cross - connection during braking of traction motors, current in any of the motor will not go to a very high value.

43.60. Regenerative Braking with D.C. Motors

In order to achieve the regenerative braking, it is essential that ***(i)*** the voltage generated by the machine should exceed the supply voltage and ***(ii)*** the voltage should bez kept at this value, irrespective of machine speed. Fig. 43.34 (*a*) shows the case of 4 series motors connected in parallel during normal running *i.e.* motoring.

One method of connection during regenerative barking, is to arrange the machines as shunt machines, with series fields of 3 machines connected across the supply in series with suitable resistance. One of the field winding is still kept in series across the 4 parallel armatures as shown in figure 43.34 (*b*).

The machine acts as a compound generator. (with slight differential compounding) Such an arrangement is quiet stable; any change in line voltage produces a change in excitation which produces corresponding change in e.m.f. of motors, so that inherent compensation is provided *e.g.* let the line voltage tends to increase beyond the e.m.f. of generators. The increased voltage across the shunt circuit increases the excitation thereby increasing the generated voltage. Vice-versa is also true. The arrangement is therefore self compensating.

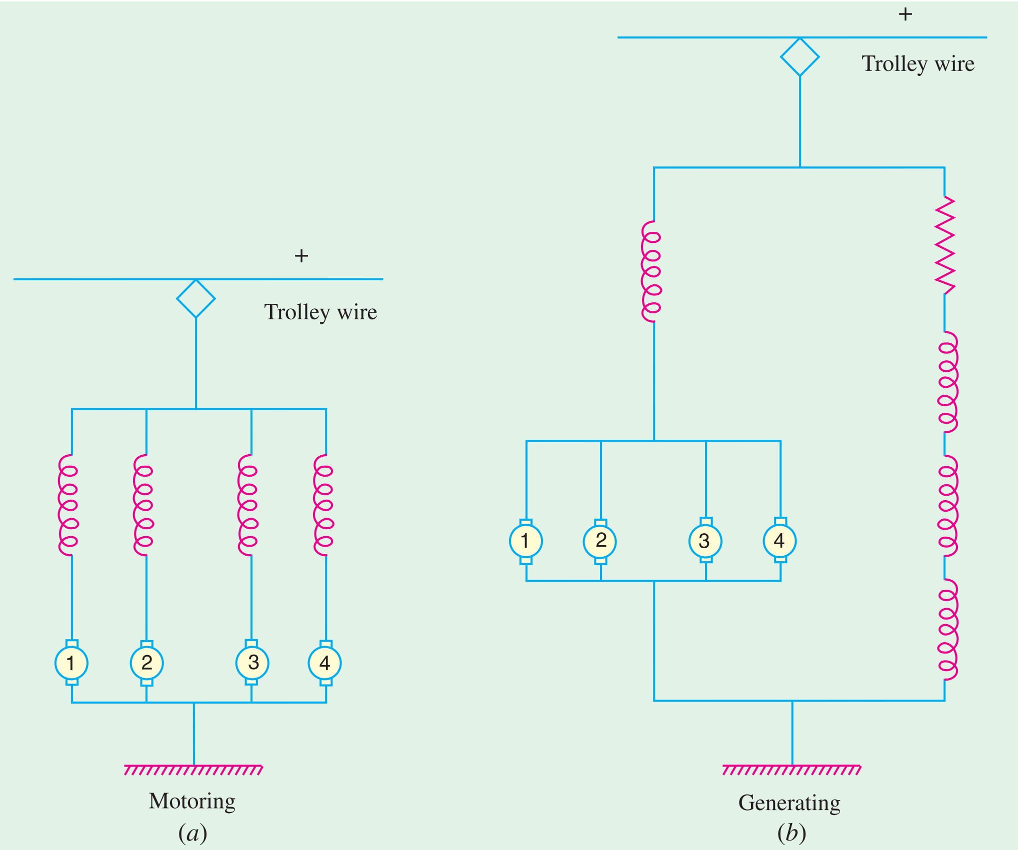


Fig. 43.34

D.C. series motor can't be used for regenerative braking without modification for obvious reasons. During regeneration current through armature reverses; and excitation has to be maintained. Hence field connection must be reversed.

Example 43.29. *Two 750 V D.C. series motors each having a resistance of 0.1 W are started on series - parallel system. Mean current through - out the starting period is 300 A. Starting period is 15 sec. and train speed at the end of this period is 25 km/hr. Calculate*

(i) Rheostatic losses during series and parallel combination of motors
(ii) Energy lost in motor
(iii) Motor output
(iv) Starting η
(v) Train speed at which transition from series to parallel must be made.

[Nagpur University, Summer 2000]

Solution.

(i)
$$t_s = \frac{1}{2}\left[\frac{V-2\,I\,R}{V-I\,R}\right]T$$

$$t_s = \frac{1}{2}\left[\frac{750-2\,(300)\,0.1}{750-(300)\,0.1}\right]15 = 7.1875 \text{ rec.}$$

$$\therefore \quad t_p = T - t_s = 7.8125 \text{ sec.}$$

$$\text{Energy lost in Rheostat} = \frac{1}{2}\,E_{b_s}\,I\,t_s + \frac{1}{2}\,\frac{E_{b_p}}{2}\,2\,I.t_p$$

$$= \frac{1}{2}\left[2\times\left[\frac{V}{2}-IR\right]\right]I\,.\,t_s + \frac{1}{2}\,[[V-IR]/2]\;2I\,.\,t_p$$

$$= \frac{1}{2}\left[2\times\left[\frac{750}{2}-300\;(0.1)\right]\right]300\times 7.1875 + \frac{1}{2}\left[\frac{750-300\;(0.1)}{2}\right]\times 2(300)\times 7.1825$$

$$= 743906.25 + 843750$$

$$= 1587656.25 \text{ watt} - \text{sec.}$$

$$= \frac{1587656.25}{3600} = \mathbf{441.00 \text{ watt - hrs.}}$$

(ii)
$$\text{Total Energy supplied} = V.I.\,t_s + 2\,I\,.\,V\,.\,t_p$$

$$= 750\times 300\;(7.1875) + 2\;(300)\;750\;(7.8125)$$

$$= 1617187.5 + 3515625$$

$$= 5132812.5 \text{ watt-sec} = 1425.7812 \text{ watt} - \text{hrs.}$$

$$\text{Energy lost in 2 Motors} = (I_a^2 \times R_a)\times 2\times 15$$

$$= (300^2\times 0.1)\times 2\times 15 = 270000 \text{ watt - sec.} = \mathbf{75 \text{ watt - hrs.}}$$

(iii) Motor O/P = Total Energy supplied – Energy lost in Rheostat – Energy lost in armature

$$= 1425.7812 - 441 - 75$$

$$= \mathbf{909.7812 \text{ watt} - \text{hrs.}}$$

(iv)
$$\eta \text{ starting} = \frac{\text{Total Energy Supplied} - \text{Energy lost in Rheostat}}{\text{Total Energy Supplied}}$$

$$= \frac{1425.7812 - 441.00}{1425.7812}\times 100$$

$$= \mathbf{69.0605\%}$$

(v) Acceleration is uniform during starting period of 15 sec. Therefore speed after which series to parallel transition must be made is given as –

$$= \frac{\text{Speed after starting period}}{\text{Total starting period}}\times t_s$$

$$= \frac{25}{15} \cdot 7.1875$$

$$= \mathbf{11.9791 \text{ km/hr.}}$$

Example 43.30. *Two 600-V motors each having a resistance of 0.1Ω are started on the series-parallel system, the mean current per motor throughtout the starting period being 300A. The starting period is 20 seconds and the train speed at the end of this period is 30 km per hour. Calculate **(i)** the rheostatic losses (in kwh) during **(a)** the series and **(b)** the parallel combinations of motors **(ii)** the train speed at which transition from series to parallel must be made.*

Solution.

Number of motors operating $= 2$

Line voltage, $V = 600$ volts

Current per motor, $I = 300$ amperes

Starting period, $T_s = 20$ seconds

Motor resistance, $R = 0.1\ \Omega$

Maximum speed, $V_m = 30$ kmph.

Back e.m.f. of each motor in full series position,

$$E_{b_s} = \frac{V}{2} - IR = \frac{600}{2} - 300 \cdot 0.1 = 270 \text{ volts.}$$

Back e.m.f. of each motor in full parallel position,

$$E_{b_p} = V - IR - 300 \cdot 0.1 = 570 \text{ volts}$$

Assuming smooth acceleration, back e.m.f. will be built up at constant rate.

Since motors take 20 seconds to build up 570 volts, therefore time taken to build up 270 volts e.m.f. will be :

$$T_{\text{series}} = 20 \cdot \frac{270}{570} = 9.4737 \text{ seconds}$$

$$T_{\text{parallel}} = 20 - 9.4737 = 10.5263 \text{ seconds}$$

(i) ***(a)*** Voltage drop in the starting rheostat in series combination at the starting instant

$$= V - 2IR = 600 - 2 \cdot 300 \cdot 0.1 = 540 \text{ volts,}$$

which reduces to zero in full series position

Energy dissipated in starting resistance during series combination

$$= \frac{(V - 2IR) + 0}{2} \cdot I \cdot \frac{T_{\text{series}}}{3600} = \frac{540 + 0}{2} \quad 300 \quad \frac{9.4737}{3600}$$

$$= \mathbf{213.1579 \text{ watt - hours}}$$

(b) Voltage drop across the starting resistance in first parallel position is equal to $V/2$ *i.e.* 300 volts which gradually reduces to zero.

Energy dissipated in starting resistance during parallel combination

$$= \frac{\frac{V}{2} + 0}{2} \cdot 2I \cdot \frac{T_{\text{parallel}}}{3600} = \frac{\frac{600}{2} + 0}{2} \cdot 2 \quad 300 \quad \frac{10.5263}{3600}$$

$$= \mathbf{263.1579 \text{ watt – hours}}$$

(ii) Acceleration, $\alpha = \dfrac{\text{Maximum speed}}{\text{Starting period}} = \dfrac{V_m}{T_s} = \dfrac{30}{20} = 1.5$ kmphps.

Speed at the end of series period $= \alpha\ T_{\text{series}} = 1.5 \times 9.4737 =$ **14.21 km/hour**

Example 43.31. *Two d.c. series motors of a motor coach have resistance of 0.1 W each. These motors draw a current of 500 A from 600 V mains during series – parallel starting period of 25 seconds. If the acceleration during starting period remains uniform, determine:*

(i) *time during which the motors operate in (a) series (b) parallel.*

(ii) *the speed at which the series connections are to be changed if the speed just after starting period is 80 kmph.*

Solution.

Number of motors operating $= 2$

Line voltage, $V = 600$ V

Current per motor, $I = 500$ A

Motor resistance, $R = 0.1\ \Omega$

Maximum speed, $V_m = 80$ kmph.

Back e.m.f. of each motor in full series position.

$$E_{b_s} = \frac{V}{2} - I\,R = \frac{600}{2} - 500 \cdot 0.1 = 250 \text{ V}$$

Back e.m.f. each motor in full parallel operation,

$$E_{b_p} = V - IR = 600 - 500 \cdot 0.1 = 550 \text{ V}$$

Since motors take 25 seconds to build up 550 V, therefore, time taken to build up 250 V, will be: (assuming smooth acceleration and building up of e.m.f. at constant rate.)

(i) Period of series operation, $T_{\text{series}} = 25 \cdot \dfrac{255}{550}$ = **11.3636 seconds**

Period of parallel operation, $T_{\text{parallel}} = T - T_{se} = 25 - 11.3636 =$ **13.6363 seconds**

(iii) Speed at which the series connections are to be changed

$$= \alpha\, T_{\text{series}} = \frac{V_m}{T} \,.\, T_{\text{series}} = \frac{80}{25} \times 11.3636 = \mathbf{36.3636\ \ kmph}$$

Example 43.32. *The following figures refer to the speed-current and torque – current characteristics of a 600 V d.c. series traction motor.*

Current, amperes :	*50*	*100*	*150*	*200*	*250*
Speed, kmph :	*73.6*	*48*	*41.1*	*37.3*	*35.2*
Torque, N-m :	*150*	*525*	*930*	*1,335*	*1,750*

Determine the braking torque at a speed of 48 kmph when operating as self excited d.c. generator. Assume resistance of motor and braking rheostat to be 0.6Ω and 3.0 Ω respectively.

Solution.

As motor :

Terminal voltage, $V = 600$ volts.

The motor current at a speed of 48 kmph (from speed-current characteristic curve),

$I = 100$ A

Back e.m.f. developed by the motor, $E_b = V - IR_m = 600 - 100 \cdot 0.6 =$ **540 V**

As Generator:

At the instant of applying rheostatic braking at speed of 48 kmph, the terminal voltage of machine will be equal to e.m.f. developed by the machine *i.e.* 540 volts.

Total resistance in the circuit $= R_m + R_{\text{rheostat}} = 0.6 + 3 = 3.6\ \Omega$

Current delivered by the machine, $I = \dfrac{540}{3.6}$ = **150 amps**

The braking torque (the torque corresponding to 150 amperes from torque-current curve)

= **930 N-m**

Tutorial Problem No. 43.1

1. A train weighs 500 tonnes. What is its mass in (*i*) tonnes and (*ii*) kilograms. **[(*i*) 500 t (*ii*) 500,000 kg]**

2. A train has a mass of 200 tonnes. What is its weight in (*i*) newtons and (*ii*) kg-wt (*iii*) tonnes-wt. **[(*i*) $19.6 \cdot 10^5$ N (*ii*) 200,000 kg. wt (*iii*) 200 t-wt)]**

3. A train has a speed of 100 km/h. What is its value in m/s ? **[27.78 m/s]**

4. A certain express train has an acceleration of 3.6 km/h/s. What is its value in m/s^2 ? **[1.0 m/s^2]**

5. If there is an ascending gradient of 15 m in a track length of 1 km, what is the value of percentage gradient ? **[1.5%]**

6. A train runs at an average speed of 45 km per hour between stations 2.5 km apart. The train accelerates at 2 km/h/s and retards at 3 km/h/s. Find its maximum speed assuming a trapezoidal speed/time curve. Calculate also the distance travelled by it before the brakes are applied. **[50.263 km/h, 2.383 km] (*Elect. Traction and Utilization B.H.U.*)**

7. The schedule speed with a 200 tonne train on an electric railway with stations 777 metres apart is 27.3 km/h and the maximum speed is 20 percent higher than the average running speed. The braking rate is 3.22 km/h/s and the duration of stops is 20 seconds. Find the acceleration required. Assume a simplified speed-time curve with free running at the maximum speed. **[2.73 km/h/s] (*Traction and Utilization of Elect. Power, Agra Univ.*)**

8. A suburban electric train has a maximum speed of 65 km/h.. The schedule speed including a station stop of 30 seconds is 43.5 km/h. If the acceleration is 1.3 km/h/s, find the value of retardation when the average distance between stops is 3 km. **[β = 1.21 km/h/s] (*Utilization of Elect. Power and Traction, Gorakhpur Univ.,*)**

9. An electric train is accelerated uniformly from rest to a speed of 40 km/h, the period of acceleration being 20 seconds. If it coasts for 60 seconds against a constant resistance of 50 N/t and is brought to rest in a further period of 10 seconds by braking, determine :

(*i*) the acceleration (*ii*) the coasting retardation (*iii*) the braking retardation (*iv*) distance travelled and (*v*) schedule speed with station stops of 10 seconds duration.

Allow 10 percent for rotational inertia. (*Elect. Traction, Punjab Univ.*)

[α = 2 km/h/s, β_c = 0.1636 km/h/s, β = 3 km/h/s., D = 0.736 km., V = 27.5 km/h]

10. The speed-time curve of an electric train on a uniform rising gradient of 1 in 100 comprises :

(*i*) uniform acceleration from rest at 2 km/h/s/ for 30 seconds.

(*ii*) coasting with power off for 70 seconds.

(*iii*) braking at 3 km/h/s to a standstill.

The weight of the train is 250 tonnes, the train resistance on level track being 49 N/tonne and allowance for rotary inertia 1%.

Calculate the maximum power developed by traction motors and total distance travelled by the train. Assume transmission efficiency as 97%.

[3,3258 kW, 1.12 km] (*Traction and Utilization of Elect. Power, Agra Univ.*)

11. A 400-tonne goods train is to be hauled by a locomotive up a gradient of 2% with an acceleration of 1 km/h/s. Co-efficient of adhesion is 20%, track resistance 40 N/tonne and effective rotating masses 10% of the dead weight. Find the weight of the locomotive and number of axles if the axle load is not increased beyond 22 tonnes.**[152.6 tonnes, 7] (*Traction and Utilization of Elect. Power, Agra Univ.*)**

12. A 500-tonne goods train is to be hauled by a locomotive up a gradient of 20% with an acceleration of 1.2 km/h/s. Co-efficient of adhesion is 25%, track resistance 40 N/ tonne and effective rotating masses 10% of dead weight. Find the weight of the locomotive and number of axles if axle load is not to exceed 20 tonnes. **[160 tonnes, 8] (*Utilization of Elect. Power, A.M.I.E. Winter*)**

13. Determine the maximum adhesive weight of a loco required to start a 2340 tonne weight (inclusive of loco) on 1 : 150 gradient and accelerate it at 0.1 km/h/s. Assume co-efficient of adhesion as 0.25, train resistance 39.2 N/tonne and rotary inertia as 8%. **[128.5 tonnes]**

(Elect. Traction, A.M.I.E., May)

14. Ore carrying trains weighing 5000 tonne each are to be hauled down a gradient of 1 in 60 at a maximum speed of 40 km/h and started on a level track at an acceleration of 0.1 m/s^2. How many locomotives, each weighing 75 tonne, will have to be employed ?

Train resistance during starting = 29.4 N/tonne
Train resistance at 40 km/h = 56.1 kg/tonne
Co-efficient of adhesion = 1/3 ; Rotational inertia = 1/10

[3 Loco] *(Engg. Service Examination U.P.S.C.)*

15. A locomotive accelerates a 400-tonne train up a gradient of 1 in 100 at 0.8 km/h/s. Assuming the coefficient of adhesion to be 0.25, determine the minimum adhesive weight of the locomotive. Assume train resistance of 60 N/tonne and allow 10% for the effect of rotational inertia.

[65.7 t] *(Elect. Traction and Utilization, Nagpur Univ.)*

16. Calculate the specific energy consumption if a maximum speed of 12.20 metres/sec and for a given run of 1525 m an acceleration of 0.366 m/s^2 are desired. Train resistance during acceleration is 52.6 N/1000 kg and during coasting is 6.12 N/1000 kg, 10% being allowable for rotational inertia. The efficiency of the equipment during the acceleration period is 50%. Assume a quadrilateral speed-time curve. **[3.38 Wh/kg-m]** *(Util. of Elect. Power, A.M.I.E. Sec. B)*

17. An electric locomotive of 100 tonne can just accelerate a train of 500 tonne (trailing weight) with an acceleration of 1 km/h/s on an upgradient of 1/1000. Tractive resistance of the track is 45 N per tonne and the rotational inertia is 10%. If this locomotive is helped by another locomotive of 120 tonnes, find, (*i*) the trailing weight that can be hauled up the same gradient under the same conditions and (*ii*) the maximum gradient, the trailing weight hauled remaining unchanged.

Assume adhesive weight expressed as percentage of total dead weight to be the same for both the locomotive. **[(*i*) 1120 t (*ii*) 3.15%]** *(Util. of Elect. Power, A.M.I.E. Sec. B.)*

18. An electric train has quadrilateral speed-time curve as follows :

(*i*) uniform acceleration from rest at 2 km/h/s for 30 sec,

(*ii*) coasting for 50 sec.

(*iii*) uniform braking to rest for 20 seconds.

If the train is moving uniform upgradient of a 10/1000, train resistance is 40 N/tonne, rotational inertia effect 10% of dead weight and duration of stop 30 seconds, find the schedule speed.

[28.4 km/h] *(Util. of Elect. Power, A.M.I.E. Sec. B.)*

19. The schedule speed with a 200 tonne train on an electric railway with stations 777 metres apart is 27.3 km/h and the maximum speed is 20% higher than the average running speed. The braking rate is 3.22 km/h/s and the duration of stops is 20 seconds. Find the acceleration required. Assume a simplified speed-time curve with the free running at the maximum speed.

[2.73 km/h/s] *(Traction & Util. of Elect. Power, Agra Univ.)*

20. An electric train has an average speed of 42 km/h on a level track between stops 1,400 metre apart. It is accelerated at 1.7 km/h/s and is braked at 3.3 km/h/s. Draw the speed-time curve for the run. Estimate the sp. energy consumption. Assume tractive resistance as 50 N/t and allow 10% for rotational inertia. **[39.48 Wh/t-km]** *(Util. of Elect. Power, A.M.I.E. Sec. B.)*

21. An electric train weighing 200 tonne has eight motors geared to driving wheels, each wheel is 90 cm diameter. Determine the torque developed by each motor to accelerate the train to a speed of 48 km/h in 30 seconds up a gradient of 1 in 200. The tractive resistance is 50 N/t, the effect of rotational inertia is 10% of the train weight, the gear ratio is 4 to 1 and gearing efficiency is 80%.

[2,067 N-m] *(Traction & Util. of Elect. Power, Agra Univ.)*

22. An electric train accelerates uniformly from rest to a speed of 48 km/h in 24 seconds. It then coasts for 69 seconds against a constant resistance of 58 N/t and is braked to rest at 3.3 km/h/s in 11 seconds.

Calculate (*i*) the acceleration (*ii*) coasting retardation and (*iii*) the schedule speed, if the station stops are of 20 seconds duration. What would be the effect on schedule speed of reducing the station stops to 15 second duration, other conditions remaining the same? Allow 10% for the rotational inertia.

[(*i*) 2 km/h/s (*ii*) 0.19 km/h/s (*iii*) 30.25 km/h]
(Util. of Elect. Power, A.M.I.E. Sec. B.)

23. An electric train accelerates uniformly from rest to a speed of 50 km/h in 25 seconds. It then coasts for 1 minute 10 seconds against a constant resistance of 70 N/t and is braked to rest at 4 km/h/s in 10 seconds. Calculate the schedule speed, if the station stops are of 15 second duration.

[31.125 km/h] ***(Util. of Elect. Power, A.M.I.E. Sec. B)***

24. An electric train has a quadrilatural speed-time curve as follows :

(*i*) uniform acceleration from rest at 2.5 km/h/s for 25 second

(*ii*) coasting for 50 second (*iii*) duration of braking 25 second.

If the train is moving along a uniform upgradient of 1 in 100 with a tractive resistance of 45 N/t, rotational inertia 10% of dead weight, duration of stops at stations 20 second and overall efficiency of transmission gear and motor 80%, calculate the schedule speed and specific energy consumption of run. **[69 km/h, 26.61 Wh/t-km]** ***(Util. of Elect. Power, A.M.I.E. Sec. B)***

25. An ore-carrying train weighing 5000 tonne is to be hauled down a gradient of 1 in 50 at a maximum speed of 30 km/h and started on a level track at an acceleration of 0.08 m/s^2. How many locomotives, each weighing 75 tonne, will have to be employed ?

Train resistance during starting =3 kg/t

Train resistance at 30 km/h = 5 kg/t

Co-efficient of adhesion = 0.3, Rotational inertia = 10%.

[4 loco] ***(Util. of Elect. Power, A.M.I.E. Sec. B.)***

26. A train with an electric locomotive weighing 300 tonne is is to be accelerated up a gradient of 1 in 33 at an acceleration of 1 km/h/s. If the train resistance, co-efficient of adhesion and effect of rotational inertia are 80 N/t, 0.25 and 12.5% of the dead weight respectively, determine the minimum adhesive weight of the locomotive. **[88 t]** ***(Util. of Elect. Power, A.M.I.E. Sec. B.)***

27. A train weighing 400 tonne has speed reduced by regenerative braking from 40 to 20 km/h over a distance of 2 km at a down gradient of 20%. Calculate the electrical energy and average power returned to the line. Tractive resistance is 40 N/t and allow rotational inertia of 10% and efficiency of conversion 75%. **[324 kW/h, 4860 kW]** ***(Util. & Traction Power, Agra Univ.)***

28. A 250-tonne motor coach having 4 motors, each developing 5,000 N-m torque acceleration, starts from rest. If upgradient is 25 in 1000, gear ratio 5, gear transmission efficiency 88%, wheel radius 44 cm, train resistance 50 N/t addition of rotational inertia 10%, calculate the time taken to reach a speed of 45 km/h.

If the supply voltage were 1500 V d.c. and efficiency of motor is 83.4%, determine the current drawn per motor during notching period. **[27.25 s, 500 A]** ***(Util. of Elect. Power, A.M.I.E. Sec. B.)***

29. An electric train weighing 100 tonne has a rotational inertia of 10%. This train while running between two stations which are 2.5 km apart has an average speed of 50 km/h. The acceleration and retardation during braking are respectively 1 km/h/s and 2 km/h/s. The percentage gradient between these two stations is 1% and the train is to move up the incline. The track resistance is 40 N/t. If the combined efficiency of the electric train is 60%, determine (*i*) maximum power at driving axle (*ii*) total energy consumption and (*iii*) specific energy consumption. Assume that journey estimation is being made in simplified trapezoidal speed-time curve.

[(*i*) 875 kW (*ii*) 23.65 kW/h (*iii*) 94.6 Wh/t-km] ***(Util. of Elect. Power, A.M.I.E. Sec. B.)***

30. A 500-tonne goods train is to be hauled by a locomotive up a gradient of 1 in 40 with an acceleration of 1.5 km/h/s. Determine the weight of the locomotive and number of axles, if axle load is not to exceed 24 tonne. Co-efficient of adhesion is 0.31, track resistance 45 N/t and effective rotating masses 10% of dead weight. [7] *(Util. of Elect. Power, A.M.I.E. Sec. B.)*

31. Two d.c. series motors of a motor coach have resistance of 0.1 W each. These motors draw a current of 500 A from 600V mains during series-parallel starting period of 20 seconds. If the acceleration during starting period remains uniform, determine :

(*i*) time during which motor operates in (*a*) series, (*b*) parallel

(*ii*) the speed at which the series connections are to be changed if the speed just after starting period is 70 km/h.

[(*i*) 9.098, 10.971 Sec. (*ii*) 31.82 km/h] *(Util. of Elect. Power and Traction, Agra Univ.)*

32. Explain how series motors are ideally suited for traction service.
(Nagpur University, Summer 2004)

33. Explain any one method for regenerative braking of D.C. motor for traction.
(Nagpur University, Summer 2004)

34. Discuss the effect of unequal wheel diameters on the parallel operation of traction motors.
(Nagpur University, Summer 2004)

35. Explain the various modes of operation in traction services with neat speed-time curve.
(Nagpur University, Summer 2004)

36. A 100 tonne motor coach is driven by 4 motors, each developing a torque of 5000 N-m during acceleration. If up-gradient is 50 in 1000, gear ratio a = 0.25, gear transmission efficiency 98%, wheel radius 0.54 M, train resistance 25 N/tonne, effective mass on account of rotational inertia is 10% higher, calculate the time taken to attain a speed of 100 kmph.
(Nagpur University, Summer 2004)

37. What are the requirements of an ideal traction system?
(J.N. University, Hyderabad, November 2003)

38. What are the advantages and disadvantages of electric traction?
(J.N. University, Hyderabad, November 2003)

39. Write a brief note on the single phase a.c. series motor and comment upon it's suitability for traction services. How does it compare in performance with the d.c. Services motor.
(J.N. University, Hyderabad, November 2003)

40. Draw the speed-time curve of a main line service and explain.
(J.N. University, Hyderabad, November 2003)

41. A train hs a scheduled speed of 40 km/hr between two stops, which are 4 kms apart. etermine the crest speed over the run, if the duration of stops is 60 sec and acceleration and retardation both are 2 km/hr/sec each. Assume simplified trapezoidal speed-time curve.
(J.N. University, Hyderabad, November 2003)

42. What are the various electric traction systems in India? Compare them.
(J.N. University, Hyderabad, November 2003)

43. Give the features of various motors used in electric traction.
(J.N. University, Hyderabad, November 2003)

44. Draw the speed-time curve of a suburban service train and explain.
(J.N. University, Hyderabad, November 2003)

45. A train accelerates to a speed of 48 km/hr in 24 sec. then it coasts for 69 sec under a constant resistance of 58 newton/tonne and brakes are applied at 3.3 km/hr/sec in 11 sec. Calculate (*i*) the acceleration (*ii*) the coasting retardation (*iii*) the scheduled speed if station stoppage is 20 secs. What is theeffect of scheduled speed if station stoppage is reduced to 15 sec duration, other conditions remaining same. Allow 10% for rotational inertia.
(J.N. University, Hyderabad, November 2003)

46. Derive an expression for specific energy output on level track using a simplified speed-time curve. What purpose is achieved by this quantity? *(J.N. University, Hyderabad, November 2003)*
47. A 400 tonne goods train is to be hauled by a locomotive up a gradient of 2% with acceleration of 1 km/hr/sec, coefficient of adhesion 20%, track resistance 40 newtons/tonne and effective rotating masses 10% of the dead weight. Find the weight of the locomotive and the number of axles if the axle load is not to increase beyond 22 tonnes. *(J.N. University, Hyderabad, November 2003)*
48. A motor has the following load cycle :
Accelerating period 0-15 sec Load rising uniformly from 0 to 1000 h.p.
Full speed period 15-85 sec Load constant at 600 h.p.
Decelerating period 85-100 sec h.p. returned to line falls uniformly from 200 to zero
Decking period 100-120 sec Motor stationary. Estimate the size of the motor.
(J.N. University, Hyderabad, November 2003)
49. Explain the characteristics of series motors and also explain how they are suitable of electric traction work? *(J.N. University, Hyderabad, November 2003)*
50. For a trapezoidal speed-time curve of a electric train, derive expression for maximum speed and distance between stops. *(J.N. University, Hyderabad, November 2003)*
51. A mail is to be run between two stations 5 kms apart at an average speed of 50 km/hr. If the maximum speed is to be limited to 70 km/hr, acceleration to 2 km/hr/sec, braking retardation to 4 km/hr/sec and coasting retardation to 0.1 km/hr/sec, determine the speed at the end of coasting, duration of coasting period and braking period. *(J.N. University, Hyderabad, November 2003)*
52. Discuss the merits and demerits of the D.C. and 1–ϕ A.C. systems for the main and suburban line electrification of the railways. *(J.N. University, Hyderabad, April 2003)*
53. Which system do you consider to be the best for the suburban railways in the vicinity of large cities? Given reasons for your answer. *(J.N. University, Hyderabad, April 2003)*
54. Derive expression for the tractive effort for a train on a level track. *(J.N. University, Hyderabad, April 2003)*
55. The maximum speed of a suburbanelectric train is 60 km/hr. Its scheduled speed is 40 km/hr and duration of stops is 30 sec. If the acceleration is 2 km/hr/sec and distance between stops is 2 kms, determine the retardation. *(J.N. University, Hyderabad, April 2003)*
56. What are various types of traction motors? *(J.N. University, Hyderabad, April 2003)*
57. What are the advantages of series parallel control of D.C. motors? *(J.N. University, Hyderabad, April 2003)*
58. Describe about duplication of railway transmission lines. *(J.N. University, Hyderabad, April 2003)*
59. Write a note on feeding and distributing system on A.C. Traction and for d.c. tram ways. *(J.N. University, Hyderabad, April 2003)*
60. For a quadrilateral speed-time curve of a electric train, derive expression for the distance between stops and speed at the end of the coasting period. *(J.N. University, Hyderabad, April 2003)*
61. A train is required to run between stations 1.6 kms apart at an average speed of 40 km/hr. The runis to be made from a quadilateral speed-time curve. The acceleration is 2 km/hr/sec. The coasting and braking retardations are 0.16 km/hr/sec and 3.2 km/hr/sec respectively. Determine the duration of acceleration, coasting and braking and the distance covered in each period. *(J.N. University, Hyderabad, April 2003)*
62. Explain the characteristics of D.C. compound motors and explain its advantage over the series motor. *(J.N. University, Hyderabad, April 2003)*
63. What are the requirements to be satisfied by an ideal traction system? *(J.N. University, Hyderabad, April 2003)*
64. What are the advantages and disdvantages of electrification of track? *(J.N. University, Hyderabad, April 2003)*

65. Discuss why a D.C. series motor is ideally suited for traction services.
(J.N. University, Hyderabad, April 2003)

66. An electric locomotive of 100 tonnes can just accelerate a train of 500 tonnes (trailing weight) with an acceleration of 1 km/hr/sec on an up gradient 1 in 1000. Tractive resistance of the track is 45 newtons/tonne and the rotational inertia is 10%. If this locomotive is helped by another locomotive of 120 tonnes, find (i) the trailing weight that can be hauled up the same gradient, under the same condition (ii) the maximum gradient, the trailing hauled load remaining unchanged. Assume adhesive weight expressed as percentage of total dead weight to be same for both the locomotives. *(J.N. University, Hyderabad, April 2003)*

67. Explain how electric regeneration braking is obtained with a D.C. locomotive. How is the braking torque varied? *(J.N. University, Hyderabad, April 2003)*

68. Explain why a series motor is preferred for the electric traction.
(J.N. University, Hyderabad, April 2003)

69. The characteristics of a series motor at 525 – V are as follows :

Current (A)	50	100	150	200
Speed (RPM)	1200	952	840	745

Determine the current when working as a generator at 1000 R.P.M. and loaded with a resistance of 3 ohms. The resistance of the motor is 0.5 ohms. *(J.N. University, Hyderabad, April 2003)*

70. Briefly explain the a.c. motors used in traction. *(J.N. University, Hyderabad, April 2003)*

71. The scheduled speed of a trolley service is to be 53 km/hr. The distance between stops is 2.8 km. The track is level and each stop is of 30 sec duration. Using simplified speed-time curve, calculate the maximum speed, assuming the acceleration to be 2 km/hr/sec, retardation 3.2 km/hr/sec, the dead weight of the car as 16 tonnes, rotational inertia as 10% of the dead weight and track resistance as 40 newtons/tonne. If the overall efficiency is 80%, calculate (*i*) the maximum power output from the driving axles (*ii*) the specific energy consumption in watt-hr/tonne-km.
(J.N. University, Hyderabad, April 2003)

72. Discuss various traction systems you know of?
(J.N. University, Hyderabad, December 2002/January 2003)

73. Explain the requirements for ideal traction and show which drive satisfies almost all the requirements.
(J.N. University, Hyderabad, December 2002/January 2003)

74. Define the adhesive weight of a locomotive which accelerates up a gradient of 1 in 100 at 0.8 kmphps. The self weight of locomotive is 350 Tonnes. Coefficient of adhesion is 0.25. Assume a trainresistance of 45 N–m/Tonne and allow 10% for the effect of rotational inertia.
(J.N. University, Hyderabad, December 2002/January 2003)

75. State Factors affecting specific energy consumption.
(J.N. University, Hyderabad, December 2002/January 2003)

76. Explain with the help of a diagram, the four quadrant speed-torque characteristic of an induction motor when running in (*i*) forward direction (*ii*) reverse direction.
(J.N. University, Hyderabad, December 2002/January 2003)

77. Explain the general features of traction motors.
(J.N. University, Hyderabad, December 2002/January 2003)

78. A 250 tonne electric train maintains a scheduled speed of 30 kmph between stations situated 5 km apart, with station stops of 30 sec. The acceleration is 1.8 kmph ps and the braking retardation is 3 kmph ps. Assuming a trapezoidal speed-time curve, calculate (*i*) maximum speed of the train (*ii*) energy output of the motors if the tractive resistance is 40 NW per tonne.
(J.N. University, Hyderabad, December 2002/January 2003)

79. Discuss the relative merits of electric traction and the factors on which the choice of traction system depends. *(J.N. University, Hyderabad, December 2002/January 2003)*

80. Explain the terms (*i*) tractiveeffort (*ii*) coefficient of adhesion (*iii*) specific energy consumption of train (*iv*) tractive resistance. *(J.N. University, Hyderabad, December 2002/January 2003)*

81. Existing traction systems in India.*(J.N. University, Hyderabad, December 2002/January 2003)*

82. Explain the terms tractive effort, coefficient of adhesion, train resistance and specific energy consumption of train. *(J.N. University, Hyderabad, December 2002/January 2003)*

83. An electric train maintains a scheduled speed of 40 kmph between stations situated at 1.5 km apart. If is accelerated at 1.7 kmph.ps and is braked at 3.2 kmph.ps. Draw the speed-time curve for the run. Estimate the energy consumption at the axle of the train. Assume tractive resistance constants at 50 NW per tonne and allow 10% for the effect of rotation inertia. *(J.N. University, Hyderabad, December 2002/January 2003)*

84. Explain the advantages of series parallel control of starting as compared to the rheostatic starting for a pair of dc traction motors. *(J.N. University, Hyderabad, December 2002/January 2003)*

85. Discuss the main features of various train services. What type of services correspond to trapezoidal and quadrilateral speed-time curves.*(J.N. University, Hyderabad, December 2002/January 2003)*

86. Existing electric traction system in India. *(J.N. University, Hyderabad, December 2002/January 2003)*

87. Briefly explain the controlling of D.C. Motor. *(Anna Univ., Chennai 2003)*

OBJECTIVE TESTS – 43

1. Diesel electric traction has comparatively limited overload capacity because
(*a*) diesel electric locomotive is heavier than a plain electric locomotive
(*b*) diesel engine has shorter life span
(*c*) diesel engine is a constant-kW output prime mover
(*d*) regenerative braking cannot be employed.

2. The most vital factor against electric traction is the
(*a*) necessity of providing a negative booster
(*b*) possibility of electric supply failure
(*c*) high cost of its maintenance
(*d*) high initial cost of laying out overhead electric supply system.

3. The direct current system used for tramways has a voltage of about ....volt.
(*a*) 750
(*b*) 1500
(*c*) 3000
(*d*) 2400

4. In electric traction if contact voltage exceeds 1500 V, current collection is invariably via a
(*a*) contact rail
(*b*) overhead wire
(*c*) third rail
(*d*) conductor rail.

5. For the single-phase ac system of track electrification, low frequency is desirable because of the following advantages
(*a*) it improves commutation properties of ac motors
(*b*) it increases ac motor efficiency
(*c*) it increases ac motor power factor
(*d*) all of the above.

6. In Kando system of track electrification, ...is converted into ....
(*a*) 1-phase ac, dc
(*b*) 3-phase ac, 1-phase ac
(*c*) 1-phase ac, 3-phase ac
(*d*) 3-phase ac, dc.

7. The main reason for choosing the composite 1-phase ac-to-dc system for all future track electrification in India is that it
(*a*) needs less number of sub-stations
(*b*) combines the advantages of high-voltage ac distribution at 50 Hz with dc series traction motors
(*c*) provides flexibility in the location of sub-stations
(*d*) requires light overhead catenary.

8. Ordinary, tramway is the most economical means of transport for
(*a*) very dense traffic of large city
(*b*) medium traffic densities
(*c*) rural services
(*d*) suburban services.

9. Unlike a tramway, a trolleybus requires no
(*a*) overhead contact wire
(*b*) driving axles
(*c*) hand brakes
(*d*) running rail.

10. The current collector which can be used at different speeds under all wind conditions and stiffness of OHE is called .... collector.
(*a*) trolley
(*b*) bow
(*c*) pantograph
(*d*) messenger.

11. The speed/time curve for city service has no........................ period.
(*a*) coasting
(*b*) free-running
(*c*) acceleration
(*d*) braking.

12. For the same value of average speed, increase in the duration of stops............. speed.
(*a*) increases the schedule
(*b*) increases the crest
(*c*) decreases the crest
(*d*) decreases the schedule.

13. A train weighing 490 tonne and running at 90 km/h has a mass of .... kg and a speed of .... m/s.
(*a*) 50,000, 25
(*b*) 490,000, 25
(*c*) 490, 25
(*d*) 50, 324.

14. A train has a mass of 500 tonne. Its weight is
(*a*) 500 t.wt
(*b*) 500,000 kg-wt
(*c*) 4,900,000 newton
(*d*) all of the above
(*e*) none of the above.

15. The free-running speed of a train does NOT depend on the
(*a*) duration of stops
(*b*) distance between stops
(*c*) running time
(*d*) acceleration.

16. A motor coach weighing 100 tonnes is to be given an acceleration of 1.0 km/h/s on an ascending gradient of 1 percent. Neglecting rotational inertia and train resistance, the tractive force required is .... newton.
(*a*) 109,800
(*b*) 37,580
(*c*) 28,760
(*d*) 125,780.

17. In a train, the energy output of the driving axles in used for
(*a*) accelerating the train
(*b*) overcoming the gradient
(*c*) overcoming train resistance
(*d*) all of the above.

18. Longer coasting period for a train results in
(*a*) higher acceleration
(*b*) higher retardation
(*c*) lower specific energy consumption
(*d*) higher schedule speed.

19. Tractive effort of an electric locomotive can be increased by
(*a*) increasing the supply voltage
(*b*) using high kW motors
(*c*) increasing dead weight over the driving axles
(*d*) both (*b*) and (*c*) (*e*)both (*a*) and (*b*).

20. Skidding of a vehicle always occurs when
(*a*) braking effort exceeds its adhesive weight
(*b*) it negotiates a curve
(*c*) it passes over points and crossings
(*d*) brake is applied suddenly.

21. Which of the following is an advantage of electric traction over other methods of traction?
(*a*) Faster acceleration
(*b*) No pollution problems
(*c*) Better braking action
(*d*) All of the above

22. Which of the following is the voltage for single phase A.C. system?
(*a*) 22 V
(*b*) 440 V
(*c*) 5 kV
(*d*) 15 kV
(*e*) None of the above

23. Long distance railways use which of the following?
(*a*) 200 V D.C.
(*b*) 25 kV single phase A.C.
(*c*) 25 kV two phase A.C.
(*d*) 25 kV three phase A.C.

24. The speed of a locomotive is controlled by
(*a*) flywheel
(*b*) gear box
(*c*) applying brakes
(*d*) regulating steam flow to engine

25. Main traction system used in India are, those using
(*a*) electric locomotives
(*b*) diesel engine locomotives
(*c*) steam engine locomotives
(*d*) diesel electric locomotives
(*e*) all of the above

26. In India diesel locomotives are manufactured at
(*a*) Ajmer
(*b*) Varanasi
(*c*) Bangalore
(*d*) Jamalpur

27. For diesel locomotives the range of horsepower is
(*a*) 50 to 200
(*b*) 500 to 1000
(*c*) 1500 to 2500
(*d*) 3000 to 5000

28. .... locomotive has the highest operational availability.
(*a*) Electric
(*b*) Diesel
(*c*) Steam

29. The horsepower of steam locomotives is
(*a*) upto 1500
(*b*) 1500 to 2000
(*c*) 2000 to 3000
(*d*) 3000 to 4000

30. The overall efficiency of steam locomotive is around
(*a*) 5 to 10 percent
(*b*) 15 to 20 percent
(*c*) 25 to 35 percent
(*d*) 35 to 45 percent

31. In tramways which of the following motors is used?
(*a*) D.C. shunt motor
(*b*) D.C. series motor
(*c*) A.C. three phase motor
(*d*) A.C. single phase capacitor start motor

32. In a steam locomotive electric power is provided through
(*a*) overhead wire
(*b*) battery system
(*c*) small turbo-generator
(*d*) diesel engine generator

33. Which of the following drives is suitable for mines where explosive gas exists?
(*a*) Steam engine
(*b*) Diesel engine
(*c*) Battery locomotive
(*d*) Any of the above

34. In case of locomotives the tractive power is provided by
(*a*) single cylinder double acting steam engine
(*b*) double cylinder, single acting steam engine
(*c*) double cylinder, double acting steam engine
(*d*) single stage steam turbine

35. Overload capacity of diesel engines is usually restricted to
(*a*) 2 percent
(*b*) 10 percent
(*c*) 20 percent
(*d*) 40 percent

36. In case of steam engines the steam pressure is
(*a*) 1 to 4 kgf/cm^2
(*b*) 5 to 8 kgf/cm^2
(*c*) 10 to 15 kgf/cm^2
(*d*) 25 to 35 kgf/cm^2

37. The steam engine provided on steam locomotives is
(*a*) single acting condensing type
(*b*) single acting non-condensing type
(*c*) double acting condensing type
(*d*) double acting non-condensing type

38. Electric locomotives in India are manufactured at
(*a*) Jamalpur
(*b*) Bangalore
(*c*) Chittranjan
(*d*) Gorakhpur

39. The wheels of a train, engine as well as bogies, are slightly tapered to
(*a*) reduce friction
(*b*) increase friction
(*c*) facilitate braking
(*d*) facilitate in taking turns

40. Automatic signalling is used for which of the following trains?

(a) Mail and express trains
(b) Superfast trains
(c) Suburban and Urban electric trains
(c) All trains

41. The efficiency of diesel locomotives is nearly
(a) 20 to 25 percent
(b) 30 to 40 percent
(c) 45 to 55 percent
(d) 60 to 70 percent

42. The speed of a superfast train is
(a) 60 kmph
(b) 75 kmph
(c) 100 kmph
(d) more than 100 kmph

43. The number of passenger coaches that can be attached to a diesel engine locomotive on broad gauge is usually restricted to
(a) 5
(b) 10
(c) 14
(d) 17

44. Which of the following state capitals is not on broad gauge track?
(a) lucknow
(b) Bhopal
(c) Jaipur
(d) Chandigarh

45. Which of the following is the advantage of electric braking?
(a) It avoids wear of track
(b) Motor continues to remain loaded during braking
(c) It is instantaneous
(d) More heat is generated during braking

46. Which of the following braking systems on the locomotives in costly?
(a) Regenerative braking on electric locomotives
(b) Vacuum braking on diesel locomotives
(c) Vacuum braking on steam locomotives
(d) All braking systems are equally costly

47. Tractive effort is required to
(a) overcome the gravity component of train mass
(b) overcome friction, windage and curve resistance
(c) accelerate the train mass
(d) do all of the above

48. For given maximum axle load tractive efforts of A.C. locomotive will be
(a) less than that of D.C. locomotive
(b) more than that of D.C. locomotive
(c) equal to that of D.C. locomotive
(d) none of the above

49. Co-efficient of adhesion reduces due to the presence of which of the following?
(a) Sand on rails
(b) Dew on rails
(c) Oil on the rails
(d) both (b) and (c)

50. Due to which of the following co-efficient of adhesion improves?
(a) Rust on the rails
(b) Dust on the rails
(c) Sand on the rails
(d) All of the above

51. Quadrilateral speed-time curve pertains to which of the following services?
(a) Main line service
(b) Urban service
(c) Sub-urban service
(d) Urban and sub-urban service

52. Which of the following is the disadvantage of electric traction over other systems of traction?
(a) Corrosion problems in the underground pip work
(b) Short time power failure interrupts traffic for hours
(c) High capital outlay in fixed installations beside route limitation
(d) Interference with communication lines
(e) All of the above

53. Co-efficient of adhesion is
(a) high in case of D.C. traction than in the case of A.C. traction
(b) low in case of D.C. traction that in the case of A.C. traction
(c) equal in both A.C. and D.C. traction
(d) any of the above

54. Speed-time curve of main line service differs from thoseof urban and suburban services on following account
(a) it has longer free running period
(b) it has longer coasting period

(*c*) accelerating and braking periods are comparatively smaller
(*d*) all of the above

55. The rate of acceleration on suburban or urban services is restricted by the consideration of
(*a*) engine power
(*b*) track curves
(*c*) passanger discomfort
(*d*) track size

56. The specific energy consumption of a train depends on which of the following?
(*a*) Acceleration and retardation
(*b*) Gradient
(*c*) Distance covered
(*d*) all of the above

57. The friction at the track is proportional to
(*a*) 1/speed
(*b*) $1/(\text{speed})^2$
(*c*) speed
(*d*) none of the above

58. The air resistance to the movement of the train is proportional to
(*a*) speed
(*b*) $(\text{speed})^2$
(*c*) $(\text{speed})^3$
(*d*) 1/speed

59. The normal value of adhesion friction is
(*a*) 0.12
(*b*) 0.25
(*c*) 0.40
(*d*) 0.75

60. The pulsating torque exerted by steam locomotives causes which of the following?
(*a*) Jolting and skidding
(*b*) Hammer blow
(*c*) Pitching
(*d*) All of the above

61. Which of the following braking systems is used on steam locomotives?
(*a*) Hydraulic system
(*b*) Pneumatic system
(*c*) Vacuum system
(*d*) None of the above

62. Vacuum is created by which of the following?
(*a*) Vacuum pump
(*b*) Ejector
(*c*) Any of the above
(*d*) None of the above

63. The resistance encountered by a train in motion is on account of
(*a*) resistance offered by air
(*b*) friction at the track
(*c*) friction at various parts of the rolling stock
(*d*) all of the above

64. Battery operated trucks are used in
(*a*) steel mills
(*b*) power stations
(*c*) narrow gauge traction
(*d*) factories for material transportation

65. .... method can bring the locomotive todead stop.
(*a*) Plugging braking
(*b*) Rheostatic braking
(*c*) Regenerative braking
(*d*) None of the above

66. The value of co-efficient of adhesion will be high when rails are
(*a*) greased
(*b*) wet
(*c*) sprayed with oil
(*d*) cleaned with sand

67. The voltage used for suburban trains in D.C. system is usually
(*a*) 12 V
(*b*) 24 V
(*c*) 220 V
(*d*) 600 to 750 V

68. For three-phase induction motors which of the following is the least efficient method of speed control?
(*a*) Cascade control
(*b*) Pole changing
(*c*) Rheostatic control
(*d*) Combination of cascade and pole changing

69. Specific energy consumption becomes
(*a*) more on steeper gradient
(*b*) more with high train resistance
(*c*) less if distance between stops is more
(*d*) all of the above

70. In main line service as compared to urban and suburban service

(*a*) distance between the stops is more
(*b*) maximum speed reached is high
(*c*) acceleration and retardation rates are low
(*d*) all of the above

71. Locomotive having monomotor bogies
(*a*) has better co-efficient of adhesion
(*b*) are suited both for passanger as well as freight service
(*c*) has better riding qualities due to the reduction of lateral forces
(*d*) has all above qualities

72. Series motor is not suited for traction duty due to which of the following account?
(*a*) Less current drain on the heavy load torque
(*b*) Current surges after temporary switching off supply
(*c*) self relieving property
(*d*) Commutating property at heavy load

73. When a bogie negotiates a curve, reduction in adhesion occurs resulting in sliding. Thus sliding is acute when
(*a*) wheel base of axles is more
(*b*) degree of curvature is more
(*c*) both (a) and (b)
(*c*) none of the above

74. Energy consumption in propelling the train is required for which of the following?
(*a*) Work against the resistance to motion
(*b*) Work against gravity while moving up the gradient
(*c*) Acceleration
(*d*) All of the above

75. An ideal traction system should have ....
(*a*) easy speed control
(*b*) high starting tractive effort
(*c*) equipment capable of with standing large temporary loads
(*d*) all of the above

76. .... have maximum unbalanced forces
(*a*) Diesel shunters
(*b*) Steam locomotives
(*c*) Electric locomotives
(*d*) Diesel locomotives

77. Specific energy consumption is affected by which of the following factors?
(*a*) Regardation and acceleration values
(*b*) Gradient
(*c*) Distance between stops
(*d*) All of the above

78. In case of .... free running and coasting periods are generally long.
(*a*) main-line service
(*b*) urban wervice
(*c*) sub-urban service
(*d*) all of the above

79. Overhead lines for power supply to tramcars are at a minimum height of
(*a*) 3 m
(b) 6 m
(*c*) 10 m
(*d*) 20 m

80. The return circuit for tram cars is through ....
(*a*) neutral wire
(*b*) rails
(*c*) cables
(*d*) common earthing

81. Specific energy consumption is least in .... service.
(*a*) main line
(*b*) urban
(*c*) suburban

82. Locomotives with monometer bogies have
(*a*) uneven distribution of tractive effect
(*b*) suitability for passanger as well as freight service
(*c*) lot of skidding
(*d*) low co-efficient of adhesion

83. .... was the first city in India to adopt electric traction.
(*a*) Delhi
(*b*) Madras
(*c*) Calcutta
(*d*) Bombay

84. .... frequency is not common in low frequency traction system
(*a*) 40 Hz
(*b*) 25 Hz
(*c*) 16Hz

85. For 25 kV single phase system power supply frequency is ....
(*a*) 60 Hz
(*b*) 50 Hz
(*c*) 25 Hz
(*d*) $16\frac{2}{3}$ Hz

86. Power for lighting in passenger coach, in a long distance electric train, is provided
(*a*) directly through overhead electric
(*b*) through individual generator of bogie and batteries
(*c*) through rails
(*d*) through locomotive

87. In India, electrification of railway track was done for the first time in which of the following years?
(*a*) 1820–1825
(*b*) 1880–1885
(*c*) 1925–1932
(*d*) 1947–1954

88. Suri transmission is ....
(*a*) electrical-pneumatic
(*b*) mechanical-electrical
(*c*) hydro-mechanical
(*d*) hydro-pneumatic

89. In case of a steam engine an average coat consumption per km is nearly
(*a*) 150 to 175 kg
(*b*) 100 to 120 kg
(*c*) 60 to 80 kg
(*d*) 28 to 30 kg

90. Which of the following happens in Kando system?
(*a*) Three phase A.C. is converted into D.C.
(*b*) Single phase A.C. is converted into D.C.
(*c*) Single phase supply is converted into three phase system
(*d*) None of the above

91. For which of the following locomotives the maintenance requirements are the least?
(*a*) Steam locomotives
(*b*) Diesel locomotives
(*c*) Electric locomotives
(*d*) Equal in all of the above

92. Which of the following methods is used to control speed of 25 kV, 50 Hz single phase traction?
(*a*) Reduced current method
(*b*) Tapchanging control of transformer
(*c*) Series parallel operation of motors
(*d*) All of the above

93. If the co-efficient of adhesion on dry rails is 0.26, which of the following could be the value for wet rails?
(*a*) 0.3
(*b*) 0.26
(*c*) 0.225
(*d*) 0.16

94. .... watt-hours per tonne km is usually the specific energy consumption for suburban services.
(*a*) 15–20
(*b*) 50–75
(*c*) 120–150
(*d*) 160–200

95. The braking retardation is usually in the range
(*a*) 0.15 to 0.30 km phps
(*b*) 0.30 to 0.6 km phps
(*c*) 0.6 to 2.4 km phps
(*d*) 3 to 5 km phps
(e) 10 to 15 km phps

96. The rate of acceleration on suburban or urban service is in the range
(*a*) 0.2 to 0.5 km phps
(*b*) 1.6 to 4.0 km phps
(*c*) 5 to 10 km phps
(*d*) 15 to 25 km phps

97. The coasting retardation is around
(*a*) 0.16 km phps
(b) 1.6 km phps
(*c*) 16 km phps
(*d*) 40 km phps

98. which of the following track is electrified
(*a*) Delhi–Bombay
(*b*) Delhi–Madras
(*c*) Delhi–Howrah
(*d*) Delhi–Ahmedabad

99. .... is the method of braking in which motor armature remains connected to the supply and draws power from it producing torque opposite to the direction of motion.
(*a*) Rheostatic braking
(*b*) Regerative braking
(*c*) Plugging

100. For 600 V D.C. line for tramcars, brack is connected to ....
(*a*) positive of the supply
(*b*) negative of the supply
(*c*) mid voltage of 300 V
(*d*) none of the above

ANSWERS

1. (*c*)	**2.** (*d*)	**3.** (*a*)	**4.** (*b*)	**5.** (*d*)	**6.** (*c*)	**7.** (*b*)	**8.** (*a*)	**9.** (*d*)	**10.** (*c*)
11. (*b*)	**12.** (*d*)	**13.** (*b*)	**14.** (*d*)	**15.** (*a*)	**16.** (*b*)	**17.** (*d*)	**18.** (*c*)	**19.** (*d*)	**20.** (*a*)
21. (*d*)	**22.** (*d*)	**23.** (*b*)	**24.** (*d*)	**25.** (*e*)	**26.** (*b*)	**27.** (*c*)	**28.** (*a*)	**29.** (*a*)	**30.** (*a*)
31. (*b*)	**32.** (*c*)	**33.** (*c*)	**34.** (*c*)	**35.** (*b*)	**36.** (*c*)	**37.** (*d*)	**38.** (*c*)	**39.** (*d*)	**40.** (*c*)
41. (*a*)	**42.** (*d*)	**43.** (*d*)	**44.** (*c*)	**45.** (*a*)	**46.** (*a*)	**47.** (*d*)	**48.** (*b*)	**49.** (*d*)	**50.** (*d*)
51. (*d*)	**52.** (*e*)	**53.** (*b*)	**54.** (*d*)	**55.** (*c*)	**56.** (*d*)	**57.** (*c*)	**58.** (*b*)	**59.** (*b*)	**60.** (*a*)
61. (*c*)	**62.** (*c*)	**63.** (*d*)	**64.** (*d*)	**65.** (*a*)	**66.** (*d*)	**67.** (*d*)	**68.** (*c*)	**69.** (*d*)	**70.** (*d*)
71. (*d*)	**72.** (*b*)	**73.** (*c*)	**74.** (*d*)	**75.** (*d*)	**76.** (*b*)	**77.** (*d*)	**78.** (*a*)	**79.** (*c*)	**80.** (*b*)
81. (*a*)	**82.** (*b*)	**83.** (*d*)	**84.** (*a*)	**85.** (*b*)	**86.** (*b*)	**87.** (*c*)	**88.** (*c*)	**89.** (*d*)	**90.** (*c*)
91. (*c*)	**92.** (*b*)	**93.** (*d*)	**94.** (*b*)	**95.** (*d*)	**96.** (*b*)	**97.** (*a*)	**98.** (*c*)	**99.** (*c*)	**100.** (*b*)

ROUGH WORK

GO To FIRST

CONTENTS

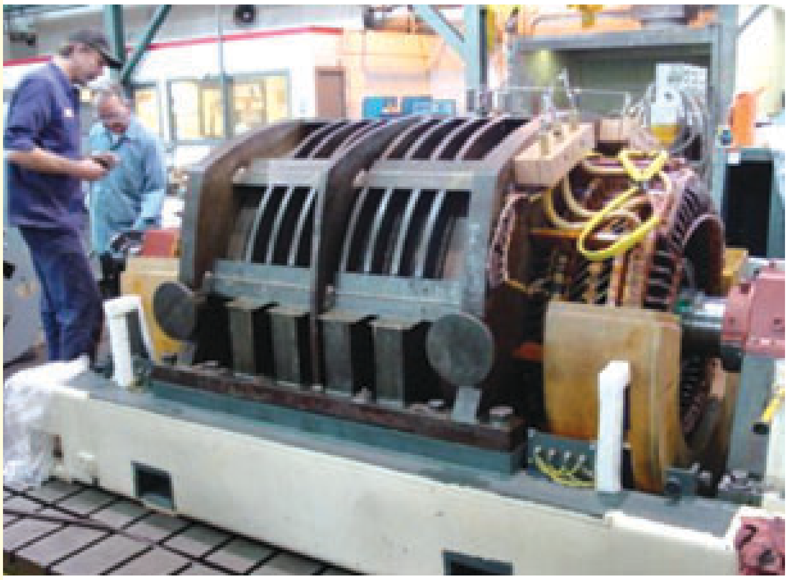
CHAPTER 44

INDUSTRIAL APPLICATIONS OF ELECTRIC MOTORS

Learning Objectives

- Advantages of Electric Drive
- Classification of Electric Drives
- Advantages of Individual Drives
- Selection Drive
- Electric Characteristics
- Types of Enclosures
- Bearings Transmission of Power
- Noise
- Size and Rating
- Estimation of Motor Rating
- Different Types of Industrial Loads
- Motors for Different Industrial Drives
- Types of Electric Braking
- Plugging Applied to DC Motors
- Plugging of Induction Motors
- Rheostatic Braking
- Rheostatic Braking of DC Motors
- Rheostatic Braking Torque
- Rheostatic Braking of Induction Motors
- Regenerative Braking
- Energy Saving in Regenerative Braking

CONTENTS



The above figure shows a squirrel cage motor. In industries electric drive is preferred over mechanical drive, because electric drive has the advantages of quick start, high torques and comparatively hassle free operation

44.1. Advantages of Electric Drive

Almost all modern industrial and commercial undertakings employ electric drive in preference to mechanical drive because it possesses the following advantages :

1. It is simple in construction and has less maintenance cost
2. Its speed control is easy and smooth
3. It is neat, clean and free from any smoke or flue gases
4. It can be installed at any desired convenient place thus affording more flexibility in the layout
5. It can be remotely controlled
6. Being compact, it requires less space
7. It can be started immediately without any loss of time
8. It has comparatively longer life.

However, electric drive system has two inherent disadvantages :

1. It comes to stop as soon as there is failure of electric supply and
2. It cannot be used at far off places which are not served by electric supply.

However, the above two disadvantages can be overcome by installing diesel-driven dc generators and turbine-driven 3-phase alternators which can be used either in the absence of or on the failure of normal electric supply.

44.2. Classification of Electric Drives

Electric drives may be grouped into three categories : group drive, individual drive and multimotor drive.

In group drive, a single motor drives a number of machines through belts from a common shaft. It is also called line shaft drive. In the case of an indvidual drive, each machine is driven by its own separate motor with the help of gears, pulley etc. In multi-motor drives separate motors are provided for actuating different parts of the driven mechanism. For example, in travelling cranes, three motors are used : one for hoisting, another for long travel motion and the third for cross travel motion. Multimotor drives are commonly used in paper mills, rolling mills, rotary printing presses and metal working machines etc.

Each type of electric drive has its own advantages and disadvantages. The group drive has following advantages :

1. It leads to saving in initial cost because one 150-kW motor costs much less than ten 15-kW motors needed for driving 10 separate machines.
2. Since all ten motors will seldomly be required to work simultaneously, a single motor of even 100-kW will be sufficient to drive the main shaft. This diversity in load reduces the initial cost still further.
3. Since a single large motor will always run at full-load, it will have higher efficiency and power factor in case it is an induction motor.
4. Group drive can be used with advantage in those industrial processes where there is a sequence of continuity in the operation and where it is desirable to stop these processes simultaneously as in a flour mill.

However, group drive is seldom used these days due to the following disadvantages :

1. Any fault in the driving motor renders all the driven equipment idle. Hence, this system is unreliable.
2. If all the machines driven by the line shaft do not work together, the main motor runs at reduced load. Consequently, it runs with low efficiency and with poor power factor.

3. Considerable amount of power is lost in the energy transmitting mechanism.
4. Dlexibility of layout of different machines is lost since they have to be so located as to suit the position of the line shaft.
5. The use of line shaft, pulleys and belts etc. makes the drive look quite untidy and less safe to operate.
6. It cannot be used where constant speed is required as in paper and textile industry.
7. Noise level at the worksite is quite high.

44.3. Advantages of Individual Drive

It has the following advantages :

1. Since each machine is driven by a separate motor, it can be run and stopped as desired.
2. Machines not required can be shut down and also replaced with a minimum of dislocation.
3. There is flexibility in the installation of different machines.
4. In the case of motor fault, only its connected machine will stop whereas others will continue working undisturbed.
5. The absence of belts and line shafts greatly reduces the risk of accidents to the operating personnel.
6. Ach operator has full control of the machine which can be quickly stopped if an accident occurs.
7. Maintenance of line shafts, bearings, pulleys and belts etc. is eliminated. Similarly there is no danger of oil falling on articles being manufactured–something very important in textile industry.

The only disadvantage of individual drive is its initial high cost (Ex 44.1). However, the use of individual drives and multimotor drives has led to the introduction of automation in production processes which, apart from increasing the productivity of various undertakings, has increased the reliability and safety of operation.

Example 44.1. *A motor costing Rs. 10,000/- is used for group drive in a certain installation. How will its total annual cost compare with the case where four individual motors each costing Rs. 4000/- were used ? With group drive, the energy consumption is 50 MWh whereas it is 45 MWh for individual drive. The cost of electric energy is 20 paise/kWh. Assume depreciation, maintenance and other fixed charges at 10% in the case of group drive and 15 per cent in the case of individual drive.*

Solution. Group Drive

Capital cost = Rs. 10,000/-

Annual depreciation, maintenance
and other fixed charges = 10% of Rs. 10,000 = Rs. 1,000/-

Annual cost of energy = Rs. 50 · 10^3 · (20/100) = Rs. 10,000/-

Total annual cost = Rs. 1,000 + Rs. 10,000 = **Rs. 11,000/-**

Individual Drive

Capital cost = 4 · Rs. 4000 = Rs. 16,000/-

Annual depreciation, maintenance
and other fixed charges = 15% of Rs. 16,000 = Rs. 2400/-

Annual cost of energy = Rs. 45 · 10^3 · (20/100) = Rs. 9000/-

Total annual cost = Rs. 9000 + Rs. 2400= **Rs. 11,400/-**

It is seen from the above example that individual drive is costlier than the group drive.

44.4. Selection of a Motor

The selection of a driving motor depends primarily on the conditions under which it has to operate and the type of load it has to handle. Main guiding factors for such a selection are as follows :

(*a*) Electrical characteristics

1. Starting characteristics
2. Running characteristics
3. Speed control
4. Braking

(*b*) Mechanical considerations

1. Type of enclosure
2. Type of bearings
3. Method of power transmission
4. Type of cooling
5. Noise level

(*c*) Size and rating of motors

1. Requirement for continuous, intermittent or variable load cycle
2. Overload capacity

(*d*) Cost

1. Capital cost
2. Running cost

In addition to the above factors, one has to take into consideration the type of current available whether alternating or direct. However, the basic problem is one of matching the mechanical output of the motor with the load requirement *i.e.* to select a motor with the correct speed/torque characteristics as demanded by the load. In fact, the complete selection process requires the analysis and synthesis of not only the load and the proposed motor but the complete drive assembly and the control equipment which may include rectification or frequency changing.

44.5. Electrical Characteristics

Electrical characteristics of different electric drives have been discussed in Vol. II of this book entitled "A.C. and D.C. Machines".

44.6. Types of Enclosures

The main function of an enclosure is to provide protection not only to the working personnel but also to the motor itself against the harmful ingress of dirt, abrasive dust, vapours and liquids and solid foreign bodies such as a spanner or screw driver etc. At the same time, it should not adversely affect the proper cooling of the motor. Hence, different types of enclosures are used for different motors depending upon the environmental conditions. Some of the commonly used motor enclosures are as under :

1. Open Type. In this case, the machine is open at both ends with its rotor being supported on pedestal bearings or end brackets. There is free ventilation since the stator and rotor ends are in free contact with the surrounding air. Such, machines are housed in a separate neat and clean room. This type of enclosure is used for large machines such as d.c. motors and generators.

2. Screen Protected Type. In this case, the enclosure has large openings for free ventilation. However, these openings are fitted with screen covers which safeguard against accidental contacts and rats entering the machine but afford no protection from dirt, dust and falling water. Screen-protected type motors are installed where dry and neat conditions prevail without any gases or fumes.

3. Drip Proof Type. This enclosure is used in very damp conditions. *i.e.* for pumping sets. Since motor openings are protected by over-hanging cowls, vertically falling water and dust are not able to enter the machine.

4. Splash-proof Type. In such machines, the ventilating openings are so designed that liquid or dust particles at an angle between vertical and 100° from it cannot enter the machine. Such type of motors can be safely used in rain.

5. Totally Enclosed (TE) Type. In this case, the motor is completely enclosed and no openings are left for ventilation. All the heat generated due to losses is dissipated from the outer surface which is finned to increase the cooling area. Such motors are used for dusty atmosphere *i.e.* sawmills, coal-handling plants and stone-crushing quarries etc.

6. Totally-enclosed Fan-cooled (TEFC) Type. In this case, a fan is mounted on the shaft external to the totally enclosed casing and air is blown over the ribbed outer surfaces of the stator and endshields (Fig. 44.1). Such motors are commonly used in flour mills, cement works and sawmills etc. They require little maintenance apart from lubrication and are capable of giving years of useful service without any interruption of production.

Fig. 44.1. A three-phase motor

7. Pipe-ventilated Type. Such an enclosure is used for very dusty surroundings. The motor is totally enclosed but is cooled by neat and clean air brought through a separate pipe from outside the dust-laden area. The extra cost of the piping is offset by the use of a smaller size motor on account of better cooling.

8. Flame-proof (FLP) Type. Such motors are employed in atmospheres which contain inflammable gases and vapours *i.e.* in coal mines and chemical plants. They are totally enclosed but their enclosures are so constructed that any explosion within the motor due to any spark does not ignite the gases outside. The maximum operating temperature at the surface of the motor is much less than the ignition temperature of the surrounding gases.

44.7. Bearings

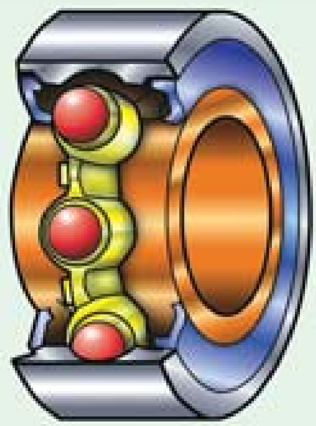
These are used for supporting the rotating parts of the machines and are of two types :

1. Ball or roller bearings **2.** Sleeve or bush bearings

(*a*) Ball Bearings

Upto about 75kW motors, ball bearings are preferred to other bearings because of their following advantages :

1. They have low friction loss
2. They occupy less space
3. They require less maintenance
4. Their use allows much smaller air-gap between the stator and rotor of an induction motor
5. Their life is long.



A ball-bearing

Their main disadvantages are with regard to cost and noise particularly at high motor speeds.

(*b*) Sleeve Bearings

These are in the form of self-aligning pourous bronze bushes for fractional kW motors and in the form of journal bearings for larger motors. Since they run very silently, they are fitted on super-silent motors used for driving fans and lifts in offices or other applications where noise must be reduced to the absolute minimum.

A sleeve bearing

44.8. Transmission of Power

There are many ways of transmitting mechanical power developed by a motor to the driven machine.

1. Direct Drive. In this case, motor is coupled directly to the driven machine with the help of solid or flexible coupling. Flexible coupling helps in protecting the motor from sudden jerks. Direct drive is nearly 100% efficient and requires minimum space but is used only when speed of the driven machine equals the motor speed.

2. Belt Drive. Flat belts are extensively used for line-shaft drives and can transmit a maximum power of about 250 kW. Where possible, the minimum distance between the pulley centres should be 4 times the diameter of the larger pulley with a maximum ratio between pulley diameters of 6 : 1. The power transmitted by a flat belt increases in proportion to its width and varies greatly with its quality and thickness. There is a slip of 3 to 4 per cent in the belt drive.

3. Rope Drive. In this drive, a number of ropes are run in V-grooves over the pulleys. It has negligible slip and is used when the power to be transmitted is beyond the scope of belt drive.

Fig. 44.2. Geared Motor Unit

4. Chain Drive. Though somewhat more expensive, it is more efficient and is capable of transmitting larger amounts of power. It is noiseless, slipless and smooth in operation.

5. Gear Drive. It is used when a high-speed motor is to drive a low-speed machine. The coupling between the two is through a suitable ratio gear box. In fact motors for low-speed drives are manufactured with the reduction gear incorporated in the unit itself. Fig. 44.2 shows such a unit consisting of a flange motor bolted to a high-efficiency gear box which is usually equipped with feet, the motor being overhung.

44.9. Noise

The noise produced by a motor could be magnetic noise, windage noise and mechanical noise. Noise level must be kept to the minimum in order to avoid fatigue to the workers in a workshop. Similarly, motors used for domestic and hospital appliances and in offices and theatres must be almost noiseless. Tranmission of noise from the building where the motor is installed to another building can be reduced if motor foundation is flexible *i.e.* has rubber pads and springs.

44.10. Motors for Different Industrial Drives

1. D.C. Series Motor. Since it has high starting torque and variable speed, it is used for heavy duty applications such as electric locomotives, steel rolling mills, hoists, lifts and cranes.

2. D.C. Shunt Motor. It has medium starting torque and a nearly constant speed. Hence, it is used for driving constant-speed line shafts, lathes, vacuum cleaners, wood-working machines, laundry washing machines, elevators, conveyors, grinders and small printing presses etc.

3. Cumulative Compound Motor. It is a varying-speed motor with high starting torque and is used for driving compressors, variable-head centifugal pumps, rotary presses, circular saws, shearing machines, elevators and continuous conveyors etc.


Heavy duty hydraulic motor for high torque and low speeds

4. Three-phase Synchronous Motor. Because its speed remains constant under varying loads, it is used for driving continuously-operating equipment at constant speed such as ammonia and air compressors, motor-generator sets, continuous rolling mills, paper and cement industries.

5. Squirrel Cage Induction Motor. This motor is quite simple but rugged and possesses high over-load capacity. It has a nearly constant speed and poor starting torque. Hence, it is used for low and medium power drives where speed control is not required as for water pumps, tube wells, lathes, drills, grinders, polishers, wood planers, fans, blowers, laundary washing machines and compressors etc.

6. Double Squirrel Cage Motor. It has high starting torque, large overload capacity and a nearly constant speed. Hence, it is used for driving loads which require high starting torque such as compressor pumps, reciprocating pumps, large refrigerators, crushers, boring mills, textile machinery, cranes, punches and lathes etc.

7. Slip-ring Induction Motor. It has high starting torque and large overload capacity. Its speed can be changed upto 50% of its normal speed. Hence, it is used for those industrial drives which require high starting torque and speed control such as lifts, pumps, winding machines, printing presses, line shafts, elevators and compressors etc.

8. Single-phase Synchronous Motor. Because of its constant speed, it is used in teleprinters, clocks, all kinds of timing devices, recording instruments, sound recording and reproducing systems.

9. Single-phase Series Motor. It possesses high starting torque and its speed can be controlled over a wide range. It is used for driving small domestic appliances like refrigerators and vacuum cleaners etc.

10. Repulsion Motor. It has high starting torque and is capable of wide speed control. Moreover, it has high speed at high loads. Hence, it is used for drives which require large starting torque and adjustable but constant speed as in coil winding machines.

11. Capacitor-start Induction-run Motor. It has fairly constant speed and moderately high starting torque. Speed control is not possible. It is used for compressors, refrigerators and small portable hoists.

12. Capacitor-start-and-run Motor. Its operating characteristics are similar to the above motor except that it has better power factor and higher efficiency. Hence, it is used for drives requiring quiet operations.

44.11. Advantages of Electrical Braking Over Mechanical Braking

1. In mechanical braking; due to excessive wear on brake drum, liner etc. it needs frequent and costly replacement. This is not needed in electrical braking and so electrical braking is more economical than mechanical braking.
2. Due to wear and tear of brake liner frequent adjustments are needed thereby making the maintenance costly.
3. Mechanical braking produces metal dust, which can damage bearings. Electrical braking has no such problems.
4. If mechanical brakes are not correctly adjusted it may result in shock loading of machine or machine parts in case of lift, trains which may result in discomfort to the occupants.
5. Electrical braking is smooth.

6. In mechanical braking the heat is produced at brake liner or brake drum, which may be a source of failure of the brake. In electric braking the heat is produced at convenient place, which in no way is harmful to a braking system.
7. In regenerative braking electrical energy can be returned back to the supply which is not possible in mechanical braking.
8. Noise produced is very high in mechanical braking.

Only disadvantage in electrical braking is that it is ineffective in applying holding torque.

44.12. Types of Electric Braking

There are three types of electric braking as applicable to electric motors in addition to eddy-current braking. These have already been discussed briefly in Art. 44.7.

1. Plugging or reverse-current braking.
2. Rheostatic or dynamic braking.
3. Regenerative braking.

In many cases, provision of an arrangement for stopping a motor and its driven load is as important as starting it. For example, a planing machine must be quickly stopped at the end of its stroke in order to achieve a high rate of production. In other cases, rapid stops are essential for preventing any danger to operator or damage to the product being manufactured. Similarly, in the case of lifts and hoists, effective braking must be provided for their proper functioning.

44.13. Plugging Applied to D.C. Motors

As discussed earlier in Art. 42.7, in this case, armature connections are reversed whereas ***field winding connections remains unchanged***. With reversed armature connections, the motor develops a torque in the ***opposite*** direction. When speed reduces to zero, motor will accelerate in the opposite direction. Hence, the arrangement is made to disconnect the motor from the supply as soon as it comes to rest. Fig. 44.3 shows running and reversed connections for shunt motors whereas Fig. 44.4 shows similar conditions for series motors.

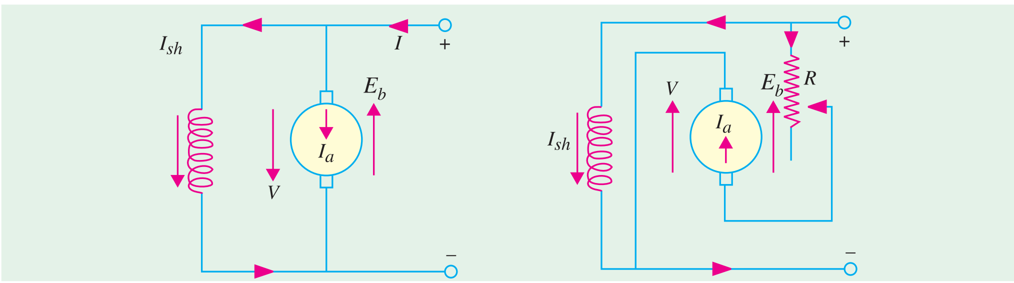


Fig. 44.3

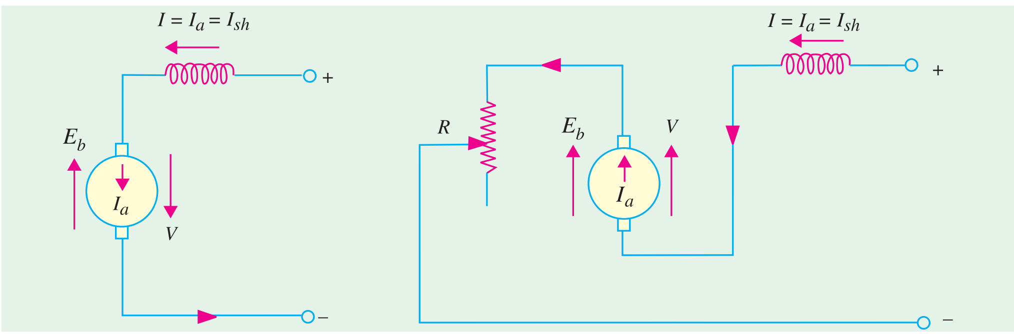


Fig. 44.4

Since with reversed connection, V and E_b are in the same direction, voltage across the armature is almost double of its normal value. In order to avoid excessive current through the armature, additional resistance R is connected in series with armature.

