Unit - V

CONTROL OF AC DRIVES

→ Most of the drives used in the industries today are electrical. Depending on the application, some of them are fixed speed and some of them variable speed. The variable speed drives, till a couple of decades back, had various limitations such as poor efficiencies, larger space, lower speeds etc. However, the advent of power electronics transformed the scene completely and today we have variable drive systems which are not only smaller in size but also very efficient, higher reliable and meeting all the stringent demands of the various industries of modern era.

→ The electric drive systems can be divided into two groups, DC drive systems and ac drive systems.

→ The dc drive systems has several advantages as far as the controller is concerned, but this technology has several disadvantages due to dc motor. As is well known, dc motors have inherent disadvantages in that they need regular maintainance, not readily available for ~~regular maintainance~~ replacements, and are bulky in size. Added to this due to the commutator sparking, they are not suitable in hazardous areas like chemical and petrochemical plants (or) in mines. With these limitations dc drive systems have become unsuitable for energy saving applications like fans and pumps.

→ AC drive systems use the ac motor as the driven element - either Induction motor (or) synchronous motor. Since most of the motors in industries are only of induction type. Induction motors, particularly squirrel-cage type induction motors have a no. of advantages when compared with dc motors. Some of these are ruggedness, lower maintainance, better reliability, lower cost, weight, volume and inertia, higher efficiency and the ability to operate in dirty and explosive environments.

→ As far as disadvantages of ac drive systems are concerned, power converters for control of ac motors are more complex, power converters for ac drives are costlier power converters for ac drives generate harmonics in the supply system and load-circuit. As a result, ac motors get derated.

Induction-Motor Drives :-

→ Induction motors have been used in the past mainly in applications requiring a constant speed because conventional methods of their speed control have either been highly inefficient (or) expensive. Hence Variable speed applications have been dominated by dc drives.

→ Availability of thyristors, power transistors, IGBTs, GTOs have allowed the development of variable speed Induction motors drives.

→ Although Variable speed Induction motors drives are generally expensive than dc drives; they are used in a no. of applications such as fans, blowers, cranes, Conveyers etc because of the advantages of Induction motors.

→ other applications involved are underground and underwater installations and explosive and dirty environments.

→ Approximately, 60% of the world's consumption of electrical energy passes through the windings of squirrel-cage induction motors in the range 1 to 125 horse power.

→ A 3-ϕ Induction motor consists of a balanced 3-ϕ winding on the stator. These windings are distributed in the stator slots. Also, these three phase windings are displaced by 120° in space w.r.to each other.
In case of squirrel cage IM,
The rotor consists of longitudinal conductor bars shorted at each end of the rotor by end rings, thus producing a cage like structure, while in wound rotor motor, the rotor also has a balanced three-phase distributed winding having same poles as stator winding.

Equivalent Circuit of Induction Motor :-

Let R_1 = Stator Resistance/phase

X_1 = Stator Leakage Reactance/phase

R_2 = Rotor resistance/phase

R_2' = perphase rotor resistance as referred to primary (or) stator

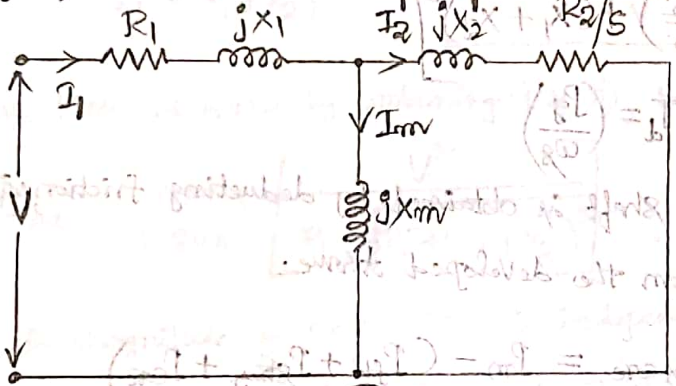
X_2 = Rotor Leakage reactance/phase at stand still

X_2' = perphase rotor reactance as referred to stator, at standstill

X_m = Magnetizing reactance perphase.

At standstill, the induced emf perphase in the equivalent rotor is equal to the stator emf E_1, and the rotor frequency is equal to the supply frequency f_1.

If the rotor slip w.r.to the fundamental rotating field is denoted by 's', the rotor emf E_2 equals SE_1 and the rotor frequency f_2 equals Sf_1



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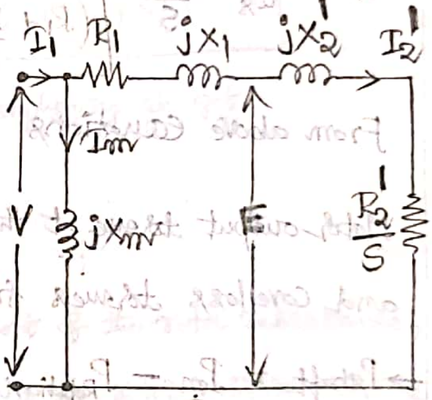

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perphase equivalent circuit of a 3-ϕ Induction-motor is shown in fig(a), Approximate equivalent circuit is shown in fig ⓑ.

→ Slip is defined by $S = \frac{\omega_s - \omega_r}{\omega_s}$ — ①

ω_s, ω_r are the synchronous speed and rotor speed respectively. Further

$$\omega_s = \frac{4\pi f}{P} \quad \text{— ②}$$

f = supply frequency, P = no. of poles.

From equation-① $\omega_r = \omega_s(1-S)$

From fig ⓑ Rotor current $I_2' = \boxed{\frac{V}{\left(R_1 + \frac{R_2'}{S}\right) + j(X_1 + X_2')}}$

→ Airgap power = power Transferred to the rotor

$$P_g = 3(I_2')^2\left(\frac{R_2'}{s}\right)$$

→ Rotor cu losses $P_{cu} = 3(I_2')^2(R_2') = sP_g$

→ Electrical power converted to mechanical power $P_m = P_g - P_{cu}$

$$P_m = 3(I_2')^2(R_2')\left(\frac{1}{s}-1\right) = 3(I_2')^2R_2'\left(\frac{1-s}{s}\right) = (1-s)P_g$$

→ Torque developed by the motor $T_d = \left(\frac{P_m}{\omega_r}\right)$

$$T_d = \frac{3(I_2')^2R_2'\left(\frac{1-s}{s}\right)}{\omega_r} = \frac{3}{\omega_s}(I_2')^2\left(\frac{R_2'}{s}\right) \quad \boxed{\because \left(\frac{1-s}{\omega_r}\right)=\left(\frac{1}{\omega_s}\right)}$$

$$T_d = \frac{3}{\omega_s}\times\frac{R_2'}{s}\times\left[\frac{V^2}{\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2}\right]$$

From above equations $T_d = \left(\frac{P_g}{\omega_s}\right)$

Motor output torque at the shaft is obtained by deducting friction, windage and coreloss torques from the developed torque.

→ $P_{shaft} = P_m - P_{Rotational\ \&\ core} = P_m - (P_{fw} + P_{stray} + P_{core})$

→ Horse power rating of the motor $= \frac{P_{shaft}}{746}$

→ $T_{shaft} = \left(\frac{P_{shaft}}{\omega_r}\right)$

→ Motor Efficiency $= \eta = \frac{P_{shaft}}{P_{in}}$

where $P_{in} = \sqrt{3}\,V_L I_L \cos\phi$

Maximum Torque (Breakdown) and power :-

→ The mechanical torque developed, $T_d = \frac{3}{\omega_s} I_2'^2\left(\frac{R_2'}{s}\right)$ —①

$$T_d = \left(\frac{3V^2R_2'}{\omega_s}\right)\left[\frac{1}{s\left\{\left(R_1+\frac{R_2'}{s}\right)^2 + (X_1+X_2')^2\right\}}\right]$$

Max torque is obtained by taking the derivative of the torque with respect to the slip and then setting the derivative to zero.

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$$\left(\frac{dT_d}{ds}\right) = \left(\frac{3V^2R_2'}{\omega_s}\right)\left\{\frac{\left[\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2\right](-1)s^{-1-1}-(s^{-1})\,2\left(R_1+\frac{R_2'}{s}\right)^{2-1}R_2'\left(\frac{-1}{s^2}\right)}{\left[\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2\right]^2}\right\}=0$$

$$\frac{-1}{s^2}\left[\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2\right]+\left(\frac{2R_2'}{s^3}\right)\left(R_1+\frac{R_2'}{s}\right)=0$$

$$\frac{1}{s^{\cancel{2}}}\left[\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2\right]=\frac{2R_2'}{s^{\cancel{3}}}\left(R_1+\frac{R_2'}{s}\right)$$

$$R_1^2+\left(\frac{R_2'}{s}\right)^2+\cancel{2\left(R_1\frac{R_2'}{s}\right)}+(X_1+X_2')^2=\cancel{\left(2R_1\frac{R_2'}{s}\right)}+2\left(\frac{R_2'}{s}\right)^2$$

$$R_1^2-\left(\frac{R_2'}{s}\right)^2+(X_1+X_2')^2=0 \Rightarrow \left(\frac{R_2'}{s}\right)^2=R_1^2+(X_1+X_2')^2$$

$$s^2=\frac{(R_2')^2}{R_1^2+(X_1+X_2')^2} \Rightarrow \boxed{s_{max,T}=\frac{\pm R_2'}{\sqrt{R_1^2+(X_1+X_2')^2}}} \quad —②$$

Max. torque is found by combining ① & ②, simplyfying we get

$$T_{max}=\left(\frac{3}{2\omega_s}\right)\left[\frac{V^2}{R_1\pm\sqrt{R_1^2+(X_1+X_2')^2}}\right]$$

→ The magnitude of max. torque is independent of the rotor resistance, while the slip at max torque is directly related to the rotor resistance. The plus sign represents motoring and the minus sign the generating condition.

