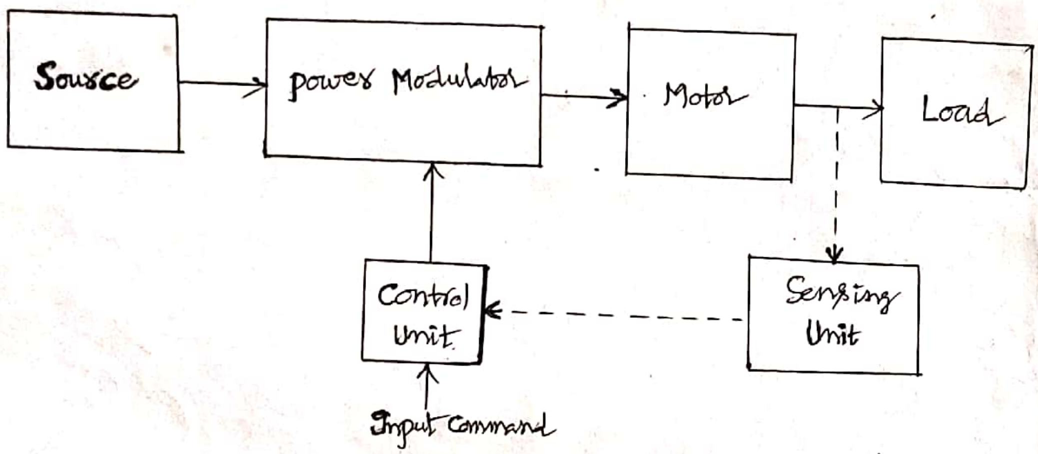
Electrical Drives – Introduction

→ Motion Control is required in large no. of Industrial & domestic applications like transportation systems, Rolling mills, paper mills, textile mills, machine tools, fans, pumps, robots, washing machines etc.

→ Systems employed for motion control are called drives and may employ any of prime movers such as Diesel (or) petrol engines, Gas (or) steam turbines, steam engines, hydraulic motors.

→ Drives employing electric motors are known as "Electrical Drives"

Block Diagram of an Electrical Drive :–



→ Load is usually a machinery designed to accomplish a given task, Ex:– fans, pumps, robots, washing machines, machine tools, trains and drills. usually load requirements can be specified interms of speed & torque demands.

→ A motor is chosen in such a way that, whose speed – Torque characteristics and capabilities com-patible to the load requirements.

→ power Modulator performs one (or) more of the following four functions :

① Modulates flow of power from the source to the motor in such a manner that motor is imparted speed – torque characteristics required by the load.

② During transient operations, such as starting, braking and speed reversal, it re, source & motor currents within permissible values, excessive current drawn from source may overload it (or) may cause a voltage **dip**.

③ converts electrical energy of the source in the form suitable to the motor. Ex:– If the source is DC and an induction motor is to be employed, then the power modulator is required to convert DC into a variable frequency ac.

④ Selects the mode of operation of the motor ie motoring (or) Braking.

... To be continued in ⑥

① Continued ...

When power modulator is employed mainly to perform function ③, it is more appropriately called converter. While ③ is the main function, depending on its circuit, a converter may also perform other functions of power modulator.

→ Controls for power modulator are built in control unit which usually operates at much lower voltage and power levels. In addition to operating the power modulator as desired, it may also generate commands for the protection of power modulator and motor.

→ Input command signal, which adjusts the operating point of the drive, forms an input to the control unit.

→ Sensing of certain drive parameters, such as motor current, speed may be required either for protection (or) for closed loop operation.

Advantages of Electrical Drives :-

① They have flexible control characteristics.

→ The steady state and dynamic characteristics of electrical drives can be shaped to satisfy load requirements. With the advent of power electronic devices such as power transistors, Thyristors, IGBTs and GTOs, linear and digital ICs and micro computers made the control even more flexible. It is possible to reshape characteristics have characteristics of drives almost at will to meet load requirements in an optimum manner.

→ Speed and torque, and transitions from one mode to another can be controlled smoothly and steplessly.

→ optimal control strategies can be implemented to achieve high dynamic performance, high efficiency (or) to minimize a suitable performance index.

→ Drives can be provided with automatic fault detection systems. programmable logic controllers (PLCs) and computers can be employed to automatically control the drive operations in a desired sequence.

② They are available in wide range of torque, speed and power.

③ Electric motors have ⓐ high efficiency

ⓑ low no-load losses

ⓒ short-time overloading capability.

ⓓ They can be made in variety of designs to make them compatible with load.

ⓔ They have longer life, low noise, low maintainance requirements and cleaner operation

④ They are suitable to almost any operating conditions, viz explosive and radioactive environment, submerged in liquids, vertical mountings etc.

⑤ Do not pollute the environment.

⑥ It can operate in all the four quadrants of speed-torque plane.

→ Electric braking gives smooth deceleration and hence increases life of the equipment compared to other forms of braking.

→ When regenerative braking is possible, considerable amount of energy is saved. These features are not available in other prime movers.

⑦ Unlike other prime movers, there is no need to refuel (or) warm-up the motor. They can be started instantly and can immediately be fully loaded.

⑧ They are supplied by electrical energy which has a number of advantages over other forms of energy. ⓐ It can be generated and transmitted to the desired point economically and efficiently. ⓑ Conversion of electrical to mechanical energy and vice-versa, ⓒ Electrical energy from one form to another can also be done efficiently and economically.

DC Drives

Introduction :-

(3) → DC motors have variable characteristics and are extensively used in variable speed drives. DC motors can provide a high starting torque and it is also possible to obtain speed control over a wide range.

(4) → The speed control methods for DC motors are normally simpler & less expensive than ac motors.

(●) → (Due to commutators, DC motors are not suitable for very high speed applications and require more maintainance than ac motors.)

(1) → Depending on the application, the drives are of fixed speed and some of them variable speed.

(2) → The variable speed drives had various limitations such as poor efficiency, large space, lower speeds etc. However the advent of power electronics we have variable speed drive systems which are not only smaller in size but also very efficient, highly reliable.

(5) DC motors can provide high starting torques which are required for Traction application Ex:- (DC-Series motor) and control over a large speed range, both below and above the rated speed can be easily achieved.

(7) Drawbacks of DC motors :-

(1) It requires reguler maintainance

(2) They are not available for replacements and bulky in size.

(3) Due to the commutator sparking, they are simply not suitable for hazardous areas like chemical & petro chemical plants (or) in mines.

(4) With these limitations DC drive systems unsuitable for energy saving applications of pumps (or) fans.

—x—

(6) → Both series and seperately excited DC motors are normally used in variable speed drives but series motors are traditionally employed for traction applications.

Basic Machine Equations and characteristics of Dc Motor :-

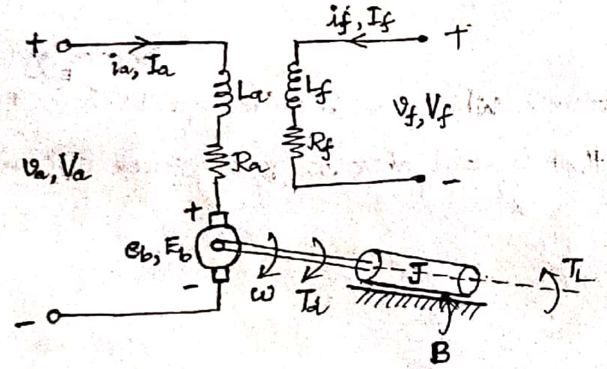
→ The DC machine Consists of a Stationary field winding and Rotating armature winding.

→ The field winding is supplied with a dc current to produce a static magnetic field pattern within the machine. This magnetic field then interacts with the current in armature conductors to produce a torque.

→ In order to sustain this torque the armature current distribution must be maintained relative to the field, irrespective of the actual rotor position. This is achieved by the action of commutator, which reverses the current in the armature conductors as they pass from under one field pole to the next.

→ Also, as the armature conductors are moving through the magnetic field produced by the field winding they have induced in them a back emf (E_b) which appears at the commutator.

Equivalent Circuit of DC Motors :- ⓐ Seperately Excited DC motors :-



The equivalent circuit of a Seperately excited DC motor as shown in fig. When Seperately excited motor is excited by a field current of i_f and an armature current of i_a flows in the armature circuit, the motor develops a back emf and a torque to balance the load torque at a particular speed. The field current i_f of a Seperately excited motor is independent of the armature current i_a and any change in the armature current has no effect on the field current. The field current is normally much Less than the armature current.

The Equations describing the characteristics of a Seperately excited DC motor can be determined from above fig. The instantaneous field current i_f is given by.

$$v_f = i_f R_f + L_f\left(\frac{di_f}{dt}\right)$$

The instantaneous armature current i_a is given by

$$v_a = i_a R_a + L_a\left(\frac{di_a}{dt}\right) + e_b$$

The back emf e_b is also known as Speed Voltage and is expressed as

$$e_b = K_v \,\omega\, i_f$$

The Torque developed by the motor

$$T_d = K_t \, i_f \, i_a$$

also $T_d = J\left(\frac{d\omega}{dt}\right) + B\omega + T_L$

ω = Motor angular speed (Rad/sec) , K_V = Voltage constant $\frac{V}{A \cdot \left(\frac{rad}{sec}\right)}$

B = Viscous friction constant $\frac{N\cdot m}{(Rad/sec)}$, K_t = Torque constant = K_V

T_L = Load Torque (N·m)

Under steady-state conditions, the time derivatives in these equations are zero and the steady state average quantities are

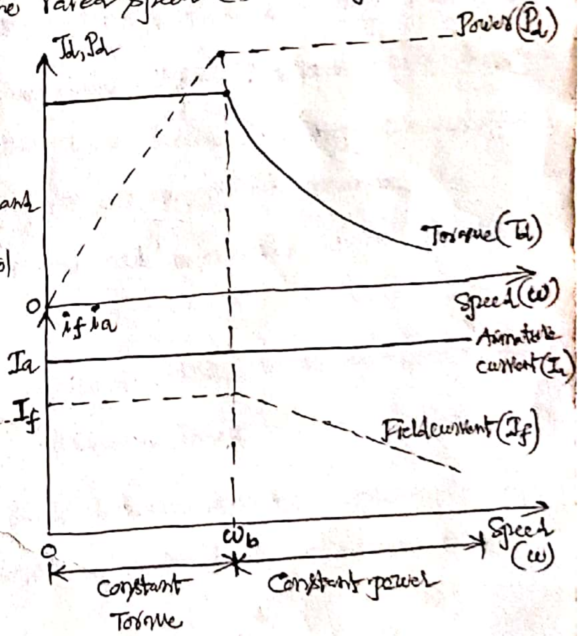
$$V_f = I_f R_f$$
$$V_a = I_a R_a + E_b = I_a R_a + K_V \omega I_f$$
$$E_b = K_V \omega I_f$$
$$T_d = K_t I_f I_a = B\omega + T_L$$

Developed power $(P_d) = T_d \omega$

From the above equation i.e. $V_a = I_a R_a + K_V \omega I_f$

$$\omega = \left(\frac{V_a - I_a R_a}{K_V I_f}\right) \quad \text{where } I_f = \left(\frac{V_f}{R_f}\right)$$

The speed, which corresponding to the rated armature voltage, rated field current, and rated armature current is known as the rated speed (or) Base speed.