This method of braking is wasteful because in addition to wasting kinetic energy of the moving parts, it draws additional energy from the supply during braking.

Braking Torque. The electric braking torque is given by

$$T_B \propto \Phi I_a = k_1 \Phi I_a; \text{ Now, } I_a = (V + E_b)/R$$

$$\therefore \quad T_B = K_1 \Phi \cdot \frac{V + E_b}{R} = k_1 \Phi \frac{V + k_2 \Phi N}{R} \qquad (\because E_b \propto \Phi N)$$

$$= \frac{K_1 \Phi V}{R} + \frac{k_1 k_2 \Phi^2 N}{R} = k_3\ \Phi + k_4\ \Phi^2 N$$

Shunt Motor

Since in the case, Φ is practically constant, $T_B = k_5 + k_6 N$.

Series Motor

$$T_B = k_3 \Phi + k_4 \Phi^2 N = k_5 I_a + k_6 N I_a^2 \qquad (\because \phi \propto I_a)$$

The value of braking torque can be found with the help of magnetisation curve of a series motor.

Example 44.2. *A 40-kW, 440-V, d.c. shunt motor is braked by plugging. Calculate (i) the value of resistance that must be placed in series with the armature circuit to limit the initial braking current to 150 A (ii) the braking torque and (iii) the torque when motor speed falls to 360 rpm.*

Armature resistance R_a = 0.1W, full-load I_a = 100 A, full-load speed = 600 rpm.

(Electric Drives & Util. Punjab Univ. : 1994)

Solution. Full-load $E_b = 440 - 100 \cdot\ 0.1 = 430$ V

Voltage across the armature at the start of braking $= V + E_b = 440 + 430 = 870$ V

(*i*) Since initial braking current is limited to 150 A, total armature circuit resistance required is

$$R_t = 870 / 150 = 5.8\ \Omega \quad \therefore \quad R = R_t - R_a = 5.8 - 0.1 = \mathbf{5.7\ \Omega}$$

(*ii*) For a shunt motor, $T_B \propto \Phi\ I_a \propto I_a$ $\quad \therefore \quad \Phi$ is constant

$$\text{Now, } \frac{\text{initial braking torque}}{\text{full-load toruqe}} = \frac{\text{initial braking current}}{\text{full-load current}}$$

Full-load torque $= 40 \cdot\ 103 / 2\pi\ (600/60) = 636.6$ N-m

$\therefore$ initial braking torque $= 636.6 \cdot\ 150 / 100 =$ **955 N-m**

(*iii*) The decrease in E_b is directly proportional to the decrease in motor speed.

$\therefore$ E_b at 360 rpm $= 430 \cdot\ 360/600 = 258$ V

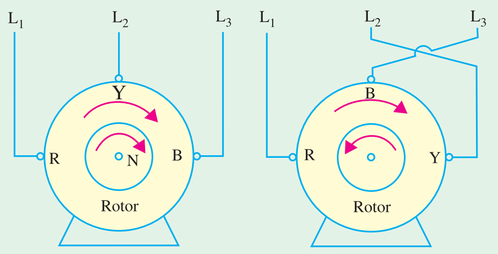
I_a at 360 rpm $= (440 + 258) / 5.8 = 120$ A

T_B at 360 rpm $= 636.6 \cdot\ 120/100 =$ **764 N-m**

44.14. Plugging of Induction Motors

This method of braking is applied to an induction motor by transposing any of its two line leads as shown in Fig. 44.5. It reverses the direction of rotation of the synchronously-rotating magnetic field which produces a torque in the reverse direction, thus applying braking on the motor. Hence, at the ***first instant*** after plugging, the rotor is running in a direction opposite to that of the stator field. It means that speed of the rotor relative to the magnetic field is $(N_s + N) \cong 2N_s$ as shown in Fig. 44.6.

In Fig 44.6. ordinate BC represents the braking torque at the instant of plugging. As seen, this torque gradually increases as motor approaches standstill condition after which motor is disconnected from the supply (otherwise it will start up again in the reverse direction).



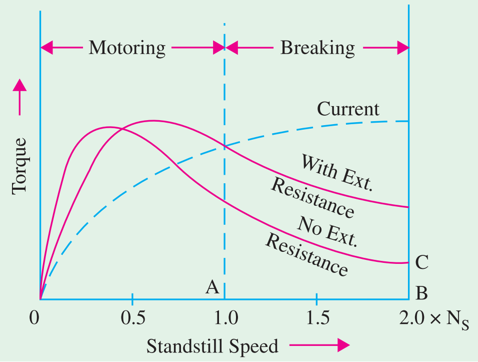


Fig. 44.5 **Fig. 44.6**

As compared to squirrel cage motors, slip-ring motors are more suitable for plugging because, in their case, external resistance can be added to get the desired braking torque.

Example 44.3. *A 30-kW, 400-V, 3-phase, 4-pole, 50-Hz induction motor has full-load slip of 5%. If the ratio of standstill reactance to resistance per motor phase is 4, estimate the plugging torque at full speed.* **(Utilisation of Elect. Energy, Punjab Univ.)**

Solution. $N_s = 120\,f/P = 120 \cdot 50/4 = 1500$ rpm

Full-load speed, $N_f = N_s(1-s) = 1500\,(1 - 0.05) = 1425$ rpm

Full-load torque, $T_f = \dfrac{30 \cdot 10^3}{2\pi \cdot 1425/60} = 200$ N -m

Since, $$T \propto \frac{sR_2\,E_2^2}{R_2^2 + s^2\,X_2^2} \quad \therefore \quad \frac{T_2}{T_1} = \frac{s_2\,R_2\,E_2^2/(R_2^2 + s_2^2\,X_2^2)}{s_1 R_2 E_2^2/(R_2^2 + s_1^2\,X_2^2)}$$

$$= \frac{s_2(R_2^2 + s_1^2\,X_2^2)}{s_1\,(R_2^2 + s_2^2\,X_2^2)} = \frac{s_2}{s_1} \cdot \frac{1 + s_1^2\,(X_2/R_2)^2}{1 + s_2^2\,(X_2/R_2)^2}$$

$$= \frac{s_1}{s_2} \cdot \frac{1 + 16 s_1^2}{1 + 16 s_2^2} \left(\frac{X_2}{R_2} = 4\right)$$

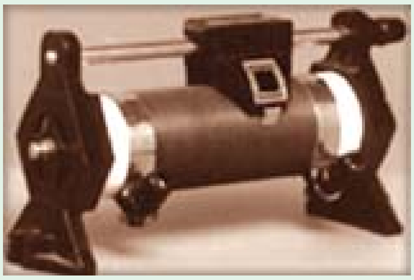
Slip, $S_p = 2 - 0.05 = 1.95$

$\therefore$ plugging torque, $$T_p = \frac{1.95}{0.05} \cdot \frac{1 + 16 \cdot (0.05)^2}{1 + 16\,(1.95)^2} \cdot T_f$$

$$= 39 \cdot \frac{1.04}{61.84}\ 200 = \mathbf{131\ N\text{-}m.}$$

44.15. Rheostatic Braking

In this method of electric braking, motor is disconnected from the supply though its field continues to be energised in ***the same direction***. The motor starts working as a generator and all the kinetic energy of the equipment to be braked is converted into electrical energy and is further dissipated in the variable external resistance *R* connected across the motor during the braking period. This external resistance must be less than the critical resistance otherwise there will not be enough current for generator excitation (Art. 44.3).



Rheostat

D.C. and synchronous motors can be braked this way but induction motors require separate d.c. source for field excitation.

This method has advantage over plugging because, in this case, no power is drawn from the supply during braking.

44.16. Rheostatic Braking of D.C. Motors

Fig. 44.7 shows connections for a d.c. shunt motor. For applying rheostatic braking armature is disconnected from the supply and connected to a variable external resistance R while the field remains on the supply. The motor starts working as a generator whose induced emf E_b depends upon its speed. At the start of braking, when speed is high, E_b is large, hence I_a is large. As speed decreases, E_b decreases, hence I_a decreases. Since $T_b \propto \Phi I_a$, it will be high at high speeds but low at low speeds. By gradually cutting out R, I_a and, hence, T_B can be kept constant throughout. Value of $I_a = E_b (R + R_a)$.

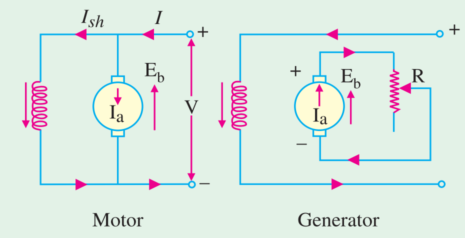


Fig. 44.7

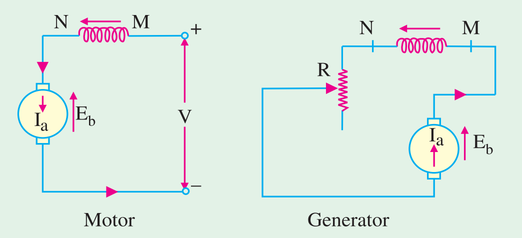


Fig. 44.8

Fig. 44.8 shows running and braking conditions for a d.c. series motor. In this case also, for rheostatic braking, the armature is disconnected from the supply and, at the same time, is connected across R. However, connections are so made that current keeps flowing through the series field ***in the same direction*** otherwise no braking torque would be produced. The motor starts working as a series generator provided R is less than the critical resistance.

44.17. Rheostatic Braking Torque

$T_B \propto \Phi I_a$. Now, $I_a = E_b/(R + R_a) = E_b/Rt$

Since $E_b \propto \Phi N$, $I_a \propto \Phi N/R_t$ $\therefore$ $\boxed{T_B \propto \Phi^2 N/R_t = k_1 \Phi^2 N}$

1. For D.C. shunt motors and synchronous motors, Φ is constant. Hence

$$\boxed{T_B = k_1 N}$$

2. In the case of series motors, flux depends on current. Hence, braking torque can be found from its magnetisation curve.

When rheostatic braking is to be applied to the series motors used for traction work, they are connected in parallel (Fig. 44.9) rather than in series because series connection produces excessive voltage across the loading rheostats.

However, it is essential to achieve electrical stability in parallel operation of two series generators. It can be achieved either by equalizing the exciting currents *i.e.* by connecting the two fields in parallel [Fig. 44.9 (*a*)] or by cross-connection [Fig. 44.9 (*b*)] where field of one machine is excited by the armature current of the other. If equalizer is not used, then the machine which happens to build up first will send current through the other ***in the opposite direction*** thereby exciting it with reverse voltage. Consequently, the two machines would be short-circuited upon themselves and may burn out on account of excessive voltage and, hence, current.

In the cross-connection of Fig. 44.9 (*b*), suppose the voltage of machine No. 1 is greater than that of No. 2. It would send a larger current through F_2 , thereby exciting it to a higher voltage. This results in stability of their parallel operation because stronger machine always helps the weaker one.

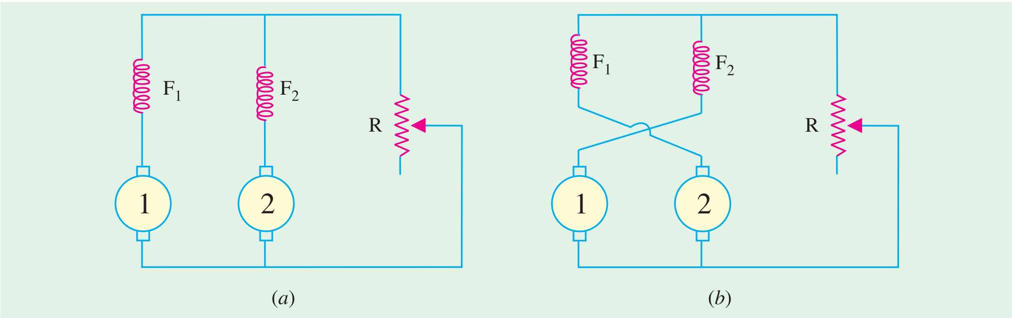


Fig. 44.9

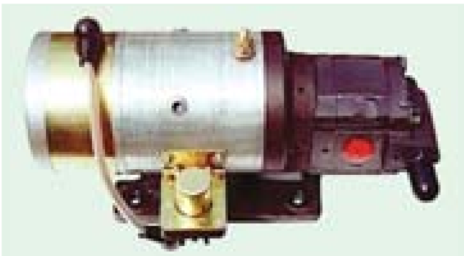
The cross-connection method has one special advantage over equalizer-connection method. If due to any reason (say, a run-back on a gradient) direction of rotation of the generators is reversed, no braking effect would be produced with connections of Fig. 44.9 (*a*) since the machines will fail to excite. However, with cross-excited fields, the machines will build up in series and being short-circuited upon themselves, will provide an emergency braking and would not allow the coach/car to run back on a gradient.

44.18. Rheostatic Braking of Induction Motors

If an induction motor is disconnected from the supply for rheostatic braking, there would be no magnetic flux and, hence, no generated emf in the rotor and no braking torque. However, if after disconnection, direct current is passed through the stator, steady flux would be set up in the air-gap which will induce current, in the short-circuited rotor. This current which is proportional to the rotor speed, will produce the required braking torque whose value can be regulated by either controlling d.c. excitation or varying the rotor resistance.

44.19. Regenerative Braking

In this method of braking, motor is not disconnected from the supply but is made to run as a generator by utilizing the kinetic energy of the moving train. Electrical energy is fed back to the supply. The magnetic drag produced on account of generator action offers the braking torque. It is the most efficient method of braking. Take the case of a shunt motor. It will run as a generator whenever its E_b becomes greater than V. Now, E_b can exceed V in two ways :



DC Shunt Motor

1. by increasing field excitation

2. by increasing motor speed beyond its normal value, field current remaining the same. It happens when load on the motor has overhauling characteristics as in the lowering of the cage or a hoist or the down-gradient movement of an electric train.

Regenerative braking can be easily applied to d.c. shunt motors though not down to very low speeds because it is not possible to increase field current sufficiently.

In the case of d.c. series motors, reversal of current necessary to produce regeneration would cause reversal of the field and hence of E_b. Consequently, modifications are necessary if regenerative braking is to be employed with d.c. series motors used in electric traction.

It may, however, be clearly understood that regenerative braking cannot be used for stopping a motor. Its main advantages are *(i)* reduced energy consumption particularly on main-line railways having long gradients and mountain railways *(ii)* reduced wear of brake shoes and wheel tyres and *(iii)* lower maintenance cost for these items.

44.20. Energy Saving in Regenerative Braking

We will now compute the amount of energy recuperated between any two points on a level track during which regenerative braking is employed. The amount of energy thus recovered and then returned to the supply lines depends on :

(i) initial and final velocities of the train during braking

(ii) efficiency of the system and *(iii)* train resistance.

Suppose regenerative braking is applied when train velocity is V_1 km/h and ceases when it is V_2 km/h. If M_e tonne is the effective mass of the train, then

$$\text{K.E. of the train at } V_1 = \frac{1}{2} M_e V_1^2 = \frac{1}{2}(1000\, M_e)\cdot\left(\frac{1000\, V_1}{3600}\right)^2 \text{ joules}$$

$$= \frac{1}{2}(1000\, M_e)\left(\frac{1000\, V_1}{3600}\right)^2 \cdot \frac{1}{3600}\text{ Wh}$$

$$= 0.01072\, M_e V_1^2 \text{ Wh} = 0.01072\,\frac{M_e}{M} V_1^2 \text{ Wh/tonne}$$

$$\text{K.E. at } V_2 = 0.01072\,\frac{M_e}{M} V_2^2 \text{ Wh/tonne}$$

Hence, energy available for recovery is $= 0.01072\,\dfrac{M_e}{M}(V_1^2 - V_2^2)$ Wh/tonne

If r N/t is the specific resistance of the train, then total resistance $= rM$ newton.

If d km is the distance travelled during braking, then

energy spent $= rM \cdot (1000\, d)$ joules $= rMd \propto \dfrac{1000}{3600}$ Wh $= 0.2778\, rd$ Wh/tonne

Hence, net energy recuperated during regenerative braking is

$$= 0.01072\,\frac{M_e}{M}(V_1^2 - V_2^2) - 0.2778\, rd \text{ Wh/tonne}$$

Gradient. If there is a *descending* gradient of G per cent over the same distance of d km, then downward force is = 98 MG newton

Energy provided during braking

$$= 98\, MG \cdot (1000\, d) \text{ joules} = 98\, MG\, d\,(1000 / 3600) \text{ Wh} = 27.25\, Gd \text{ Wh/tonne}$$

Hence, net energy recuperated in this case is

$$= \left[0.01072\,\frac{M_e}{M}(V_1^2 - V_2^2) - 0.2778\, rd + 2725\, Gd\right] \text{ Wh/tonne}$$

$$= 0.01072\,\frac{M_e}{M}(V_1^2 - V_2^2) + d\,(27.75\, G - 0.2778\, r) \text{ Wh/tonne}$$

If η is the system efficiency, net energy returned to the line is

(i) **level track**

$$= \eta\left[0.01072\,\frac{M_e}{M}(V_1^2 - V_2^2) - 0.2778\, rd\right] \text{ Wh/tonne}$$

(*ii*) **descending gradient**

$$= \eta\left[0.01072\,\frac{M_e}{M}\,(V_1^2 - V_2^2) + d\,(27.25\,G - 0.2778\,r)\right] \text{ Wh/tonne}$$

Example 44.4. *A 500-t electric trains travels down a descending gradient of 1 in 80 for 90 seconds during which period its speed is reduced from 100 km/h to 60 km/h by regenerative braking. Compute the energy returned to the lines of kWh if tractive resistance = 50 N/t; allowance for rotational inertia = 10% ; overall efficiency of the system = 75 %.*

Solution. Here $G = 1 \cdot 100 / 80 = 1.25\%$ $\qquad M_e/M = 1.1$

$$d = \left(\frac{V_1 + V_2}{2}\right) \cdot t = \left(\frac{100 + 60}{2}\right) \frac{90}{3600} = 2 \text{ km}$$

Hence, energy returned to the supply line

$$= 0.75\,[(0.01072 \times 1.1\,(1002 - 602) + 2\,(27.25 \times 1.25 - 0.2778 \times 50)] \text{ Wh/t}$$

$$= 0.75\,[75.5 + 2\,(34 - 13.9)] = 86.77 \text{ Wh/t}$$

$$= 86.77 \cdot 500 \text{ Wh} = 86.77 \cdot 500 \cdot 10^{-3} \text{ kWh} = \mathbf{43.4\ kWh}$$

Example 44.5. *A 350-t electric train has its speed reduced by regenerative braking from 60 to 40 km/h over a distance of 2 km along down gradient of 1.5%. Caculate* **(*i*)** *electrical energy and* **(*ii*)** *average power returned to the line. Assume specific train resistance = 50 N/t ; rotational inertia effect = 10% ; conversion efficiency of the system = 75%.* **(Elect. Power, Bombay Univ.)**

Solution . (*i*) Energy returned to the line is

$$= 0.75\,[0.01072 \cdot 1.1\,(60^2 - 40^2) + 2\,(27.25 \cdot 1.5 - 0.2778 \cdot 50)] \text{ Wh/t}$$

$$= 58.2 \text{ Wh/t} = 58.2 \cdot 350 \cdot 10^{-3} = \mathbf{20.4\ kWh}$$

(*ii*) Average speed $= (60 + 40)/2 = 50$ km/h ; time taken $= 2/50$ h $= 1/25$ h

$$\therefore \quad \text{power returned} = \frac{20.4 \text{ kWh}}{1/25\text{h}} = \mathbf{510\ kW}$$

Example 44.6. *If in Example 42.4, regenerative braking is applied in such a way that train speed on down gradient remains constant at 60 km/h, what would be the power fed into the line?*

Solution : Since no acceleration is involved, the down-gradient tractive effort which drives the motors as generators is

$$F_t = (98\,MG - Mr) \text{ newton} = (98 \cdot 350 \cdot 1.5 - 350 \cdot 50) = 33{,}950 \text{ N}$$

Power that can be recuperated is

$$= F_t \cdot \left(\frac{1000}{3600}\right) V = 0.2778\,F_t\,V \text{ watt} = 0.2778 \cdot 33{,}950 \cdot 60 = 565{,}878 \text{ W}$$

Since $\eta = 0.75$, the power that is actually returned to the line is

$$= 0.75 \cdot 565{,}878 \cdot 10^{-3} = \mathbf{424.4\ kW}$$

Example 44.7. *A train weighing 500 tonne is going down a gradient of 20 in 1000. It is desired to maintain train speed at 40 km/h by regenerative braking. Calculate the power fed into the line. Tractive resistance is 40 N/t and allow rotational intertia of 10% and efficiency of conversion of 75%.* **(Util. of Elect. Power, A.M.I.E. Sec. B.)**

Solution. Down-gradient tractive effort which drives the motors as generators is

$$F_t = (98\,MG - Mr) = (98{,}000 \cdot 500 \cdot 2 - 500 \cdot 40) = 78{,}000 \text{ N}$$

Power that can be recuperated is $= 0.2778\,F_tV = 0.2778 \cdot 78{,}000 \cdot 40 = 866{,}736$ W

Since $\eta = 0.75$, the power that is actually fed into the lines is

$$= 0.75 \cdot 866{,}736 \cdot 10^{-3} = \mathbf{650\ kW.}$$

Example 44.8. *A 250-V d.c. shunt motor, taking an armature current of 150 A and running at 550 r.p.m. is braked by reversing the connections to the armature and inserting additional resistance in series with it. Calculate :*

(*a*) *the value of series resistance required to limit the initial current to 240 A.*

(*b*) *the initial value of braking torque.*

(*c*) *the value of braking torque when the speed has fallen to 200 r.p.m.*

The armature resistance is 0.09 Ω. Neglect winding friction and iron losses.

(Traction and Util. of Elect. Power, Agra Univ.)

Solution. Induced emf at full-load, $E_b = 250 - 150 \cdot\ 0.09 = 236.5$ V

Voltage across the armature at braking instant = $V + E_b = 250 + 236.5 = 486.5$ V

(*a*) Resistance required in the armature circuit to limit the initial current to 240 A

$$= \frac{486.5}{240} = \mathbf{2.027\ \Omega}$$

Resistance to be added in the armature circuit = 2.027 − 0.09 = **1.937 Ω**

(*b*) F.L. Torque, $T_f = VI/2\pi\ (N/60) = 250 \cdot\ (550/60) = 650$ N-m

$$\text{Initial braking torque} = T_f \frac{\text{initial braking current}}{\text{full-load current}} = \frac{650 \cdot\ 240}{150} = \mathbf{1040\ N\text{-}m}$$

(*c*) When speed falls to 200 r.p.m., back emf also falls in the same proportion as the speed.

∴ $E_b = E_b \cdot\ 200/550 = 236.5 \cdot\ 200.550 = 94.6$ V

∴ current drawn = (250 + 94.6)/2.027 = 170 A

∴ braking torque = 650 · 170/150= **737 N-m**

Example 44.9. *A 400 V 3-ph squirrel cage induction motor has a full load slip of 4%. A stand-still impedance of 1.54Ω and the full load current = 30A. The maximum starting current which may be taken from line is 75A. What taping must be provided on an auto-transformer starter to limit the current to this value and what would be the starting torque available in terms of full load torque ?*

[Nagpur University, Winter 1994]

Solution.
$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = X$$

or
$$V_1 I_1 = V_2 I_2 = X$$

$$I_1 = 75\text{A}$$

$$V_1 = \frac{400}{\sqrt{3}} = 231 \text{ V and } I_1 = I_2 X$$

$$I_1 = \frac{V_2}{Z} X$$

$$I_1 = \frac{XV_1}{1.54} X$$

$$I_1 = \frac{X^2 \cdot\ 231}{1.54}$$

$$\Rightarrow \quad 75 = \frac{X^2 \cdot\ 231}{1.54}$$

$$\Rightarrow \quad X^2 = \frac{75 \cdot\ 1.54}{231}$$

$$X = 0.7071$$

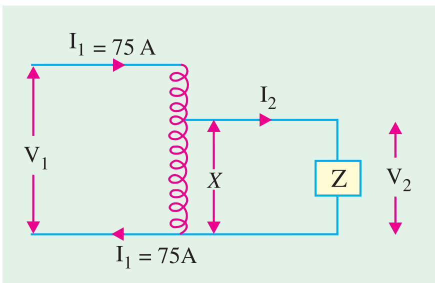


Fig. 44.10

$$\frac{T_s}{T_{FL}} = X^2\left(\frac{I_S}{I_{FL}}\right)^2 \cdot \text{Slip}_{(FL)}$$

Now $$I_2 = I_s = \frac{I_1}{X} = \frac{75}{0.708} = 106\ A$$

$$s_{FL} = 0.04. \quad I_s = 106\text{ A} \quad I_{FL} = 30\text{ A}.$$

$$\therefore \quad \frac{T_s}{T_{HL}} = (0.701)^2\left(\frac{106}{30}\right)^2 \cdot 0.04$$

$$\therefore \quad T_s = 0.25\ T_{FL}$$

Example 44.10. *A 220V, 10 H.P. shunt motor has field and armature resistances of 122W and 0.3W. respectively. Calculate the resistance to be inserted in the armature circuit to reduce the speed to 80% assuming motor η at full load to be 80%.*

(a) When torque is to remain constant.

(b) When torque is proportional to square of the speed. **[Nagpur University, Winter 1994]**

Solution. $$I_f = \frac{220}{112} = 1.8\text{ Amp.}$$

Motor $$O/P = 10 \cdot 746 = 7460\text{ W}$$

$$\therefore \quad \text{Motor } I/P = \frac{7460}{0.8} = 9300\text{ W}$$

Line current $$I_L = \frac{9300}{220} = 42.2\text{ Amp.}$$

$$\therefore \quad I_a = 42.2 - 1.8 = 40.4\text{ A}$$

$$\therefore \quad E_{b_1} = 220 - 40.4 \cdot 0.3 = 208\text{ V}$$

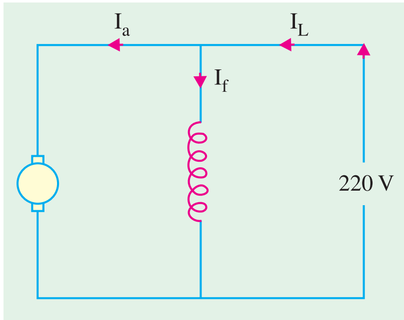


Fig. 44.11

Now $$\frac{N_2}{N_1} = \frac{E_{b_2}}{E_{b_1}} \quad \because \phi \text{ is constant}$$

$$0.8 = \frac{E_{b_2}}{E_{b_1}} \quad \therefore 0.8 = \frac{E_{b_2}}{208} \Rightarrow E_{b_2} = \mathbf{166.4\ V}$$

(a) $\because$ Torque remains constant and ϕ is constant

$\therefore$ I_a at reduced speed will also remain same

$$\therefore \quad E_{b_2} = V - I_{a_2}\ R \quad \text{where } R \text{ is total resistance}$$

$$166.4 = 220 - 40.4 \cdot R \quad \therefore \quad R = \frac{220 - 166.4}{40.0} = 1.34\ \Omega$$

$\therefore$ Additional resistance in armature circuit = $1.34 - 0.3 =$ **1.04 Ω**

(b) $$\frac{T_2}{T_1} = \left(\frac{N_2}{N_1}\right)^2$$

$$T \propto I_a \quad \text{also} \quad T \propto \phi\, I_a$$

$\because$ $T \propto I_a$ ($\because$ ϕ is constant)

$$\frac{T_2}{T_1} = (0.8)^2 = 0.64$$

$$\therefore \quad \frac{T_2}{T_1} = \frac{I_{a_2}}{I_{a_2}} \quad \therefore 0.64 = \frac{I_{a_2}}{40.4} \Rightarrow I_{a_2} = 25.3\text{ A}$$

$$E_{b_2} = 220 - 25.3 \cdot R$$

$$166.4 = 220 - 25.5936 \cdot R$$

$\therefore$ $R = \mathbf{2.0943\ \Omega}$

$\therefore$ Additional resistance $= 2.0943 - 0.3 = \mathbf{1.7943\ \Omega}$

Example 44.11. *A 37.5 H.P., 220 V D.C. shunt motor with a full load speed of 535 r.p.m. is to be braked by plugging. Estimate the value of resistance which should be placed in series with it to limit the initial braking current to 200 amps. What would be the initial value of the electric braking torque and the value when the speed had fallen to half its full load value? Armature resistance of motor is 0.086 Ω and full load armature current is 140 amps.*

Solution. $E = V - I_a R_a$

Back e.m.f. of motor $= E = 220 - 140 \cdot 0.086 = 220 - 12 = 208$ Volts.

Total voltage during braking $= E + V$

$= 220 + 208 = 428$ V

$$R = \frac{V}{I}$$

Resistance required $= \dfrac{428}{200} = 2.14\ \Omega$

There is already 0.086 Ω present in aramature.

$\therefore$ Resistance to be added $= 2.14 - 0.086 = 2.054\ \Omega$

Torque $\propto \phi I$ or Torque $\propto I$ ($\because \phi$ is constant for shunt motor)

$$\frac{\text{Initial braking torque}}{\text{Initial braking current}} = \frac{\text{F.L. toruqe}}{\text{F.L. current}}$$

$$\text{Power} = \text{Torque} \cdot \omega$$

$$\omega = \frac{2\pi N}{60} \text{ rad/sec.}$$

$$37.5 \cdot 746 = T \cdot \frac{2\pi \cdot 535}{60}$$

Full load torque $= 499.33$ Nw-m.

Initial braking torque $= 499.33 \cdot \dfrac{200}{140} = 713.328$ Nw-m.

→ At half – speed back e.m.f. falls to half its original value $= 208/2 = 104$ V

$$\text{Current} = \frac{220 + 104}{2.14} = 151 \text{ Amps.}$$

Electric braking torque at $\frac{1}{2}$ speed $= 499.33 \cdot \dfrac{151}{140} = \mathbf{538.56\ Nw\text{-}m.}$

Example 44.12. *A 500 V series motor having armature and field resistances of 0.2 and 0.3 Ω, runs at 500 r.p.m. when taking 70 Amps. Assuming unsaturated field find out its speed when field diverter of 0.684 Ω is used for following load whose torque*

(a) *remains constant*

(b) *varies as square of speed.*

Solution. When no diverter connected, $E_{b_1} = 500 - 70\,(0.2 + 0.3) = 465$ V

(a) If I_{a_2} be the armature current when diverter is used, then current flowing through

$$\text{field} = I_{f2} = I_{a_2} \cdot \frac{0.684}{0.3 + 0.684} = 0.695\, I_{a_2}$$

$\because$ Load torque is constant

$\therefore$ $I_{a_1} \phi_1 = I_{a_2} \phi_2$ $(\because \phi \propto I_a)$

$$\therefore \quad I_{a_1}\phi_1 = I_{a_2}(0.695)\, I_{a_2} \Rightarrow I_{a_2} = \frac{I_{a_1}}{\sqrt{0.695}} = \frac{70}{\sqrt{0.695}} = 84 \text{ A}$$

$$\therefore \text{ Field current} = I_{f_2} = 0.695\, I_{a_2} = 0.695 \cdot 84 = 58.4 \text{ A}$$

$$\text{Resistance of field with diverter} = \frac{0.3 \cdot 0.684}{0.3 + 0.684} = 0.208\ \Omega$$

Total field and armature resistance = 0.2 + 0.208 = 0.408 Ω

$$E_{b_2} = 500 - 84\ (0.408) = 465.8 \text{ V}$$

$$\frac{N_1}{N_2} = \frac{E_{b_1}}{E_{b_2}} \cdot \frac{\phi_2}{\phi_1}$$

$$\frac{500}{N_2} = \frac{465}{465.8} \cdot \frac{58.4}{70} \Rightarrow N_2 = \textbf{600 r.p.m}$$

(*b*)
$$\frac{T_1}{T_2} = \left(\frac{N_1}{N_2}\right)^2 \because \frac{T_1}{T_2} = \frac{I_{a_1}\phi_1}{I_{a_2}\phi_2} = \frac{I_{a_1} \cdot I_{a_1}}{I_{a_2} \cdot 0.695\, I_{a_2}}$$

$$\therefore \quad \left(\frac{N_1}{N_2}\right)^2 = \frac{I_{a_1} \cdot I_{a_1}}{Ia_2^2 \cdot 0.695} \Rightarrow \frac{N_1}{N_2} = \frac{I_{a_1}}{I_{a_2}\sqrt{0.695}} = \frac{70}{I_{a_2}\sqrt{0.695}}$$

$$\frac{N_1}{N_2} = \frac{E_{b_1}}{E_{b_2}} \cdot \frac{\phi_2}{\phi_1}$$

$$\frac{70}{I_{a_2}\sqrt{0.695}} = \frac{465}{500 - I_{a_2}\ (0.2\ )\ 0.208)} \cdot \frac{0.695\, I_{a_2}}{70}$$

$$I_{a_2}^2 + 7.42\, I_{a_2} - 9093 = 0$$

$$\Rightarrow \quad I_{a_2} = 91.7 \text{ A} \qquad \because \text{negative value is absurd.}$$

$$\frac{N_1}{N_2} = \frac{70}{I_{a_2}\sqrt{0.695}} \Rightarrow \frac{500}{N_2} = \frac{70}{91.7\sqrt{0.695}}$$

$$\therefore \quad N_2 = \textbf{546 r.p.m.}$$

Example 44.13. *A 200 V series motor runs at 1000 r.p.m. and takes 20 Amps. Armature and field resistance is 0.4 W. Calculate the resistance to be inserted in series so as to reduce the speed to 800 r.p.m., assuming torque to vary as cube of the speed and unsaturated field.*

Solution.
$$\frac{T_1}{T_2} = \left(\frac{N_1}{N_2}\right)^3 = \left(\frac{1000}{800}\right)^3 = \frac{125}{64}$$

$$\therefore \quad \frac{T_1}{T_2} = \frac{I_{a_1}\phi_1}{I_{a_2}\phi_2} = \frac{20 \cdot 20}{I_{a_2} \cdot I_{a_2}} \qquad \because \phi \propto I_a \text{ for series motor.}$$

$$\frac{125}{64} = \frac{20^2}{I_{a_2}^{\ 2}} \quad I_{a_2}\ I_{a_2} = 14.3 \text{ Amp}$$

$$E_{b_1} = 200 - 20 \cdot 0.4 = 192 \text{ V.}$$

$$\frac{E_{b_1}}{E_{b_2}} = \frac{N_1}{N_2} \cdot \frac{\phi_1}{\phi_2}$$

$$\frac{192}{E_{b_2}} = \frac{1000}{800} \cdot \frac{20}{14.3}$$

$$E_{b_2} = 110 \text{ V} \; ; \qquad E_{b_2} = V - IR$$

$$110 = 200 - 14.3 \cdot R \; ; \quad R = \frac{90}{14.3} = 6.3 \; \Omega$$

Additional resistance required = 6.3 – 0.4 = **5.9 Ω**

Example 44.14. *A 220V, 500 r.p.m. D.C. shunt motor with an armature resistance of 0.08Ω and full load armature current of 150 Amp. is to be braked by plugging. Estimate the value of resistance which is to be placed in series with the armature to limit initial braking current to 200 Amps. What would be the speed at which the electric braking torque is 75% of its initial value.*

Solution. Back e.m.f. of motor $= E_{b_1} = V - I_a R_a$

$$= 220 - 150 \cdot 0.08 = 208 \text{ V}$$

Voltage across armature when braking starts

$$= 220 + 208 = 428 \text{ V}$$

Initial braking current to be limited to 200 A.

∴ Resistance in armature circuit $= \frac{428}{200} = 2.14 \; \Omega$

∴ External resistance required = 2.14 – 0.08 = 2.06 Ω

Since field Flux ϕ is constant therefore 75% torque will be produced when armature current is 75% of 200 Amp. *i.e.* 150Amp.

Let N_2 be the speed in r.p.m. at which 75% braking torque is produced. At this speed generated e.m.f. in armature

$$\because \quad \frac{E_{b_1}}{E_{b_2}} = \frac{N_1}{N_2} \; ; \; \frac{208}{E_{b_2}} = \frac{500}{N_2} \quad \therefore \quad E_{b_2} = \frac{208}{500} N_2$$

Voltage across armature when braking starts

$$150 \cdot 2.14 = \left(220 + \frac{208}{500} N_2\right) \text{Volts}$$

$$\therefore \quad N_2 = \textbf{243 r.p.m.}$$

Example 44.15. *A D.C. series motor operating at 250 V D.C. mains and draws 25 A and runs at 1200 r.p.m. R_a = 0.1 Ω and R_{se} = 0.3 Ω.*

A resistance of 25 Ω is placed in parallel with the armature of motor. Determine:

(i) The speed of motor with the shunted armature connection, if the magnetic circuit remains unsaturated and the load torque remains constant.

(ii) No load speed of motor. **[Nagpur University Winter 1995]**

Solution.

$$\frac{N_2}{N_1} = \frac{E_{b_2}}{E_{b_1}} \cdot \frac{\phi_1}{\phi_2}$$

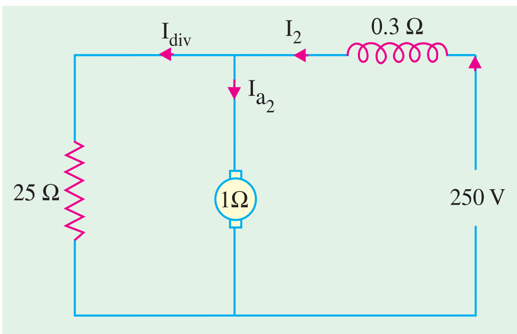


Fig. 44.12

Voltage across diverter = 250 – 0.3 I_2

$$I_{\text{div}} = \frac{250 - 0.3 I_2}{25}$$

$$I_{a_2} = I_2 - \frac{250 - 0.3 I_2}{25}$$

$$= 1.012 \; I_2 - 10$$

As T is constant ∴ $\phi_1 \; I_{a_1} = \phi_2 \; I_{a_2}$

$$\therefore \quad I_{a_1}^2 = I_2 \, (I_{a_2})$$

$$(25)^2 = I_2 \; (1.012 \, I_2 - 10)$$

$$1.012\, I_2^2 - 10 \cdot I_2 - 625 = 0 \Rightarrow I_2 = 30.27\,A \text{ (neglecting negative value)}$$

$$(25)^2 = (30.27)\ I_{a_2} \Rightarrow I_{a_2} = 20.65\text{ A}$$

$$E_{b_1} = V - I_{a_1}(R_a + R_{se}) = 250 - 25\,(0.4) = 240\text{ Volts}$$

$$E_{b_2} = V - I_2\,(R_{se}) - I_{a_2}\,(R_a) = 250 - 30.27\,(0.3) - 0.1\,(20.65) = 238.85\text{ V.}$$

$$\frac{N_2}{N_1} = \frac{E_{b_2}}{E_{b_1}} \cdot \frac{\phi_1}{\phi_2}$$

$$\frac{N_2}{1200} = \frac{238.85}{240} \cdot \frac{2.5}{20.27} \quad \therefore \quad N_2 = \textbf{986 r.p.m.}$$

(ii) Series motor on no load.

Series motor can't be started on no load. When flux is zero, motor tries to run at infinite speed, which is not possible. So in the process, it tries to draw very high current from supply and fuse blows-out.

Example 44.16. *A 4 pole, 50Hz, slip ring Induction Motor has rotor resistance and stand still reactance referred to stator of 0.2 Ω and 1 Ω per phase respectively. At full load, it runs at 1440 r.p.m. Determine the value of resistance to be inserted in rotor in ohm/ph to operate at a speed of 1200 r.p.m., if :*

(i) Load torque remains constant. (ii) Load torque varies as square of the speed.

Neglect rtator resistance and leakage reactance.

Solution. *(i)* Load torque constant

$$\Rightarrow T \propto \frac{s}{R_2} \qquad N_s = 1500\text{ rpm}$$

$$\therefore \quad T_1 \propto \frac{s_1}{R_2} \qquad T_2 \propto \frac{s_2}{(R_1 + r)}$$

$$s_1 = \frac{1500 - 1400}{1500} = 0.04\ s_2 = \frac{1500 - 1240}{1500} = 0.2$$

As $$T_1 = T_2 \quad \therefore \quad \frac{s_1}{R_2} = \frac{s_2}{R_1 + r}$$

$$\frac{0.04}{0.2} = \frac{0.2}{0.2 + r}$$

$$\therefore \quad r = 0.8\ \Omega$$

(ii) Load torque varies as square of the speed.

$$\frac{T_1}{T_2} = \left[\frac{N_1}{N_2}\right]^2 = \left[\frac{1440}{1200}\right]^2 = 1.44$$

$$\frac{T_1}{T_2} = 1.44 = \frac{\dfrac{R_2 s_1}{R_2^2 + (s_1\,X_2)^2}}{\dfrac{(R_2 + r)\,s_2}{(R_2 + r)^2 + (s_2\,X_2)^2}} = \frac{\dfrac{0.2 \cdot 0.04}{0.2^2 + (0.04 \cdot 1)^2}}{\dfrac{(0.02 + r)\,(0.2)}{(0.2 + r)^2 + (0.2 \cdot 1)^2}}$$

Substituting $$R_2 + r = R$$

$$1.44 = \frac{0.1923}{\dfrac{0.2\,R}{R^2 + 0.04}}$$

$$\therefore \quad 0.1923\,R^2 - 0.288\,R + 0.007652 = 0$$

$$\Rightarrow \quad R = 1.47 \text{ and } 0.0272, \text{ But } R > 0.2 \ \therefore \ R = 1.47\ \Omega$$

$$\therefore \quad R = 0.2 + r;\ 1.47 = 0.2 + r \ \Rightarrow \ r = 1.27\ \Omega$$

Tutorial Problem No. 44.1

1. The characteristics of a series traction motor at 525 V are as follows :

current	:	50	70	80	90	A
speed	:	33.8	26.9	25.1	23.7	km/h
Gross torque	:	217	352	423	502	N-m

Determine the gross braking torque at a speed of 25.7 km/h when operating as self-excited series generator and loaded with an external resistance of 6 Ω. Resistance of motor = 0.5 Ω.
[382.4 N-m] (***London Univ.***)

2. The characteristics of a series motor at 525 V are as follows :

current	:	75	125	175	225	A
speed	:	1200	950	840	745	r.p.m.

Calculate the current when operating as a generator at 1000 r.p.m. and loaded on a rheostat having a resistance of 3.25 Ω. The resistance of motor is 3.5 Ω. **[150 A]** (***London Univ.***)

3. A train weighing 400 tonne travels a distance of 10 km down a gradient of 2%, getting its speed reduced from 40 to 20 km/h, the train resistance is = 50 N/t, allowance for rotational inertia = 10% and overall efficiency = 72%. Estimate (*i*) power and (*ii*) energy returned to the line.
[(*i*) 363 kW (*ii*) 121 kWh] (***Elect. Power, Bombay Univ.***)

4. A 400-tonne train travels down a gradient of in 100 for 20 seconds during which period its speed is reduced from 80 km/h to 50 km/h by regenerative braking. Find the energy returned to the lines if the tractive resistance is 49 N/t and allowance for rotational inertia is 7.5%. Overall efficiency of motors is 75%. **[28.2 kWh]** (***A.M.I.E.***)

5. A 400-tonne train travels down a gradient of 1 in 70 for 120 seconds during which period its speed is reduced from 80 km/h to 50 km/h by regenerative braking. Find the energy returned to the line if tractive resistance is 49 N/t and allowance for rotational inertia is 7.5%. Overall efficiency of motors is 75%. **[30.12 kWh]** (***A.M.I.E.***)

6. A train weighing 500 tonne is going down a gradient of 20 in 1000. It is desired to maintain train speed at 40 km/h by regenerative braking. Calculate the power fed into the line. Tractive resistance is 40 N/t and allow rotational inertia of 10% and efficiency of conversion of 75%.
[650 kW] (***Utilization of Elect. Power, A.M.I.E.***)

7. A 18.65 kW, 220-V D.C. shunt motor whith a full-load speed of 600 r.p.m. is to be braked by plugging. Estimate the value of the resistance which should be placed in series with it to limit the current to 130A. What would be the initial value of the electric braking torque and value when speed has fallen to half of its full-load vlaue ? Armature resistance of motor is 0.1 W. Full-load armature current is 95 A. **[3.211 Ω, 400.5 N-m, 302.57 N-m]** (***Util of Elect. Power, A.M.I.E. Sec. B.***)

8. A 400-tonne train travels down a gradient of 1 in 70 for 120 seconds during which period its speed is reduced from 80 km/h to 50 km/h by regenerative braking. Find the energy returned to the lines if tractive resistance is 5 kg / tonne and allowance for rotational inertia is 7.5 %. Overall efficiency of motor is 75%. **[30.64%]**

9. What are the advantages of Electrical Drive over other Drives? What are the mainfeatures of Group Drive and an Individual Drive? *(Nagpur University, Summer 2004)*

10. What are the essential requirements of starting of any motor? With the help of neat diagram explain 'open circuit transition' and 'closed circuit transition' in Auto transformer starting of Induction Motor. *(Nagpur University, Summer 2004)*

11. What is the principle of speed control of D.C. motors for, below the base speed and above the base speed.Explain with neat N-T characteristics. *(Nagpur University, Summer 2004)*

12. A 400 V, 25 h.p., 450 rpm, D.C. shunt motor is braked by plugging when running on full load. Determine the braking resistance necessary if the maximum braking current is not to exceed twice the full load current. Determine also the maximum braking torque and the braking torque when the motor is just reaching zero speed. The efficiency of the motor is 74.6% and the armature resistance is 0.2 Ω. *(Nagpur University, Summer 2004)*

13. Mention the Advantage of PLC over conventional motor control.
(Nagpur University, Summer 2004)

14. Suggest the motors required for following Drives :-
(*i*) Rolling mills (*ii*) Marine drive (*iii*) Home appliances (*iv*) Pump
(*v*) Refrigeration and air-conditioning (*vi*) Lifts. *(Nagpur University, Summer 2004)*

15. Explain with neat block diagram the digital control of Electrical Drives. *(Nagpur University, Summer 2004)*

16. Explain Series parallel control of traction motor. *(Nagpur University, Summer 2004)*

17. Write short Notes on Speed reversal by contactor and relay. *(Nagpur University, Summer 2004)*

18. Write short Notes on Ratings of contactors. *(Nagpur University, Summer 2004)*

19. Write short Notes on Magnetic time-delay relay. *(Nagpur University, Summer 2004)*

20. Discuss the advantages and disadvantages of electric drive over other drives. *(J.N. University, Hyderabad, November 2003)*

21. Though a.c. is superior to d.c. for electric drives, sometimes d.c. is preferred. Give the reasons and mention some of the applications. *(J.N. University, Hyderabad, November 2003)*

22. A d.c. series motor drives a load, the torque of which varies as the square of the speed. The motor takes current of 30 amps, when the speed is 600 r.p.m. Determine the speed and current when the field winding is shunted by a diverter, the resistance of which is 1.5 times that of the field winding. The losses may be neglected. *(J.N. University, Hyderabad, November 2003)*

23. State the condition under which regenerative braking with d.c. services motor is possible and with the aid of diagrams of connection, explain the various methods of providing regeneration. *(J.N. University, Hyderabad, November 2003)*

24. Explain what you mean by "Individual drive" and "Group drive". Discuss their relative merits and demerits. *(J.N. University, Hyderabad, November 2003)*

25. A 500 V d.c. series motor runs at 500 r.p.m. and takes 60 amps. The resistances of the field and the armature are 0.3 and 0.2 Ohms, respectively. Calculate the value of the resistance to be shunted with the series field winding in order that the speed may be increased to 600 r.p.m., if the torque were to remain constant. Saturation may be neglected. *(J.N. University, Hyderabad, November 2003)*

26. A motor has the following duty cycle :
Load rising from 200 to 400 h.p. – 4 minutes
Uniform load 300 h.p. – 2 minutes
Regenerative braking h.p. Returned to supply from 50 to zero – 1 minute.
Remains idle for 1 minute.
Estimate the h.p. of the motor. *(J.N. University, Hyderabad, November 2003)*

27. What are various types of electric braking used? *(J.N. University, Hyderabad, November 2003)*

28. Explain how rheostatic braking is done in D.C. shunt motors and series motors. *(J.N. University, Hyderabad, November 2003)*

29. Describe how plegging, rheostics braking and regenerative braking are employed with D.C. series motor. *(J.N. University, Hyderabad, November 2003)*

30. Where is the use of Individual drive recommended and why? *(J.N. University, Hyderabad, November 2003)*

31. The speed of a 15 h.p. (Metric) 400 V d.c. shunt motor is to be reduced by 25% by the use of a controller. The field current is 2.5 amps and the armature resistance is 0.5 Ohm. Calculate the resistance of the controller, if the torque remains constant and the efficiency is 82%. *(J.N. University, Hyderabad, November 2003)*

32. Explain regenerative braking of electric motors. *(J.N. University, Hyderabad, November 2003)*

33. "If a high degree of speed control is required, d.c. is perferable to a.c. for an electric drive". Justify. *(J.N. University, Hyderabad, April 2003)*

34. A 200 V shunt motor has an armature resistance of 0.5 ohm. It takes a current of 16 amps on full load and runs at 600 r.p.m. If a resistance of 0.5 ohm is placed in the armature circuit, find the ratio of the stalling torque to the full load torque. *(J.N. University, Hyderabad, April 2003)*

35. What are the requirements of good electric braking? *(J.N. University, Hyderabad, April 2003)*

36. Explain the method of rheostatic braking. *(J.N. University, Hyderabad, April 2003; Anna University, Chennai 2003)*

37. Mean horizontal Candlepower *(J.N. University, Hyderabad, April 2003)*

38. Mean hemispherical Candlepower *(J.N. University, Hyderabad, April 2003)*

39. Luminous flux. *(J.N. University, Hyderabad, April 2003)*

40. Define : (*i*) Luminous intensity (*ii*) Point source (*iii*) Lumen and (*iv*) Uniform point source. *(J.N. University, Hyderabad, April 2003)*

41. Prove that Luminous intensity of a point source is equal to the luminous flux per unit solid angle. *(J.N. University, Hyderabad, April 2003)*

42. Discuss the various factors that govern the choice of a motor for a given service. *(J.N. University, Hyderabad, April 2003)*

43. A 6 pole, 50 Hz slip ring induction motor with a rotor resistance per phase of 0.2 ohm and a stand still reactance of 1.0 ohm per phase runs at 960 r.p.m. at full load. Calculate the resistance to be inserted in the rotor circuit to reduce the speed to 800 r.p.m., if the torque remains unaltered. *(J.N. University, Hyderabad, April 2003)*

44. Compare the features of individual and group drives. *(J.N. University, Hyderabad, April 2003)*

45. What is an electric drive? Classify various types of electric drives and discuss their merits and demerits. *(J.N. University, Hyderabad, December 2002/January 2003)*

46. Suggest, with reasons the electric drive used for the following applications. (*i*) Rolling mills (*ii*) Textile mills (*iii*) Cement mills (*iv*) Paper mills (*v*) Coal mining (*vi*) Lift, Cranes, Lathes and pumps. *(J.N. University, Hyderabad, December 2002/January 2003)*

47. A 100 hp, 500 rpm d.c. shunt motor is driving a grinding mill through gears. The moment of inertia of the mill is 1265 kgm^2. If the current taken by the motor must not exceed twice full load current during starting, estimate the minimum time taken to run the mill upto full speed. *(J.N. University, Hyderabad, December 2002/January 2003)*

48. Explain the different methods of electric braking of a 3 phase induction motor. *(J.N. University, Hyderabad, December 2002/January 2003)*

49. A 50 hp, 400V, 750 rpm synchronous motor has a moment of inertia 20 kgm^2 and employs rheostatic braking for obtaining rapid stopping in case of emergency when the motor is running at full load, star connected braking resistor of 2 ohm per phase is switched on. Determine the time taken and the number of revolutions made before the motor is stopped. Assume as efficiency of 90% and a full load power factor of 0.95. *(J.N. University, Hyderabad, December 2002/January 2003)*

50. Explain regenerative braking of induction motor. *(J.N. University, Hyderabad, December 2002/January 2003)*

51. What is dynamic braking? *(Anna University, Chenni, Summer 2003)*

52. What is regenerative braking? *(Anna University, Chenni, Summer 2003)*

53. What are braking systems applicable to a DC shunt motor? *(Anna University, Chenni, Summer 2003)*

54. What for Series motor Regenerative Braking is not suited? *(Anna University, Chenni, Summer 2003)*

55. What are the important stages in controlling an electrical drive. *(Anna University, Chenni, Summer 2003)*

56. Explain rheostatic braking of D.C. motors. *(Anna University, Chennai 2003)*

OBJECTIVE TESTS – 44

1. A steel mill requires a motor having high starting torque, wide speed range and precise speed control. Which one of the following motors will you choose ?
(*a*) d.c. shunt motor
(*b*) synchronous motor
(*c*) d.c. series motor
(*d*) slip-ring induction motor.

2. Heavy-duty steel-works cranes which have wide load variations are equipped with .... motor.
(*a*) double squirrel-cage

(b) d.c. series
(c) slip-ring induction
(d) cumulative compound.

3. A reciprocating pump which is required to start under load will need ....motor.
(a) repulsion
(b) squirrel-cage induction
(c) synchronous
(d) double squirrel-cage induction.

4. Motors used in wood-working industry have .... enclosure.
(a) screen protected (b) drip proof
(c) TEFC (d) TE

5. Single-phase synchronous motors are used in teleprinters, clocks and all kinds of timing devices becasue of their
(a) low starting torque
(b) high power factor
(c) constant speed
(d) over-load capacity.

6. Which motor is generally used in rolling mills, paper and cement industries ?
(a) d.c. shunt motor
(b) double squirrel-cage motor
(c) slip-ring induction motor
(d) three-phase synchronous motor

7. Direct drive is used for power transmission only when
(a) negligible slip is required
(b) large amount of power is invloved
(c) speed of the driven machine equals the motor speed
(d) high-speed motor is to drive a low-speed machine.

8. Which type of enclosure will be most suitable for motors employed in atmospheres containing inflammable gases and vapours ?
(a) pipe-ventilated
(b) totally enclosed, fan-cool
(c) flame proof
(d) screen-protected.

9. While plugging d.c. motors, ... connections are reversed
(a) supply
(b) armature
(c) field
(d) both armature and field

10. During rheostatic braking of a d.c., motor,
(a) its field is disconnected from the supply
(b) its armature is reverse-connected
(c) it works as a d.c. generator
(d) direction of its field current is reversed.

11. Rheostatic braking may be applied to an induction motor provided
(a) separate d.c. source for field excitation is available
(b) it is a squirrel cage type
(c) it is slip-ring type
(d) variable external resistance is available

12. During regenerative braking of electric motors, they are
(a) disconnected from the supply
(b) reverse-connected to the supply
(c) made to run as generators
(d) made to stop.

13. Regenerative braking
(a) can be used for stopping a motor
(b) cannot be easily applied to d.c. series motors
(c) can be easily applied to d.c. shunt motors
(d) cannot be used wen motor load has over-hauling characteristics

14. Net energy saved during regenerative braking of an electric train
(a) increases with increase in specific resistance
(b) is high with high down gradient
(c) decreases with reduction in train speed due to braking
(d) is independent of the train weight.

15. The selection of an electric motor for any application depends on which of the following factors?
(a) Electrical characteristics
(b) Mechanical characteristics
(c) Size and reating of motors
(d) cost
(e) All of teh above

16. For a particular application the type of electric and control gear are determined by which of the following considerations?
(a) Starting torque
(b) Conditions of environment
(c) Limitation on starting current
(d) Speed control range and its nature
(e) all of the above

17. Which of the following motors is preferred for traction work?
(a) Universal motor
(b) D.C. series motor
(c) Synchronous motor
(d) three-phase induction motor

18. Which of the following motors always starts

on load?
(*a*) Conveyor motor (*b*) Floor mill motor
(*c*) Fan motor (*d*) All of the above

19. .... is preferred for automatic drives.
(*a*) Squirrel cage induction motor
(*b*) Synchronous motors
(*c*) Ward-Leonard controlled D.C. motors
(*d*) Any of the above

20. When the load is above .... a synchronous motor is found to be more economical.
(*a*) 2 kW (*b*) 20 kW
(*c*) 50 kW (*d*) 100 kW

21. The load cycle for a motor driving a power press will be ....
(*a*) variable load
(*b*) continuous
(*c*) continuous but periodical
(*d*) intermittent and variable load

22. Light duty cranes are used in which of the following?
(*a*) Power houses
(*b*) Pumping station
(*c*) Automobile workshops
(*d*) all of the above

23. While selecting an electric motor for a floor mill, which electrical characteristics will be of least significance?
(*a*) Running characteristics
(*b*) Starting charasteristics
(*c*) Efficiency
(*d*) Braking

24. Which of the following motors are preferred for overhead travelling cranes?
(*a*) Slow speed motors
(*b*) Continuous duty motors
(*c*) Short time rated motors
(*d*) None of the above

25. .... is preferred for synthetic fibre mills.
(*a*) Synchronous motor
(*b*) Reluctance motor
(*c*) Series motor
(*d*) Shunt motor

26. Ward-Leonard controlled D.C. drives are generally used for .... excavators.
(*a*) Light duty (*b*) Medium duty
(*c*) Heavy duty (*d*) All of the above

27. Which of the following motors is used for elevators?
(*a*) Induction motor
(*b*) Synchronous motor
(*c*) Capacitor start single phase motor
(*d*) Any of the above

28. Which part of a motor needs maximum attention for maintenance?
(*a*) Frame (*b*) Bearing
(*c*) Stator winding (*d*) Rotor winding

29. .... need frequent starting and stopping of electric motors.
(*a*) Paper mills
(*b*) Grinding mills
(*c*) Air-conditioners
(*d*) Lifts and hoists

30. Which feature, while selecting a motor for centrifugal pump, will be of least significance?
(*a*) Starting characteristics
(*b*) Operating speed
(*c*) Horse power
(*d*) Speed control

31. ...... motor is a constant speed motor.
(*a*) Synchronous motor
(*b*) Schrage motor
(*c*) Induction motor
(*d*) Universal motor

32. The starting torque is case of centrifugal pumps is generally
(*a*) less than running torque
(*b*) same as running torque
(*c*) slightly more than running torque
(*d*) double the running torque

33. Which of the following motors are best for the rolling mills?
(*a*) Single phase motors
(*b*) Squirrel cage induction motors
(*c*) Slip ring induction motors
(*d*) D.C. motors

34. .... is not a part of ball bearing?
(*a*) Inner race (*b*) Outer race
(*c*) Cage (*d*) Bush

35. The starting torque of a D.C. motor is independent of which of the following?
(*a*) Flux
(*b*) Armature current
(*c*) Flux and armature current
(*d*) Speed

36. Rotor of a motor is usually supported on .... bearings.
(*a*) ball or roller (*b*) needle
(*c*) bush (*d*) thrust

37. For which of the following applications D.C. motors are still preferred?
(*a*) High efficiency operation
(*b*) Reversibility

(c) Variable speed drive
(d) High starting torque

38. In a paper mill where constant speed is required
(a) synchronous motors are preferred
(b) A.C. motors are preferred
(c) individual drive is preferred
(d) group drive is preferred

39. A reluctance motor ......
(a) is provided with slip rings
(b) requires starting gear
(c) has high cost
(d) is compact

40. The size of an excavator is usually expressed in terms of
(a) 'crowd' motion (b) angle of swing
(c) cubic metres (d) travel in metres

41. For blowers which of the following motors in preferred?
(a) d.C. series motor
(b) D.C. shunt motor
(c) Squirrel cage induction motor
(d) Wound rotor induction motor

42. Belted slip ring induction motor is almost invariably used for
(a) water pumps
(b) jaw crushers
(c) centrifugal blowers
(d) none of the above

43. Which of the following is essentially needed while selecting a motor?
(a) Pulley (b) Starter
(c) Foundation pedal (d) Bearings

44. Reluctance motor is a ....
(a) variable torque motor
(b) low torque variable speed motor
(c) self starting type synchronous motor
(d) low noise, slow speed motor

45. .... method of starting a three phase induction motor needs six terminals.
(a) Star-delta
(b) Resistance starting
(c) Auto-transformer
(d) None of the above

46. In .... method of starting three phase induction motors the starting voltage is not reduced.
(a) auto-transformer
(b) star-delta
(c) slip ring
(d) any of the above

47. In jaw crushers a motor has to often start against ...... load.
(a) heavy (b) medium
(c) normal (d) low

48. For a motor-generator set which of the following motors will be preferred?
(a) Synchronous motor
(b) Slip ring induction motor
(c) Pole changing induction motor
(d) Squirrel cage induction motor

49. Which of the following motors is usually preferred for kiln drives?
(a) Cascade controlled A.C. motor
(b) slip ring induction motor
(c) three phase shunt would commutator motor
(d) Any of the above

50. Heat control switches are used in ....
(a) transformers
(b) cooling ranges
(c) three phase induction motors
(d) single phase

51. .... has relatively wider range of speed control
(a) Synchronous motor
(b) Ship ring induction motor
(c) Squirrel cage induction motor
(d) D.C. shunt motor

52. In squirrel cage induction motors which of the following methods of starting cannot be used?
(a) Resistance in rotor circuit
(b) Resistance in stator circuit
(c) Auto-transformer starting
(d) Star-delta starting

53. In which of the following applications the load on motor changes in cyclic order?
(a) Electric shovels
(b) Cranes
(c) Rolling mills
(d) All of the above

54. Flame proof motors are used in
(a) paper mills
(b) steel mills
(c) moist atmospheres
(d) explosive atmospheres

55. Which of the following machines has heavy fluctuation of load?
(a) Printing machine
(b) Punching machine
(c) Planer
(d) Lathe

56. For derries and winches which of the following drives can be used?
(a) Pole changing squirrel cage motors
(b) D.C. motors with Ward-leonard control

(c) A.C. slip ring motors with variable resistance
(d) Any of the above

57. Battery operated scooter for braking uses
(a) plugging
(b) mechanical braking
(c) regenerative braking
(d) rheostatic braking

58. .... has least range of speed control.
(a) Slip ring induction motor
(b) Synchronous motor
(c) D.C. shunt motor
(d) Schrage motor

59. .... has the least value of starting torque to full load torque ratio.
(a) D.C. shunt motor
(b) D.C. series motor
(c) Squirrel cage induction motor
(d) Slip ring induction motor

60. In case of .... speed control by injecting e.m.f. in the rotor circuit is possible.
(a) d.c. shunt motor
(b) schrage motor
(c) synchronous motor
(d) slip ring induction motor

61. A pony motor is used for the starting which of the following motors?
(a) Squirel cage induction motor
(b) Schrage motor
(c) Synchronous motor
(d) None of the above

62. In .... the speed can be varied by changing the position of brushes.
(a) slip ring motor
(b) schrage motor
(c) induction motor
(d) repulsion motor

63. In which of the following applications variable speed operation is preferred?
(a) Exhaust fan
(b) Ceiling fan
(c) Refrigerator
(d) Water pump

64. Heavy duty cranes are used in
(a) ore handling plants
(b) steel plants
(c) heavy engineering workshops
(d) all of the above

65. the travelling speed of cranes varies from
(a) 20 to 30 m/s
(b) 10 to 15 m/s
(c) 5 to 10 m/s
(d) 1 to 2.5 m/s

66. Besides a constant speed a synchronous rotor possesses which of the following advantages?
(a) Lower cost
(b) Batter efficiency
(c) High power factor
(d) All of the above

67. By the use of which of the following D.C. can be obtained from A.C.?
(a) Silicon diodes
(b) Mercury are rectifier
(c) Motor generator set
(d) any of the above

68. Which of the following motors is preferred when quick speed reversal is the main consideration?
(a) Squirrel cage induction motor
(b) Wound rotor induction motor
(c) Synchronous motor
(d) D.C. motor

69. Which of the following motors is preferred when smooth and precise speed control over a wide range is desired?
(a) D.C. motor
(b) Squirrel cage induction motor
(c) Wound rotor induction motor
(d) Synchronous motor

70. For crane travel which of the following motors is normally used?
(a) Synchronous motor
(b) D.C. differentially compound motor
(c) Ward-Leonard controlled D.C. shunt motor
(d) A.C. slip ring motor

71. The capacity of a crane is expressed in terms of
(a) type of drive
(b) span
(c) tonnes
(d) any of the above

72. the characteristics of drive for crane hoisting and lowering are which of the following?
(a) Precise control
(b) Smooth movement
(c) Fast speed control
(d) All of the above

73. Which of the following motors is preferred for boom hoist of a travelling crane?
(a) Single phase motor
(b) Synchronous motor
(c) A.C. slip ring motor

(*d*) Ward-Leonard controlled D.C. shunt motor

74. A wound rotor induction motor is preferred, as compared to squirrel cage induction motor, when major consideration is
(*a*) slop speed operation
(*b*) high starting torque
(*c*) low windage losses
(*d*) all of the above

75. Which of the following motors has series characteristics?
(*a*) Shadel pole motor
(*b*) Repulsion motor
(*c*) Capacitor start motor
(*d*) None of the above

76. Which of the following happens when star-delta starter is used?
(*a*) Starting voltage is reduced
(*b*) Starting current is reduced
(*c*) Both (*a*) and (*b*)
(*d*) None of the above

77. For a D.C. shunt motor which of the following is incorrect?
(*a*) Unsuitable for heavy duty starting
(*b*) Torque varies as armature current
(*c*) Torque-armature current is a straight line
(*d*) Torque is zero for zero armature current

78. For which of the following applications motor has to start with high acceleration?
(*a*) Oil expeller
(*b*) Floor mill
(*c*) Lifts and hoists
(*d*) centrifugal pump

79. Which of the following types of motor enclosure is safest?
(*a*) totally enclosed
(*b*) Totally enclosed fan cooled
(*c*) Open type
(*d*) Semi closed

80. While selecting motor for an air conditioner which of the following characteristics is of great importance?
(*a*) Type of bearings
(*b*) Type of enclosure
(*c*) Noise
(*d*) Arrangement for power transmission
(*e*) None of the above

81. The diameter of the rotor shaft for an electric motor depends on which of the following?
(*a*) r.p.m. only
(*b*) Horse power only
(*c*) Horse power and r.p.m.
(*d*) Horse power, r.p.m. and power factor

82. Which of the following alternatives will be cheaper?
(*a*) A 100 H.P. A.C. three phase motor
(*b*) Four motors of 25 H.P. each
(*c*) Five motors of 20 H.P. each
(*d*) Ten motors of 10 H.P. each

83. The cost of an induction motor will increase as
(*a*) horsepower rating increases but r.p.m. decreases
(*b*) horsepower rating decreases but r.p.m. increases
(*c*) horsepower rating and operating speed increases
(*d*) horsepower rating and operating speed decreases

84. in series motor which of the following methods can be used for changing the flux per pole?
(*a*) Tapped field control
(*b*) Diverter field control
(*c*) Series-parallel control
(*d*) Any of the above

ANSWERS

1. (*c*)	**2.** (*b*)	**3.** (*d*)	**4.** (*c*)	**5.** (*c*)	**6.** (*d*)	**7.** (*c*)	**8.** (*c*)	**9.** (*b*)	**10.** (*c*)
11. (*a*)	**12.** (*c*)	**13.** (*c*)	**14.** (*b*)	**15.** (*e*)	**16.** (*e*)	**17.** (*b*)	**18.** (*d*)	**19.** (*c*)	**20.** (*d*)
21. (*d*)	**22.** (*d*)	**23.** (*d*)	**24.** (*c*)	**25.** (*b*)	**26.** (*c*)	**27.** (*a*)	**28.** (*b*)	**29.** (*d*)	**30.** (*d*)
31. (*a*)	**32.** (*a*)	**33.** (*d*)	**34.** (*d*)	**35.** (*d*)	**36.** (*a*)	**37.** (*c*)	**38.** (*c*)	**39.** (*d*)	**40.** (*c*)
41. (*c*)	**42.** (*b*)	**43.** (*b*)	**44.** (*c*)	**45.** (*a*)	**46.** (*c*)	**47.** (*a*)	**48.** (*a*)	**49.** (*d*)	**50.** (*b*)
51. (*d*)	**52.** (*a*)	**53.** (*d*)	**54.** (*d*)	**55.** (*b*)	**56.** (*d*)	**57.** (*b*)	**58.** (*b*)	**59.** (*c*)	**60.** (*d*)
61. (*c*)	**62.** (*b*)	**63.** (*b*)	**64.** (*d*)	**65.** (*d*)	**66.** (*c*)	**67.** (*d*)	**68.** (*c*)	**69.** (*a*)	**70.** (*d*)
71. (*c*)	**72.** (*d*)	**73.** (*c*)	**74.** (*b*)	**75.** (*b*)	**76.** (*c*)	**77.** (*a*)	**78.** (*c*)	**79.** (*b*)	**80.** (*c*)
81. (*c*)	**82.** (*a*)	**83.** (*a*)	**84.** (*d*)						

GO To FIRST

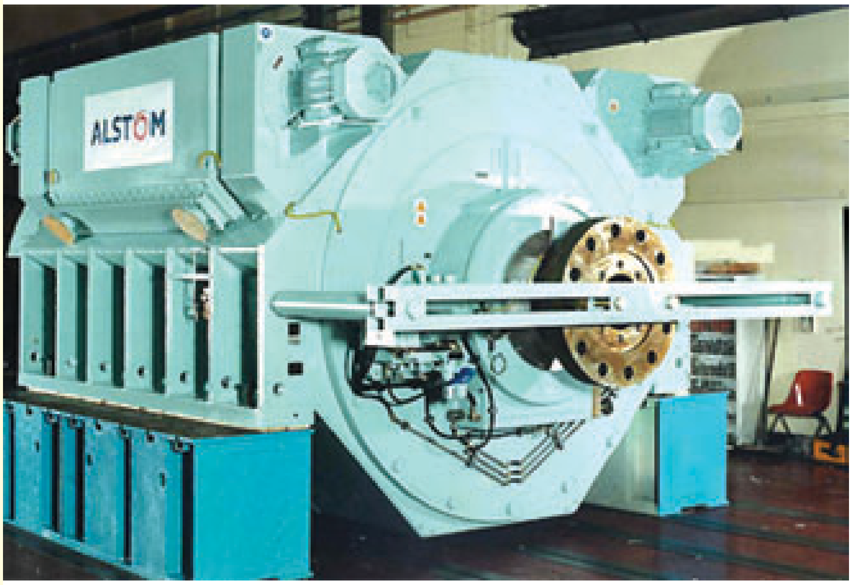
CONTENTS

CHAPTER 45

Learning Objectives

- Size and Rating
- Estimation of Motor Rating
- Different Types of Industrial Loads
- Heating of Motor or Temperature Rise
- Equation for Heating of Motor
- Heating Time Constant
- Equation for Cooling of Motor or Temperature Fall
- Cooling Time Constant
- Heating and Cooling Curves
- Load Equalization
- Use of Flywheels
- Flywheel Calculations
- Load Removed (Flywheel Accelerating)
- Choice of Flywheel

RATING AND SERVICE CAPACITY



Generator converts mechanical energy into electrical energy using electromagnetic induction

CONTENTS

45.1. Size and Rating

The factors which govern the size and rating of motor for any particular service are its maximum temperature rise under given load conditions and the maximum torque required. It is found that a motor which is satisfactory from the point of view of maximum temperature rise usually satisfies the requirement of maximum torque as well. For class-A insulation, maximum permissible temperature rise is 40ºC whereas for class – B insulation, it is 50ºC. This temperature rise depends on whether the motor has to run continuously, intermittently or on variable load.

Different ratings for electrical motors are as under:

1. Continuous Rating. It is based on the maximum load which a motor can deliver for an indefinite period without its temperature exceeding the specified limits and also possesing the ability to take 25% overload for a period of time not exceeding two hours under the same conditions.

For example, if a motor is rated continuous 10 KW, it means that it is capable of giving an output of 10 KW continuously for an indefinite period of time and 12.5 KW for a period of two hours without its temperature exceeding the specified limits.

2. Continuous Maximum Rating. It is the load capacity as given above but without overload capacity. Hence, these motors are a little bit inferior to the continuous-rated motors.

3. Intermittent Rating. It is based on the output which a motor can deliver for a specified period, say one hour or ½ hour or ¼ hour without exceeding the temperature rise.

This rating indicates the maximum load of the motor for the specified time followed by a no-load period during which the machine cools down to its original temperature.

45.2. Estimation of Motor Rating

Since primary limitation for the operation of an electric motor is its temperature rise, hence motor rating is calculated on the basis of its average temperature rise. The average temperature rise depends on the average heating which itself is proportional to the square of the current and the time for which the load persists.

For example, if a motor carries a load L_1 for time t_1 and load L_2 for time t_2 and so on, then

$$\text{Average heating} \propto L_1^2 t_1 + L_2^2 t_2 + \ldots\ldots + L_n^2 t_n$$

In fact, heating is proportional to square of the current but since load can be expressed in terms of the current drawn, the proportionality can be taken for load instead of the current.

$$\therefore \text{ size of the motor } = \sqrt{\frac{L_1^2 t_1 + L_2^2 t_2 + \ldots\ldots + L_n^2 t_n}{t_1 + t_2 + \ldots\ldots t_n}}$$

Generally, load on a motor is expressed by its load cycle. Usually, there are periods of no-load in the cycle. When motor runs on no-load, heat generated is small although heat dissipation continues at the same rate as long as the machine is running. Hence, there is a difference in the heating of a motor running at no-load and when at rest. It is commonly followed practice in America to consider the period at rest as one – third while calculating the size of motor. It results in giving a higher motor rating which is advantageous and safe.

Example 45.1 *An electric motor operates at full-load of 100 KW for 10 minutes, at ¾ full load for the next 10 minutes and at ½ load for next 20 minutes, no-load for the next 20 minutes and this cycle repeats continuously. Find the continuous rating of the suitable motor.*

Solution.

$$\text{Size of the motor required} = \sqrt{\frac{100^2 \cdot 10 + 75^2 \cdot 10 + 50^2 \cdot 20 + 0 \cdot 20}{10+10+20+20}}$$

$$= 61 \text{ KW}$$

According to American practice, we will consider the period of rest as (20/3) minutes. In that case, the motors size is

$$= \sqrt{\frac{100^2 \cdot 10 + 75^2 \cdot 10 + 50^2 \cdot 20 + 0 \cdot 20}{10+10+20+(20/3)}}$$

= 66 KW

Example 45.2. *An electric motor has to be selected for a load which rises uniformly from zero to 200 KW in 10 minutes after which it remains constant at 200 KW for the next 10 minutes, followed by a no-load period of 15 minutes before the cycle repeats itself. Estimate a suitable size of continuously rated motor.*

Solution.

$$\text{Motor size} = \sqrt{\frac{(200/2)^2 \cdot 10 + (200)^2 \cdot 10 + 0 \cdot 15}{10+10+(15 \cdot 1/3)}}$$

= 140 KW

According to American practice, no-load has been taken as one third.

Example 45.3. *A certain motor has to perform the following duty cycle:*

100 KW for 10 minutes	*No-load for 5 minutes*
50 KW for 8 minutes	*No-load for 4 minutes*

The duty cycle is repeated indefinitely. Draw the curve for the load cycle. Assuming that the heating is proportional to the square of the load, determine suitable size of a continuously-rated motor. **[Utilisation of Electric Power A.M.I.E.]**

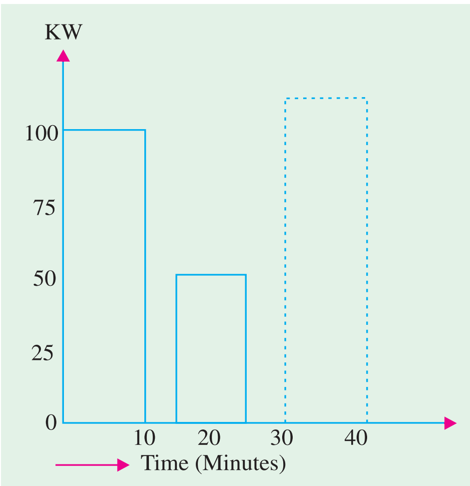


Fig. 45.1

Solution.

As explained above, heating is prorortional to the square of the current and hence, to the square of the load.

∴ size of the continuously-rated motor

$$\sqrt{\frac{100^2 \cdot 10 + 50^2 \cdot 8}{10+5+8+4}}$$

= 66.67 kW

Hence, the motor of **70 KW** would be adequate. The curve of the load cycle is shown in Fig. 45.1

The ultimate usefulness of the above factors is to select a motor of as small a size as possible compatible with temperature rise and to ensure that the motor has ample overload torque to cater for maximum-load conditions. Obviously, over-motoring of any industrial drive will result in a waste of electrical energy, a low power factor and unnecessarily high capital cost for the motor and control gear.