Max power output :- From the max power transfer theorem

$$\frac{R_2'(1-s)}{s}=\sqrt{(R_1+R_2')^2+(X_1+X_2')^2}=Z$$

$$R_2'-sR_2'=sZ \rightarrow s=\frac{R_2'}{R_2'+Z}=s_{maxp}$$

$$s_{maxp}=\frac{R_2'}{R_2'+\sqrt{(R_1+R_2')^2+(X_1+X_2')^2}}$$

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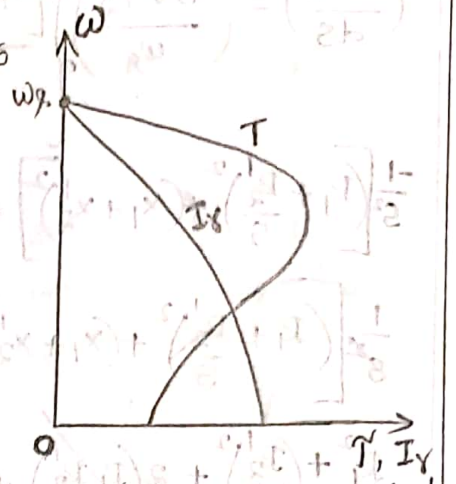
→ The natures of speed-torque and speed-rotor current characteristics are shown in fig. Both rotor current and torque are zero at synchronous speed. With decrease in speed, both increases. While torque reduces after reaching the breakdown value, the rotor current continues to increase, reaching a max value at zero speed. Drop in speed from no-load to full load depends on the rotor resistance. When rotor resistance is low, the drop is quite small, and therefore motor operates essentially at a constant speed. The breakdown torque is a measure of short time torque overload capability of the motor.



→ Sometimes, torque is expressed interms of Smax and Tmax, which can be expressed as follows.

$$\left(\frac{T_d}{T_{max}}\right) = 2\left[1+\left(\frac{R_1}{R_2'}\right)S_{max}\right] \Big/ \left[\frac{S}{S_{max}} + \frac{S_{max}}{S} + 2\left(\frac{R_1}{R_2'}\right)S_{max}\right]$$

→ For slips much smaller than Smax, second term of the denominator dominates. Therefore speed-torque relation from 0 to rated torque is approximately represented by a straight line.

→ For slips much larger than Smax, first term of the denominator dominates and speed-torque relation takes a hyperbolic shape in this region

→ In the whole region of motor operation, the term $\left(\frac{R_1 S_{max}}{R_2'}\right)$ is small compared to '1' and dominating term in the denominator. Therefore

$$\boxed{\left(\frac{T_d}{T_{max}}\right) = \frac{2}{\left(\frac{S}{S_{max}}\right)+\left(\frac{S_{max}}{S}\right)}}$$

Operating regions and Speed-Torque characteristics of a polyphase IM :-

The general shape of the torque-speed (or) torque-slip curve with the motor connected to a constant voltage, constant frequency source is shown in fig.

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(I) Motoring Region ($0 \le S \le 1$) :- For this range of slip, the machine acts as a motor and develops the mechanical output or torque developed is in the direction in which the rotor rotates. Also :

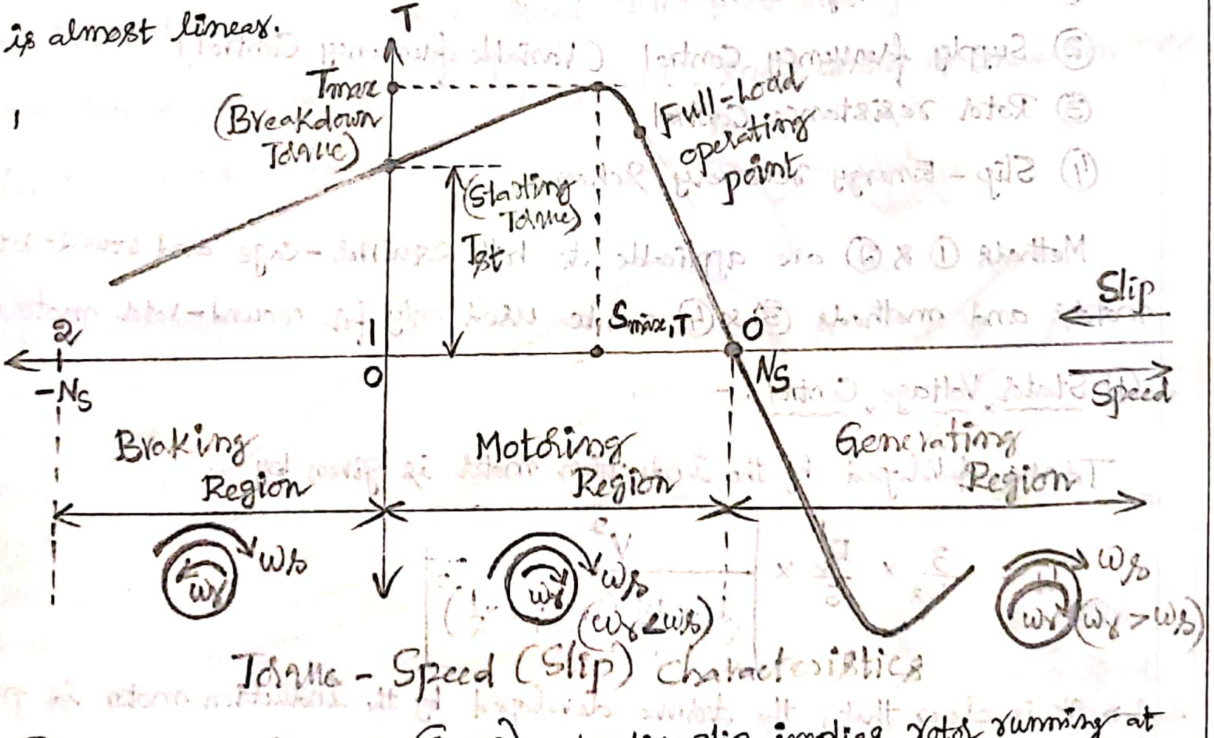
(a) Torque is zero at $S = 0$

(b) The torque has a max. value called the breakdown torque at slip $S_{max,T}$ the motor would decelerate to a halt if it is loaded with more than the breakdown torque.

(c) At $S = 1$, ie Motor is at standstill, the torque corresponds to the starting torque (T_{st}). In a normal designed motor starting torque is much less than the breakdown torque.

(d) The normal operating point is located well below the breakdown torque. The full load slip is usually 2-8%.

(e) From No-Load to somewhat beyond full load, the torque-slip characteristic is almost linear.



Torque - Speed (Slip) characteristics

(II) Generating Region :- ($S<0$), Negative slip implies rotor running at super synchronous speed ($N>N_s$), The load resistance is negative, which means that mechanical power must be put in while electrical power is put out at the machine terminals, ie the machine can be acts as a generator.

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Ⅲ Braking region ($S > 1$) :–

The motor runs in opposite direction to the rotating field, absorbing mechanical power, which is dissipated as heat in the rotor copper.

→ Starting Torque $T_{st} = \left(\frac{3V^2 R_2'}{\omega_s}\right)\left[\frac{1}{(R_1+R_2')^2+(X_1+X_2')^2}\right]$

→ The starting torque increases by adding resistance in the rotor circuit.

Speed Control of Induction Motors :–

→ The Induction motor fulfills admirably the requirements of a substantially constant speed drive. Many motor applications, however, require multiple speed (or) adjustable speed ranges.

→ The Various speed control methods are :

① Stator Voltage Control
② Supply frequency Control (Variable frequency Control)
③ Rotor resistance Control
④ Slip – Energy recovery Scheme.

Methods ① & ② are applicable to both squirrel-cage and wound-rotor motors and methods ③ & ④ can be used only for wound-rotor motors.