In practice, for a speed less than the base speed, the armature current & field currents are maintained constant to meet the torque demand and the armature voltage V_a is varied to control the speed.

For speed higher than the base speed, the armature voltage is maintained at the rated value and the field current is varied (decreased) to control the speed. However, the power developed by the motor ($= T \times \omega$) remains constant.

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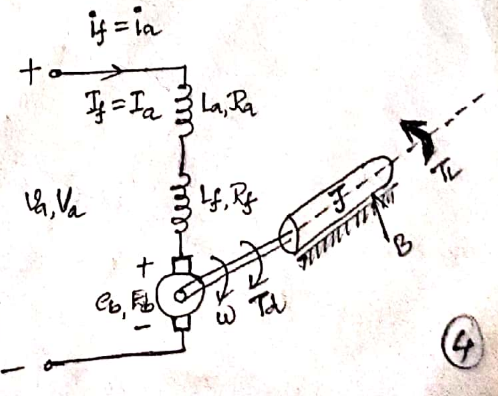
(b) DC Series Motor :-

The field of a dc motor may be connected in series with the armature circuit then the motor is known as a series motor. The field circuit is designed to carry the armature current.



$$E_b = K_V \omega I_a$$

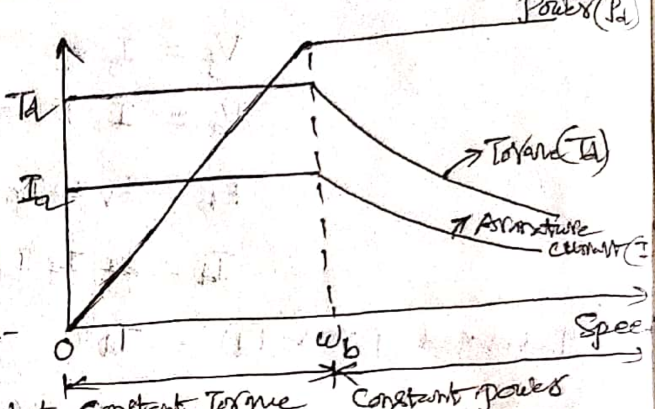
$$V_a = (R_a + R_f) I_a + E_b = (R_a + R_f) I_a + K_V \omega I_a$$

$$T_d = K_t I_a I_f = K_t I_a^2 = B\omega + T_L$$

The speed of a DC series motor is given by $\omega = \left(\frac{V_a - (R_a + R_f) I_a}{K_V I_a}\right)$

From the equation of torque, it is clear that series motor can develops high starting torque and hence DC series motor commonly used in Traction application

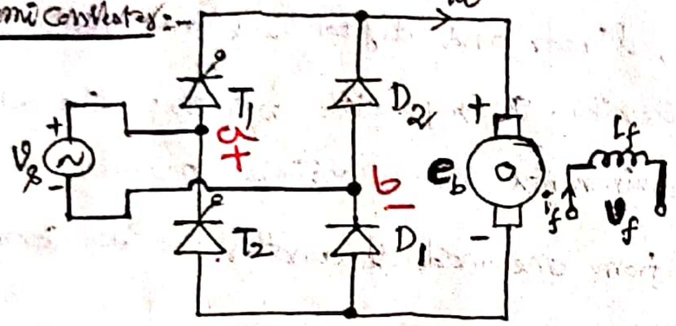
For a speed up to the base speed, The armature voltage is varied and the torque is maintained constant. once the rated armature voltage is applied the speed - Torque relationship follows the natural characteristics of the motor & power ($= T \times \omega$) remains constant.



As the torque demand is reduced, the speed increases. At a very light load, the speed could be very high and it is not advisable to run a DC series motor without a load.

(I) Controlled Rectifier fed DC seperately excited motor Drives: –

(a) Semi converter:–



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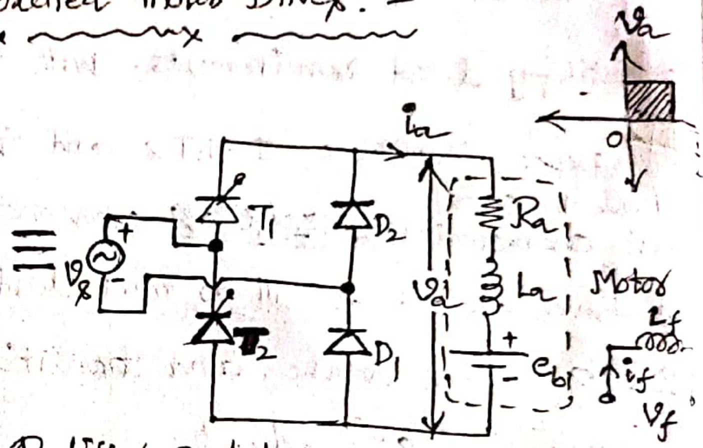


Single phase Half controlled Bridge (Semi) Rectifier Control of DC seperately excited M...

→ Semi-converters are one quadrant converters, that is, they have one polarity of voltage and current at the DC terminals.

→ The armature voltage is controlled by a semiconverter and the field circuit is f... from the ac supply through a diode bridge rectifier.

→ The motor current cannot reverse due to the thyristors in the converters.

→ Due to the semi converter operation, the average output voltage is always positiv...

→ Therefore power flow ($= V_a i_a$) is always positive that's power flow is directed from source to load.

→ So by using semiconverters regeneration (or) reverse power flow is not possible.

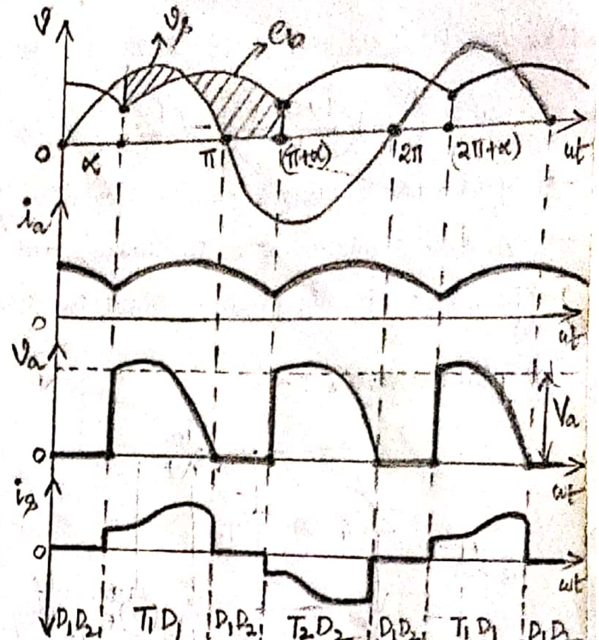
→ The armature current may continuous (or) discontinuous depending on the operating conditions and circuit parameters.

→ In a cycle of source voltage defined by $v_s = V_m \sin\omega t$

D_1, T_1 is conducted from α to π

D_2, T_2 is conducted from $(\alpha+\pi)$ to 2π

→ Motor terminal voltage & current waveforms for continuous conduction mode as shown in fig.



→ For the period $\alpha \le \omega t \le \pi$, the motor is connected to the input supply through T_1 & D_1 and the motor terminal voltage is same as the supply voltage.

→ As the input voltage is reversed after $\omega t = \pi$, V_a becomes ~~negative~~ reversed, and D_2 gets forward biased at π, T_1 is turned off, D_1 is already in forward biased and the energy stored in armature inductance freewheels through the diodes D_1 & D_2. In other words the current freewheels through the diodes D_1 & D_2 and the armature voltage is zero.

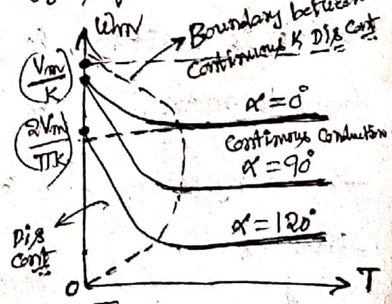
→ At $\omega t = (\pi+\alpha)$, T_2 is triggered and the armature current flows through T_2 & D_2 upto $\omega t = 2\pi$

→ It is clear that from the above discussion,

(i) When the thyristor conducts from α to π, energy is transferred from source to armature circuit. This energy partially stored in inductance, partially stored in the kinetic energy of the moving system and partially used to supply the mechanical load.

(ii) During freewheeling action, (π to $\pi+\alpha$), energy is recovered from the inductance and is converted to mechanical form to supplement the kinetic energy in supplying the mechanical load. The freewheeling armature current continues to produce electromagnetic torque in the motor. During this period, no energy is fed back to the supply.