45.3. Different Types of Industrial Loads

The three different types of industrial loads under which electric motors are required to work are as under:

(i) continuous load *(ii)* intermittent load and *(iii)* variable or fluctuating load.

The size of the motor depends on two factors. Firstly, on the temperature rise which, in turn, will depend on whether the motor is to operate on continuous, intermittent or variable load. Secondly, it will depend on the maximum torque to be developed by the motor. Keeping in mind the load torque requirements, the rating of the motor will be decided by the load conditions as described below.

(*i*) Continuous Load. In such cases, the calculation of motor size is simpler because the loads like pumps and fans require a constant power input to keep them operating. However, it is essential to calculate the KW rating of the motor correctly. If the KW rating of the motor is less than what is required, the motor will overheat and consequently burn out. If, on the other hand, KW rating is more than what is needed by the load, the motor will remain cool but will operate at lower efficiency and power.

(*ii*) Intermittent Loads. Such loads can be of the following two types:

(*a*) In this type of load, motor is loaded for a short time and then shut of for a sufficient by long time, allowing the motor to cool down to room temperature as shown in Fig. 45.2. In such cases, a motor with a short time rating is used as in a kitchen mixie.

Torque motors are designed to provide maximum torque at locked rotor or near stalled conditions. Their applications are in servo and positioning systems, tension reels, automatic door openers, and filament winding equipment.

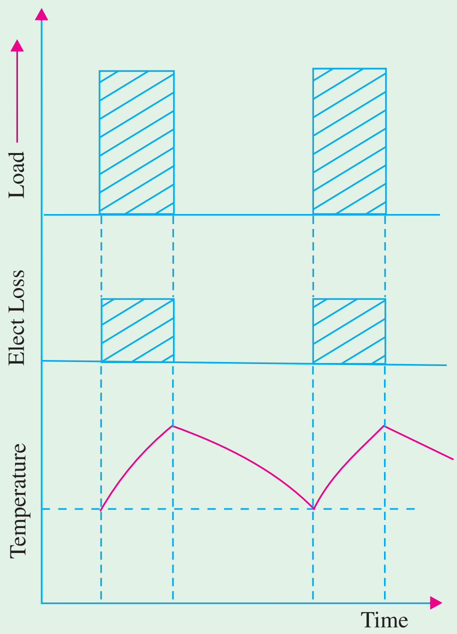


Fig. 45.2

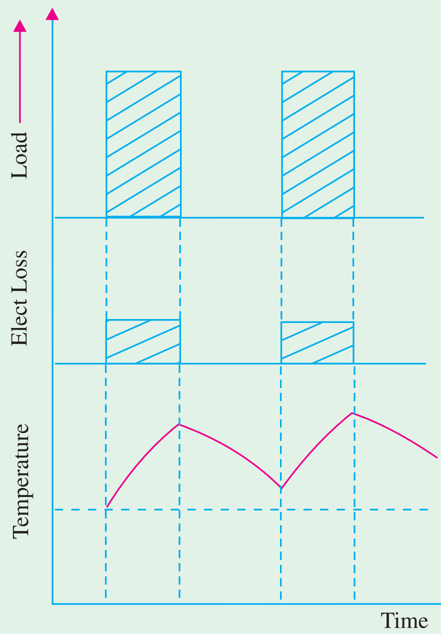


Fig. 45.3

(*b*) In this type of load, motor is loaded for a short time and then it is shut off for a short time. The shut off time is so short that the motor cannot cool down to the room temperature as shown in Fig.45.3. In such cases, a suitable continuous or short-time rated motor is chosen which, when operating on a given load cycle, will not exceed the specified temperature limit.

(*iii*) Variable Loads. In the case of such loads, the most accurate method of selecting a suitable motor is to draw the heating and cooling curves as per the load fluctuations for a number of motors. The smallest size motor which does not exceed the permitted temperature rise when operating on the particular load cycle should be chosen for the purpose.

However, a simpler but sufficiently accurate method of selection of a suitable rating of a motor is to assume that heating is proportional to the square of the current and hence the square of the load. The suitable continuous rating of the motor would equal the r.m.s. value of the load current.

Example 45.4. *A motor has to perform the following duty cycle*

100 H.P.	*For*	*10 min*
No Load	”	*5 min*
60 H.P.	”	*8 min*
No Load	”	*4 min*

which is repeated infinitely. Determine the suitable size of continuously rated motor.

Solution.

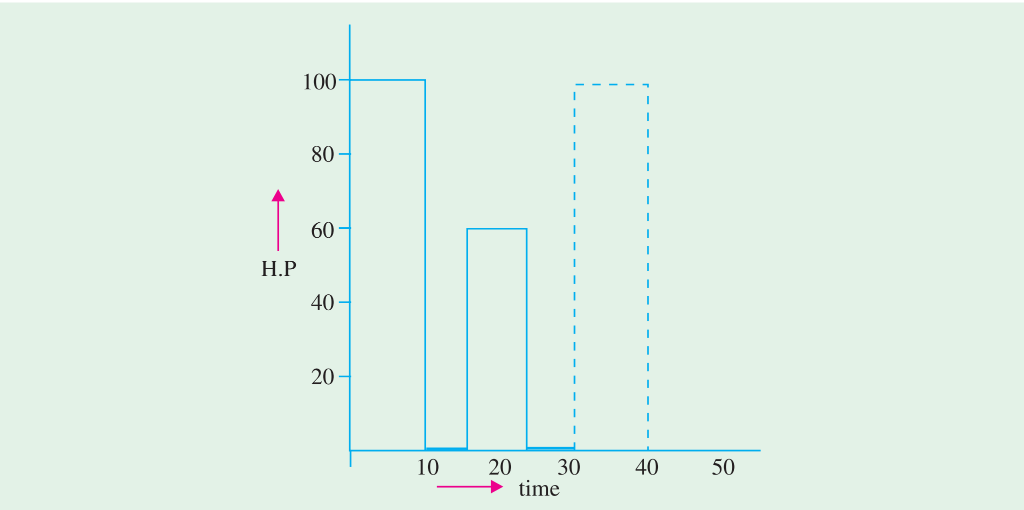


Fig. 45.4

$$\text{R.M.S. H.P.} = \sqrt{\left\{\frac{1}{\text{Time for one cycle}}\right\}\int \text{HP}^2 dt}$$

$$\text{R.M.S. H.P.} = \left[\frac{\sum \text{HP}^2 \cdot \text{time}}{\text{Time for one cycle}}\right]^{\frac{1}{2}}$$

$$= \sqrt{\frac{100^2 \cdot 10 + 50^2 \cdot 8}{10+5+8+4}} = 69.07 \text{ H.P.}$$

$\simeq$ **75 H.P. motor can be used.**

Example 45.5. *A motor working in a coal mine has to exert power starting from zero and rising uniformly to 100 H.P. in 5 min after which it works at a constant rate of 50 H.P. for 10 min. Then, a no load period of 3 min. The cycle is repeated indefinitely, estimate suitable size of motor.*
[Nagpur University Summer 2000]

Solution.

(*a*) For time period : 0 - 5 min

$$\Rightarrow \quad y = mx + c$$

$$\text{Slope} = \frac{(100-0)}{5}$$

$$m = 20 \text{ HP/min}$$

$$\therefore \quad y = 20\,x + 0$$

$$\mathbf{y = 20\,x}$$

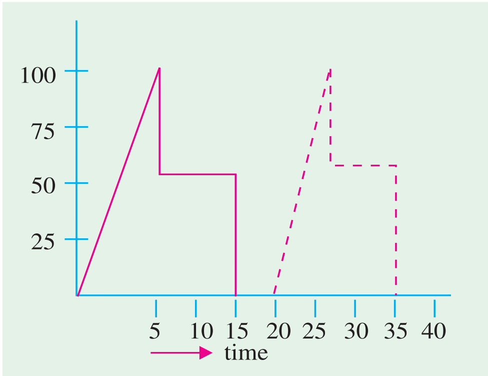


Fig. 45.5

(*b*) For total time period : 0 - 18 min

R.M.S. H P^2

$$= \left\{\left[\int_0^5 y^2\,dx\right] + 50^2 \times 10 + 0^2 \times 3\right\}/18$$

$$\Rightarrow \text{H.P.}^2 \times 18 = \left[\int_0^5 (20\,x)^2\,dx\right] + 25000 = \left[\frac{400\,x^3}{3}\right]_0^5 + 25000$$

$$\therefore \text{H.P.}^2 \times 18 = \frac{400 \times 125}{3} + 25000$$

$$\Rightarrow \text{H.P.} = \sqrt{\frac{41666.67}{18}} = 48.11 \text{H.P.} \simeq 50 \text{ H.P. motor can used}$$

or Same problem can be solved by Simpson's 1/3rd Rule of Integration

$$\text{H. P.} = \sqrt{\frac{\frac{1}{3} \times 100^2 \times 5 + 50^2 \times 10}{18}}$$

H. P. = 48.11 H.P. ; $\therefore$ **H. P. $\simeq$ 50 H.P.**

Example 45.6. *A motor has following duty cycle*

Load rising from 200 to 400 H.P.	-	*4 min.*
Uniform load 300 H. P.	-	*2 min.*
Regenerative braking - H.P. returned to		
supply from 50 to zero	-	*1 min.*
Remaining idle for	-	*1 min.*

Estimate suitable H. P. rating of the motor. motor can be used.
[Nagpur University Winter 1994]

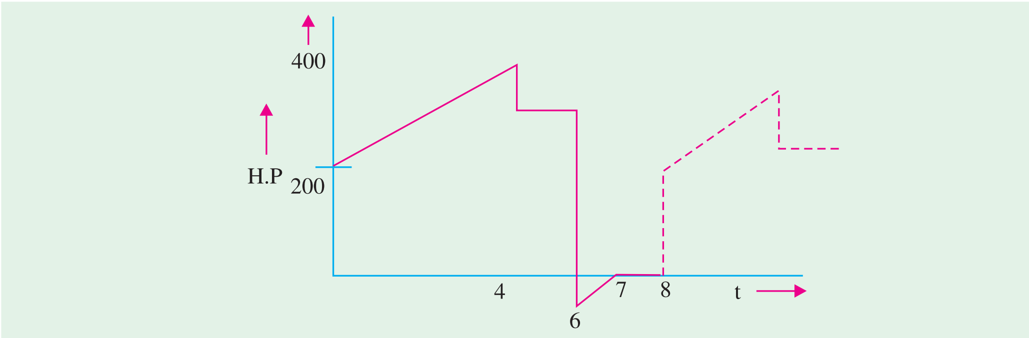


Fig. 45.6

Solution.

$$\text{H. P.} = \sqrt{\frac{\frac{1}{3}(H_1^2 + H_1 H_2 + H_2^2)\, t_1 + H_3^2\, t_2 + \frac{1}{3} H_4^2\, t_3}{8}}$$

$$= \sqrt{\frac{\frac{1}{3}(200^2 + 200 \cdot 400 + 400^2) \times 4 + 300^2 \times 2 + \frac{1}{3} 50^2 \times 1}{8}}$$

$$= \sqrt{\frac{1662500}{24}} = \mathbf{263\ H.\ P.}$$

Note. During regenerative braking, even though H.P. is returned to line, machine will be carrying current. So far heating is concerned, it is immaterial whether machine is taking current from or giving current to line.

This problem can be solved by another method as follows:-

(*a*) For time period : 0 - 4 min

$$\rightarrow \int_0^4 (50x + 200)^2\, dx = \int_0^4 (250x^2 + 20000x + 40000)\, dx$$

$$= 2500\left[\frac{x^3}{3}\right]_0^4 + 20000\left[\frac{x^2}{2}\right]_0^4 + 40000\,x$$

$$= 2500\left[\frac{4^3}{3}\right] + 20000\left[\frac{4^2}{2}\right] + 40000 \cdot 4 = \mathbf{373333.3\ H.P.}$$

(*b*) For time period : 4 - 6 min

$$\rightarrow (300)^2 \cdot 2 = \mathbf{180000\ H.P.}$$

(*c*) For time period : 6 - 7 min

$$\rightarrow \int_0^1 (50\,x)^2\, dx = 2500\left[\frac{x^3}{3}\right]_0^1 = \frac{2500}{3} = 833.33\,\text{H.P}$$

$$\therefore \text{ R.M.S. H.P.} = \sqrt{\frac{373333.33 + 180000 + 833.33}{8}} = 263.1$$

$\simeq$ **300 H.P. motor will be suitable**

Example 45.7. *The load cycle of a motor for 15 min. in driving some equipment is as follows :*

0 - 5 min	-	*30 H. P.*
5 - 9 min	-	*No Load*
9 - 12 min	-	*45 H. P.*
12 - 15 min	-	*No Load*

The load cycle is repeated indefinitely. Suggest a suitable size of continuously rated motor.

Solution.

$$\text{R.M.S. H.P} = \left[\frac{30^2 \cdot 5 + 45^2 \cdot 3}{15}\right]^{\frac{1}{2}}$$

$$= 26.55 \text{ H. P.}$$

$\therefore$ R.M.S. H.P $\simeq$ **30 H. P. motor will be suitable.**

Example 45.8. *A motor driving a colliery winder has the following acceleration period*

load cycle 0 - 15 sec.	:	*Load rising uniformly from 0 - 1000 H.P.*
Full speed period	:	*15 - 85 sec. Load const. at 600 H.P.*
Decceleration period	:	*85 to 95 sec. regenerative braking the H. P. returned uniformly from 200 to 0 H. P.*
95 - 120 sec.	:	*Motor stationary.*

Estimate the size of continuously rated motor.

Solution.

$$\text{R.M.S. H. P.} = \left[\frac{\frac{1}{3}(1000)^2 \cdot 15 + 600^2 \cdot 70 + \frac{1}{3}(200)^2 \cdot 10}{120}\right]^{\frac{1}{2}}$$

$$= 502 \text{ H. P.}$$

$\cong$ **505 H. P. motor can be used.**

45.4. Heating of Motor or Temperature Rise

The rise in temperature of a motor results from the heat generated by the losses and an expression for this temperature rise is obtained by equating the rate at which heat is being generated by these losses to the rate at which heat is being absorbed by the motor for raising the temperature of motor and in dissipation from the surfaces exposed to cooling media.

So long as the temperature of machine rises, the generated heat will be stored in body and the rest will be dissipated to cooling medium depending upon the temperature difference. This is called as unstable or transient situation.

If the temperature of body rises, it has to store heat. The amount of heat *i.e.* stored depends upon the heat capacity of the body. If the temperature of the machine remains constant *i.e.* it doesn't rise, then no further storage of heat takes place and all the heat *i.e.* generated must be dissipated. So rate of heat generation in motor equals rate of heat dissipation from the cooling surface. This is called a stable situation.

45.5. Equation for Heating of Motor

Let,

$W \rightarrow$ Heat generated in motor due to powerloss in watts.

$G \rightarrow$ Weight of motor (kg)

S → Average specific heat in (Watt - Sec.) to raise the temperature of unit weight through 1°C.

$G \times S$ → Heat required to raise the temperature of motor through 1°C (Watt - Sec.)

θ → Temperature rise above cooling medium in °C.

θ_f → Final temperature rise in °C.

A → Cooling surface area of motor.

λ → Rate of heat dissipation from the cooling surface.
[(Watts/Unit area/°C rise in temperature.) above cooling medium]

$A\lambda$ → Rate of heat dissipation in Watts /°C rise in temperature for a motor.

Assumptions

1. Loss 'W' remains constant during temperature rise.
2. Heat dissipation is proportional to the temperature difference between motor and cooling medium.
3. Temperature of cooling medium remains constant.

{Rate of heat generation in motor}
= {Rate of heat absorption by the motor} + {Rate of heat dissipation from cooling surface}

$$\rightarrow \quad W = GS\frac{d\theta}{dt} + A\lambda\theta$$

$$\text{or} \quad W - A\lambda\theta = GS\frac{d\theta}{dt}$$

$$\rightarrow \quad \frac{W}{A\lambda} - \theta = \frac{GS}{A\lambda}\frac{d\theta}{dt}$$

$$\rightarrow \quad \frac{d\theta}{\left(\frac{W}{A\lambda} - \theta\right)} = \frac{dt}{\frac{GS}{A\lambda}}$$

By integrating,

$$\log_e\left(\frac{W}{A\lambda} - \theta\right) = -\frac{A\lambda}{GS}t + C \quad \text{..... (2)}$$

At $t = 0$, $\theta = \theta_1$ [Initial temperature rise *i.e.* difference between the temperature of cooling medium and temperature of motor, during starting]

If starting from cold position, $\theta_1 = 0$

Substituting the values of t and θ in above equation.

$$C = \log_e\left(\frac{W}{A\lambda} - \theta_1\right)$$

$$\therefore \quad (2) \Rightarrow \log_e\left[\frac{\left(\frac{W}{A\lambda} - \theta\right)}{\left(\frac{W}{A\lambda} - \theta_1\right)}\right] = -\frac{A\lambda}{GS}t$$

by taking antilog,

$$\frac{\left(\frac{W}{A\lambda} - \theta\right)}{\left(\frac{W}{A\lambda} - \theta_1\right)} = e^{-\frac{A\lambda}{GS}t}$$

$$\therefore \quad \theta = \frac{W}{A\lambda} - \left(\frac{W}{A\lambda} - \theta_1\right) e^{-\frac{A\lambda}{GS}t} \quad \text{..... (3)}$$

When, the final temperature rise of θ_f is reached, all the heat generated is dissipated from the cooling surface so that,

equation (1) becomes $W = A\lambda\ \theta_f$ or $\theta_f = \frac{W}{A\lambda}$

And $\frac{GS}{A\lambda}$ = Heating time constant

$$\therefore \quad \frac{A\lambda}{GS} = \frac{1}{T}$$

Then equation (3) becomes;

$$\theta = \theta_f - (\theta_f - \theta_1)\ e^{\frac{-t}{T}}$$

If starting from cold, then $\theta_1 = 0$

$$\therefore \quad \theta = \theta_f\ (1 - e^{\frac{-t}{T}})$$

45.6. Heating Time Constant

Heating time constant of motor is defined as the time required to heat up the motor upto 0.633 times its final temperature rise.

$\theta = (1 - e^{-t/T})$

At $t = T$, $\theta = 0.633\ \theta_f$

After time	$t = T$	θ reaches to 63.3 % of θ_f
	$t = 2T$	θ reaches to 86.5 % of θ_f
	$t = 3T$	θ reaches to 95 % of θ_f
	$t = 4T$	θ reaches to 98.2 % of θ_f
	$t = 5T$	θ reaches to 99.3 % of θ_f

T = Heating time constant.
= 90 min for motors upto 20 H.P.
= 300 min for larger motors.

45.7. Equation for Cooling of Motor or Temperature Fall

If rate of heat generation is less than rate of heat dissipation, cooling will take place.

$\therefore$ {Rate of heat generation in motor}+{Rate of heat absorption by motor}={Rate of heat dissipation from cooling surface}

$$W + GS\frac{d\theta}{dt} = A\lambda'\theta$$ where λ' = Rate of heat dissipation during cooling surface

$$W - A\lambda'\theta = -GS\frac{d\theta}{dt} \quad \Rightarrow \quad \frac{W}{A\lambda'} - \theta = -\frac{GS}{A\lambda'}\frac{d\theta}{dt}$$

$$\theta - \frac{W}{A\lambda'} = \frac{GS}{A\lambda'}\frac{d\theta}{dt} \quad \Rightarrow \quad \frac{d\theta}{\theta - \frac{W}{A\lambda'}} = \frac{dt}{\frac{GS}{A\lambda'}}$$

$$\therefore \quad \int \frac{d\theta}{\theta - \frac{W}{A\lambda'}} = \int \frac{dt}{\frac{GS}{A\lambda'}}$$

$$\log_e\left(\theta - \frac{W}{A\lambda'}\right) = -\frac{A\lambda'}{GS}t + C$$

At $t = 0$ Let $\theta = \theta_o$ Difference of temperature between cooling medium and motor (Temperature rise at which cooling starts.)

$$\therefore \quad C = \log_e\left(\theta_0 - \frac{W}{A\lambda'}\right)$$ Put this value of C in the abve equation.

$$\therefore \quad \log_e \frac{\theta - \frac{W}{A\lambda'}}{\theta_0 - \frac{W}{A\lambda'}} = -\frac{A\lambda'}{GS}t$$

If θ_f' is final temperature drop (above that of cooling medium), then at this temperature whatever heat is generated will be dissipated.

$$\therefore \quad W = A\lambda'\theta_f' \quad \Rightarrow \quad \theta_f' = \frac{W}{A\lambda'}$$

$$\therefore \quad \log_e\left\{\frac{\theta - \theta_f'}{\theta_0 - \theta_f}\right\} = -\frac{t}{T'}$$ Where T' is cooling time constant $= \frac{GS}{A\lambda'}$

$$\therefore \quad \frac{\theta - \theta_f'}{\theta_0 - \theta_f'} = e^{-t/T} \quad \Rightarrow \quad (\theta - \theta_f') = (\theta_0 - \theta_f')e^{\frac{-t}{T'}}$$

$$\theta = \theta_f' + (\theta_0 - \theta_f')e^{\frac{-t}{T'}}$$

If motor is disconnected from supply, there will be no losses taking place and so final temperature reached will be ambient temperature. Hence $\theta_f' = 0$ ($\because W = 0$)

$$\therefore \quad \theta = \theta_0 . e^{\frac{-t}{T'}}$$

If $t = T'$, then $\theta = \theta_0 . e^{-1} \Rightarrow \theta = \frac{\theta_0}{e} = 0.368\,\theta_0$; $\therefore \theta = 0.368\,\theta_0$

45.8. Cooling Time Constant

Cooling time constant is defined as the time required to cool machine down to 0.368 times the initial temperature rise above ambient temperature.

By putting different values of T' in $\theta = \theta_0 . e^{-t/T'}$

∴ After time t	=	T'	θ has fallen to	36.8% of θ_0
t	=	$2T'$	θ has fallen to	13.5% of θ_0
t	=	$3T'$	θ has fallen to	5% of θ_0

t	=	$4T'$	θ has fallen to	1.8% of θ_0
t	=	$5T'$	θ has fallen to	0.7% of θ_0

45.9. Heating and Cooling Curves

(*a*) Motor continuously worked on Full Load.

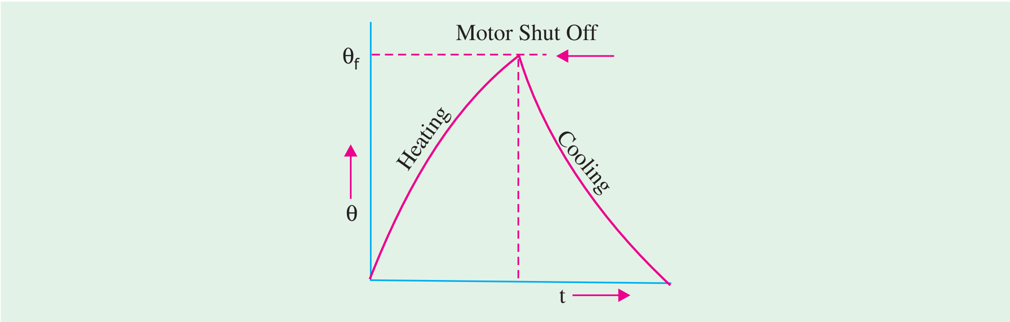


Fig. 45.7

Maximum permissible temperature rise.

Motor reaches final temperature rise and then cooling is carried out to ambient temperature.

(*b*) Motor Run for short time

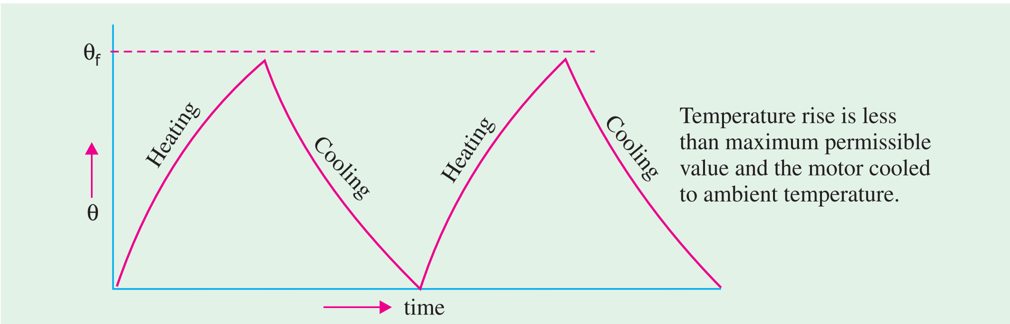


Fig. 45.8

(*c*) Cooling period not sufficient to cool down the motor to its ambient temperature.

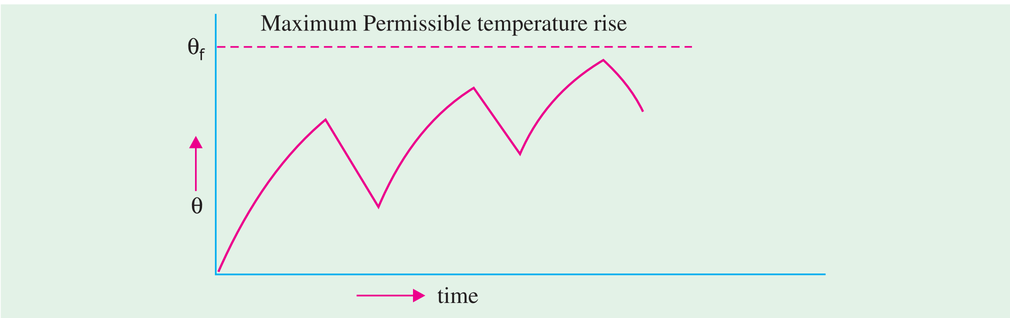


Fig. 45.9

* For intermittent loads, a motor of smaller rating can be used without exceeding maximum permissible temperature rise.

Example 45.9. *A 40 KW motor when run continuously on full load, attains a temperature of 35°C, above the surrounding air. Its heating time constant is 90 min. What would be the 1/2 hour rating of the motor for this temperature rise? Assume that the machine cools down completely between each load period and that the losses are proportional to square of the load,*

Solution.

Let '*P*' KW be the ½ hour rating of the motor

θ_f – Final temperature rise at P K W

θ_f' – Final temperature rise at 40 KW

$\therefore$ Losses at P KW $\propto P^2$

Losses at 40 K W $\propto 40^2$

$$\Rightarrow \frac{\theta_f}{\theta_f'} = \frac{\text{Losses at } P\text{KW}}{\text{Losses at } 40\,\text{KW}} = \left(\frac{P}{40}\right)^2 \quad \therefore \ \theta_f = \left(\frac{P}{40}\right)^2 \theta_f'$$

As the machine cools down completely, for '*P*' KW the equation will be

$$\theta = \theta_f\left(1 - e^{\frac{1}{T}}\right) \quad \text{where} \quad \theta_f = \left(\frac{P}{40}\right)^2 \times 35$$

$$\Rightarrow \quad 35 = \left(\frac{P}{40}\right)^2 \times 35\left(1 - e^{-\frac{0.5}{1.5}}\right); \qquad \therefore \ \text{P} = \textbf{75.13 KW}$$

Example 45.10. *Determine the one - hour rating of a 15 H.P. motor having heting time constant of 2 hours. The motor attains the temperature rise of 40°C on continuous run at full load. Assume that the losses are proportional to square of the load and the motor is allowed to cool down to the ambient temperature before being loaded again.* **[Nagpur University Summer 2001]**

Solution.

Let 'P' H. P be one - hour rating of the motor

$$\text{Losses at this load} = \text{Original losses} \times \left(\frac{P}{15}\right)^2.$$

Let θ_f be the final temperature rise at P H.P. and θ_f' at 15 H P

$$\therefore \ \frac{\theta_f}{\theta_f'} = \frac{\text{Losses at P H.P.}}{\text{Original Losses}} = \left(\frac{P}{15}\right)^2$$

$$\theta_f = \theta_f'\left(\frac{P}{15}\right)^2 = 40\left(\frac{P}{15}\right)^2$$

$$\theta = \theta_f\left(1 - e^{\frac{-t}{T}}\right)$$

$$40 = 40\left[\frac{P}{15}\right]^2\left(1 - e^{\frac{-1}{2}}\right)$$

P = 23.96 H.P.

$P \simeq$ **24 H.P.**

Example 45.11. *The heating and cooling time constants of a motor are 1 hour and 2 hours respectively. Final temperature rise attained is 100ºC. This motor runs at full load for 30 miniutes and then kept idle for 12 min. and the cycle is repeated indefinitely. Determine the temperature rise of motor after one cycle.* **[Nagpur University Winter 1997]**

Solution.
$$\theta = \theta_f\left(1-e^{\frac{-t}{T}}\right)$$
$$=100\left(1-e^{\frac{-30}{60}}\right)=39.34°$$
$$\theta=\theta_0\, e^{-\frac{t}{T'}}=39.34e^{\frac{-12}{120}}=\mathbf{35.6°C}$$
= Temperature rise of motor after 1 cycle.

Example 45.12. *Calculate the maximum overload that can be carried by a 20 KW output motor, if the temperature rise is not to exceed 50ºC after one hour on overload. The temperature rise on full load, after 1 hour is 30ºC and after 2 hours is 40ºC. Assume losses proportional to square of load.*

Solution.
$$\theta=\theta_f\left(1-e^{\frac{-t}{T}}\right)$$
$$30=\theta_f\left(1-e^{\frac{-1}{T}}\right) \quad \text{and} \quad 40=\theta_f\left(1-e^{-\frac{2}{T}}\right)$$
$$\frac{1-e^{\frac{-2}{T}}}{1-e^{\frac{-1}{T}}}=\frac{40}{30} \qquad \text{Put } x=e^{\frac{-1}{T}}$$
$$\therefore \frac{1-x^2}{1-x}=\frac{4}{3} \qquad \therefore \frac{(1-x)\,(1+x)}{(1-x)}=\frac{4}{3}$$
$$\Rightarrow \quad 1+x=\frac{4}{3}$$
$$\therefore\ x=\frac{1}{3}=e^{-1/T} \quad \Rightarrow \quad T = 0.91 \text{ hrs.}$$
To find θ_f $\Rightarrow$ $30=\theta_f\left(1-e^{\frac{-1}{T}}\right)\Rightarrow 30=\theta_f\left(1-\frac{1}{3}\right)\Rightarrow \theta_f=45°C$

After 1 hr. $\quad 50=\theta_f\left(1-\frac{1}{e^T}\right)$
$$50=\theta_f\left(1-\frac{1}{3}\right) \qquad \therefore\ \theta_f=75°\text{C}$$
Let the maximum overload capacity of 20 KW motor is *P* KW
$$\therefore\ \frac{\theta_f}{\theta'_f}=\frac{\text{Losses at PK W}}{\text{Original Losses}}=\left(\frac{P}{20}\right)^2$$

$\therefore \quad \dfrac{75}{45} = \left(\dfrac{P}{20}\right)^2 \qquad \therefore \quad P = 25.8$ **kW**

Example 45.13. *In a transformer the temperature rise is 25°C after 1 hour and 37.5°C after 2 hours, starting from cold conditions. Calculate its final steady temperature rise and the heating time constant. If the transformer temperature falls from the final steady value to 40°C in 1.5 hours when disconnected, calculate its cooling time constant. Ambient temperature is 30°C.*

Solution. $\theta = \theta_f \left(1 - e^{\frac{-1}{T}}\right)$

$$25 = \theta_f \left(1 - e^{\frac{-1}{T}}\right) \quad \text{and} \quad 37.5 = \theta_f \left(1 - e^{\frac{-2}{T}}\right)$$

$$\therefore \quad \frac{37.5}{25} = \frac{1 - e^{\frac{-2}{T}}}{1 - e^{\frac{-1}{T}}}, \qquad \text{Put } x = e^{-\frac{1}{T}}$$

$$1.5 = \frac{1 - x^2}{1 - x}, \qquad 1.5 = \frac{(1-x)(1+x)}{(1-x)}$$

$$1.5 = 1 + x \qquad \therefore \quad x = 0.5$$

$$\therefore \quad e^{-\frac{1}{T}} = 0.5 \qquad \therefore \quad T = 1.44 \text{ hrs}$$

$$25 = \theta_f \left(1 - e^{\frac{-1}{T}}\right) \quad \Rightarrow \quad 25 = \theta_f \left(1 - e^{\frac{-1}{1.44}}\right) \quad \Rightarrow \quad \theta_f = 50°\text{C}$$

Cooling : Temperature rise after 1.5 hours above ambient temperature $= 40 - 30 = 10$°C.

$\because$ The transformer is disconnected $\theta = \theta_0 \, e^{\frac{-t}{T'}}$

$$10 = 50\, e^{\frac{-1.5}{T'}} \qquad \therefore \quad T' = \mathbf{0.932 \text{ hrs}}$$

Example 45.14. *The initial temperature of machine is 45°C. Calculate the temperature of machine after 1.2 hours, if its final steady temperature rise is 85°C and the heating time constant is 2.4 hours. Ambient temperature is 25°C*

Solution.

$$\theta = \theta_f - (\theta_f - \theta_1)\, e^{-t/T} \qquad \theta = 85 - (85 - 20)\ e^{-12/24}$$

$\theta = 45.54$°C - Temperature rise above cooling medium

$\therefore$ Temperature of machine after 1.2 hours is = 45 . 54 + 25 = **70 .54°C**

Example 45.15. *The following rises were observed in a temperature rise test on a D.C. machine at full loads.*

After 1 hour — 15°C

After 2 hours — 25°C

Find out *(i) Final steady temperature rise and time constant.*

(ii) The steady temperature rise after 1 hour at 50% overload, from cold. Assume that the final temperature rise on 50% overload is 90°C.

[Nagpur University Summer 1998]

Solution. $\theta = \theta_f\,(1 - e^{\frac{-t}{T}})$, as motor is starting from cold.

$$15 = \theta_f (1 - e^{\frac{-1}{T}}) \qquad \text{and} \qquad 25 = \theta_f\,(1 - e^{-\frac{2}{T}})$$

$$\therefore \qquad \frac{25}{15} = \frac{\theta_f\left(1 - e^{\frac{-2}{T}}\right)}{\theta_f\left(1 - e^{\frac{-1}{T}}\right)}$$

$$\therefore \quad e^{\frac{-1}{T}} = \frac{25}{15} - 1 \qquad , \qquad e^{\frac{-1}{T}} = \frac{2}{3}$$

$$\therefore\ T = 2.466 \text{ hours,} \qquad 15 = \theta_f\left(1 - e^{\frac{-1}{T}}\right)$$

by putting value of T,

$$15 = \theta_f\left(1 - e^{\frac{-1}{2.466}}\right)$$

$\Rightarrow$ θ_f = **45°C**

(ii) On 50% overload θ_f = 90°C

$\therefore$ Final temperature rise after 1 hour at 50% overload is $\theta = \theta_f\,(1 - e^{\frac{-t}{T}})$

$$\theta = 90\left(1 - e^{\frac{-1}{2.466}}\right) = \mathbf{30^\circ C}$$

45.10. Load Equalization

If the load fluctuates between wide limits in space of few seconds, then large peak demands of current will be taken from supply and produce heavy voltage drops in the system. Large size of conductor is also required for this.

Process of smoothing out these fluctuating loads is commonly referred to as load equalization and involves storage of energy during light load periods which can be given out during the peak load period, so that demand from supply is approximately constant. Tariff is also affected as it is based on M.D. (Maximum Demand)

For example, in steel rolling mill, when the billet is in between the rolls it is a peak load period and when it comes out it is a light load period, when the motor has to supply only the friction and internal losses, as shown in figure 45.10.

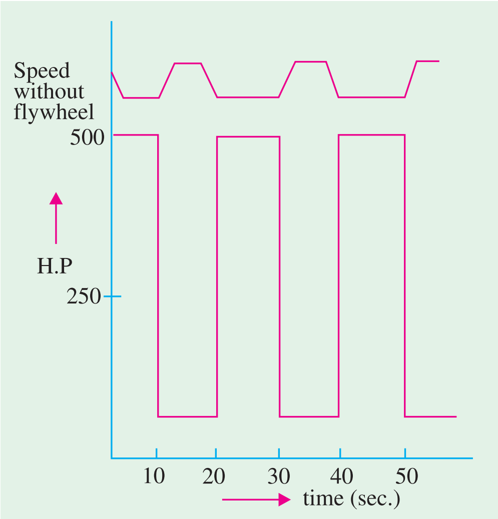


Fig. 45.10

45.11. Use Of Flywheels

The method of Load Eqalization most commonly employed is by means of a flywheel. During peak load period, the flywheel deccelarates and gives up its stored kinetic energy, thus reducing the load demanded from the supply. During light load periods, energy is taken from supply to accelerate flywheel, and replenish its stored energy ready for the next peak. Flywheel is mounted on the motor shaft near the motor. The motor must have drooping speed characteristics, that is, there should be a drop in speed as the load comes to enable flywheel to give up its stored energy. When the Ward - Leonard system is used with a flywheel, then it is called as Ward - Leonard Ilgner control.

45.12. Flywheel Calculations

The behaviour of flywheel may be determined as follows.

Fly wheel Decelerating :- (or Load increasing)

Let T_L → Load torque assumed constant during the time for which load is applied in kg-m

T_f → Torque supplied by flywheel in kg-m

T_o → Torque required on no load to overcome friction internal losses etc., in kg-m

T_m → Torque supplied by the motor at any instant, in kg-m

ω_o → No Load speed of motor in rad/sec.

ω → Speed of motor at any instant in rad/sec.

s → motor slip speed (ω_o - ω) in rad/sec.

I → Moment of inertia of flywheel in kg-m^2

g → Acceleration due to gravity in m/sec^2

t → time in sec.

When the flywheel deacelerates, it gives up its stored energy.

$$\rightarrow \quad T_m = T_L - T_f \quad \text{or} \quad T_L = T_m + T_f \qquad \text{..... (1)}$$

Energy stored by flywheel when running at speed 'ω' is 1/2 Iω^2/g.

If speed is reduced from ω_0 to ω.

The energy given up by flywheel is

$$= \frac{1}{2}\frac{I}{g}\left(\omega_0^2 - \omega^2\right)$$

$$= \frac{1}{2}\frac{I}{g}\left(\omega_0 + \omega\right)(\omega_0 - \omega) \qquad \text{.... (2)}$$

$\left(\dfrac{\omega_0 + \omega}{2}\right)$ = mean speed. Assuming speed drop of not more than 10%., this may be assumed equal to ω.

$$\therefore \quad \left(\frac{\omega_0 + \omega}{2}\right) \simeq \omega \qquad \text{Also} \qquad (\omega_0 - \omega) = s$$

∴ From equation (2), Energy given up $= \dfrac{I}{g}\omega . s$

Power given up $= \dfrac{I}{g}\omega . \dfrac{ds}{dt}$

but Torque $= \dfrac{\text{Power}}{\omega}$

$\therefore$ Torque supplied by flywheel.

$$T_f = \frac{I}{g}\frac{ds}{dt}$$

$\therefore$ From equation (1) , $T_m = T_L - \frac{I}{g}\frac{ds}{dt}$

For values of slip speed upto 10% of No - load speed, slip is proportional to Torque

or $\quad s = K\, T_m$

$$\therefore \quad T_m = T_L - \frac{I}{g} K \frac{dT_m}{dt}$$

This equation is similar to the equation for heating of the motor W – Aλθ = G.S. $\frac{d\theta}{dt}$

i.e. $\quad (T_L - T_m) = \frac{I}{g} K \frac{dT_m}{dt} \qquad \Rightarrow \quad g\frac{dt}{IK} = \frac{dT_m}{(T_L - T_m)}$

By integrating both sides.

$$-ln(T_L - T_m) = \frac{tg}{IK} + C_1 \qquad \text{.... (3)}$$

At $t = 0$, when load starts increasing from no load *i.e.* $T_m = T_o$

Hence, at $t = 0 \quad T_m = T_o$

$\therefore$ $C_1 = -\ln\,(T_L - T_o)$

By substituting the value of C_1 above, in equation (3) $-$ in $(T_L - T_m) = \frac{tg}{IK} - \text{In} \quad (T_L - T_0)$

$$\therefore \quad ln\left(\frac{T_L - T_m}{T_L - T_0}\right) = -\frac{tg}{IK} \qquad \Rightarrow \quad \left(\frac{T_L - T_m}{T_L - T_0}\right) = e^{\frac{-tg}{Ik}}$$

$$\Rightarrow \quad (T_L - T_m) = (T_L - T_0)\, e^{\frac{-tg}{Ik}} \qquad \therefore \quad T_m = T_L - (T_L - T_0)\, e^{\frac{-tg}{Ik}}$$

If the Load torque falls to zero between each rolling period, then $T_m = T_L - \left(1 - e^{\frac{-tg}{IK}}\right) \quad (\therefore\ T_0 = 0)$

45.13. Load Removed (Flywheel Accelerating)

Slip speed is decreasing and therefore $\frac{ds}{dt}$ is negative

$$T_m = T_0 + T_f = T_0 - \frac{I}{g}\frac{ds}{dt} \qquad \Rightarrow \quad T_0 - T_m = \frac{I}{g} K \frac{dT_m}{dt}$$

$$\frac{g\,dt}{I\,K} = \frac{dT_m}{T_0 - T_m}$$

After integrating both sides,

$-\text{In}\ (T_0 - T_m) = \frac{tg}{IK} + C$ At $t = 0$, $T_m = T_m{}'$ motor torque at the instant, when load is removed

$\therefore\ C = -\ \ln\,(T_o - T_m{}')$ Putting this value of C in the above equation

$$-\ ln\ (T_0 - T_m) = \frac{tg}{IK} - \text{In}\ (T_0 - T_m{}')$$

$$\therefore \quad \ln\left(\frac{T_0 - T_m}{T_0 - T_m'}\right) = \frac{-tg}{IK} \qquad \therefore \quad T_0 - T_m = (T_0 - T_m')\, e^{\frac{-tg}{IK}}$$

$$\therefore \quad T_m = T_0 + (T_m' - T_0)\, e^{\frac{-tg}{IK}}$$

Where T_m' = the motor torque, at the instant the load is removed.

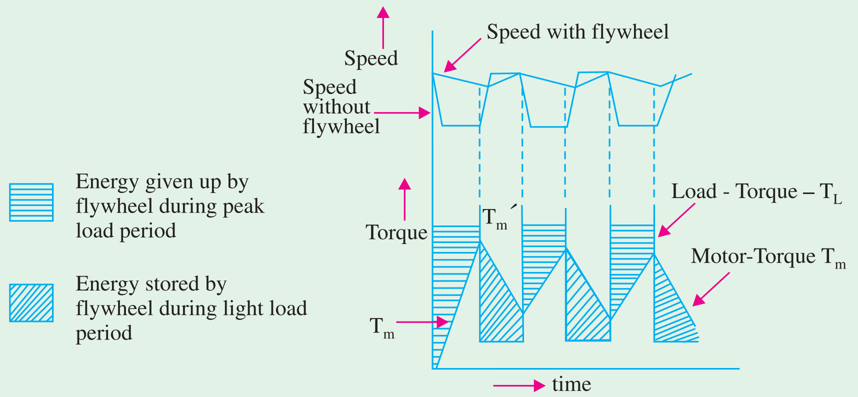


Fig. 45.11. Rolling mill drive with Flywheel

45.14. Choice of Flywheel

There are two choices left for selecting a flywheel to give up its maximum stored energy:

1. Large drop in speed and small flywheel (But with this the quality of production will suffer, since a speed drop of 10 to 15% for maximum load is usually employed).
2. Small drop in speed and large flywheel. (This is expensive and creates additional friction losses. Also design of shaft and bearing of motor is to be modified.) So compromise is made between the two and a proper flywheel is chosen.

The above figure shows the flywheel of a motor as a separate part

Example 45.16. *The following data refers to a 500 H.P. rolling mill, induction motor equipped with a flywheel.*

No load speed	$\rightarrow$	*40 r.p.m.*
Slip at full load (torque)	$\rightarrow$	*12%*
Load torque during actual rolling	$\rightarrow$	*41500 kg - m*
Duration of each rolling period	$\rightarrow$	*10 sec.*

Determine inertia of flywheel required in the above case to limit motor torque to twice its full load value. Neglect no - load losses and assume that the rolling mill torque falls to zero between each rolling period. Assume motor slip proportional to full load torque.

[Nagpur University Summer 1996]

Solution. $\omega = \dfrac{2\pi N}{60} = \dfrac{2\pi \times 40}{60} = 4.189 \text{ rad/sec}$

given, $T_0 = 0$ $\qquad T_m = T_L - (T_L - T_0)\,e^{\frac{-tg}{IK}}$

$t = 10$ sec.

$T_L = 41500$ kg - m

$T_m = 2 \times T_{\text{Full Load}}$

Now $T_{Full\ Load} = \dfrac{500 \times 735.5}{0.88 \times 4.189}$ N - m. $\qquad \because$ s = 12%

(1–s) = 0.88

= 99765 N-m

= 10169.7 kg-m

$\therefore$ T_m = 2 × 10169.7

= 20339.5 kg

s = $\omega_0 - \omega$

$= \dfrac{2\pi}{60}(N_0 - N)$

$= \dfrac{2\pi}{60}(40 - 0.88(40))$

$= \dfrac{2\pi}{60}(4.8) = 0.503$ rad/ sec.

s = $K\ T_{FL}$

$0.503 = K\,(10169.7) \quad \Rightarrow \quad K = 4.91 \times 10^{-5}$

$$T_m = T_L - (T_L - T_0)\,e^{\frac{-tg}{IK}}$$

$\because T_0 = 0 \qquad \therefore T_m = T_L\left(1 - e^{\frac{-tg}{IK}}\right)$

$$20339.5 = 41500\left(1 - {}_e\dfrac{-10 \times 981}{1 \times 4.91 \times 10^{-5}}\right)$$

$\therefore$ I = **2.9663 × 10^6 kg - m²**

Example 45.17. *A 6 pole, 50 Hz Induction Motor has a flywheel of 1200 kg-m² as moment of inertia. Load torque is 100 kg - m. for 10 sec. No load period is long enough for the flywheel, to regain its full speed. Motor has a slip of 6% at a torque of 50 kg-m. Calculate*

(i) Maximum torque exerted by motor.

(ii) Speed at the end of deaceleration period. **[Nagpur University Winter 1996]**

Solution. *(i)* $T_m = T_L - (T_L - T_0)\,e^{\frac{-tg}{IK}}$

Assume $T_0 = 0, \quad \rightarrow \quad T_m = T_L\,(1 - e^{\frac{-tg}{IK}})$

$T_L = 100$ kg – m, $\quad t = 10$ sec, $\quad g = 9.81$ m/sec², $\quad I = 1200$ kg – m² $\quad s = \omega_0 - \omega$

$$s = KT \quad \therefore \quad \text{slip speed} = s = \frac{2\pi}{60}(N_0 - N)$$

$$N_S = \frac{120\,f}{p} = \frac{120 \times 50}{6} = 1000 \text{ rpm} = N_0$$

N = 0.94 × 1000 = 940 rpm.

$$\therefore \quad S = \frac{2\pi}{60}(1000 - 940) = 2\pi \text{ rad/sec} \quad \text{or} \quad s = \frac{2\pi N}{60} = \frac{2\pi \times 1000 \times 0.06}{60}$$

$$s = 2\pi = 6.283 \text{ rad/sec}$$

$$\therefore \ K = \frac{S}{T} = \frac{2\pi}{50} = 0.04\pi = 0.125$$

$$\therefore \quad T_m = T_L\left(1 - e^{\frac{-tg}{IK}}\right) = \left(1 - e^{\frac{-10 \times 9.81}{1200 \times 0.04\pi}}\right)$$

T_m = **47.83 kg - m**

(*ii*) Slip speed = 0.04 π × 47.8 rad / sec

s = KT_m

s = 0.125 (47.83)

s = 5.98 rad/sec

$$s = 5.98\frac{60}{2\pi} \text{ rpm} = 57.5 \text{ rpm} = \text{slip speed}$$

∴ Actual speed = 1000 – 57.5 = **942.5 rpm**

Example 45.18. *An Induction Motor equipped with a flywheel is driving a rolling mill which requires a Load Torque of 1900 N - m for 10 sec. followed by 250 N - m for 30 sec. This cycle being repeated indefinitely. The synchronous speed of motor is 750 r.p.m and it has a slip of 10% when delivering 1400 N-m Torque. The total Moment of Inertia of the flywheel and other rotating parts is 2100 kg-m². Draw the curves showing the torque exerted by the motor and the speed for five complete cycles, assuming that initial torque is zero.* **[Nagpur University Summer 1998]**

Solution.

T_L = 1900 N- m for 10 sec.

T_L = 250 N- m for 30 sec.

T_0 = 0 (assumed)

Slip = 10% at 1400 N – m torque

Slip = 750 × 0.1 = 75 r.p.m.

Ns = 750 r.p.m.

s = 10%

I = 2100 Kg- m², T_m = 1400 N – m

$$= \frac{75 \times 2\pi}{60} = 7.85 \text{ rad/sec.}$$

$$s = K\,T_m\,; \ K = \frac{S}{T_m} = \frac{7.85}{1400} = 0.0056$$

(*i*) **During 1st cycle :**

(*a*) Flywheel de-acelerating :

$$T_m = T_L - (T_L - T_0)\,e^{\frac{-t}{IK}} \qquad \text{[When torque is taken in N - m.]}$$

→ After 10 sec

$$T_m = 1900 - (1900 - 0)\, e^{-0.085 \cdot 10} \qquad \because \frac{1}{IK} = 0.085$$

T_m = 1088 N- m
Slip = 0.0056 × 1088 = 6.08 rad/sec
Slip = 58 r.p.m.
Speed = 750 – 58 = **692 r.p.m.**

(*b*) Flywheel acacelerating (Off Load Period)


Flywheel

$$T_m = T_0 + (T_m{}' - T_0)\, e^{-\frac{t}{IK}}$$

T_0 = No load torque = 280 N- m

$T_m{}'$ = 1088 N-m (T_m at the beginning of the period *i.e.* the motor torque at the instant when load is removed)

After 30 sec.,

T_m = 280 + (1088 – 280) $e^{-0.085 \cdot 30}$

T_m = 343 N-m

∴ Slip at this T_m = 0.0056 × 343 = 1.92 rad/ sec = 18.34 r.p.m

∴ Speed = (750 – 18.34) r.p.m. = **731.6 r.p.m.**

(*ii*) **During 2nd cycle :**

(*a*) Flywheel deacelerating T_0 = 343 N-m.

T_m = 1900 – (1900 – 343) $e^{-0.085 \cdot 30}$
= 1235 N-m.

∴ Slip at this T_m = 0.0056 × 1235 = 6.92 rad/ sec
= 66 r.p.m.

→ speed = 750 – 66 = **684 r.p.m.**

(*b*) Off Load Period:

$$T_m = 280 + (1235 - 280)\, e^{-0.085 \cdot 30}$$

= 354.6 N-m.

∴ Slip at this T_m = 0.0056 × 354.6 = 1.99 rad/sec
= 19 r.p.m.

speed = 750 – 19 = 731.0 r.p.m.

(*iii*) **During 3rd Cycle :**

(*a*) On Load period : T_m can be found as above.

T_m = 1263 N – m
Speed = **683.6 r.p.m.**

(*b*) Off Load period

T_m = 354.6 N – m
speed = **731.0 r.p.m.**

Initial condition at the beginning of the 3rd peak load are thus practically the same as that at the beginning of 2nd. Therefore Motor Torque in this and all succeeding load cycles will follow a similar curve to that in second period.

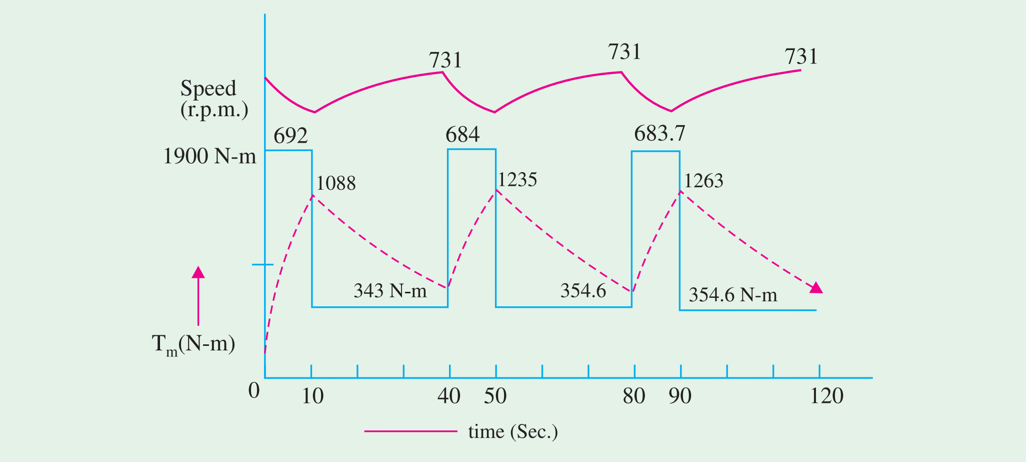


Fig. 45.12

Example 45.19. *A motor fitted with a flywheel supplies a load torque of 150 kg-m for 15 sec. During the no-load period, the flywheel regains its original speed. The motor torque is required to be limited to 85 kg-m. Determine moment of inertia of flywheel. The no - load speed of motor is 500 r.p.m. and it has a slip of 10% on full load.*

Solution.

$$T_m = T_L - (T_L - T_0)\, e^{\frac{-tg}{IK}}$$

$$T_m = T_L\left(1 - e^{\frac{-tg}{IK}}\right), \qquad \because\ T_0 = 0\ \text{kg}-\text{m}$$

$T_m = 85$ kg-m, $T_L = 150$ kg-m, $T_0 = 0$ kg-m, $t = 15$ sec., I = ?, g = 9.81 m/sec^2

$s = \text{K}\ \text{T}_{\text{F.L.}}$, where $s = \omega_0 - \omega$

$$\frac{2\pi\,(500)\times 0.1}{60} = \text{K}\times 85 \ \Rightarrow\ \text{K} = 0.0617$$

$$\therefore\ 85 = 150\left(1 - e^{\frac{-15\times 9.81}{I\times 0.627}}\right); \qquad \therefore\ \text{I} = \mathbf{2884\ kg\text{-}m^2}$$

Example 45.20. *A $3-\phi$, 50 KW, 6 pole, 960 r.p.m. induction motor has a constant load torque of 300 N-m and at wide intervals additional torque of 1500 N-m for 10 sec. Calculate*

(a) *The moment of inertia of the flywheel used for load equalization, if the motor torque is not to exceed twice the rated torque.*

(b) *Time taken after removal of additional load, before the motor torque becomes 700 N-m.*

Solution.

(a) $$P = T\times\omega \qquad \therefore\ T = P/\omega$$

$$\therefore\ T_{F.L.} = \frac{50\times 10^3}{\dfrac{2\pi\times 960}{60}} = 497.36\ \text{N-m.}$$

$$\therefore\ T_m = 2\times T_{FL} = 2\times 497.36 = 994.72\ \text{N}-\text{m}$$

$$T_L = 1500 + 300 = 1800 \text{ N-m}$$

$$N_S = \frac{120\,f}{P} = 1000 \text{ r.p.m.}$$

$\therefore$ F.L. slip $= 1000 - 960 = 40$ rpm $= 40$ r.p.m. $= 4\%$

$\therefore$ $s = K\ T_{F.L.}$

$$\frac{2\pi(40)}{60} = K \times 497.36 \qquad \therefore \quad K = 8.42 \times 10^{-3}$$

$$T_m = T_L - (T_L - T_0)\,e^{\frac{-t}{IK}} \quad \text{as torque is in N - m}$$

$$994.72 = 1800 - (1800 - 300) \times e^{\frac{-10}{I \times 8.42 \times 10^{-3}}}$$

$\therefore$ $I =$ **1909 kg– m²**

(*b*) $$T_m = T_0 + (T_m{}' - T_0)\,e^{\frac{-t}{IK}}$$

$$700 = 300 + (994.72 - 300)\,e^{\frac{-t}{1909 \times 8.42 \times 10^{-3}}}$$

$\therefore$ $t =$ **8.87 sec.**

Example 45.21. *A 3-phase, 8 pole, 50 c.p.s. Induction Motor equipped with a flywheel supplies a constant load torque of 100 N-m and at wide intervals an additional load torque of 300 N-m for 6 sec. The motor runs at 735 r.p.m., at 100 N-m torque. Find moment of inertia of the flywheel, if the motor torque is not to exceed 250 N-m.*

Solution.

$$T_0 = 100\,N - m. \qquad \therefore \quad T_L = 100 + 300 = 400 \text{ N - m}$$

$$N_S = \frac{120\,f}{P} = \frac{120\,f}{P} = 750 \text{ rpm.}$$

Slip at 100 N-m torque $= 750 - 735 = 15$ r.p.m.

$s = K\ T_m$

$$\frac{2\pi}{60}(15) = K(100) \qquad \therefore \quad K = 0.0157 \quad ; \qquad T_m = T_L - (T_L - T_0)\,e^{\frac{-t}{IK}}$$

$$250 = 400 - (400 - 100)\,e^{\frac{-6}{I(0.0157)}}$$

$\therefore$ $I =$ **552 kg - m²**

Example 45.22. *A 6 pole, 50 Hz, 3 - ϕ wound rotor Induction Motor has a flywheel coupled to its shaft. The total moment of inertia is 1000 kg-m². Load torque is 1000 N-m for 10 sec. followed by a no load period which is long enough for the motor to reach its no – load speed. Motor has a slip of 5% at a torque of 500 N-m. Find*

(a) Maximum torque developed by motor

(b) Speed at the end of deaceleration period. **[Nagpur University Winter 1996]**

Solution.

(*a*) $$T_m = T_L\left(1 - e^{\frac{-t}{IK}}\right)$$

$$s = KT_m \qquad \text{But } N_S = \frac{120\,f}{P} = 1000\,\text{r.p.m.}$$

$$\frac{2\pi}{60}(1000 \times 0.05) = K\,(500)\;;\quad K = 6.2 \times 10^{-3}$$

$$T_m = 1000\left(1 - e^{\frac{-10}{1000 \cdot 6.2 \cdot 10^{-3}}}\right);\quad T_m = \mathbf{796.39\ N-m}$$

(*b*) $$s = K\,T_{F.L.}$$

$$\frac{2\pi}{60}(100 - N) = 6.2 \cdot 10^{-3} \cdot 790.39$$

$\therefore$ N = **952.2 r.p.m.**

Example 45.23. *A motor fitted with a flywheel supplies a load torque of 1000 N-m. for 2 sec. During no load period, the flywheel regains its original speed. The motor torque is to be limited to 500 N-m. Find moment of inertia of the flywheel. No load speed of the motor is 500 r.p.m. and its full load slip is 10%.*

Solution.

$$s = K\,T_{F.L.}$$

$$\frac{2\pi}{60}(500 \cdot 0.1) = K\,500,\qquad K = 0.0104\;;\qquad T_m = T_L\left(1 - e^{\frac{-t}{IK}}\right)$$

$$500 = 1000\left\{1 - e^{\frac{-2}{I(0.0104}}\right\};\quad I = \mathbf{277.44\ kg\text{-}m^2}$$

Tutorial Problem No. 45.1

1. A motor driving a colliery winding equipment has to deliver a load rising uniformly from zero to a maximum of 1500 KW in 20 sec. during the accelerating period, 750 KW for 40 sec. during the full speed period and during the deceleration period of 10 sec., when regenerative braking is taking place from an initial value of 250 KW to zero and then a no load period of 20 sec. Estimate remittable KW rating of the motor. **[648 KW]**

2. A constant speed drive has the following duty cycle:

Load rising from 0 to 400 KW	–	5 minutes
Uniform load of 400 KW	–	5 minutes
Regenerative power of 400 KW returned to supply	–	4 minutes
Remains idle for	–	2 minutes

Estimate power rating of motor. **[380 H. P.]**

[*Nagpur University Winter 96*]

3. Determine the rated current of a transformer for the following duty cycle:
- 500 A for 3 minutes
- Sharp increase to 1000 A and constant at this value for 1 minute
- Gradually decreasing to 200 A. for 2 minutes
- Constant at this value for 2 minutes
- Gradually increasing to 500 A during 2 minutes repeated indefinitely. **[540 A]**

4. An induction motor has to perform the following duty cycle:

75 KW for 10 miniutes, No load for 5 minutes
45 KW for 8 minutes, No load for 4 minutes

which is repeated indefinitely.
Determine suitable capacity of a continuously rated motor. **[70 H. P.]**

5. A 25 H.P. motor has heating time constant of 90 min. and when run continuously on full load attains a temperature of 45^{0}C. above the surrounding air. What would be the half hour rating of the motor for this temperature rise, assuming that it cools down completely between each load period and that the losses are proportional to square of the load. **[47 H.P.]**
6. At full load of 10 H.P., temperature rise of a motor is 25^0 C. after 1 hr. and 40^{o}C after 2 hrs. Find (*a*) Heating time constant of motor, (*b*) Final temperature rise on full load. **[T = 1. 96 hrs, θ_f = 62.5ºC]**
7. A totally enclosed motor has a temperature rise of 20^{o}C after half an hour and 35^{0}C after one hour on full load. Determine temperature rise after 2 hours on full load. **[54.68ºC]**
8. A 25 H.P., 3-ϕ, 10 pole, 50 c.p.s. induction motor provided with a flywheel has to supply a load torque of 800 N-m for 10 sec, followed by a no load period, during which the flywheel regains its full speed. Full load slip of motor is 4% and torque-speed curve may be assumed linear over the working range. Find moment of inertia of flywheel, if the motor torque is not to exceed twice the full load torque. Assume efficiency = 90%. **[718 kg-m^2]**
9. A motor fitted with a flywheel has to supply a load torque of 200 kg-m for 10 sec, followed by a no load period. During the no load period, the motor regains its speed. It is desired to limit the motor torque to 100 kg-m. What should be the moment of inertia of flywheel. No load speed of motor is 500 r.p.m. and has a slip of 10% at a torque of 100 kg-m. . **[I = 2703 kg-m^2]**
10. A 50 Hz., 3-ϕ, 10 pole, 25H.P., induction motor has a constant load torque of 20 kg-m and at wide intervals additional torque of 100 kg-m for 10 sec. Full load slip of the motor is 4% and its efficiency is 88%. Find -
(*a*) Moment of inertial of flywheel , if motor torque not to exceed twice full load torque.
(*b*) Time taken after removal of additional load, before motor torque is 45 kg- m.
[I = 1926 kg-m^2, t = 9.99 sec.]
11. Define the following terms regarding the ratings of motor :-
(*i*) Continuous rating (*ii*) short time rating (*iii*) Intermittent rating.
(Nagpur University, Summer 2004)
12. With the help of heating and cooling curves define and explain the terms :
(*i*) Heating time constant (*ii*) Cooling time constant. ***(Nagpur University, Summer 2004)***
13. What do you mean by 'load-equilisation' it is possible to apply this scheme for reversible drive? Why? ***(Nagpur University, Summer 2004)***
14. A motor is equipped with the flywheel has to supply a load torque of 600 N-m for 10 seconds, followed by no load period long enought for flywheel to regain its full speed. It is desired to limit the motor torque of 450 N-m. What should be moment of inertia of the flywheel? the no load speed of the motor is 600 rpm and has 8% slip at a torque of 450 N-m. The speed-torque characteristics of the motor can be assumed to be a straight line in the region of interest.
(Nagpur University, Summer 2004)
15. A motor has the following load cycle :
Accelerating period 0-15 sec Load rising uniformly from 0 to 1000 h.p.
Full speed period 15-85 sec Load constant at 600 h.p.
Decelerating period 85-100 sec h.p. returned to line falls uniformly 200 to zero
Decking period 100-120 sec Motor stationary. Estimate the size the motor.
(J.N. University, Hyderabad, November 2003)
16. A motor driving a load has to deliver a load rising uniformly from zero to maximum of 2000 h.p. in 20 sec during the acceleration period, 1000 h.p. for 40 sec during the full speed period and during the deceleration period of 10 sec when regenerating braking taking place the h.p. returned to the supply falls from 330 to zero. The interval for decking before the next load cycle starts is 20 sec. Estimate the h.p. Rating of the motor. ***(J.N. University, Hyderabad, November 2003)***
17. Draw and explain the output vs. time characteristics of any three types of loads.
(J.N. University, Hyderabad, November 2003)

18. Discuss series and parallel operation of series and shunt motors with unequal wheeldiameters. Comment on the load sharing in each case. *(J.N. University, Hyderabad, November 2003)*

19. Discuss the various factors that govern the size and the rating of a motor for a particular service. *(J.N. University, Hyderabad, April 2003)*

20. A motor has to deliver a load rising uniformly from zero to a maximum of 1500 Kw in 20 sec during the acceleration period, 1,000 Kw for 50 sec during the full load period and during the deceleration period of 10 sec when regenerative braking takes place the Kw returned to the supply falls from an initial value of 500 to zero uniformly. The interval for decking before the next load cycle starts is 20 sec. Estimate the rating of the motor. *(J.N. University, Hyderabad, April 2003)*

21. Derive an expression for the temperature rise of an equipment in terms of the heating time constant. *(J.N. University, Hyderabad, April 2003)*

22. At full load of 10 h.p., the temperature rise of a motor is 25 degree C after one hour, and 40 degree C after 2 hours. Find the final temperature rise on full load. Assume that the iron losses are 80% of full load copper losses. *(J.N. University, Hyderabad, April 2003)*

23. Explain what you mean by Lord Equalization and how it is accomplished. *(J.N. University, Hyderabad, April 2003)*

24. A motor fitted with a flywheel supplies a load torque of 150 kg-m for 15 sec. During the no load period the flywheel regains its originalspeed. The motor torque is required to be limited to 85 kg-m. Determine the moments of inertia of the flywheel. The no load speed of the motor is 500 r.p.m. and it has a slip of 10% on full load. *(J.N. University, Hyderabad, April 2003)*

25. Discuss the various losses that occur in magnetic conductors which cause the temperature rise in any electrical apparatus and suggest how they can be reduced. *(J.N. University, Hyderabad, April 2003)*

26. The outside of a 12 h.p. (metric) motor is equivalent to a cylinder of 65 cms diameter and 1 meter length. The motor weighs 400 Kg and has a specific heat of 700 Joules per kg per degree C. The outer surface is capable of heat dissipation of 12 W per meter square per degree C. Find the final temperature rise and thermal constant of the motor when operating at full load with an effciency of 90%. *(J.N. University, Hyderabad, April 2003)*

27. "A flywheel is not used with a synchronous motor for load equalization". Discuss. *(J.N. University, Hyderabad, April 2003)*

28. A 25 h.p. 3-phase 10 pole, 50 Hz induction motor fitted with flywheel has to supply a load torque of 750 Nw-m for 12 sec followed by a no load period during which the flywheel regains its original speed. Full load slip of the motor is 4% and the torque-speed curve is linear. Find the moment of inertia of the flywheel if the motor torque is not to exceed 2 times the full load torque. *(J.N. University, Hyderabad, April 2003)*

29. Explain what do you mean by Load Equalization and how it is accomplished. *(J.N. University, Hyderabad, April 2003)*

30. A motor fitted with a flywheel supplies a load torque of 150 kg-m for 15 sec. During the no load period the flywheel regains its original speed. The motor torque is required to be limited to 85 kg-m. Determine the moments of inertia of the flywheel. The no load speed of the motor is 500 r.p.m. and it has aslip of 10% on full load. *(J.N. University, Hyderabad, April 2003)*

31. A 100 hp motor has atemperature rise of 50^oC when running continuously on full load. It has a time constant of 90 minutes. Determine 1/2 hr rating of the motor for same temperature rise. Assume that the losses are proportional to the square of the load and motor cools completely between each load period. *(J.N. University, Hyderabad, December 2002/January 2003)*

32. Explain 'load equalisation'. How this can be achieved in industrial drives. *(J.N. University, Hyderabad, December 2002/January 2003)*

33. Obtain the expression for temperature rise of a electrical machine. State the assumptions made if any. ***(J.N. University, Hyderabad, December 2002/January 2003)***

34. A 75 kW, 500 rpm dc shunt motor is used to drive machinery for which the stored energy per kW is 5400 Joules. Estimate the time taken to start the motor, if the load torque is equal to full load torque during the starting period and the current is limited to 1 1/2 times the full load current. ***(J.N. University, Hyderabad, December 2002/January 2003)***

OBJECTIVE TESTS – 45

1. Heat dissipation is assumed proportional to
(*a*) Temperature difference
(*b*) Temperature difference between motor and cooling medium
(*c*) Temperature of cooling medium

2. Temperature of cooling medium is assumed
(*a*) constant (*b*) variable

3. When the motor reaches final temperature rise its temperature remains
(*a*) constant
(*b*) falls
(*c*) rises.

4. For intermittent load, a motor of smaller rating can be used
(*a*) true (*b*) false

5. If motor is disconnected from supply, final temperature reached will be the ambient temperature
(*a*) true (*b*) false

6. Final temperature rise is theoretically attained only after
(*a*) fixed time
(*b*) variable time
(*c*) infinite time

7. Motor is derated when taken at altitude
(*a*) Yes (*b*) No

8. The rolling mill load
(*a*) is constant
(*b*) fluctuates widely within long intervals of time
(*c*) fluctuates widely within short intervals of time
(*d*) varies

9. Size of motor is decided by
(*a*) load
(*b*) current
(*c*) heat produced in motor
(*d*) torque

10. Tariff is affected by sudden load drawn by motor
(*a*) true (*b*) false

11. Flywheel helps in smoothing only
(*a*) speed fluctuations
(*b*) current fluctuations
(*c*) both of the above

12. To use flywheel, motor should have
(*a*) constant speed characteristics
(*b*) drooping speed characteristics
(*c*) variable speed characteristics

13. During light load period
(*a*) flywheel absorbs energy
(*b*) flywheel gives up energy
(*c*) flywheel does nothing

14. During peak load periods
(*a*) flywheel absorbs energy
(*b*) flywheel gives up energy
(*c*) flywheel does nothing

15. Large size of flywheel
(*a*) can be used practically
(*b*) can't be used practically

ANSWERS

1. (*b*)	**2.** (*a*)	**3.** (*a*)	**4.** (*a*)	**5.** (*a*)	**6.** (*c*)	**7.** (*a*)	**8.** (*c*)	**9.** (*c*)	**10.** (*a*)
11. (*c*)	**12.** (*b*)	**13.** (*a*)	**14.** (*b*)	**15.** (*b*)					

GO To FIRST

CONTENTS

CHAPTER 46

Learning Objectives

- Classes of Electronic AC Drives
- Variable Frequency Speed Control of a SCIM
- Variable Voltage Speed Control of a SCIM
- Chopper Speed Control of a WRIM
- Electronic Speed Control of Synchronous Motors
- Speed Control by Current-fed D.C. Link
- Synchronous Motor and Cycloconverter

ELECTRONIC CONTROL OF A.C. MOTORS

Efficient control of motors becomes critical where high precision, accuracy, flexibility, reliability and faster response are of paramount importance. Electronic and digital controls are employed in such conditions

CONTENTS

46.1. Classes of Electronic A.C. Drives

AC motors, particularly, the squirrel-cage and wound-rotor induction motors as well as synchronous motors lend themselves well to electronic control of their speed and torque. Such a control is usually exercised by varying voltage and frequency. Majority of the electronic a.c. drives can be grouped under the following broad classes :

1. **static frequency changers** like cyclo-converters which convert incoming high line frequency directly into the desired low load frequency. Cyclo-converters are used both for synchronous and squirrel-cage induction motors.
2. **variable-voltage controllers** which control the speed and torque by varying the a.c. voltage with the help of SCRs and gate turn-off thyristors (GTOs).
3. **rectifier-inverter systems** with natural commutation.
4. **rectifier-inverter systems** with self-commutation.

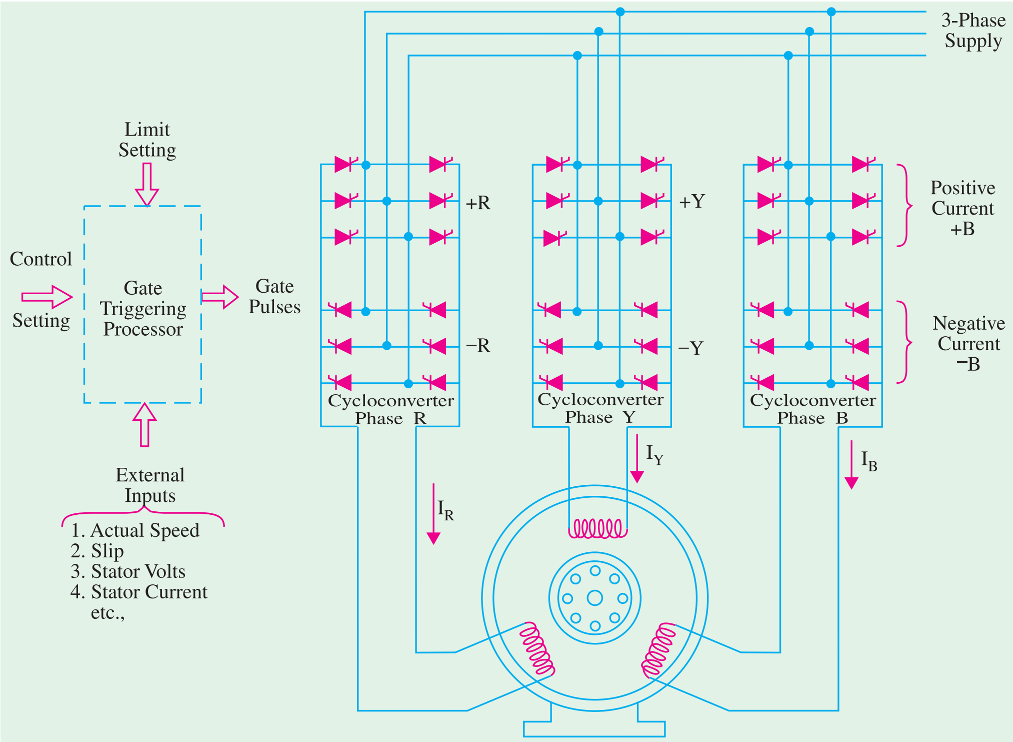


Fig. 46.1

46.2. Variable-frequency Speed Control of a SCIM

Fig. 46.1 shows a 3-phase SCIM connected to the outputs of three 3-phase cycloconverters. As seen, each cyclo-converter consists of two 3-phase thyristor bridges, each fed by the same 3-phase, 50-Hz line. The $+R$ bridge generates the positive half-cycle for R-phase whereas $-R$ generates the negative half. The frequency of the cycloconverter output can be reduced to any value (even upto zero) by controlling the application of firing pulses to the thyristor gates. This low frequency permits excellent speed control. For example, the speed of a 4-pole induction motor can be varied from zero to 1200 rpm on a 50-Hz line by varying the output frequency of the cycloconverter from zero to 40 Hz. The stator voltage is adjusted in proportion to the frequency in order to maintain a constant flux in the motor.

This arrangement provides excellent torque/speed characteristics in all 4-quadrants including regenerative braking. However, such cycloconverter-fed motors run about 10°C hotter than normal and hence require adequate cooling. A small part of the reactive power required by SCIM is provided by the cycloconverter, the rest being supplied by the 3-phase line. Consequently, power factor is poor which makes cycloconverter drives feasible only on small and medium power induction motors.

46.3. Variable Voltage Speed Control of a SCIM

In this method, the speed of a SCIM is varied by varying the stator voltage with the help of three sets of SCRs connected back-to back (Fig. 46.2). The stator voltage is reduced by delaying the firing (or triggering) of the thyristors. If we delay the firing pulses by 100°, the voltage obtained is about 50% of the rated voltage which decreases the motor speed considerably.

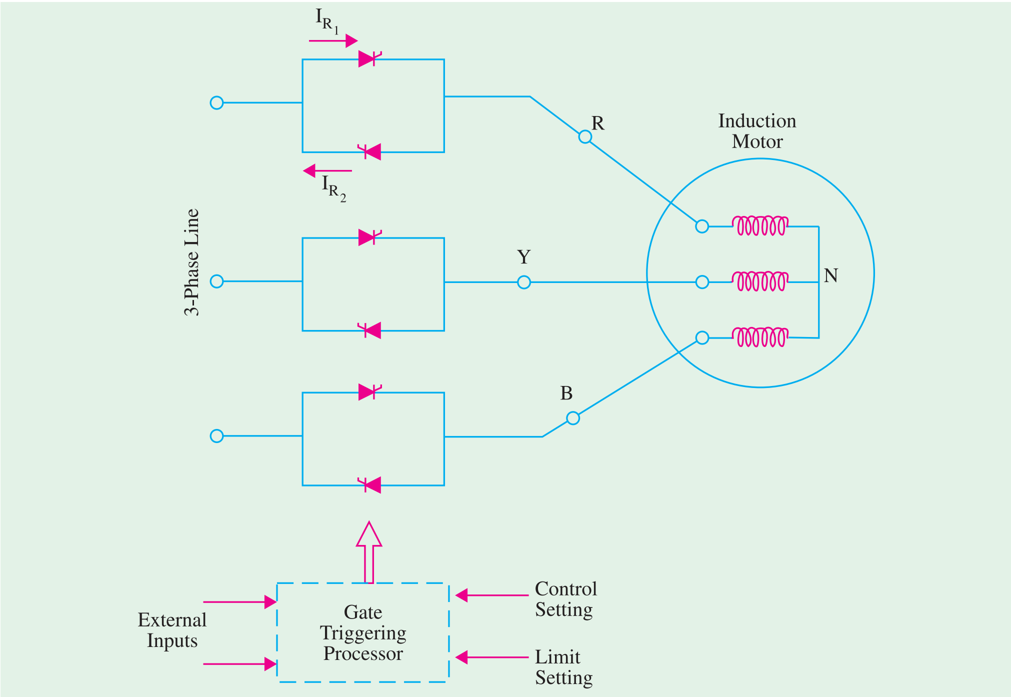


Fig. 46.2

Unfortunately, I^2R losses are considerable due to distortion in voltage. Moreover, p.f. is also low due to large lag between the current and voltage. Hence, this electronic speed control method is feasible for motors rated below 15 kW but is quite suitable for small hoists which get enough time to cool off because of intermittent working. Of course, p.f. can be improved by using special thyristors called gate turn-off thyristors (GTOs) which force the current to flow almost in phase with the voltage (or even lead it).