① Stator Voltage Control :–

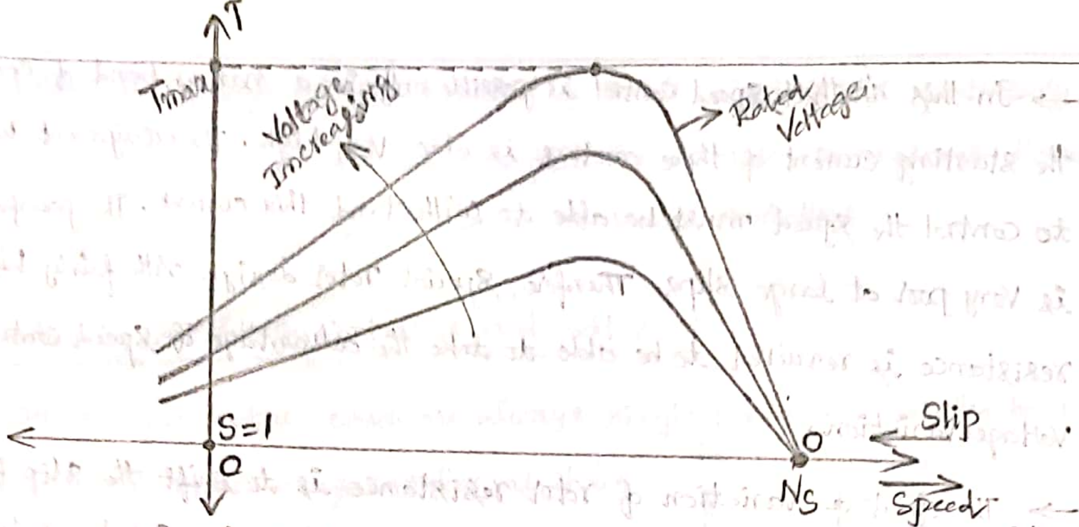
Torque developed by the induction motor is given by

$$T_d = \frac{3}{\omega_s} \times \frac{R_2'}{s} \times \left[\frac{V^2}{\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2}\right]$$

→ It is clear that, the torque developed by the induction motor is proportional to the square of terminal voltage at a constant value of the supply frequency and slip.

→ When the applied voltage is varied, a set of speed-torque curves can be obtained as shown in fig.

Typical Speed - Torque curves for Variation in Stator Voltage (Low-Res Rotor)



→ When the Voltage applied is 'n' times the rated value, the torque ordinates will be n^2 times the ordinates corresponding to full voltage.

→ If constant torque is required at different Voltages, the slip of the motor increases when the Voltage is reduced. To accommodate the required rotor current there is a consequent increase in the slip of the motor. The power factor of the motor deteriorates at low Voltages.

→ Below fig shows the torque-speed curve of the load. From the fig, it is clear that depending upon the type of load, speed control of Induction motor in a limited range is possible.

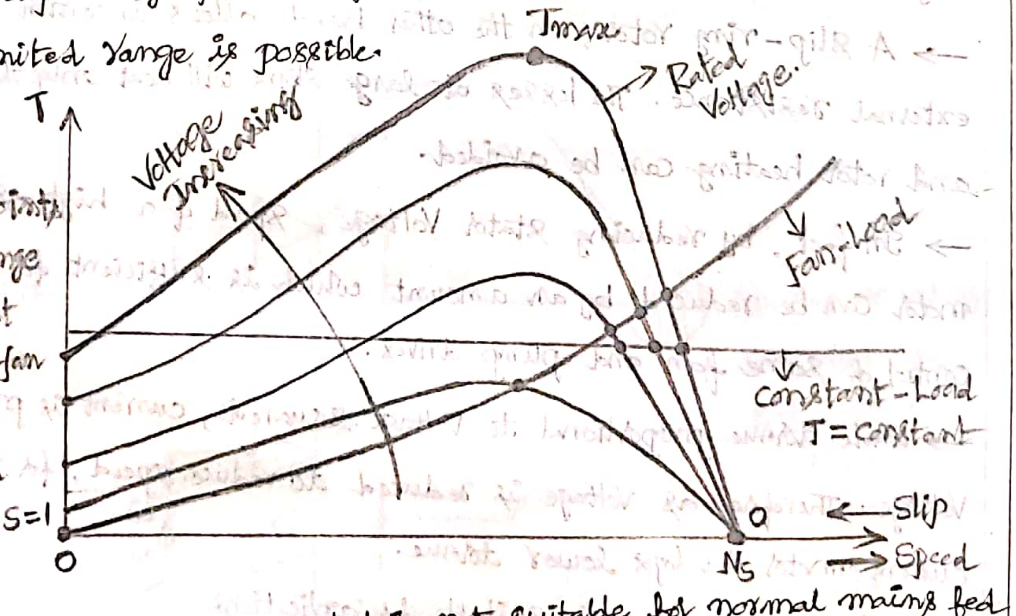


fig: operating points and speed range for constant Torque and fan type load (Low-Rotor Resistance)

→ This method of speed control is not suitable for normal mains fed 3-ϕ Induction motor whose typical torque-speed curves are as shown above. The portion of the curve beyond the ~~position~~ point of max torque is unstable. The normal cage motors have small resistance and therefore, the unstable portion is large.

→ In this method, speed control is possible only in a narrow band of speeds. the starting current of these motors is also very high. The equipment used to control the speed must be able to withstand this current. The powerfactor is very poor at large slips. Therefore, special rotor design with fairly high resistance is revuired to be able to take the advantage of speed control by voltage variation.

→ The effect of variation of rotor resistance is to shift the slip for max torque towards unity. The portion of unstable region can be reduced (or) even eliminated by properly designing the rotor. This increases the range of speed control. This is helpful in reducing the starting current and improving the powerfactor. The method is highly suitable for speed control of solid induction motors which have inherent high rotor resistance.

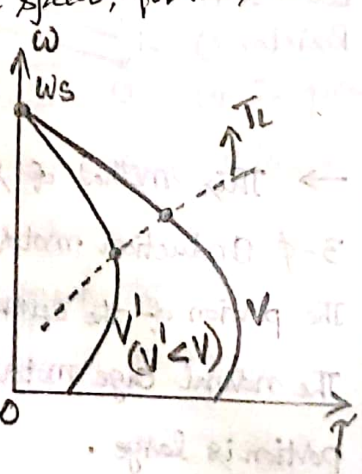
→ However, in cage rotors with high inherent resistance for the purpose of the speed control by stator voltage variation, the rotor losses at large slips are dissipated in the rotor itself causing heating of the rotor.

→ A slip-ring rotor, on the other hand, allows insertion of the revuired external resistance. The losses at large slips will heat only the resistance and rotor heating can be avoided.

→ In fact, by reducing stator voltage, speed of a high-slip induction motor can be reduced by an amount which is sufficient for the speed control of some fan and pump drives.

→ while torque proportional to voltage squared, current is proportional to voltage. Therefore, as voltage is reduced to reduce speed, for the same current motor develops lower torque.

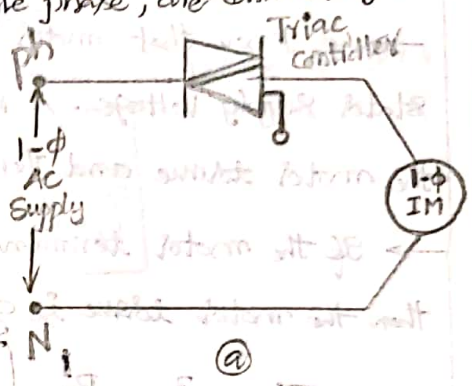
→ consevuently, method is suitable for applications where torque demand reduces with speed, which points towards its suitability for fan and pump drives.



→ Variable Voltage for speed control of small size motors, particularly for single-phase, is sometimes obtained using auto-transformers. However more common method is the use of ac voltage controllers.

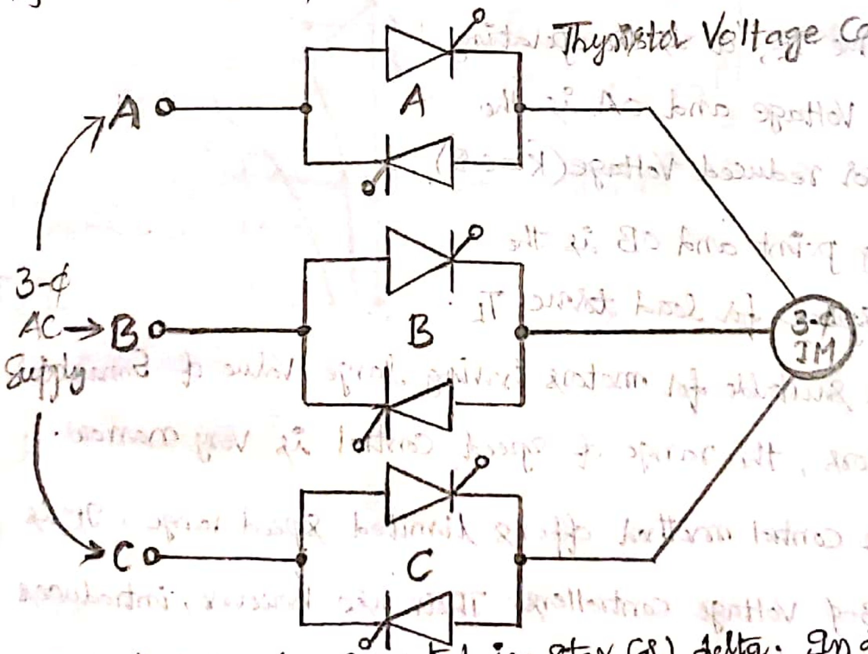
Control by AC Voltage Controllers and Soft Start :-

→ Domestic fan motors, which are always single phase, are controlled by a single phase triac voltage controller as shown.