Torque – Speed characteristics :- (continuous conduction mode)



The armature voltage equations are as follows :

$$v_a = R_a i_a + L_a\left(\frac{di_a}{dt}\right) + e_b = V_m \sin\omega t \quad \alpha \le \omega t \le \pi$$

$$0 = R_a i_a + L_a\left(\frac{di_a}{dt}\right) + e_b \quad \pi \le \omega t \le (\pi+\alpha)$$

Average output voltage $V_a = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t = \frac{V_m}{\pi}\left(-\cos\omega t\right)_{\alpha}^{\pi} = \frac{V_m}{\pi}\left(\cos\alpha - \cos\pi\right)$

$$V_a = \frac{V_m}{\pi}(1+\cos\alpha)$$

The steady-state speed equation is given by

$$\omega = \frac{V_a - I_a R_a}{K_a\phi} = \left(\frac{V_a}{K_a\phi}\right) - \left(\frac{I_a R_a}{K_a\phi}\right) = \left(\frac{V_m}{\pi}\right)\left(\frac{1+\cos\alpha}{K_a\phi}\right) - \frac{R_a T}{(K_a\phi)^2} \quad \left(\because T = K_a\phi I_a\right) \quad \left(I_a = \frac{T}{K_a\phi}\right)$$

no-load speed ($T=0$) is given by $\omega_0 = \frac{V_m}{\pi}\left(\frac{1+\cos\alpha}{K_a\phi}\right)$.

→ In case of shunt and separately excited motors, with a constant field current, the flux can be assumed to be constant, Hence $K_a\phi = K'$(Constant)

$$\omega = \left(\frac{V_m}{\pi}\right)\left(\frac{1+\cos\alpha}{K}\right) - \left(\frac{R_a T}{K^2}\right), \quad \omega_0 = \left(\frac{V_m}{\pi}\right)\left(\frac{1+\cos\alpha}{K}\right)$$

→ Speed - Torque curves are as shown in fig.

→ A 1-ϕ semi converter is cheaper and gives higher power factor compared to 1-ϕ fully controlled rectifier. But it only provides control in Quadrant - I.

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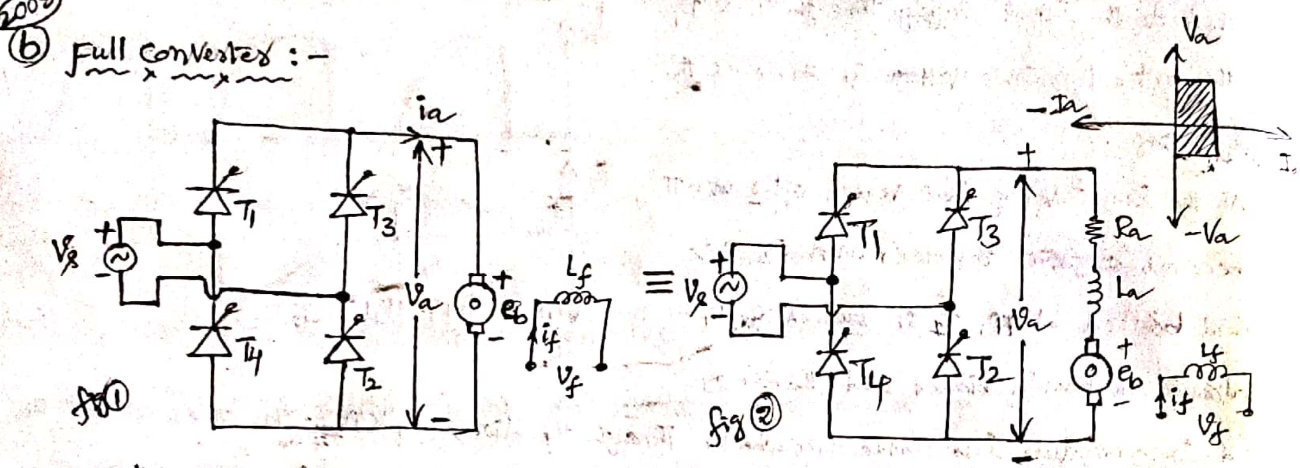
(b) Full Converter :-



→ Full converter is a two quadrant converter (I & IV) in which the voltage polarity of the output can reverse, but the current remains in unidirectional because thyristors doesn't allows the current in reverse direction through them.

→ The armature voltage is controlled by full converter and the field current is (controlled) supplied by diode bridge rectifier.

→ The motor current cannot reverse due to thyristors in the circuits.

→ When the converter operates in Quadrant - I, both voltage & current are positive, so power flow ($=V_a I_a$) is positive, Hence power is delivered from ac source to dc motor load.

→ When the converter operates in Quadrant - IV, voltage is negative but current is positive, so power flow ($=V_a i_a$) is negative, Hence power is delivered from dc motor load to ac source.

→ So by using full converter, power flow is possible in both forward & reverse directions.

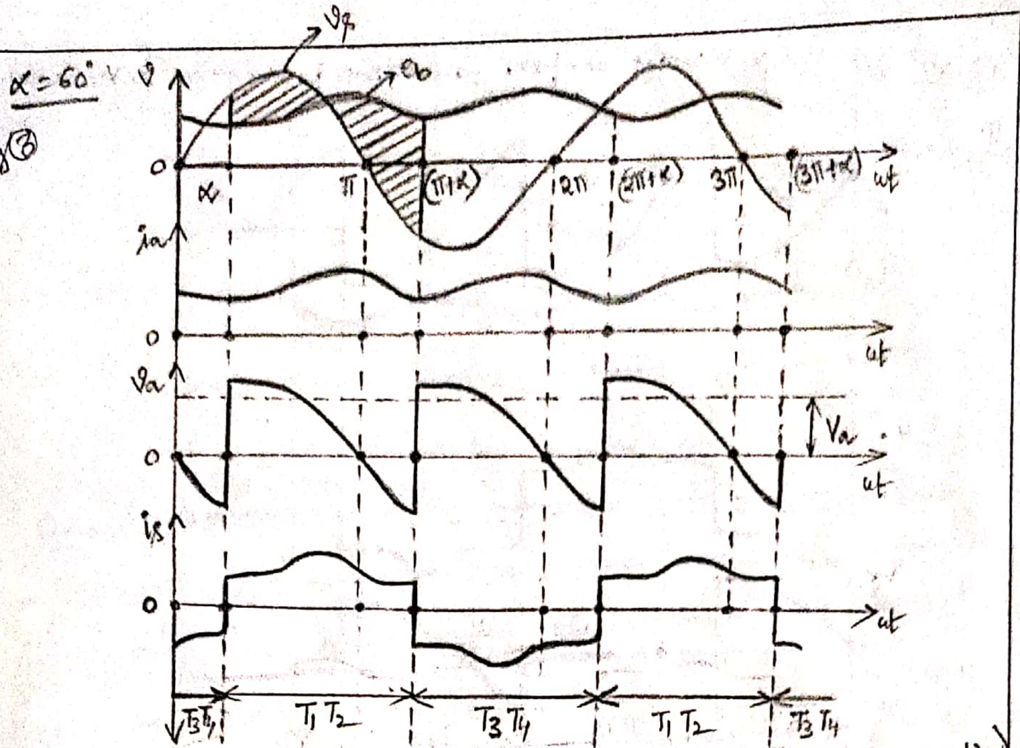
→ The armature current may continuous (or) discontinuous depending on the operating conditions and circuit parameters.

→ In a cycle of source voltage defined by $v_s = V_m \sin\omega t$

T_1, T_2 are conducted from α to $(\pi+\alpha)$

T_3, T_4 are conducted from $(\pi+\alpha)$ to $(2\pi+\alpha)$

fig ③



· Voltage & current waveforms for continuous conduction (Motoring operation)

→ As thyristors T_1 and T_2 are conducted from α to $(\pi+\alpha)$, the motor is connected to the supply, and the current is transferred from source to armature circuit of the motor.

→ At $\omega t = (\pi+\alpha)$ T_3 and T_4 are conducted and T_1, T_2 are turned off due to the reverse voltage appear across the thyristors T_1 and T_2 but the current is remains flow in the same direction for the negative supply voltage across the motor terminals.

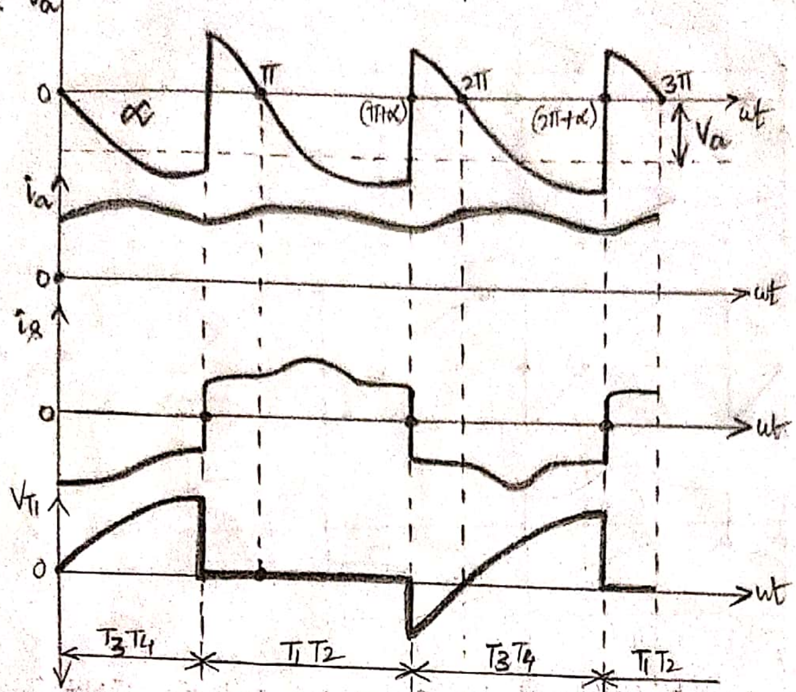
→ During α to π, voltage is positive and current is positive and hence the energy flows from the supply to the motor.

→ During π to $(\pi+\alpha)$, voltage is negative but current is positive and hence some of the motor energy is transferred to the supply system.

→ The voltage and current waveforms for firing angle greater than 90°, are shown in below fig. The average output voltage V_a is now negative. If the motor back emf e_b is reversed, the motor will behave as a DC generator and the power is fed back to the supply. This is known as inversion operation and is used in regenerative braking of the motor.