A commonly used electronic power inverter

46.4. Speed Control of a SCIM with Rectifier-Inverter System

A rectifier-inverter system with a d.c. link is used to control the speed of a SCIM. The inverter used is a self-commuted type (different from a naturally commutated type) which converts d.c. power into a.c. power at a frequency determined by the frequency of the pulses applied to the thyristor gates. The rectifier is connected to the 3-phase supply line whereas the inverter is connected to the stator of the SCIM.

Two types of links are used :

1. constant-current d.c. link —for speed control of *individual* motors.
2. constant-voltage d.c. link —for speed control of several motors.

As shown in Fig. 46.3, the constant-current link supplies constant current to the inverter which then feeds it sequentially (through proper switching sequence) to the three phases of the motor. Similarly, the constant-voltage dc link (Fig. 46.4) provides a constant voltage to the inverter which is switched from one phase of the motor to the next in a proper sequence.

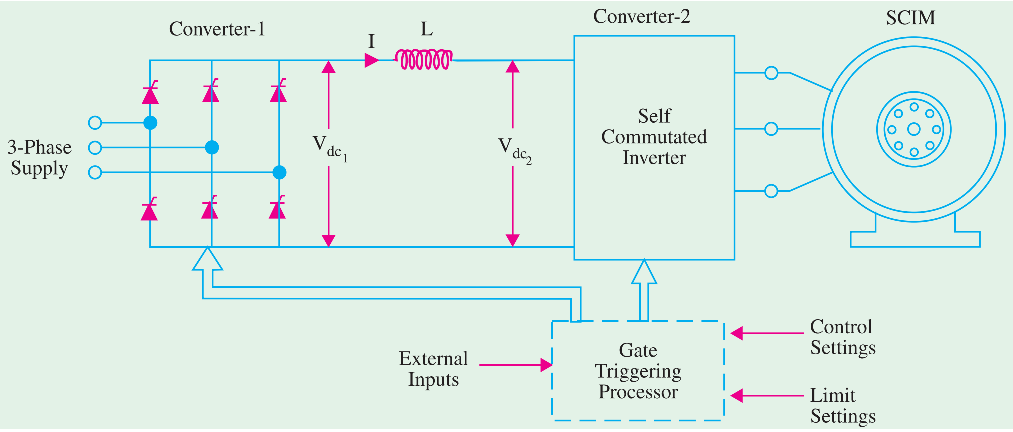


Fig. 46.3

The arrangement of Fig. 46.3 gives speed control with high efficiency in all 4 quadrants in addition to the facility of regenerative braking. Heavy inertia loads can be quickly accelerated because motor develops full break-down torque right from the start. The output frequency of the inverter varies over a range of 20 : 1 with a top frequency of about 1 kHz. The a.c. voltage supplied by the inverter is changed in proportion to the frequency so as to maintain the stator flux constant.

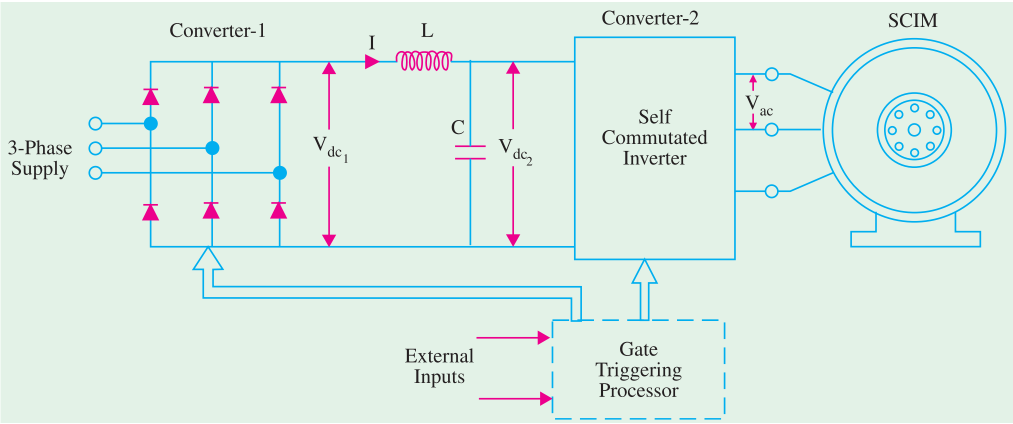


Fig. 46.4

Consequently, d.c. link voltage V_{dc1} has to be reduced as the motor speeds up. This is accomplished by increasing the firing angle of the thyristors in converter 1. Unfortunately, this leads to increase in the reactive power drawn from the 3-phase line which results in poor power factor. To improve the p.f., use of capacitors is necessary. The direction of rotation can be changed by altering the phase sequence of the pulses that trigger the gates of converter 2.

The voltage-fed frequency converter of Fig. 46.4 consists of a rectifier and a self-commutated inverter connected by a d.c. link and is often used for group drives in textile mills. The 3-phase bridge rectifier produces d.c. voltage V_{dc1} which is smoothened up by the LC filter before being applied to the inverter. The inverter successively switches its output ac voltage V_{ac} to the three phases of the motor. This voltage is varied in proportion to the frequency so as to maintain constant flux in the motor. Since, V_{ac} depends on V_{dc2} which itself depends on V_{dc1}, it is V_{dc1} which is changed as frequency varies. In this system, motor speed can be controlled from zero to maximum while developing full breakdown torque.

A simple electronic control system

46.5. Chopper Speed Control of a WRIM

As discussed in Art. 30.18 (*d*), the speed of a WRIM can be controlled by inserting three variable resistors in the rotor circuit. The all-electronic control of speed can be achieved by connecting a 3-phase bridge rectifier across the rotor terminals and then feed the rotor output to a single fixed resistor or R_0 via a chopper (Fig. 46.5).

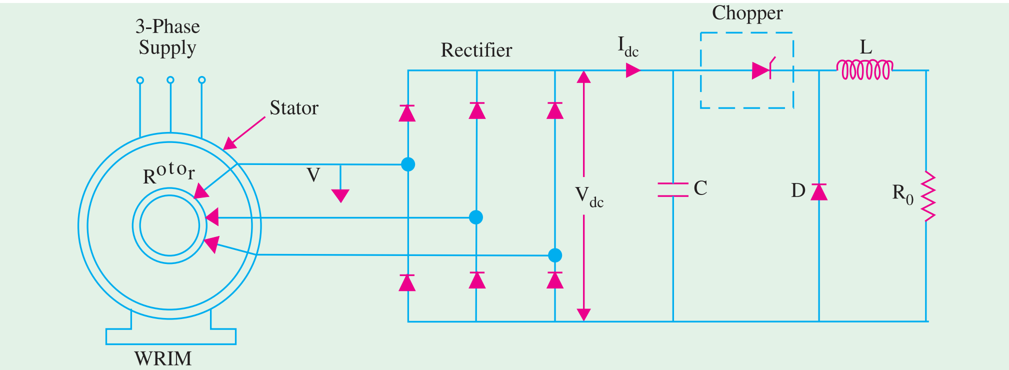


Fig. 46.5

The capacitor C supplies the high current pulses drawn by the chopper. The inductor L and free-wheeling diode D serve the same purpose as discused in Art. 28.14. By varying the chopper on-time TON, the apparent resistance R_a across the bridge rectifier can be made either high or low. The value of apparent resistance is given by $R_a = R_0/f^2\ T_{ON}^2$ where f is the OFF/ON switching frequency of the chopper. The resulting torque/speed characteristic is similar to the one obtained with a 3-phase rheostat.

Example 46.1. *The wound-rotor induction motor of Fig.43.5 is rated at 30-kW, 975 rpm, 440-V, 50 Hz. The open-circuit line voltage is 400 V and the load resistance is 0.5 Ω. If chopper frequency is 200 Hz, calculate* T_{ON} *so that the motor develops a gross torque of 200 N-m at 750 rpm. Also, calculate the magnitude of the current pulses drawn from the capacitor.*

Solution. Obviously, N_S = 1000 rpm. Hence, slip at 750 rpm is = (1000 – 750)/1000 = 0.25. The rotor line voltage at 750 rpm is = sE_2 = 0.25 · 400 = 100 V.

The d.c. voltage of 3-phase bridge rectifier is V_{dc} = 1.35 V = 1.35 · 100 = 135 V.

Now, $T_g = P^2/2\pi N_s; P^2 = T_g \cdot 2\pi N_s$ = 200 · 2π · (1000/60) = 20,950 W

Part of P^2 dissipated as heat = sP^2 = 0.25 · 20,950 = 5,238 W

The power is actually dissipated in R_0 and is, obviously, equal to the rectifier output $V_{dc}.I_{dc}$.

$$\therefore \quad V_{dc} \cdot I_{dc} = 5238 \quad \text{or} \quad I_{dc} = 5238/135 = 38.8 \text{ A}$$

The apparent resistance at the input to the chopper is

$$R_a = V_{dc}/I_{dc} = 135/38.8 = 3.5\ \Omega$$

Now, $R_a = R_0/f^2$ ड़$^2_{टछ}$ or $T_{ON} = \sqrt{R_0/f^2 R_a} = \sqrt{0.5/200^2 \cdot 3.5} =$ **1.9 ms**

Current in R_0 can be found from the relation

$$I_0^2 R_0 = 5238 \quad \text{or} \quad I_0 = \sqrt{5238/0.5} = \mathbf{102\ A}$$

As seen, capacitor delivers current pulses of magnitude ड़$^2_0$ A and a pulse width of 1.9 ms at the rate of 200 pulses/second. However, the rectifier continuously charges C with a current of 38.8 A.

46.6. Electronic Speed Control of Synchronous Motors

The speed of such motors may be controlled efficiently by using *(i)* current-fet delink and *(ii)* cycloconverter as discussed below :

46.7. Speed Control by Current-fed DC Link

As shown in Fig. 46.6, the typical circuit consists of three converters two of which are connected between the three-phase source and the synchronous motor whereas the third converter (bridge rectifier) supplies dc field excitation for the rotor. Converter-1 (*C*-1) acts as a controlled rectifier and feeds d.c. power to converter-2 (*C*-2). The converter-2 behaves as a naturally commutated inverter whose a.c. voltage and frequency are established by the motor. The function of the smoothing inductor *L* is to maintain a ripple-free current in the d.c. link between the two converters. Converter-1 acts as a current source and controls *I*.

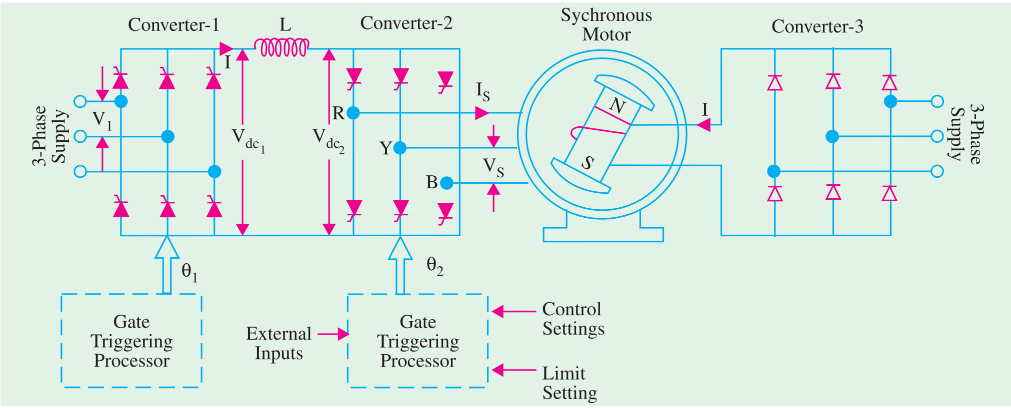


Fig. 46.6

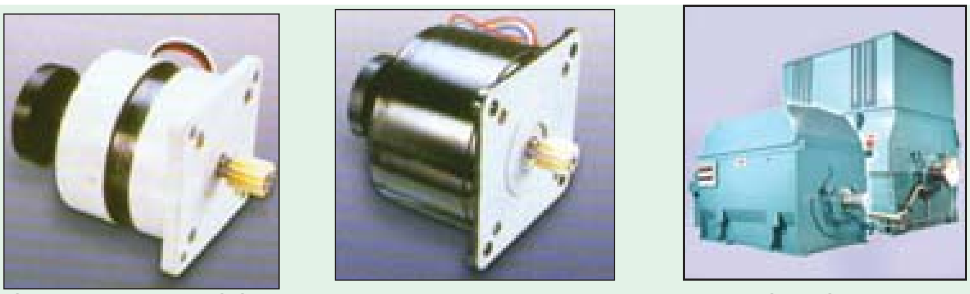
The converter-2 is naturally commutated by voltage V_s induced across motor terminals by its revolving magnetic flux. The revolving flux which depends on the stator currents and the d.c. field exciting current I_{f1} is usually kept constant. Consequently, V_s is proportional to motor speed.

As regards various controls, information picked off from various points is processed in the gate-triggering processors which then send out appropriate gate firing pulses to converters 1 and 2. The processors receive information about the desired rotor speed, its actual speed, instantaneous rotor position, field current, stator voltage and current etc. The processors check whether these inputs represent normal or abnormal conditions and send appropriate gate firing pulses either to correct the situation or meet a specific demand.

Gate triggering of C-1 is done at line frequency (50 Hz) whereas that of C-2 is done at motor frequency. In fact, gate pulses of C-2 are controlled by rotor position which is sensed by position transducers mounted at the end of the shaft. The motor speed can be increased by increasing either d.c. link current *I* or exciting current I_f.

Now, $V_{dc2} = 1.35\, V_s \cos\alpha_1$ and $V_{dc1} = 1.35\, V_s \cos\alpha_1$

where V_{dc2} = d.c. voltage generated by *C*-2, V_{dc1} = d.c. voltage supplied by *C*-1



Special features of A C Synchronous motors: 1. Bi-directional, 2. Instantaneous Start, Stop and Reverse, 3. Identical Starting and Running Currents, 4. Residual Torque always present, 5. No damage due to stalling, 6. Low speed of 60 rpm. Applications of AC Synchronous Motors are found in: 1. Actuators, 2. Remote control of switches 3. Winding machines, 4. Machine tool applications, 6. Valve controls, 6. Printing machines, 7. Automatic welding machines, 8. Medical equipment, 9. Conveyor systems, 10. Paper feeders

$$\alpha_2 \;=\; \text{firing angle of } C\text{-2}\,; \quad \alpha_1 = \text{firing angle of } C\text{-1}$$

The firing angle α_1 is automatically controlled and supplies I which is sufficient to develop the required torque. This method of speed control is applied to motors ranging from 1 kW to several MW. Permanent-magnet synchronous motors used in textile industry and brushless synchronous motors for nuclear reactor pumps are controlled by this method.

46.8. Synchronous Motor and Cycloconverter

As shown in Fig. 46.7, the arrangement consists of three cycloconverters connected to the three

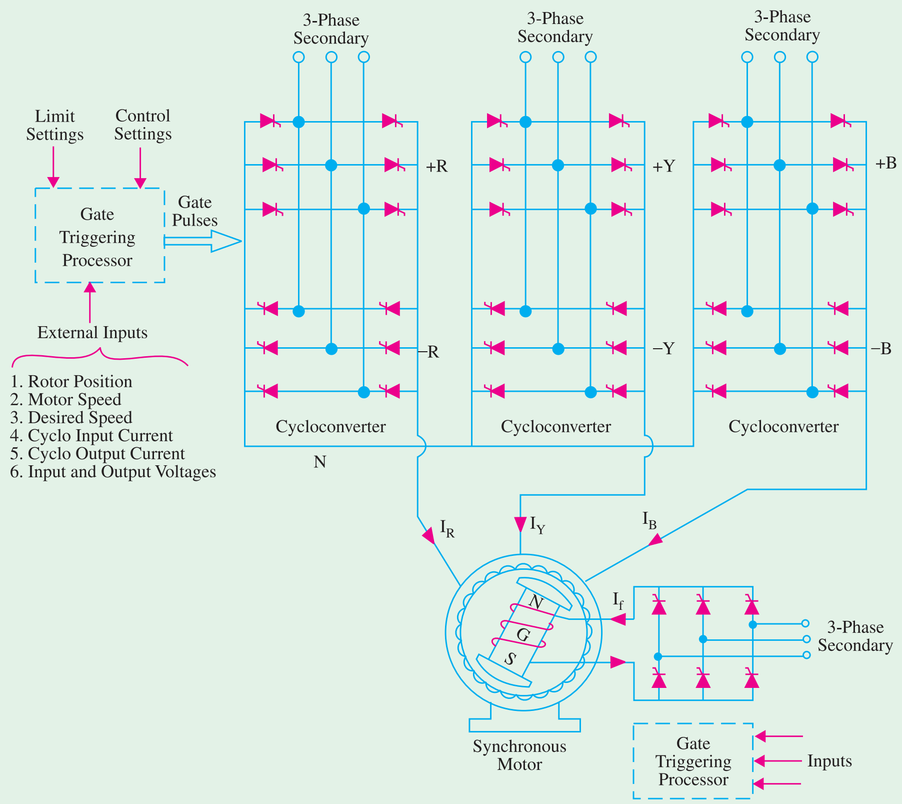


Fig. 46.7

one phases of the synchronous motor and one controlled rectifier for supplying field exciting current I_f to the rotor. Each cycloconverter is composed of two three-phase bridges and supplies a single-phase output. As is well known, a cycloconverter can directly convert a.c. power at higher frequency to one at a lower frequency. With a line frequency of 50 Hz, the cycloconverter output frequency can be varied from zero to 10 Hz.

The cycloconverters and the controlled rectifier function as current sources. The air-gap flux is kept constant by controlling the magnitude of the stator currents and exciting current I_f. By proper timing of gate pulses, motor can be made to operate at unity power factor.

The speed of cycloconverter-driven large slow-speed synchronous motors can be continuously varied from zero to 15 rpm. Such low speeds permit direct drive of the ball mill without using a gear reducer. Such high-power low-speed systems are also being introduced as propeller drives on board the ships.

46.9. Digital Control of Electric Motors

Advantages of Digital Control

1. High precision and accuracy
2. Better speed regulation
3. Faster response
4. Flexibility
5. Better time response
6. Improved performance
7. Economical
8. Easy software control
9. Reliability
10. The greatest advantage of the digital control is that by changing the program, desired control technique can be implemented without any change in the hardware.

The speed information can be fed into microcomputer using a D.C. Tacho (Speed encoder) and A/D converter (Speed *I/P* module). The motor current data is usually fed into the computer through a fast A/D converter. A synchronizing circuit interface (Line synchronizing circuit) is required so that the micro-computer can synchronize the generation of the firing pulse data with the supply line frequency. The gate pulse generator is shown as receiving a firing signal from microcomputer.

A set of instruction (Program) is stored in memory and those are executed by computer for proper functioning of a drive. A typical program flow - chart for this drive system is shown in figure (46.9). The sequence of instructions allows the computer to process data for speed regulation, current regulation and reversal operation.

46.10. Application of Digital Control

The above operations can be clearly understood by considering one of the applications of Digital Control system, such as Digital Control System for Speed Control of D.C. drives using a Micro-computer :

Various components and their operations shown in Fig. 46.8 are discussed below :

(i) Thyristor Converter

PC based control systems can be built where a phase-controlled rectifier supplies a D.C. motor. The main control to be handled is to turn on & off SCRs. Thyristor power converter in this case is a dual converter – one for forward and other for reverse direction.

(ii) Gate Pulse Generator and Amplifier

PC is used for firing angle control of dual converter. It can be programmed using suitable software to perform the function of firing range selection, firing pulse generation, etc. The firing pulses so obtained are amplified, if needed to turn *ON* the SCR reliably. Changeover signal decides whether to

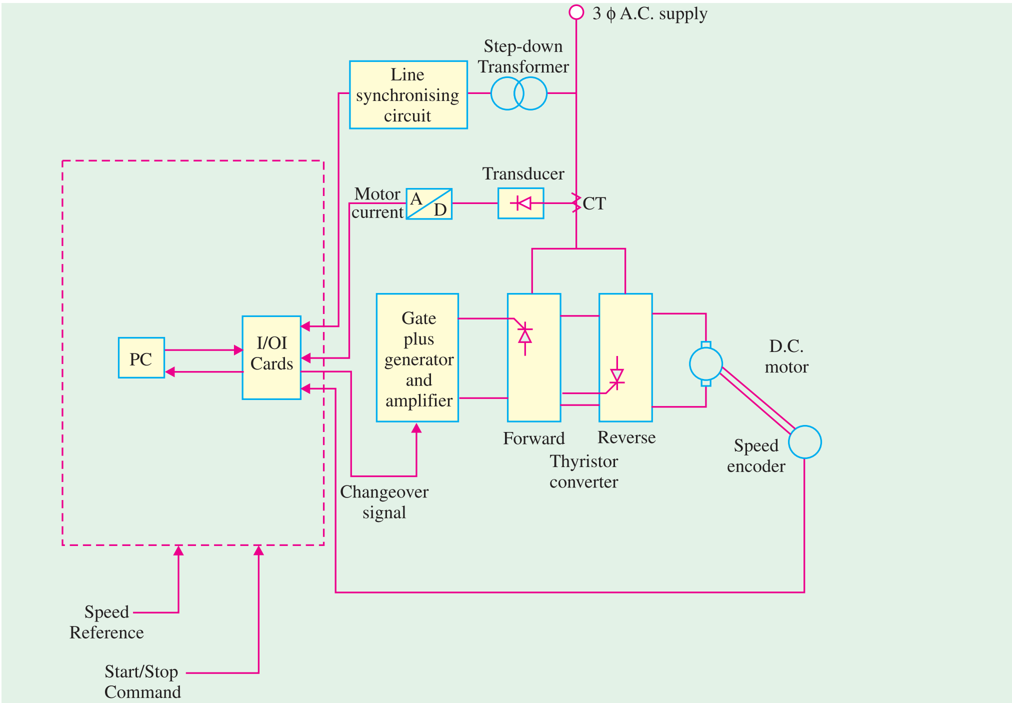


Fig. 46.8

switch *ON* forward or reverse group of SCRs. The gate pulse generator is shown as receiving a firing signal from *PC*.

(iii) Speed Encoder and Input Module

The speed information can be fed to PC through speed input module. The speed measurement is done digitally by means of speed/shaft encoder. It consists of a disc with definite number of holes drilled on it. This disc is fixed on to the shaft. Using a light source and a phototransistor; a series of pulses is obtained, as the shaft rotates. This pulse train is processed and shaped. These optically coded pulses are counted to get actual speed of motor.

(iv) A/D Converter and Transducer

The motor current drawn from supply is stepped down with the help of current transformer. It is converted to D.C. voltage output with the help of current transducer. As PC can't process analog signals, this analog current signal is fed to A/D converter to obtain digital signal which is fed to PC.

(v) Line Synchronizing Circuit

This is required so that PC can synchronize the generation of firing pulse data, with supply line frequency.

(vi) I/O Cards

Input/ Output cards are required to interface PC with the outside world.

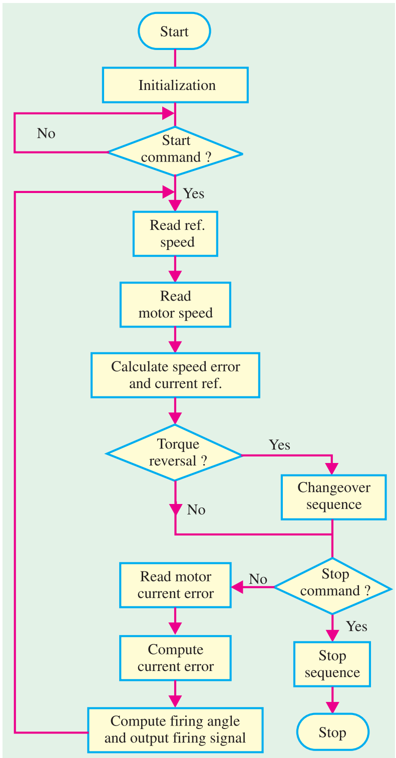


Fig. 46.9. Program flow chart for digital control of motor.

OBJECTIVE TESTS – 46

1. The function of a cycloconverter is to convert
   (*a*) ac power into d.c. power
   (*b*) direct current into alternating current
   (*c*) high ac frequency directly to low ac frequency
   (*d*) a sine wave into a rectangular wave.
2. Major disadvantage of using three sets of SCRs for variable-voltage speed control of a SCIM is the
   (*a*) considerable I^2R loss
   (*b*) poor power factor
   (*c*) long delay of thyristor firing pulses
   (*d*) necessity of using a processor.
3. In the current-fed frequency converter arrangement for controlling the speed of an individual SCIM, the direction of rotation can be reversed by
   (*a*) changing the output frequency of the inverter
   (*b*) altering the phase sequence of pulses that trigger converter-2
   (*c*) interchanging any two line leads
   (*d*) reversing the d.c. link current.
4. In the chopper speed control method for a WRIM, the motor speed inversely depends on
   (*a*) fixed resistor across the rectifier
   (*b*) chopper switching frequency
   (*c*) chopper ON time TON
   (*d*) both (*b*) and (*c*).
5. In the synchronous motor drive using current-fed dc link
   (*a*) converter-2 functions as a self-commutated inverter
   (*b*) converter-1 works as an uncontrolled rectifier
   (*c*) converter-3 is a controlled rectifier
   (*d*) gate triggering of converter-2 is done at motor frequency.
6. In the three cycloconverter drive of a synchronous motor
   (*a*) each cycloconverter produces a 3-phase output
   (*b*) all cycloconverters act as voltage sources
   (*c*) a 3-phase controlled rectifier provides field exciting current.
   (*d*) air-gap flux is kept constant by controlling stator currents only.

ANSWERS

1. (*c*) **2.** (*a*) **3.** (*b*) **4.** (*d*) **5.** (*d*) **6.** (*c*)

GO To FIRST

CONTENTS

CHAPTER 47

Learning Objectives

- Introduction
- Advantages of Electric Heating
- Different Methods of Heat Transfer
- Methods of Electric Heating
- Resistance Heating
- Requirement of a Good Heating Element
- Resistance Furnaces or Ovens
- Temperature Control of Resistance Furnaces
- Design of Heating Element
- Arc Furnaces
- Direct Arc Furnace
- Indirect Arc Furnace
- Induction Heating
- Core Type Induction Furnace
- Indirect Core Type Induction Furnace
- Coreless Induction Furnace
- High Frequency Eddy Current Heating
- Dielectric Heating
- Dielectric Loss
- Advantages of Dielectric Heating
- Applications of Dielectric Heating
- Choice of Frequency
- Infrared Heating

ELECTRIC HEATING

The above figure shows an electric arc furnace, producing steel. Electric heating is widely used in furnaces in metallurgical and chemical industries

CONTENTS

47.1. Introduction

Electric heating is extensively used both for domestic and industrial applications. Domestic applications include *(i)* room heaters *(ii)* immersion heaters for water heating *(iii)* hot plates for cooking *(iv)* electric kettles *(v)* electric irons *(vi)* pop-corn plants *(vii)* electric ovens for bakeries and *(viii)* electric toasters etc.

Industrial applications of electric heating include *(i)* melting of metals *(ii)* heat treatment of metals like annealing, tempering, soldering and brazing etc. *(iii)* moulding of glass *(iv)* baking of insulators *(v)* enamelling of copper wires etc.

47.2. Advantages of Electric Heating

As compared to other methods of heating using gas, coal and fire etc., electric heating is far superior for the following reasons :

(i) **Cleanliness.** Since neither dust nor ash is produced in electric heating, it is a clean system of heating requiring minimum cost of cleaning. Moreover, the material to be heated does not get contaminated.

(ii) **No Pollution.** Since no flue gases are produced in electric heating, no provision has to be made for their exit.

(iii) **Economical.** Electric heating is economical because electric furnaces are cheaper in their initial cost as well as maintenance cost since they do not require big space for installation or for storage of coal and wood. Moreover, there is no need to construct any chimney or to provide extra heat installation.

(iv) **Ease of Control.** It is easy to control and regulate the temperature of an electric furnace with the help of manual or automatic devices. Temperature can be controlled within $\pm 5°C$ which is not possible in any other form of heating.

(v) **Special Heating Requirement.** Special heating requirements such as uniform heating of a material or heating one particular portion of the job without affecting its other parts or heating with no oxidation can be met only by electric heating.

(vi) **Higher Efficiency.** Heat produced electrically does not go away waste through the chimney and other by products. Consequently, most of the heat produced is utilised for heating the material itself. Hence, electric heating has higher efficiency as compared to other types of heating.

(vii) **Better Working Conditions.** Since electric heating produces no irritating noises and also the radiation losses are low, it results in low ambient temperature. Hence, working with electric furnaces is convenient and cool.

(viii) **Heating of Bad Conductors.** Bad conductors of heat and electricity like wood, plastic and bakery items can be uniformly and suitably heated with dielectric heating process.

(ix) **Safety.** Electric heating is quite safe because it responds quickly to the controlled signals.

(x) **Lower Attention and Maintenance Cost.** Electric heating equipment generally will not require much attention and supervision and their maintenance cost is almost negligible. Hence, labour charges are negligibly small as compared to other forms of heating.

47.3. Different Methods of Heat Transfer

The different methods by which heat is transferred from a hot body to a cold body are as under:

1. Conduction

In this mode of heat transfer, one molecule of the body gets heated and transfers some of the heat to the adjacent molecule and so on. There is a temperature gradient between the two ends of the body being heated.

Consider a solid material of cross-section A sq.m. and thickness x metre as shown in Fig. 47.1. If T_1 and T_2 are the temperatures of the two sides of the slab in °K, then heat conducted between the two opposite faces in time t seconds is given by:

$$H = \frac{KA(T_1 - T_2)t}{x}$$

where K is thermal conductivity of the material.

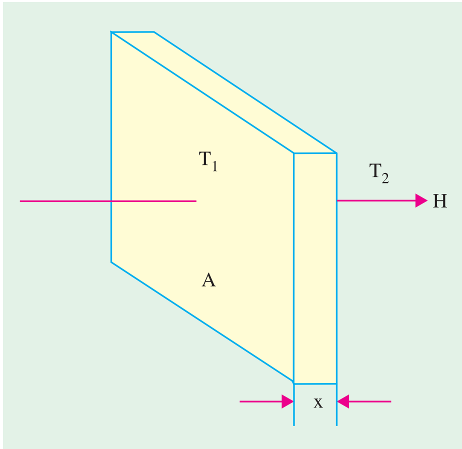


Fig. 47.1

2. Convection

In this process, heat is transferred by the flow of hot and cold air currents. This process is applied in the heating of water by immersion heater or heating of buildings. The quantity of heat absorbed by the body by convection process depends mainly on the temperature of the heating element above the surroundings and upon the size of the surface of the heater. It also depends, to some extent, on the position of the heater. The amount of heat dissipated is given by

$H = a(T_1 - T_2)$, where a and b are constants and T_1 and T_2 are the temperatures of the heating surface and the fluid in °K respectively.

In electric furnaces, heat transferred by convection is negligible.

3. Radiation

It is the transfer of heat from a hot body to a cold body in a straight line without affecting the intervening medium. The rate of heat emission is given by Stefan's law according to which

Heat dissipated, $$H = 5.72\,eK\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \text{ W/m}^2$$

where K is radiating efficiency and e is known as emissivity of the heating element.

If d is the diameter of the heating wire and l its total length, then its surface area from which heat is radiated = $\pi \cdot d \; l$. If H is the power radiated per m^2 of the heating surface, then total power radiated as heat = $H \cdot \pi d l$. If P is the electrical power input to the heating element, then $P = \pi dl \cdot H$.

47.4. Methods of Electric Heating

Basically, heat is produced due to the circulation of current through a resistance. The current may circulate directly due to the application of potential difference or it may be due to induced eddy currents. Similarly, in magnetic materials, hysteresis losses are used to create heat. In dielectric heating, molecular friction is employed for heating the substance. An arc established between an electrode and the material to be heated can be made a source of heat. Bombarding the surface of material by high energy particles can be used to heat the body.

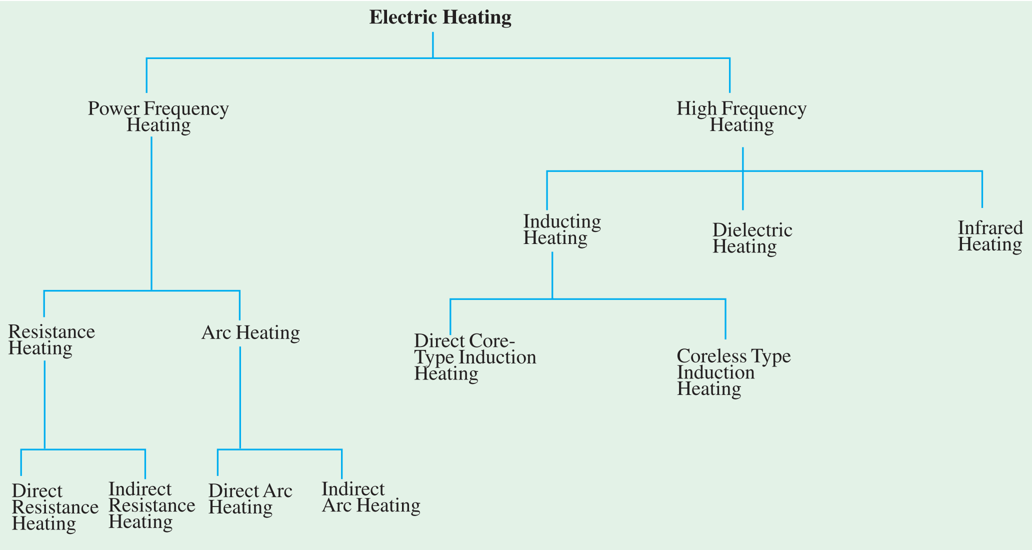
Room heater is a familiar appliance where electric heating is employed

Different methods of producing heat for general industrial and domestic purposes may be classified below :

47.5. Resistance Heating

It is based on the I^2R effect. When current is passed through a resistance element I^2R loss takes place which produces heat. There are two methods of resistance heating.

(*a*) Direct Resistance Heating. In this method the material (or charge) to be heated is treated as a resistance and current is passed through it. The charge may be in the form of powder, small solid pieces or liquid. The two electrodes are inserted in the charge and connected to either a.c. or d.c. supply (Fig. 47.2). Obviously, two electrodes will be required in the case of d.c. or single-phase a.c. supply but there would be three electrodes in the case of 3-phase supply. When the charge is in the form of small pieces, a powder of high resistivity material is sprinkled over the surface of the charge to avoid direct short circuit. Heat is produced when current passes through it. This method of heating has high efficiency because the heat is produced in the charge itself.



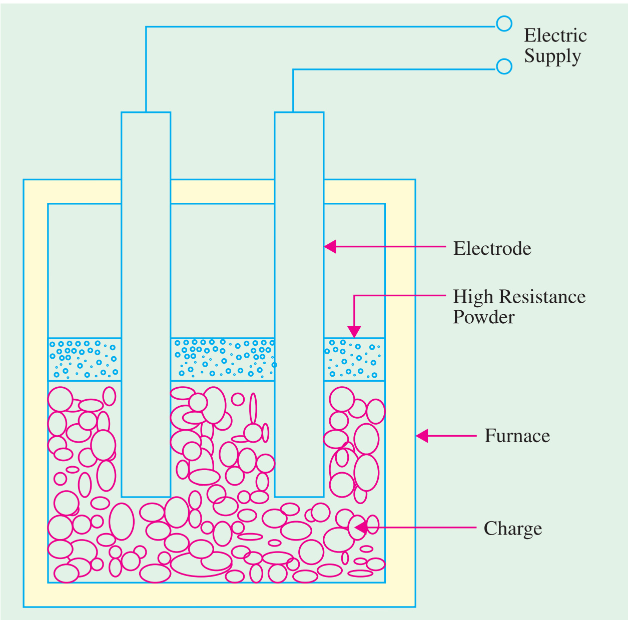


Fig. 47.2

(*b*) Indirect Resistance Heating. In this method of heating, electric current is passed through a resistance element which is placed in an electric oven. Heat produced is proportional to I^2R losses in the heating element. The heat so produced is delivered to the charge either by radiation or convection or by a combination of the two.

Sometimes, resistance is placed in a cylinder which is surrounded by the charge placed in the jacket as shown in the Fig. 47.3. This arrangement provides uniform temperature. Moreover, automatic temperature control can also be provided.

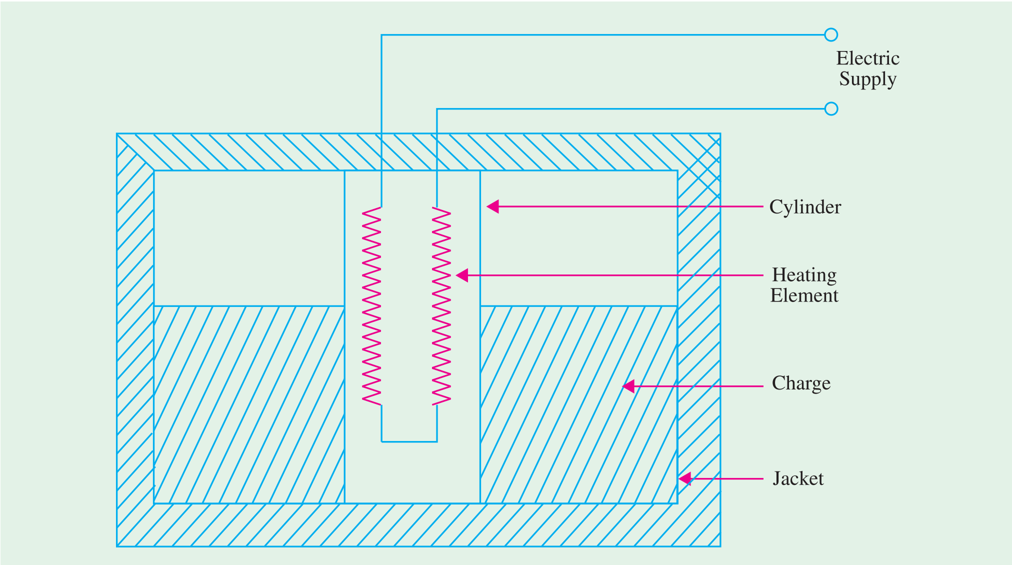


Fig. 47.3

47.6. Requirement of a Good Heating Element

Indirect resistance furnaces use many different types of heating elements for producing heat. A good heating element should have the following properties :

(1) High Specific Resistance. When specific resistance of the material of the wire is high, only short length of it will be required for a particular resistance (and hence heat) or for the same length of the wire and the currrent, heat produced will be more.

(2) High Melting Temperature. If the melting temperature of the heating element is high, it would be possible to obtain higher operating temperatures.

(3) Low Temperature Coefficient of Resistance. In case the material has low temperature coefficient of resistance, there would be only small variations in its resistance over its normal range of temperature. Hence, the current drawn by the heating element when cold (*i.e.*, at start) would be practically the same when it is hot.

(4) High Oxidising Temperature. Oxidisation temperature of the heating element should be high in order to ensure longer life.

(5) Positive Temperature Coefficient of Resistance. If the temperature coefficient of the resistance of heating element is negative, its resistance will decrease with rise in temperature and it will draw more current which will produce more wattage and hence heat. With more heat, the resistance will decrease further resulting in instability of operation.

(6) Ductile. Since the material of the heating elements has to have convenient shapes and sizes, it should have high ductility and flexibility.

(7) Mechanical Strength. The material of the heating element should posses high mechanical strength of its own. Usually, different types of alloys are used to get different operating temperatures. For example maximum working temperature of ***constant*** an (45% Ni, 55% Cu) is 400°C, that of *nichrome* (50%, Ni 20% Cr) is 1150°C, that of ***Kantha*** (70% Fe, 25% Cr, 5% Al) is 1200° C and that of ***silicon carbide*** is 1450°C.

With the passage of time, every heating element breaks open and becomes unserviceable. Some of the factors responsible for its failure are :

(1) Formation of hot spots which shine brighter during operation, **(2)** Oxidation **(3)** Corrosion **(4)** Mechanical failure.

47.7. Resistance Furnaces or Ovens

These are suitably-insulated closed chambers with a provision for ventilation and are used for a wide variety of purposes including heat treatment of metals like annealing and hardening etc., stoving of enamelled wares, drying and baking of potteries, vulcanizing and hardening of synthetic materials and for commercial and domestic heating. Temperatures upto 1000°C can be obtained by using heating elements made of nickel, chromium and iron. Ovens using heating elements made of graphite can produce temperatures upto 3000°C. Heating elements may consist of circular wires or rectangular ribbons. The ovens are usually made of a metal framework having an internal lining of fire bricks. The heating element may be located on the top, bottom or sides of the oven. The nature of the insulating material is determined by the maximum temperature required in the oven.

An enclosure for charge which is heated by radiation or convection or both is called a ***heating chamber***.

47.8. Temperature Control of Resistance Furnaces

The temperature of a resistance furnace can be changed by controlling the I^2R or V^2/R losses.

Following different methods are used for the above purpose :

(1) Intermittent Switching. In this case, the furnace voltage is switched ON and OFF intermittently. When the voltage supply is switched off, heat production within the surface is stalled and hence its temperature is reduced. When the supply is restored, heat production starts and the furnace temperature begins to increase. Hence, by this simple method, the furnace temperature can be limited between two limits.

Electric resistance furnace

(2) By Changing the Number of Heating Elements. In this case, the number of heating elements is changed without cutting off the supply to the entire furnace. Smaller the number of heating elements, lesser the heat produced.

In the case of a 3-phase circuit, equal number of heating elements is switched off from each phase in order to maintain a balanced load condition.

(3) Variation in Circuit Configuration. In the case of 3-phase secondary load, the heating elements give less heat when connected in a star than when connected in delta because in the two cases, voltages across the elements is different (Fig. 47.4). In single-phase circuits, series and parallel grouping of the heating elements causes change in power dissipation resulting in change of furnace temperature.

As shown in Fig. 47.5 heat produced is more when all these elements are connected in parallel than when they are connected in series or series-parallel.

(4) Change of Applied Voltage. ***(a)*** Obviously, lesser the magnitude of the voltage applied to the load, lesser the power dissipated and hence, lesser the temperature produced. In the case of a furnace transformer having high voltage primary, the tapping control is kept in the primary winding because the magnitude of the primary current is less. Consider the multi-tap step-down transformer shown in Fig. 47.6.

Resistance heating tube furnace

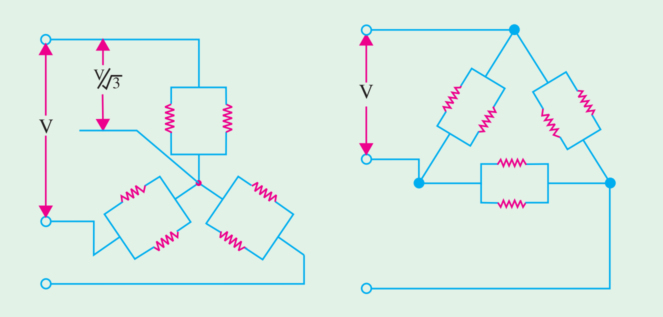


Fig. 47.4

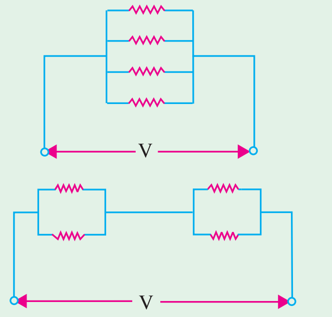


Fig. 47.5

Let the four tappings on the primary winding have 100%, 80%, 60% and 50%. When 100% primary turns are used, secondary voltage is given by $V_2 = (N_2/N_1)V_i$ where V_i is the input voltage. When 50% tapping is used, the number of primary turns involved is $N_1/2$. Hence, available secondary voltage $V_2 = (2N_2/N_1)V_i$. By selecting a suitable primary tapping, secondary voltage can be increased or decreased causing a change of temperature in the furnace.

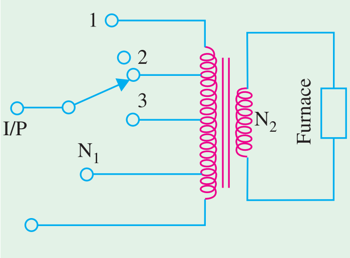


Fig. 47.6

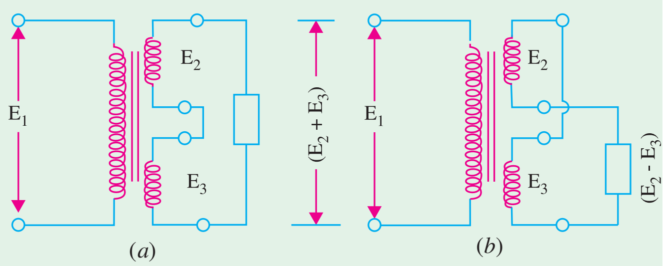


Fig. 47.7

***(b)* Bucking-Boosting the Secondary Voltage.** In this method, the transformer secondary is wound in two sections having unequal number of turns. If the two sections are connected in series-aiding, the secondary voltage is boosted *i.e.*, increased to $(E_2 + E_3)$ as shown in Fig. 47.7 (*a*).

When the two sections are connected in series-opposing [Fig. 47.7 (*b*)] the secondary voltage is reduced *i.e.*, there is bucking effect. Consequently, furnace voltage becomes $(E_2 - E_3)$ and, hence, furnace temperature is reduced.

***(c)* Autotransformer Control.** Fig. 47.8 shows the use of tapped autotransformer used for decreasing the furnace voltage and, hence, temperature of small electric furnaces. The required voltage can be selected with the help of a voltage selector.

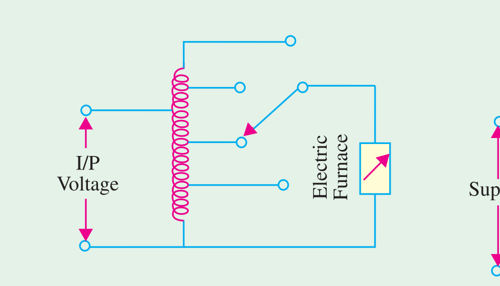


Fig. 47.8

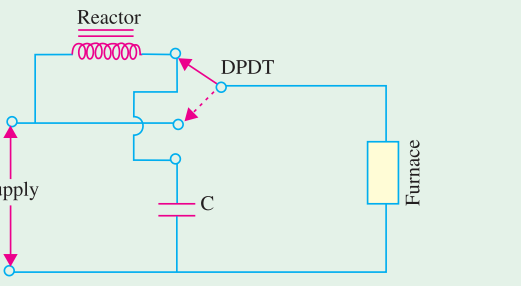


Fig. 47.9

(*d*) Series Reactor Voltage. In this case, a heavy-duty core-wounded coil is placed in series with the furnace as and when desired. Due to drop in voltage across the impedence of the coil, the voltage available across the furnace is reduced. With the help of D.P.D.T. switch, high/low, two-mode temperature control can be obtained as shown in the Fig. 47.9. Since the addition of series coil reduces the power factor, a power capacitor is simultaneously introduced in the circuit for keeping the p.f. nearly unity. As seen, the inductor is connected in series, whereas the capacitor is in parallel with the furnace.

47.9. Design of Heating Element

Normally, wires of circular cross-section or rectangular conducting ribbons are used as heating elements. Under steady-state conditions, a heating element dissipates as much heat from its surface as it receives the power from the electric supply. If P is the power input and H is the heat dissipated by radiation, then $P = H$ under steady-state conditions.

As per Stefan's law of radiation, heat radiated by a hot body is given by

$$H = 5.72\, eK\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \text{W/m}^2$$

where T_1 is the temperature of hot body in °K and T_2 that of the cold body (or cold surroundings) in °K

$$\text{Now,} \quad P = \frac{V^2}{R}, \quad \text{and} \quad R = \rho\frac{l}{A} = \rho\frac{l}{\pi d^2/4} = \frac{4\rho l}{\pi d^2}$$

$$\therefore \quad P = \frac{V^2}{4\rho l/\pi d^2} = \frac{\pi d^2 V^2}{4\rho l} \quad or \quad \frac{l}{d^2} = \frac{\pi V^2}{4 l \rho} \qquad \ldots(i)$$

Total surface area of the wire of the element = $(\pi d) \times l$

If H is the heat dissipated by radiation per second per unit surface area of the wire, then heat radiated per second

$$= (\pi d) \times l \times H \qquad \ldots(ii)$$

Equating (*i*) and (*ii*), we have

$$P = (\pi d) \times l \times H \quad \text{or} \quad \frac{\pi d^2 V^2}{4\rho l} = (\pi d) \times H \quad \text{or} \quad \frac{d}{l^2} = \frac{4\rho H}{V^2} \qquad \ldots(iii)$$

We can find the values of l and d from Eq. (*i*) and (*iii*) given above.

Ribbon Type Element

If w is the width of the ribbon and t its thickness, then

$$P = \frac{V^2}{R} = \frac{V^2}{\rho l/A} = \frac{V^2}{\rho l/Twt} = \frac{wtV/l^2}{\rho l} \quad or \quad \frac{t}{wt} = \frac{V^2}{\rho P} \qquad \ldots(iv)$$

Heat lost from ribbon surface = $2wl\,H$ (neglecting the side area $2tl$)

$$\therefore \quad \frac{wtV^2}{\rho l} = 2wlH \quad \text{or} \quad \frac{t}{l^2} = \frac{2\rho H}{V^2} \qquad \ldots(v)$$

Values of l and w for a given ribbon of thickness t can be found from Eqn. (*iv*) and (*v*) given above.

Example 47.1. *A resistance oven employing nichrome wire is to be operated from 220 V single-phase supply and is to be rated at 16 kW. If the temperature of the element is to be limited to 1,170°C and average temperature of the charge is 500°C, find the diameter and length of the element wire.*

Radiating efficiency = 0.57, Emmissivity=0.9, Specific resistance of nichrome=(109×10^{-8}) ohm-m. **(Utili. of Elect. Energy, Punjab Univ.)**

Solution. P = 16 kW = 16,000 W

From Article 47.9, $\dfrac{l}{d^2} = \dfrac{\pi V^2}{4\rho P} = \dfrac{\pi \times (220)^2}{4 \times 109 \times 10^{-8} \times 16{,}000} = 2{,}179{,}660$ ... (*i*)

$$\text{Now,} \quad H = 5.72eK\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] W/\text{m}^2 = 5.72 \times 0.9 \times 0.57\left[\left(\frac{1443}{100}\right)^4 - \left(\frac{773}{100}\right)^4\right]$$

$= 116{,}752$ W/m^2

Now, total heat dissipated/s = electrical power input

$\therefore \quad (\pi d) \times l \times 116{,}752 = 16{,}000; \quad \therefore \quad dl = 0.0436$

or $\quad d^2 l^2 = 0.0019$ ...(*ii*)

From Eqn. (*i*) and (*ii*), l^3 = 2,179,660 × 0.0019 = 4141

$\therefore \quad l$ = **16.05 m**

d = 0.0436/16.05 = 2.716×10^{-3} m = **2.716 mm**

Example 47.2. *A 30-kW, 3-φ, 400-V resistance oven is to employ nickel-chrome strip 0.254 mm thick for the three star-connected heating elements. If the wire temperature is to be 1,100°C and that of the charge to be 700°C, estimate a suitable width for the strip. Assume emissivity = 0.9 and radiating efficiency to be 0.5 and resistivity of the strip material is 101.6×10^{-8} Ω - m. What would be the temperature of the wire if the charge were cold ?*

(Utili. of Elect. Power A.M.I.E. Sec. B)

Solution. Power/phase = 30 × 1000/3 = 10,000 W, $V_{ph} = 400/\sqrt{3} = 231$ V

If R is the resistance of the strip, $R = V_{ph}^2/P = 231^2/10{,}000$ = 5.34 Ω

Resistance of the strip, $\quad R = \dfrac{\rho l}{wt} \quad or \quad \dfrac{l}{w} = \dfrac{5.34 \times 0.245 \times 10^{-3}}{101.6 \times 10^{-8}} = 1335$ ...(*i*)

Heat dissipated from surface of the strip,

$$H = 5.72 \times 0.9 \times 0.5\left[\left(\frac{1373}{100}\right)^4 - \left(\frac{973}{100}\right)^4\right] = 68{,}400 \text{ W/m}^2$$

Surface area of the strip = $2wl$; Total heat dissipated = $2wl \times H$

$\therefore \quad 68{,}400 \times 2 \times wl = 10{,}000 \quad$ or $\quad wl = 0.0731$ ...(*ii*)

From Eqn. (*i*) and (*ii*), we get w = 0.0731/1335 or w = **7.4 mm**

Example 47.3. *A cubic water tank has surface area of 6.0 m² and is filled to 90% capacity six times daily. The water is heated from 20°C to 65°C. The losses per square metre of tank surface per 1°C temperature difference are 6.3 W. Find the loading in kW and the efficiency of the tank. Assume specific heat of water = 4,200 J/kg/°C and one kWh = 3.6 MJ.* **(A.M.I.E. Sec. B)**

Solution. If l is the side of the tank, then total surface area of the tank = $6l^2$

$\therefore\ 6l^2 = 6$ or $l = 6/6 = 1\ \text{m}^2$

Volume of the tank = $l^3 = 1\text{m}^3$

Volume of water to be heated daily = $6 \times (1 \times 0.9) = 5.4\ \text{m}^3$

Since $1\,m^3$ of water weighs 1000 kg, mass of water to be heated daily = 5.4 × 1000 = 5400 kg

Heat required to raise the temperature of water = 5400 × 4200 (65 – 20) = 1020 MJ = 1020/3.6 = 283.3 kWh

Daily loss from the surface of the tank = 6.3 × 6 × (65 – 20) × 24/1000 = 40.8 kWh

Energy supplied per day = 283.3 + 40.8 = 324.1 kWh

Loading in kW = 324.1/24 = **3.5 kW**

Efficiency of the tank = 283.3 × 100/324.1 = 87.4%

47.10. Arc Furnaces

If a sufficiently high voltage is applied across an air-gap, the air becomes ionized and starts conducting in the form of a continuous spark or arc thereby producing intense heat. When electrodes are made of carbon/graphite, the temperature obtained is in the range of 3000°C-3500C. The high voltage required for striking the arc can be obtained by using a step-up transformer fed from a variable a.c. supply as shown in Fig. 47.10 (*a*).

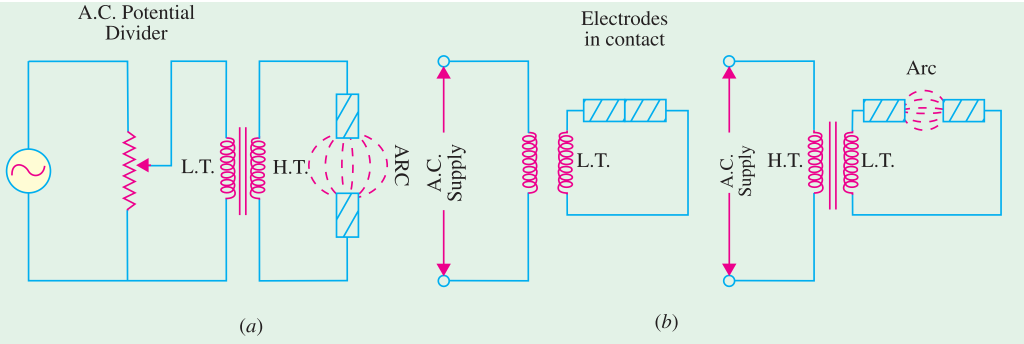


Fig. 47.10

An arc can also be obtained by using low voltage across two electrodes initially in contact with each other as shown in Fig. 47.10 (*b*). The low voltage required for this purpose can be obtained by using a step-down transformer. Initially, the low voltage is applied, when the two electrodes are in contact with each other. Next, when the two electrodes are gradually separated from each other, an arc is established between the two.

Arc furnaces can be of the following two types :

1. Direct Arc Furnace

In this case, arc is formed between the two electrodes and the charge in such a way that electric current passes through the body of the charge as shown in Fig. 47.11 (*a*). Such furnaces produce very high temperatures.

2. Indirect Arc Furnace

In this case, arc is formed between the two electrodes and the heat thus produced is passed on to the charge by radiation as shown in Fig. 47.11 (*b*).

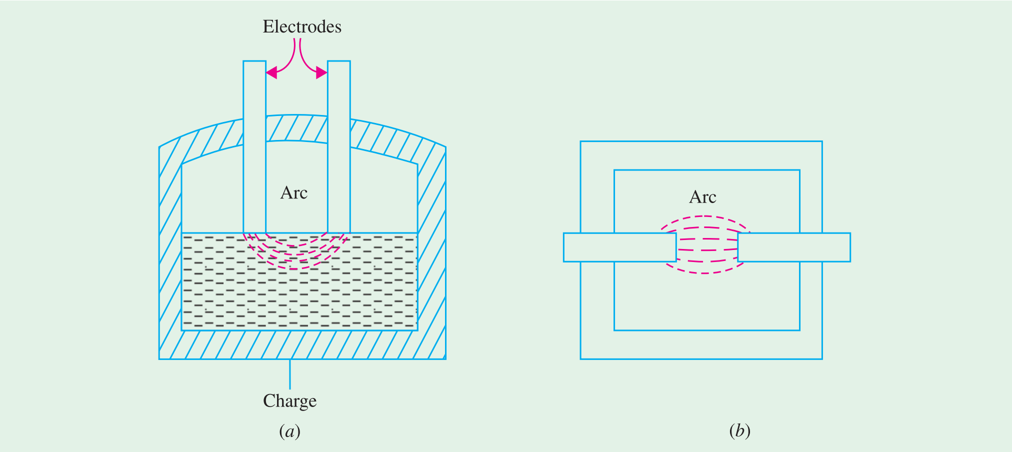


Fig. 47.11

47.11. Direct Arc Furnace

It could be either of conducting-bottom type [Fig. 47.12 (*a*)] or non-conducting bottom type [Fig. 47.12 (*b*)].

As seen from Fig. 47.12 (*a*), bottom of the furnace forms part of the electric circuit so that current passes through the body of the charge which offers very low resistance. Hence, it is possible

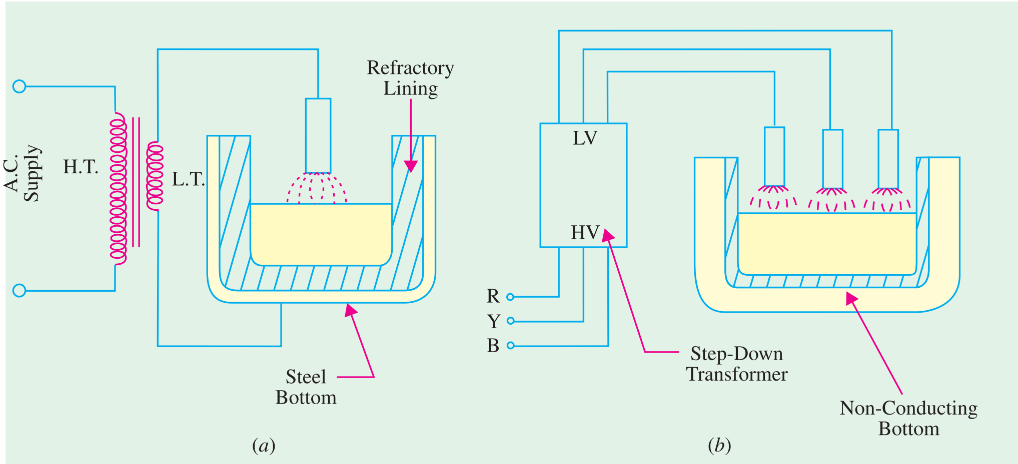


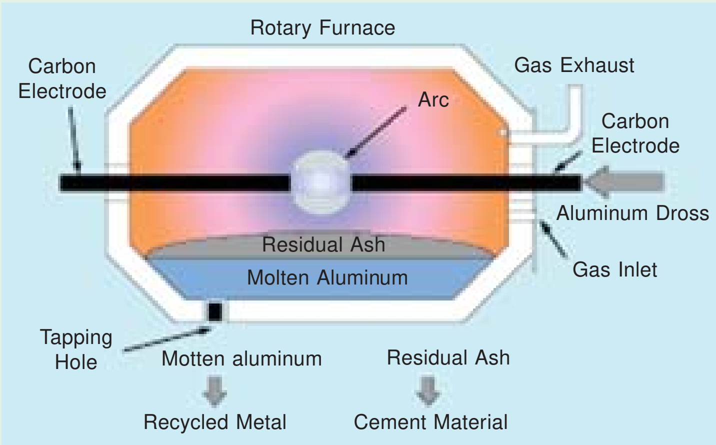
Fig. 47.12

to obtain high temperatures in such furnaces. Moreover, it produces uniform heating of charge without stirring it mechanically. In Fig. 47.12 (*b*), no current passes through the body of the furnace.

Most common application of these furnaces is in the production of steel because of the ease with which the composition of the final product can be controlled during refining.

Most of the furnaces in general use are of non-conducting bottom type due to insulation problem faced in case of conducting bottom.

47.12. Indirect Arc Furnace



Schematic view of an indirect electric arc furnace

Fig. 47.13 shows a single-phase indirect arc furnace which is cylindrical in shape. The arc is struck by short-circuiting the electrodes manually or automatically for a moment and then, withdrawing them apart. The heat from the arc and the hot refractory lining is transferred to the top layer of the charge by radiation. The heat from the hot top layer of the charge is further transferred to other parts of the charge by conduction.

Since no current passes through the body of the charge, there is no inherent stirring action due to electro-magnetic forces set up by the current. Hence, such furnaces have to be rocked continuously in order to distribute heat uniformly by exposing different layers of the charge to the heat of the arc. An electric motor is used to operate suitable grinders and rollers to impart rocking motion to the furnace. Rocking action provides not only thorough mixing of the charge, it also increases the furnace efficiency in addition to increasing the life of the refractory lining material. Since in this furnace, charge is heated by radiation only, its temperature is lower than that obtainable in a direct arc furnace. Such furnaces are mainly used for melting non-ferrous metals although they can be used in iron foundaries where small quantities of iron are required frequently.

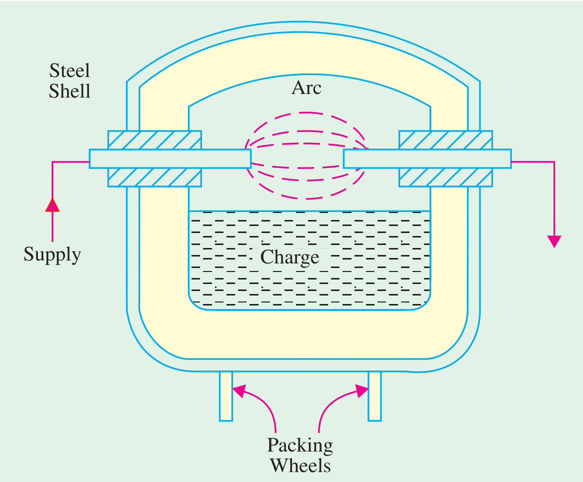


Fig. 47.13

Example 47.4. *A 4-phase electric arc furnace has the following data :*

Current drawn = 5000 A ; *Arc voltage* $= 50$ V

Resistance of transformer referred to secondary $= 0.002\ \Omega$

Resistance of transformer referred to secondary $= 0.004\ \Omega$

(i) Calculate the power factor and kW drawn from the supply.

(ii) If the overall efficiency of the furnace is 65%, find the time required to melt 2 tonnes of steel if latent heat of steel = 8.89 kcal/kg, specific heat of steel = 0.12, melting point of steel = 1370°C and initial temperature of steel = 20°C.

(Utilisation of Elect. Power, A.M.I.E. Sec. B)

Solution. Voltage drop due to transformer resistance $= 5000 \times 0.002 = 10$ V

Voltage drop due to transformer reactance $= 5000 \times 0.004 = 20$ V.

Since arc voltage drop is resistive in nature, it is vectorially added to the transformer resistance drop.

Open circuit transformer secondary voltage/phase = $\sqrt{(50+10)^2+20^2}=63.25\,\text{V}$

(*i*) Supply p.f.= (50 + 10)/63.25 = **0.9487**

Power drawn/phase by the secondary = 5000 × 63.25 × 0.9487 = 300,000 W = 300 kW

Total power drawn from the supply = 3 × 300 = **900 kW**

(*ii*) Energy required to melt 2 tonnes of steel = $ms\,(t_2 - t_1)$ + mL = 2000 × 0.12 × (1370 – 20) + 2000 × 8.89 = 341,780 kcal.= 341,780/860 = 397.4 kWh

Power actually utilised = 900 × 0.65 = 585 kW

Time required for melting steel = 397.4/585 = 0.679 hours = **40 minutes 46 seconds.**

Example. 47.5. *If a 3-phase arc furnace is to melt 10 tonne steel in 2 hours, estimate the average input to the furnace if overall efficiency is 50%. If the current input is 9,000 A with the above kW input and the resistance and reactance of furnace leads (including transformer) are 0.003 Ω and 0.005 Ω respectively, estimate the arc voltage and total kVA taken from the supply Specific heat of steel = 444 J kg^{-1}°C^{-1}*

Latent heat of fusion of steel = 37.25 kJ/kg

Melting point of steel = 1,370 °C **(Utilisation of Elect. Energy, Punjab Univ. 1989.)**

Solution. Energy required to melt 10 tonnes of steel = 10,000 × 444 (1370 – 20) + 10,000 × 37,250 = 6366.5 × 106 J = 1768.5 kWh

It has been assumed in the above calculation that the initial melting temperature of steel is 20°C.

Since time taken is two hours, average output power = 1768.5/2 = 884.25 kW

Average input power = 884.25/0.5=1768.5 kW

Voltage drop due to the resistance of the furnace leads (including transformer) = 9000 × 0.003 = 27 V

Voltage drop due to reactance of the furnace leads (including transformer) = 9000 × 0.005 = 45 V

If VA is the arc drop (which is assumed resistive in nature) then

$$\text{O.D. secondary voltage/phase} = \sqrt{(V_A+27)^2+45^2}$$

$$P.F. = \frac{V_A+27}{(V_A+27)^2+(45)^2}$$

Total power input = 3 × power drawn/phase

$$\therefore \quad 1768.5\times 10^3 = 3\times 9000\,\sqrt{(V_A+27)^2+(35)^2}\cdot (V_A+27)/\sqrt{(V_A+27)^2+(45)^2}$$

$$\therefore \quad V_A + 27 = 65.5 \quad \text{or} \quad V_A = 65.5 - 27 = \mathbf{38.5\ V}$$

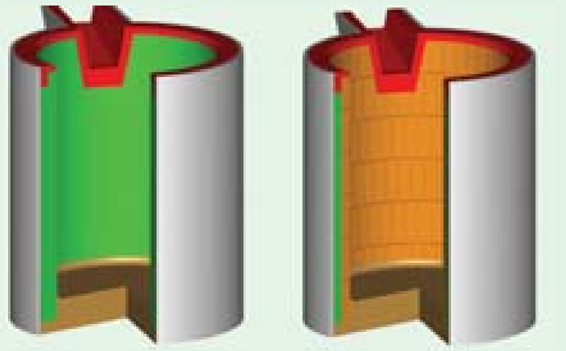
$$\text{O.C. secondary voltage/phase} = \sqrt{(V_A+27)^2+(45)^2} = 79.5\,\text{V}$$

Total kVA taken from supply line = 3 × 9000 × 79.5 × 10^{-3} = **2145 kVA.**

47.13. Induction Heating

This heating process makes use of the currents induced by the electro-magnetic action in the charge to be heated. In fact, induction heating is based on the principle of transformer working. The primary winding which is supplied from an a.c. source is magnetically coupled to the charge which acts as a short circuited secondary of single turn. When an a.c. voltage is applied to the primary, it induces voltage in the secondary *i.e.* charge. The secondary current heats up the charge in the same way as any electric current does while passing through a resistance. If V is the voltage induced in the charge and R is the charge resistance, then heat produced = V^2/R. The value of current induced in the charge depends on (*i*) magnitude of the primary current (*ii*) turn ratio of the transformer *(iii)* co-efficient of magnetic coupling.

Low-frequency induction furnaces are used for melting and refining of different metals. However, for other processes like case hardenning and soldering etc., high-frequency eddy-current heating is employed. Low-frequency induction furnaces employed for the melting of metals are of the following two types :



(*a*) (*b*)

Inside views of an induction furnaces: (*a*) Rammed induction furnace and (*b*) bricked induction furnace

(*a*) Core-type Furnaces — which operate just like a two winding transformer. These can be further sub-divided into *(i)* Direct core-type furnaces *(ii)* Vertical core-type furnaces and *(iii)* Indirect core-type furnaces.

(*b*) Coreless-type Furnaces — in which an inductively-heated element is made to transfer heat to the charge by radiation.

47.14. Core Type Induction Furnace

It is shown in Fig. 47.14 and is essentially a transformer in which the charge to be heated forms a single-turn short-circuited secondary and is magnetically coupled to the primary by an iron core. The furnace consists of a circular hearth which contains the charge to be melted in the form of an annular ring. When there is no molten metal in the ring, the secondary becomes open-circuited there-by cutting off the secondary current. Hence, to start the furnace, molted metal has to be poured in the annular hearth. Since, magnetic coupling between the primary and secondary is very poor, it results in high leakage and low power factor. In order to nullify the effect of increased leakage reactance, low primary frequency of the order of 10 Hz is used. If the transformer secondary current density exceeds 500 A/cm^2 then, due to the interaction of secondary current with the alternating magnetic field, the molten metal is squeezed to the extent that secondary circuit is interrupted. This effect is known as "pinch effect".

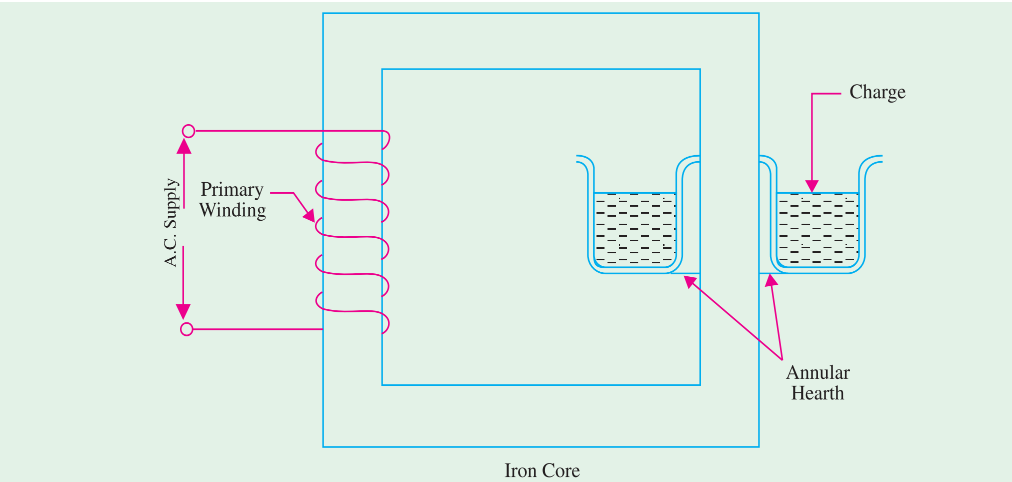


Fig. 47.14

This furnace suffers from the following drawbacks :

1. It has to be run on low-frequency supply which entails extra expenditure on motor-generator set or frequency convertor.
2. It suffers from pinching effect.
3. The crucible for charge is of odd shape and is very inconvenient for tapping the molten charge.
4. It does not function if there is no molten metal in the hearth *i.e.* when the secondary is open. Every time molten metal has to be poured to start the furnace.
5. It is not suitable for intermittent service.

However, in this furnace, melting is rapid and clean and temperature can be controlled easily. Moreover, inherent stirring action of the charge by electro-magnetic forces ensures greater uniformity of the end product.

47.15. Vertical Core-Type Induction Furnace

It is also known as Ajax-Wyatt furnace and represents an improvement over the core-type furnace discussed above. As shown in Fig. 47.15, it has vertical channel (instead of a horizontal one) for the charge, so that the crucible used is also vertical which is convenient from metallurgical point of view. In this furnace, magnetic coupling is comparatively better and power factor is high. Hence, it can be operated from normal frequency supply. The circulation of the molten metal is kept up round the Vee portion by convection currents as shown in Fig. 47.15.

As Vee channel is narrow, even a small quantity of charge is sufficient to keep the secondary circuit closed. However, Vee channel must be kept full of charge in order to maintain continuity of secondary circuit. This fact makes this furnace suitable for continuous operation. The tendency of the secondary circuit to rupture due to pinch-effect is counteracted by the weight of the charge in the crucible.

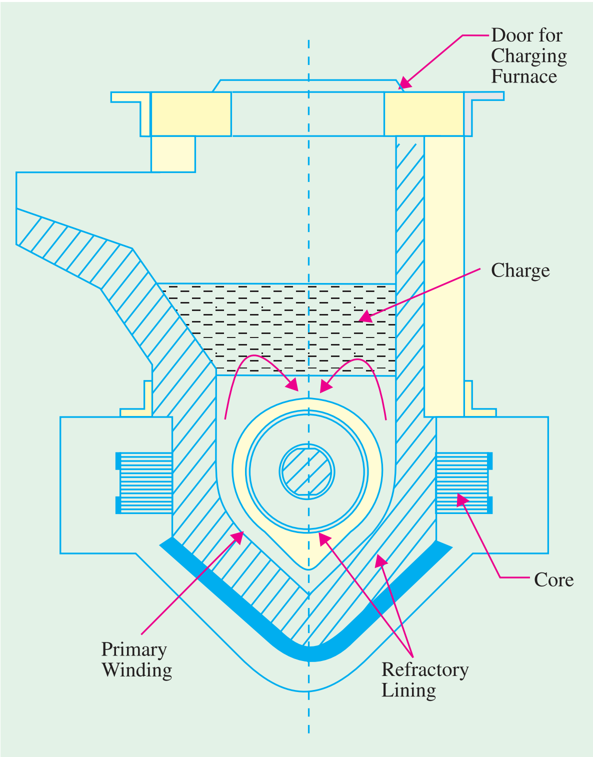


Fig. 47.15

The choice of material for inner lining of the furnace depends on the type of charge used. Clay lining is used for yellow brass. For red brass and bronze, an alloy of magnetia and alumina or corundum is used. The top of the furnace is covered with an insulated cover which can be removed for charging. The furnace can be tilted by the suitable hydraulic arrangement for taking out the molten metal.

This furnace is widely used for melting and refining of brass and other non-ferrous metals. As said earlier, it is suitable for continuous operation. It has a p.f. of 0.8-0.85. With normal supply frequency, its efficiency is about 75% and its standard size varies from 60-300 kW, all single-phase.

47.16. Indirect Core-Type Induction Furnace

In this furnace, a suitable element is heated by induction which, in turn, transfers the heat to the charge by radiation. So far as the charge is concerned, the conditions are similar to those in a resistance oven.

As shown in Fig. 47.16, the secondary consists of a metal container which forms the walls of the furnace proper. The primary winding is magnetically coupled to this secondary by an iron core. When primary winding is connected to a.c. supply, secondary current is induced in the metal container by transformer action which heats up the container. The metal container transfers this heat to the charge. A special advantage of this furnace is that its temperature can be automatically controlled without the use of an external equipment. The part AB of the magnetic circuit situated inside the oven chamber consists of a special alloy which loses its magnetic properties at a particular temperature but regains them when cooled back to the same temperature. As soon as the chamber attains the critical temperature, reluctance of the magnetic circuit increases manifold thereby cutting off the

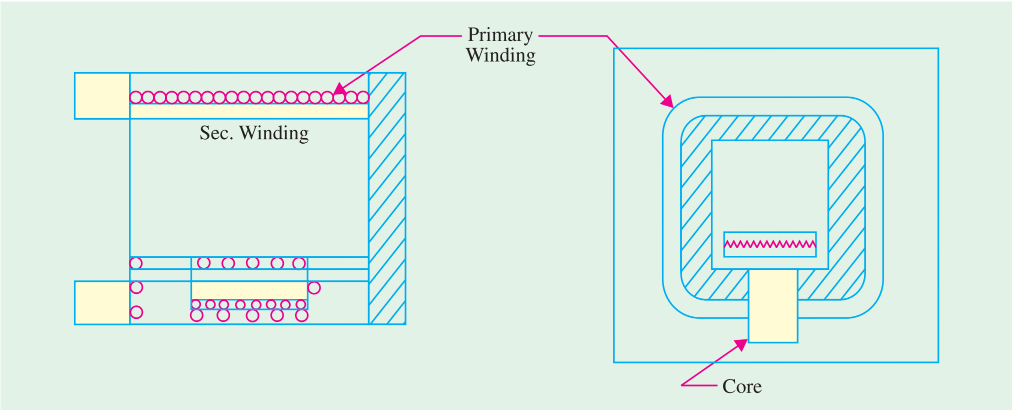


Fig. 47.16

heat supply. The bar *AB* is detachable and can be replaced by other bars having different critical temperatures.