→ Speed control is obtained by varying the firing angle of the triac. These controllers commonly known as solid state fan regulators are now preferred over conventional variable resistance regulators because of high efficiency.

→ Industrial fans and pumps are usually driven by three phase motors as shown in fig. Below fig. shows the commonly used thyristor voltage controller for speed control of 3-ϕ motors.



ⓑ 3-ϕ AC Voltage Controller fed 3-ϕ Induction Motor

→ The motor may be connected in star (or) delta. In delta connection, third harmonic voltage produced by motor back emf causes circulating current through the windings which increases losses and thermal loading of motor.

→ Speed control is obtained by varying conduction period of thyristors.

→ For low power ratings, anti-parallel thyristor pair in each phase can be replaced by a triac.

→ Since voltage controllers, both single and three phase, allow a stepless control of voltage from its zero value. They are also used for soft start of motors.

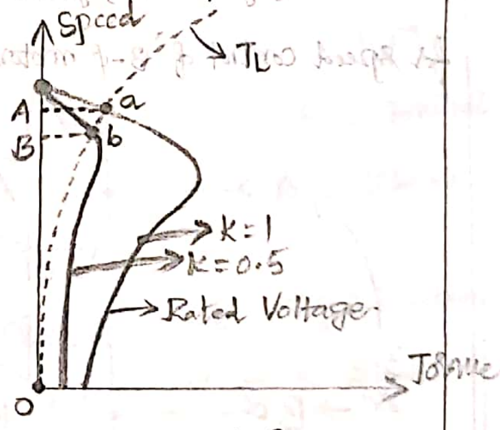
Torque-Speed characteristics :-

→ We know that motor torque is proportional to the square of the stator supply voltage. A reduction in the supply voltage will reduce the motor torque and therefore the speed of the drive.

→ If the motor terminal voltage is reduced to KV_1 where $K<1$, then the motor torque is given by

$$T_d = \frac{3}{\omega_s} \times \frac{R_2'}{s} \times \left[\frac{(KV_1)^2}{\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2}\right]$$

→ The speed-torque characteristics of induction motor for variable stator voltage is as shown in fig.



→ For load torque T_L, 'a' is the operating point at rated voltage and OA is the motor speed. For reduced voltage ($K=0.5$), 'b' is the operating point and OB is the reduced motor speed for load torque T_L.

This method is suitable for motors having large value of S_{max}. For low slip motors, the range of speed control is very narrow.

Stator voltage control method offers limited speed range. It is usual to use 3-φ voltage controllers. Their use however, introduces pronounced harmonic contents and input supply PF for the voltage controller is low. These are therefore used for low-power drives like fans, blowers and centrifugal pumps requiring low starting torque. For these type of loads, the load torque is proportional to speed squared and input current is max. when slip $S = 1/3$.

Ⓠ A 2.8 kW, 400V, 50Hz, 4 pole, 1370 rpm, delta connected squirrel-cage Induction motor has following parameters referred to the stator:

$$R_s = 2\Omega,\ R_r' = 5\Omega,\ X_s = X_r' = 5\Omega,\ X_m = 80\Omega$$

Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated speed at rated voltage. Calculate

① Motor Terminal Voltage, current and torque at 1200 rpm

② Motor speed, current and torque for the terminal voltage of 300V.

Ⓐ Torque $T = \frac{3}{\omega_s} \times \frac{V^2}{S} \times \left[\frac{R_r'}{\left(R_s+\frac{R_r'}{S}\right)^2 + (X_s+X_r')^2}\right]$

$$T = \frac{3}{\omega_s} \times \frac{V^2}{S} \times \left[\frac{R_2'}{\left(R_1+\frac{R_2'}{S}\right)^2 + (X_1+X_2')^2}\right]$$

Synchronous speed $= \frac{120f}{P} = \frac{120\times50}{4} = 1500$ rpm $= 50\pi$ (rad/sec)

$$S = \frac{N_S - N_r}{N_S} = \frac{1500-1370}{1500} = 0.0867$$

$$T = \frac{3}{50\pi} \times \frac{400^2}{0.0867} \times \left[\frac{5}{\left(2+\frac{5}{0.0867}\right)^2 + (5+5)^2}\right] = 48.13\ \text{Nm}.$$

For Fan type of loads $T_L \propto (\text{Speed})^2$ $\quad N_r = N_S(1-S)$

$\because N_S$ is constant

$T_L = K(1-S)^2$ $\quad N_r \propto (1-S)$

At full load $T = T_L$

$K(1-0.0867)^2 = 48.13 \Rightarrow K = 57.7 \Rightarrow T_L = 57.7(1-S)^2$

① Given that $N_r = 1200$ rpm.

Slip $S = \frac{N_S - N_r}{N_S} = \frac{1500-1200}{1500} = 0.2$

At $S = 0.2$, Torque $T_L = 57.7(1-0.2)^2 = 36.9$ Nm.

Since $T = T_L = 36.9$ Nm

$$36.9 = \frac{3}{50\pi} \times \frac{V^2}{0.2} \times \frac{5}{\left(2+\frac{5}{0.2}\right)^2 + (5+5)^2} \Rightarrow V = 253.2V$$

$$I_2' = \frac{V}{\left(R_1+\frac{R_2'}{s}\right)+j(X_1+X_2')} = \frac{253.2}{\left(2+\frac{5}{0.2}\right)+j(5+5)} = 8.246-j3.054$$

$$I_m = \frac{V}{jX_m} = \frac{253.2}{j80} = -j3.165$$

$$I_s = I_2' + I_m = 8.246-j3.054-j3.165 = 10.328\angle{-37^\circ} = (I_s)_{ph}$$

$(I_s)_L$ = Line current = $\sqrt{3}\times 10.328 = 17.89A$.

② At $V = 300V$

$$T = \frac{3}{50\pi}\times\frac{300^2}{s}\times\frac{5}{\left(2+\frac{5}{s}\right)^2+(5+5)^2} = \frac{27\times10^4 s}{10\pi(104s^2+20s+25)}$$

At Steady State $T = T_L$

$$\frac{27\times10^4 s}{10\pi(104s^2+20s+25)} = 57.7(1-s)^2$$

Simplyfying we get $104s^4-188s^3+89s^2-179s+25=0$

which gives $s = 0.147$

Hence torque produced by the motor $T_L = 57.7(1-0.147)^2$
$T_L = 41.94$ Nm

Speed $N_r = N_s(1-s) = 1500(1-0.147) = 1279$ rpm

$$I_2' = \frac{V}{\left(R_1+\frac{R_2'}{s}\right)+j(X_1+X_2')} = \frac{300}{\left(2+\frac{5}{0.147}\right)+j(5+5)} = \frac{300}{36+j10} = (7.73-j2.14)A$$

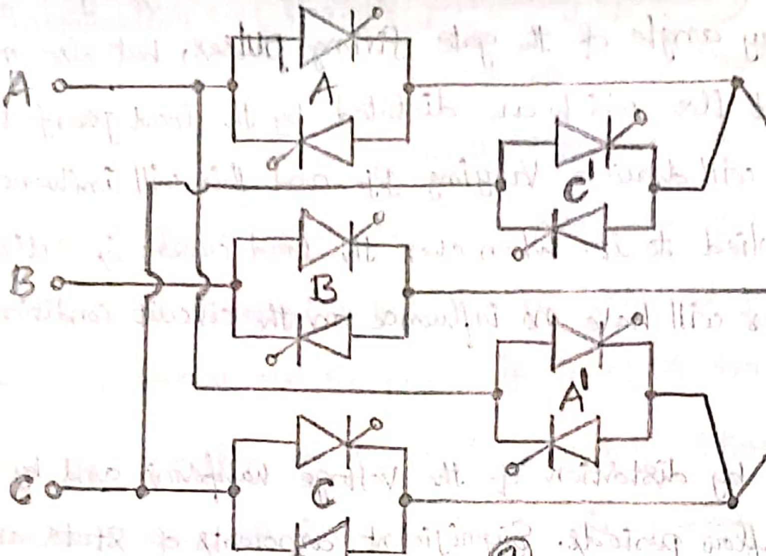
$$I_m = \frac{V}{jX_m} = \frac{300}{j80} = -j3.75$$

$$I_s = I_m + I_r' = 9.75\angle{-37.3^\circ}A = (I_s)_{ph}$$

$(I_s)_L$ = Line current = $\sqrt{3}\times 9.75 = 16.88A$

Four-Quadrant AC Voltage controllers: —

The four-quadrant operation with plugging is obtained by the use of the circuit as shown in fig.