$\alpha = 135^\circ$ Voltage & current waveforms for continuous conduction (Inversion Mode)

fig (4)



Torque - Speed characteristics :- (Continuous conduction Mode)

→ The average output voltage of the converter is given by

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t \, d\omega t = \frac{1}{\pi}(V_m)\left(-\cos\omega t\right)_{\alpha}^{\pi+\alpha} = \left(\frac{-V_m}{\pi}\right)\left(\cos\omega t\right)_{\alpha}^{\pi+\alpha}$$

$$V_a = \left(\frac{-V_m}{\pi}\right)\left[\cos(\pi+\alpha) - \cos\alpha\right] = \left(\frac{-V_m}{\pi}\right)\left(-\cos\alpha - \cos\alpha\right) = \left(\frac{2V_m}{\pi}\right)\cos\alpha$$

→ The Armature Voltage equations are expressed as follows.

$$V_a = V_m \sin\omega t = i_a R_a + L_a\left(\frac{di_a}{dt}\right) + e_b \qquad \alpha \le \omega t \le \pi$$

$$V_a = -V_m \sin\omega t = i_a R_a + L_a\left(\frac{di_a}{dt}\right) + e_b \qquad \pi \le \omega t \le (\pi+\alpha)$$

$$V_a = V_m \sin\omega t = i_a R_a + L_a\left(\frac{di_a}{dt}\right) + e_b \qquad (\pi+\alpha) \le \omega t \le 2\pi$$

$$V_a = -V_m \sin\omega t = i_a R_a + L_a\left(\frac{di_a}{dt}\right) + e_b \qquad 2\pi \le \omega t \le (2\pi+\alpha) \ldots$$

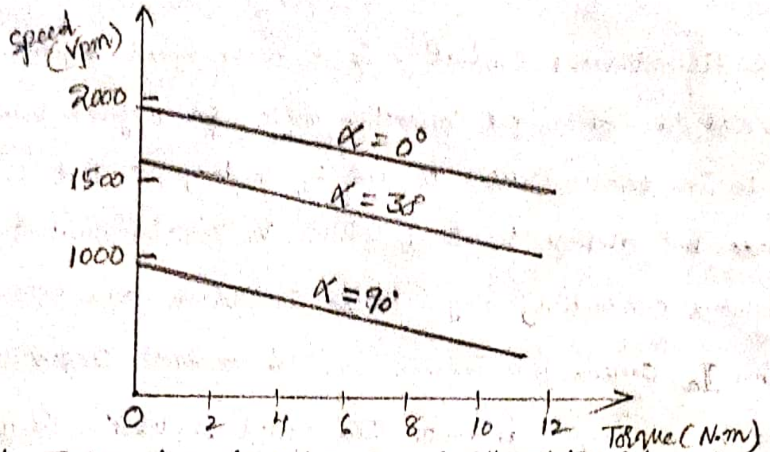
→ The steady-state speed equation is given by

$$\omega = \frac{V_a - I_a R_a}{K_a\phi} = \frac{\left(\frac{2V_m}{\pi}\right)\cos\alpha - I_a R_a}{K_a\phi} = \left(\frac{2V_m}{\pi}\right)\left(\frac{\cos\alpha}{K}\right) - \left(\frac{R_a T}{K^2}\right) \quad -(1)$$

→ no-load speed of the motor is given by

$$\omega_0 = \left(\frac{2V_m}{\pi}\right)\left(\frac{\cos\alpha}{K}\right) \quad (\because T = 0)$$

where $K = K_a\phi$ ($\because$ for shunt & seperately excited DC motors flux ϕ = constant for constant field current) fig ⑤



Speed – Torque characteristics of 1-ϕ full converter fed DC seperately excited Motor.

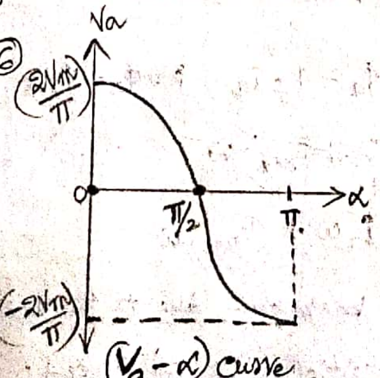
→ In continuous conduction, the speed – Torque characteristics are parallel straight lines, whose slope, according to ① depends on the armature circuit resistance R_a.

→ It is clear that from the average output voltage expression (Average a_v voltage), As the 'α' varies its magnitude also varies. When working in Quadrant – I ω is positive for $\alpha \leq 90°$, and polarities of V_a & E_b are shown in below figure.

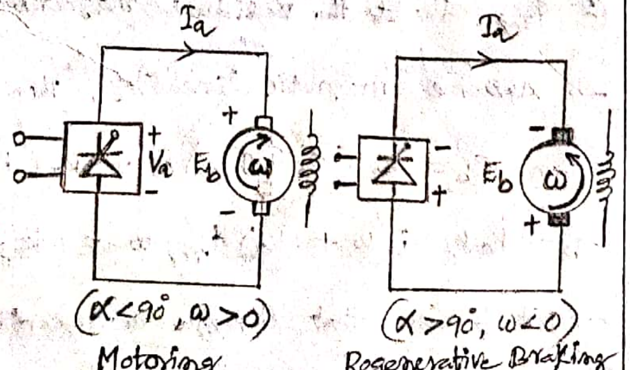
→ If the polarity of I_a is positive will results in rectifier to deliver power and the motor to consume it; thus giving forward motoring.

→ polarities of E_b, I_a and V_a for operation in Quadrant-IV is shown in figure ⑥. As the armature voltage V_a is reversed, speed is reversed and hence E_b gets reversed. The armature current is given by $I_a = \left(\frac{V + E_b}{R_a}\right)$, and hence machine is working as a generator, and produces braking torque.

fig ⑥



$(V_a - \alpha)$ curve



→ Two Quadrant operation capability of the drive can be utilized only with overhauling loads (or) other active loads which can drive the motor in reverse direction.

Note :-

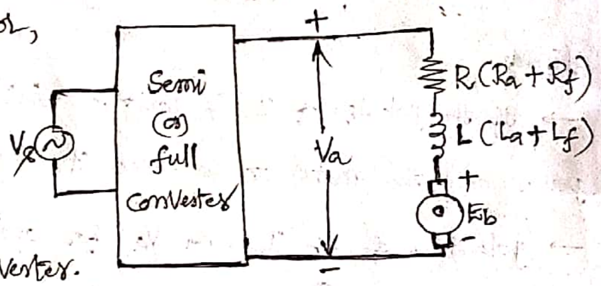
→ Effect of discontinuous conduction is to make speed regulation poor. because in case of continuous conduction mode, for a given value of α any increase in torque causes ω and E_b to drop, so that I_a and T can increase but average terminal voltage V_a remains constant. In case of discontinuous conduction, any increase in torque and accompanied increase in I_a causes β to increase and V_a to drop. Consequently speed drops by a larger amount. Thus speed regulation is poor.

(II) Controlled Rectifier fed DC series motor Drives :-

→ 1-ϕ controlled rectifier fed DC series motors are employed in traction applications, such as cranes, hoists, elevators, vehicles etc.

→ Speed control of DC series motor is difficult, because any change in the load current will immediately be reflected in a speed change.

→ consider the DC series motor, the field circuit is in series with armature circuit. The motor terminal voltage is controlled by semi (or) full converter.



→ Back emf is expressed by $e_b = K_a \phi \omega$

where ϕ = flux, it has two components viz:

① ϕ_a, produced by the armature current.

② ϕ_{res}, due to the residual magnetism, and is assumed to be constant

→ Assume magnetic linearity, then $\phi_a = K_f i_a$, $\phi = \phi_a + \phi_{res}$

then $e_b = K_a(\phi_a + \phi_{res})\omega = K_a(K_f i_a + \phi_{res})\omega$

$e_b = (K_a K_f) i_a \omega + (K_a)\phi_{res}\omega = (K_{af}) i_a \omega + (K_{res})\omega$

→ It is clear that $(K_{res})\omega$ represents back emf due to the residual magnetism, and is small, proportional to the speed.

→ The back emf due to the flux produced by the armature current is the major voltage.

→ Average back emf is given by

$$E_b = K_{af}\, I_a\, \omega + K_{res}\, \omega$$

→ Torque developed by the motor $T = K_a \phi I_a$, ϕ_{res} neglected then

$$T = K_a (K_f I_a) I_a = K_{af} I_a^2$$

→ It is clear that from the torque expression, Torque is developed in the same direction for either direction of current. So speed is reversed is achieved by reversing the field winding (or) the armature terminals.

→ Average developed torque is given by

$$T = K_{af} I_{ar}^2 \quad (I_a = \text{Average armature current}) \; (I_{ar} = \text{RMS current})$$

→ Voltage equation of the armature circuit is given by

$$V_a = (R_a + R_f)\, i_a + (L_a + L_f)\left(\frac{di_a}{dt}\right) + e_b$$

$$V_a = R i_a + L\left(\frac{di_a}{dt}\right) + e_b$$

→ Average armature Voltage is given by

$$V_a = R I_a + E_b = R I_a + K_{af} I_a \omega + K_{res} \omega$$

$$I_a = \frac{(V_a - K_{res}\omega)}{(R + K_{af}\omega)}, \quad T \simeq K_{af}\left(\frac{V_a - K_{res}\omega}{R + K_{af}\omega}\right)^2$$

2008 (a) 1-φ Semi converter Drives:-

→ In case of series motor drive, the current is flows through the armature and field at $\omega t = \alpha$, and is continuous upto $(\pi + \alpha)$.

→ fig (a) shows the power circuit for a speed control of a dc series motor by a 1-φ semi converter, and corresponding current, voltage waveforms are shown in fig (b).