47.17. Coreless Induction Furnace

As shown in Fig. 47.17, the three main parts of the furnace are ***(i)*** primary coil ***(ii)*** a ceramic crucible containing charge which forms the secondary and ***(iii)*** the frame which includes supports and tilting mechanism. The distinctive feature of this furnace is that it contains no heavy iron core with the result that there is no continuous path for the magnetic flux. The crucible and the coil are relatively light in construction and can be conveniently tilted for pouring.

The charge is put into the crucible and primary winding is connected to a high-frequency a.c. supply. The flux produce by the primary sets up eddy-currents in the charge and heats it up to the melting point. The charge need not be in the molten state at the start as was required by core-type furnaces. The eddy- currents also set up electromotive forces which produce stirring action which is essential for obtaining uniforms quality of metal. Since flux density is low (due to the absence of the magntic core) high frequency supply has to be used because eddy-current loss $W_e \propto B^2 f^2$. However, this high frequency increases the resistance of the primary winding due to skin effect, thereby increasing primary Cu losses. Hence, the primary winding is not made of Cu wire but consists of hollow Cu tubes which are cooled by water circulating through them.

Since magnetic coupling between the primary and secondary windings is low, the furnace p.f. lies between 0.1 and 0.3. Hence, static capacitors are invariably used in parallel with the furnace to improve its p.f.

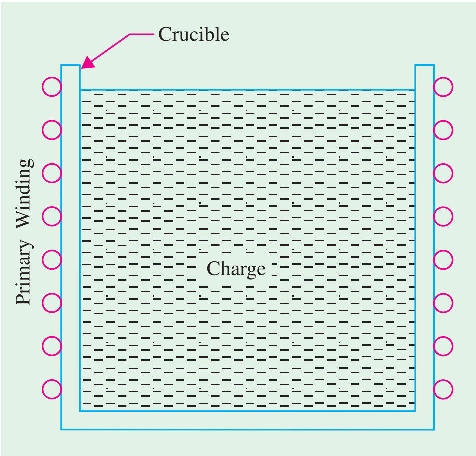


Fig. 47.17

Such furnaces are commonly used for steel production and for melting of non-ferrous metals like brass, bronze, copper and aluminum etc., along with various alloys of these elements. Special application of these furnaces include vacuum melting, melting in a controlled atmosphere and melting for precision casting where high frequency induction heating is used. It also finds wide use in electronic industry and in other industrial activities like soldering, brazing hardening and annealing and sterilizing surgical instruments etc.

Some of the advantages of coreless induction furnaces are as follows :

(1) They are fast in operation.

(2) They produce most uniform quality of product.

(3) They can be operated intermittenly.

(4) Their operation is free from smoke, dirt, dust and noises.

(5) They can be used for all industrial applications requiring heating and melting.

(6) They have low erection and operating costs.

(7) Their charging and pouring is simple.

47.18. High Frequency Eddy-current Heating

For heating an article by eddy-currents, it is placed inside a high frequency a.c. current-carrying coil (Fig. 47.18). The alternating magnetic field produced by the coil sets up eddy-currents in the article which, consequently, gets heated up. Such a coil is known as heater coil or work coil and the material to be heated is known as ***charge or load***. Primarily, it is the eddy-current loss which is responsible for the production of heat although hysteresis loss also contributes to some extent in the case of non-magnetic materials.

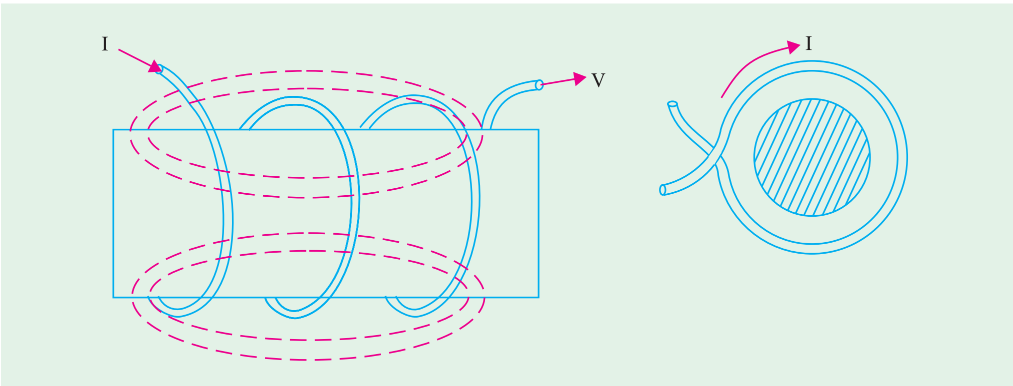


Fig. 47.18

The eddy-current loss $W_e \propto B^2 f^2$. Hence, this loss can be controlled by controlling flux density B and the supply frequency f. This loss is greatest on the surface of the material but decreases as we go deep inside. The depth of the material upto which the eddy-current loss penetrates is given by

$$d = \frac{1}{2\pi}\sqrt{\frac{\rho \cdot 10^9}{\propto_r \cdot f}}$$

where ρ = resistivity of the molten metal

f = supply frequency

$\propto_r$ = relative permeability of the charge

Eddy Current Heater

Advantages of Eddy-current Heating

(1) There is negligible wastage of heat because the heat is produced in the body to be heated.

(2) It can take place in vacuum or other special environs where other types of heating are not possible.

(3) Heat can be made to penetrate any depth of the body by selecting proper supply frequently.

Applications of Eddy-current Heating

(1) Surface Hardening. The bar whose surface is to be hardened by heat treatment is placed within the working coil which is connected to an a.c. supply of high frequency. The depth upto which the surface is to be hardened can be obtained by the proper selection of frequency of the coil current. After a few seconds, when surface has reached the proper temperature, a.c. supply is cut off and the bar is at once dipped in water.

(2) Annealing. Normally, annealing process takes long time resulting in scaling of the metal which is undesirable. However, in eddy-current heating, time taken is much less so that no scale formation takes place.

(3) Soldering. Eddy-current heating is economical for precise high-temperature soldering where silver, copper and their alloys are used as solders.

Example. 47.6. *Determine the efficiency of a high-frequency induction furnace which takes 10 minutes to melt 2 kg of a aluminium initially at a temperature of 20°C. The power drawn by the furnace is 5 kW, specific heat of aluminium = 0.212, melting point of alumimium = 660° C and latent heat of fusion of alumimium. = 77 kcal/kg.*

Solution. Heat required to melt aluminium = 2 × 77 = 154 kcal

Heat required to raise the temperature of aluminium from 20°C to 660°C

= 2 × 0.212 × (660 – 20) = 2 × 0.212 × 640 = 271.4 kcal

Total heat required = 154 + 271.4 = 425.4 kcal

Heat required per hour = 425.4 × 60/10 = 2552.4 kcal

Power delivered to aluminium = 2552.4/860 = 2.96 kW

∴ efficiency = output/input = 2.97/5 = **0.594 or 59.4%**

Example 47.7. *A low-frequency induction furnace has a secondary voltage of 20V and takes 600 kW at 0.6 p.f. when the hearth is full. If the secondary voltage is kept constant, determine the power absorbed and the p.f. when the hearth is half-full. Assume that the resistance of the secondary circuit is doubled but the reactance remains the same.*

Solution. Secondary current = $600 \times 10^3/20 \times 0.6 = 5 \times 10^4$ A

If this current is taken as the reference quantity, then secondary voltage is

$$V_2 = 20(0.6 + j\,0.8) = (12 + j16)\text{V}$$

Hence, secondary impedence, $Z_2 = (12 + j\,16)/5 \times 10^4 = (2.4 + j\,3.2) \times 10^{-4}$ ohm

Now, if the secondary resistance is double, then total impedence when the hearth is half-full is

$$= Z_2 = (4.8 + j3.2) \times 10^{-4} \text{ ohm}$$

Now, secondary current $I_2 = 20/(4.8 + j3.2) \times 10^{-4}$

$$= 20/5.77 \angle 33.7° \times 10^4 = 3.466 \angle -33.7° \times 10^4 \text{ A}$$

Now p.f. = cos 33.7° = 0.832

Hence, power absorbed = $20 \times 3.466 \times 10^4 \times 0.832 \times 10^{-3}$ = **580 kW**

Example 47.8. *Estimate the energy required to melt 0.5 tonne of brass in a single-phase induction furnace. If the melt is to be carried out in 0.5 hour, what must be the average power input to the furnace?*

Specific heat of brass = 0.094
Latent heat of fusion of brass = 30 kilocal/kg
Melting point of brass = 920°C
Furnace efficiency = 60.2%
The temperature of the cold charge may be taken as 20°C

Solution. Total amount of heat required to melt 0.5 kg of brass.

$$= (0.5 \times 1000) \times 39 + 500 \times 0.094 \times (920 — 20)$$
$$= 61{,}800 \text{ kcal} = 61{,}800/860 = 71.86 \text{ kWh}$$

Total furnace input = 71.86/0.602 = **119.4 kWh**

Example 47.9. *A low-frequency induction furnace whose secondary voltage is maintained constant at 10 V, takes 400 kW at 0.6 p.f. when the hearth is full. Assuming the resistance of the secondary circuit to vary inversely as the height of the charge and reactance to remain constant, find the height upto which the hearth should be filled to obtain maximum heat.*

(Utili. of Elect. Power and Traction, Gorakhpur Univ.)

Solution. Secondary current $I_2 = P/V_2 \cos\phi$

$$= 400 \times 10^3/10 \times 0.6 = 6.667 \times 10^4 \text{ A}$$

Impedence of the secondary circuit when hearth is full

$$Z_2 = V_2/I_2 = 10/6.667 \times 10^4 = 1.5 \times 10^{-4} \ \Omega$$

Secondary resistance when hearth is full, $R_2 = Z_2 \cos\phi$

$$= 1.5 \times 10^{-4} \times 0.6 = 0.9 \times 10^{-4} \ \Omega$$

Reactance of the secondary circuit, $X_2 = Z_2 \sin\phi$

$$= 1.5 \times 10^{-4} \times 0.8 = 1.2 \times 10^{-4} \ \Omega$$

In the second, let the height of the charge be x times of the full hearth *i.e.* $h = x$H

Since resistance varies inversely as the height of the charge

$$= R_2 = R_2/x = 0.9 \times 10^{-4}/x \ \Omega$$

Power drawn and hence heat produced will be maximum where secondary resistance equals its reactance.

$$\therefore \quad 0.9 \times 10^{-4}/x = 1.2 \times 10^{-4} \quad \text{or} \quad x = \mathbf{3/4}$$

Hence, maximum heat would be produced in the charge when its height is three-fourth the height of the hearth.

47.19. Dielectric Heating

It is also called high-frequency capacitative heating and is used for heating insulators like wood, plastics and ceramics etc. which cannot be heated easily and uniformly by other methods. The supply frequency required for dielectric heating is between 10-50 MHz and the applied voltage is upto 20 kV. The overall efficiency of dielectric heating is about 50%.

47.20. Dielectric Loss

When a practical capacitor is connected across an a.c. supply, it draws a current which leads the voltage by an angle ϕ, which is a little less than 90° or falls short of 90° by an angle δ. It means that there is a certain component of the current which is in phase with the voltage and hence produces some loss called dielectric loss. At the normal supply frequency of 50 Hz, this loss is negligibly small but at higher frequencies of 50 MHz or so, this loss becomes so large that it is sufficient to heat the dielectric in which it takes place. The insulating material to be heated is placed between two conducting plates in order to form a parallel-plate capacitor as shown in Fig. 47.19 (*a*).

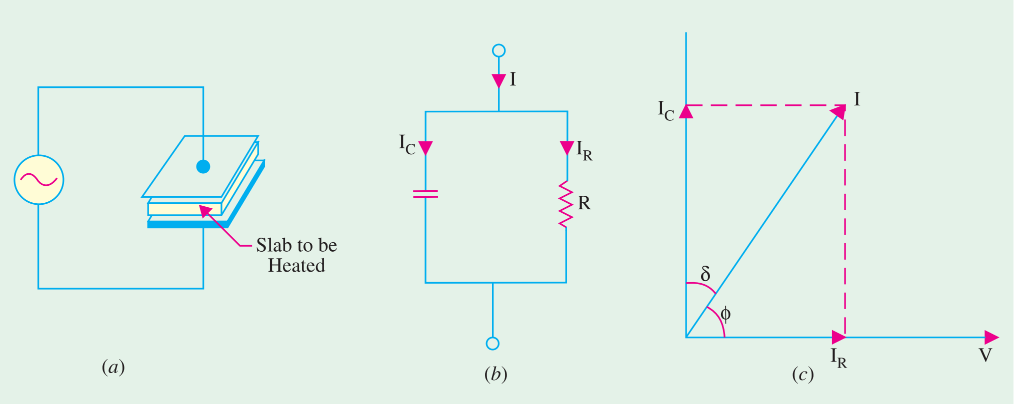


Fig. 47.19

Fig. 47.19 (*b*) shows the equivalent circuit of the capacitor and Fig. 47.19 (*c*) gives its vector diagram.

Power drawn from supply $= VI \cos \phi$

Now, $I_c = I = V/X_c = 2\pi f\, CV$

$\therefore$ $\boxed{P = V(2\pi fCV) \cos \phi = 2\pi fCV^2 \cos \phi}$

Now, $\phi = (90 - \delta)$, $\cos \phi = \cos (90 - \delta) = \sin \delta = \tan \delta = \delta$

where δ is very small and is expressed in radians.

$$\boxed{P = 2\pi fCV^2\delta \text{ watts}}$$

Here, $C = \epsilon_0 \epsilon_r \dfrac{A}{d}$ where d is the thickness and A is the surface area of the dielectric slab.

This power is converted into heat. Since for a given insulator material, C and δ are constant, the dielectric loss is directly proportional to $V^2 f$. That is why high-frequency voltage is used in dielectric heating. Generally, a.c. voltage of about 20 kV at a frequency of 10-30 MHz is used.

47.21. Advantages of Dielectric Heating

1. Since heat is generated within the dielectric medium itself, it results in uniform heating.
2. Heating becomes faster with increasing frequency.
3. It is the only method for heating bad conductors of heat.
4. Heating is fastest in this method of heating.
5. Since no naked flame appears in the process, inflammable articles like plastics and wooden products etc., can be heated safely.
6. Heating can be stopped immediately as and when desired.

47.22. Applications of Dielectric Heating

Since cost of dielectric heating is very high, it is employed where other methods are not possible or are too slow. Some of the applications of dielectric heating are as under :

Dielectric heating

1. For gluing of multilayer plywood boards.
2. For baking of sand cores which are used in the moulding process.
3. For preheating of plastic compounds before sending them to the moulding section.
4. For drying of tobacco after glycerine has been mixed with it for making cigarattes.
5. For baking of biscuits and cakes etc. in bakeries with the help of automatic machines.
6. For electronic sewing of plastic garments like raincoats etc. with the help of cold rollers fed with high-frequency supply.
7. For dehydration of food which is then sealed in air-tight containers.
8. For removal of moistures from oil emulsions.
9. In diathermy for relieving pain in different parts of the human body.
10. For quick drying of glue used for book binding purposes.

Example. 47.10. *A slab of insulating material 150 cm^2 in area and 1 cm thick is to be heated by dielectric heating. The power required is 400 W at 30 MHz. Material has relative permittivity of 5 and p.f. of 0.05. Determine the necessary voltage. Absolute permittivity = 8.854 × 10^{-12} F/m.*
(Utilisation of Elect. Energy, Punjab Univ.)

Solution. $P = 400\ W$, p.f. = 0.05, $f = 30 \times 10^6$ Hz

$C = \in_0 \in_r \; A/d = 8.854 \times 10^{-12} \times 5 \times 150 \times 10^{-4}/1 \times 10^{-2} = 66.4 \times 10^{-12}$ F

Now, $P = 2\pi f C V^2 \cos\phi$ or $400 = 2\pi \times 30 \times 10^6 \times 66.4 \times 10^{-12} \times V^2 \times 0.05$ or $V =$ **800 V**

Example. 47.11. *An insulating material 2 cm thick and 200 cm^2 in area is to be heated by dielectric heating. The material has relative permitivity of 5 and power factor of 0.05. Power required is 400 W and frequency of 40 MHz is to be used. Determine the necessary voltage and the current that will flow through the material. If the voltage were to be limited to 700 V, what will be the frequency to get the same loss?* **(A.M.I.E. Sec. B)**

Solution. $C = 8.854 \times 10^{-12} \times 5 \times 200 \times 10^{-4}/2 \times 10^{-2} = 44.27 \times 10^{-12}$ F

$$P = 2\pi f C V^2 \cos\phi \quad \text{or} \quad V = \sqrt{400/2\pi \times 40 \times 10^6 \times 44.27 \times 10^{-12} \times 0.05} = \mathbf{848\ V}$$

Current flowing through the material,

$$I = P/V \cos\phi = 400/848 \times 0.05 = \mathbf{9.48\ A}$$

Heat produced $\propto V^2 f$

$$\therefore \quad V_2^2 f_2 = V_1^2 f_1 \quad \text{or} \quad f_2 = f_1 (V_1/V_2)^2 = 40 \times 10^6 (848/700)^2 = \mathbf{58.7\ MHz}$$

Example 47.12. *A plywood board of 0.5 × 0.25 × 0.02 metre is to be heated from 25 to 125°C in 10 minutes by dielectric heating employing a frequency of 30 MHz. Determine the power required in this heating process. Assume specific heat of wood 1500/J/kg/°C; weight of wood 600 kg/m^3 and efficiency of process 50%.* **(Utilisation of Traction, B.H.U.)**

Solution. Volume of plywood to be heated = 0.5 × 0.25 × 0.02 = 0.0025 m^3

Weight of plywood = 0.0025 × 600 = 1.5 kg

Heat required to raise the temperature of plywood board from 25° to 125°

$= 1.5 \times 1500\ (125 - 25) = 2{,}25{,}000$ J or W-s

or $H = 2{,}25{,}000/60 \times 60 = 62.5$ Wh

Since heating is to be done in 10 minutes, power required $= 62.5/(10/60) = 375$ W

Since efficiency is 50%, power input = 375/0.5 = **700 W**

47.23. Choice of Frequency

The selection of frequency for heating is important because it has a great bearing on the work to be heated and the method of its heating whether by induction heating or dielectric heating. Furnaces running on power frequency of 50 Hz can be of 1 MW capacity whereas those running on medium frequencies (500 Hz to 1000 Hz) have a capacity of 50 kW and those running on high frequency (1 MHz to 2 MHz) have capacities ranging from 200 kW to 500 kW.

1. Induction Heating. While choosing frequency for induction heating, the following factors are considered :

(*a*) Thickness of the surface to be heated. Higher the frequency, thinner the surface that will get heated.

(*b*) The time of continuous heating. Longer the duration of heating, deeper the penetration of heat in the work due to conduction.

(*c*) The temperature to be obtained. Higher the temperature, higher the capacity of the generator required.

2. Dielectric Heating. The power consumed during dielectric heating, $P = 2\pi f C V^2 \cos\phi$. As seen, $P \propto f \times C \times V^2 \times \cos\phi$. Hence, rate of heat production can be increased by increasing voltage or voltage across any specimen is limited by its thickness or because of the consideration of potential gradient, breakdown voltage and safety etc., Voltages ranging from 600 V to 3000 V are used for dielectric heating, although voltages of 20 kV or so are also used sometimes.

Rate of heat production can also be increased by applying high potential but it is also limited because of the following considerations :

(*a*) Possibility of formation of standing waves between the surface of two electrodes having wavelength nearly equal to or more than one quarter of the wavelength of the particular frequency used.

(*b*) Necessity of employing special matching circuit at higher frequencies due to the fact that maximum power transfer takes place when the oscillator impedence equals the load impedence.

(*c*) At higher frequencies it is difficult for tuning inductance to resonate with the charge capacitance.

(*d*) At higher frequencies, it is almost impossible to get uniform voltage distribution.

(*e*) Since higher frequencies disturb near-by radio station services, special arrangement has to be made to stop radiations from the high-frequency generator used for the purpose.

47.24. Infrared Heating

When tungsten filament lamps are operated at about 2300°C (instead of 3000°C), they produce plenty of heat radiations called ***infrared radiations***. With the help of suitable reflectors, these infrared radiations are focused on the surface to be heated. The lamps so employed have ratings varying from 250 W to 1000 W operating at 115 W. Lower voltage results in robust filaments. With this arrangement, the charge temperature obtain is between 200°C and 300°C. The heat emission intensity obtained is about 7000 W/m^2 as compared to 1500 W/m^2 obtained with ordinary resistance furnaces. In this type of heating, heat absorption remains practically constant whatever the charge temperature whereas it falls rapidly as the temperature of charge rises in the ordinary resistance furnace.

Infrared heating is used for paint drying and for drying foundary moulds, for low temperature heating of plastics and for various dehydration and other processes.

Tutorial Problem No. 47.1

1. A slab of insulating material 150 cm^2 in area and 1 cm. thick is to be heated by dielectric heating. The power required is 400W at 30 MHz. Material has permitivity of 5 and p.f. 0.05. Determine the voltage necessary. Absolute permittivity = 8.854×10^{-12} F/m.
[800 V] *(Utilisation of Elect. Energy, Punjab Univ.)*

2. A 20-kW, 1-phase, 220-V resistance oven employs circular nickel chrome wire for its heating elements. If the wire temperature is not to exceed 1107° C and the temperature of the charge is to be 500°C, calculate the length and size of wire required. Assume a radiating efficiency of 0.6 and the specific resistance of nickel chrome as 100×10^{-6} Ω cm and emissivity 0.9.
[l =17.1 m, d = 0.3 cm] *(Utilisation of Elect. Power, A.M.I.E.)*

3. An electric toaster consists of two resistance elements each of 190 ohm. Calculate the power drawn from 250 V a.c. single-phase supply, when the elements are connected in (*i*) parallel and (*ii*) series.
[(*i*) 658 W (*ii*) 164.5 W]

4. A 15-kW, 220-V, single-phase resistance oven employs nickel-chrome wire for its heating elements. If the wire temperature is not to exceed 1,000°C and the temperature of the charge is to be 600°C, calculate the diameter and length of the wire. Assume radiating efficiency to be 0.6 and emissivity as 0.9. For nickel chrome resistivity is 1.016×10^{-6} Ω–m. **[3.11 mm, 24.24 m]**
(Utili. of Elect. Power, A.M.I.E. Sec. B)

5. A 30-kW, 3-phase, 400-V resistance oven is to employ nickel-chrome strip 0.025 cm thick for the 3-phase star-connected heating elements. If the wire temperature is to be 1100°C and that of charge is to be 700°C, estimate a suitable width for the strip. Assume radiating efficiency as 0.6 and emissivity as 0.90. The specific resistance of the nichromealloy is 1.03×10^{-6} Ω–m. State any assumptions made. **[6.86 mm]** *(Utili. of Elect. Power, A.M.I.E. Sec. B.)*

6. Estimate the efficiency of a high-frequency induction furnace which takes 10 minutes to melt 1.8 kg of a aluminium, the input to the furnace being 5 kW and initial temperature 15°C. Given :
Specific heat of aluminium = 880 J/kg/°C
Melting point of aluminium = 660°C
Latent heat of fusion of aluminium = 32 kJ/kg and 1J = 2.78×10^{-7} kWh.
[36 %] *(Elect. Drives and Util. of Elect. Energy, Punjab Univ.)*

7. A 3-phase electric arc furnace has the following data :
Current drawn = 5,000 A ; Arc voltage = 50 V
Resistance of transformer referred to primary =0.002 Ω
Resistance of transformer referred to secondary=0.004 Ω
(*i*) Calculate the power factor and kW drawn from the supply.
(*ii*) If the overall efficiency of furnace is 65%, find the time required to melt 2 tonnes of steel when latent heat of steel = 8.89 kcal/kg. Specific heat of steel = 0.12, melting point of steel = 1370°C and initial temperature of steel = 20°C.
[(*i*) 0.9847; 900 kW, (*ii*) 40 min. 46 s.] *(Utili. of Elect. Power, A.M.I.E. Sec. B.)*

8. Dielectric heating is to be employed to heat a slab of insulating material 20 mm thick and 1530 mm^2 in area. Power required is 200 W and a frequency of 3 MHz is to be used. The material has a permitivity of 5 and p.f. of 0.05. Determine the voltage necessary and the current which will flow through the material. **[8000 V ; 0.5 A]** *(Elect. Drives and Utili of Elect. Energy, Punjab Univ.)*

9. What are the advantages of electrically produced heat? What are the properties to be possessed by the element used in resistance oven? *(J.N. University, Hyderabad, November 2003)*

10. A 20 kW single-phase, 220 V resistance oven employs circular nichrome wire for its heating element, if the wire temperature is not to exceed 1227° and the temperature of the charge is to be 427°C, calculate the size and length of the wire required. Assume emissivity = 0.9, radiating efficiency = 0.6 and specific resistance of wire = $1.09 \cdot 10^{-6}$Ω–m.
(J.N. University, Hyderabad, November 2003)

11. Discuss the various modes of heat dissipation. *(J.N. University, Hyderabad, November 2003)*
12. Explain in brief how heating is done in the following cases?
(*i*) Resistance heating, (*ii*) Induction heating, (*iii*) Dielectric heating.
(J.N. University, Hyderabad, November 2003)
13. 90 Kg of tin is to smelt during an hour in smelting furnace. Determine the suitable rating of teh furnace, if melting temperature = 230°C, specific heat = 0.055, latent heat of liquidification is 13.3 Kcal/kg. Take the initial temperature of the metal as 35°C.
(J.N. University, Hyderabad, November 2003)
14. Explain the principle of Induction heating, What are the applications ofinduction heating.
(J.N. University, Hyderabad, November 2003)
15. With a neat sketch explain the working principle of coreless type induction furnace.
(J.N. University, Hyderabad, November 2003)
16. Explain with a neat sketch the principle of coreless type induction furnace.
(J.N. University, Hyderabad, November 2003)
17. 100 kg of tin is to smelt in one hour in a smelting furnance. Determine the suitable rating of furnace if smelting temperature of tin is 235°C; specific heat is 0.055, latent heat of liquidification 13.3 Kcal/kg. Take initial temperature of metal as 35°C.*(J.N. University, Hyderabad, November 2003)*
18. A low frequency Induction Furnace whose secondary voltage is maintained constant at 12 Volts takes 300 Kw at 0.65 p.f. when the head of the charge and reactance to remain constant, find the height upto which the hearth should be filled to obtain maximum heat.
(J.N. University, Hyderabad, November 2003)
19. Give relative advantages and disadvantages of direct and indirect electric arc furnances.
(J.N. University, Hyderabad, April 2003)
20. An electric arc furnace consuming 5 KW takes 15 minutes to just melt 1.5 Kgs of aluminium, the initial temperature being 15°C. Find the efficiency of the furnace. Specific heat of aluminium is 0.212, melting point 658°C and latent heat of fusion is 76.8 Cal per gram.
(J.N. University, Hyderabad, April 2003)
21. What are the causes of failure of heating elements? *(J.N. University, Hyderabad, April 2003)*
22. Six resistances each of 40ohms are used as heating elements in furnace. Find the power of the furnace for various connections to a three phase 230 V supply.
(J.N. University, Hyderabad, April 2003)
23. What are different methods of heat transfer Explain in brief ?
(J.N. University, Hyderabad, April 2003)
24. What are the advantages of radiant heating ? *(J.N. University, Hyderabad, April 2003)*
25. Describe various types of electric heating equipment. *(J.N. University, Hyderabad, April 2003)*
26. What are the causes of failure of heating elements? *(J.N. University, Hyderabad, April 2003)*
27. Six resistances each of 40 ohms are used as heating elements in furnace. Find the power of the furnace for various connections to a three phase 230 V supply.
(J.N. University, Hyderabad, April 2003)
28. Explain why very high frequencies should not be used for dielectric hearing.
(J.N. University, Hyderabad, December 2002/January 2003)
29. A wooden board 30 cms × 15 cms × 2 cms is to be heated from 20°C to 180°C in 10 minutes by dielectric heating using 40 MHz supply. Specific heat of wood 0.35 and density 0.55 gm/cc. $\varepsilon_r = 5$ and p.f. 0.05. Estimate the voltage across the specimen and current during heating. Assume loss of energy by conduction, convection and radiation as 10%.
(J.N. University, Hyderabad, December 2002/January 2003)
30. Write short Notes on The Ajax-yatt furnace.
(J.N. University, Hyderabad, December 2002/January 2003)
31. Discuss the different methods of electric heating and their relative merits
(J.N. University, Hyderabad, December 2002/January 2003)
32. Dielectric heating is to be employed to heat a slab of insulating meterial of 20 mm thick and 1500 mm^2 in area. The power required is 200 watts at a frequency of 30 MHz. The material has a permittivity of 5 and a power factor of 0.05. Determine the voltage necessary and the current which flows through the material. *(J.N. University, Hyderabad, December 2002/January 2003)*

33. State the advantages of electric heating.
(J.N. University, Hyderabad, December 2002/January 2003)

34. Brifely explain the different methods of electric heating.
(J.N. University, Hyderabad, December 2002/January 2003)

35. Estimate the energy required to melt 500 kg of brass in a single phase Ajax-wyatt furnace.Ifthe melting is to be carried out in 3/4 hour, what must be the avarage power input to the furnace.
(J.N. University, Hyderabad, December 2002/January 2003)

OBJECTIVE TESTS – 47

1. As compared to other methods of heating using gas and coal etc, electric heating is far superior because of its.
(*a*) cleanliness
(*b*) ease of control
(*c*) higher efficiency
(*d*) all of the above.

2. Magnetic materials are heated with the help of
(*a*) hysteresis loss (*b*) electric arc
(*c*) electric current (*d*) radiation.

3. In the indirect resistance heating method, heat is delivered to the charge
(*a*) direcly (*b*) by radiation
(*c*) by convection (*d*) both (*b*) and (*c*).

4. The main requirements of a good heating element used in a resistance furnaces are
(*a*) high resistivity
(*b*) high melting-temperature
(*c*) positive resistance-temperature coefficient
(*d*) all of the above.

5. Electric ovens using heating elements of .... can produce tempera- tures up to 3000°C
(*a*) nickel (*b*) graphite
(*c*) chromium (*d*) iron.

6. The temperature of resistance furnaces can be controlled by changing the
(*a*) applied voltage
(*b*) number of heating elements
(*c*) circuit configuration
(*d*) all of the above.

7. Which of the following heating method is based on the transformer principle ?
(*a*) resistance heating
(*b*) eddy-current heating
(*c*) induction heating
(*d*) dielectric heating.

8. When graphite electrodes are used in arc furnaces, the temperature obtained is in the range of ....degree centi-grade.
(*a*) 3000-3500 (*b*) 2500-3000
(*c*) 2000-2500 (*d*) 1500-2000

9. Which of the following furnace suffers from pinch effect?
(*a*) resistance furnace
(*b*) core type induction furnace
(*c*) coreless induction furnace
(*d*) vertical core type induction furnace.

10. Which of the following induction furnace has the lowest power factor?
(*a*) vertical core type
(*b*) indirect core type
(*c*) coreless type
(*d*) core type.

11. The coreless induction furnace uses high-frequency electric supply in order to obtain high
(*a*) flux density
(*b*) eddy-current loss
(*c*) primary resistance
(*d*) power factor.

12. Inflammable articles like plastic and wooden products etc, can be safely heated by using................... heating.
(*a*) eddy-current (*b*) dielectric
(*c*) induction (*d*) resistance

13. Which of the following is an advantages of heating by electricity?
(*a*) Quicker operation
(*b*) Higher efficiency
(*c*) Absence of flue gases
(*d*) All of the above

14. ...... has the highest value of thermal conductivity.
(*a*) Copper (*b*) Aluminium
(*c*) Brass (*d*) Steel

15. Which of the following heating methods has maximum power factor?
(*a*) Arc heating
(*b*) Dielectric heating
(*c*) Induction heating
(*d*) Resistance heating

16. ...... method has leading power factor
(*a*) Resistance heating
(*b*) Dielectric heating
(*c*) Arc heating
(*d*) Induction heating

17. ...... is used for heating non-conducting meterials.
(*a*) Eddy current heating
(*b*) Arc heating
(*c*) Induction heating
(*d*) Dielectric heating

18. Which of the following methods of heating is not dependent on the frequency of supply?
(*a*) Induction heating
(*b*) Dielectric heating
(*c*) Electric resistance heating
(*d*) All of the above

19. When a body reflects entire radiation incident on it, then it is known as
(*a*) white body (*b*) grey body
(*c*) black body (*d*) transparent body

20. For the transmission of heat from one body to another
(*a*) temperature of the two bodies must be different
(*b*) both bodies must be solids
(*c*) both bodies must be in contact
(*d*) at least one of the bodies must have some source of heating

21. Heat transfer by condition will not occur when
(*a*) bodies are kept in vacuum
(*b*) bodies are immersed in water
(*c*) bodies are exposed to thermal radiations
(*d*) temperatures of the two bodies are identical

22. A perfect black body is one that
(*a*) transmits all incident radiations
(*b*) absorbs all incident radions
(*c*) reflects all incident radiations
(*d*) absorbs, reflects and transmits all incident radiations

23. Heat is transferred simultaneously by condition, convection and radiation
(*a*) inside boiler furnaces
(*b*) during melting of ice
(*c*) through the surface of the insulted pipe carring steam
(*d*) from refrigerator coils to freezer of a refrigerator

24. The process of heat transfer during the re-entry of satellites and missiles, at very high speeds, into earth's atmosphere is known as
(*a*) ablation
(*b*) radiation
(*c*) viscous dissipation
(*d*) irradiation

25. Which of the following has the highest value of thermal conductivity?
(*a*) Water (*b*) Steam
(*c*) Solid ice (*d*) Melting ice

26. Induction heating process is based on which of the following principles?
(*a*) Thermal ion release principle
(*b*) Nucleate heating principle
(*c*) Resistance heating principle
(*d*) Electro-magnetic induction principle

27. Which of the following insulating materials is suitable for low temperature applications?
(*a*) Asbestos paper
(*b*) Diatomaceous earth
(*c*) 80 percent magnesia
(*d*) Cork

28. A non-dimensional number generally associated with natural convection heat transfer is
(*a*) Prandtl number
(*b*) Grash off number
(*c*) Pecelet number
(*d*) Nusselt number

29. The temperature inside a furnace is usually measured by which of the following?
(*a*) Optical pyrometer
(*b*) Mercury thermometer
(*c*) Alcohol thermometer
(*d*) Any of the above

30. Which of the following will happen if the thickness of refractory wall of furnace is increased?
(*a*) Heat loss through furnace wall will increase
(*b*) Temperature inside the furnace will fall
(*c*) Temperature on the outer surface of furnace walls will drop
(*d*) Energy consumption will increase

31. The material of the heating element for a furnace should have
(*a*) lower melting point
(*b*) higher temperature co-efficient
(*c*) high specific resistance
(*d*) all of the above

32. In a resistance furnace the atmosphere is ....
(*a*) oxidising (*b*) deoxidising
(*c*) reducing (*d*) neutral

33. By which of the following methods the temperature inside a resistance furnance can be varied?
(*a*) By disconnecting some of the heating elements
(*b*) By varying the operating voltage
(*c*) By verying the current through heating elements
(*d*) By any of the above method

34. In induction heating ...... is abnormally high.
(a) phase angle (b) frequency
(c) current (d) voltage

35. By the use of which of the following high frequency power supplyv for induction furnaces can be obtained?
(a) Coreless transformers
(b) Current transformers
(c) Motor-generator set
(d) Multi-phase transformer

36. Induction furnaces are employed for which of the following?
(a) Heat treatment of castings
(b) Heating of insulators
(c) Melting aluminium
(d) None of the above

37. In an electric room heat convector the method of heating used is
(a) arc heating
(b) resistance heating
(c) induction heating
(d) dielectric heating

38. In a domestic cake baking oven the temperature is controlled by
(a) voltage variation
(b) thermostat
(c) auto-transformer
(d) series-parallel operation

39. In an electric press mica is used
(a) as an insulator
(b) as a device for power factor improvement
(c) for dielectric heating
(d) for induction heating

40. Induction heating takes place in which of the following?
(a) Insulating materials
(b) Conducting materials which are magnetic
(c) Conducting materialswhich are non-magnetic
(d) Conducting materials which may or may not be magnetic

41. For heating element high resistivity material is chosen to
(a) reduce the length of heating element
(b) increase the life of the heating element
(c) reduce the effect of oxidation
(d) produce large amount of heat

42. In resistance heating highest working temperature is obtained from heating elements made of ....
(a) nickel copper (b) nichrome
(c) silicon carbide (d) silver

43. For intermittent work which of the following furnaces is suitable?
(a) Indirect arc furnace
(b) Core less furnace
(c) Either of the above
(d) None of the above

44. Due to which of the following reasons it is desirable to have short arc length?
(a) To achieve better heating
(b) To increase the life of roof refractory
(c) To have better stirring action
(d) To reduce problem of oxidation
(e) All of the above

45. In the indirect resistance heating method, maximum heat-transfer takes place by
(a) radiation (b) convection
(c) conduction (d) any of the above

46. Property of low temperature co-efficient of heating element is desired due to which of the following reasons?
(a) To avoid initial rush of current
(b) To avoid change in kW rating with temperature
(c) Both (a) and (b)
(d) Either (a) or (b)

47. Which of the following methods is used to control temperature in resistance furnaces?
(a) Variation of resistance
(b) Variation of voltage
(c) Periodical switching on and off of the supply
(d) All of the above methods

48. It is desirable to operate the arc furnace at power factor of
(a) zero (b) 0.707 lagging
(c) unity (d) 0.707 leading

49. Radiations from a black body are proportional to
(a) T (b) T^2
(c) T^3 (d) T^4

50. In arc furnace the function of choke is
(a) to stabilize the arc
(b) to improve power factor
(c) to reduce severity of the surge
(d) none of the above

51. Ajax Wyatt furnace is started when
(a) it is filled below core level
(b) it is filled above core level
(c) it is fully empty
(d) none of the above

52. In electric press, mica is used because it is .... conductor of heat but/and .... conductor of electricity.
(a) bad, good (b) bad, bad
(c) good, bad (d) good, good

53. Resistance variation method of temperature control is done by connecting resistance elements in

(a) series
(b) parallel
(c) series-parallel connections
(d) star-delta connections
(e) all of the above ways

54. Hysteresis loss and eddy current loss are used in
(a) induction heating of steel
(b) dielectric heating
(c) induction heating of brass
(d) resistance heating

55. In heating the ferromagnetic material by induction heating, heat is produced due to
(a) induced current flow through the charge
(b) hysteresis loss taking place below curie temperature
(c) due to hysteresis loss as well as eddy current loss taking place in the charge
(d) one of the above factors

56. Radiant heating is used for which of the following?
(a) Annealing of metals
(b) Melting of ferrous metals
(c) Heating of liquids in electric kettle
(d) Drying of paints and varnishes

57. Which of the following devices is necessarily required for automatic temperature control in a furnace?
(a) Thermostat
(b) Thermocouple
(c) auto-transformer
(d) Heating elements of variable resistance material

58. For radiant heating around 2250ºC, the heating elements are made of
(a) copper alloy (b) carbon
(c) tungsten alloy (d) stainless steel alloy

59. Which of the following is an advantage of eddy current heating?
(a) The amount of heat generated can be controlled accurately
(b) Heat at very high rate can be generated
(c) The area of the surface over which heat is produced can be accurately controlled
(d) All of the above

60. The electrode of a direct arc furnace is made of
(a) tungsten
(b) graphite
(c) silver
(d) copper

61. Direct arc furnaces have which of the following power factors?
(a) Unity
(b) Low, lagging
(c) Low, leading
(d) Any of the above

62. In direct arc furnace, which of the following has high value?
(a) Current
(b) Voltage
(c) Power factor
(d) All of the above

ANSWERS

1. (d)	**2.** (a)	**3.** (d)	**4.** (d)	**5.** (b)	**6.** (d)	**7.** (c)
8. (a)	**9.** (b)	**10.** (d)	**11.** (b)	**12.** (b)	**13.** (d)	**14.** (a)
15. (d)	**16.** (b)	**17.** (d)	**18.** (c)	**19.** (a)	**20.** (a)	**21.** (d)
22. (b)	**23.** (a)	**24.** (a)	**25.** (c)	**26.** (d)	**27.** (b)	**28.** (b)
29. (a)	**30.** (c)	**31.** (c)	**32.** (a)	**33.** (d)	**34.** (b)	**35.** (c)
36. (a)	**37.** (b)	**38.** (b)	**39.** (a)	**40.** (d)	**41.** (a)	**42.** (c)
43. (a)	**44.** (e)	**45.** (a)	**46.** (c)	**47.** (d)	**48.** (b)	**49.** (d)
50. (a)	**51.** (d)	**52.** (c)	**53.** (e)	**54.** (a)	**55.** (c)	**56.** (d)
57. (b)	**58.** (c)	**59.** (d)	**60.** (b)	**61.** (b)	**62.** (a)	

GO To FIRST

CONTENTS

CHAPTER 48

Learning Objectives

- Definition of Welding
- Welding Processes
- Four Positions of Arc Welding
- Electrodes for Metal Arc Welding
- Advantages of Coated Electrodes
- Arc Welding Machines
- V-I Characteristics of Arc Welding D.C. Machines
- D.C. Welding Machines with Motor Generator Set
- AC Rectified Welding Unit
- AC Welding Machines
- Carbon Arc Welding
- Submerged Arc Welding
- Gas Shield Arc Welding
- TIG Welding
- MIG Welding
- MAG Welding
- Resistance Welding
- Spot Welding
- Seam Welding
- Projection Welding
- Butt Welding
- Flash Butt Welding
- Upset Welding
- Stud Welding
- Electrogas Welding
- Electron Beam Welding

ELECTRIC WELDING

Electricity is used to generate heat necessary to melt the metal to form the necessary joints

CONTENTS

48.1. Definition of Welding

It is the process of joining two pieces of metal or non-metal at faces rendered plastic or liquid by the application of heat or pressure or both. Filler material may be used to effect the union.

48.2. Welding Processes

All welding processes fall into two distinct categories :

1. Fusion Welding—It involves melting of the parent metal. Examples are:

(*i*) Carbon arc welding, metal arc welding, electron beam welding, electroslag welding and electrogas welding which utilize electric energy and

(*ii*) Gas welding and thermit welding which utilize chemical energy for the melting purpose.

2. Non-fusion Welding—It does not involve melting of the parent metal. Examples are:

(*i*) Forge welding and gas non-fusion welding which use chemical energy.

(*ii*) Explosive welding, friction welding and ultrasonic welding etc., which use mechanical energy.

(*iii*) Resistance welding which uses electrical energy.

Proper selection of the welding process depends on the (*a*) kind of metals to be joined (*b*) cost involved (*c*) nature of products to be fabricated and (*d*) production techniques adopted.
The principal welding processes have been tabulated in Fig. 48.1

48.3. Use of Electricity in Welding

Electricity is used in welding for generating heat at the point of welding in order to melt the material which will subsequently fuse and form the actual weld joint. There are many ways of producing this localised heat but the two most common methods are as follows :

1. resistance welding—here current is passed through the inherent resistance of the joint to be welded thereby generating the heat as per the equation $I^2 Rt/J$ kilocalories.

2. arc welding—here electricity is conducted in the form of an arc which is established between the two metallic surfaces

48.4. Formation and Characteristics of Electric Arc

An electric arc is formed whenever electric current is passed between two metallic electrodes which are separated by a short distance from each other. The arc is started by momentarily touching the positive electrode (anode) to the negative metal (or plate) and then withdrawing it to about 3 to 6 mm from the plate. When electrode first touches the plate, a large short-circuit current flows and as it is later withdrawn from the plate, current continues to flow in the form of a spark across the air gap so formed. Due to this spark (or discharge), the air in the gap becomes ionized *i.e.* is split into negative electrons and positive ions. Consequently, air becomes conducting and current is able to flow across the gap in the form of an arc.

As shown in Fig. 48.2, the arc consists of ***lighter*** electrons which flow from cathode to anode and ***heavier*** positive ions which flow from anode to cathode. Intense heat is generated when high-velocity electrons strike the anode. Heat generated at the cathode is much less because of the low velocity of the impinging ions. It is found that nearly **two-third** of the heat is developed at the anode which burns into the form of a crater where temperature rises to a value of 3500-4000°C. The remaining one-third of the heat is developed near the cathode. The above statement is true in all d.c. systems of welding where positive side of the circuit is the hottest side. As a result, an electrode connected to the positive end of the d.c. supply circuit will burn 50% faster than if connected to the negative end. This fact can be used for obtaining desired penetration of the base metal during welding.

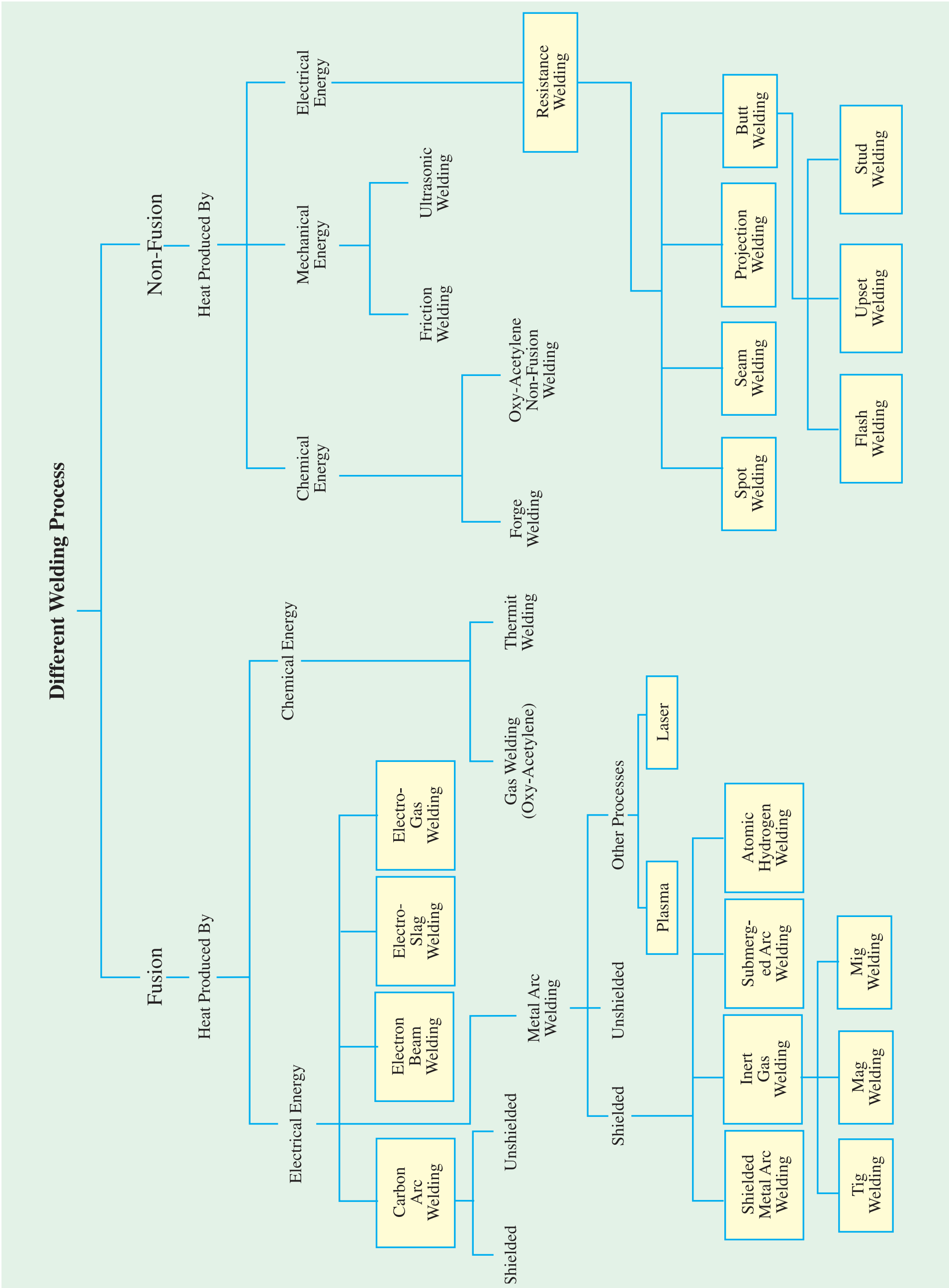


Fig. 48.1

If positive supply end is connected to the base metal (which is normally grounded), penetration will be greater due to more heat and, at the same time, the electrode will burn away slowly [Fig. 48.3 (*a*)] since it is connected to the negative end of the supply. If supply connections are reversed, the penetration of heat zone in the base metal will be comparatively shallow and, at the same time, electrode will burn fast [Fig. 48.3 (*b*)]. AC supply produces a penetration depth that is nearly halfway between that achieved by the d.c. positive ground and negative ground as shown in Fig. 48.3 (*c*).

It may be noted that with a.c. supply, heat is developed equally at the anode and cathode due to rapid reversal of their polarity. The arc utilized for arc welding is a low-voltage high-current discharge. The voltage required for striking the arc is higher than needed for maintaining it. Moreover, amperage increases as voltage decreases after the arc has been established. Fig 48.4 shows V/I characteristics of an electric arc for increasing air-gap lengths. The voltage required to strike a d.c. arc is about 50-55 V and that for a.c. arc is 80-90 V. The voltage drop across the arc is nearly 15-20 V. It is difficult to maintain the arc with a voltage less than 14 V or more than 40 V.

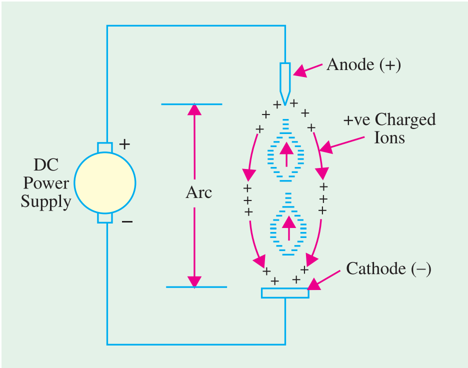


Fig. 48.2

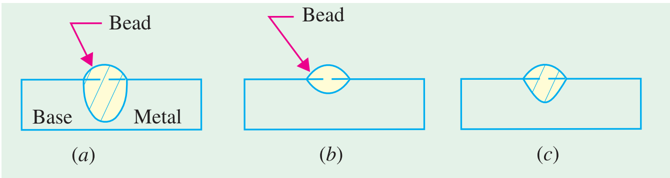


Fig. 48.3

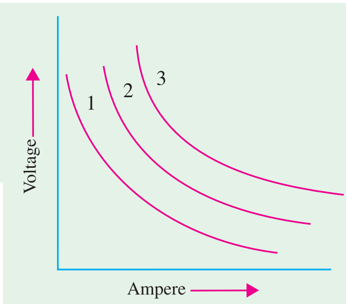


Fig. 48.4

48.5. Effect of Arc Length

In metal arc welding, a fairly short arc length is necessary for getting good welds. Short arc length permits the heat to be concentrated on the workpiece, is more stable because effect of magnetic blow is reduced and the vapours from the arc surround the electrode metal and the molten pool thereby preventing air from destroying the weld metal. When arc length is long

1. large amount of heat is lost into the surrounding area thus preventing good penetration and fusion;
2. arc flame is very unstable since effect of magnetic blow is increased. Hence, arc flame will have a tendency to blow out;
3. air is able to reach the molten globule of metal as it passes from the electrode to the weld and weld pool. It leads to the contamination of the weld due to absorption of oxygen and nitrogen;
4. weld deposits have low strength, poor ductility, high porosity, poor fusion and excessive spatter.

The length of arc required for welding will depend on the kind of electrode used, its coating, its diameter, position of welding and the amount of current used. Usually, shorter arc length are necessary for vertical, horizontal and overhead welding than for flat welding.

An electric arc is produced when electricity is passed between two electrodes

48.6. Arc Blow

An arc column can be considered as a flexible current-carrying conductor which can be easily deflected by the magnetic field set up in its neighbourhood by the positive and negative leads from the d.c. welding set. The two leads carry currents in the opposite directions and hence, set up a repulsive magnetic force which pulls the arc away from the weld point particularly when welding corners where field concentration is maximum. The deflection of the arc is called **arc blow**. This condition is encountered only with d.c. welding sets and is especially noticeable when welding with bare electrodes. It is experienced most when using currents above 200 A or below 40 A.

Due to arc blow, heat penetration in the required area is low which leads to incomplete fusion and bead porosity apart from excessive weld spatter.

Arc blow can be avoided by using a.c. rather than d.c. welding machines because reversing currents in the welding leads produce magnetic fields which cancel each other out thereby eliminating the arc blow. However, with d.c. welding machines, arc blow effects can be minimized by (*i*) welding away from the earth ground connection, (*ii*) changing the position of the earth connection on the work, (*iii*) wrapping the welding electrode cable a few turns around the work, (*iv*) reducing the welding current or electrode size, (*v*) reducing the rate of travel of the electrode and (*vi*) shortening the arc column length etc.

48.7. Polarity in DC Welding

Arc welding with the electrode connected to the positive end of the d.c. supply is called reverse polarity.* Obviously, the workpiece is connected to the negative end.

A better name for d.c. reverse polarity (DCRP) *is* ***electrode-positive*** as shown in Fig. 48.5 (*a*). As stated earlier in Art. 48.4, two-third of the arc heat is developed at the anode. Hence, in DCRP welding, electrode is the hottest whereas workpiece is comparatively cooler. Consequently, electrode burns much faster but weld bead is relatively shallow and wide. That is why thick and heavily-coated electrodes are used in DCRP welding because they require more heat for melting.

Arc welding with the electrode connected to the negative end of the d.c. supply is called **straight polarity**.** Obviously, the workpiece is connected to the positive end as shown in Fig. 48.5 (*b*). A better name for d.c. straight polarity (DCSP) is ***electrode-negative***.

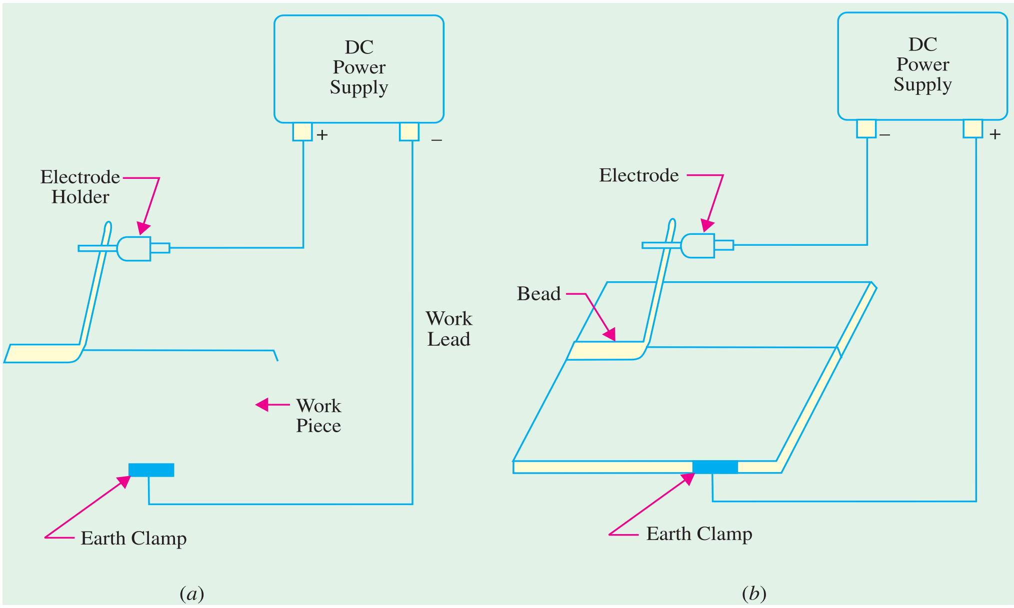


Fig. 48.5

* In British literature, it is called straight polarity.

** In British literature, it is called reverse polarity.

In DCSP welding, workpiece is the hottest, hence base metal penetration is narrow and deep. Moreover, bare and medium-coated electrodes can be used in this welding as they require less amount of heat for melting.

It is seen from the above discussion that polarity necessary for the welding operation is determined by the type of electrode used.

It is also worth noting that in a.c. welding, there is no choice of polarity because the circuit becomes alternately positive, first on one side and then on the other. In fact, it is a combination of D CSP and D CRP.

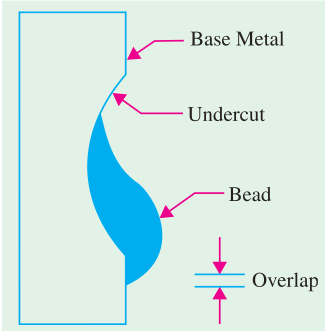


Fig. 48.6

48.8. Four Positions of Arc Welding

There are four basic positions in which manual arc welding is done.

1. Flat position. It is shown in Fig. 48.7 (*a*). Of all the positions, flat position is the easiest, most economical and the most used for all shielded arc welding. It provides the strongest weld joints. Weld beads are exceedingly smooth and free of slag spots. This position is most adaptable for welding of both ferrous and non-ferrous metals particularly for cast iron.

2. Horizontal Position. It is the second most popular position and is shown in Fig. 48.7 (*b*). It also requires a short arc length because it helps in preventing the molten puddle of the metal from sagging. However, major errors that occur while welding in horizontal position are under-cutting and over-lapping of the weld zone (Fig. 48.6).

3. Vertical Position. It is shown in Fig. 48.7 (*c*). In this case, the welder can deposit the bead either in the uphill or downhill direction. Downhill welding is preferred for thin metals because it is faster than the uphill welding. Uphill welding is suited for thick metals because it produces stronger welds.

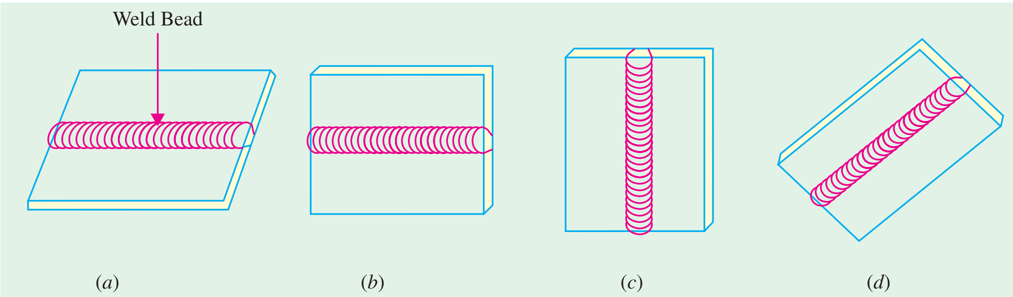


Fig. 48.7.

4. Overhead Position. It is shown in Fig. 48.7 (*d*). Here, the welder has to be very cautious otherwise he may get burnt by drops of falling metal. This position is thought to be the most hazardous but not the most difficult one.

48.9. Electrodes for Metal Arc Welding

An electrode is a filler metal in the form of a wire or rod which is either bare or coated uniformly with flux. As per IS : 814-1970, the contact end of the electrode is left bare and clean to a length of 20-30 mm. for inserting it into electrode holder (Fig. 48.8).

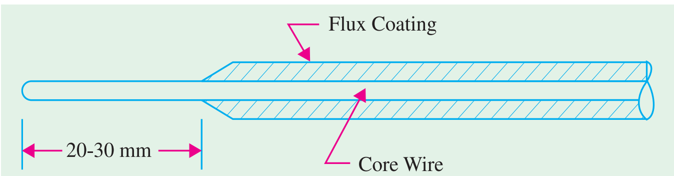


Fig. 48.8

Metal arc welding was originally done with bare electrodes which consisted of a piece of wire or rod of the same metal as the base metal. However, due to atmospheric contamination, they produced brittle and poor quality welds.

Hence, bare wire is no longer used except for automatic welding in which case arrangement is made to protect the weld area from the atmosphere by either powdered flux or an inert gas. Since 1929, coated electrodes are being extensively used for shielded arc welding. They consist of a metal core wire surrounded by a thick flux coating applied by extrusion, winding or other processes. Depending on the thickness of the flux coating, coated electrodes may be classified into *(i)* lightly-dusted (or dipped) electrodes and *(ii)* semi-coated (or heavy-coated) electrodes. Materials commonly used for coating are *(i)* titanium oxide *(ii)* ferromanganese *(iii)* silica flour *(iv)* asbestos clay *(v)* calcium carbonate and *(vi)* cellulose with sodium silicate often used to hold ingredients together.

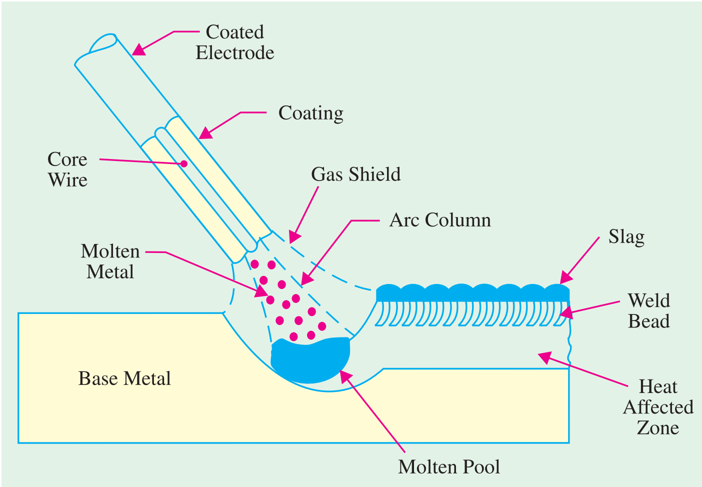


Fig. 48.9

Electrode coating contributes a lot towards improving the quality of the weld. Part of the coating burns in the intense heat of the arc and provides a gaseous shield around the arc which prevents oxygen, nitrogen and other impurities in the atmosphere from combining with the molten metal to cause a poor quality brittle and weak weld. Another portion of the coating flux melts and mixes with the impurities in the molten pool causing them to float to the top of the weld where they cool in the form of slag (Fig. 48.9). This slag improves the bead quality by protecting it from the contaminating effects of the atmosphere and causing it to cool down more uniformly. It also helps in controlling the basic shape of the weld bead.

The type of electrode used depends on the type of metal to be welded, the welding position, the type of electric supply whether a.c. or d.c. and the polarity of the welding machine.

48.10. Advantages of Coated Electrodes

The principal advantages of using electrode coating are as under :

1. It stablizes the arc because it contains ionizing agents such as compounds of sodium and potassium.
2. It fluxes away impurities present on the surface being welded.
3. It forms slag over the weld which *(i)* protects it from atmospheric contamination *(ii)* makes it cool uniformly thereby reducing the changes of brittleness and *(iii)* provides a smoother surface by reducing 'ripples' caused by the welding operation.
4. It adds certain materials to the weld metal to compensate for the loss of any volatile alloying elements or constituents lost by oxidization.
5. It speeds up the welding operation by increasing the rate of melting.
6. It prevents the sputtering of metal during welding.

7. it makes it possible for the electrode to be used on a.c. supply. In a.c. welding, arc tends to cool and interrupt at zero-current positions. But the shielding gases produced by the flux keep the arc space ionized thus enabling the coated electrodes to be used on a.c. supply.

It is worth noting that efficiency of all coated (or covered) electrodes is impaired by dampness. Hence, they must always be stored in a dry space. If dampness is suspected, the electrodes should be dried in a warm cabinet for a few hours.

48.11. Types of Joints and Types of Applicable Welds

Bureau of Indian Standards (B.I.S.) has recommended the following types of joints and the welds applicable to each one of them (Fig. 48.10).

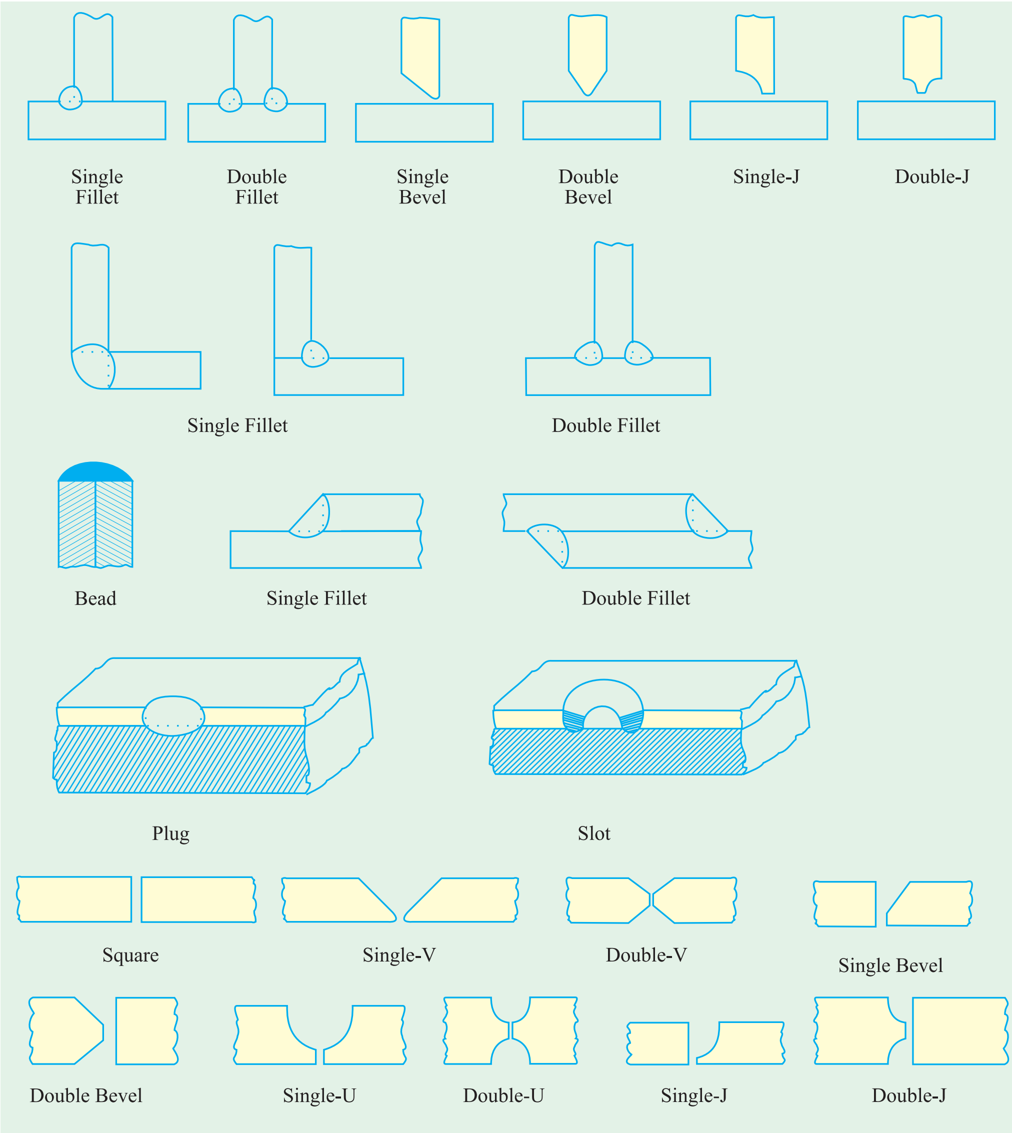


Fig. 48.10

1. Tee joint — with six types of welds.
2. Corner joint — with two types of welds.
3. Edge joint — with one type of weld.
4. Lap joint — with four types of welds.
5. Butt joint — with nine types of welds.

48.12. Arc Welding Machines

Welding is never done directly from the supply mains. Instead, special welding machines are used which provided currents of various characteristics. Use of such machines is essential for the following reasons :

1. To convert a.c. supply into d.c. supply when d.c. welding is desired.
2. To reduce the high supply voltage to a safer and suitable voltage for welding purposes.
3. To provide high current necessary for arc welding without drawing a corresponding high current from the supply mains.
4. To provide suitable voltage/current relationships necessary for arc welding at minimum cost.

There are two general types of arc welding machines :

(*a*) d.c. welding machines

(*i*) motor-generator set

(*ii*) a.c. transformers with rectifiers

(*b*) a.c. welding machines

48.13. V-I Characteristics of Arc Welding DC Machines

It is found that during welding operation, large fluctuations in current and arc voltage result from the mechanism of metal transfer and other factors. The welding machine must compensate for such changes in arc voltage in order to maintain an even arc column. There are three major voltage/current characteristics used in modern d.c. welding machines which help in controlling these current fluctuations :

1. drooping arc voltage (DAV).
2. constant arc voltage (CAV).
3. rising arc voltage (RAV).

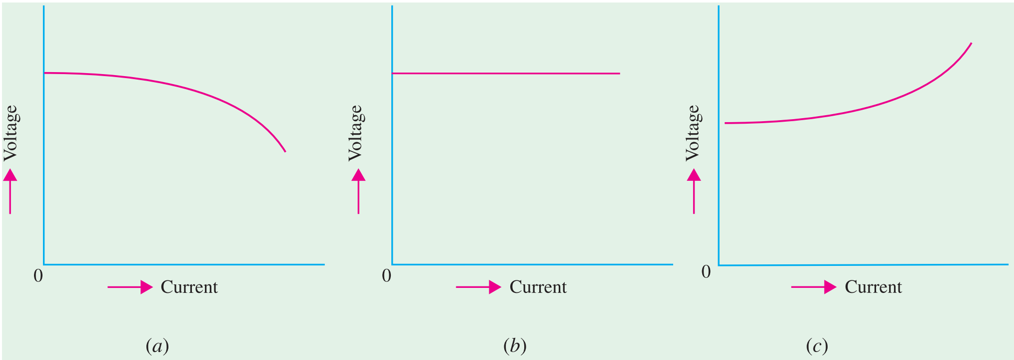


Fig. 48.11

The machines with DAV characteristics have high open-circuit voltage which drops to a minimum when arc column is started. The value of current rises rapidly as shown in Fig. 48.11 (*a*). This type of characteristic is preferred for manual shield metal arc welding.

The CAV characteristic shown in Fig. 48.11 (*b*) is suitable for semi-automatic or automatic welding processes because voltage remains constant irrespective of the amount of current drawn.

Because of its rising voltage characteristic, RAV has an advantage over CAV because it maintains a constant arc gap even if short circuit occurs due to metal transfer by the arc. Moreover, it is well-adopted to fully automatic process.

DC welding machines can be controlled by a simple rheostat in the exciter circuit or by a combination of exciter regulator and series of field taps. Some arc welding are equipped with remote-controlled current units enabling the operator to vary voltage-amperage requirement without leaving the machines.

DC and AC welding machines

48.14. DC Welding Machines with Motor Generator Set

Such a welding plant is a self-contained single-operator motor-generator set consisting of a reverse series winding d.c. generator driven by either a d.c. or an a.c. motor (usually 3-phase). The series winding produces a magnetic field which opposes that of the shunt winding. On open-circuit, only shunt field is operative and provides maximum voltage for striking the arc. After the arc has been established, current flows through the series winding and sets up a flux which opposes the flux produced by shunt winding. Due to decreases in the net flux, generator voltage is decreased (Art. 48.13). With the help of shunt regulator, generator voltage and current values can be adjusted to the desired level. Matters are so arranged that despite changes in arc voltage due to variations in arc length, current remains practically constant. Fig. 48.12 shows the circuit of a d.c. motor-generator type of welding machine.

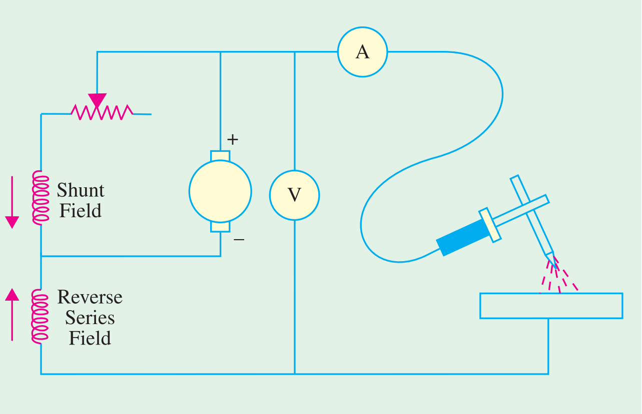


Fig. 48.12

Advantages. Such a d.c. welder has the following advantages :

1. It permits portable operation.
2. It can be used with either straight or reverse polarity.
3. It can be employed on nearly all ferrous and non-ferrous materials.
4. It can use a large variety of stick electrodes.
5. It can be used for all positions of welding.

Disadvantages

1. It has high initial cost.
2. Its maintenance cost is higher.
3. Machine is quite noisy in operation.
4. It suffers from arc blow.

48.15. AC Rectified Welding Unit

It consists of a transformer (single-or three-phase) and a rectifier unit as shown in Fig. 48.13. Such a unit has no moving parts, hence it has long life. The only moving part is the fan for cooling the transformer. But this fan is not the basic part of the electrical system. Fig. 48.13 shows a single-phase full-wave rectified circuit of the welder. Silicon diodes are used for converting a.c. into d.c. These diodes are hermetically sealed and are almost ageless because they maintain rectifying characteristics indefinitely.

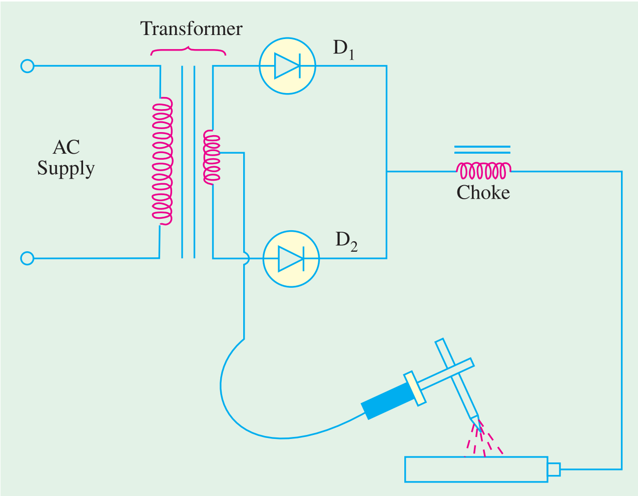


Fig. 48.13

Such a transformer-rectifier welder is most adaptable for shield arc welding because it provides both d.c. and a.c. polarities. It is very efficient and quiet in operation. These welders are particularly suitable for the welding of *(i)* pipes in all positions *(ii)* non-ferrous metals *(iii)* low-alloy and corrosion-heat and creep-resisting steel *(iv)* mild steels in thin gauges.

48.16. AC Welding Machines

As shown in Fig. 48.14, it consists of a step-down transformer with a tapped secondary having an adjustable reactor in series with it for obtaining drooping V/I characteristics. The secondary is tapped to give different voltage/ current settings.

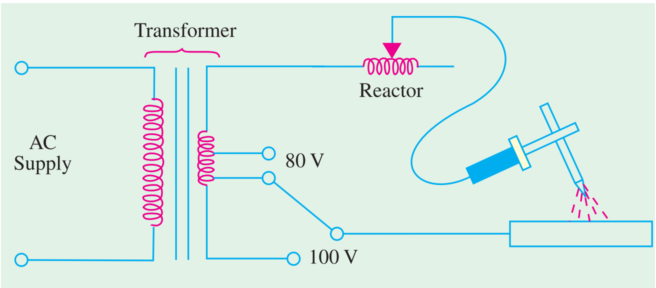


Fig. 48.14

Advantages. This a.c. welder which can be operated from either a single-phase or 3-phase supply has the following advantages :

(i) Low initial cost
(ii) Low operation and maintenance cost
(iii) Low wear
(iv) No arc blow

Disadvantages. *(i)* its polarity cannot be changed *(ii)* it is not suitable for welding of cast iron and non-ferrous metals.

48.17. Duty Cycle of a Welder

The duty cycle of an arc welder is based on a working period of 10 minutes. For example, if a welder is operated for 2 minutes in a period of 10 minutes, then its percentage duty cycle is (2/10) × 100 = 20 percent. Conversely, a 10 percent duty cycle would mean that the welder would be operated for 10 percent of 10 minutes *i.e.* for one minute only in a period of 10 minutes.

Usually, values of maximum amperage and voltage are indicated along with the duty cycle. It is advisable to adhere to these values. Suppose a welding machine has maximum amperage of 300A and voltage of 50 V for a duty cycle of 60 percent. If this machine is operated at higher settings and for periods longer than 6 minutes, then its internal insulation will deteriorate and cause its early failure.

48.18. Carbon Arc Welding

(*a*) General

Carbon arc welding was the first electric welding process developed by a French inventor Auguste de Meritens in 1881. In this process, fusion of metal is accomplished by the heat of an electric arc. No pressure is used and generally, no shielding atmosphere is utilized. Filler rod is used only when necessary. Although not used extensively these days, it has, nevertheless, certain useful fields of application.

Carbon arc welding differs from the more common shield metal arc welding in that ***it uses non-consumable carbon or graphic electrodes*** instead of the consumable flux-coated electrodes.

(*b*) Welding Circuit

The basic circuit is shown in Fig. 48.15 and can be used with d.c. as well as a.c. supply. When direct current is used, the electrode is mostly negative (DCSP). The process is started by adjusting the amperage on the d.c. welder, turning welder ON and bringing the electrode into contact with the workpiece. After the arc column starts, electrode is withdrawn 25 – 40 mm away and the arc is maintained at this distance. The arc can be extinguished by simply removing the electrode from the workpiece completely. The only function of the carbon arc is to supply heat to the base metal. This heat is used to melt the base metal or filler rod for obtaining fusion weld Depending on the type and size of electrodes, maximum current values range from 15 A to 600 A for single-electrode carbon arc welding.