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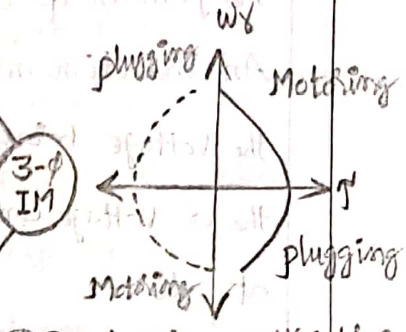

ⓑ Speed-Torque curves for a fixed Stator Voltage & +Ve, -Ve phase sequence

→ Thyristor pairs A, B and C provide operation in quadrants I and IV. The speed torque curve at a fixed stator voltage and for operation in quadrants I and IV is shown by a solid line as shown above.

→ Use of thyristor pairs A'BC' changes the phase sequence and thus gives operation in quadrants II and III. The speed-torque curve for the same stator voltage and operation in quadrants II and III is shown by a dotted line as shown above.

→ While changing from one set of thyristor pairs to another, that is from ABC to A'BC' and vice-versa, care should be taken to ensure that the incoming pair is activated only after the outgoing pair is fully turned-off. Failure to satisfy this condition will cause short-circuiting of the supply by the conducting thyristors of the two pairs. The protection against such fault can be provided only by the fuse links and not by the current control.

→ This method of speed control has a few limitations, however:

① The output Voltage from an ac Voltage Controller is dependent not only on the delay angle of the gate firing **pulses**, but also on the periods of current flow which are dictated by the load powerfactor. An induction motor will draw a Varying PF and this will influence the Voltage being applied to it. When ever the load current is Continuous the ac Voltage controller will have no influence on the circuit conditions at all.

② Control is achieved by distortion of the Voltage waveforms and by the reduction of current flow periods. Significant amounts of stator and rotor harmonic currents will flow and eddy currents will be induced in the iron core. These will cause additional motor heating and alter the motor performance compared with sinusoidal operation.

→ The practical results of these limitations are:

(i) The motors performance can only be predicted after a full under-
standing of the motor, thyristor converter and the load.
(ii) A closed loop speed control based on a tachogenerator speed mea-
surement is essential to ensure stable performance.
(iii) The system gains most practical application where the load is
predictable and where the load torque required at reduced speed is
relatively low.

→ As far as the thyristor Voltage ratings are concerned, the normal
crest working Voltage is the peak of the supply line Voltage, but high tran-
sients can occur if the circuit is opened while in operation by switches
(or) fuses. The stored energy in the motor has to be allowed for an assess-
ment of thyristor Voltage safety margins and surge suppression requirements.

→ The most significant factor in current ratings is the possibility of thyristors
having to carry the normal motor starting currents during a period when
the thyristors are unable to influence the circuit due to adverse load (or)
power factor conditions.

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CONTROL OF INDUCTION MOTOR THROUGH STATOR FREQUENCY

Introduction :- (Variable Frequency operation)

The synchronous speed is directly proportional to the supply frequency. Hence, by changing the supply frequency, the synchronous speed, and motor speed can be controlled below and above the normal full load speed.

→ The motor terminal voltage can be considered proportional to the product of the frequency and the flux, if the stator drop is neglected.

→ Any reduction in the supply frequency without a change in terminal voltage causes an increase in the airgap flux.

→ Induction motors are designed to operated at the knee point of the magnetization characteristics to make full use of the magnetic material. Therefore, the increase in flux will saturate the motor. This will increase the magnetizing current, distort the line current and voltage, increase the core losses and stator copper losses and produce high pitch acoustic noise.

→ While any increase in flux beyond the rated value is undesirable from the consideration of saturation effects, a decrease in flux is also avoided to retain the torque capability of motor. Therefore, the variable frequency control ~~control~~ below ~~the~~ rated frequency is generally carried out by reducing the machine phase voltage along with the frequency in such a manner that flux is maintained constant.

→ Above the rated frequency, the motor is operated at a constant voltage because of the limitation imposed by stator insulation or by supply voltage limitations.

→ per-unit frequency $K = \frac{f}{f_{rated}}$

where f = operating frequency

f_{rated} = Rated frequency

ⓐ Operation below the rated frequency $(K < 1)$:-

→ It is desirable to operate the motor at constant flux below the rated frequency to avoid the saturation effects as described above.

→ The motor will operate at constant flux if I_m is maintained constant at all operating points.

→ From equivalent circuit $I_m = \frac{E_{rated}}{X_m} = \frac{E_{rated}}{2\pi f_{rated} L_m} = \frac{E_{rated}}{f_{rated}} \times \frac{1}{2\pi L_m}$ — ①

L_m = Magnetizing inductance.

→ At operating frequency 'f', $I_m = \frac{E}{K X_m} = \frac{E}{K f_{rated}} \times \frac{1}{2\pi L_m}$ — ②

→ To operated the motor at constant flux at all operating conditions, the following condition must satisfy. ⇒ ① = ②

Simplifying we get $E = K E_{rated}$

→ It is clear that the flux will remain constant if the backemf is changes in the same ratio as the frequency, in other words, when (E/f) ratio is maintained constant.

Motor operation for a constant (E/f) ratio :-

At operating frequency 'f' $I_2' = \frac{K E_{rated}}{\sqrt{\left(\frac{R_2'}{s}\right)^2 + (K X_2')^2}} = \frac{E_{rated}}{\sqrt{\left(\frac{R_2'}{Ks}\right)^2 + (X_2')^2}}$ — ③

where slip $S = \frac{K\omega_s - \omega_r}{K\omega_s}$

Developed torque $T_d = \frac{3}{K\omega_s} \times (I_2')^2 \left(\frac{R_2'}{s}\right)$

$$T_d = \frac{3}{\omega_s} \times \frac{1}{K} \times \frac{R_2'}{S} \times \left[\frac{E_{rated}^2}{\left(\frac{R_2'}{Ks}\right)^2 + (X_2')^2}\right] \quad -④$$

→ Now backemf 'E' maintained constant for a given frequency.

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→ The power transferred is max at Slip Smax

$S_{max} = \pm \frac{R_2'}{kx_2'}$ '+' for motoring ;
'−' for regenerative braking

Substitute Smax in developed torque (T_d) equation, we get

$$T_{max} = \pm \frac{3}{2\omega_s} \times \left(\frac{E^2_{rated}}{x_2'}\right)$$

→ It is clear that from the above equation, for a Variable frequency Control at a constant flux, the breakdown torque is remains constant for all frequencies, both during motoring and regenerative braking.

→ From equations ③ & ④, it is clear that for a constant (SK), the motor current I_2' and torque T_d are constant.

→ If $\bar{E}$ is the reference vector, the impedance of the rotor circuit is given by $Z_2' = R_2' + j\boxed{(KS)}x_2'$, then the phase angle of I_2' is given by $\theta_r = \tan^{-1}\left[\frac{(KS)x_2'}{R_2'}\right]$

Since θ_r is constant for a given value of (SK), the motor current also be constant. Thus the motor torque is constant when the flux and (KS) are maintained constant.

→ As mentioned above $S = \frac{k\omega_s - \omega_r}{k\omega_s} \Rightarrow (KS) = \frac{k\omega_s - \omega_r}{\omega_s}$

$(KS) = \left(\frac{\omega_{ss}}{\omega_s}\right)$, where ω_{ss} = Slip Speed = $(k\omega_s - \omega_r)$.

From above equation, a constant value of (KS) implies the motor operation at a constant slip speed ω_{ss}.

→ where ω_{ss} is the drop in motor speed from its no-load speed $(k\omega_s)$ when the machine is loaded.

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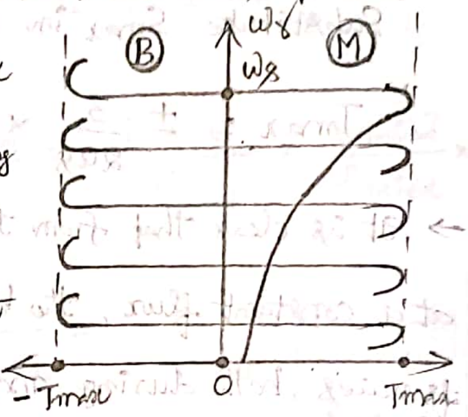
→ It is clear that from the above, for any value of T_d, the drop in the motor speed from its no-load speed ($K\omega_s$) is the same for all frequencies. Hence the machine speed – torque characteristics for $(0 < S < S_{max})$ are parallel curves. The nature of the speed – torque curves for the variable frequency operation at a constant flux are shown in fig. for both motoring & braking operations.

→ The operation of the machine at a constant slip speed also implies the operation at a constant rotor frequency as shown by the following equation.



fig①

$$SK = S\frac{f}{f_{rated}} = \frac{(Sf)}{f_{rated}} = \frac{f_r}{f_{rated}} = \frac{\omega_r}{\omega_{rated}}$$

For $S < S_{max}$, $\left(\frac{R_2'}{S}\right) >> (KX_2')$

Hence from ④ $T_d = \frac{3}{\omega_s} \times \frac{1}{\cancel{(KS)}} \times \cancel{(R_2')} \times \frac{E_{rated}^2}{\cancel{(R_2')^2}/\cancel{(KS)^2}}$

$$T_d = \left[\frac{3}{\omega_s} \times \frac{E_{rated}^2}{(R_2')}\right] \times (KS) = (\text{constant})\ \omega_{ss}. \quad \left[\because \omega_{ss} = \omega_s \times (KS)\right]$$

$$(\omega_s = \text{constant})$$

→ The above equation suggests that for $(S < S_{max})$, the speed – torque curves are nearly straight lines. Since they are also parallel, the speed – torque characteristics are approximately straight lines for $(S < S_{max})$, when the flux is maintained constant.