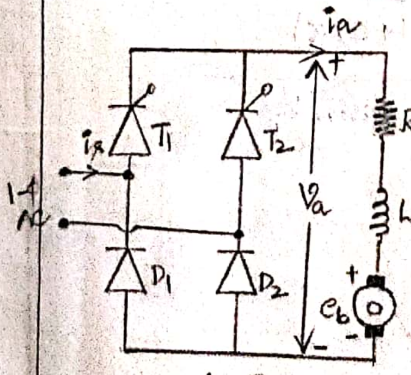


fig (a)

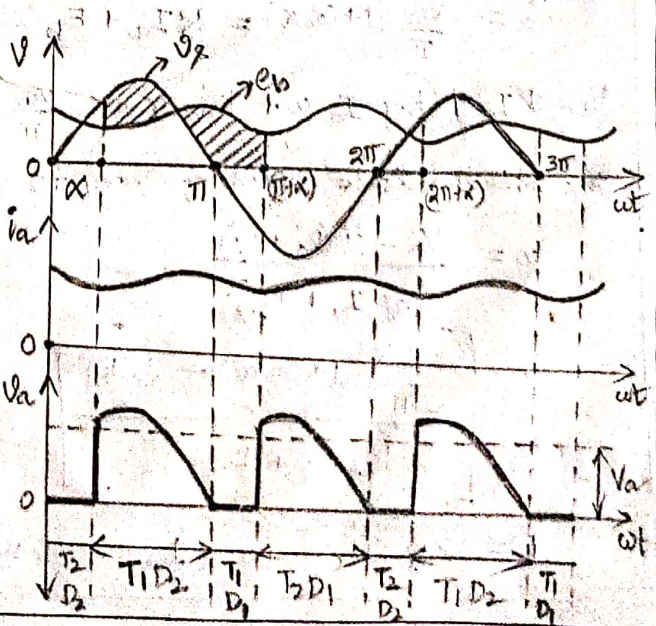


fig (b)

→ In case of seperately excited DC motors, a large back emf E_b is always present, even when the motor armature current is zero. The back emf E_b tends to oppose the armature current and hence the motor current decays rapidly. This leads to discontinuous motor current over a wide range of operation.

→ In case of DC series motors, The back emf is proportional to the motor current (Speed is assumed constant and back emf due to residual flux is very small), Therefore, the back emf decreases as the motor current decreases and hence the motor current tends to be ~~constant~~. continuous. But in case of seperately excited DC motors, 'E_b' stays constant and accelerates decay of 'i_a'

→ It is clear that motor current is continuous over a wide range of operation in DC series motor drives.

→ At high speed and low current motor current becomes discontinuous.

Torque - Speed characteristics :- (Continuous Conduction mode)

The armature voltage equations are given by

$$V_a = i_a(R_a + R_f) + (L_a + L_f)\left(\frac{di_a}{dt}\right) + e_b = V_m \sin\omega t \quad (\alpha \le \omega t \le \pi)$$

$$0 = i_a(R_a + R_f) + (L_a + L_f)\left(\frac{di_a}{dt}\right) + e_b \quad (\pi \le \omega t \le \pi + \alpha)$$

The average output voltage is given by

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t = \frac{V_m}{\pi}(-\cos\omega t)_{\alpha}^{\pi} = \frac{V_m}{\pi}(\cos\alpha - \cos\pi)$$

$$V_a = \frac{V_m}{\pi}(1 + \cos\alpha) = RI_a + E_b$$

$$V_a = RI_a + (K_{af} I_a \omega + K_{res}\omega) = \frac{V_m}{\pi}(1 + \cos\alpha)$$

The steady-state speed of the motor is given by

$$\omega = \frac{V_a - I_a(R_a + R_f)}{(K_{af} I_a + K_{res})}$$

$$\omega = \left[\frac{\left(\frac{V_m}{\pi}\right)(1 + \cos\alpha) - I_a R}{(K_{af} I_a + K_{res})}\right]$$

$$T = K_{af} I_{ar}^2 \quad (I_{ar} = \text{RMS value of armature current})$$

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$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t = \frac{V_m}{\pi}(-\cos\omega t)_{\alpha}^{\pi} = \frac{V_m}{\pi}(\cos\alpha - \cos\pi)$$

$$V_a = \frac{V_m}{\pi}(1+\cos\alpha) = RI_a + E_b$$

$$V_a = RI_a + (K_{af}\, I_a\, \omega + K_{res}\, \omega) = \frac{V_m}{\pi}(1+\cos\alpha)$$

The steady-state speed of the motor is given by

$$\omega = \frac{V_a - I_a(R_a+R_f)}{(K_{af}\, I_a + K_{res})}$$

$$\omega = \left[\frac{\left(\frac{V_m}{\pi}\right)(1+\cos\alpha) - I_a R}{(K_{af}\, I_a + K_{res})}\right]$$

$$T = K_{af}\, I_{ar}^2 \quad (I_{ar} = \text{RMS value of armature current})$$

→ We know that, the torque developed by the DC series motor is proportional to the square of the motor current.

→ If the ripple in the motor current can be neglected, then $I_a \approx I_{av}$

Then $T = K_{af} I_{av}^2 \approx K_{af} I_a^2$

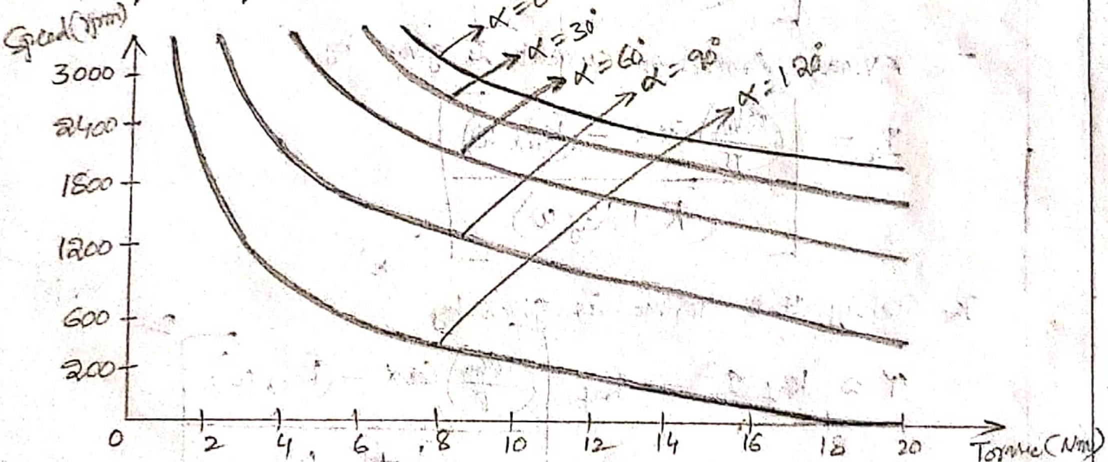
→ Average armature current is given by

$$V_a = (R I_a + K_{af}\,\omega I_a) + K_{res}\,\omega$$

$$I_a = \frac{(V_a - K_{res}\,\omega)}{(R + K_{af}\,\omega)} = \left[\frac{\left(\frac{V_m}{\pi}\right)(\cos\alpha + 1) - K_{res}\,\omega}{(R + K_{af}\,\omega)}\right]$$

$$T \approx K_{af}\left[\frac{\left(\frac{V_m}{\pi}\right)(1+\cos\alpha) - K_{res}\,\omega}{(R + K_{af}\,\omega)}\right]^2$$

→ The torque – speed characteristics under the assumption of continuous and ripple free current can be obtained by the above equation for different values of the firing angle.



ⓑ 1-Φ full converter drives: –

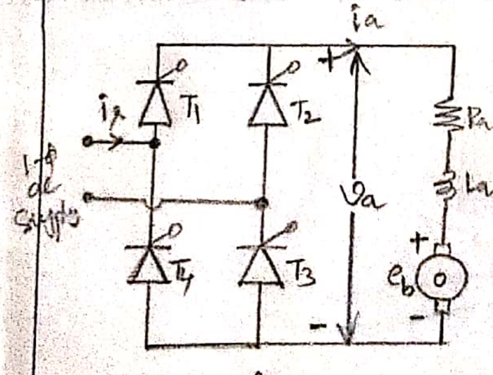


fig ⓐ

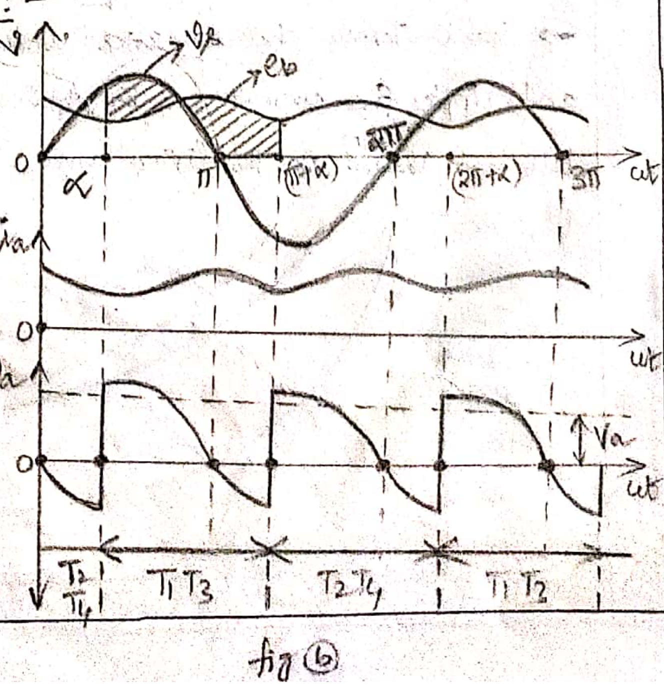


fig ⓑ

→ power circuit of a 1-ϕ full converter fed series motor shown in fig ⓐ and corresponding voltage and current waveforms shown in fig ⓑ.