(*c*) Electrodes

These are made of either carbon or graphite, are usually 300 mm long and 2.5 – 12 mm in diameter. Graphite electrodes are harder, more brittle and last longer than carbon electrodes. They can withstand higher current densities but their arc column is harder to control. Though considered non-consumable, they do disintegrate gradually due to vaporisation and oxidisation.

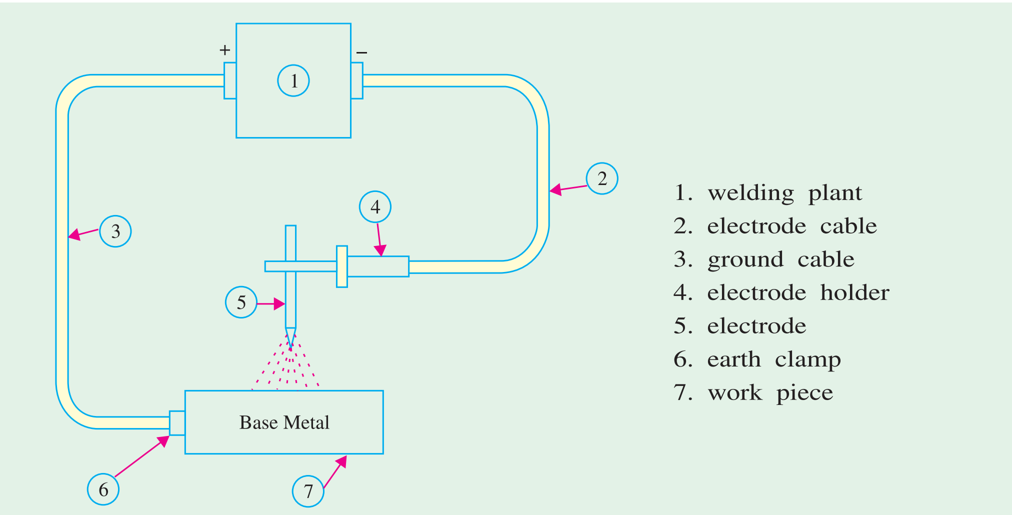


Fig. 48.15

(*d*) Applications

1. The joint designs that can be used with carbon arc welding are butt joints, bevel joints, flange joints, lap joints and fillet joints.
2. This process is easily adaptable for automation particularly where amount of weld deposit is large and materials to be fabricated are of simple geometrical shapes such as water tanks.
3. It is suitable for welding galvanised sheets using copper-silicon-manganese alloy filler metal.
4. It is useful for welding thin high-nickel alloys.
5. Monel metal can be easily welded with this process by using a suitable coated filler rod.
6. Stainless steel of thinner gauges is often welded by the carbon-arc process with excellent results.

(*e*) Advantages and Disadvantages

1. The main advantage of this process is that the temperature of the molten pool can be easily controlled by simply varying the arc length.
2. It is easily adaptable to automation.
3. It can be easily adapted to inert gas shielding of the weld and
4. It can be used as an excellent heat source for brazing, braze welding and soldering etc.

Its disadvantages are as under :

1. A separate filler rod has to be used if any filler material is required.
2. Since arc serves only as a heat source, it does not transfer any metal to help reinforce the weld joint.
3. The major disadvantage of the carbon-arc process is that blow holes occur due to magnetic arc blow especially when welding near edges of the workpiece.

48.19. Submerged Arc Welding

In this ***fusion*** process, welding is done under a blanket of granulated flux which shields the weld from all bad effects of atmospheric gases while a consumable electrode is continuously and mechanically fed into the arc. The arc, the end of the bare metal electrode and the molten weld pool are all submerged under a thick mound of finely-divided granulated powder that contains deoxidisers, cleansers and other fluxing agents. The fluxing powder is fed from a hopper that is carried on the welding head itself (Fig. 48.16). This hopper spread the powder in a continuous mound ahead of the

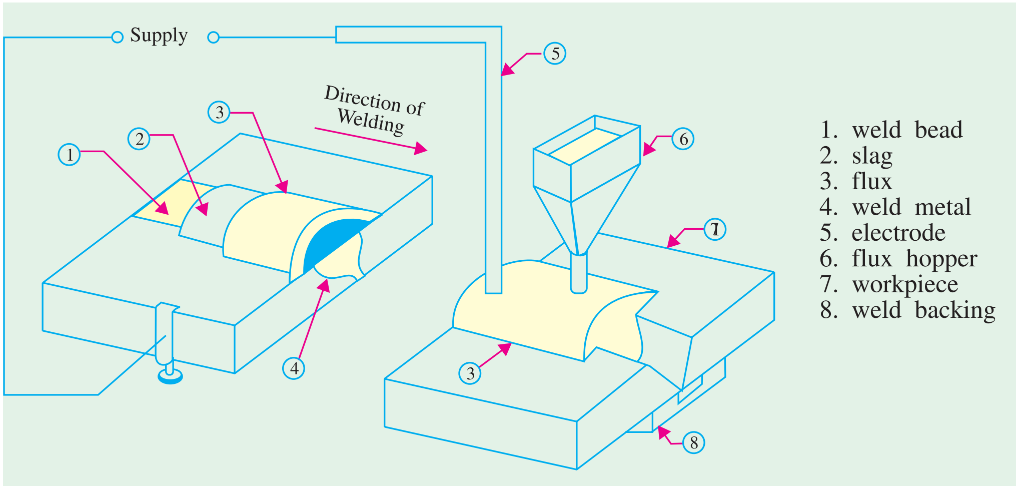


Fig. 48.16

electrode in the direction of welding. Since arc column is completely submerged under the powder, there is no splatter or smoke and, at the same time, weld is completely protected from atmospheric contamination. Because of this protection, weld beads are extremely smooth. The flux adjacent to the arc column melts and floats to the top of the molten pool where it solidifies to form slag. This slag is easy to remove. Often it cracks off by itself as it cools. The unused flux is removed and is reused again and again.

The electrode is either a bare wire or has a slight mist of copper coated over it to prevent oxidation. In automatic or semi-automatic submerged arc welding, wire electrode is fed mechanically through an electrically contacting collet. Though a.c. power supply may be used, yet d.c. supply is more popular because it assures a simplified and positive control of the welding process. This process requires high current densities about 5 to 6 times of those used in ordinary manual stick electrode welding. As a result, melting rate of the electrode as well as welding speed become much higher. Faster welding speed minimizes distortion and warpage.

The submerged arc process is suitable for

1. Welding low-alloy, high-tensile steels.

2. Welding mild, low-carbon steels.

3. Joining medium-carbon steel, heat-resistant steels and corrosion-resistant steels etc.

4. Welding nickel, Monel and other non-ferrous metals like copper.

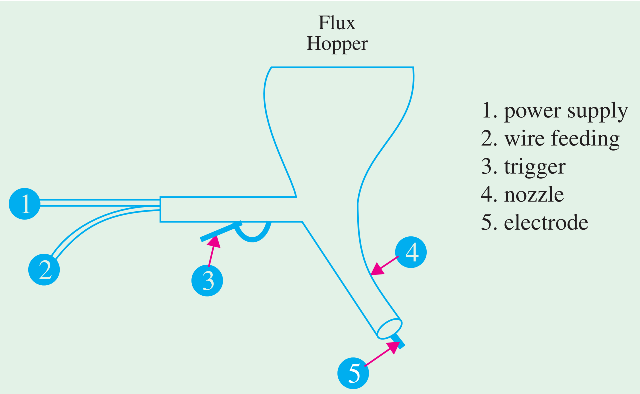


Fig. 48.17

This process has many industrial applications such as fabrication of pipes, boiler pressure vessels, railroad tank cars, structural shapes etc. which demand welding in a straight line. Welds made by this process have high strength and ductility. A major advantage of this process is that fairly thick sections can be welded in a single pass without edge preparation.

Submerged arc welding can be done manually where automatic process is not possible such as on curved lines and irregular joints. Such a welding gun is shown in Fig. 48.17. Both manual and automatic submerged arc processes are most suited for flat and slightly downhill welding positions.

48.20. Twin Submerged Arc Welding

As shown in Fig. 48.18, in this case, two electrodes are used simultaneously instead of one. Hence, weld deposit size is increased considerably. Moreover, due to increase in welding current (upto 1500 A), much deeper penetration of base metal is achieved.

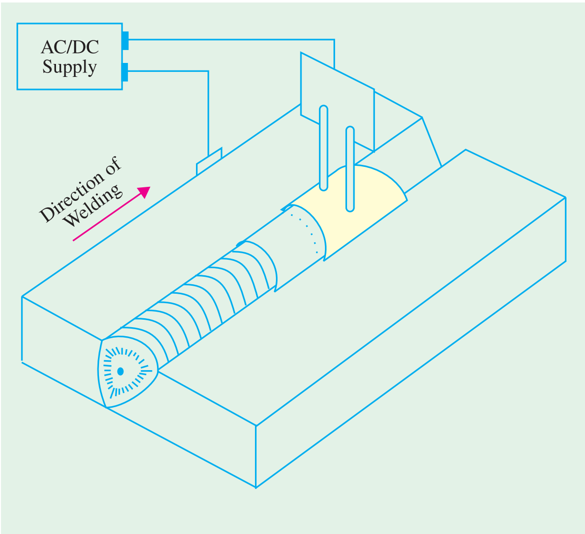


Fig. 48.18

48.21. Gas Shield Arc Welding

In this fusion process, welding is done with bare electrodes but weld zone is shielded from the atmosphere by a gas which is piped to the arc column. Shielding gases used are carbon dioxide, argon, helium, hydrogen and oxygen. No flux is required. Different processes using shielding gas are as follows.

(*a*) Tungsten inert-gas (TIG) Process

In this process, non-consumable tungsten electrode is used and filler wire is fed separately. The weld zone is shielded from the atmosphere by the inert gas (argon or helium) which is ducted directly to the weld zone where it surrounds the tungsten and the arc column.

(*b*) Metal inert-gas (MIG) Process

It is a refinement of the TIG process. It uses a bare consumable (*i.e.* fusible) wire electrode which acts as the source for the arc column as well as the supply for the filler material. The weld zone is shielded by argon gas which is ducted directly to the electrode point.

48.22. TIG Welding

(*a*) Basic Principle

It is an electric process which uses a bare non-consumable tungsten electrode for striking the arc only (Fig. 48.19). Filler material is added separately. It uses an inert gas to shield the weld puddle from atmospheric contamination. This gas is ducted directly to the weld zone from a gas cylinder.

(*b*) Welding Equipment

The usual TIG welding system consists of the following (Fig. 48.20).

1. A standard shield arc welding machine complete with cables etc.

2. A supply of inert gas complete with hose, regulators etc.

3. A source of water supply (in the case of water-cooled torches).

4. A TIG torch with a control switch to which all the above are connected.

(*c*) Electrodes

The electrodes are made of either pure tungsten or zirconiated or thoriated tungsten. Addition of zironium or thorium (0.001 to 2%) improves electron emission tremendously.

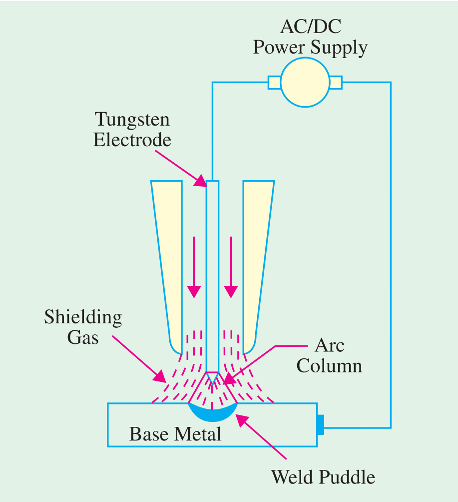


Fig. 48.19

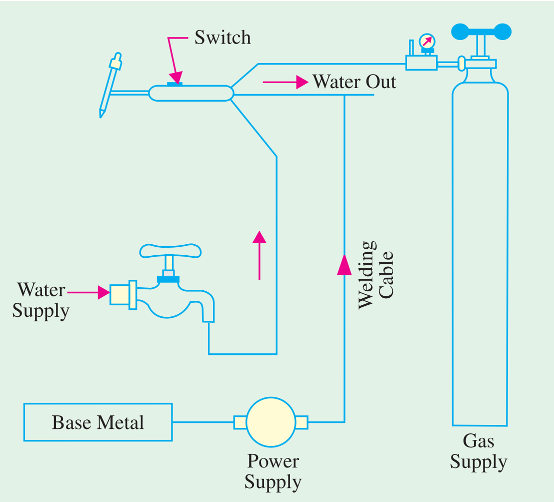


Fig. 48.20

(*d*) Power Supply

The three basic power supplies used in TIG operation are :

1. DCSP power supply–here electrode is negative, runs cooler and, hence, can be thin.
2. DCRP power supply–here electrode is positive and hot. Hence, it has to be large.
3. A.C. high frequency (ACHF) power supply–it is a combination of standard a.c. supply of 50 Hz and high-voltage high-frequency d.c. supply. The function of this d.c. supply is to sustain the arc when a.c. supply is at zero current positions.

(*e*) Advantages of TIG Welding

1. It provides maximum protection to weld bead from atmospheric contamination.
2. TIG welds are stronger, more ductile and more corrosion-resistant than those of shield metal arc welding.
3. Since no flux is used, there is no flux entrapment in the bead.
4. Since no flux is required, a wider variety of joint designs can be used.
5. No post-weld cleansing is necessary.
6. There is no weld splatter or sparks that could damage the surface of the base metal.
7. It gives relatively fast welding speeds.
8. It is suitable for welding food or medical containers where entrapment of any decaying organic matter could be extremely harmful.
9. It is suitable for all welding positions–the flat, horizontal, vertical and overhead positions. The joints suitable for TIG welding process are (*i*) butt joint (*ii*) lap joint (*iii*) T-joint, (*iv*) corner joint and (*v*) edge joint.

(*f*) Applications

1.	aluminium and its alloys	—	AC/DCRP
2.	magnesium and its alloys	—	ACHF
3.	stainless steel	—	DCSP
4.	mild steel, low-alloy steel, medium	—	DCSP
	-carbon steel and cast iron	—	DCSP
5.	copper and allows	—	DCSP
6.	nickel and alloys	—	DCSP

TIG welding is also used for dissimilar metals, hardfacing and surfacing of metals. Special industrial applications include manufacture of metal furniture and air-conditioning equipment.

Fig. 48.21 shows Phillips 400-D compact fan-cooled DC TIG welding set which has an open-circuit voltage of 80 V and a welding current of 400 A with 60% duty cycle and 310 A with 100% duty cycle.

Fig. 48.21 (TIG welding set)

48.23. MIG Welding

(*a*) Basic Principle

It is also called inert-gas consumable- electrode process. The fusible wire electrode is driven by the drive wheels. Its function is two-fold: to produce arc column and to provide filler material. This process uses inert gas for shielding the weld zone from atmospheric contamination. Argon is used to weld non-ferrous metals though helium gives better control of porosity and arc stability. This process can deposit large quantities of weld metal at a fast welding speed. The process is easily adaptable to semi-automatic or fully automatic operations.

(b) Welding Equipment

The basic MIG welding system (Fig. 48.23) consists of the following :

1. Welding power supply
2. Inert gas supply with a regulator and flow meter
3. Wire feed unit containing controls for wire feed, gas flow and the ON/OFF switch for MIG torch
4. MIG torch
5. Depending on amperage, a water cooling unit.

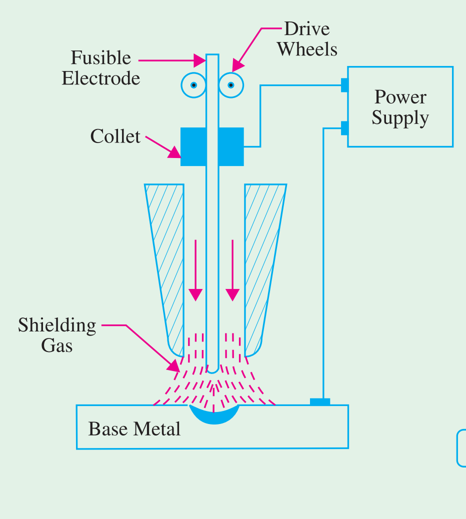


Fig. 48.22

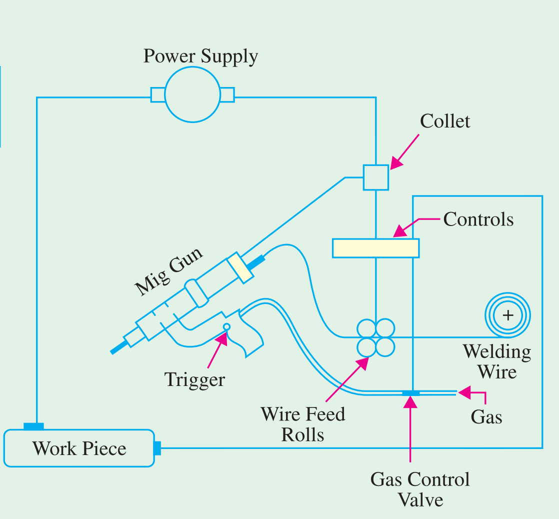


Fig. 48.23

(c) Electrode

It is a bare wire fed to the MIG gun by a suitable wire-feed mechanism.

(d) Power Supply

The major power supply used for MIG welding is DCRP and the machines which provide this supply are motor-generator sets or a.c. transformers with rectifiers (Art. 48.14). They have either CAV or RAV characteristics (Art. 48.12). The CAV supply gives the operator great latitude in arc length and is helpful in preventing the wire electrode from stubbing. A DCRP current produces deeper penetration and a cleaner weld surface than other types of current.

The RAV machines are more suitable for automatic operation. They are capable of handling large diameter wires than CAV machines.

Fig. 48.24 shows semi-automatic forced-air cooled arc welding set MIG-400. It consists of

(i) Indarc 400 MMR rectifier which is basically a 3-phase transformer rectifier with silicon

Fig. 48.24.
MIG-400 Welding Set. (Courtesy : Indian Oxygen Ltd. Calcutta)

diodes and a constant potential output. It provides maximum current of 400 A at 40 V for 75% duty cycle and 350 A at 42 V for 100% duty cycle.

(ii) Indarc Wire Feeder which has a twin roll drive system, designed to feed 0.8 to 2.4 mm diameter welding wires to a hand-operated MIG welding torch.

(iii) MIG Torches which are available in both air-cooled and water-cooled varieties. Fig. 48.25 (*a*) and (*b*) show light-weight swan-necked torches which are designed to operate upto 360 A and 400 A with CO_2 as shielding gas. Fig. 48.25 (*c*) shows a heavy-duty water-cooled torch designed to operate upto 550 A with CO_2/mixed shielding gases at 100% duty cycle.

(iv) CO_2 Kit for hard wire applications and Argon Kit for soft wire applications.

(*e*) Advantages of MIG Welding

1. Gives high metal deposit rates varying from 2 to 8 kg/h.
2. Requires no flux.
3. Requires no post-welding cleaning.
4. Gives complete protection to weld bead from atmospheric contamination.
5. Is adaptable for manual and automatic operations.
6. Can be used for a wide range of metals both ferrous and non-ferrous.
7. Is easy to operate requiring comparatively much less operating skill.
8. Is especially suited for horizontal, vertical and overhead welding positions.

(*f*) Applications

With inert gas shielding, this process is suitable for fusion welding of *(i)* aluminium and its alloys *(ii)* nickel and its alloys *(iii)* copper alloys *(iv)* carbon steels *(v)* low-alloy steels *(vi)* high strength steels and *(vii)* titanium.

48.24. MAG Welding

As discussed earlier, in MIG welding process, the shielding gas used is monoatomic (argon or helium) and is inert *i.e*. chemically inactive and metal transfer takes place by axial pulverization. In MAG (metal-active-gas) process, shielding, gas used is chemically active *i.e*. carbon dioxide or its mixture with other gases. Transfer of metal takes place in big drops.

48.25. Atomic Hydrogen Welding

(*a*) General

It is a non-pressure fusion welding process and the welder set is used only as heat supply for the base metal. If additional metal is required, a filler rod can be melted into the joint. It uses two tungsten electrodes between which an arc column (actually, an arc fan) is maintained by an a.c. supply.

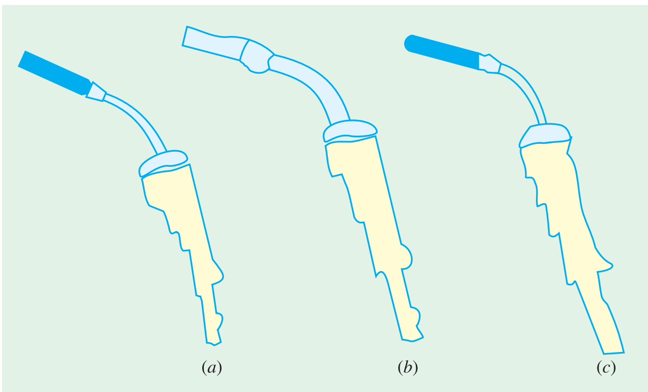


Fig. 48.25

(*b*) Basic Principle

As shown in Fig. 48.26, an arc column is struck between two tungsten electrodes with an a.c. power supply. Soon after, normal molecular hydrogen (H_2) is forced through this arc column. Due to intense heat of the arc column, this diatomic hydrogen is dissociated into atomic hydrogen (H).

However, atomic hydrogen being unstable, recombines to form stable molecular hydrogen. In so doing, it releases intense heat at about 3750°C which is used to fuse the metals.

(*c*) Welding Equipment

The welding equipment essentially consists of the following :

1. Standard welding machine consisting of a step-down transformer with tapped secondary (not shown in Fig. 48.27) energised from normal a.c. supply. Amperage requirement ranges from 15 A to 150 A
2. Hydrogen gas supply with an appropriate regulator
3. Atomic hydrogen welding torch having an ON-OFF switch and a trigger for moving the two tungsten electrodes close together for striking and maintaining the arc column.

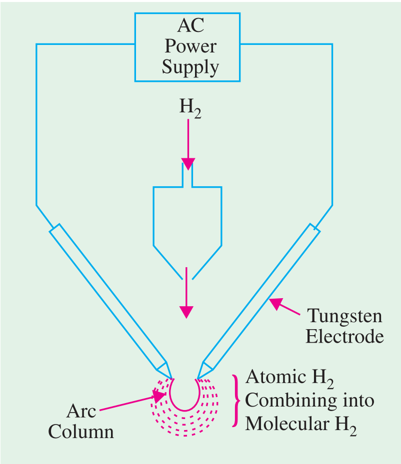


Fig. 48.26

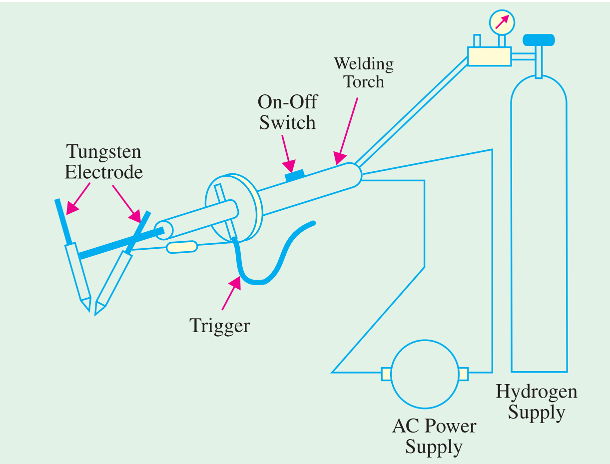


Fig. 48.27

(*d*) Method of Welding

The torch is held in the right hand with first finger resting lightly on the trigger. The arc is struck either by allowing the two tungsten electrodes to touch and separate or by drawing the separated electrodes over a carbon block. At the same time, a stream of hydrogen is allowed to flow through the arc. As soon as the arc strikes, an intensely hot flame extends fanwise between the electrodes. When this fan touches the workpiece, it melts it down quickly. If filler material is required, it can be added from the rod held in the left hand as in gas welding.

(*e*) Advantages

1. Arc and weld zone are shrouded by burning hydrogen which, being an active reducing agent, protects them from atmospheric contamination.
2. Can be used for materials too thin for gas welding.
3. Can weld quite thick sections.
4. Gives strong, ductile and sound welds.
5. Can be used for welding of mild steel, alloy steels and stainless steels and aluminium alloys.
6. Can also be used for welding of most non-ferrous metals such as nickel, monel, brass, bronze, tungsten and molybdenum etc.

48.26. Resistance Welding

It is fundamentally a heat and squeeze process. The term ***'resistance welding'*** denotes a group of processes in which welding heat is produced by the resistance offered to the passage of electric current through the two metal pieces being welded. These processes differ from the fusion processes in the sense that no extra metal is added to the joint by means of a filler wire or electrode. According to Joule's law, heat produced electrically is given by $H = I^2Rt/J$. Obviously, amount of heat produced depends on.

(i) square of the current *(ii)* the time of current and *(iii)* the resistance offered.

As seen, in simple resistance welding, high-amperage current is necessary for adequate weld. Usually, R is the contact resistance between the two metals being welded together. The current is passed for a suitable length of time controlled by a timer. The various types of resistance welding processes may be divided into the following four main groups :

(i) spot welding *(ii)* seam welding *(iii)* projection welding and *(iv)* butt welding which could be further subdivided into flash welding, upset welding and stud welding etc.

Advantages

Some of the advantages of resistance welding are as under :

1. Heat is localized where required
2. Welding action is rapid
3. No filler material is needed
4. Requires comparatively lesser skill
5. Is suitable for large quantity production
6. Both similar and dissimilar metals can be welded
7. Parent metal is not harmed
8. Difficult shapes and sections can be welded.

Only disadvantages are with regard to high initial as well as maintenance cost.

It is a form of resistance welding in which the two surfaces are joined by spots of fused metal caused by fused metal between suitable electrodes under pressure.

48.27. Spot Welding

The process depends on two factors :

1. Resistance heating of small portions of the two workpieces to plastic state and

2. Application of forging pressure for welding the two workpieces.

Heat produced is $H = I^2Rt/J$. The resistance R is made up of *(i)* resistance of the electrodes and metals themselves *(ii)* contact resistance between electrodes and workpieces and *(iii)* contact resistance between the two workpieces. Generally, contact resistance between the two workpieces is the greatest.

Spot welding machine

As shown in 48.28 (*b*), mechanical pressure is applied by the tips of the two electrodes. In fact, these electrodes not only provide the forging pressure but also carry the welding current and concentrate the welding heat on the weld spot directly below them.

Fig. 48.28 (*a*) shows diagrammatically the basic parts of a modern spot welding. It consists of a step-down transformer which can supply huge currents (upto 5,000 A) for short duration of time.

The lower arm is fixed whereas the upper one is movable. The electrodes are made of low-resistance, hard-copper alloy and are either air cooled or butt-cooled by water circulating through the rifled drillings in the electrode. Pointed electrodes [Fig. 48.29 (*a*)] are used for ferrous materials

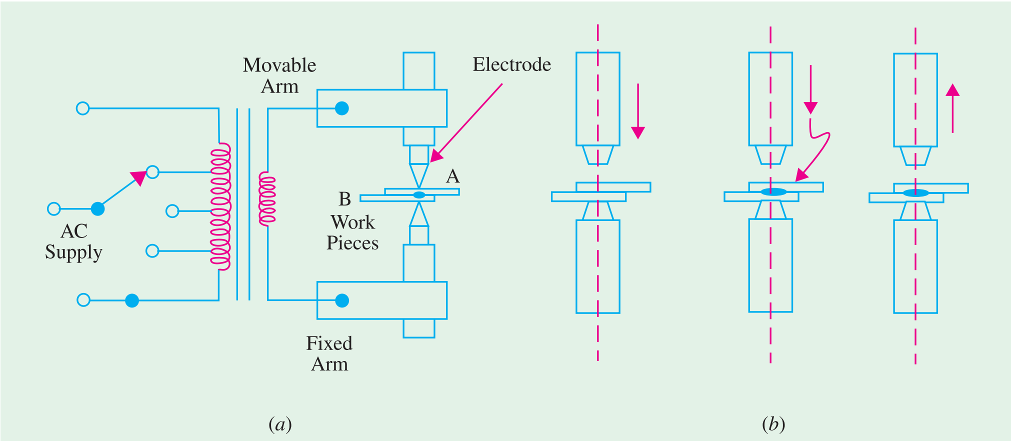


Fig. 48.28

whereas domed electrodes [Fig. 48.25 (*b*)] are used for non-ferrous materials. Flat domes are used when spot-welding deformation is not desired. The weld size is determined by the diameter of the electrode.

The welding machine is cycled in order to produce the required heat timed to coincide with the pressure exerted by the electrodes as shown in Fig. 48.28 (*a*). As the movable electrode comes down and presses the two workpieces *A* and *B* together, current is passed through the assembly. The metals under the pressure zone get heated upto about 950°C and fuse together. As they fuse, their resistance is reduced to zero, hence there is a surge of current. This surge is made to switch off the welding current automatically. In motor-driven machines, speeds of 300 strokes/minute are common.

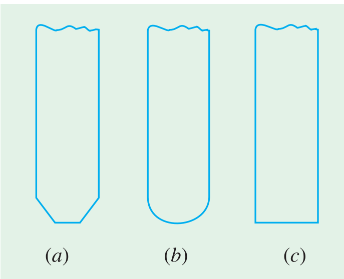


Fig. 48.29

Spot welders are of two different types. One is a stationary welder which is available in different sizes. The other has a stationary transformer but the electrodes are in a gun form.

Electric resistance spot welding is probably the best known and most widely-used because of its low cost, speed and dependability. It can be easily performed by even a semi-skilled operator. This process has a fast welding rate and quick set-up time apart from having low unit cost per weld.

Spot welding is used for galvanized, tinned and lead-coated sheets and mild steel sheet work. This technique is also applied to non-ferrous materials such as brass, aluminium, nickel and bronze etc.

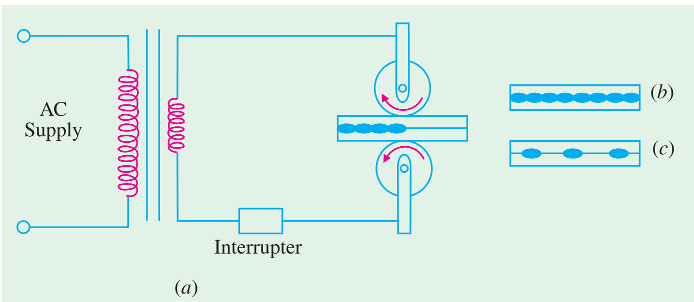


Fig. 48.30

48.28. Seam Welding

The seam welder differs from ordinary spot welder only in respect of its electrodes which are of disc or roller shape as shown in Fig. 48.30 (*a*). These copper wheels are power driven and rotate whilst gripping the work. The current is so applied through the wheels that the weld spots either overlap as in Fig. 48.30 (*b*) or are made at regular intervals as in Fig. 48.30 (*c*). The continuous or overlapped seam weld is also called ***stitch weld*** whereas the other is called roll weld.

Seam welding is confined to welding of thin materials ranging in thickness from 2 mm to 5 mm. It is also restricted to metals having low hardenability rating such as hot-rolled grades of low-alloy steels. Stitch welding is commonly used for long water-tight and gas-tight joints. Roll welding is used for simple joints which are not water-tight or gas-tight. Seam welds are usually tested by pillow test.

48.29. Projection Welding

It can be regarded as a mass-production form of spot welding. Technically, it is a cross between spot welding and butt welding. It uses the same equipment as spot welding. However, in this process, large-diameter flat electrodes (also called platens) are used. This welding process derives its name from the fact that, prior to welding, projections are raised on the surfaces to be welded [Fig. 48.31 (*a*)]. As seen, the upper and lower platens are connected across the secondary of a step-down transformer and are large enough to cover all the projections to be welded at one stroke of the machine. When platen *A* touches the workpiece, welding current flows ***through each projection***.

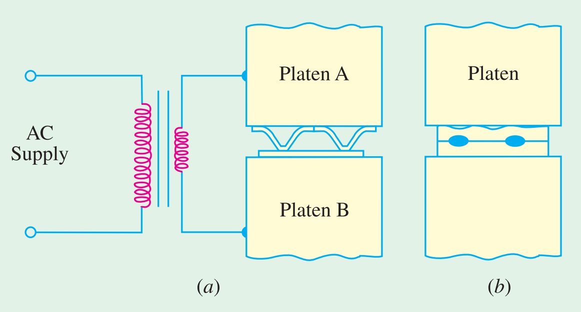


Fig. 48.31

The welding process is started by first lowering the upper platen *A* on to the work-piece and then applying mechanical pressure to ensure correctly-forged welds. Soon after, welding current is switched on as in spot welding. As projection areas heat up, they collapse and union takes place at all projections simultaneously [Fig. 48.31 (*b*)].

It is seen that projections serve many purposes :

1. They increase the welding resistance of the material locally.
2. They accurately locate the positions of the welds.
3. They speed up the welding process by making it possible to perform several small welds simultaneously.
4. They reduce the amount of current and pressure needed to form a good bond between two surfaces.
5. They prolong the life of the electrode considerably because the metal itself controls the heat produced.

Projection welding is used extensively by auto manufactures for joining nuts, bolts and studs to steel plates in car bodies. This process is especially suitable for metals like brass, aluminium and copper etc. manily due to their high thermal conductivity.

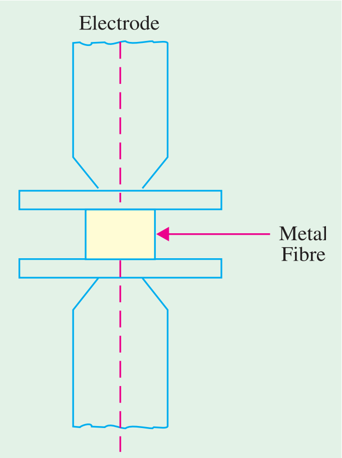


Fig. 48.32

A variation of projection welding is the metal fibre welding which uses a metal fibre rather than a projection point (Fig. 48.32). This metal fibre is generally a felt material. Instead of projections, tiny elements of this felt material are placed between the two metals which are then projection-welded in the usual way.

48.30. Butt Welding

In this case, the two workpieces are brought into contact end-to-end and the butted ends are heated by passing a heavy current through the joint. As in other forms of resistance welding, the weld heat is produced mainly by the electrical resistance of the joint faces. In this case, however, the electrodes are in the form of powerful vice clamps which hold the work-pieces and also convey the forging pressure to the joint [Fig. 48.33].

This process is useful where parts have to be joined end-to-end or edge-to-edge. *i.e.* for welding pipes, wires and rods. It is also employed for making continuous lengths of chain.

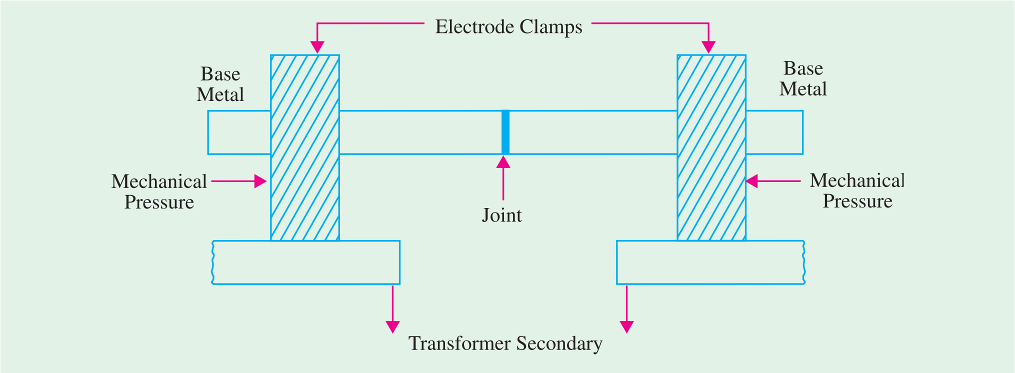


Fig. 48.33

48.31. Flash Butt Welding

It is also called by the simple name of ***flash welding***. It is similar to butt welding but with the difference that here current is applied when ends of the two metal pieces are quite close to each other ***but do not touch intimately***. Hence, an arc or flash is set up between them which supplies the necessary welding heat. As seen, in the process heat is applied ***before*** the two parts are pressed together.

As shown in Fig. 48.34 (*a*), the workpieces to be welded are clamped into specially designed electrodes one of which is fixed whereas the other is movable. After the flash has melted their faces, current is cut off and the movable platen applies the forging pressure to form a fusion weld. As shown in Fig. 48.34 (*b*), there is increase in the size of the weld zone because of the pressure which forces the soft ends together.

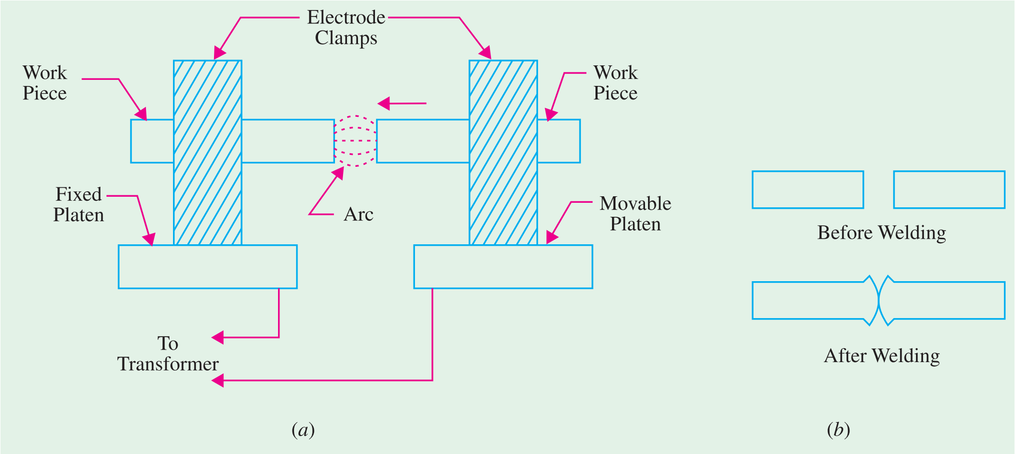


Fig. 48.34

Advantages

1. Even rough or irregular ends can be flash-welded. There is no need to level them by machining and grinding because all irregularities are burnt away during flashing period.
2. It is much quicker than butt welding.
3. It uses considerably less current than butt welding.
4. One of its major advantages is that dissimilar metals with different welding temperatures can be flash-welded.

Applications

1. To assemble rods, bars, tubings, sheets and most ferrous metals.
2. In the production of wheel rims for automobiles and bicycles.
3. For welding tubular parts such as automobile break cross-shafts.
4. For welding tube coils for refrigeration plants etc.

48.32. Upset Welding

In this process, ***no flash is allowed to occur*** between the two pieces of the metals to be welded. When the two base metals are brought together to a single interface, heavy current is passed between them which heats them up. After their temperature reaches a value of about 950°C, the two pieces of base metal are pressed together more firmly. This pressing together is called ***upsetting***. This upsetting takes place ***while current is flowing and continues even after current is switched off***. This upsetting action mixes the two metals homogeneously while pushing out many atmospheric impurities.

48.33. Stud Welding

(*a*) Basic Principle

It is similar to flash welding because it incorporates a method of drawing an arc between the stud (a rod) and the surface of the base metal. Then, the two molten surfaces are brought together under pressure to form a weld. Stud welding eliminates the need for drilling holes in the main structure.

(*b*) Welding Equipment

The stud welding equipment consists of a stud welding gun, a d.c. power supply capable of giving currents upto 400 A, a device to control current and studs and ferrules which are used not only as arc shields but also as containing walls for the molten metal.

(*c*) Applications

It is a low-cost method of fastening extensions (studs) to a metal surface. Most of the ferrous and non-ferrous metals can be stud-welded successfully. Ferrous metals include stainless steel, carbon steel and low-alloy steel. Non-ferrous metals include aluminium, lead-free brass, bronze and chrome-plated metals.

Stud welding finds application in the installations of conduit pipe hangers, planking and corrugated roofings.

This process is also used extensively in shipbuilding, railroad and automotive industries.

48.34. Plasma Arc Welding

(*a*) Basic Principle

It consists of a high-current electronic arc which is forced through a small hole in a water-coled metallic nozzle [Fig. 48.35 (*a*)]. The plasma gas itself is used to protect the nozzle from the extreme heat of the arc. The plasma arc is shielded by inert gases like argon and helium which are pumped through an extra passageway within the nozzle of the plasma torch. As seen, plasma arc consists of electronic arc, plasma gas and gases used to shield the jet column. The idea of using the nozzle is to

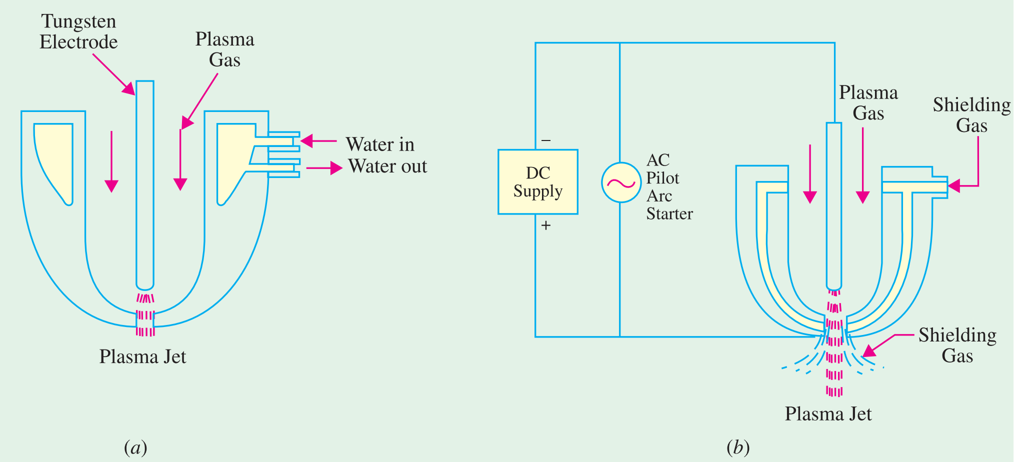


Fig. 48.35

constrict the arc thereby increasing its pressure. Collision of high-energy electrons with gas molecules produces the plasma which is swept through the nozzle and forms the current path between the electrode and the workpiece. Plasma jet torches have temperature capability of about 35,000°C.

(*b*) Electrodes

For stainless steel welding and most other metals, straight polarity tungsten electrodes are used. But for aluminium welding, reverse polarity water-cooled copper electrodes are used.

Plasma arc welding

(*c*) Power Supply

Plasma arc welding requires d.c. power supply which could be provided either by a motor-generator set or transformer-rectifier combination. The latter is preferred because it produces better arc stability. The d.c. supply should have an open-circuit voltage of about 70V and drooping voltage-ampere characteristics. A high-frequency pilot arc circuit is employed to start the arc [Fig. 48.35 (*b*)].

(*d*) Method of Welding

Welding with plasma arc jet is done by a process called 'keyhole' method. As the plasma jet strikes the surface of the workpiece, it burns a hole through it. As the torch progresses along the work-piece, this hole also progresses alongwith but is filled up by the molten metal as it moves along. obviously, 100 percent penetration is achieved in this method of welding. Since plasma jet melts a large surface area of the base metal, it produces a weld bead of wineglass design as shown in Fig. 48.36. The shape of the bead can be changed by changing the tip of the nozzle of the torch. Practically, all welding is done mechanically.

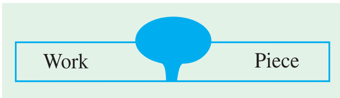


Fig. 48.36

(*e*) Applications

1. Plasma arc welding process has many aerospace applications.
2. It is used for welding of reactive metals and thin materials.
3. It is capable of welding high-carbon steel, stainless steel, maraging steel, copper and copper alloys, brass alloys, aluminium and titanium.
4. It is also used for metal spraying.

5. It can be modified for metal cutting purposes. It has been used for cutting aluminium, carbon steel, stainless steel and other hard-to-cut steels. It can produce high-quality dross-free aluminium cuts 15 cm deep.

(*f*) Disadvantages

1. Since it uses more electrical equipment, it has higher electrical hazards.
2. It produces ***ultra-violet and infra-red*** radiations necessitating the use of tinted lenses.
3. It produces high-pitched noise (100 dB) which makes it necessary for the operator to use ear plugs.

48.35. Electroslag Welding

(*a*) General

It is a metal-arc welding process and may be considered as a further development of sub-merged-arc welding.

This process is used for welding joints of thick sections of ferrous metals in a single pass and without any special joint preparation. Theoretically, there is no upper limit to the thickness of the weld bead. It is usually a vertical uphill process.

It is called ***electroslag*** process because heat is generated by passing current through the molten slag which floats over the top of the metal.

(*b*) Welding Equipment

As shown in Fig. 48.37, two water-cooled copper shoes (or dams) are placed on either side of the joint to be welded for the purpose of confining the molten metal in the joint area. The electrode is fed into the weld joint almost vertically from special wire guides. There is a mechanical device which raises the shoes and wire-feed mechanism as the weld continues upwards till it is completed. An a.c. welding machine has 100 percent duty cycle and which can supply currents upto 1000 A if needed.

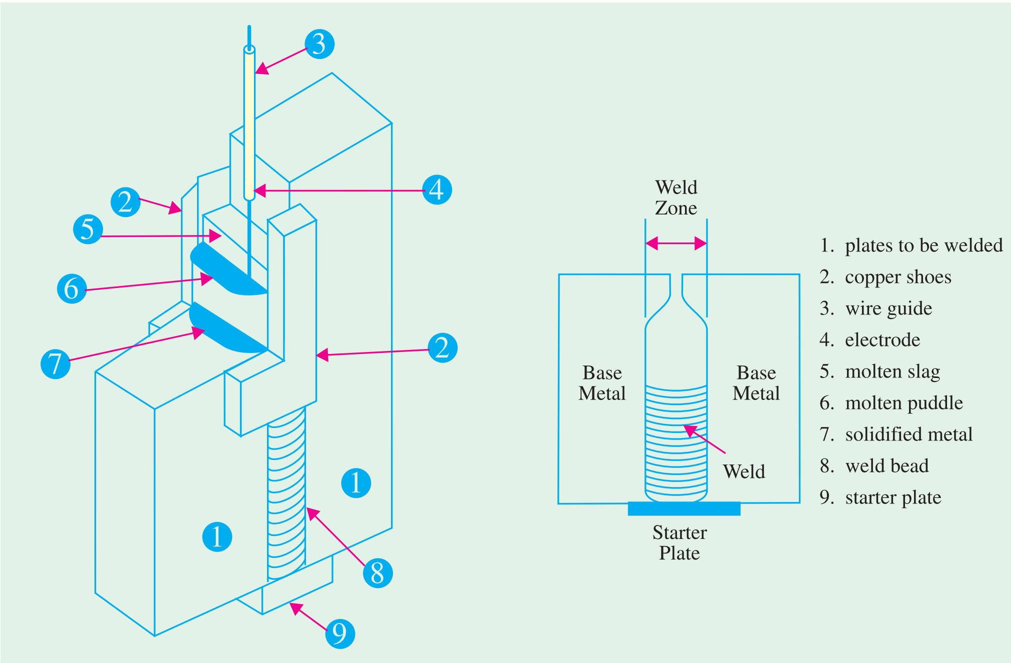


Fig. 48.37

(*c*) Welding Process

The electroslag process is initiated just like submerged arc process by starting an electric arc beneath a layer of granular welding flux. When a sufficient thick layer of hot flux or molten slag is formed, arc action stops and from then onwards, current passes from the electrode to workpiece through the molten slag. At this point, the process becomes truly electroslag welding. A starting plate is used in order to build up proper depth of conductive slag before molten pool comes in contact with the workpieces.

The heat generated by the resistance to the flow of current through the molten slag is sufficient to melt the edges of the workpiece and the filler electrode. The molten base metal and filler metal collect at the bottom of the slag pool forming the weld pool. When weld pool solidfies, weld bead is formed which joins the faces of the base metal as shown in Fig. 48.33 (*b*).

As welding is continued upwards, flux flows to the top in the form of molten slag and cleanses the impurities from the molten metal. A mechanism raises the equipment as the weld is completed in the uphill vertical position.

(*d*) Advantages

1. It needs no special joint preparation.
2. It does welding in a single pass rather than in costly multiple passes.
3. There is theoretically no maximum thickness of the plate it can weld.
4. There is also no theoretical upper limit to the thickness of the weld bead. Weld beads upto 400 mm thick have been performed with the presenttly-available equipment.
5. This process requires less electrical power per kg of deposited metal than either the submerged arc welding process or the shield arc process.
6. It has high deposit rate of upto 20 kg of weld metal per hour.
7. It has lower flux consumption.
8. Due to uniform heating of the weld area, distortion and residual stresses are reduced to the minimal amounts.

However, for electroslag welding, it is necessary to have only a square butt joint or a square edge on the plates to be welded.

(*e*) Applications

It is commonly used in the fabrication of large vessels and tanks. Low-carbon steels produce excellent welding properties with this process.

48.36. Electrogas Welding

This process works on the same basic principle as the electroslag process but has certain additional features of submerged arc welding. Unlike electroslag process, the electrogas process uses an inert gas for shielding the weld from oxidation and there is a continuous arc (as in submerged arc process) to heat the weld pool.

48.37. Electron Beam Welding

In this process, welding operation is performed in a vacuum chamber with the help of a sharply-focussed beam of high-velocity electrons. The electrons after being emitted from a suitable electrode are accelerated by the high anode voltage and are then focussed into a fine beam which is finally directed to the workpiece. Obviously, this process needs no electrodes. The electron beam produces intense local heat which can melt not only the metal but can even boil it. A properly-focussed electron beam can completly penetrate through the base metal thereby creating a small hole whose walls are molten. As the beam moves along the joint, it melt the material coming in contact with it. The molten metal flows back to the previously-melted hole where it fuses to make a perfect weld for the entire depth of penetration.

Electron-beam welding has following advantages :

1. It produces deep penetration with little distortion.
2. Its input power is small as compared to other electrical welding devices.
3. Electron-beam weld is much narrower than the fusion weld.
4. It is especially suitable for reactive metals which become contaminated when exposed to air because this process is carried out in vacuum.
5. It completely eliminates the contamination of the weld zone and the weld bead because operation is performed in a vacuum chamber.

Electron beam welding facility

6. It is especially suited to the welding of beryllium which is being widely used in the fabrication of industrial and aerospace components.
7. Its high deposition rate produces welds of excellent quality with only a single pass.
8. It is the only process which can join high temperature metals such as columbium.

At present, its only serious limitations are that it is extremely expensive and is not available in portable form. However, recently a non-vacuum electron-beam welder has been developed.

48.38. Laser Welding

It uses an extremely concentrated beam of coherent monochromatic light *i.e.* light of only one colour (or wavelength). It concentrates tremendous amount of energy on a very small area of the workpiece to produce fusion. It uses solid laser (ruby, saphire), gas laser (CO_2) and semiconductor laser. Both the gas laser and solid laser need capacitor storage to store energy for later injection into the flash tube which produces the required laser beam.

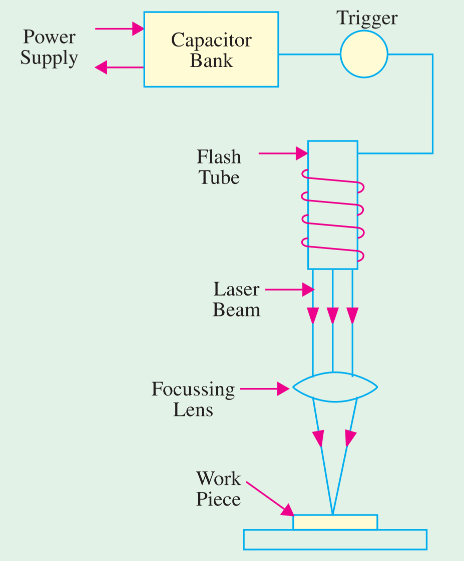


Fig. 48.38

The gas laser welding equipment consists of *(i)* capacitor bank for energy storage *(ii)* a triggering device *(iii)* a flash tube that is wrapped with wire *(iv)* lasing material *(v)* focussing lens and *(vi)* a worktable that can rotate in the three *X*, *Y* and *Z* directions.

When triggered, the capacitor bank supplies electrical energy to the flash tube through the wire. This energy is then converted into short-duration beam of laser light which is pin-pointed on the workpiece as shown in Fig. 48.38. Fusion takes place immediately and weld is completed fast.

Since duration of laser weld beam is very short (2 ms or so), two basic welding methods have been adopted. In the first method, the workpiece is moved so fast that the entire joint is welded in a single burst of the light. The other method uses a number of pulses one after the other to form the weld joint similar to that formed in electric resistance seam welding (Art 48.31).

Laser welding is used in the aircraft and electronic industries for lighter gauge metals.

Some of the advantages of laser welding process are as follows :

1. It does not require any electrode.
2. It can make welds with high degree of precision and on materials as thin as 0.025 mm.
3. It does not heat the workpiece except at one point. In fact, heat-affected zone is virtually non-existent.
4. Liquidus is reached only at the point of fusion.
5. It can produce glass-to-metal seals as in the construction of klystron tubes.
6. Since laser beam is small in size and quick in action, it keeps the weld zone uncontaminated.
7. It can weld dissimilar metals with widely varying physical properties.
8. It produces minimal thermal distortion and shrinkage because area of heat-affected zone is the minimum possible.
9. It can easily bond refractory materials like molybdenum, titanium and tantalium etc.

However, the major disadvantage of this process is its slow welding speed. Moreover, it is limited to welding with thin metals only.

Tutorial Problem No. 48.1

1. Describe various types of electric arc welding processes.
   (J.N. University, Hyderabad, December 2002/January 2003)
2. Compare resistance welding and arc welding.
   (J.N. University, Hyderabad, December 2002/January 2003)
3. Briefly explain the different methods of electric welding and state their relative merits.
   (J.N. University, Hyderabad, December 2002/January 2003)
4. Give the comparison between A.C. and D.C. welding.
   (J.N. University, Hyderabad, December 2002/January 2003)
5. Explain the different methods of electric welding and their relative advantages.
   (J.N. University, Hyderabad, December 2002/January 2003)

OBJECTIVE TESTS – 48

1. The basic *electrical* requirement in arc welding is that there should be
   (*a*) coated electrodes
   (*b*) high open-circuit voltage
   (*c*) no arc blow
   (*d*) d.c. power supply.
2. Welding is not done directly from the supply mains because
   (*a*) it is customary to use welding machines
   (*b*) its voltage is too high
   (*c*) its voltage keeps fluctuating
   (*d*) it is impracticable to draw heavy currents.
3. A.C. welding machine cannot be used for welding
   (*a*) MIG
   (*b*) atomic hydrogen
   (*c*) resistance
   (*d*) submerged arc.
4. In electric welding, arc blow can be avoided by
   (*a*) using bare electrodes
   (*b*) welding away from earth ground connection
   (*c*) using a.c. welding machines
   (*d*) increasing arc length.

5. In DCSP welding
   (*a*) electrode is the hottest
   (*b*) workpiece is relatively coole
   (*c*) base metal penetration is deep
   (*d*) heavily-coated electrodes are used.
6. Overhead welding position is thought to be the most
   (*a*) hazardous
   (*b*) difficult
   (*c*) economical
   (*d*) useful.
7. The *ultimate* aim of using electrode coating is to
   (*a*) provide shielding to weld pool
   (*b*) prevent atmospheric contamination
   (*c*) improve bead quality
   (*d*) cleanse the base metal.
8. In electrode-positive welding .... of the total heat is produced at the electrode.
   (*a*) one-third
   (*b*) two-third
   (*c*) one-half
   (*d*) one-fourth.
9. Submerged arc process is characterised by
   (*a*) deep penetration
   (*b*) high welding current
   (*c*) exceptionally smooth beads
   (*d*) all of the above.
10. The major disadvantage of carbon arc welding is that
   (*a*) there is occurrence of blow holes
   (*b*) electrodes are consumed fast
   (*c*) separate filler rod is needed
   (*d*) bare electrodes are necessary.
11. In atomic hydrogen welding, electrodes are long-lived because
   (*a*) two are used at a time
   (*b*) arc is in the shape of a fan
   (*c*) of a.c. supply
   (*d*) it is a non-pressure process.
12. Unlike TIG welding, MIG welding
   (*a*) requires no flux
   (*b*) uses consumable electrodes
   (*c*) provides complete protection from atmospheric contamination
   (*d*) requires no post-weld cleansing.
13. The major power supply used in MIG welding is
   (*a*) a.c. supply
   (*b*) DCSP
   (*c*) electrode-negative
   (*d*) DCRP.
14. MIG welding process is becoming increa- singly popular in welding industry mainly because of
   (*a*) its easy operation
   (*b*) its high metal deposit rate
   (*c*) its use in both ferrous and non-ferrous metals.
   (*d*) both (*a*) and (*b*).
15. A weld bead of wineglass design is produced in .... welding.
   (*a*) plasma arc
   (*b*) electron beam
   (*c*) laser
   (*d*) MAG.
16. Spot welding process basically depends on
   (*a*) Ohmic resistance
   (*b*) generation of heat
   (*c*) application of forging pressure
   (*d*) both (*b*) and (*c*).
17. Electric resistance seam welding uses .... electrodes.
   (*a*) pointed
   (*b*) disc
   (*c*) flat
   (*d*) domed.
18. Projection welding can be regarded as a mass production form of .... welding.
   (*a*) seam
   (*b*) butt
   (*c*) spot
   (*d*) upset.
19. In the process of electroslag welding, theoretically there is no upper limit to the
   (*a*) thickness of weld bead
   (*b*) rate of metal deposit
   (*c*) slag bath temperature
   (*d*) rate of slag consumption.
20. High temperature metals like columbium can be easily welded by..................... welding.
   (*a*) flash
   (*b*) MIG
   (*c*) TIG
   (*d*) electron beam.
21. During resistance welding heat produced at the joint is proportional to
   (*a*) I^2R
   (*b*) kVA
   (*c*) current
   (*d*) voltage
22. Grey iron in usually welded by .... welding
   (*a*) gas
   (*b*) arc

(*c*) resistance
(*d*) MIG

23. The metal surfaces, for electrical resistance welding must be.......
(*a*) lubricated
(*b*) cleaned
(*c*) moistened
(*d*) rough

24. In a welded joint poor fusion is due to which of the following?
(*a*) Improper current
(*b*) High welding speed
(*c*) Uncleaned metal surface
(*d*) Lack of flux

25. For arc welding, D.C. is produced by which of the following?
(*a*) motor-generator set
(*b*) regulator
(*c*) transformer
(*d*) none of the above

26. ..... welding process uses consumable electrodes.
(*a*) TIG
(*b*) MIG
(*c*) Laser
(*d*) All of the above

27. Which of the following equipment is generally used for arc welding?
(*a*) single phase alternator
(*b*) two phase alternator
(*c*) three phase alternator
(*d*) transformer

28. Which of the following is not an inert gas?
(*a*) argon
(*b*) carbon dioxide
(*c*) helium
(*d*) all of the above

29. Electronic components are joined by which of the following methods?
(*a*) brazing
(*b*) soldering
(*c*) seam welding
(*d*) spot welding
(*e*) none of the above

30. Resistance welding cannot be used for
(*a*) dielectrics
(*b*) ferrous materials
(*c*) non-ferrous metals
(*d*) any of the above

31. Electric arc welding process produces temperature upto
(*a*) 1000^oC
(*b*) 1500^oC
(*c*) 3500^oC
(*d*) 5550^oC

32. Increased heat due to shorter arc is harmful on account of
(*a*) under-cutting of base material
(*b*) burn through
(*c*) excessive porosity
(*d*) all of the above

33. Arc blow results in which of the following?
(*a*) Non-uniform weld beads
(*b*) Shallow weld puddle given rise to weak weld
(*c*) Splashing out of metal from weld puddle
(*d*) All of the above defects

34. Inseam welding
(*a*) the work piece is fixed and disc electrodes move
(*b*) the work piece moves but rotating electrodes are fixed
(*c*) any of the above
(*d*) none of the above

35. In arc welding major personal hazards are
(*a*) flying sperks
(*b*) weld spatter
(*c*) harmful infrared and ultra-violet rays from the arc
(*d*) all of the above

36. In spot welding composition and thickness of the base metal decides
(*a*) the amount of squeeze pressure
(*b*) hold time
(*c*) the amount of weld current
(*d*) all above

37. Helium produces which of the following?
(*a*) deeper penetration
(*b*) faster welding speeds
(*c*) narrower heat affected zone in base metal
(*d*) all of the above

38. Due to which of the following reasons aluminium is difficult to weld?
(*a*) it has an oxide coating
(*b*) it conducts away heat very rapidly
(*c*) both (a) and (b)
(*d*) none of the above

39. Welding leads have
(*a*) high flexibility
(*b*) high current handling capacity
(*c*) both (a) and (b)
(*d*) none of the above

40. Air craft body is
(*a*) spot welded

(b) gas welded
(c) seam welded
(d) riveted

41. For arc welding current range is usually
(a) 10 to 15 A
(b) 30 to 40 A
(c) 50 to 100 A
(d) 100 to 350 A

42. Spot welding is used for
(a) thin metal sheets
(b) rough and irregular surfaces
(c) costings only
(d) thick sections

43. Galvanising is a process of applying a layer of
(a) aluminium
(b) lead
(c) copper
(d) zinc

44. A seamless pipe has
(a) steam welded joint
(b) spot welded joint
(c) arc welded joint
(d) no joint

45. Motor-generator set for D.C. arc welding has generator of
(a) series type
(b) shunt type
(c) differentially compound type
(d) level compound type

46. Plain and butt welds may be used on materials upto thickness of nearly
(a) 5 mm
(b) 10 mm
(c) 25 mm
(d) 50 mm

47. In argon arc welding argon is used as a
(a) flux
(b) source of heat
(c) agent for heat transfer
(d) shield to protect the work from oxidation

48. During arc welding as the thickness of the metal to be welded increases
(a) current should decrease, voltage should increase
(b) current should increases, voltage remaining the same
(c) current should increase, voltage should decrease
(d) voltage should increase, current remaining the same

49. In D.C. arc welding
(a) electrode is made positive and workpiece negative
(b) electrode is made negative and workpiece positive
(c) both electrode as well as workpiece are made positive
(d) both electrode as well as workpiece are made negative

50. The purpose of coating on arc welding electrodes is to
(a) stabilise the arc
(b) provide a protecting atmosphere
(c) provide slag to protect the molten metal
(d) all of the above

51. 50 percent duty cycle of a welding machine means
(a) machine input is 50 percent of rated input
(b) machine efficiency is 50 percent
(c) machine work on 50 percent output
(d) machine works for 5 minutes in a duration of 10 minutes

ANSWERS

1. (b)	2. (d)	3. (a)	4. (c)	5. (c)	6. (a	7. (c)	8. (b)	9. (d)
10. (a)	11. (c)	12. (b)	13. (d)	14. (d)	15. (a)	16. (d)	17. (b)	18. (c)
19. (a)	20. (d)	21. (a)	22. (a)	23. (b)	24. (a)	25. (a)	26. (b)	27. (d)
28. (b)	29. (b)	30. (a)	31. (d)	32. (d)	33. (d)	34. (c)	35. (d)	36. (d)
37. (d)	38. (c)	39. (d)	40. (c)	41. (d)	42. (a)	43. (d)	44. (d)	45. (d)
46. (c)	47. (d)	48. (b)	49. (b)	50. (d)	51. (d)			

GO To FIRST

CONTENTS

CHAPTER 49

Learning Objectives

- Radiations from a Hot Body
- Solid Angle
- Definitions
- Calculation of Luminance (L)
- Laws of Illumination or Illuminance
- Polar Curves of C.P. Distribution
- Uses of Polar Curves
- Determination of M.S.C.P and M.H.C.P. from Polar Diagrams
- Integrating Sphere or Photometer
- Diffusing and Reflecting Surfaces
- Lighting Schemes
- Illumination Required for Different Purposes
- Space / Height Ratio
- Design of Lighting Schemes and Layouts
- Utilisation Factor ((h)
- Depreciation Factor (P)
- Floodlighting
- Artificial Source of Light
- Incandescent Lamp
- Filament Dimensions
- Incandescent Lamp Characteristics
- Clear and Inside
- Frosted Gas-filled Lamps
- Discharge Lamps
- Sodium Vapour Lamp

ILLUMINATION

When some materials are heated above certain temperatures, they start radiating energy in the form of light. This phenomenon is called luminance. Electric lamps are made based on this phenomenon.

CONTENTS

49.1. Radiations From a Hot Body

The usual method of producing artificial light consists in raising a solid body or vapour to incandescence by applying heat to it. It is found that as the body is gradually heated above room temperature, it begins to radiate energy in the surrounding medium in the form of electromagnetic waves of various wavelengths. The ***nature*** of this radiant energy depends on the temperature of the hot body. Thus, when the temperature is low, radiated energy is in the form of heat waves only but when a certain temperature is reached, light waves are also radiated out in addition to heat waves and the body becomes luminous. Further increase in temperature produces an increase in the amount of both kinds of radiations but the colour of light or visible radiation changes from bright red to orange, to yellow and then finally, if the temperature is high enough, to white. As temperature is increased, the wavelength of the visible radiation goes on becoming shorter. It should be noted that heat waves are identical to light waves except that they are of longer wavelength and hence produce no impression on the retina. Obviously, from the point of view of light emission, heat energy represents so much wasted energy.

The ratio $\dfrac{\text{energy radiated out in the form of light}}{\text{total energy radiated out by the hot body}}$ is called the ***radiant*** efficiency of the luminous source and, obviously, depends on the temperature of the source. As the temperature is increased beyond that at which light waves were first given off, the radiant efficiency increases, because light energy will increase in greater proportion than the total radiated energy. When emitted light becomes white *i.e.*, it includes all the visible wavelengths, from extreme red to extreme violet, then a further increase in temperature produces radiations which are of wavelength smaller than that of violet radiations. Such radiations are invisible and are known as ultra-violet radiations. It is found that maximum radiant efficiency would occur at about 6200°C and even then the value of this maximum efficiency would be 20%. Since this temperature is far above the highest that has yet been obtained in practice, it is obvious that the actual efficiency of all artificial sources of light *i.e.* those depending on ***temperature incandescence***, is low.

As discussed above, light is radiant energy which is assumed to be propagated in the form of transverse waves through an invisible medium known as ether. These light waves travel with a velocity of $2.99776 \cdot 10^8$ m/s or $3 \cdot 10^8$ m/s approximately but their wavelengths are different. The wavelength of red light is nearly 0.000078 cm and that of violet light 0.000039 cm. Since these wavelengths are very small, instead of using 1 cm as the unit for their measurement, a submultiple 10^{-8} cm is used. This submultiple is known as Angstrom Unit (A.U.)

$$1 \text{ A.U.} = 10^{-8} \text{ cm} = 10^{-10} \text{ m}$$

Hence, the wave-length of red light becomes $\lambda_r = 7800 \cdot 10^{-10}$ m or 7800 A.U. and $\lambda_v = 3900 \cdot 10^{-10}$ m or 3900 A.U. The sensation of colour is due to the difference in the wavelengths and hence frequencies of the light radiations.

49.2. Solid Angle

Consider an area A which is part of a sphere of radius r (Fig. 49.1). Let us find the solid angle ω subtended by this area at the centre C of the sphere. For this purpose, let point C be joined to every point on the edges of the area A. Then, the angle enclosed by the cone at point C gives the solid angle. Its value is

$$\omega = \frac{A}{r^2} \text{ steradian}$$

The unit of solid angle is ***steradian*** (sr). If, in the above equation, $A = r^2$, then $\omega = 1$ steradian. Hence, steradian is defined as the angle subtended at the centre of a sphere by a part of its surface having an area equal to (radius)^2.

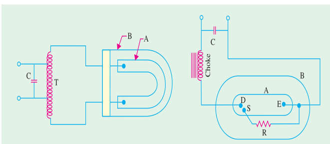


Fig. 49.1

Fireworks radiate light energy of different frequencies, which appear in different colours

Obviously, the solid angle subtended at the centre by whole of the spherical surface = $4\pi\, r^2/r^2 = 4\pi$ steradian (sr).

49.3. Definitions

Before proceeding further, definitions of a few principal terms employed in connection with illumination, are given below :

1. Candela. It is the unit of luminous intensity of a source. It is defined as 1/60th of the luminous intensity per cm^2 of a black body radiator at the temperature of solidification of platinum (2045°K).

A source of one candela (*cd*) emits one lumen per steradian. Hence, total flux emitted by it allround is $4\pi \cdot 1 = 4\pi$ lumen.

2. Luminous Flux (F or Φ). It is the light energy radiated out per second from the body in the form of luminous light waves.

Since, it is a rate of flow of energy, it is a sort of *power* unit. Unit of luminous flux is *lumen* (lm). It is defined as the ***flux contained per unit solid angle of a source of one candela or standard candle*** (Fig. 49.2).

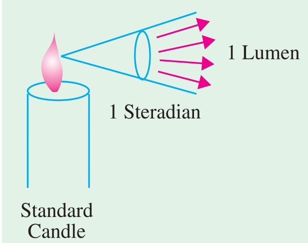


Fig. 49.2

Approximate relation between lumen and electric unit of power *i.e.* watt is given as

$$1 \text{ lumen} = 0.0016 \text{ watt (approx.)}$$

3. Lumen-hour. It is the quantity of light delivered in one hour by a flux of one lumen.*

4. Luminous Intensity (I) or Candle-power of a point source in any particular direction is given by the ***luminous flux radiated out per unit solid angle in that direction***. In other words, it is solid angular flux density of a source in a specified direction.

If $d\Phi$ is the luminous flux radiated out by a source within a solid angle of $d\omega$ steradian in any particular direction, then $I = d\Phi/d\omega$.

If flux is measured in lumens and solid angle in steradian, then its unit is lumen/steradian (lm/sr) or candela (*cd*).

If a source has an average luminous intensity of I lm/sr (or I candela), then total flux radiated by it all around is $\Phi = \omega I = 4\pi I$ lumen.

Generally, the luminous intensity or candle power of a source is different in different directions. The average candle-power of a source is the average value of its candle power in all directions. Obviously, it is given by total flux (in lm) emitted in all directions in all planes divided by 4π. This average candle-power is also known as ***mean spherical candle-power*** (M.S.C.P.).

$$\therefore \qquad \text{M.S.C.P.} = \frac{\text{total flux in lumens}}{4\,\pi}$$

If the average is taken over a hemisphere (instead of sphere), then this average candle power is known as ***mean hemispherical candle-power*** (M.H.S.C.P.).

It is given by the total flux emitted in a hemisphere (usually the lower one) divided by the solid angle subtended at the point source by the hemisphere.

$$\therefore \qquad \text{M.H.S.C.P.} = \frac{\text{flux emitted in a hemisphere}}{2\,\pi}$$

* It is similar to watt-hour (Wh)

5. Reduction Factor of a source is given by the ratio, f = M.S.C.P./M.H.C.P. where M.H.C.P. is the mean horizontal candle power.

It is also referred to as spherical reduction factor.

6. Illuminance or Illumination (E). When the luminous flux falls on a surface, it is said to be illuminated. The illumination of a surface is measured by the normal luminous flux per unit area received by it.

If $d\Phi$ is the luminous flux incident normally on an area dA, then $E = d\Phi/dA$ or $E = \Phi/A$.

Unit. Since flux Φ is measured in lumens and area in m^2, unit of E is lm/m^2 or lux. The alternative name is metre-candle (m-cd). Let us see why ? Imagine a sphere of radius of one metre around a point source of one candela. Flux radiated out by this source is 4π lumen. This flux falls normally on the curved surface of the sphere which is $= 4\pi$m^2. Obviously, illumination at every point on the inner surface of this sphere is 4π $lm/4\pi$ m^2 = 1 lm/m^2. However, the term lm/m^2 is to be perferred to metre-candle.

7. Luminance (L) of an Extended Source. Suppose ΔA is an element of area of an ***extended*** source and Δt its luminous intensity when viewed in a direction making an angle ϕ with the perpendicular to the surface of the source (Fig. 49.3), then luminance of the source element is given by

$$L = \frac{\Delta I}{\Delta A \cos\phi} = \frac{\Delta I}{\Delta A'}\ cd/\text{m}^2 \quad ...(i)$$

where $\Delta A' = \Delta A \cos\phi$

= area of the source element projected onto a plane perpendicular to the specified direction.

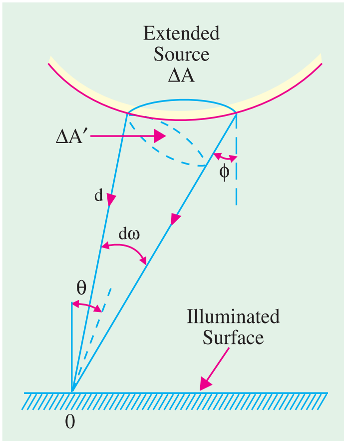


Fig. 49.3

As will be seen from Art. 49.5.

$$E = \frac{I\cos\theta}{d^2} \quad \text{or} \quad \Delta E = \frac{\Delta I}{d^2}\cos\theta$$

Substituting the value of ΔI from Eq. (i) above, we get

$$\Delta E = \frac{L.\Delta A'}{d^2}\cos\theta = L\cos\theta.\,d\omega$$

where $d\omega = \Delta A'/d^2$ steradian

$$E = \int L\cos\theta\,.\,d\omega = L\int\cos\theta\,.\,d\omega$$

—if L is constant.

8. Luminous Exitance (M) of a Surface. The luminous exitance (M) at a point on a surface is defined as luminous flux emitted per unit area in all directions. If an element of an illuminated area ΔA emits a total flux of $\Delta\Phi$ in all directions (over a solid angle of 2π steradian) then

$$M = \Delta\Phi/\Delta A \quad lm/\text{m}^2$$

It can be proved that $M = \pi L$ in the case of a uniform diffuse ***source***.

9. Transmittance (T) of an Illuminated Diffuse Reflecting Surface. It is defined as the ratio of the total luminous flux transmitted by it to the total flux incident on it.

The relation between luminous exitance (M) of a surface transmitting light and illuminance (E) on the other side of it is

$$M = TE \quad \text{or} \quad T = M/E$$

Since light falling on a surface is either transmitted, reflected or absorbed the following relation holds good

$$T + \rho + \alpha = 1$$ where α is the absorptance of the surface.

10. Reflection Ratio or Coefficient of Reflection or Reflectance (ρ). It is given by the luminous flux reflected from a small area of the surface to the total flux incident upon it

$\rho = M/E$ *i.e.* ratio of luminous exitance and illuminance.

It is always less than unity. Its value is zero for ideal 'black body' and unity for a perfect reflector.

11. Specific Output or Efficiency of a lamp is the ratio of luminous flux to the power intake. Its unit is lumen/watt (lm/W). Following relations should be taken note of :

(*a*) $$\frac{\text{lumen}}{\text{watt}} = \frac{4\pi \cdot \text{ M.S.C.P.}}{\text{watt}}$$

or $$\frac{\text{lm}}{\text{W}} = \frac{4\,\pi}{\text{watt/M.S.C.P.}}$$

(*b*) since f = M.S.C.P./M.H.C.P. ∴ $\text{lm/W} = \dfrac{4\,\pi\,f}{\text{watt/M.S.C.P.}}$

(*c*) Obviously, $\text{watts/M.S.C.P.} = \dfrac{4\,\pi}{1\text{m/W}} = \dfrac{\text{watt/M.H.C.P.}}{f}$

(*d*) Also $\text{watts/M.H.C.P.} = \dfrac{4\,\pi\,f}{1\text{m/W}} = f \cdot \text{ watts/M.S.C.P.}$

12. Specific Consumption. It is defined as the ratio of the power input to the average candle-power. It is expressed in terms of watts per average candle or watts/M.S.C.P.

The summary of the above quantities along with their units and symbol is given in Table 49.1.

Table 49.1

Name of Qty	*Unit*	*Symbols*
Luminous Flux	Lumen	F or Φ
Luminous Intensity (candle-power)	Candela	I
Illumination or Illuminance	lm/m^2 or lux	E
Luminance or Brightness	cd/m^2	L or B
Luminous Exitance	lm/m^2	M

49.4. Calculation of Luminance (L) of a Diffuse Reflecting Surface

The luminance (or brightness) of a surface largely depends on the character of the surface, if it is itself not the emitter. In the case of a polished surface, the luminance depends on the angle of viewing. But if the surface is matt and diffusion is good, then the luminance or brightness is practically independent of the angle of viewing. However, the reflectance of the surface reduces the brightness proportionately. In Fig. 49.4 is shown a perfectly diffusing surface of small area A. Suppose that at point M on a hemisphere with centre O and radius R, the illuminance is L cd/m^2. Obviously, ***luminous intensity*** at point M is $= L \cdot A \cos\theta$ candela (or lumen/steradian). Now, the hemisphere can be divided into a number of zones as shown. Consider one such zone MN between θ and (θ + $d\theta$). The width of this zone is $R.d\theta$ and length $2\pi R \sin\theta$ so that its area (shown shaded) is $= 2\pi R^2 \sin\theta.\, d\theta$. Hence, it subtends a solid angle $= 2\pi R^2 \sin\theta.d\theta/R^2 = 2\pi \sin\theta.\, d\theta$ steradian at point O. The luminous flux passing through this zone is

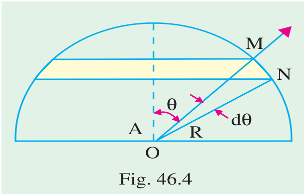


Fig. 49.4

$$d\Phi = L\,A\cos\theta \cdot 2\pi\sin\theta.d\,\theta = \pi L\,A \cdot 2\sin\theta\cos\theta\,d\,\theta = \pi\,LA\sin 2\,\theta\,d\theta \text{ lumen}$$

Total flux passing through the whole hemisphere is

$$\Phi = \int_0^{\pi/2} \pi LA \sin 2\,\theta\,.\,d\theta = \pi LA \text{ lumen}$$

If the ***illumination*** of the surface (produced by a light source) is E lm/m^2 and ρ is its reflection coefficient, then $\Phi = \rho\, A\ E$ lumen.