→ The operation of the machine at constant flux requires a closed loop control of flux. When the operating point changes, the closed loop control adjusts the motor voltage to maintain a constant flux. The closed loop control becomes complicated because the measurement of flux is always difficult. Hence the flux is (maintained) controlled indirectly by operating the machine at a constant (V/f) ratio for most of the frequency range, except at low frequencies, where the (V/f) ratio is increased to compensate for the stator resistance drop.

→ The above discussion stated that by maintaining (V/f) ratio constant for various frequencies, the flux remains constant. The (V/f) ratio is chosen equal to its value at the rated voltage and frequency. As the load on the machine is increased, the stator resistance drop increases, and backemf decreases and the flux reduces. Consequently, the machine does not operate exactly at a constant flux.

→ From the approximate equivalent circuit

$$T_d = \frac{3}{\omega_s} \times \frac{R_2'}{S} \times \left[\frac{V_{rated}^2}{\left(R_1+\frac{R_2'}{S}\right)^2+(X_1+X_2')^2}\right]$$

$$T_{max} = \frac{3}{2\omega_s} \times \left[\frac{V_{rated}^2}{R_1 \pm \sqrt{R_1^2+(X_1+X_2')^2}}\right]$$

→ When the operating frequency is 'f', the syn. speed, terminal voltage, and reactance will have the values $K\omega_s$, KV_{rated}, KX respectively.

$$T_d = \frac{3}{K\omega_s} \times \left(\frac{R_2'}{S}\right) \times \left[\frac{K^2 V_{rated}^2}{\left(R_1+\frac{R_2'}{S}\right)^2+(KX_1+KX_2')^2}\right]$$

$$T_d = \left(\frac{3}{\omega_s}\right) \times \left(\frac{R_2'}{KS}\right) \times \left[\frac{V_{rated}^2}{\left(\frac{R_1}{K}+\frac{R_2'}{KS}\right)^2+(X_1+X_2')^2}\right] \quad (K<1)$$

$$T_{max} = \frac{3}{2K\omega_s} \times \frac{K^2 V_{rated}^2}{R_1 \pm \sqrt{R_1^2+(X_1+X_2')^2 K^2}}$$

$$= \frac{3}{2\omega_s} \times \left[\frac{V_{rated}^2}{\left(\frac{R_1}{K}\right) \pm \sqrt{\left(\frac{R_1}{K}\right)^2+(X_1+X_2')^2}}\right] \quad (K<1)$$

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→ When f is large $\left(\frac{R_1}{k}\right) << (x_1 + x_2')$ giving a constant value of Tmax, both for motoring and regenerative braking. However for low values of 'f', the max torque capability is altered. It decreases for motoring and increases for braking. What is true for max torque is also true for the rated torque.

→ This behavior can also be explained from consideration of flux. When the motor operates at a frequency 'f' with a constant (V/f) control, the terminal voltage and all reactance are reduced by a factor 'k' but the stator resistance remains fixed. The resistances drop, which is negligible for high values of 'f'. As a result, the (E/f) ratio decreases decreasing flux and the motor torque capability. The lower the frequency the greater the reduction in the torque capability.

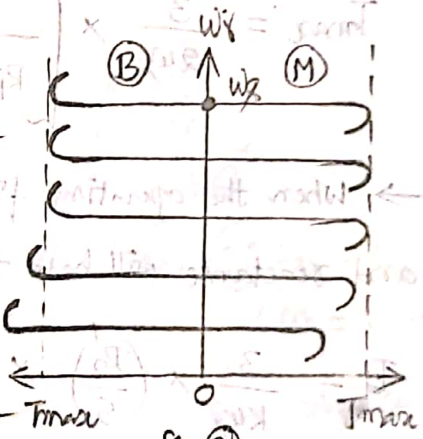


fig ②

→ Figure shows the nature of the speed-torque characteristics for constant (V/f) control and for f < frated. The decrease in motoring torque and increase in braking torque at low frequencies have higher values for motors of lower power rating.

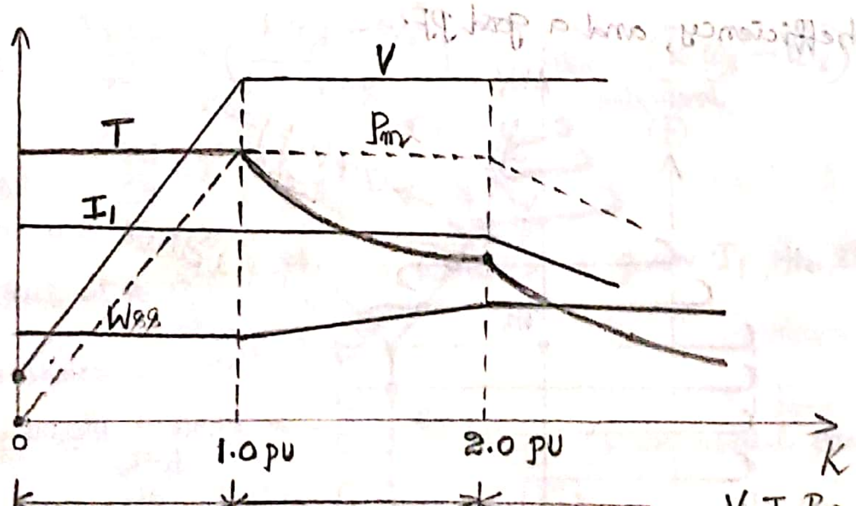
→ To make full use of the motor's torque capability at the start and for low speeds, the (V/f) ratio is increased to compensate for the stator resistance drop at low frequencies as shown in fig ③. This allows a constant max torque to be obtained for motoring operation at all frequencies.

→ The motoring speed-torque characteristics becomes similar to that shown in fig ②. The braking torque which is already high at low frequencies is increased further. The large increase in braking torque may cause severe mechanical stress on the motor and the load.

→ To obtain a linear relation between V and f, V may also be varied as $V = V_0 + K \cdot f$, where V_0 is chosen to produce the nominal flux at zero speed and the constant 'K' is chosen to get the rated terminal voltage at the rated frequency.

→ To get a high torque to current ratio and high efficiency and PF, the motor is operated for $S < S_{max}$, that is on the portion of speed-torque curves with a negative slope. Therefore in figs ② & ③ only the portions with negative slope are shown. However, a complete characteristics is shown for the rated frequency to provide a comparision between the starting and low speed torque, available with variable frequency control and constant frequency operation. There is a large increase in the starting and low speed torques with variable freq control. The corresponding currents are also reduced by a large amount. Thus, the starting and low speed power performance of a variable frequency drive is far superior compared to that with the fixed frequency operation.

Operating Regions of Induction motor :-



V, T, Pm, I_1 & Wss curves Versus per unit frequency (K)

fig ③

ⓑ operation above the rated frequency ($K>1$):-

→ The operation at a frequency higher than the rated frequency takes place at a constant terminal voltage (V_{rated}) (or) at the max voltage available from the variable frequency source if it is less than the V_{rated}.

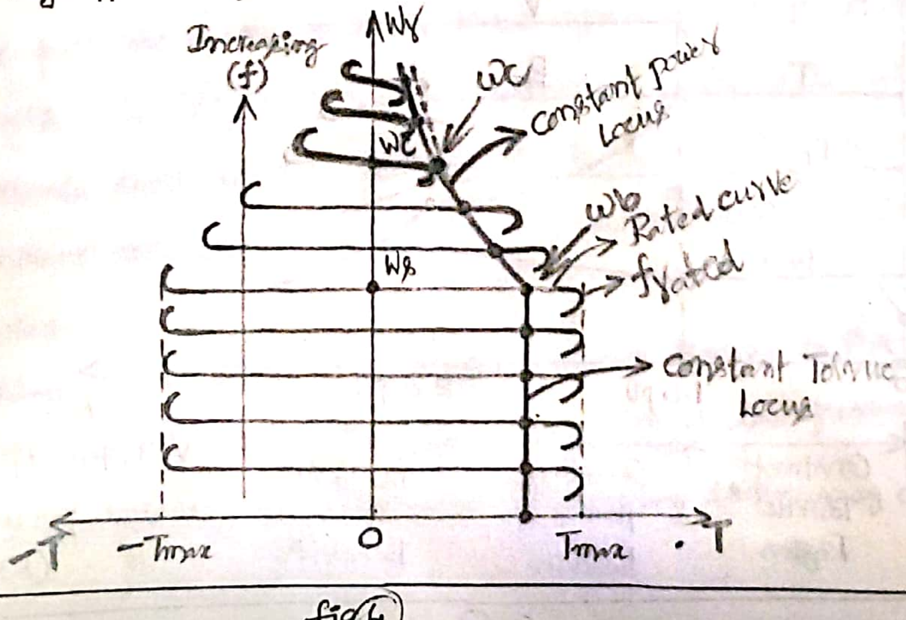
→ As the terminal voltage is maintained constant, the flux decreases in the inverse ratio of per unit frequency 'K'. The motor, therefore, operates in the field weakening mode.