→ T_1, T_2 are triggered at $\omega t = \alpha$ and remains in conduction upto $\omega t = (\pi+\alpha)$

→ T_3, T_4 are triggered at $\omega t = (\pi+\alpha)$ and remains in conduction upto $\omega t = (2\pi+\alpha)$

Speed - Torque characteristics :- (Continuous current Mode)

→ The average output voltage is given by

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t = \left(\frac{V_m}{\pi}\right)\left(-\cos\omega t\right)_{\alpha}^{\pi+\alpha} = \frac{V_m}{\pi}\left[\cos\alpha - \cos(\pi+\alpha)\right]$$

$$\rightarrow V_a = \left(\frac{V_m}{\pi}\right)\left(\cos\alpha + \cos\alpha\right) = \left(\frac{2V_m}{\pi}\right)\cos\alpha = \left(R I_a + K_{af} I_a \omega\right) + K_{res}\,\omega$$

The steady-state speed is given by

$$\omega = \left[\frac{\left(\frac{2V_m}{\pi}\right)\cos\alpha - (R I_a)}{(K_{af} I_a + K_{res})}\right]$$

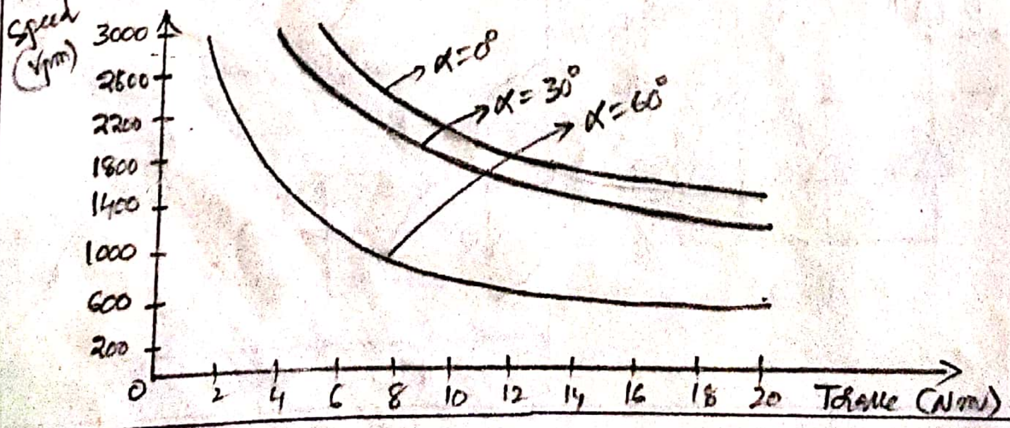
The Average Armature current is given by

$$I_a = \left[\frac{\left(\frac{2V_m}{\pi}\right)\cos\alpha - (K_{res}\,\omega)}{(R + K_{af}\,\omega)}\right]$$

The Steady State Torque is given by

$$\tau \approx K_{af} I_a^2 = K_{af}\left[\frac{\left(\frac{2V_m}{\pi}\right)\cos\alpha - (K_{res}\,\omega)}{(R + K_{af}\,\omega)}\right]^2$$

→ Speed - Torque characteristics under the assumption of continuous and ripple free current can be obtained from the above equation for different values of the firing angle.



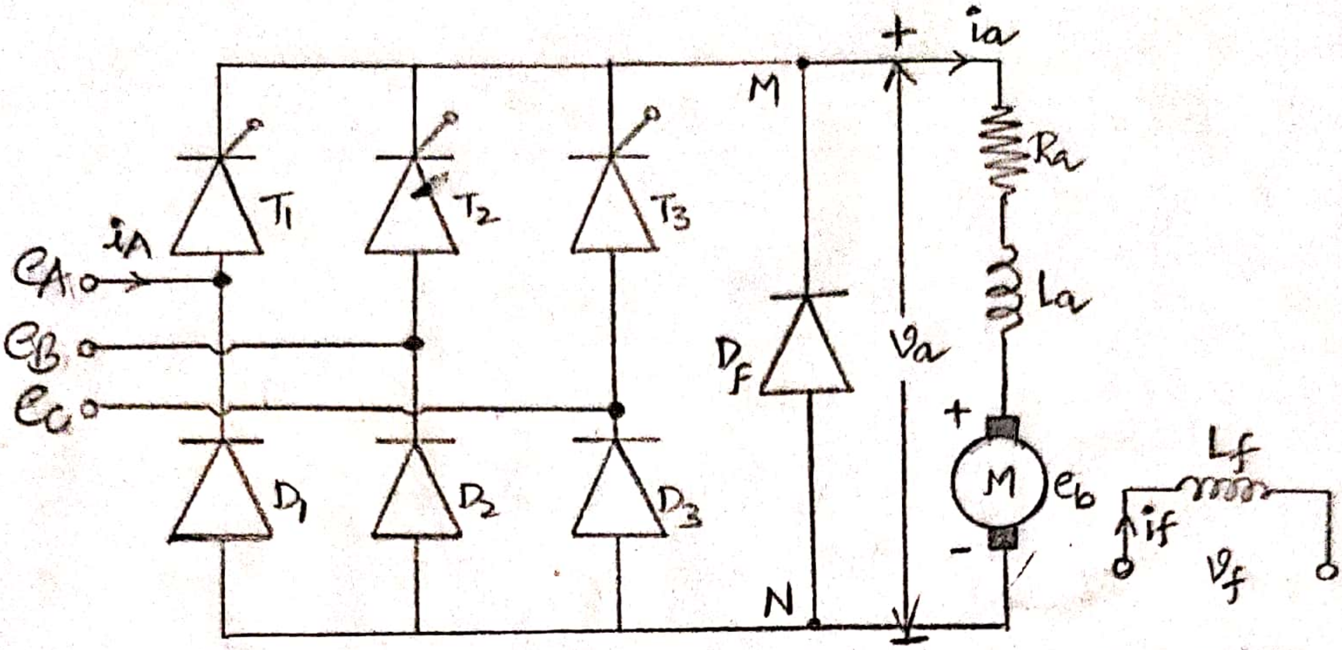


fig ① ⓐ 3-ϕ Semiconverter fed DC Sp. excited Motor.

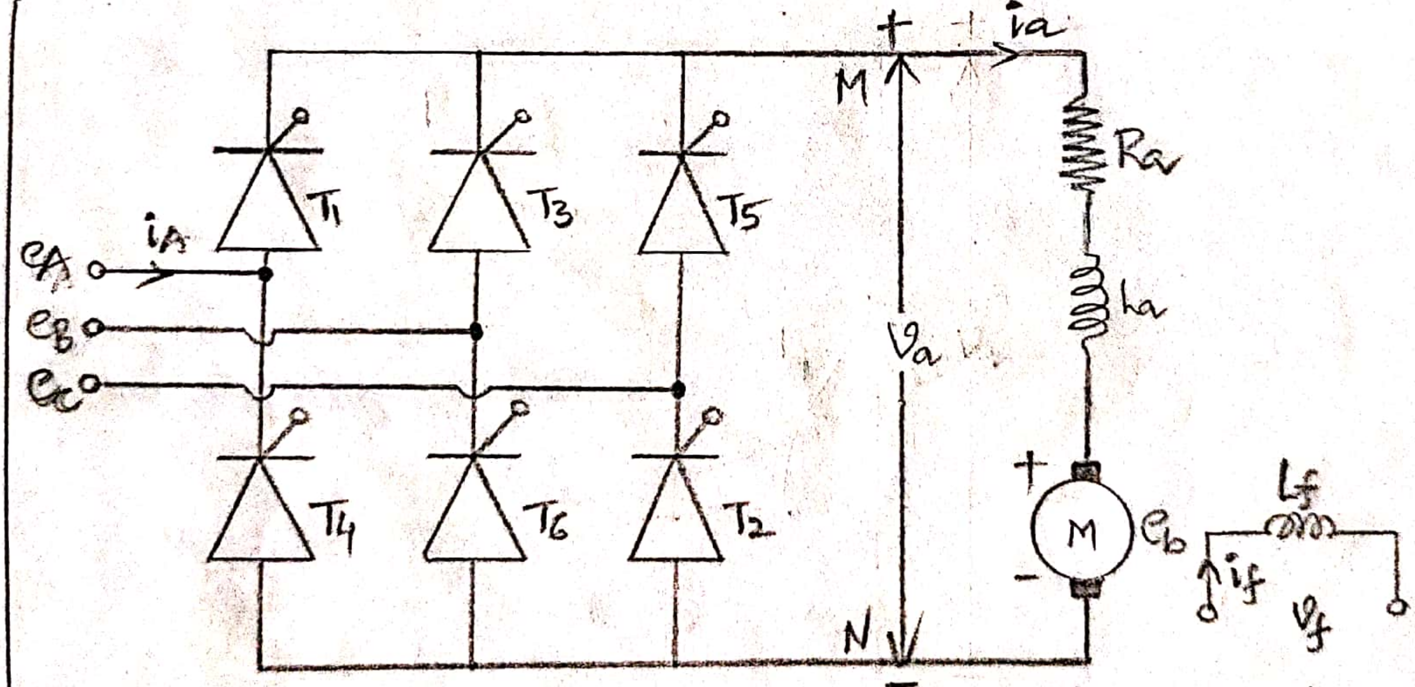


fig ② ⓐ 3-ϕ full Converter fed DC Seperately excited Motor.

Unit - II

Control of DC Motors by 3-ϕ Converters

(I) Introduction :-

→ 3-ϕ drives are used for high power applications.

→ 3-ϕ drives are better compared to 1-ϕ drives because

① The output ripple is small

② The ripple frequency is large, hence less inductance is required.

③ Filtering requirement is less.

④ In a 3-ϕ drives, the armature current is mostly continuous and hence the motor performance is better compared to that of 1-ϕ drives.

(I) Controlled Rectifier fed DC Seperately Excited Motor Drives :-

(a) Semi converters :-

→ The power circuit of 3-ϕ Semi converter fed DC seperately excited motor is shown in fig①ⓐ, corresponding current, Voltage waveforms are as shown in fig①ⓑ.

→ It is a one-quadrant drive and is limited to applications in the range of 15–150 Hp. The field converter may be a 1-ϕ (or) 3-ϕ Semi converter.