Equating the two values of flux, we have $\pi L A = \rho A\ E$

or $\qquad L = \rho E/\pi \text{ cd/m}^2 = \rho E \text{ lm/m}^2$

For example, consider a perfectly diffusing surface having $\rho = 0.8$ and held at a distance of 2 metres from a source of luminous intensity 100 candela at right angles to the direction of flux. Then

$$E = 100/22 = 25 \text{ lm/m}^2$$

$$L = \rho E/\pi = 25 \cdot\ 0.8/\pi = 6.36 \text{ cd/m}^2 = 636 \cdot\ \pi = 20 \text{ lm/m}^2$$

49.5. Laws of Illumination or Illuminance

The illumination ***(E)*** of a surface depends upon the following factors. The source is assumed to be a point source or is otherwise sufficiently away from the surface to be regarded as such.

(i) ***E*** is directly proportional to the luminous intensity ***(I)*** of the source or $E \propto I$

(ii) ***Inverse Square Law***. The illumination of a surface is inversely proportional to the square of the distance of the surface from the source.

In other words, $E \propto 1/r^2$

Proof

In Fig. 49.5 are shown portions of the surfaces of three spheres whose radii are in the ratio 1 : 2 : 3. All these portions, obviously, subtend the same solid angle at the source and hence receive the same amount of total flux. However, since their areas are in the ratio of 1 : 4 : 9, their illuminations are in the ratio $1 : \frac{1}{4} : \frac{1}{9}$.

(iii) ***Lambert's Cosine Law***. According to this law, E is directly proportional to the cosine of the ***angle made by the normal to the illuminated surface with the direction of the incident flux***.

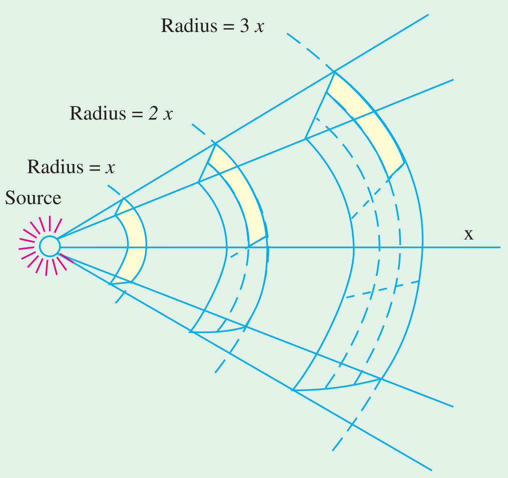


Fig. 49.5

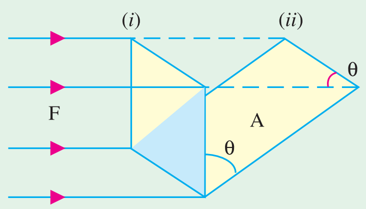


Fig. 49.6

Proof

As shown in Fig. 49.6, let Φ be the flux incident on the surface of area A when in position 1. When this surface is turned back through an angle θ, then the flux incident on it is $\Phi \cos \theta$. Hence, illumination of the surface when in position 1 is $E_1 = \Phi/A$. But when in position 2.

$$E_2 = \frac{\Phi \cos\theta}{A} \qquad \therefore \qquad E_2 = E_1 \cos\theta$$

Combining all these factors together, we get $E = I\cos\theta/r^2$. The unit is lm/m^2.

The above expression makes the determination of illumination possible at a given point provided the position and the luminous intensity or candle power (in the given direction) of the source (or sources) by which it is illuminated, are known as illustrated by the following examples.

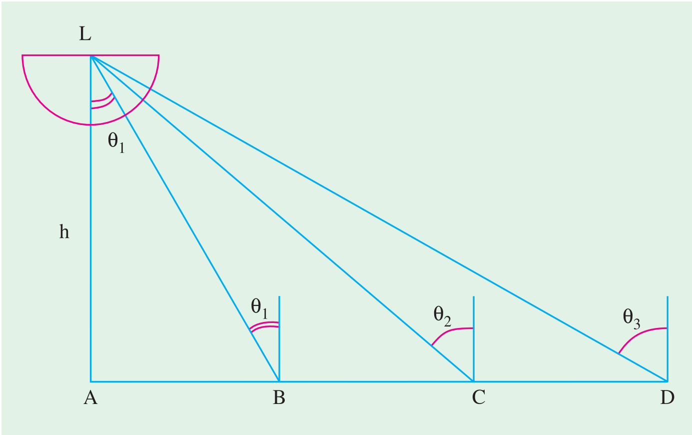


Fig. 49.7

Consider a lamp of uniform luminous intensity suspended at a height h above the working plane as shown in Fig. 49.7. Let us consider the value of illumination at point A immediately below the lamp and at other points B,C,D etc., lying in the working plane at different distances from A.

$$E_A = \frac{I}{h^2} \text{ —since } \theta = 0 \text{ and } \cos\theta = 1$$

$$E_B = \frac{I}{LB^2}\cdot\cos\theta_1. \qquad \text{Since,} \quad \cos\theta_1 = h/LB$$

$$\therefore \quad E_B = \frac{I}{LB^2}\cdot\frac{h}{LB} = I\cdot\frac{h}{LB^2} = \frac{1}{h^2}\cdot\frac{h^3}{LB^3} = \frac{1}{h^2}\left(\frac{h}{LB}\right)^3$$

$$\text{Now} \quad \frac{1}{h^2} = E_A \text{ and } \left(\frac{h}{LB}\right)^3 = \cos^3\theta_1$$

$$\therefore \quad E_B = E_A\cos^3\theta_1$$

Similarly, $E_C = E_A.\cos^3\theta_2$ and $E_D = E_A\cos^3\theta_3$ and so on.

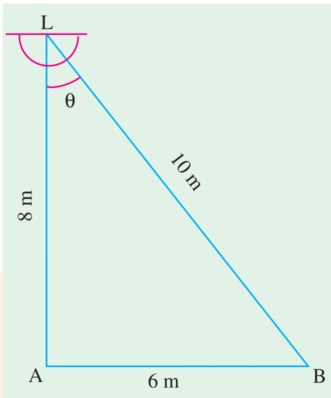


Fig. 49.8

Example 49.1. *A lamp giving out 1200 lm in all directions is suspended 8 m above the working plane. Calculate the illumination at a point on the working plane 6 m away from the foot of the lamp.* **(Electrical Technology, Aligarh Muslim Univ.)**

Solution. Luminous intensity of the lamp is

$$I = 1200/4\pi = 95.5 \text{ cd}$$

As seen from Fig. 49.8.

$$L_B = \sqrt{8^2 + 6^2} = 10 \text{ m} ; \cos\theta = 8/10 = 0.8$$

$$\text{Now,} \quad E = I\cos\theta/r^2$$

$$\therefore \quad E_B = 95.5\cdot\ 0.8/10^2 = \mathbf{0.764\ lm/m^2}$$

Example 49.2. *A small light source with intensity uniform in all directions is mounted at a height of 10 metres above a horizontal surface. Two points A and B both lie on the surface with point*

A directly beneath the source. How far is B from A if the illumination at B is only 1/10 as great as at A ? **(A.M.I.E.)**

Solution. Let the intensity of the lamp be I and the distance between A and B be x metres as shown in Fig. 49.9.

Illumination at point $A, E_A = I/10^2 = I/100$ lux

Illumination at point B,

Illumination at point B,

$$E_B = \frac{I}{10^2} \cdot \left[\frac{10}{\sqrt{10^2 + x^2}}\right]^2 = \frac{10\,I}{(100 + x^2)^{3/2}}$$

Since $$E_B = \frac{E_A}{10},$$

$$\therefore \quad \frac{10\,I}{(100 + x^2)^{3/2}} = \frac{1}{10} \cdot \frac{I}{100}, \qquad \therefore \quad x = \mathbf{19.1\ m}$$

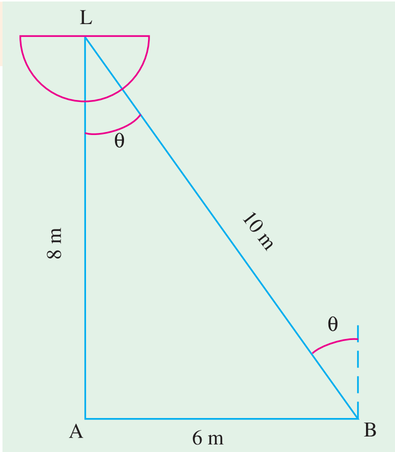


Fig. 49.9

Example 49.3. *A corridor is lighted by 4 lamps spaced 10 m apart and suspended at a height of 5 m above the centre line of the floor. If each lamp gives 200 C.P. in all directions below the horizontal, find the illumination at the point on the floor mid-way between the second and third lamps.*

(Electrical Engineering, Bombay Univ.)

Solution. As seen from 49.10, illumination at point C is due to all the four lamps. Since point C is symmetrically situated between the lamps, illumination at this point is twice that due to L_1 and L_2.

(*i*) illumination due to $L_1 = I \cos\theta_1 / L_1C^2 \quad L_1C = \sqrt{5^2 + 15^2} = 15.8$ m

$\cos\theta = 5/15.8$

$$\text{illumination due to } L_1 = \frac{220 \cdot (5/15.8)}{250} = \mathbf{0.253\ lm/m^2}$$

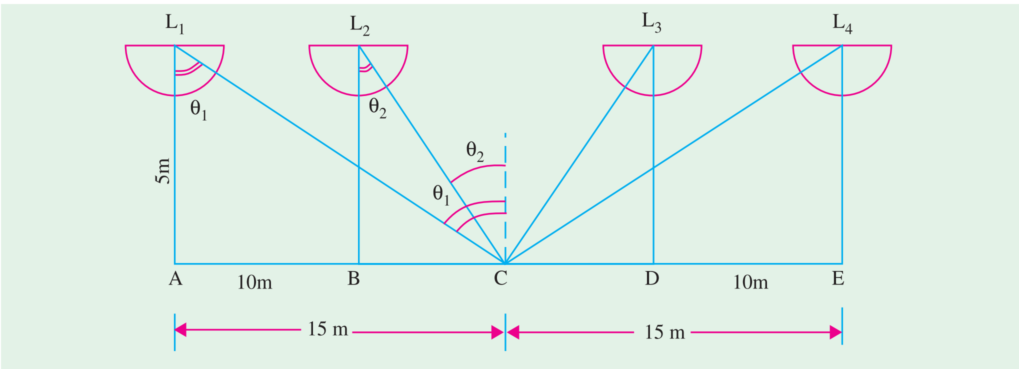


Fig. 49.10

(*ii*) $L_2C = 5/\sqrt{2}$ m ; $\theta_2 = 45°$; $\cos\theta_2 = 1/\sqrt{2}$

$$\text{Illumination due to } L_2 = \frac{200 \cdot 1/\sqrt{2}}{50} = 2.83 \text{ lm/m}^2$$

$\therefore$ illumination at C due to L_1 and $L_2 = 3.08$ lm/m^2

Illumination at C due to all the four lamps, $E_C = 2 \cdot 3.08 =$ **6.16 lm/m²**

Example 49.4. *Two lamps A and B of 200 candela and 400 candela respectively are situated 100 m apart. The height of A above the ground level is 10 m and that of B is 20 m. If a photometer is placed at the centre of the line joining the two lamp posts, calculate its reading.*

(Electrical Technology, Gujarat Univ.)

Solution. When the illumination photometer is placed at the centre point, it will read the value of combined illumination produced by the two lamps (Fig. 49.11).

Now, $L_1C = \sqrt{10^2 + 50^2}$

$= 51$ m

$L_2C = \sqrt{20^2 + 50^2}$

$= 53.9$ m

$\cos\theta_1 = 10/51$;

$\cos\theta_2 = 20/53.9$

Illumination at point C due to lamp L_1

$$= \frac{200 \cdot 10}{51 \cdot 2600}$$

$= $ **0.015 lm/m²**

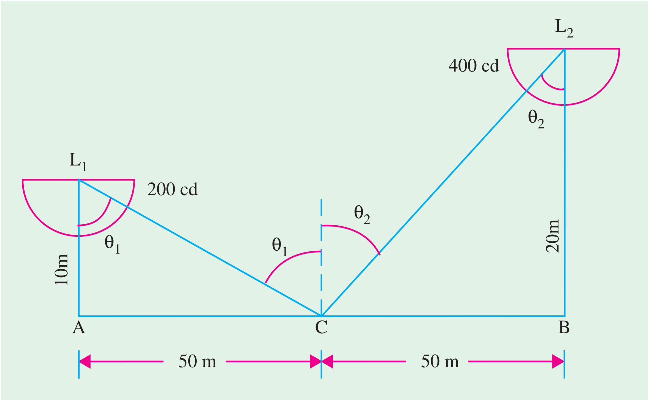


Fig. 49.11

Similarly, illumination due to lamp L_2

$$= \frac{400 \cdot 20/53.9}{2900} = \textbf{0.051 lm/m}^2$$

$\therefore \quad E_C = 0.015 + 0.051$

$= $ **0.066 lm/m² or lux**

Example 49.5. *The average luminous output of an 80-W fluorescent lamp 1.5 metre in length and 3.5 cm diameter is 3300 lumens. Calculate its average brightness. If the auxiliary gear associated with the lamp consumes a load equivalent to 25 percent of the lamp, calculate the cost of running a twin unit for 2500 hours at 30 paise per kWh.*

Solution. Surface area of the lamp $= \pi \cdot 0.035 \cdot 1.5 = 0.165$ m²

Flux emitted per unit area $= 3300/0.165 = 2 \times 10^4$ lm/m²

$$\therefore \quad B = \frac{\text{flux emitted per unit erea}}{\pi} \text{ cd/m}^2 = 2 \cdot \frac{10^2}{\pi} = \textbf{6,382 cd/m}^2$$

Total load of twin fitting $= 2[80 + 0.25 \cdot 80] = 200$ W

Energy consumed for 2500 hr $= 2500 \cdot 200 \cdot 10^{-3} = 500$ kWh

cost $=$ Rs. $500 \cdot 0.3 =$ **Rs. 150.**

Example 49.6. *A small area 7.5 m in diameter is to be illuminated by a lamp suspended at a height of 4.5 m over the centre of the area. The lamp having an efficiency of 20 lm/w is fitted with a reflector which directs the light output only over the surface to be illuminated, giving uniform candle power over this angle. Utilisation coefficient = 0.40. Find out the wattage of the lamp. Assume 800 lux of illumination level from the lamp.* **(A.M.I.E.)**

Solution. $A = \pi d^2/4 = 44.18$ m², $E = 800$ lux

Luminous flux reaching the surface $= 800 \cdot 44.18 = 35,344$ lm

Total flux emitted by the lamp = 35,344/0.4 = 88,360 lm

Lamp wattage = 88,360/20 = **4420 W**

Example 49.7. *A lamp of 100 candela is placed 1 m below a plane mirror which reflects 90% of light falling on it. The lamp is hung 4 m above ground. Find the illumination at a point on the ground 3 m away from the point vertically below the lamp.*

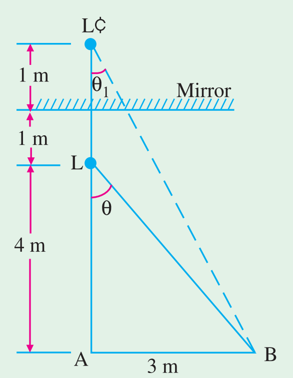


Fig. 49.12

Solution. The lamp and mirror arrangement is shown in Fig. 49.12. The lamp L produces an image L' as far behind the mirror as it is in front. Height of the image from the ground is (5 + 1) = 6m. L' acts as the secondary source of light and its candle power is = 0.9 · 100 = 90 candela.

Illumination at point B equals the sum of illumination due to L and that due to L'.

$$\therefore \quad E_B = \frac{100}{(LB)^2} \cdot \cos\theta + \frac{90}{(L'B)^2} \cos\theta_1$$

$$= \frac{100}{5^2} \cdot \frac{4}{5}\ \frac{90}{45}\ \frac{6}{\sqrt{45}} = \mathbf{5\ lux}$$

Example. 49.8. *A light source having an intensity of 500 candle in all directions is fitted with a reflector so that it directs 80% of its light along a beam having a divergence of 15°. What is the total light flux emitted along the beam? What will be the average illumination produced on a surface normal to the beam direction at a distance of 10 m?* **(A.M.I.E.)**

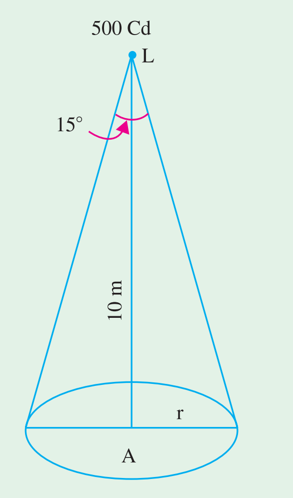


Fig. 49.13

Solution. Total flux emitted along the beam = 0.8 (4π · 500) = **5,227 lm**

Beam angle, θ = 15°, l = 10 m

Radius of the circle to be illuminated, $r = l \tan \theta/2$

= 10 tan 15°/2 = 1.316 m

Area of the surface to be illuminated, $A = \pi r^2 = \pi \cdot 1.316^2$

= 5.44 m^2

∴ Average illumination = 5227/5.44 = **961 lux**

Example 49.9. *A lamp has a uniform candle power of 300 in all directions and is fitted with a reflector which directs 50% of the total emitted light uniformly on to a flat circular disc of 20 m diameter placed 20 m vertically below the lamp. Calculate the illumination (a) at the centre and (b) at the edge of the surface without the reflector. Repeat these two calculations with the reflector provided.* **(Electrical Engg., Grad I.E.T.E.)**

Solution. It should be noted that the formula $E = I \cos\theta/r^2$ will not be applicable when the reflector is used. Moreover, with reflector, illumination would be uniform.

Without Reflector

(*a*) $E = 300 \cdot 1/20^2$ = **0.75 lm/m²**

(*b*) Here, $\theta = \tan^{-1}(10/20) = 26.6°$, $\cos\theta = 0.89$; $x^2 = 10^2 + 20^2 = 500$

∴ $E = 300 \cdot 0.89/500$ = **0.534 lm/m²**

With Reflector

Luminous output of the lamp = 300 · 4π lumen

Flux directed by the reflector $= 0.5 \cdot 1200\,\pi = 600\,\pi$ lm

Illumination produced on the disc $= 600\,\pi/100\,\pi =$ **6 lm/m²**

It is the same at every point of the disc.

Example 49.10. *A light is placed 3 m above the ground and its candle power is 100 cos θ in any downward direction making an angle q with the vertical. If P and Q are two points on the grond, P being vertically under the light and the distance PQ being 3 m, calculate.*

(a) the illumination of the ground at P and also at Q.

(b) the total radiations sent down by the lamp.

Solution. With reference to Fig. 49.14

(*a*) C.P. along $LP = 100 \cdot \cos 0° = 100$ cd $\quad\therefore\quad E_P = 100/3^2 =$ **11.1 lm/m²**

C.P. along $LQ = 100 \cdot \cos 45° = 70.7 \quad\therefore\quad E_Q = 70.7 \cdot \cos 45°/18 =$ **1.39 lm/m²**

(*b*) Consider an imaginary hemisphere of radius *r* metre at whose centre lies the given lamp (Fig. 49.15).

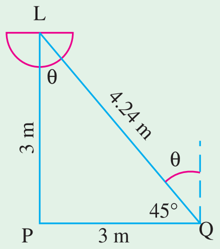


Fig. 49.14

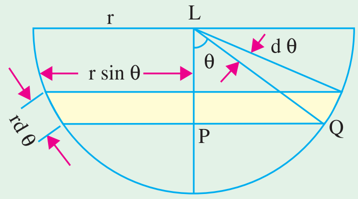


Fig. 49.15

C.P. along $LQ = 100 \cos\theta \quad\therefore\quad E_Q = 100\cos\theta/r^2$

The area of the elementary strip at an angular distance θ from the vertical and of width $PQ = r.\,d\theta$ is $= (2\pi\, r \sin\theta) \cdot r.d\theta = 2\pi r^2 \sin\theta\, d\theta$.

Flux incident on the shaded area

$$= \frac{100\cos\theta}{r^2} 2\pi\, r^2 \sin\theta.\, d\theta = 100\,\pi.\, 2\sin\theta.\cos\theta\, d\theta = 100\,\pi\sin 2\theta\, d\theta.$$

Total flux over the hemisphere can be obtained by integrating the above expression between proper limits.

$$\therefore \qquad \text{total flux} = \int_0^{\pi/2} 100\,\pi\sin 2\theta\, d\theta = 100\,\pi \left| -\frac{\cos 2\theta}{2} \right|_0^{\pi/2} = \frac{100\,\pi}{2}$$

$$= 100\,\pi = \mathbf{314.lm.}$$

Example 49.11. *A drawing office containing a number of boards and having a total effective area of 70 m² is lit by a number of 40 W incandescent lamps giving 11 lm/W. An illumination of 80 lux is required on the drawing boards. Assuming that 60% of the total light emitted by the lamps is available for illuminating the drawing boards, estimate the number of lamps required.*

Solution. Let *N* be the number of 40 W lamps required.

Output/lamp $= 40 \cdot 11 = 440$ lm ; Total flux $= 440\,N$ lm

Flux actually utilized $= 0.6 \cdot 440\,N = 264\,N$ lm

Illumination required $= 80$ lux $= 80$ lm/m²

Total flux required at the rate of 80 lm/m² $= 80 \cdot 70$ lm $= 5600$ lm

$264\,N = 5600 \quad\therefore\quad N =$ **21**

Example 49.12. *A perfectly diffusing surface has a luminous intensity of 10 candles at an angle of 60° to the normal. If the area of the surface is 100 cm^2, determine the brightness and total flux radiated.*

Solution. Brightness B is defined as the luminous intensity divided by the projected area (Fig. 49.16).

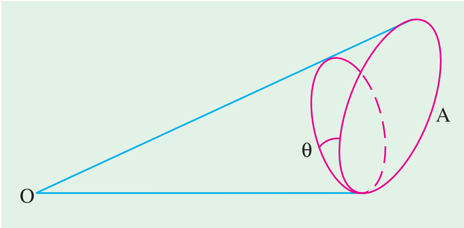


Fig. 49.16

$$\text{Luminous intensity} = 10 \text{ candela}$$
$$\text{Projected area} = A \cos\theta = 100 \cdot \cos 60^\circ = 50 \text{ cm}^2$$
$$\therefore \quad B = 10/50 \cdot 10^{-4} = 2 \cdot 10^3 \text{ cd/m}^2$$
$$= \mathbf{2\pi \cdot 10^3 \text{ lm/m}^2} \text{—Art. 46.4}$$
$$\text{Total flux radiated} = 2\pi \cdot 10^3 \cdot 100 \cdot 10^{-4} = \mathbf{68.2 \text{ lm}}$$

Example 49.13. *Calculate the brightness (or luminance) of snow under an illumination of* **(a)** *44,000 lux and* **(b)** *0.22 lux. Assume that snow behaves like a perfect diffusor having a reflection factor of 85 per cent.*

Solution. (*a*) $L = \rho E/\pi = 44{,}000 \cdot 0.85/\pi \text{ cd/m}^2 = \mathbf{1.19 \cdot 10^4 \text{ cd/m}^2}$

(*b*) $L = \dfrac{0.22 \cdot 0.85}{\pi} = \mathbf{5.9 \cdot 10^{-2} \text{ cd/m}^2}$

Example 49.14. *A 21 cm diameter globe of dense opal glass encloses a lamp emitting 1000 lumens and has uniform brightness of 4 · 10^3 lumen/m^2 when viewed in any direction. What would be the luminous intensity of the globe in any direction? Find what percentage of the flux emitted by the lamp is absorbed by the globe.*

Solution. Surface area of the globe $= \pi d^2 = \pi \cdot 21^2 = 1{,}386 \text{ cm}^2 = 0.1386 \text{ m}^2$

Flux emitted by the globe is $= 0.1386 \cdot 4 \cdot 10^3 = 554.4$ lumen

Now, 1 candela $= 4\pi$ lumens

Hence, luminous intensity of globe is $= 554.4/4\pi =$ **44 cd**

Flux absorbed by the globe is $= 1000 - 554.4 = 445.6$ lm.

$\therefore$ percentage absorption $= 445.6 \cdot 100/1000 =$ **44.56%**

Example 49.15. A *2.5 cm diameter disc source of luminance 1000 cd/cm^2 is placed at the focus of a specular parabolic reflector normal to the axis. The focal length of the reflector is 10 cm, diameter 40 cm and reflectance 0.8. Calculate the axial intensity and beam-spread. Also show diagrammatically what will happen if the source were moved away from the reflector along the axis in either direction.* **(A.M.I.E. Sec. B, Winter 1991)**

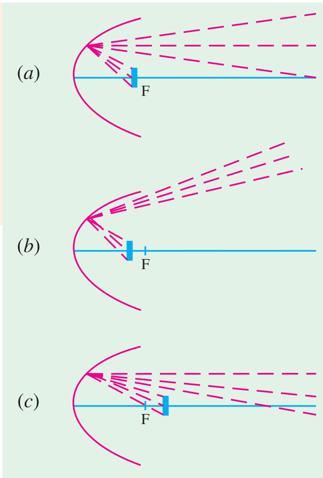


Fig. 49.17

Solution. The axial or beam intensity I depends upon

(*i*) luminance of the disc source *i.e.* L

(*ii*) aperture of the reflector *i.e.* A

(*iii*) reflectivity of the reflector *i.e.* r

$\therefore \quad I = \rho A L$ candela

Now, $L = 1000 \text{ cd/cm}^2 = 10^7 \text{ cd/m}^2$

$A = \pi d^2/4 = \pi \cdot 0.4^2/4 = 125.7 \cdot 10^{-3} \text{ m}^2$

$\therefore \quad I = 0.8 \cdot 125.7 \cdot 10^{-3} \cdot 10^7 =$ **1,005,600 cd**

To a first approximation, the beam spread for disc source is determined by reflector focal length and the size of the disc source. If θ is the total beam spread when the source is at the focus of the reflector [Fig. 49.17] (*a*)] then

$$\theta = 2 \tan^{-1} (r/f)$$

Here, $r = 2.5/2 = 1.25 \text{ cm} ; f = 10 \text{ cm}$

∴ $\theta = 2 \tan^{-1}(1.25/10) = 2 \cdot 7°7' = \mathbf{14°14'}$

The effect of axial movement of the source is shown in Fig. 49.17 (*b*) and (*c*).

Example 49.16. *A 22 diameter globe of opal glass encloses a lamp of uniform luminous intensity 120 C.P. Thirty per cent of light emitted by the lamp is absorbed by globe. Determine* **(a)** *luminance of globe* **(b)** *C.P. of globe in any direction.*

Solution.

(*a*) Flux emitted by source $= 120 \cdot 4\pi$ lm ; flux emitted by globe $= 0.7 \cdot 480\,\pi$ lm

$$\therefore \quad L = \frac{0.7 \cdot 480\pi}{\pi \cdot 0.22^2} = \mathbf{6{,}940\ lm/m^2}$$

(*b*) Since 1 candela $= 4\,\pi$ lm

∴ candle-power or luminous intensity of the globe is

$$= \frac{\text{flux in lumens}}{4\,\pi} = \frac{0.7 \cdot 480\pi}{\pi \cdot 4} = \mathbf{84\ cd}$$

Example 49.17. *A 0.4 m diameter diffusing sphere of opal glass (20 percent absorption) encloses an incandescent lamp with a luminous flux of 4850 lumens. Calculate the average luminance of the sphere.* **(A.M.I.E. Sec. B, Summer 1993)**

Solution. Flux emitted by the globe 80% or 4850 = 3880 lm

Surface area of the globe $= 4\pi r^2 = \pi d^2 \text{m}^2$

$$B = \frac{\text{flux emitted}}{\text{surfacr area}} = \frac{3880}{\pi \cdot 0.4^2} = \mathbf{7{,}720\ lm/m^2}$$

Tutorial Problem No. 49.1

1. A high-pressure mercury-vapour lamp is mounted at a height of 6 m in the middle of a large road crossing. A special reflector directs 100 C.P. maximum in a cone of 70º to the vertical line. Calculate the intensity of illumination on the road surface due to this beam of 100 C.P. ***(Electrical Engineering, Bombay Univ.)***

2. A room 6m · 4 m is illuminated by a single lamp of 100 C.P. in all directions suspended at the centre 3 m above the floor level. Calculate the illumination (*i*) below the lamp and (*ii*) at the corner of the room. ***(Mech. & Elect. Engg. : Gujarat Univ.)***

3. A lamp of 100 candle-power is placed at the centre of a room 10 m · 6m · 4 m high. Calculate the illumination in each corner of the floor and at a point in the middle of a 6 m wall at a height of 2 m from the floor. ***(Utilization of Elect. Power A.M.I.E.)***

4. A source of 5000 lumen is suspended 6.1 m. above ground. Find out the illumination (*i*) at a point just below the lamp and (*ii*) at a point 12.2 m away from the first, assuming uniform distribution of light from the source. **[(*i*) 10.7 lux (*ii*) 0.96 lux]** ***(A.M.I.E. Sec. B)***

5. Determine the average illumination of a room measuring 9.15 m by 12.2 m illuminated by a dozen 150 W lamps. The luminous efficiency of lamps may be taken as 14 lm/W and the co-efficient of utilisation as 0.35. **[79 lux]** ***(A.M.I.E. Sec. B)***

6. Two lamps are hung at a height of 9 m from the floor level. The distance between the lamps is one metre. Lamp one is of 500 candela. If the illumination on the floor vertically below this lamp is 20 lux, find the candle power of the lamp number two. **[1140 candela]** ***(Utili. of Elect. Power A.M.I.E.)***

7. Two powerful street lamps of 1,000 candela and 800 candela (assumed uniform in all directions) are mounted 12.5 m above the road level and are spaced 25 metres apart. Find the intensity of horizontal illumination produced at a point on the ground in-between the lamp posts and just below the lamp posts. **[4.07 lux, 6.86 lux, 5.69 lux]** ***(A.M.I.E.)***

8. It is required to provide an illumination of 100 lux in a factory hall 30 m by 15 m. Assume that the depreciation factor is 0.8, coefficient of utilisation is 0.4 and efficiency of lamp is 14 lm/W. Suggest the number of lamps and their ratings. The sizes of the lamps available are 100, 250, 400 and 500 W. **[40 lamps of 250 W in 5 rows]**

9. It is required to provide an illumination of 100 lm/m^2 in a workshop hall 40m · 10m and efficiency of lamp is 14 lm/W. Calculate the number and rating of lamps and their positions when trusses are provided at mutual distance of 5m. Take coefficient of utilisation as 0.4 and depreciation factor as 0.8. **[14 lamps of 750 W each]**

10. A drawing hall 30 m by 15 m with a ceiling height of 5 m is to be provided with a general illumination of 120 lux. Taking a coefficient of utilization of 0.5 and depreciation factor of 1.4, determine the number of flourscent tubes required, their spacing, mounting height and total wattage.
Taking luminous efficiency of flourescent tube as 40 Im/W for 80 W tubes.
[48, 24 twin-tube units each tube of 80 W; row spacing of 5 m and unit spacing of 3.75m, 3840 W]
(Utilisation of Elect. Power, A.M.I.E.)

49.6. Laws Governing Illumination of Different Sources

The laws applicable to the illumination produced by the following three types of sources will be considered.

(*i*) Point Source

As discussed in Art. 49.5, the law governing changes in illumination due to point source of light is $E = I \cos \theta / d^2$.

(*ii*) Line Source

Provided the line source is of infinite length and of uniform intensity, the illumination at a point lying on a surface parallel to and facing the line source is given by

$$E = \frac{\pi I}{2d} \text{ lm/m}^2$$

where I = luminous intensity normal to the line source (in candles per-meter length of the sources)

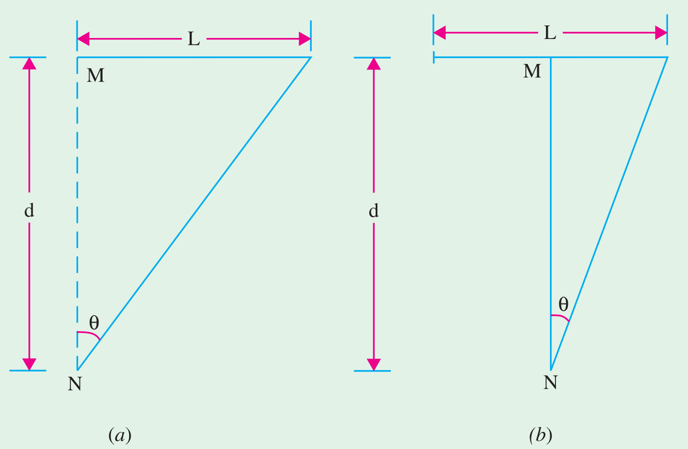


Fig. 49.18

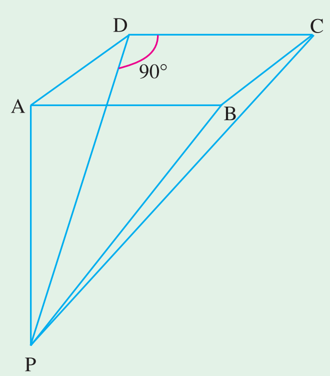


Fig. 49.19

However, in practice, the line sources are of finite length, so that the following law applies

$$E = \frac{I}{4\,d}\,(\sin 2\theta + 2\theta)\ \text{lm/m}^2 \qquad \text{—Fig. 49.18 }(a)$$

$$= \frac{I}{2\,d}\,(\sin 2\theta + 2\theta)\ \text{lm/m}^2 \qquad \text{—Fig. 49.18 }(b)$$

where I = candle power per metre length in a direction normal to the line source

$$= \frac{\Phi}{\pi^2 L}\ \text{cd/m}$$

where Φ is the total flux of the source in lumens and L is the length of the line source in metres.

(*iii*) Surface Source

Provided the surface source is of infinite area and of uniform brightness, illumination at any point facing the source is independant of the distance between the point and the surface source. Mathematically, its value is $E = \pi L$ *l*m/m^2 where L is the luminance of the surface source in cd/m^2.

In case the surface source is limited and rectangular in shape (Fig. 49.19), the law governing the illumination at a point P is

$$E = \frac{L}{2}\,(\alpha' \sin\beta + \beta' \sin a)$$

where $\alpha = \angle APD\ ;\ \alpha' = \angle BPC\ ;\ \beta = \angle APB\ ;\ \beta' = \angle DPC$

Note. (*i*) In case, distance d is more than 5 times the greatest dimension of the source, then irrespective of its shape, the illumination is found to obey inverse square law. This would be the case for illumination at points 5 metres or more away from a fluorescent tube of length one metre.

(*ii*) In the case of surface sources of large area, such as luminous daylights covering the whole ceiling of a large room, illumination is found to be practically constant irrespective of the height of the working place.

It may be noted that a point source produces deep shadows which may, however, be cancelled by installing a large number of fittings. Usually, glare is present. However, point sources are of great practical importance where accurate light control is required as in search-lights.

Line sources give more diffusion but cast shadows of objects lying parallel to them thus hindering vision.

Large-area surface sources though generally of low brightness, produce minimum glare but no shadows. However, the final effect is not liveliness but one of deadness.

Example 49.18. *A show case is lighted by 4 metre of architectural tubular lamps arranged in a continuous line and placed along the top of the case. Determine the illumination produced on a horizontal surface 2 metres below the lamps in a position directly underneath the centre of the 4 m length of the lamps on the assumption that in tubular lamps emit 1,880 lm per metre run. Neglect the effect of any reflectors which may be used.*

Solution. As seen in Art 49.10

$$E = \frac{I}{2d}\,(\sin 2\theta + 2\theta)\ \text{lm/m}^2 \text{ and } I = \frac{\Phi}{\pi^2 L}\ \text{cd/m}$$

As seen from Fig. 49.15

$$\theta = \tan^{-1}(L/2\,d)$$

$$= \text{tan–1}(4/2) = 45°$$

$$I = 4 \cdot 1{,}880/\pi^2 \cdot 4$$

$$= \mathbf{188\ cd/m}$$

$$\therefore \quad E = \frac{188}{2 \cdot 2}\left(\sin 90° + \frac{\pi}{2}\right) = \mathbf{121\ lm/m^2}$$

49.7. Polar Curves of C.P. Distribution

All our calculations so far were based on the tacit assumption that the light source was of equal luminous intensity or candle-power in all directions. However, lamps and other sources of light, as a rule, do not give uniform distribution in the space surrounding them.

If the actual luminous intensity of a source in various directions be plotted to scale along lines radiating from the centre of the source at corresponding angles, we obtain the polar curve of the candle power.

Suppose we construct a figure consisting of large number of spokes radiating out from a point—the length of each spoke representing to some scale the candle power or luminous intensity of the source in that particular direction. If now we join the ends of these spokes by some suitable material, say, by linen cloth, then we get a surface whose shape will represent to scale the three dimensional candle power distribution of the source placed at the centre. In the ideal case of a point source having equal distribution in all directions, the surface would be spherical.

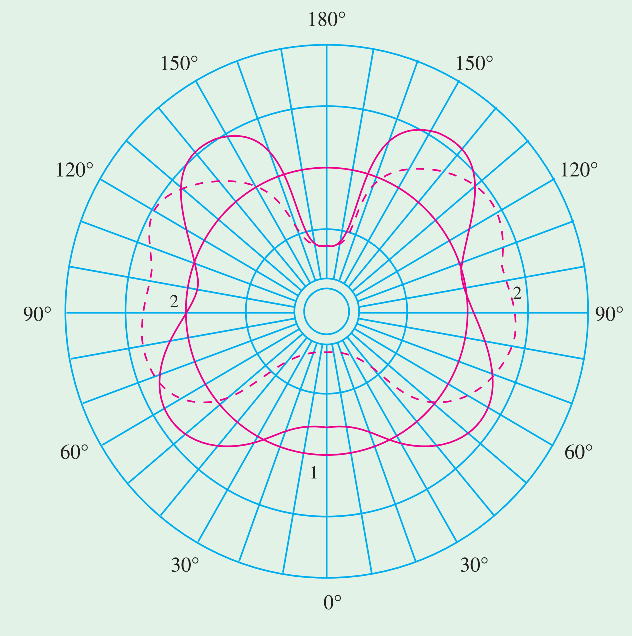


Fig. 49.20

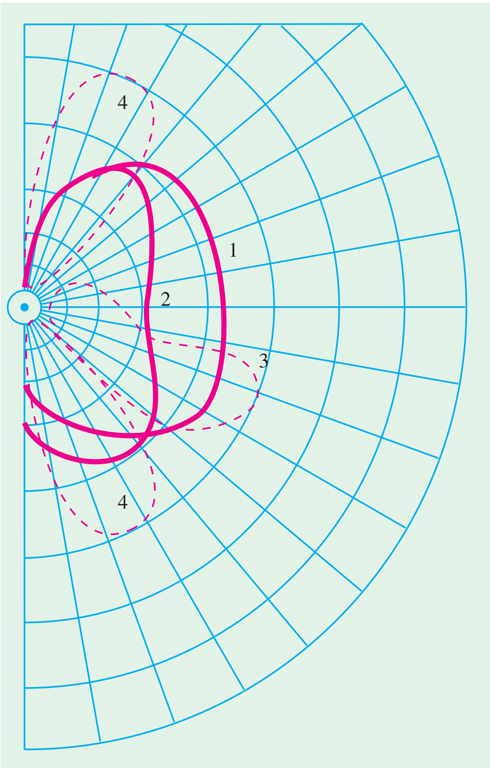


Fig. 49.21

It would be realized that it is difficult to give a graphic representation of such a 3-dimensional model in a plane surface. Therefore, as with engineering drawings, it is usual to draw only one or more elevations and a plan of sections through the centre of the source. Elevations represent c.p. distribution in the ***vertical*** plane and the plans represent c.p. distribution in ***horizontal*** plane. The number of elevations required to give a complete idea of the c.p. distribution of the source in all directions depends upon the shape of the plan *i.e.* on the horizontal distribution. If the distribution is uniform in every horizontal plane *i.e.* if the polar curve of horizontal distribution is a circle, then only one vertical curve is sufficient to give full idea of the space distribution.

In Fig. 49.20 are shown two polar curves of c.p. distribution in a vertical plane. Curve 1 is for vacuum type tungsten lamp with zig-zag filament whereas curve 2 is for gas filled tungsten lamp with filament arranged as a horizontal ring.

If the polar curve is symmetrical about the vertical axis as in the figures given below, then it is sufficient to give only the polar curve within one semicircle in order to completely define the distribution of c.p. as shown in Fig. 49.21.

The curves 1 and 2 are as in Fig. 49.20, curves 3 is for d.c. open arc with plain carbons and curve 4 is for a.c. arc with plain carbons. However, if the source and/or reflector are not symmterical about vertical axis, it is impossible to represent the space distribution of c.p. by a single polar diagram and even polar diagrams for two planes at right angles to each other give no definite idea as to the distribution in the intermediate planes.

Consider a filament lamp with a helmet-type reflector whose axis is inclined and cross-section elliptical—such reflectors are widely used for lighting shop windows. Fig. 49.22 represents the distribution of luminous intensity of such source and its reflector in two planes at right angles to each other.

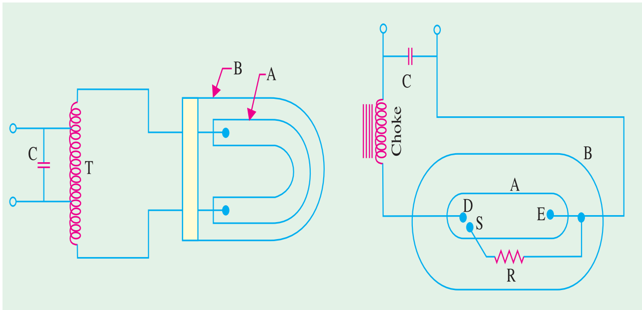


Fig. 49.22

The importance of considering the polar curves in different planes when the c.p. distribution in asymmetrical is even more strikingly depicted by the polar curves in YY plane and XX plane of a lamp with a special type of reflector designed for street lighting purposes (Fig. 49.23).

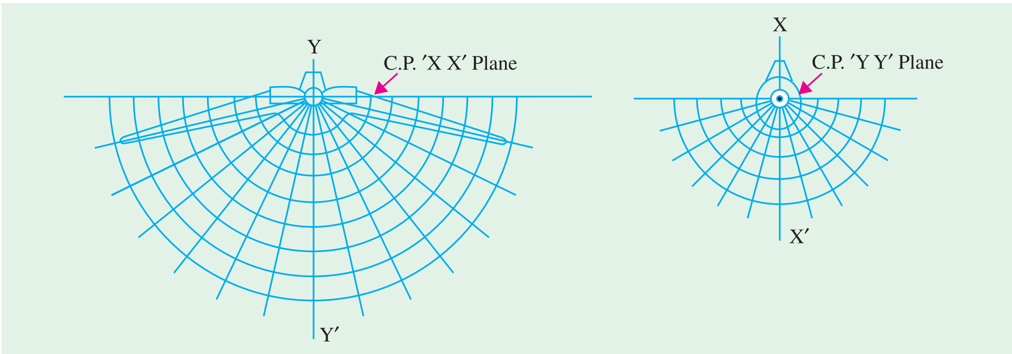


Fig. 49.23

It would be realized from above that the polar distribution of light from any source can be given any desired form by using reflectors and/or refractors of appropriate shape.

In Fig. 49.24 is shown the polar curve of c.p. distribution of a straight type of lamp in a horizontal plane.

49.8. Uses of Polar Curves

Polar curves are made use of in determining the M.S.C.P. etc. of a source. They are also used in determining the actual illumination of a surface *i.e.* while calculating the illumination in a particular direction, the c.p. in that particular direction as read from the vertical polar curve, should be employed.

49.9. Determination of M.S.C.P. and M.H.C.P. from Polar Diagrams

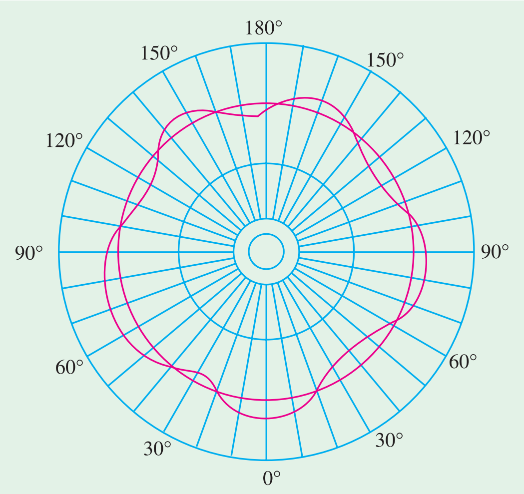


Fig. 49.24

In Fig. 49.25 (*a*) is shown the polar distribution curve of a filament lamp in a horizontal plane and the polar curve in Fig. 49.25 (*b*) represents the c.p. distribution in a vertical plane. It will be seen that the horizontal candle-power is almost uniform in all directions in that plane. However, in the vertical plane, there is a large variation in the candle power which falls to zero behind the cap of the lamp. The curve in Fig. 49.25 (*a*) has been drawn with the help of a photometer while the lamp is rotated about a vertical axis, say, 10° at a time. But the curve in Fig. 49.25 (*b*) was drawn while the lamp was rotated in a vertical plane about a horizontal axis passing through the centre of the filament.

The M.H.C.P. is taken as the mean of the readings in Fig. 49.25 (*a*). However, a more accurate result can be obtained by plotting candle power on an angular base along the rectangular axes and by determining the mean height of the curve by the mid-ordinate or by Simpson's rule.

The M.S.C.P. of the lamp can be obtained from the vertical polar curve of Fig. 49.25 (*b*) by Rousseau's construction as explained below :

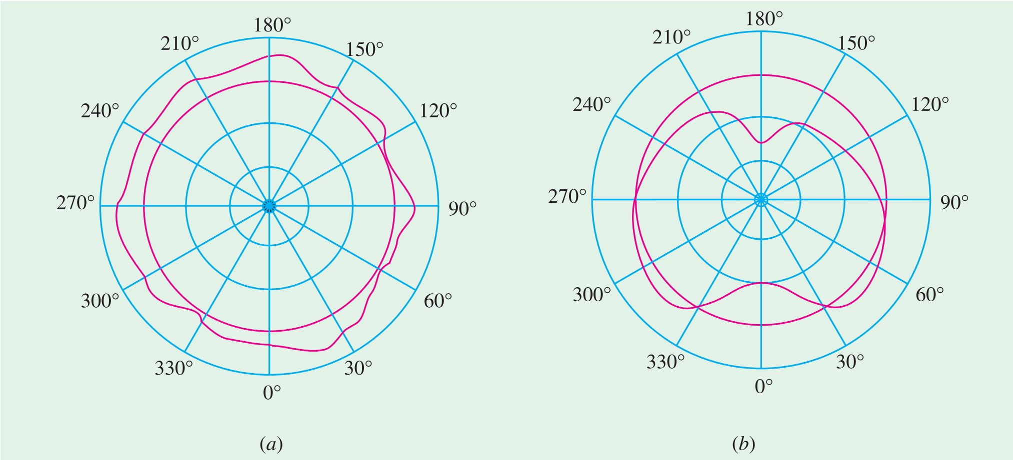


Fig. 49.25

Only half of the vertical polar curve is shown in the figure (Fig. 49.26) since it is symmetrical about the vertical axis. With *O* is the centre and radius *OR* equal to the maximum radius of the polar curve, a semi-circle *LRM* is drawn. A convenient number of points on this semi-circle (say 10° points) are projected onto any vertical plane as shown. For example, points *a,b,c* etc. are projected to *d,e,f* and so on. From point *d*, the horizontal line *dg* is drawn equal to the intercept *OA* of the polar diagram on the radius *oa*. Similarly, *eh* = *OB*, *fk* = *OC* and so on. The points *g, h, k* etc., define the Rousseau figure. The average width *w* of this figure represents the M.S.C.P. to the same scale as that of the candle powers in the polar curve. The average width is obtained by dividing the Rousseau area by the base of the Rousseau figure *i.e.* length lm which is the projection of the semi-circle *LM* on the vertical axis. The area may be determined by Simpson's rule or by using a planimeter.

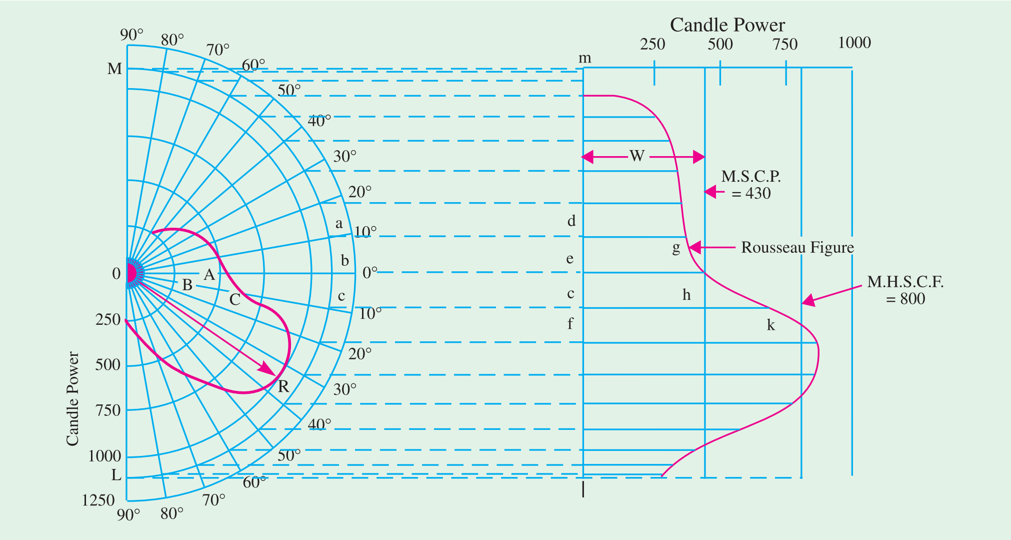


Fig. 49.26

$$\therefore \qquad \text{M.S.C.P.} = \frac{\text{area of Rousseau figure}}{\text{length of the base}}$$

As explained earlier, the M.H.C.P. of an incandescent lamp can be easily obtained by mounting the lamp with its axis vertical and taking photometer readings in the horizontal plane while the lamp is rotated about its axis in steps of 10° or so. A definite ratio exists between the M.H.C.P. and M.S.C.P. of each particular type of filament. M.S.C.P. of a lamp can be found by multiplying M.H.C.P. by a factor known as spherical reduction factor which, as defined earlier, is

$$\text{Spherical reduction factor} \quad f = \frac{\text{M.S.C.P.}}{\text{M.H.C.P.}} \qquad \therefore \quad \text{M.S.C.P.} = f \cdot \text{M.H.C.P.}$$

For the particular lamp considered, $f = 430/80 = 0.54$ (approx.)

Typical values of this factor are :

Ordinary vacuum-type tungsten lamp having zig-zag filament	0.76 – 0.78
Gas-filled tungsten lamp with filament in the form of broad shallow V's	0.85 – 0.94
Gas-filled tungsten lamp with filament in the shape of a horizontal ring	1.0 – 1.2

The total lumen output is given by the relation ; lumen output = $4\pi \cdot$ M.S.C.P.

In the present case, lumen output $= 4\pi \cdot 430$

$= 5{,}405$ lm

49.10. Integrating Sphere or Photometer

The M.S.C.P. is usually measured by means of an integrating photometer, the most accurate form of which consists of a hollow sphere (as originally proposed by Ulbricht) whose diameter is large (at least 6 times) as compared to that of the lamp under test. The interior surface of the hollow sphere is whitened by means of a special matt white paint. When the lamp is placed inside the sphere (not

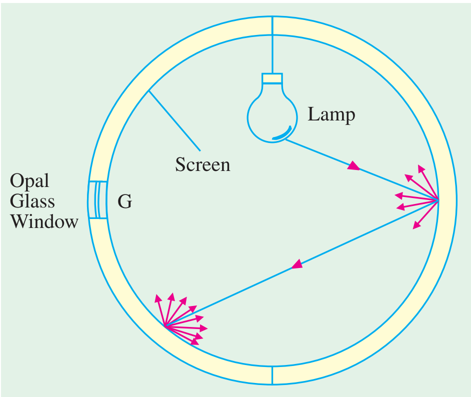


Fig. 49.27

necessarily at its centre) then due to successive reflections, its light is so diffused as to produce a uniform illumination over the whole surface. At some point, a small matt opal-glass window, shaded from the direct rays of the source, is made in the hollow sphere.

The brightness of the matt opal glass is proportional to that of the interior surface of the sphere. By using a suitable illumination photometer, the illumination of the window can be measured which can be used to find out the total flux emitted by the source.

$$\text{Total flux} = \text{illumination (1m/m}^2) \cdot \text{ surface area of the sphere (m}^2)$$

$$\therefore \quad \text{M.S.C.P.} = \frac{\text{total flux}}{4\,\pi} \text{ candela}$$

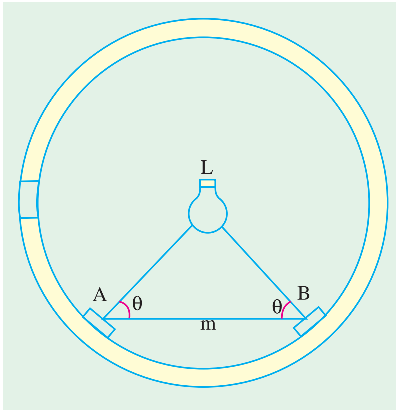


Fig. 49.28

Theory. In Fig. 49.28 is shown a light source L of luminous intensity I candela and having a total flux output of F_L placed at the centre of an integrating sphere of radius r and reflection factor ρ. Let E_A and E_B represent the illuminations at two points A and B, each of infinitely small area da and db respectively and distance m apart. We will now consider total illumination (both direct and reflected) at point A.

Obviously, $\quad E_A$ directly due to $L = I/r^2$

$\qquad\qquad E_B$ directly due to $L = I/r^2$

Luminous intensity of B in the direction of A is

$$I_B = \frac{\rho . E_B . A_B}{\pi} \text{ candela} \qquad \text{—Art. 45.4}$$

where $\quad A_B$ = projected area of B at right angles to the line $BA = db.\cos\theta$

$$\therefore \quad I_B = \frac{\rho . I . db \cos\theta}{\pi\, r^2} \text{ candela}$$

Hence, illumination of A due to B is $= \dfrac{I_B \cos\theta}{m^2} = \dfrac{\rho I . db \cos^2\theta}{\pi\, r^2 \cdot m^2}$

Now, as seen from Fig. 49.28, $\quad m = 2r\cos\theta$

$\therefore$ illumination of A due to B becomes

$$= \frac{\rho . I . db \cos^2\theta}{\pi\, r^2 \cdot 4r^2 \cos^2\theta} = \frac{\rho}{4\pi\, r^2} \cdot \frac{I}{r^2} \cdot db = \frac{\rho}{S} . E_B . db = \frac{\rho\, F_B}{D}$$

where $\quad F_B$ = flux incident on B and A = surface area of the sphere

Hence, total illumination due to first reflection $= \sum \dfrac{\rho\, F_B}{S} = \dfrac{\rho\, F_B}{S}$

Now, consider any other point C. Illumination on B due to point $C = \rho\, F_L/S$. The illumination on A due to C as reflected from B.

$$= \left[\rho . \left(\frac{\rho F_L}{S}\right) . \frac{db \cos\theta}{\pi}\right] . \frac{\cos\theta}{m^2} = \frac{\rho F_L}{S} . \frac{\rho . db \cos\theta}{\pi} . \frac{\cos\theta}{4r^2 \cos^2\theta}$$

$$= \frac{\rho F_L}{S} \cdot \frac{\rho . db}{S}$$

Total illumination due to two reflections $= \sum \dfrac{\rho F_L}{S} \cdot \dfrac{\rho . db}{S} = \dfrac{\rho^2 F_L}{S}$ $\qquad (\because \Sigma ab = S)$

Continuing this way, it can be proved that total illumination at point A from all reflections from all points

$$= \frac{\rho F_L}{S} \left(1 + \rho^2 + \rho^3 + \ldots\ldots\ldots\ldots + \rho^{n-1}\right) = \frac{\rho F_L}{S} \left(\frac{1}{1 - \rho}\right)$$

Hence, total illumination at A from direct and reflected lights is

$$= E_A + \frac{\rho F_L}{S}\left(\frac{1}{1-\rho}\right)$$

If A is shielded from lamp L, then its illumination is proportional to F_L because $\frac{\rho}{S}\left(\frac{1}{1-\rho}\right)$ is a constant factor. Obviously, if either brightness or illumination at one point in the sphere is measured, it would be proportional to the light output of the source. This fact is made use of while using this sphere as a globe photometer.

Example 49.19. *If an integrating sphere 0.6 m in diameter whose inner surface has a reflection coefficient of 0.8 contains a lamp producing on the portion of the sphere, screened from direct radiation, a luminance of 1000 cd/m², what is the luminous flux yield of the source ?*

(A.M.I.E. Sec. B. Summer 1986)

Solution. Obviously, the screened portion of the sphere receives light by reflection only. Reflection illumination of the screened portion is

$$E = \frac{\rho F_1}{S}\left(\frac{1}{1-\rho}\right) = \frac{0.8\, F_L}{\pi \cdot 0.6^2}\left(\frac{1}{1-0.8}\right) = \frac{100\, F_L}{9\pi}\ \text{lm/m}^2$$

Also $L = \rho E/\pi$ — Art. 49.4

$$\therefore \quad 1000 = \frac{100\, F_L}{9\pi} \cdot \frac{0.8}{\pi} \quad \text{or} \quad F_L = \mathbf{1/25\ lm}$$

49.11. Diffusing and Reflecting Surfaces : Globes and Reflectors

When light falls on polished metallic surfaces or silvered surfaces, then most of it is reflected back according to the laws of reflection *i.e.* the angle of incidence is equal to the angle of reflection. Only a small portion of the incident light is absorbed and there is always the image of the source. Such reflection is known as ***specular*** reflection.

However, as shown in Fig. 49.29 (*b*), if light is incident on coarse surfaces like paper, frosted glass, painted ceiling etc., then it is scattered or diffused in all directions, hence no image of the source is formed. Such reflection of light is called ***diffuse reflection***. A perfect diffuser is one that scatters light uniformly in all directions and hence appears equally bright from whatever direction it is viewed. A white blotting paper is the nearest approach to a diffuser.

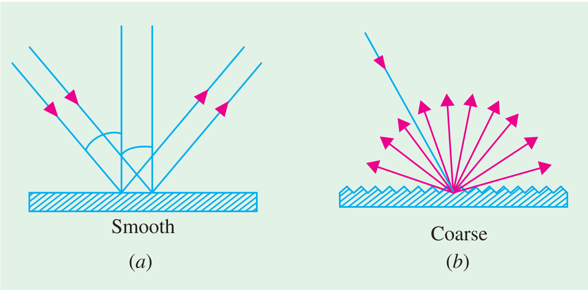


Fig. 49.29

By reflecting factor of a surface is meant the ratio = $\frac{\text{reflected light}}{\text{incident light}}$

It is also known as reflection ratio or coefficient of reflection of a surface.

If the light is incident on a transparent surface, then some of it is absorbed and greater percentage of it passes through and emerges on the other side.

To avoid direct glare from electric arcs and incandescent filament lamps, they are surrounded more or less completely by diffusing shades or globes. In addition, a reflector may also be embodied to prevent the escape of light in directions where it serves no useful purpose. In that case, so far as the surroundings are concerned, the diffusing globe is the source of light. Its average brilliancy is lower the more its diffusing area. Depending on the optical density, these globes absorb 15 to 40% of light emitted by the encircled bulb. The bulbs may also be frosted externally by etching or sand-blasting but internal frosting is better because there is no sharp scratching or cracks to weaken the glass.

In domestic fittings, a variety of shades are used whose main purpose is to avoid glare. Properly designed and installed prismatic glass shades and holophane type reflectors have high efficiency and are capable of giving accurate predetermined distribution of light.

Regular metallic reflection is used in search-light mirrors and for general lighting purposes. But where it is used for general lighting, the silvered reflectors are usually fluted to make the illumination as uniform as possible.

Regular cleaning of all shades, globes, and reflectors is very important otherwise the loss of light by absorption by dust etc., collected on them becomes very serious.

Various types of reflectors are illustrated in Figs. 49.30 to 49.34. Fig. 49.30 shows a holophane stiletto reflector used where extensive, intensive or focussing light distribution is required.

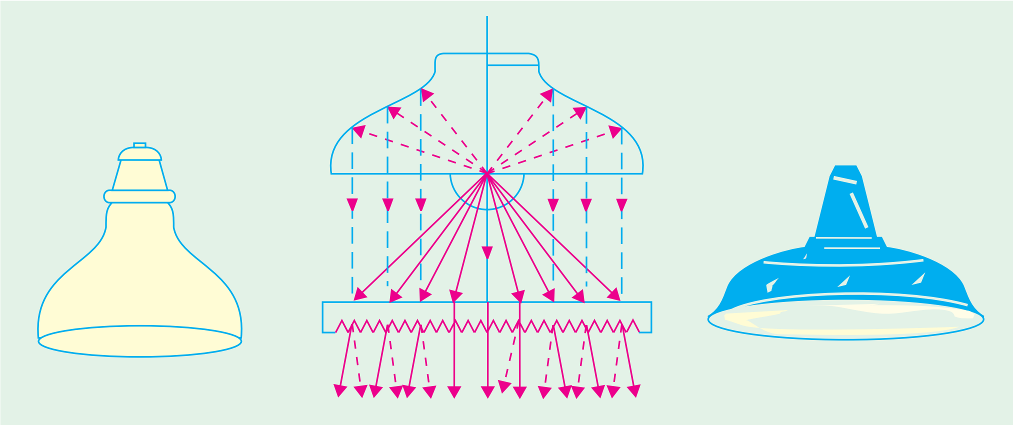


Fig. 49.30 **Fig. 49.31** **Fig. 49.32**

The optical combination of a lamp, reflector and a lens plate, as shown in Fig. 49.31, provides a high degree of light control. Multiple panels can be conveniently incorporated in fittings suited to different architectural schemes.

The dispersive reflector of Fig. 49.32 is suitable for practically all classes of industrial installations. The reflector is a combination of concave and cylindrical reflecting surfaces in the form of a deep bowl of wide dispersive power. It gives maximum intensity between 0º and 45º from the vertical.

The concentrating reflector of parabolic form shown in Fig. 49.33 is suitable for situations requiring lofty installations and strongly-concentrated illumination as in public halls, foundries and power stations etc. They give maximum intensity in zones from 0º to 25º from the vertical.

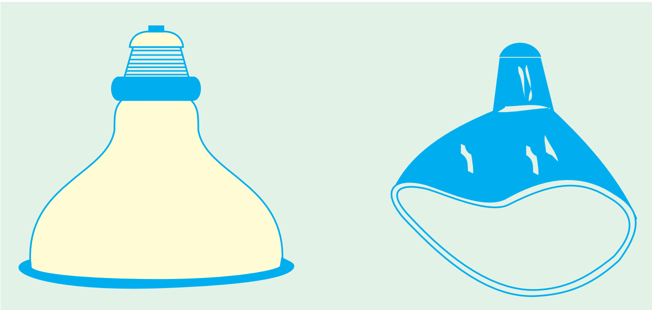


Fig. 49.33 **Fig. 49.34**

The elliptical angle reflector shown in Fig. 49.34 is suitable for the side lighting of switchboards, show windows etc., because they give a forward projection of light in the vertical plane and spread the light in the horizontal plane.

49.12. Lighting Schemes

Different lighting schemes may be classfied as *(i)* direct lighting *(ii)* indirect lighting and *(iii)* semi-direct lighting *(iv)* semi-indirect lighting and *(v)* general diffusing systems.

(i) Direct Lighting

As the name indicates, in the form of lighting, the light from the source falls directly on the object or the surface to be illuminated (Fig. 49.35). With the help of shades and globes and reflectors of various types as disscussed in Art. 49.11, most of the light is directed in the lower hemisphere and also the brilliant source of light is kept out of the direct line of vision. Direct illumination by lamps in suitable reflectors can be supplemented by standard or bracket lamps on desk or by additional pendant fittings over counters.

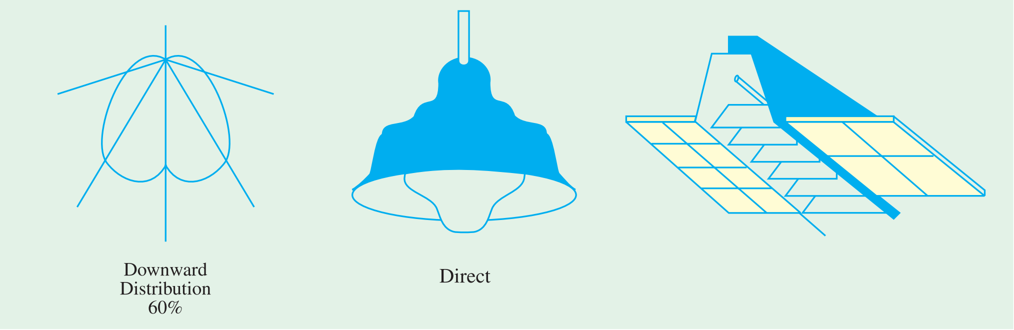


Fig. 49.35

The fundamental point worth remembering is planning any lighting installation is that sufficient and sufficiently uniform lighting is to be provided at the working or reading plane. For this purpose, lamps of suitable size have to be so located and furnished with such fittings as to give correct degree and distribution of illumination at the required place. Moreover, it is important to keep the lamps and fittings clean otherwise the decrease in effective illumination due to dirty bulbs or reflectors may amount to 15 to 25% in offices and domestic lighting and more in industrial areas as a result of a few weeks neglect.

Direct lighting, though most efficient, is liable to cause glare and hard shadows.

(ii) Indirect Lighting

In this form of lighting, light does not reach the surface directly from the source but indirectly by diffuse reflection (Fig. 49.36). The lamps are either placed behind a cornice or in suspended ***opaque*** bowls. In both cases, a silvered reflector which is corrugated for eliminating striations is placed beneath the lamp.

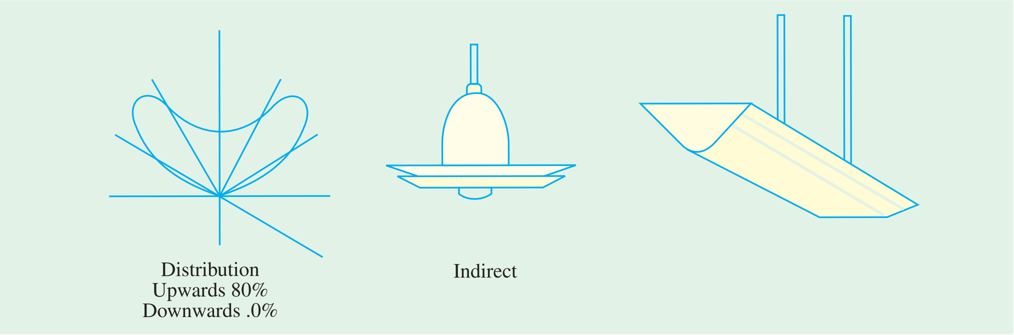


Fig. 49.36

In this way, maximum light is thrown upwards on the ceiling from which it is distributed all over the room by diffuse reflection. Even gradation of light on the ceiling is secured by careful adjustement of the position and the number of lamps. In the cornice and bowl system of lighting, bowl fittings are generally suspended about three-fourths the height of the room and in the case of cornice lighting, a frieze of curved profile aids in throwing the light out into the room to be illuminated. Since in indirect lighting whole of the light on the working plane is received by diffuse reflection, it is important to keep the fittings clean.

One of the main characteristics of indirect lighting is that it provides shadowless illumination which is very useful for drawing offices, composing rooms and in workshops especially where large machines and other obstructions would cast troublesome shadows if direct lighting were used.

However, many people find purely indirect lighting flat and monotonous and even depressive. Most of the users demand 50 to 100% more light at their working plane by indirect lighting than with direct lighting. However, for appreciating relief, a certain proportion of direct lighting is essential.

(*iii*) Semi-direct System

This system utilizes luminaries which send most of the light downwards directly on the working plane but a considerable amount reaches the ceilings and walls also (Fig. 49.37).

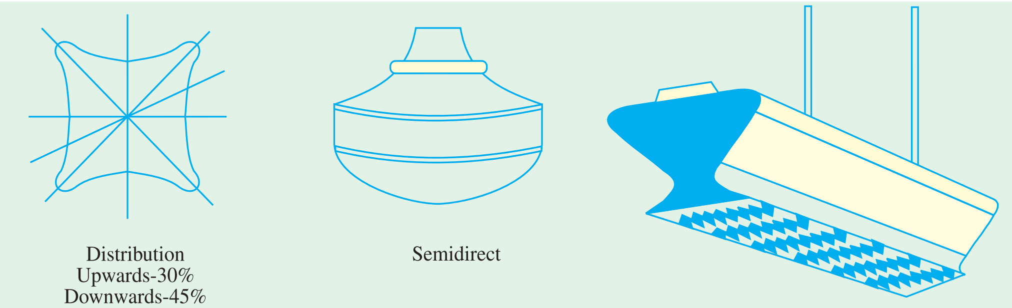


Fig. 49.37

The division is usually 30% upwards and 45% downwards. Such a system is best suited to rooms with high ceilings where a high level of uniformly-distributed illumination is desirable. Glare in such units is avoided by using diffusing globes which not only improve the brightness towards the eye level but improve the efficiency of the system with reference to the working plane.

(*iv*) Semi-indirect Lighting

In this system which is, in fact, a compromise between the first two systems, the light is partly received by diffuse reflection and partly direct from the source (Fig. 49.38). Such a system, therefore, eliminates the objections of indirect lighting mentioned above. Instead of using opaque bowls with reflectors, translucent bowls without reflector are used. Most of the light is, as before, directed upwards to the ceiling for diffuse reflection and the rest reaches the working plane directly except for some absorption by the bowl.

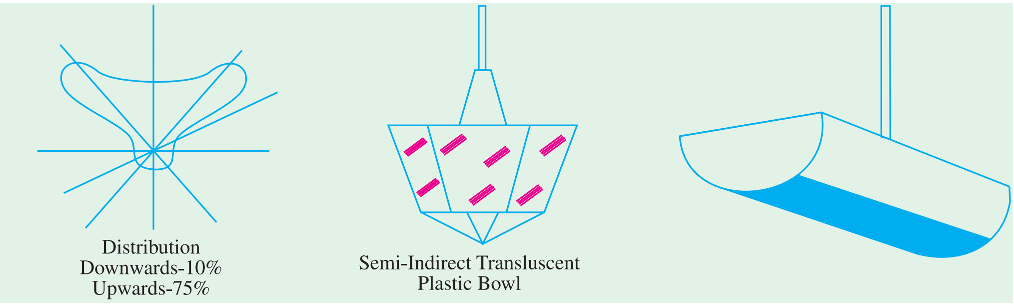


Fig. 49.38

(v) General Diffusing System

In this system, luminaries are employed which have almost equal light distribution downwards and upwards as shown in Fig. 49.39.

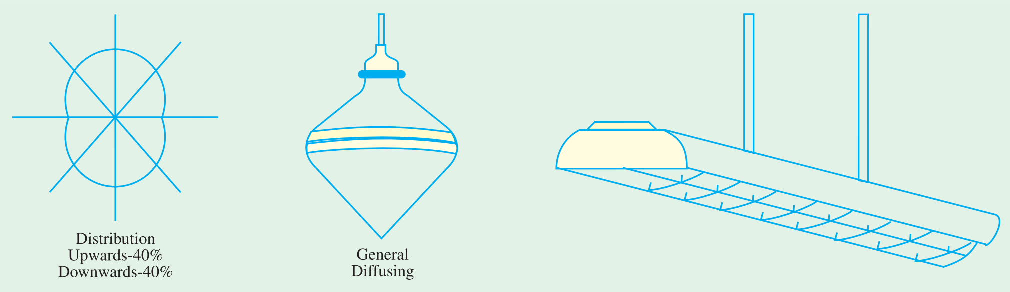


Fig. 49.39

49.13. Illumination Required for Different Purposes

There has been a steady movement towards higher intensities for artificial illumination during the last few decades. The movement is likely to continue because the highest intensities in average installations are much less than those of the diffused daylight. The human eye posses a tremendous power of accommodation and it can work comfortably within an enormous range of illuminations.

For example, at full noon, sun provides about 120,000 lm/m^2, diffuse day-light near a window is of the order of 600 lm/m^2 (value varying widely) and full moon-light gives 0.1 to 0.3 lm/m^2. For reading, usually 20 to 30 lm/m^2 is generally considered sufficient, though daylight illumination is much higher.

Some persons can read without much strain even when illumination is as low as 3 lm/m^2. Because of this, it is difficult to lay down definite values of illumination for various purposes but the following summary will be found useful :

Purpose and Places	*lm/m^2*
Precision work, displays, tasks requiring rapid discrimination	above 500
Extra fine machine work, around needles of sewing machines, fine engraving, inspection of fine details having low contrast	200-500
Proof-reading, drawing, sustained reading, fine assembling, skilled bench-work	100-200
Drawing offices, art exhibition, usual reading	60-100
In museums, drill halls, for work of simple nature not involving close attention to fine details	40-60
Usual observation as in bed-rooms, waiting rooms, auditoriums and general lighting in factories	20-40
Hospital wards, yards, railway platforms and corridors	5-10

49.14. Space/Height Ratio

It is given by the ratio : $\dfrac{\text{horizontal distance between two lamps}}{\text{mounting height of lamps}}$

This ratio depends on the nature of the polar curve of a lamp ***when used along with its reflector***. A reflector has tremendous influence on the shape of the polar curve of the lamp, hence the value of space/height ratio, in fact, depends entirely on the type of reflector used. For obtaining uniform illumination on the working plane, it is essential to choose a correct value for this ratio.

In other words, it means that a reflector gives uniform illumination for a definite value of this ratio only. The ratio may be found easily if the polar curve of the type of fixture used is known. For reflectors normally used in indoor lighting, the value of this ratio lies between 1 and 2.

49.15. Design of Lighting Schemes and Lay-outs

A well-designed lighting scheme is one which

(i) provides adequate illumination *(ii)* avoids glare and hard shadows *(iii)* provides sufficiently uniform distribution of light all over the working plane.

Before explaining the method of determining the number, size and proper arrangement of lamps in order to produce a given uniform illumination over a certain area, let us first consider the following two factors which are of importance in such calculations.

49.16. Utilization Factor or Coefficient of Utilization (η)

It is the ratio of the lumens actually received by a particular surface to the total lumens emitted by a luminous source.

$$\therefore \qquad \eta = \frac{\text{lumens actually received on working plane}}{\text{lumens emitted by the light source}}$$

The value of this factor varies widely and depends on the following factors :

1. the type of lighting system, whether direct or indirect etc.
2. the type and mounting height of the fittings
3. the colour and surface of walls and ceilings and
4. to some extent on the shape and dimensions of the room.

For example, for direct lighting, the value of η varies between 0.4 and 0.6 and mainly depends on the shape of the room and the type and mounting height of fittings but very little on the colour of walls and ceiling. For indirect lighting, its value lies between 0.1 and 0.35 and the effect of walls and ceiling, from which light is reflected on the working plane, is much greater. Exact determination of the value of utilization factor is complicated especially in small rooms where light undergoes multiple reflections.

Since the light leaving the lamp in different directions is subjected to different degrees of absorption, the initial polar curve of distribution has also to be taken into account. Even though manufacturers of lighting fittings supply tables giving utilization factors for each type of fitting under specified conditions yet, since such tables apply only to the fittings for which they have been compiled, a good deal of judgment is necessary while using them.

49.17. Depreciation Factor (*p*)

This factor allows for the fact that effective candle power of all lamps or luminous sources deteriorates owing to blackening and/or accumulation of dust or dirt on the globes and reflectors etc. Similarly, walls and ceilings etc., also do not reflect as much light as when they are clean. The value of this factor may be taken as 1/1.3 if the lamp fittings are likely to be cleaned regularly or 1/1.5 if there is much dust etc.

$$p = \frac{\text{illumination under actual condtions}}{\text{illumination when everything is perfectly clean}}$$

Since illumination is specified in lm/m^2, the area in square metre multiplied by the illumination required in lm/m^2 gives the total useful luminous flux that must reach the working plane. Taking into consideration the utilization and depreciation or maintenance factors, the expression for the gross lumens required is

$$\text{Total lumens,} \qquad \Phi = \frac{E \cdot A}{\eta \cdot p}$$

where E = desired illumination in lm/m^2 ; A = area of working plane to be illuminated in m^2
p = depreciation or maintenance factor ; η = utilization factor.

The size of the lamp depends on the number of fittings which, if uniform distribution is required, should not be far apart. The actual spacing and arrangement is governed by space/height values and by the layout of ceiling beams or columns. Greater the height, wider the spacing that may be used, although the larger will be the unit required. Having settled the number of units required, the lumens per unit may be found from (total lumens/number of units) from which the size of lamp can be calculated.