→ The torque expressions for the operation in this freq range are

$$T_d = \frac{3}{\omega_s} \times \frac{R_2'}{Ks} \times \left[\frac{V_{rated}^2}{\left(R_1 + \frac{R_2'}{s}\right)^2 + K^2 (X_1 + X_2')^2} \right], \quad K>1$$

$$T_{max} = \frac{3}{2\omega_s K} \times \left[\frac{V_{rated}^2}{R_1 \pm \sqrt{R_1^2 + K^2 (X_1 + X_2')^2}} \right], \quad K \geq 1$$

→ Since $K>1$, the breakdown torque decreases with the increase in frequency and speed. The speed-torque curves for operation for field weakening mode of operation are shown in fig④. Here also the motor is made to operate for $S < S_m$ to get high torque per ampere, high efficiency, and a good PF.



fig④

Torque and power capabilities :-

→ The torque and power variations for a given stator current and for frequencies below and above the rated frequency are shown by dots as shown above.

→ When the stator current has the max. permissible value, these will represent the max. torque and power capabilities of the machine.

→ When the motor operates at a constant flux and a given stator current, the developed torque and slip speed have constant values at all frequencies. Thus for $K<1$, the variable frequency control with a constant flux gives constant torque operation.

→ When constant (V/f) control is used and the (V/f) ratio is increased at low frequencies to compensate for the stator resistance drop, at the max. permissible current the drive operates essentially at a constant flux providing constant torque operation.

→ For $K>1$, $I_2' = \dfrac{V_{rated}}{\sqrt{\left(R_1+\frac{R_2'}{s}\right)^2+(X_1+X_2')^2K^2}}$ (From approximate equivalent ckt)

Since the slip is small $I_2' = \dfrac{V_{rated}}{(R_2'/s)} = \dfrac{s V_{rated}}{R_2'}$

$$I_2' = \frac{V_{rated}}{R_2'} \times \left(\frac{K\omega_s-\omega_r}{K\omega_s}\right), \quad \omega_{sl} = (K\omega_s-\omega_r)$$

$$\omega_{sl} = \frac{R_2'\omega_s}{V_{rated}} \times (K I_2')$$

Thus at a given I_2' and hence at a given I_1, the slip speed ω_{sl} increases linearly with 'K'.

$$I_2' = \frac{E_2}{\sqrt{R_2'^2+(sX_2')^2K^2}} = \frac{E_1}{\sqrt{\left(\frac{R_2'}{s}\right)^2+(X_2')^2K^2}}$$ (From actual equivalent ckt)

Since slip is small $\left(\frac{R_2'}{s}\right) >> (X_2'K) \Rightarrow I_2' = \dfrac{E_1}{(R_2'/s)}$

Hence I_2' is in phase with E_1. If the Rotor resistance loss is neglected, the developed power P_m is given by $P_m = 3E_1I_2'$, if the stator drop is neglected $E_1 = V_{rated}$, $P_m = 3V_{rated}I_2'$ consequently, P_m is constant for a given I_2' and therefore, for a given I_1. Thus for $K > 1$, the variable frequency control at a constant voltage gives constant power operation. When operating at the max permissible current, the motor developes constant max power as shown in figs ③ & ④ the max torque decreases with speed.

→ At a critical speed ω_c, the breakdown torque is reached. Any attempt to operate the motor at the max current beyond this speed will stall the motor. This is also the limit of the constant power operation. The value of ω_c depends on the breakdown torque of the machine. The range of constant power operation is higher for a motor with higher breakdown torque.

→ The speed & frequency at the transition from constant torque to constant power operation are called) base speed & base frequency respectively. respectively. They usually be equal to ω_s & f_{rated} respectively. But this will not always be so.

→ There are some applications like traction; where speed control in a wide range is required and the torque demand in the high speed range is low. For such applications, control beyond the constant power range is required. To prevent the torque from exceeding breakdown torque, the motor is operated at a constant slip speed and the machine current and power are allowed to decrease as shown. Now, the motor current reduces inversely with speed and the torque decreases inversely as the speed squared. This characteristics is often referred to as the series motor characteristics. The torque produced in this region is somewhat higher than that produced by a series motor.

Control and advantages: -

→ The motor is always operated on the portion of the speed - Torque curves with a negative slope, by limiting either the slip speed (or) the current, for getting the advantages of high torque to current ratio, high efficiency and a good PF.

① When motoring, a decrease in speed command decreases the supply frequency. This shifts the operating point to regenerative braking. The drive decelerates under the influence of braking torque and load torque. Then the frequency alone is reduced with speed to maintain the operation on the portion of speed - torque curves with a negative slope. As a result the operation shifts to the motoring operation and the drive settles at the desired speed.

② When motoring, an increase in the speed command increases the supply frequency, the motor torque exceeds the load torque and the drive accelerates. Again the operation is maintained on the portion of the speed - Torque curves with a negative slope by limiting the slip speed. The drive finally settles at the desired speed.

Advantages: -

① High torque to current ratio over the wide range of speeds.

② Good transient performance, and good running performance.

③ High efficiency & good PF

④ Since regenerative braking is also possible at zero speed, it provides highly efficient drive with excellent running & transient performance.

Applications of Variable frequency control :-

① In special applications requiring maintenance free operation, such as underground and underwater installations and also in applications involving explosive and contaminated environments such as in mines and chemical industry variable frequency induction motor drives have already gained popularity.

② Because of the advantages of squirrel-cage induction motor and variable frequency control, the variable frequency ac drives find applications in traction, mill runout tables, pumps, fans, blowers, compressors, spindle drives, conveyers, machine tools, ...

③ Due to the availability of power transistors with improved ratings and characteristics, general purpose low-power variable frequency drives are now available with a cost comparable to that of dc drives.

④ The recent progress in GTOs may provide variable frequency drives which will completely very well and probably replaced dc drives in medium and low range high power drives.

→ The variable frequency supply to an induction motor for speed control can be obtained by using

① Voltage Source Inverter (VSI) (or) Voltage fed Inverter (VFI)

② current Source Inverter (CSI) (or) current fed Inverter (CFI)

③ Cyclo Converter.

Control of induction motors by Voltage Source Inverters :-

→ Variable frequency and variable voltage supply for induction motor control can be obtained either from a voltage source inverters (VSI) or a cycloconverter.

→ Voltage source inverter allows a variable frequency supply to be obtained from a DC supply.

→ An inverter belongs to the Voltage source category, if viewed from the load side, the ac terminals of the inverter function as a Voltage source. Because of a low internal impedance, the terminal Voltage of a Voltage source inverter substantially constant with Variations in load. The below fig shows a VSI employing transistors. Any other self - commutated device can be used instead of a transistor.

→ Generally MOSFET is used in low Voltage and low power inverters
IGBT and power Transistors are used upto medium power levels
GTO and IGCT are used for high power levels.

→ VSI can be operated as a stepped wave inverter (or) a pulse width modulated (PWM) inverter.

→ When operated as a stepped wave inverter, transistors are switched in the sequence of their numbers with a time difference of T/6 and each transistor kept on for the duration T/2, where 'T' is time period for one cycle. Resultant waveform as shown in fig ①ⓑ.

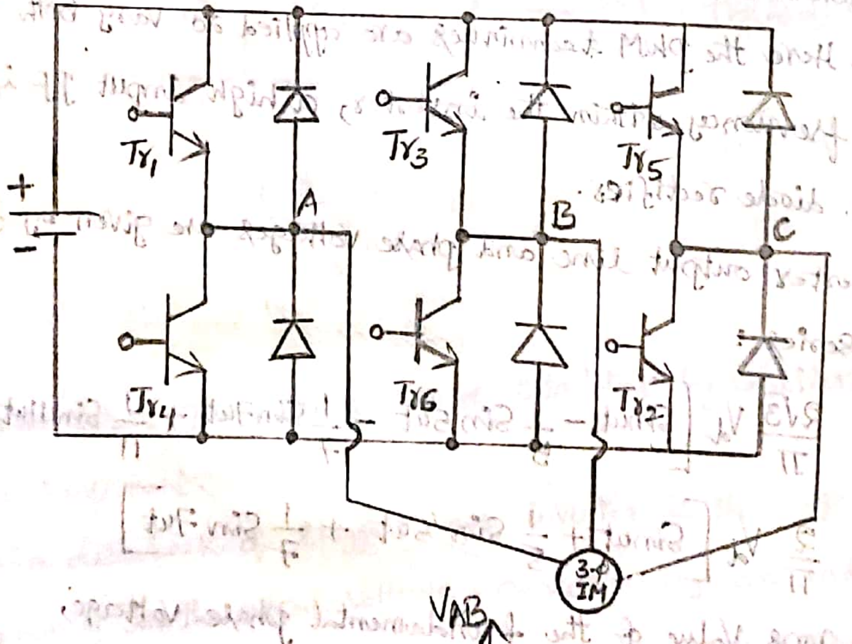


fig ①ⓐ.