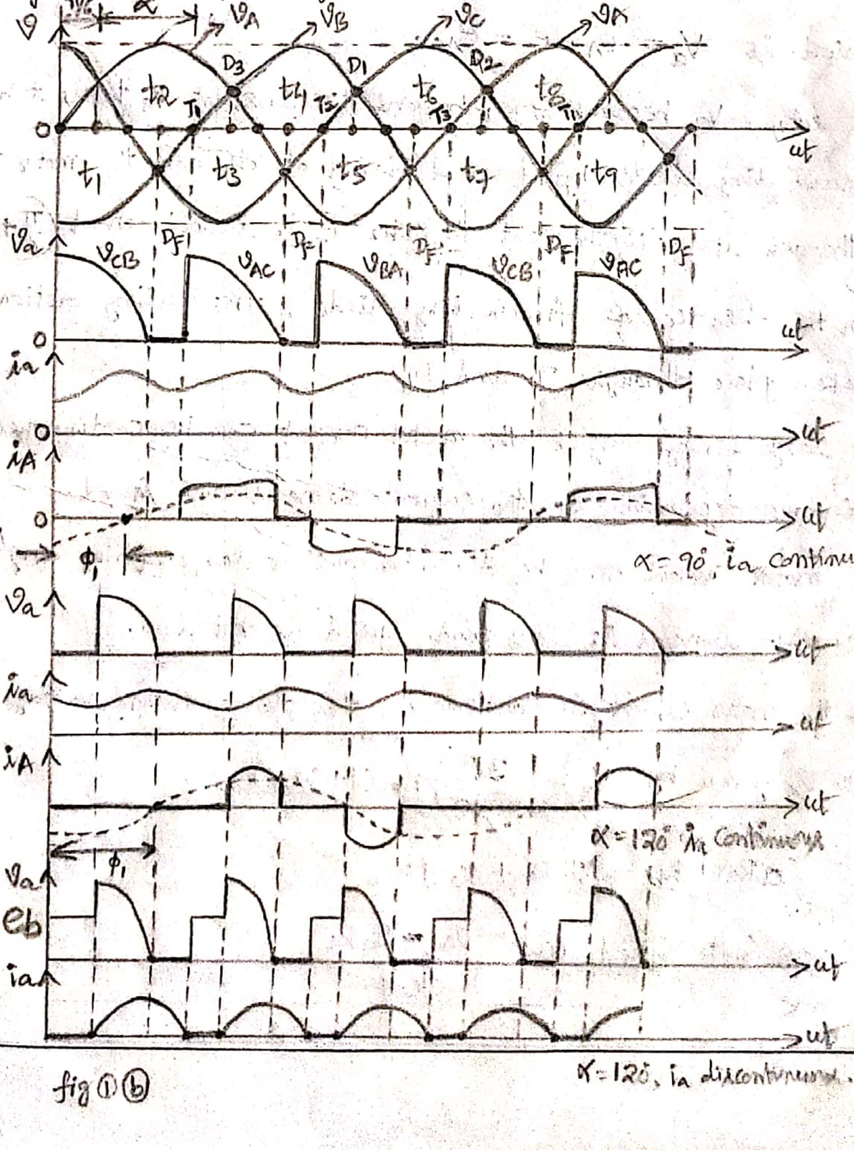


fig ①ⓑ

→ The conduction periods of Thyristors & Diodes as shown in fig(b).

→ The Diodes D_1, D_2 and D_3 conducting during the intervals t_4 to t_6, t_6 to t_8, and t_2 to t_4 respectively.

→ The triggering angles for T_1, T_2 and T_3 are the instants t_1, t_3 and t_5 respectively. These are the crossing points of the phase voltages e_A, e_B and e_C respectively.

→ In case of 3-ϕ (phase) converters SCRs are triggered for 120°, whereas in case of 1-ϕ converters SCRs are conducted for 180°; Hence Thyristors are switched faster in 3-ϕ converters and hence the time available for any current decay is less compared to the 1-ϕ case. As a result, the motor current becomes continuous.

→ From fig(b), thyristor T_1 and diode D_3 conduct during the interval $\left(\frac{\pi}{6}+\alpha\right) \leq \omega t \leq \omega t_4$. Hence The motor terminal M connected to e_A and terminal N connected to e_C. The motor terminal voltage during this period is $V_a = e_A - e_C = e_{AC}$.

→ At ωt_4, V_a becomes zero, beyond this instant V_a tends to be "−Ve" and freewheeling diode D_F forward biased at ωt_4 and the motor current flows through it until the next thyristor T_2 is turned-on at $\left(\frac{\pi}{6}+\alpha+\frac{2\pi}{3}\right)$.

→ In the absence of freewheeling diode, freewheeling action would have taken place through T_1 and D_1.

→ At large firing angles the motor current can be continuous (or) discontinuous depending on the current demand and speed.

→ The motor current may be discontinuous at large firing angles if the current demand is low and speed is not low.

→ If the motor current is continuous, then the armature voltage of the motor is given by $V_a = \left(\frac{3\sqrt{3}}{2\pi}\right) E_m (1+\cos\alpha)$

→ $V_a = I_a R_a + E_b = I_a R_a + K_a \phi \omega$

The steady state speed $\omega = \dfrac{V_a - I_a R_a}{K_a \phi}$

$$\omega = \left[\frac{\left(\frac{3\sqrt{3}}{2\pi}\right) E_m(1+\cos\alpha)}{K_a\phi} - \frac{R_a T}{(K_a\phi)^2} \right]$$

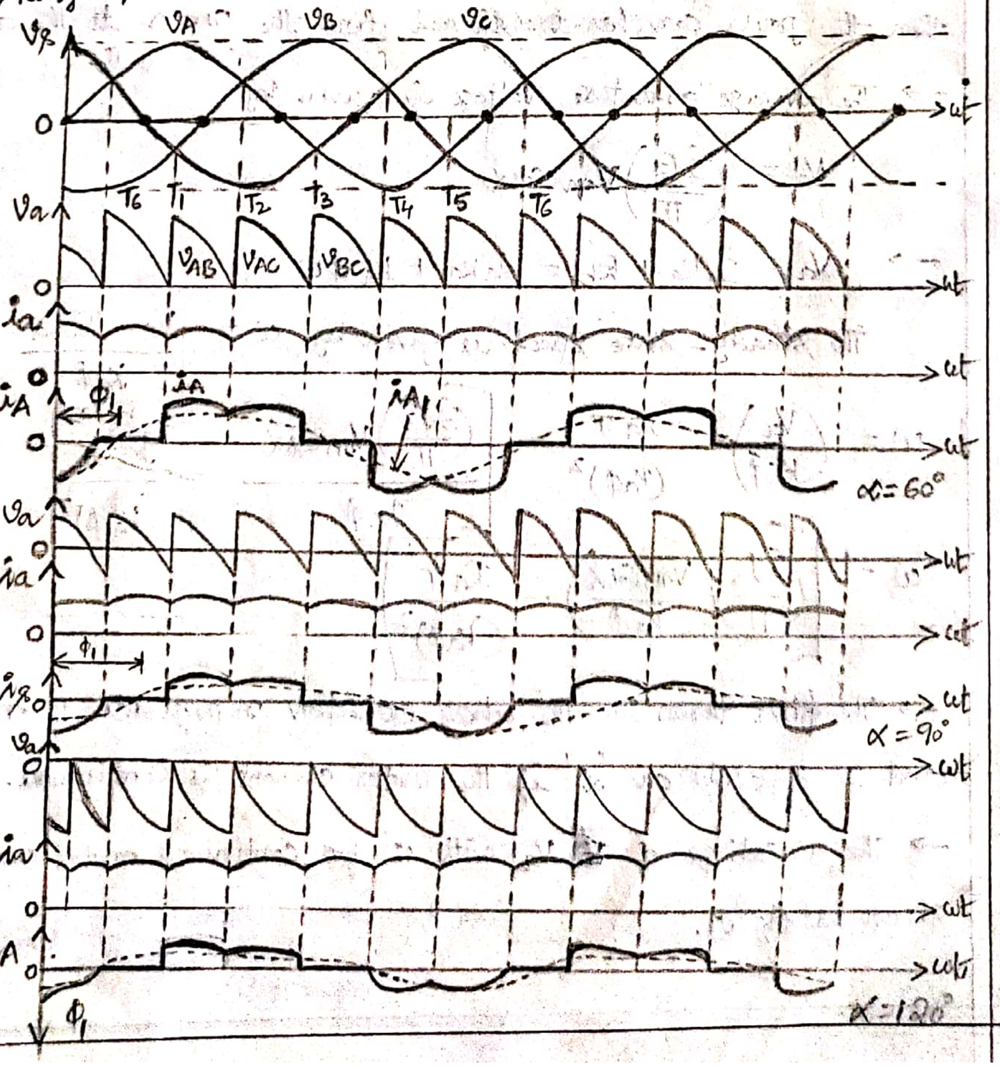
$$\omega = \left[\left(\frac{3\sqrt{2}}{2\pi}\right)\left(\frac{E_m(\cos\alpha+1)}{K_a\phi}\right) - \frac{R_a T}{(K_a\phi)^2} \right]$$

→ The fundamental component of the input current is also shown in fig (b). The displacement angle ϕ_1 increases as the firing angle increases. Thus the input powerfactor will decrease as the firing angle increases.

(b) Full converter :-

→ fig (a) shows the power circuit of a 3-φ full converter fed DC seperately excited motor. Corresponding voltage and current waveforms are shown in fig (b).

→ It is a two-quadrant drive, and is limited to the applications in the range of 100-150 Hp.



the thyristors are fired at an angle

→ In case of 3-φ full converters, the motor terminal voltage is six pulses per cycle.

of 60° and the ripple in the motor terminal voltage is

→ As the SCRs are triggered at a fast rate, the motor current is

mostly continuous. Therefore, the filtering requirement is less than that in

the semi converter system.

→ Thyristor T_1 turned-on at $\omega t = \left(\frac{\pi}{6} + \alpha\right)$. prior to this instant,

T_6 was turned-ON. Therefore during the interval $\left(\frac{\pi}{6} + \alpha\right) \le \omega t \le \left(\frac{\pi}{6} + \alpha + \frac{\pi}{3}\right)$

thyristors T_1 & T_6 conducts. The terminal voltage during this instant is

$V_a = V_A - V_B = V_{AB}$.

→ Thyristor T_2 is triggered at $\left(\frac{\pi}{6} + \alpha + \frac{\pi}{3}\right)$ and immediatly T_6 is Reverse

biased and turned-off, Then the current is transfered from T_6 to

T_2, then the motor is connected to A and C phases and hence the

terminal voltage during this instant is $V_a = V_A - V_C = V_{AC}$.

→ For the firing angle $\alpha = 120°$, the motor terminal voltage

becomes negative. This is the inversion operation of the converter.

then the power can be transferred from the motor to the ac supply.

→ The average armature voltage is given by

$$V_a = \left(\frac{3\sqrt{3}}{\pi}\right) V_m \cos\alpha$$

→ $$V_a = I_a R_a + E_b = I_a R_a + K_a \phi \omega$$

The steady-state speed is given by $\omega = \dfrac{V_a - I_a R_a}{K_a \phi}$

$$\omega = \left(\frac{V_a}{K_a \phi}\right) - \frac{R_a T}{(K_a \phi)^2} = \left[\frac{\left(\frac{3\sqrt{3}}{\pi}\right) V_m \cos\alpha}{K_a \phi} - \frac{R_a T}{(K_a \phi)^2}\right]$$

$$\omega = \left[\left(\frac{3\sqrt{3}}{\pi}\right)\left(\frac{V_m \cos\alpha}{K_a \phi}\right) - \frac{R_a T}{(K_a \phi)^2}\right]$$

→ The first term in the above equation represents the no-load speed

and is depends on 'α' if the motor current is continuous.