Example 49.20. *A room 8 m × 12 m is lighted by 15 lamps to a fairly uniform illumination of 100 lm/m^2. Calculate the utilization coefficient of the room given that the output of each lamp is 1600 lumens.*

Solution. Lumens emitted by the lamps = 15 × 1600 = 24,000 lm

Lumens received by the working plane of the room = 8 × 12 × 100 = 9600 lm

Utilization coefficient = 9600/24,000 = **0.4 or 40%.**

Example 49.21. *The illumination in a drawing office 30 m × 10 m is to have a value of 250 lux and is to be provided by a number of 300-W filament lamps. If the coefficient of utilization is 0.4 and the depreciation factor 0.9, determine the number of lamps required. The luminous efficiency of each lamp is 14 lm/W.* **(Elect. Drives & Utilization, Punjab Univ. Dec. 1994)**

Solution. $\Phi = EA/\eta p$; $E = 250$ lm/m^2, $A = 30 \times 10 = 300$ m^2; $\eta = 0.4$, $p = 0.9$

$\therefore$ $\Phi = 250 \times 300/0.4 \times 0.9 = 208{,}333$ lm

Flux emitted/lamp = 300 × 14 = 4200 lm; No. of lamps reqd.= 208,333/4200 = **50.**

Example 49.22. *Find the total saving in electrical load and percentage increase in illumination if instead of using twelve 150 W tungsten-filament lamps, we use twelve 80 W fluorescent tubes. It may be assumed that* **(i)** *there is a choke loss of 25 per cent of rated lamp wattage* **(ii)** *average luminous efficiency throughout life for each lamp is 15 lm/W and for each tube 40 lm/W and* **(iii)** *coefficient of utilization remains the same in both cases.*

Solution. Total load of filament lamps = 12 × 150 = 1800 W

Total load of tubes = 12 (80 + 0.25 × 80) = 1200 W

Net saving in load = 1800 − 1200 = **600 W**

If A is the room area and η the corfficient of utilization, then

illumination with lamps, $E_1 = \dfrac{12 \times 150 \times 15\eta}{A}$ = **27,000 η/A lm/m^2**

illumination with tubes, $E_2 = \dfrac{12 \times 80 \times 40\eta}{A}$ = **38,400 η/A lm/m^2**

increase in illumination $= \dfrac{38,400 - 27,000}{27,000}$ = **0.42 or 42%**

Example 49.23. *A football pitch 120 m × 60 m is to be illuminated for night play by similar banks of equal 1000 W lamps supported on twelve towers which are distributed around the ground to provide approximately uniform illumination of the pitch. Assuming that 40% of the total light emitted reaches the playing pitch and that an illumination of 1000 lm/m^2 is necessary for television purposes, calculate the number of lamps on each tower. The overall efficiency of the lamp is to be taken as 30 lm/W.* **(Elect. Technology-I, Bombay Univ.)**

Solution. Area to be illuminated = 120 × 60 = 7,200 m^2

Flux required $= 7,200 \cdot 1,000 = 7.2 \cdot 10^6$ lm

Since only 40% of the flux emitted reaches the ground, the total luminous flux required to be produced is $= 7.2 \cdot 10^6/0.4 = 18 \cdot 10^6$ lm

Flux contributed by each tower bank $= 18 \cdot 10^6/12 = 1.5 \cdot 10^6$ lm

Output of each 1000-W lamp $= 30 \cdot 1000 = 3 \cdot 10^4$ lm

Hence, number of such lamps on each tower is $= 1.5 \cdot 10^6/3 \cdot 10^4 =$ **50**

Example 49.24. *Design a suitable lighting scheme for a factory 120 m · 40 m with a height of 7 m. Illumination required is 60 lux. State the number, location and mounting height of 40 W fluorescent tubes giving 45 lm/W.*

Depreciation factor = 1.2 ; utilization factor = 0.5

(Electric Drives & Util. Punjab Univ. 1993)

Solution. $\Phi = \dfrac{60 \cdot 120 \cdot 40}{0.5 \cdot (1/1.2)} = 691,200$ lm; Flux per tube $= 45 \cdot 40 =$ **1800 lm.**

No. of fluorescent tubes reqd. = 691,200/1800 = 384. If twin-tube fittings are employed, then number of such fittings required. = 384/2 = **192.**

These can be arranged in 8 rows of 24 fittings each. Assuming that the working plane is 1 metre above the floor level and the fittings are fixed 1 metre below the ceiling, we get a space/height factor of unity both along the length as well as width of the factory bay.

Example 49.25. *A drawing hall in an engineering college is to be provided with a lighting installation. The hall is 30 m · 20 m · 8 m (high). The mounting height is 5 m and the required level of illumination is 144 lm/m^2. Using metal filament lamps, estimate the size and number of single lamp luminaries and also draw their spacing layout. Assume :*

Utilization coefficient = 0.6; maintenance factor = 0.75; space/height ratio=1

lumens/watt for 300-W lamp = 13, lumens/watt for 500-W lamp = 16.

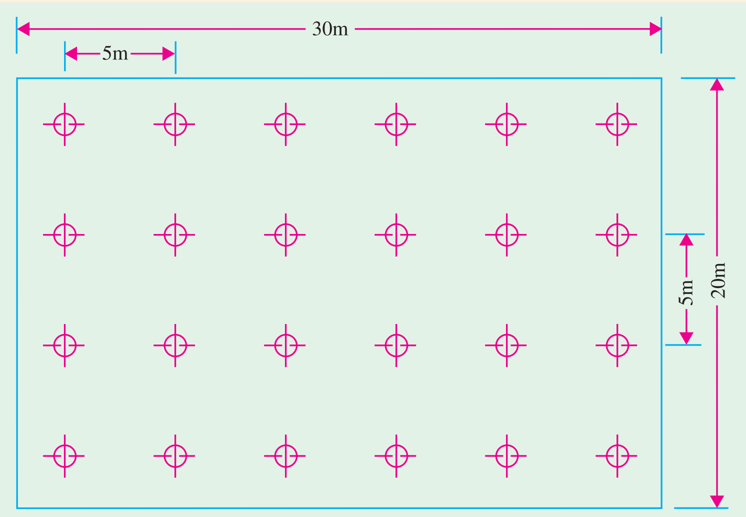


Fig. 49.40

Solution. Flux is given by $\Phi = EA/\eta p = 30 \cdot 20 \cdot 144/0.6 \cdot 0.75 = 192,000$ lm

Lumen output per 500-W lamp $= 500 \cdot 16 = 8,000$

∴ No. of 500-W lamps required = 192,000/8000 = **24**

Similarly, No. of 300-W lamps required = 192,000/3900 = **49**

The 300-W lamps cannot be used because their number cannot be arranged in a hall of 30 m · 20 m with a space/height ratio of unity. However, 500-W lamps can be arranged in 4 rows of 6 lamps each with a spacing of 5 m both in the width and the length of the hall as shown in Fig. 49.40.

Example 49.26. *Estimate the number and wattage of lamps which would be required to illuminate a workshop space 60 × 15 metres by means of lamps mounted 5 metres above the working plane. The average illumination required is about 100 lux.*

Coefficient of utilization=0.4 ; Luminous efficiency=16 lm/W.

Assume a spacing/height ratio of unity and a candle power depreciation of 20%.

(Utilization of Electrical Energy, Madras Univ.)

Solution. Luminous flux is given by $\Phi = \dfrac{EA}{\eta p} = \dfrac{100 \times (60 \times 15)}{0.4 \times 1/1.2} = 27 \times 10^4$ lm

Total wattage reqd. $= 27 \times 10^4/16 =$ **17,000 W**

For a space/height ratio of unity, only three lamps can be mounted along the width of the room. Similarly, 12 lamps can be arranged along the length of the room. Total number of lamps required is 12 × 3 = **36**. Wattage of each lamp is = 17,000/36 = 472 W. We will take the nearest standard lamp of **500 W**. These thirty-six lamps will be arranged as shown in Fig. 49.41.

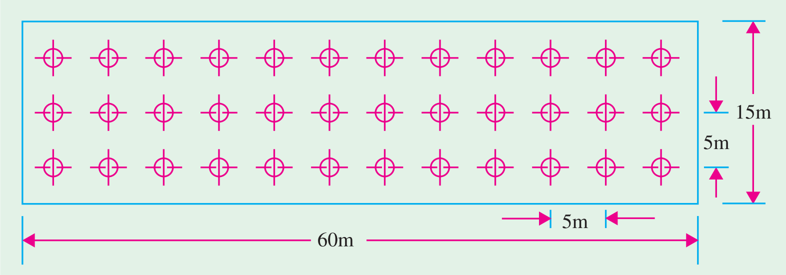


Fig. 49.41

Example 49.27. *A drawing hall 40 m × 25 m × 6 high is to be illuminated with metal-filament gas-filled lamps to an average illumination of 90 lm/m^2 on a working plane 1 metre above the floor. Estimate suitable number, size and mounting height of lamps. Sketch the spacing layout.*

Assume coefficient of utilization of 0.5, depreciation factor of 1.2 and spacing/height ratio of 1.2

Size of lamps	*200 W*	*300 W*	*500 W*
Luminous efficiency (in lm/W)	*16*	*18*	*20*

(Elect. Technology, Bombay Univ.)

Solution. Total flux required is $\Phi = \dfrac{40 \times 25 \times 90}{0.5 \times 1/1.2} = 216{,}000$ lm

Lumen output of each 200-W lamp is 3200 lm, of 300-W lamp is 5,400 lm and of 500-W lamp is 10,000 lm.

No. of 200-W lamps reqd. $= \dfrac{216{,}000}{3{,}200} =$ **67**; No. of 300-W lamps reqd.$= \dfrac{216{,}000}{5{,}400} =$ **40**

No. of 500-W lamps reqd. = 216,000/10,000 = **22**

With a spacing/height ratio of 1.2, it is impossible to arrange both 200-W and 300-W lamps. Hence, the choice falls on 500-W lamp. If instead of the calculated 22, we take 24 lamps of 500 wattage, they can be arranged in four rows each having six lamps as shown in Fig. 49.42. Spacing along the length of the hall is 40/6 = 6.67 m and that along the width is 25/4 = 6.25 m.

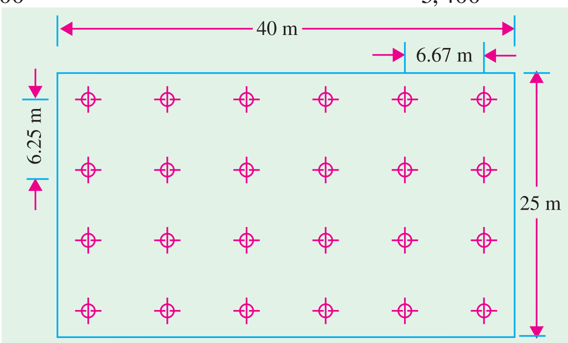


Fig. 49.42

Since mounting height of the lamps is 5 m above the working plane, it gives a space/height ratio of 6.7/5 = 1.5 along the length and 6.25/5 = 1.4 along the width of the hall.

Example 49.28. *A school classroom, 7 m · 10 m · 4 m high is to be illuminated to 135 lm/m^2 on the working plane. If the coefficient of utilization is 0.45 and the sources give 13 lumens per watt, work out the total wattage required, assuming a depreciation factor of 0.8 . Sketch roughly the plan of the room, showing suitable positions for fittings, giving reasons for the positions chosen.*

Solution. Total flux required is $\Phi = EA/\eta p$

Now $\quad E = 135$ lm/m^2 ;

$A = 7 \cdot 10 = 70$ m^2 ;

$\eta = 0.45$; $p = 0.8$

$F = 135 \cdot 7 \cdot 10/0.45 \cdot 0.8 = 26{,}250$ lm

Total wattage reqd. $= 26{,}250/13 =$ **2020 W**

Taking into consideration the dimensions of the room, light fitting of 200 W would be utilized.

No. of fittings required $= 2020/200 =$ **10**

As shown in Fig. 49.43, the back row of fittings has been located 2/3 m from the rear wall so as to ***(i)*** provide adequate illumination on the rear desk and ***(ii)*** to minimise glare from paper because light would be incident practically over the shoulders of the students. The two side fittings help eliminate shadows while writing. One fitting has been provided at the chalk board end of the classroom for the benefit of the teacher. The fittings should be of general diffusing pendant type at a height of 3 m from the floor.

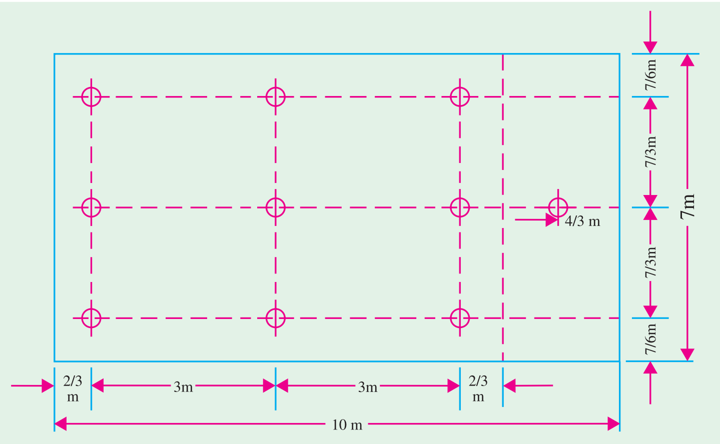


Fig. 49.43

Example 49.29. *A hall 30 m long and 12 m wide is to be illuminated and the illumination required is 50 lm/m^2. Calculate the number, the wattage of each unit and the location and mounting height of the units, taking a depreciation factor of 1.3 and utilization factor of 0.5, given that the outputs of the different types of lamp are as under :*

Watts :	*100*	*200*	*300*	*500*	*1000*
Lumens :	*1615*	*3650*	*4700*	*9950*	*21500*

(Utili. of Elect. Power, A.M.I.E.)

Solution. Area to be illuminated, $A = 30 \cdot 12 = 360$ m^2

Illumination required, $\quad E = 50$ lm/m^2, $p = 1/1.3$, $\eta = 0.5$

Now, $\quad \Phi = EA/\eta p = 50 \cdot 360/0.5 \cdot (1/1.3) = 46{,}800$ lm

If 100-W lamps are used, No. reqd. = 46,800/1615 = 29

If 200-W lamps are used, No. reqd. = 46,800/3650 = 13

If 300-W lamps are used, No. reqd. = 6,800/4700 = 10

If 500-W lamps are used, No. reqd. = 46,800/9950 = 5

If 1000-W lamps are used, No. reqd. = 46,800/21500 = 2

If we take the mounting height of 5 m, then 300 W lamps would be suitable. The No. of lamps required would be 10, arranged in two rows, each row having 5 lamps thus giving a spacing of 6 m in lengths as well as width and space/height ratio of 6/5 = 1.2.

If we use lamps of low power, their number would be large thereby increasing the number of fittings and hence cost. Lamps of higher voltage would be few in number but will not give a desirable space/height ratio.

Tutorial Problem No. 49.2

1. A room 30 m · 15 m is to be illuminated by 15 lamps to give an average illumination of 40 lm/m^2. The utilization factor is 4.2 and the depreciation factor is 1.4. Find the M.S.C.P. of each lamp.
[561 cd] ***(Elect. Technology-1. Bombay Univ.)***

2. A factory space of 33 m · 13 m is to be illuminated with an average illumination of 72 lm/m^2 by 200 W lamps. The coefficient of utilization is 0.4 and the depreciation factor is 1.4. Calculate the number of lamps required. The lumen output of a 200-W lamp is 2,730 lm.
[40] ***(Elect. Technology-I, Bombay Univ.)***

3. A drawing hall 30 m · 15 m with a ceiling height of 5 m is to be provided with an illumination of 120 lux. Taking the coefficient of utilization of 0.5, depreciation factor of 1.4, determine the No. of fluorescent tubes required and their spacing, mounting height and total wattage. Take luminous efficiency of fluorescent tube as 40 lm/W for 80-W tube. ***(A.M.I.E. Sec. B, Summer)***

4. A room 40 m · 15 m is to be illuminated by 1.5 m 80-W fluorescent tubes mounted 3.5 m above the working plane on which an average illumination of 180 lm/m^2 is required. Using maintenance factor of 0.8 and the utilization factor of 0.5, design and sketch a suitable layout. The 80-W fluorescent tube has an output of 4,500 lm. ***(Electrical Technology, Bombay Univ.)***

5. A hall is to be provided with a lighting installation. The hall is 30 m · 20 m · 8 m (high). The mounting height is 5 m and the required level of illumination is 110 lux. Using metal filament lamps, estimate the size and number of single lamp luminaries and draw their spacing layout. Assume depreciation factor = 0.8, utilization coefficient = 0.6 and space/height ratio = 1.

Watt :	200	300	500
Lumen/watt :	10	12	12.3

[24 lamps, 500 W] ***(Services & Equipment-II, Calcutta Univ.)***

6. It is required to provide an illumination of 100 lux in a factory hall 30 m · 12 m. Assume that the depreciation factor is 0.8, the coefficient of utilization 0.4 and the efficiency of proposed lamps 14 lm/W. Calculate the number of lamps and their disposition.
(Utilization of Elect. Energy, Madras Univ.)

7. Define the terms : (*i*) Lux (*ii*) Luminous Flux (*iii*) Candle Power.
A workshop 100 m · 50 m is to be illuminated with intensity of illumination being 50 lux. Design a suitable scheme of lighting if coefficient of utilization = 0.9 ; Depreciation factor = 0.7 and efficiency of lamps = 80 lm/W. Use 100-W lamps. ***(Electrical Engineering-III, Poona Univ.)***

49.18. Floodlighting

It means 'flooding' of large surfaces with the help of light from powerful projectors. Flooding is employed for the following purposes :

1. For aesthetic purposes as for enhancing the beauty of a building by night *i.e.* flood lighting of ancient monuments, religious buildings on important festive occassions etc.
2. For advertising purposes *i.e.* flood lighting, huge hoardings and commercial buildings.
3. For industrial and commercial purposes as in the case of railway yards, sports stadiums and quarries etc.

Usually, floodlight projectors having suitable reflectors fitted with standard 250-, 500-, or 1,000-watt gas-filled tungsten lamps, are employed. One of the two typical floodlight installations often used is as shown in Fig. 49.44 (*a*). The projector is kept 15 m to 30 m away from the surface to be floodlighted and provides approximately parallel beam having beam spread of 25° to 30°. Fig. 49.44 (*b*) shows the case when the projector cannot be located away from the building. In that case, an asymmetric reflector is used which directs more intense light towards the top of the building.

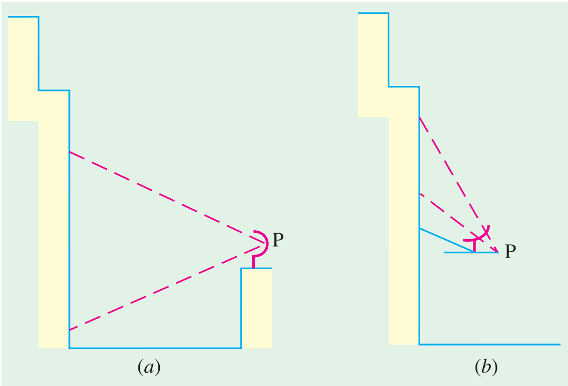


Fig. 49.44

The total luminous flux required to floodlight a building can be found from the relation, $\Phi = EA/\eta \cdot p$.

However, in the case of flood-lighting, one more factor has to be taken into account. That factor is known as waste-light factor (W). It is so because when several projectors are used, there is bound to be a certain amount of overlap and also because some light would fall beyond the edges of the area to be illuminated. These two factors are taken into account by multiplying the theoretical value of the flux required by a waste-light factor which has a value of nearly 1.2 for regular surfaces and about 1.5 for irregular objects like statues etc. Hence, the formula for calculation of total flux required for floodlighting purposes is

$$\Phi = \frac{EAW}{\eta p}$$

Example 49.30. *It is desired to floodlight the front of a building 42 m wide and 16 m high. Projectors of 30° beam spread and 1000-W lamps giving 20 lumen/watt are available. If the desired level of illumination is 75 lm/m² and if the projectors are to be located at ground level 17 m away, design and show a suitable scheme. Assume the following :*

Coefficient of utilization = 0.4 ; Depreciation factor = 1.3; Waste-light factor = 1.2.

(Electrical Power-II ; M.S. Univ. Baroda)

Solution. $\Phi = \frac{EAW}{\eta p}$

Here $E = 75 \text{ lm/m}^2$; $A = 42 \cdot 16 = 672 \text{ m}^2$; $W = 1.2$; $\eta = 0.4$; $p = 1/1.3$

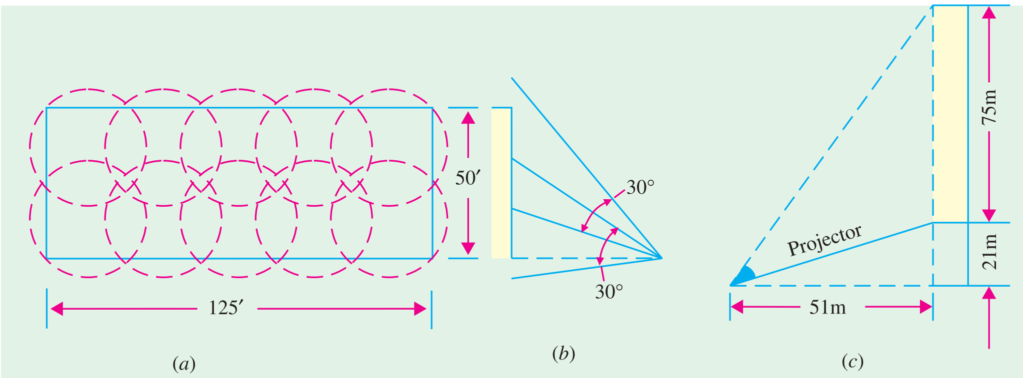


Fig. 49.45

$$\therefore \qquad \Phi = \frac{7.5 \times 672 \times 1.2}{0.4 \times 1/1.3} = 196{,}500 \text{ lm}$$

Lumen output of each 1,000-W lamp = 1,000 × 20 = 20,000 lm

No. of lamps required = 196,500/20,000 = **10.**

With a beam spread* of 30°, it is possible to cover the whole length and width of the building by arranging the 10 projectors in two rows as shown in Fig. 49.45 (*a*).

Example 49.31. *Estimate the number of 1000-W floodlight projectors required to illuminate the up per 75 m of one face of a 96 m tower of width 13 m if approximate initial average luminance is to be 6.85 cd/m². The projectors are mounted at ground level 51m from base of the tower. Utilization factor is = 0.2; reflection factor of wall = 25% and efficiency of each lamp = 18 lm/W.*

(A.M.I.E. Sec. B., Winter 1992)

Solution. $B = 6.85 \text{ cd/m}^2$ Now, $B = \rho E/\pi \text{ cd/m}^2$ —Art 49.4

$\therefore \quad E = pB/\rho = 6.85\,\pi/0.25 = 27.4\,\pi \text{ lm/m}^2$

Area to be floodlighted $= 13 \times 75 = 975 \text{ m}^2$

$\therefore$ flux required $= 27.4\,\pi \times 975$ lm

Taking utilization factor into account, the flux to be emitted by all the lamps

$= 27.4\,\pi \times 975/0.2$ lm

Flux emitted by each lamp $= 18 \times 1000 = 18{,}000$ lm

$$\therefore \text{ No. of lamps reqd.} = \frac{27.4\,\pi \times 975}{0.2 \times 18{,}000} = \mathbf{24 \text{ (approx.)}}$$

49.19. Artificial Sources of Light

The different methods of producing light by electricity may, in a board sense, be divided into three groups.

1. By ***temperature incandescence***. In this method, an electric current is passed through a filament of thin wire placed in vacuum or an inert gas. The current generates enough heat to raise the temperature of the filament to luminosity.

Incandescent tungsten filament lamps are examples of this type and since their output depends on the temperature of their filaments, they are known as ***temperature radiators***.

2. By establishing an arc between two carbon electrodes. The source of light, in their case, is the incandescent electrode.

3. ***Discharge Lamps***. In these lamps, gas or vapour is made luminous by an electric discharge through them. The colour and intensity of light *i.e.* candle-power emitted depends on the nature of the gas or vapour only. It should be particularly noted that these discharge lamps are luminiscent-light lamps and do not depend on temperature for higher efficiencies. In this respect, they differ radically from incandescent lamps whose efficiency is dependent on temperature. Mercury vapour lamp, sodium-vapour lamp, neon-gas lamp and fluorescent lamps are examples of light sources based on discharge through gases and vapours.

49.20. Incandescent Lamp

An incandescent lamp essentially consists of a fine wire of a high-resistance metal placed in an evacuated glass bulb and heated to luminosity by the passage of current through it. Such lamps were

---

* It indicates the divergence of a beam and may be defined as the angle within which the minimum illumination on a surface normal to the axis of the beam is 1/10th of the maximum.

produced commercially for the first time by Edison in 1879. His early lamps had filaments of carbonized paper which were, later on, replaced by carbonized bamboo. They had the disadvantage of negative temperature coefficient of resistivity. In 1905, the metallized carbon-filament lamps were put in the market whose filaments had a positive temperature coefficient of resistivity (like metals). Such lamps gave 4 lm/W.

An incandescent lamp

At approximately the same time, osmium lamps were manufactured which had filaments made of osmium which is very rare and expensive metal. Such lamps had a very fair maintenance of candle-power during their useful life and an average efficiency of 5 lm/W. However, osmium filaments were found to be very fragile.

In 1906 tantalum lamps having filaments of tantalum were produced which had an initial efficiency of 5 lm/watt.

All these lamps were superseded by tungsten lamps which were commercially produced in about 1937 or so. The superiority of tungsten lies mainly in its ability to withstand a high operating temperature without undue vaporisation of the filament. The necessity of high working temperature is due to the fact that the amount of visible radiation increases with temperature and so does the radiant efficiency of the luminous source. The melting temperature of tungsten is 3655°K whereas that of osmium is 2972°K and that of tantalum is 3172°K. Actually, carbon has a higher melting point than tungsten but its operating temperature is limited to about 2073°K because of rapid vaporization beyond this temperature.

In fact, the ideal material for the filament of incandescent lamps is one which has the following properties :

1. A high melting and hence operating temperature
2. A low vapour pressure
3. A high specific resistance and a low temperature coefficient
4. Ductility and
5. Sufficient mechanical strength to withstand vibrations.

Since tungsten possesses practically all the above mentioned qualities, it is used in almost all modern incandescent lamps. The earlier lamps had a square-cage type filament supported from a central glass stem enclosed in an evacuated glass bulb. The object of vacuum was two fold :

(*a*) to prevent oxidation and

(*b*) to minimize loss of heat by convection and the consequent lowering of filament temperature. However, vacuum favoured the evaporation of the filament with the resulting blackening of the lamp so that the operating temperature had to be kept as low as 2670º K with serious loss in luminous efficiency.

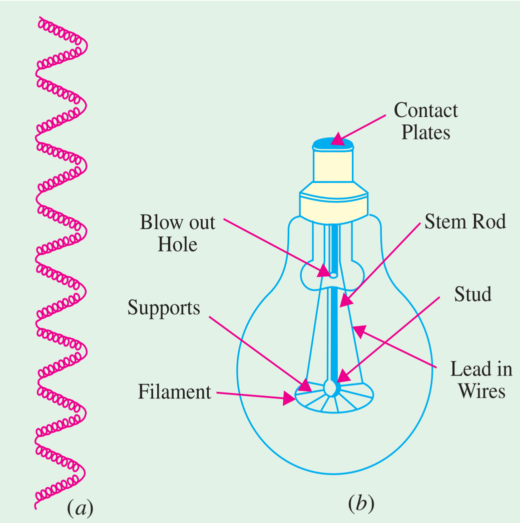


Fig. 49.46

It was, later on, found that this difficulty could be solved to a great extent by inserting a chemically inert gas like nitrogen or argon. The presence of these gases within the glass bulb decreased the evaporation of the filament and so lengthened its life. The filament could now be run at a relatively higher temperature and hence higher luminous efficiency could be realized. In practice, it was found that an admixture of 85% argon and about 15 percent nitrogen gave the best results.

However, introduction of gas led to another difficulty *i.e.* loss of heat due to convection which offsets the additional increase in efficiency. However, it was found that for securing greater efficiency, a concentrated filament having a tightly-wound helical construction was necessary. Such a coiled filament was less exposed to circulating gases, its turns supplying heat to each other and further the filament was mechanically stronger. The latest improvement is that the coiled filament is itself 'coiled' resulting in 'coiled-coil' filament Fig. 49.46 (*a*) which leads to further concentrating the heat, reducing the effective exposure to gases and allows higher temperature operation, thus giving greater efficiency. The construction of a modern coiled-coil gas-filled filament lamp is shown in Fig. 49.46 (*b*). The lamp has a 'wreath' filament *i.e.* a coiled filament arranged in the form of a wreath on radial supports.

A electric filament is a metallic wire, usually made of tungsten, when heated to luminance by passing electricity, radiates light

49.21. Filament Dimensions

There is found to be a definite relation between the diameter of a given filament and the current. Consider a filament operating at a fixed temperature and efficiency. Then since no heat is being utilized for further raising the temperature, all the heat produced in a given time is mostly lost by radiation (if vacuum is good). In other words,

Heat produced per second = heat lost per second by radiation.

$$\text{Now, power intake} = I^2 R = I^2 \cdot \frac{\rho l}{A} = \frac{I^2 \rho l}{\pi d^2/4} = I^2 \left(\frac{4\rho l}{\pi d^2}\right)$$

where, I = filament current in amperes, l = filament length

A = filament cross-section, d = filament diameter

r = resistivity of filament material at the working temperature.

Heat radiated per second from the surface is proportional to the area of the surface and emissivity of the material

$\therefore$ heat lost/second $\propto$ surface area × emissivity σ

$$\therefore \quad I^2 (4\text{r}l/\pi d^2) \propto l \times \pi d \times \sigma \quad \text{or} \quad I^2 \propto d^3 \qquad \ldots(i)$$

$$\therefore \quad I \propto d^{1.5} \quad \text{or} \quad d \propto I^{2/3}$$

In general, for two filaments of the same material working at the same temperature and efficiency, the relation as seen from (*i*) above is

$$\left(\frac{I_1}{I_2}\right)^2 = \left(\frac{d_1}{d_2}\right)^3$$

It would be noticed that the above expressions are similar to those concerning fusing current of a given material under stated conditons (Preece's Rule).

Moreover, for two filaments working at the same temperature, the flux per unit area is the same. Denoting their lengths by l_1 and l_2 and their diameters by d_1 and d_2 respectively, we have, Lumen output $\propto l_1\, d_1 \propto l_2\, d_2$ or $l_1 d_1 = l_2 d_2 =$ constant.

Example 49.32. *If the filament of a 32 candela, 100-V lamp has a length l and diameter d, calculate the length and diameter of the filament of a 16 candela 200-V lamp, assuming that the two lamps run at the same intrinsic brilliance.*

Solution. Using the above relation $\quad 32 \propto l_1 d_1 \quad$ and $\quad 16 \propto l_2 d_2$

$$\therefore \qquad l_2 d_2 = \frac{1}{2} l_1 d_1$$

Assuming that the power intakes of the two lamps are proportional to their outputs, we have

$$32 \propto 100\, I_1 \text{ and } 16 \propto 200\, I_2 \qquad \therefore\ I_2 = I_1 \cdot (16/200) \cdot (100/32) = \frac{1}{4} I_1$$

Also $I_1 \propto d_1^{3/2}$ and $I_2 \propto d_2^{3/2}$ $\qquad \therefore\ (d_2/d_1)^{3/2} = I_2/I_1 = \dfrac{1}{4}$

$$\therefore \qquad d_2 = 0.4\, d_1 \text{ (approx.)}$$

$$\therefore \qquad l_2 = \frac{1}{2} l_1 \cdot (d_1/d_2) = \frac{1}{2} \cdot (1/0.3968)\ l_1 = 1/26\, l_1.$$

Actually, this comparison is not correct because a thicker filament can be worked at a somewhat higher temperature than a thinner one.

Example 49.33. *An incandescent lamp has a filament of 0.005 cm diameter and one metre length. It is required to construct another lamp of similar type to work at double the supply voltage and give half the candle power. Assuming that the new lamp operates at the same brilliancy, determine suitable dimensions for its filament.* **(Elect. Technology, Utkal Univ.)**

Solution. Let I_1 and I_2 be the luminous intensities of the two lamps. Then

$$I_1 \propto l_1 d_1 \text{ and } I_2 \propto l_2 d_2 \qquad \therefore\ \frac{l_2 d_2}{l_1 d_1} = \frac{I_2}{I_1} = \frac{1}{2} \text{ or } l_2 d_2 = \frac{1}{2} l_1 d_1$$

Assuming that the power intakes of the two lamps are proportional to their outputs, we have

$$I_1 \propto V_1\, i_1 \text{ and } I_2 \propto V_2 i_2 \qquad \therefore\ \frac{V_2 i_2}{V_1 i_1} = \frac{I_2}{I_1}$$

$$\therefore \qquad i_2 = i_1 (V_1/V_2)\,(I_2/I_1) = i_1 \cdot \frac{1}{2} \cdot \frac{1}{2} = \frac{1}{4} i_1 \qquad \text{Now, } i_1 \propto d_1^{3/2} \text{ and } i_2 \propto d_2^{3/2}$$

$$\therefore \qquad (d_2/d_1)^{3/2} = (i_2/i_1) = \frac{1}{4} \qquad \therefore\ d_2 = 0.3968\, d_1$$

$$\therefore \qquad l_2 = \frac{1}{2} l_1 \frac{d_1}{d_2} = \frac{1}{2} l_1 \cdot \left(\frac{1}{0.3968}\right) = 1.26\, l_1$$

Now, $\qquad d_1 =$ **0.005 cm ;** $\quad l_1 =$ **100 cm**

$\therefore \qquad d_2 = 0.3968 \times 0.005 =$ **0.001984 cm.** $\qquad l_2 = 1.26 \times 100 =$ **126 cm.**

Example 49.34. *A 60 candle power, 250-V metal filament lamp has a measured candle power of 71.5 candela at 260 V and 50 candela at 240 V.*

(*a*) *Find the constant for the lamp in the expression $C = aV^b$ where C = candle power and V = voltage.*

(*b*) *Calculate the change of candle power per volt at 250 V. Determine the percentage variation of candle power due to a voltage variation of ± 4% from the normal value.* **(A.M.I.E. Sec. B)**

Solution. (*a*) $C = aV^b \quad \therefore \quad 71.5 = a \times 260^b$ and $50 = a \times 240^b$

$\therefore \quad 71.5/50 = (260/240)^b$, $b = $ **4.5**

Substituting this value of b in the above equation, we get

$a = 50/240^{4.5}$, $\quad a = $ **0.98×10^{-9}**

Hence, the expression for the candle power of the lamp becomes $C = 0.98 \times 10^{-9}\ V^{4.5}$ candela

(*b*) Differentiating the above expression and putting $V = 250$ V, we get

$$\frac{dC}{dV} = 0.98 \cdot 10^{-9} \cdot 4.5 \cdot 250^{3.5} = \textbf{4.4 candela per volt}$$

When voltage increases by 4%, $C_2/C_1 = 1.04^{4.5}$

% change in candle power $= \dfrac{C_2 - C_1}{C_1} \cdot 100 = (1.04^{4.5} - 1) \cdot 100 = 19.3$

When voltage falls by 4%, $C_2/C_1 = 0.96^{4.5}$

$\therefore$ % change in candle power $= (0.96^{4.5} - 1) \times 100 = $ **−16.8**

49.22. Incandescent Lamp Characteristics

The operating characteristics of an incandescent lamp are materially affected by departure from its normal working voltage. Initially, there is a rapid heating up of the lamp due to its low thermal capacity, but then soon its power intake becomes steady. If the filament resistance were not dependent on its temperature, the rate of generation of heat would have been directly proportional to the square of voltage applied across the lamp. However, because of (*i*) positive temperature coefficient of resistance and (*ii*) complex mechanism of heat transfer from filament to gas, the relations between the lamp characteristics and its voltage are mostly experimental. Some of the characteristics of gas-filled lamps are given below.

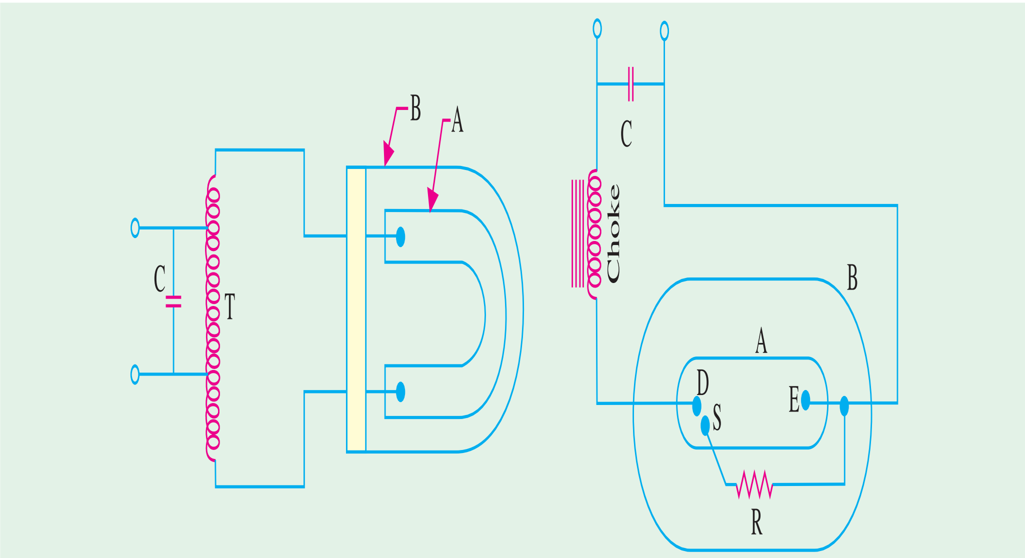


Fig. 49.47

(*i*) It is found that candle power or lumen output of the lamp varies with the voltage as lumen output $\propto V^{3.3}$.

(*ii*) Variation of lumen output in terms of current is given by : lumen output $\propto I^5$

(*iii*) Life of the lamp is given by : life $\propto 1/V^{13}$

(*iv*) Wattage is given by $W \propto V^{1.43}$

(*v*) Its lumen/watt is given by : lm/watt $\propto V^2$

The characteristic curves are plotted in Fig. 49.47. The life characteristic is very revealing. Even a small undervoltage considerably increases its life whereas overvoltage of as small a value as 5% shortens its life by 50%.

49.23. Clear and Inside-frosted Gas-filled Lamps

The advantages of clear glass-filled lamps are that they facilitate light control and are necessary for use in lighting units where accurate distribution is required such as in flood-lights for buildings, projectors and motor-car headlights. However, they produce hard shadows and glare from filaments. Inside-frosted gas-filled lamps have luminous output nearly 2 per cent less than clear glass lamps of the same rating, but they produce softer shadows and practically eliminate glare from filaments. Such lamps are ideal for use in industrial open fittings located in the line of sight at low mounting heights and in diffuse fittings of opal glass type in order to avoid the presence of filament striations on the surface of the glassware etc.

Another new type of incandescent lamp is the inside-silica coated lamp which, due to the fine coating of silica on the inside of its bulb, has high diffusion of light output. Hence, the light from the filament is evenly distributed over the entire bulb surface thus eliminating the noticeably-bright spot around the filament area of an inside-frosted lamp. Such lamps are less glaring, soften shadows and minimize the brightness of reflections from specular (shiny) surfaces.

49.24. Discharge Lamps

In all discharge lamps, an electric current is passed through a gas or vapour which renders it luminous. The elements most commonly used in this process of producing light by gaseous conduction are neon, mercury and sodium vapours. The colours (*i.e.* wavelength) of light produced depends on the nature of gas or vapour. For example, the neon discharge yields orange-red light of nearly 6,500 A.U. which is very popular for advertising signs and other spectacular effects. The pressure used in neon tubes is usually from 3 to 20 mm of Hg. Mercury-vapour light is always bluish green and deficient in red rays, whereas sodium vapour light is orange-yellow.

Discharge lamps are of two types. The first type consists of those lamps in which the colour of light ***is the same as produced by the discharge through the gas or vapour***. To this group belong the neon gas lamps, mercury vapour (M.V.) and sodium vapour lamps. The other type consists of vapour lamps which use the phenomenon of fluorescence. In their case, the discharge through the vapour produces ultra-violet waves which cause fluorescence in certain materials known as phosphors. The radiations from the mercury discharge (especially 2537 A° line) impinge on these phosphors which absorb them and then re-radiate them at longer wave-lengths of visible spectrum. The inside of the fluorescent lamp is coated with these phosphors for this purpose. Different phosphors have different exciting ranges of frequency and give lights of different colours as shown in table 49.2.

Table 49.2

Phosphor	*Lamp Colour*	*Exciting range A°*	*Emitted wavelenght A°*
Calcium Tangstate	Blue	2200 - 3000	4400
Zinc Silicate	Green	2200 - 2960	5250
Cadmium Borate	Pink	2200 - 3600	6150
Cadmium Silicate	Yellow-pink	2200 - 3200	5950

49.25. Sodium Vapour Lamp

Sodium vapour lamp

One type of low-pressure sodium-vapour lamp along with its circuit connection is shown in Fig. 49.48. It consists of an inner U-tube A made of a special sodium-vapour-resisting glass. It houses the two electrodes and contains sodium together with the small amount of neon-gas at a pressure of about 10 mm of mercury and one per cent of argon whose main function is to reduce the initial ionizing potential. The discharge is first started in the neon gas (which gives out redish colour). After a few minutes, the heat of discharge through the neon gas becomes sufficient to vaporise sodium and then discharge passes through the sodium vapour. In this way, the lamp starts its normal operation emitting its characteristic yellow light.

The tungsten-coated electrodes are connected across auto-transformer *T* having a relatively high leakage reactance. The open-circuit voltage of this transformer is about 450 V which is sufficient to initiate a discharge through the neon gas. The leakage reactance is used not only for starting the current but also for limiting its value to safe limit. The electric discharge or arc strikes immediately after the supply is switched on whether the lamp is hot or cold. The normal burning position of the lamp is horizontal although two smaller sizes of lamp may be burnt vertically. The lamp is surrounded by an outer glass envelope *B* which serves to reduce the loss of heat from the inner discharge tube *A*. In this way, *B* helps to maintain the necessary high temperature needed for the operation of a sodium vapour lamp irrespective of draughts. The capacitor *C* is meant for improving the power factor of the circuit.

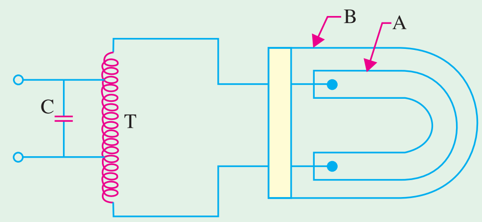


Fig. 49.48

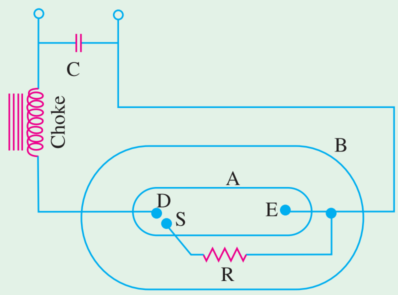


Fig. 49.49

The light emitted by such lamps consists entirely of yellow colour. Solid objects illuminated by sodium-vapour lamp, therefore, present a picture in monochrome appearing as various shades of yellow or black.

49.26. High-pressure Mercury Vapour Lamp

Like sodium-vapour lamp, this lamp is also classified as electric discharge lamp in which light is produced by gaseous conduction. Such a lamp usually consists of two bulbs — an arc-tube containing the electric discharge and an outer bulb which protects the arc-tube from changes in temperature. The inner tube or arc tube *A* is made of quartz (or hard glass) the outer bulb *B* of hard glass. As shown in Fig. 49.49, the arc tube contains a small amount of mercury and argon gas and houses three electrodes *D, E* and *S*. The main electrodes are *D* and *E* whereas *S* is the auxiliary starting electrode. *S* is connected through a high resistance *R* (about 50 kΩ) to the main electrode situated at the outer end of the tube. The main electrodes consist of tungsten coils with electron-emitting coating or elements of thorium metal.

When the supply is switched on, initial discharge for the few seconds is established in the argon gas between *D* and *S* and then in the argon between *D* and *E*. The heat produced due to this discharge through the gas is sufficient to vaporise mercury. Consequently, pressure inside *A* increases to about one or two atmospheres and the p.d. across *D* and *E* grows from about 20 to 150 V, the operation taking about 5-7 minutes. During this time, discharge is established through the mercury vapours which emit greenish-blue light.

The choke serves to limit the current drawn by the discharge tube *A* to a safe limit and capacitor *C* helps to improve the power factor of the circuit.

True colour rendition is not possible with mercury vapour lamps since there is complete absence of red-light from their radiations. Consequently, red objects appear black, all blues appear mercury-spectrum blue and all greens the mercury-spectrum green with the result that colour values are distorted.

Correction for colour distortion can be achieved by

1. Using incandescent lamps (which are rich in red light) in combination with the mercury lamps.
2. Using colour-corrected mercury lamps which have an inside phosphor coat to add red colour to the mercury spectrum.

Stroboscopic (Flickering) effect in mercury vapour lamps is caused by the 100 on and off arc strikes when the lamps are used on the 50-Hz supply. The effect may be minimized by

1. Using two lamps on lead-lag transformer
2. Using three lamps on separated phases of a 3-phase supply and
3. Using incandescent lamps in combination with mercury lamps.

In the last few years, there has been tremendous improvement in the construction and operation of mercury-vapour lamps, which has increased their usefulness and boosted their application for all types of industrial lighting, floodlighting and street lighting etc. As compared to an incandescent lamp, a mercury-vapour lamp is (*a*) smaller in size (*b*) has 5 to 10 times longer operating life and (*c*) has 3 times higher efficiency *i.e.* 3 times more light output for given electrical wattage input.

Typical mercury-vapour lamp applications are :

1. High-bay industrial lighting — where high level illumination is required and colour rendition is not important.
2. Flood-lighting and street-lighting
3. Photochemical applications — where ultra-violet output is useful as in chlorination, water sterilization and photocopying etc.
4. For a wide range of inspection techniques by ultra-violet activation of fluorescent and phosphorescent dyes and pigments.
5. Sun-tan lamps — for utilizing the spectrum lines in the erythemal region of ultra-violet energy for producing sun-tan.

49.27. Fluorescent Mercury-vapour Lamps

Basically, a fluorescent lamp consists of a long glass tube internally coated with a suitable fluorescent powder. The tube contains a small amount of mercury along with argon whose function is to facilitate the starting of the arc. There are two sealed-in electrodes at each end of the tube. Two basic types of electrodes are used in fluorescent lamps :

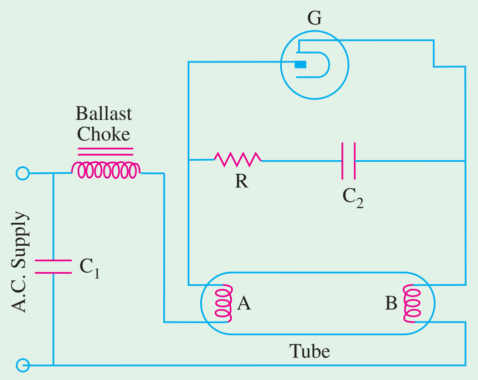


Fig. 49.50

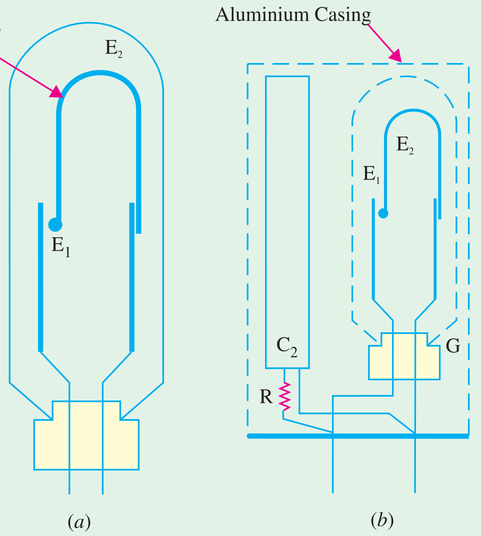


Fig. 49.51

1. The coated-coil tungsten wire type. This type is used in standard pre-heat, rapid-start, instant-start lamps etc.

2. The inside-coated metal cylinder type which operates at a lower and more even temperature than the tungsten type and is called 'cold cathode'.*

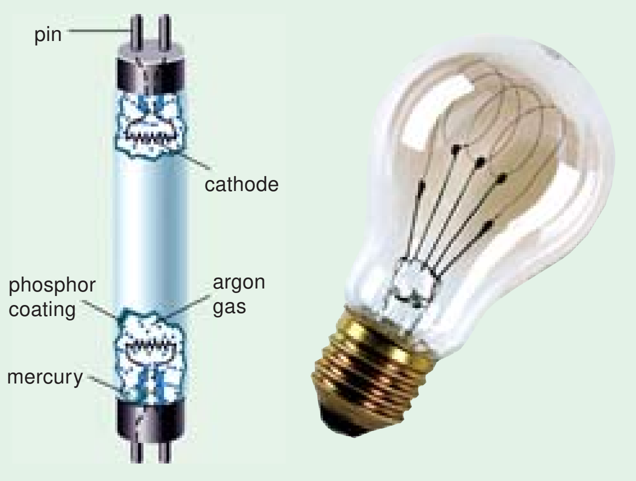
Circuits employed for the control of fluorescent lamps can be divided into two main groups **(*i*)** switch-start circuits and **(*ii*)** startless circuits requiring no starter. There are two types of starters **(*a*)** glow type — which is a voltage-operated device and **(*b*)** thermal switch — which is a current-operated device. Fig. 49.50 shows a flourescent tube fitted with a glow starter *G*. As shown separately in Fig. 49.51 (*a*), the glow switch consists of two electrodes enclosed in a glass bulb filled with a mixture of helium and hydrogen or argon or neon at low pressure. One electrode E_1 is fixed whereas the other E_2 is movable and is made of a U-shaped bimetallic strip. To reduce radio interference, a small capacitor C_2 is connected across the switch. The resistor *R* checks capacitor surges and prevents the starter electrodes or contacts from welding together. The complete starter switch along with the capacitor and resistor is contained in an aluminium casing is shown in Fig. 49.51 (*b*). Normally, the contacts are open and when supply is switched on, the glow switch receives almost full mains voltage**. The voltage is sufficient to start a glow discharge between the two electrodes E_1 and E_2 and the heat generated is sufficient to bend the bimetallic strip E_2 till it makes contact with the fixed electrode E_1, thus closing the contacts. This action completes the main circuit through the choke and the lamp electrodes *A* and *B* (Fig. 49.50). At the same time, since the glow between E_1 and E_2 has been shorted out, the bimetallic strip cools and the contacts E_1 and E_2 open. By this time, lamp electrodes *A* and *B* become heated to incandescence and the argon gas in their immediate vicinity is ionized. Due to opening of the glow switch contacts, a high inductive e.m.f. of about 1000 volts is induced in the choke. This voltage surge is sufficient to initiate a discharge in the argon gas lying between electrodes *A* and *B*. The heat thus produced is sufficient to vaporize mercury and the p.d. across the fluorescent tube falls to about 100 or 110 V which is not sufficient to restart the glow in

* A cold cathode fluorescent lamp requires higher operating voltage than the other type. Although cold cathode lamps have less efficiency, they have much longer life than other lamps.

** It is so because only the small discharge current flows and voltage drop across the choke is negligible.

G. Finally, the discharge is established through the mercury vapour which emits ultra-violet radiations. These radiations impinge on the fluorescent powder and make it emit visible light.

The function of the capacitor C_1 is to improve the power factor of the circuit. It may be noted that the function of the highly-inductive choke (also called ballast) is *(i)* to supply large potential for starting the arc or discharge and *(ii)* to limit the arc current to a safe value.



A fluorescent lamp radiates more light compared to an incandescent filament bulb, for the same amount of power consumed

49.28. Fluorescent Lamp Circuit with Thermal Switch

The circuit arrangement is shown in Fig. 49.52. The switch has a bimetallic strip close to a resistance *R* which produces heat. The switch is generally enclosed in hydrogen-filled glass bulb *G*. The two switch electrodes E_1 and E_2 are normally closed when the lamp is not in operation. When normal supply is switched on, the lamp filament electrodes *A* and *B* are connected together through the thermal switch and a large current passes through them. Consequently, they are heated to incandescence. Meanwhile heat produced in resistance *R* causes the bimetallic strip E_2 to break contact. The inductive surge of about 1000 V produced by the choke is sufficient to start discharge through mercury vapours as explained in Art. 49.27. The heat produced in *R* keeps the switch contacts E_1 and E_2 open during the time lamp is in operation.

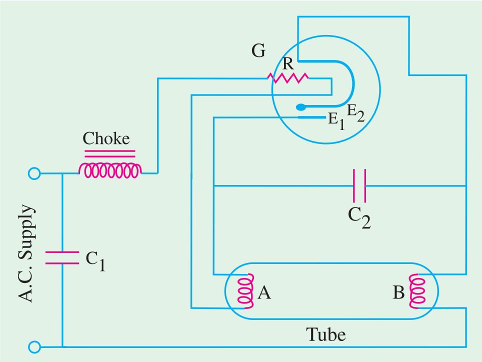


Fig. 49.52

49.29. Startless Fluorescent Lamp Circuit

Such a circuit (Fig. (49.53) which does not require the use of a starter switch is commercially known as 'instant-start' or 'quick-start'. In this case, the normal starter is replaced by a filament heating transformer whose secondaries *SS* heat up the lamp electrodes *A* and *B* to incandescence in a fraction of a second. This combination of pre-heating and application of full supply voltage across lamp electrodes *A* and *B* is sufficient to start ionization in the neighbourhood of the electrodes which further spreads to the whole tube. An earthed strip *E* is used to ensure satisfactory starting.

The advantages of startless method are

1. It is almost instantaneous starting.
2. There is no flickering and no false starts.
3. It can start and operate at low voltage of 160-180 V.
4. Its maintenance cost is lower due to the elimination of any starter-switch replacements.
5. It lengthens the life of the lamp.

49.30. Stroboscopic Effect of Fluorescent Lamps

Stroboscopic or flickering effect produced by fluorescent lamps is due to the periodic fluctuations in the light output of the lamp caused by cyclic variations of the current on a.c. circuits. This phenomenon creates multiple-image appearance of moving objects and makes the movement appear jerky. In this connection, it is worth noting that

1. This flicker effect is more pronounced at lower frequencies.
2. Frequency of such flickers is twice the supply frequency.
3. The fluorescent powder used in the tube is slightly phosphorescent, hence stroboscopic effect is reduced to some extent due to after-glow.

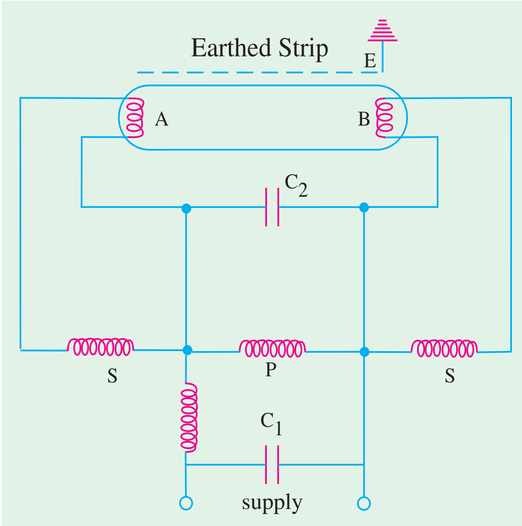


Fig. 49.53

Stroboscopic effect is very troublesome in the following cases :

1. When an operator has to move objects very quickly particularly those having polished finish. These objects would appear to move with jerky motion which over a long period would produce visual fatigue.
2. In the case of rotating machines whose frequency of rotation happens to be a multiple of flicker frequency, the machines appear to decrease in speed of rotation or be stationary. Sometimes the machines may even seem to rotate in the opposite direction.

Some of the methods employed for minimizing stroboscopic effect are given below :

1. By using three lamps on the seperate phases of a 3-phase supply. In this case, the three light waves reaching the working plane would overlap by 120° so that the resultant fluctuation will be very much less than from a single fluorescent lamp.
2. By using a 'twin lamp' circuit on single-phase supply as shown in Fig. 49.54, one of the chokes has a capacitor in series with it and the lamp. In this way, a phase displacement of nearly 120° is introduced between the branch currents and also between the two light waves thereby reducing the resultant fluctuation.
3. By operating the lamps from a high frequency supply. Obviously, stroboscopic effect will entirely disappear on d.c. supply.

49.31. Comparison of Different Light Sources

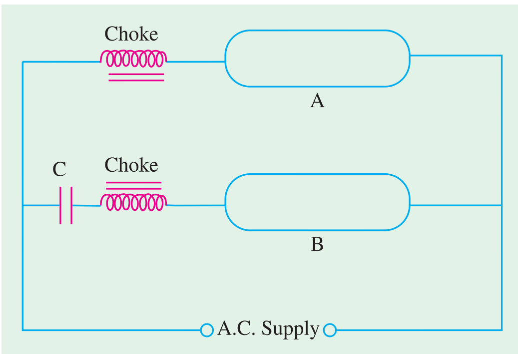


Fig. 49.54

1. Incandescent Lamps. They have instantaneous start and become momentarily off when the supply goes off. The colour of their light is very near the natural light. Their initial cost of installation is minimum but their running cost is maximum. They work equally well both on d.c. and a.c. supply and frequent switching does not affect their life of operation. Change of supply voltage affects their efficiency, output and life in a very significant way. They have an average working life of 1000 hours and luminous efficiency of 12 lm/W. Since their light has no stroboscopic effects, the incandescent lamps are suitable for domestic, industrial, street lighting and floodlights etc. They are available in a wide range of voltage ratings and, hence are used in automobiles, trains, emergency lights, aeroplanes and signals for railways etc.

2. Flourescent Lamps. They have a reaction time of one second or a little more at the start. They go off and restart when the supply is restored. The colour of their light varies with the phosphor coating. Their initial cost of installation is maximum but running cost is minimum. Since stroboscopic effect is present, they are suitable for semi-direct lighting, domestic, industrial, commercial, roads and halls etc. Change in voltage affects their starting although light output does not change as remarkably as in the case of incandescent lamps. Colour of their light changes with the different phosphor coating on the inner side of the tube. Frequent switching affects their life period. They have quite high utility but their voltage rating is limited. Hence, their use is confined to mains voltage or complicated inverter circuits which convert 12 V d.c. into high volt d.c.. They have an average working life of 4000 hours and a luminous efficiency of 40 lm/W.

3. Mercury Vapour Lamps. They take 5 to 6 minutes for starting. They go off and cannot be restarted after the recovery of the voltage till the pressure falls to normal. They suffer from high colour distortion. Their initial cost of installation is high but lesser than that of flourescent lamps. Their running cost is much less than incandescent lamps but higher than flourescent tubes for the same levels of illumination. Stroboscopic effect is present in their light. They are suitable for open space like yards, parks and highway lighting etc. Change in voltage effects their starting time and colour of radiations emitted by them. Switching does not affect their life period. They have very limited utility that too on mains voltage. They are suitable for vertical position of working. They have an average working life of 3000 hours and an efficiency of 40 lm/W.

4. Sodium Vapour Lamps. They have a starting time of 5 to 6 minutes. They go off and cannot be restarted after the recovery of the voltage till its value falls to the normal value. The colour of their light is yellowish and produces colour distortion.Their initial cost of installation is maximum although their running cost is less than for filament lamps but more than for flourescent lamps. They have stroboscopic effect and are suitable for use in open spaces, highways and street lighting etc. Change in voltage affects their starting time and colour of their radiations. They work on a.c. voltage and frequent switching affects their life. They are not suitable for local lighting. The colour of their light cannot be changed. They are very suitable for street lighting purposes. Their position of working is horizontal. They have a working life of about 3000 hours and efficiency of 60-70 lm/W.

Tutorial Problem No. 49.3

1. Explain $\cos^3 \phi$ law. *(J.N. University, Hyderabad, November 2003)*
2. A lamp of 500 candle power is placed at the centre of a room,(20 m · 10 m · 5 m.) Calculate the illumination in each corner of the floor and a point in the middle of a 10 m wall at a height of 2 m from floor. *(J.N. University, Hyderabad, November 2003)*
3. Enumerate the various factors, which have to be considered while designing any lighting scheme. *(J.N. University, Hyderabad, November 2003)*
4. Prove that 1 candle/sq. feet = (πfl – L.) *(J.N. University, Hyderabad, November 2003)*
5. A lamp giving 300 c.p. in all directions below the horizontal is suspended 2 metres above the centre of a square table of 1 metre side. Calculate the maximum and minimum illumination on the surface of the table. *(J.N. University, Hyderabad, November 2003)*
6. Explain the various types of lighting schemes with relevant diagrams. *(J.N. University, Hyderabad, November 2003)*
7. Discuss inverse square law? Corire law of Illustration. *(J.N. University, Hyderabad, November 2003)*

8. A lamp fitted with 120 degrees angled cone reflector illuminates circular area of 200 meters in diameter.The illumination of the disc increases uniformly from 0.5 metre-candle at the edge to 2 meter-candle at the centre.
Determine :
(*i*) the total light received (*ii*) Average illumination of the disc (*iii*) Average c.p. of the source.
(J.N. University, Hyderabad, November 2003)

9. Discuss the flood lighting with suitable diagrams. *(J.N. University, Hyderabad, November 2003)*

10. Explain the measurement techniques used for luminous intensity.
(J.N. University, Hyderabad, November 2003)

11. Write short notes on :
(*i*) Bunsen photometer head (*ii*) Lummer-Brodherm photometer head (*iii*) Flicker photometer head.
(J.N. University, Hyderabad, November 2003)

12. What do you understand by polar curves as applicable to light source? Explain.
(J.N. University, Hyderabad, November 2003)

13. Mean spherical Candlepower. *(J.N. University, Hyderabad, April 2003)*

14. Explain how you will measure the candlepower of a source of light.
(J.N. University, Hyderabad, April 2003)

15. Explain the Rosseau's construction for calculating M.S.C.P. of a lamp.
(J.N. University, Hyderabad, April 2003)

16. What do you mean by International Luminosity curve? Explain.
(J.N. University, Hyderabad, April 2003)

17. Explain in detail the primary standard of luminous intensity with relevant diagram.
(J.N. University, Hyderabad, April 2003)

18. Explain with sketches the constructional features of a filament lamp.
(J.N. University, Hyderabad, April 2003)

19. Explain how the standard lamps canbe calibrated w.r.t. primary and secondary standards.
(J.N. University, Hyderabad, April 2003)

20. Briefly explain the various laboratory standards used in Illumination.
(J.N. University, Hyderabad, April 2003)

21. Write short notes on :
(*a*) High pressure mercury vapour lamp (*i*) M.A. Type (*ii*) M.T. Type
(*b*) Mercury fluorescent lamp.
(J.N. University, Hyderabad, April 2003)

22. Explain with connection diagram the operation of the low pressure fluorescent lamp and state its advantage. *(J.N. University, Hyderabad, April 2003)*

23. Explain clearly the following :
Illumination, Luminous efficiency, MSCP, MHCP and solid angle.
(J.N. University, Hyderabad, December 2002/January 2003)

24. A small light source with uniform intensity is mounted at a height of 10 meters above a horizontal surface. Two points A and B both lie on the surface with point A directly beneath the source. How far is B from A if the illumination at B is only 1/15th of that at A?
(J.N. University, Hyderabad, December 2002/January 2003)

25. Discuss the : (*i*) Specular reflection principle (*ii*) Diffusion principle of street lighting.
(J.N. University, Hyderabad, December 2002/January 2003)

26. Determine the height at which a light source having uniform spherical distribution should be placed over a floor in order that the intensity of horizontal illumination at a given distance from its vertical line may be greatest. *(J.N. University, Hyderabad, December 2002/January 2003)*

27. What is a Glare? *(J.N. University, Hyderabad, December 2002/January 2003)*

28. With the help of a neat diagram, explain the principle of operation of fluorescent lamp.
(J.N. University, Hyderabad, December 2002/January 2003)

29. A machine shop 30 m long and 15 m wide is to have a general illumination of 150 lux on the work plane provided by lamps mounted 5 m above it. Assuming a coefficient of utilization of 0.55, determine suitable number and position of light. Assume any data if required.
(J.N. University, Hyderabad, December 2002/January 2003)

30. Laws of illumination. *(J.N. University, Hyderabad, December 2002/January 2003)*

31. Working principle of sodium vapour lamp.
(J.N. University, Hyderabad, December 2002/January 2003)

32. Explain the principle of operation of sodium vapour lamp and its advantages.
(J.N. University, Hyderabad, December 2002/January 2003)

33. A corridor is lighted by lamps spaced 9.15 m apart and suspended at a height of 4.75 m above the centre line of the floor. If each lamp gives 100 candle power in all directions, find the maximum and minimum illumination on the floor along the centre line. Assume and data if required.
(J.N. University, Hyderabad, December 2002/January 2003)

34. Discuss the laws of illumination and its limitations in practice.
(J.N. University, Hyderabad, December 2002/January 2003)

35. State the functions of starter and choke in a fluorescent lamp.
(J.N. University, Hyderabad, December 2002/January 2003)

36. Mercury Vapour Lamp. *(J.N. University, Hyderabad, December 2002/January 2003)*

37. Describe briefly (*i*) conduit system (*ii*) C.T.S. system of writing.
(Bangalore University, January/February 2003)

38. With a neat circuit diagram, explain the two way control of a filament lamp.
(Belgaum Karnataka University, February 2002)

39. With a neat sketch explain the working of a sodium vapour lamp.
(Belgaum Karnataka University, February 2002)

40. Mention the different types of wiring. With relevant circuit diagrams and switching tables, explain two-way and three-way control of lamps.
(Belgaum Karnataka University, January/February 2003)

41. With a neat sketch explain the working of a fluorescent lamp.
(Belgaum Karnataka University, January/February 2003)

OBJECTIVE TESTS – 49

1. Candela is the unit of
(*a*) flux
(*b*) luminous intensity
(*c*) illumination
(*d*) luminance.

2. The unit of illuminance is
(*a*) lumen
(*b*) cd/m^2
(*c*) lux
(*d*) steradian.

3. The illumination at various points on a horizontal surface illuminated by the same source varies as
(*a*) $\cos^3\theta$
(*b*) $\cos\theta$
(*c*) $1/r^2$
(*d*) $\cos^2\theta$.

4. The M.S.C.P. of a lamp which gives out a total luminous flux of 400 π lumen is .... candela.
(*a*) 200
(*b*) 100
(*c*) 50
(*d*) 400.

5. A perfect diffuser surface is one that
(*a*) diffuses all the incident light
(*b*) absorbs all the incident light
(*c*) transmits all the incident light
(*d*) scatters light uniformly in all directions.

6. The direct lighting scheme is most efficient but is liable to cause
(*a*) monotony
(*b*) glare
(*c*) hard shadows
(*d*) both (*b*) and (*c*).

7. Total flux required in any lighting scheme depends inversely on
(*a*) illumination

(b) surface area
(c) utilization factor
(d) space/height ratio.

8. Floodlighting is NOT used for .... purposes.
(a) reading
(b) aesthetic
(c) advertising
(d) industrial.

9. Which of the following lamp has minimum initial cost of installation but maximum running cost ?
(a) incandescent
(b) fluorescent
(c) mercury vapour
(d) sodium vapour.

10. An incandescent lamp can be used
(a) in any position
(b) on both ac and dc supply
(c) for street lighting
(d) all of the above.

11. The average working life of a fluorescent lamp is about....................... hours.
(a) 1000
(b) 4000
(c) 3000
(d) 5000.

12. The luminous efficiency of a sodium vapour lamp is about .... lumen/watt.
(a) 10
(b) 30
(c) 50
(d) 70

13. Which of the following statements is correct?
(a) Light is a form of heat energy
(b) Light is a form of electrical energy
(c) Light consists of shooting particles
(d) Light consists of electromagnetic waves

14. Luminous efficiency of a fluorescent tube is
(a) 10 lumens/watt
(b) 20 lumens/watt
(c) 40 lumens/watt
(c) 60 lumens/watt

15. Candela is the unit of which of the following?
(a) Wavelength
(b) Luminous intensity
(c) Luminous flux
(d) Frequency

16. Colour of light depends upon
(a) frequency
(b) wave length
(c) both (a) and (b)
(d) speed of light

17. Illumination of one lumen per sq. metre is called ....
(a) lumen metre
(b) lux
(c) foot candle
(d) candela

18. A solid angle is expressed in terms of ....
(a) radians/metre
(b) radians
(c) steradians
(d) degrees

19. The unit of luminous flux is ....
(a) watt/m^2
(b) lumen
(c) lumen/m^2
(d) watt

20. Filament lamps operate normally at a power factor of
(a) 0.5 lagging
(b) 0.8 lagging
(c) unity
(d) 0.8 leading

21. The filament of a GLS lamp is made of
(a) tungsten
(b) copper
(c) carbon
(d) aluminium

22. Find diameter tungsten wires are made by
(a) turning
(b) swaging
(c) compressing
(d) wire drawing

23. What percentage of the input energy is radiated by filament lamps?
(a) 2 to 5 percent
(b) 10 to 15 percent
(c) 25 to 30 percent
(d) 40 to 50 percent

24. Which of the following lamps is the cheapest for the same wattage?
(a) Fluorescent tube
(b) Mercury vapour lamp
(c) GLS lamp
(d) Sodium vapour lamp

25. Which of the following is not the standard rating of GLS lamps?
(a) 100 W
(b) 75 W
(c) 40 W
(d) 15 W

26. In houses the illumination is in the range of
(a) 2–5 lumens/watt
(b) 10–20 lumens/watt

(c) 35–45 lumens/watt
(d) 60–65 lumens/watt

27. "The illumination is directly proportional to the cosine of the angle made by the normal to the illuminated surface with the direction of the incident flux''. Above statement is associated with
(a) Lambert's cosine law
(b) Planck's law
(c) Bunsen's law of the illumination
(d) Macbeth's law of illumination

28. The colour of sodium vapour discharge lamp is
(a) red
(b) pink
(c) yellow
(d) bluish green

29. Carbon arc lamps are commonly used in
(a) photography
(b) cinema projectors
(c) domestic lighting
(d) street lighting

30. Desired illumination level on the working plane depends upon
(a) age group of observers
(b) whether the object is stationary or moving
(c) Size of the object to be seen and its distance from the observer
(d) whether the object is to be seen for longer duration or shorter duration of time
(e) all above factors

31. On which of the following factors dies the depreciation or maintenance factor depend?
(a) Lamp cleaning schedule
(b) Ageing of the lamp
(c) Type of work carried out at the premises
(d) All of the above factors

32. In lighting installating using filament lamps 1% voltage drop results into
(a) no loss of light
(b) 1.5 percent loss in the light output
(c) 3.5 percent loss in the light output
(d) 15 percent loss in the light output

33. For the same lumen output, the running cost of the fluorescent lamp is
(a) equal to that of filament lamp
(b) less than that of filament lamp
(c) more than that of filament lamp
(d) any of the above

34. For the same power output
(a) high voltage rated lamps will be more sturdy
(b) low voltage rated lamps will be more sturdy
(c) both low and high voltage rated lamps will be equally sturdy

35. The cost of a fluorescent lamp is more than that of incandescent lamp because of which of the following factors?
(a) More labour is required in its manufacturing
(b) Number of components used is more
(c) Quantity of glass used is more
(d) All of the above factors

36. Filament lamp at starting will take current
(a) less than its full running current
(b) equal to its full running current
(c) more than its full running current

37. A reflector is provided to
(a) protect the lamp
(b) provide better illumination
(c) avoid glare
(d) do all of the above

38. The purpose of coating the fluorescent tube from inside with white power is
(a) to improve its life
(b) to improve the appearance
(c) to change the colour of light emitted to white
(d) to increase the light radiations due to secondary emissions

39. .... will need lowest level of illumination.
(a) Audiotoriums
(b) Railway platform
(c) Displays
(d) Fine engravings

40. Due to moonlight, illumination is nearly
(a) 3000 lumens/m^2
(b) 300 lumens/m^2
(c) 30 lumens/m^2
(d) 0.3 lumen/m^2

41. Which of the following instruments is used for the comparison of candle powers of different sources?
(a) Radiometer
(b) Bunsen meter
(c) Photometer
(d) Candle meter

42. .... photometer is used for comparing the lights of different colours?
(a) Grease spot
(b) Bunsen
(c) Lummer brodhum
(d) Guilds flicker

43. In the fluorescent tube circuit the function of choke is primarily to
(a) reduce the flicker

(b) minimise the starting surge
(c) initiate the arc and stabilize it
(d) reduce the starting current

44. ...... cannot sustain much voltage fluctuations.
(a) Sodium vapour lamp
(b) Mercury vapour lamp
(c) Incandescent lamp
(d) Fluorescent lamp

45. The function of capacitor across the supply to the fluorescent tube is primarily to
(a) stabilize the arc
(b) reduce the starting current
(c) improve the supply power factor
(d) reduce the noise

46. ...... does not have separate choke
(a) Sodium vapour lamp
(b) Fluorescent lamp
(c) Mercury vapour lamp
(d) All of the above

47. In sodium vapour lamp the function of the leak transformer is
(a) to stabilize the arc
(b) to reduce the supply voltage
(c) both (a) and (b)
(d) none of the above

48. Most affected parameter of a filament lamp due to voltage change is
(a) wattage
(b) life
(c) luminous efficiency
(d) light output

49. In electric discharge lamps for stabilizing the arc
(a) a reactive choke is connected in series with the supply
(b) a condenser is connected in series to the supply
(c) a condenser is connected in parallel to the supply
(d) a variable resistor is connected in the circuit

50. For precision work the illumination level required is of the order of
(a) 500-1000 lumens/m^2
(b) 200-2000 lumens/m^2
(c) 50-100 lumens/m^2
(d) 10-25 lumens/m^2

51. ...... is a cold cathode lamp.
(a) Fluorescent lamp
(b) Neon lamp
(c) Mercury vapour lamp
(d) Sodium vapour lamp

52. In case of ...... least illumination level is required.
(a) skilled bench work
(b) drawing offices
(c) hospital wards
(d) find machine work

53. For normal reading the illumination level required is around
(a) 20-40 lumens/m^2
(b) 60-100 lumens/m^2
(c) 200-300 lumens/m^2
(d) 400-500 lumens/m^2

54. In electric discharge lamps light is produced by
(a) cathode ray emission
(b) ionisation in a gas or vapour
(c) heating effect of current
(d) magnetic effect of current

55. A substance which change its electrical resistance when illuminated by light is called ....
(a) photoelectric
(b) photovoltaic
(c) phatoconductive
(d) none of the above

56. In case of ...... power factor is the highest.
(a) GLS lamps
(b) mercury arc lamps
(c) tube lights
(d) sodium vapour lamps

57. A mercury vapour lamp gives ..... light.
(a) white
(b) pink
(c) yellow
(d) greenish blue

58. Sometimes the wheels of rotating machinery, under the influence of fluorescent lamps appear to be stationary. This is due to the
(a) low power factor
(b) stroboscopic effect
(c) fluctuations
(d) luminescence effect

59. Which of the following bulbs operates on least power?
(a) GLS bulb
(b) Torch bulb
(c) Neon bulb
(d) Night bulb

60. The flicker effect of fluorescent lamps is more pronounced at
(a) lower frequencies
(b) higher frequencies
(c) lower voltages
(d) higher voltages

61. Which of the following application does not need ultraviolet lamps?
(*a*) Car lighting
(*b*) Medical purposes
(*c*) Blue print machine
(*d*) Aircraft cockpit dashboard lighting

62. Which gas can be filled in GLS lamps?
(*a*) Oxygen
(*b*) Carbon dioxide
(*c*) Xenon
(*d*) Any inert gas

ANSWERS

1. (*b*)	**2.** (*c*)	**3.** (*a*)	**4.** (*b*)	**5.** (*d*)	**6.** (*d*)	**7.** (*c*)	**8.** (*a*)	**9.** (*a*)	**10.** (*d*)
11. (*b*)	**12.** (*d*)	**13.** (*d*)	**14.** (*d*)	**15.** (*b*)	**16.** (*c*)	**17.** (*b*)	**18.** (*c*)	**19.** (*b*)	**20.** (*c*)
21. (*a*)	**22.** (*d*)	**23.** (*b*)	**24.** (*c*)	**25.** (*b*)	**26.** (*d*)	**27.** (*a*)	**28.** (*c*)	**29.** (*b*)	**30.** (*e*)
31. (*d*)	**32.** (*c*)	**33.** (*b*)	**34.** (*b*)	**35.** (*d*)	**36.** (*c*)	**37.** (*d*)	**38.** (*d*)	**39.** (*b*)	**40.** (*d*)
41. (*c*)	**42.** (*d*)	**43.** (*c*)	**44.** (*c*)	**45.** (*c*)	**46.** (*a*)	**47.** (*c*)	**48.** (*b*)	**49.** (*a*)	**50.** (*a*)
51. (*b*)	**52.** (*c*)	**53.** (*b*)	**54.** (*b*)	**55.** (*c*)	**56.** (*a*)	**57.** (*d*)	**58.** (*b*)	**59.** (*b*)	**60.** (*a*)
61. (*a*)	**62.** (*d*)								

GO To FIRST