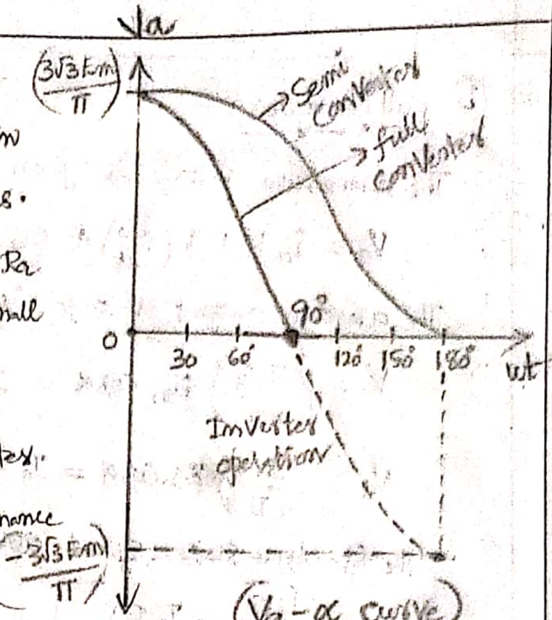
→ The variations of [illegible] V_a with 'α' for continuous motor current are

shown in fig ©.

→ The second term in the above equation represents the decrease in speed as the motor torque increases.

→ Since the armature resistance R_a is small, the decrease in speed is small ie good speed regulation.

→ In fact, 3-φ drives provide better speed regulation and improved performance compared to 1-φ drives.



($V_a - \alpha$ curve)

2008

(II) Controlled rectifier fed DC series Motor Drives :-

(a) Semiconverter :-

The armature voltage equations are given by

$$V_a = i_a R + L\left(\frac{di_a}{dt}\right) + e_b$$

The average output voltage is given by

$$V_a = \left(\frac{3\sqrt{3}}{2\pi}\right) E_m\left(1+\cos\alpha\right) = R I_a + \left(K_{af} I_a \omega + K_{res}\,\omega\right)$$

The steady state speed of the motor is given by

$$\omega = \frac{V_a - I_a R}{\left(K_{af} I_a + K_{res}\right)} = \left[\frac{\left(\frac{3\sqrt{3}}{2\pi}\right) E_m(1+\cos\alpha) - I_a R}{\left(K_{af} I_a + K_{res}\right)}\right]$$

$$T = K_{af} I_{ar}^2 \quad (I_{ar} = \text{RMS value of ar current})$$

If the ripple in the motor current can be neglected, $I_a \approx I_{ar}$

$$T \approx K_{af} I_a^2$$

$$V_a = R I_a + K_{af}\,\omega I_a + K_{res}\,\omega$$

$$I_a = \frac{\left(V_a - K_{res}\omega\right)}{\left(R + K_{af}\omega\right)}$$

$$I_a = \left[\frac{\left(\frac{3\sqrt{3}}{2\pi}\right) E_m(1+\cos\alpha) - K_{res}\,\omega}{\left(R + K_{af}\omega\right)}\right]$$

$$T \approx K_{af}\left[\frac{\left(\frac{3\sqrt{3}}{2\pi}\right) E_m(1+\cos\alpha) - K_{res}\,\omega}{\left(R + K_{af}\omega\right)}\right]^2$$

(2008) (b) Full converter :-

The armature voltage is given by

$$V_a = i_a R + L\left(\frac{di_a}{dt}\right) + e_b$$

The average output voltage is given by

$$V_a = \left(\frac{3\sqrt{3}}{\pi}\right) E_m \cos\alpha = I_a R + E_b$$

$$V_a = \left(\frac{3\sqrt{3}}{\pi}\right) E_m \cos\alpha = I_a R + \left(K_{af} I_a \omega + K_{res} \omega\right)$$

The steady-state speed equation is given by

$$\omega = \left[\frac{(V_a - I_a R)}{(K_{af} I_a + K_{res})}\right] = \left[\frac{\left(\frac{3\sqrt{3}}{\pi}\right) E_m \cos\alpha - I_a R}{(K_{af} I_a + K_{res})}\right]$$

$$T \approx K_{af} I_a^2$$

$$I_a = \left[\frac{(V_a - K_{res}\,\omega)}{(R + K_{af}\,\omega)}\right] = \left[\frac{\left(\frac{3\sqrt{3}}{\pi}\right) E_m \cos\alpha - K_{res}\,\omega}{(R + K_{af}\,\omega)}\right]$$

$$T \approx K_{af} \left[\frac{\left(\frac{3\sqrt{3}}{\pi}\right) E_m \cos\alpha - K_{res}\,\omega}{R + K_{af}\,\omega}\right]^2$$

Note :-

Semiconverter :-

① For firing angle $\alpha \leq 60^\circ$, each thyristor conducts for 120°

② For $60^\circ < \alpha < 180^\circ$ each thyristor conducts for $(180^\circ - \alpha)$

③ Freewheeling diode comes into conduction only when firing angle more than 60° $(\alpha > 60^\circ)$

④ Freewheeling diode conducts for $(\alpha - 60^\circ)$ in case load current is continuous.

⑤ conduction angle of thyristor + conduction angle of freewheeling diode $= 120^\circ$, when armature current (or) load current is continuous.

⑥ A 3-ϕ semiconverter has a unique feature of working as a 6-pulse converter for $\alpha < 60^\circ$ and as a 3-pulse converter for $\alpha \geq 60^\circ$

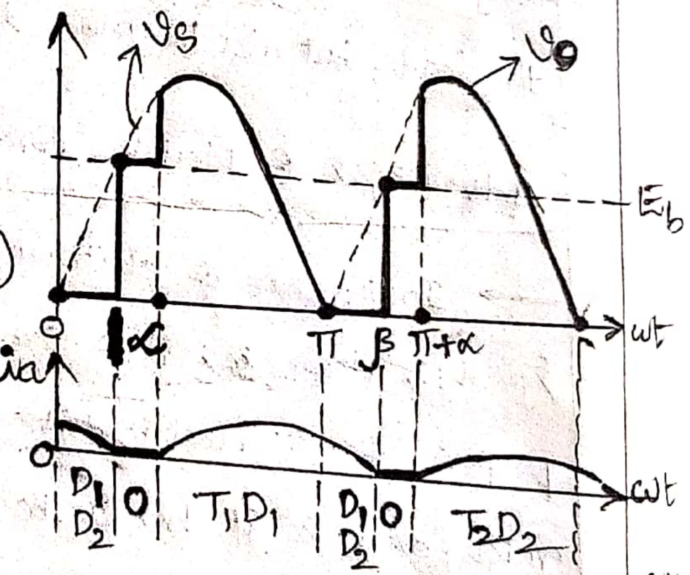
(7) In a 3-ϕ semiconverter, SCRs are gated at an interval of 120°, whereas in case of a 1-ϕ semiconverter, SCRs are fired at an interval of 180°.

1-ϕ half controlled Rectifier control of Seperately excited DC motor drive :- (Key points)

Discontinuous conduction mode :-

$$I_0 = \frac{V_m}{\pi R}(1+\cos\alpha) + \frac{E_b}{\pi R}(\pi+\alpha-\beta)$$

$$V_0 = \frac{V_m(1+\cos\alpha) + E_b(\pi+\alpha-\beta)}{\pi}$$



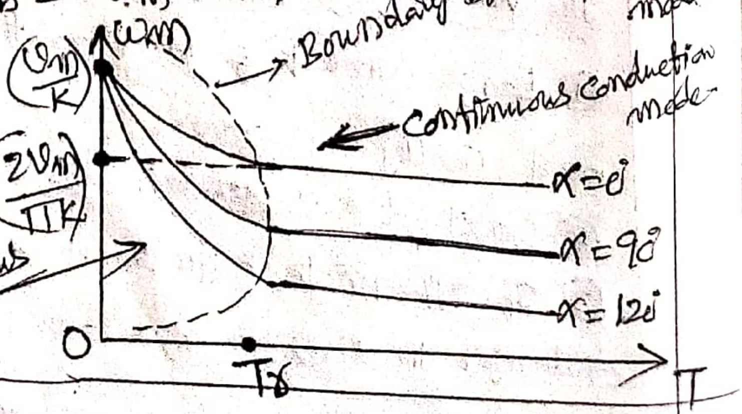
From $(\alpha \le \omega t \le \beta)$

$$V_a = i_a R_a + L_a \frac{di_a}{dt} + E_b = V_m \sin\omega t$$

From $(\beta \le \omega t \le \pi+\alpha)$

$$V_a = E_b \text{ and } i_a = 0$$

$$\omega_m = \left[\frac{V_m(\cos\alpha + \text{[redacted]})}{K(\beta-\alpha)}\right] - \frac{\pi R_a}{K^2(\beta-\alpha)} T$$



- For torques less than rated, a low power drive mainly operates in discontinuous conduction.
- Effect of discontinuous conduction is to make speed regulation poor.
- In continuous conduction, for a given 'α', any increase in torque causes ω_m and E_b to drop so that, I_a and T can increase. Avg terminal voltage V_a remains constant.
- In discontinuous conduction, any increase in torque and accompanied increase in 'I_a' causes 'β' to increase and V_a to drop. Consequently speed drops by a larger amount.

1-φ fully controlled Rectifier control of separately excited DC motor Drive (Keypoints) :-

Discontinuous conduction mode :-

$$v_a = i_a R_a + L_a \frac{di_a}{dt} + E_b = V_m \sin\omega t$$
$$(\alpha \le \omega t \le \beta)$$

$$v_a = E \text{ and } i_a = 0 \quad (\beta \le \omega t \le \pi + \alpha)$$

$$V_a = \frac{V_m(\cos\alpha - \cos\beta) + (\pi + \alpha - \beta)E_b}{\pi}$$

$$I_a = \frac{V_m(\cos\alpha - \cos\beta) + (\pi + \alpha - \beta)E_b}{\pi R}$$