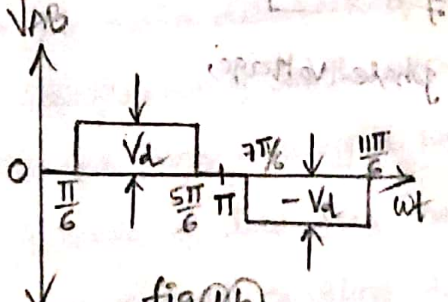


fig ①ⓑ
Six - Step Inverter

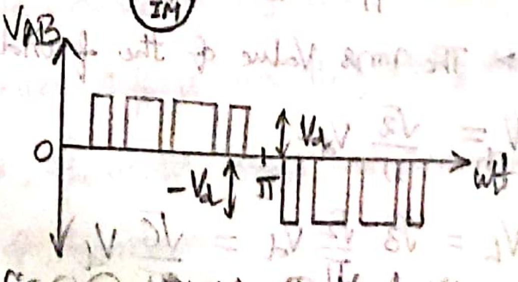


fig ①ⓒ PWM - Inverter.

→ Frequency of inverter operation is Varied by Varying 'T'

→ The output Voltage of the inverter is Varied by Varying dc input Voltage.

→ When supply is dc, Variable dc input voltage is obtained by connecting a chopper between dc supply and inverter as shown in fig ②ⓐ.

→ When supply is ac, Variable dc input Voltage is obtained by connecting a controlled rectifier between ac supply and inverter as shown in fig ②ⓑ. The rectifier is line-commutated and the inverter is forced commutated. The section between the rectifier and inverter is known as dc link. The dc link includes a series inductance and a shunt capacitor, which smooths the dc input Voltage to the inverter. This system is not able to regenerate, because of reversal of current is not allowed by the thyristors. If regeneration is necessary, it may be replaced the phase controlled by dual converter as shown in fig ②ⓒ

→ A system in which the dc link Voltage is constant is shown in fig ②ⓓ. Here the PWM techniques are applied to Vary both the Voltage and the frequency within the inverter, a high input PF is obtained from the diode rectifier.

→ Inverter output line and phase Voltages are given by following fourier series :

$$V_{AB} = \frac{2\sqrt{3}}{\pi} V_d \left[\sin\omega t - \frac{1}{5}\sin 5\omega t - \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t \ldots \right]$$

$$V_{AN} = \frac{2}{\pi} V_d \left[\sin\omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t \right]$$

→ The rms Value of the fundamental phase Voltage;

$$V_{ph} = \frac{\sqrt{2}}{\pi} V_d .$$

$$V_L = \sqrt{3}\,\frac{\sqrt{2}}{\pi} V_d = \frac{\sqrt{6}}{\pi} V_d$$

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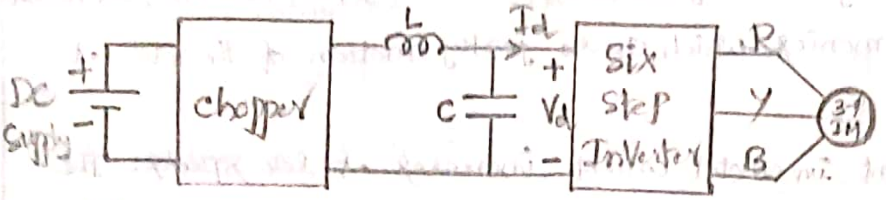

fig ②ⓐ

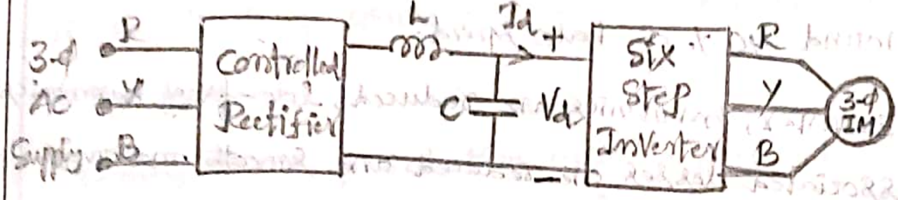

fig ②ⓑ

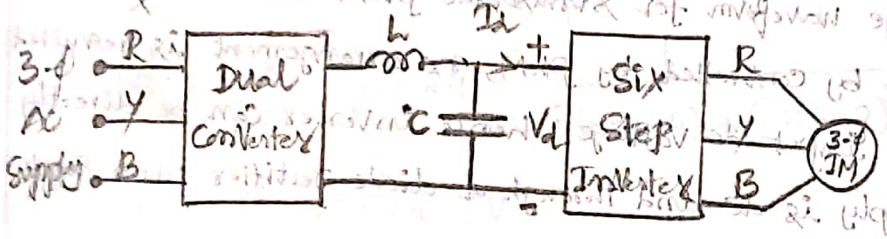

fig ②ⓒ

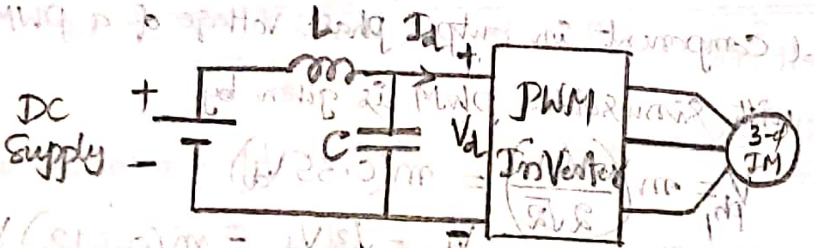

fig ②ⓓ

→ The torque for a given speed can be calculated by considering only fundamental component.

→ The main drawback of stepped wave inverter is the large harmonics of low frequency in the output voltage. Consequently, an induction motor drive fed from a stepped wave inverter suffers from the following drawbacks:

① Because of low-freq harmonics, the motor losses are increased at all speeds causing derating of the motor.

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② Motor develops pulsating torques due to fifth, seventh, eleventh and thirteenth harmonics which cause jerky motion of the rotor at low speeds.

③ Harmonic content in motor current increases at low speeds. The machine saturates at light loads at low speeds due to high (V/f) ratio. These two effects overheat the machine at low speeds, thus limiting lowest speeds to around 40% of base speed.

→ By using PWM inverter, harmonics are reduced, low-freq harmonics are eliminated, associated losses are reduced and smooth motion is obtained at low speeds.

→ The output voltage waveform for sinusoidal PWM modulation is shown in ①ⓒ. Since output voltage can by controlled by PWM, no arrangement is required for the variation of input dc voltage, hence inverter can be directly connected when supply is dc and through a diode rectifier when supply is ac.

→ The fundamental component in output phase voltage of a PWM inverter operating with sinusoidal PWM is given by

$$V_{ph_1} = m\left(\frac{V_d}{2\sqrt{2}}\right) = m(0.35V_d)$$

$$V_{L_1} = \sqrt{3}\,V_{ph_1} = m(0.612)V_d$$

where m = modulation index.

→ The harmonics in the motor current produce torque pulsation and derate the motor. For a given harmonic content in motor terminal voltage, the current harmonics are reduced when the motor has higher leakage inductance; this reduces derating and torque pulsations. Therefore, when fed from VSI, induction motors with large (compared to when fed from sinusoidal supply) leakage inductance are used.

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(2008) (Q) A 3-ϕ star connected induction motor operating at a frequency of 60Hz consists of 4 poles. The parameters of the stator and rotor referred to stator side are $R_1 = R_2 = 0.024\,\Omega$, and $X_1 = X_2 = 0.18\,\Omega$. If the motor is controlled by the variable freq control with (V/f) constant ratio determine the following parameters at an operating frequency of 12 Hz. Starting torque and rotor current in terms of their values at rated frequency.

(A) Starting torque of induction motor is given by

$$\omega_s = \frac{4\pi f}{P}$$

$$\omega_s = \frac{4\pi\,60}{4} = 60\pi$$

$$T_{st_1} = \frac{3}{\omega_s} \times \frac{R_2'}{1} \times \frac{V^2}{\left(R_1 + \frac{R_2'}{1}\right)^2 + (X_1 + X_2')^2}$$

$$T_{st_1} = \frac{3}{60\pi} \times 0.024 \times \frac{1}{(2\times 0.024)^2 + (0.18\times 2)^2} \times V^2$$

$$T_{st_1} = (2.897\times 10^{-3})\,V^2$$

$$I_{st_1} = \frac{V}{\sqrt{\left(R_1 + \frac{R_2'}{1}\right)^2 + (X_1 + X_2')^2}} = \frac{V}{\sqrt{(2\times 0.024)^2 + (0.18\times 2)^2}} = (2.753)\,V$$

At operating frequency ratio 'k', where $k = \frac{12}{60} = \frac{1}{5} = 0.2$

$$T_{st_2} = \frac{3}{\omega_s} \times \frac{R_2'}{k} \times \frac{V^2}{\left(\frac{R_1 + R_2'}{k}\right)^2 + (X_1 + X_2')^2}$$

$$T_{st_2} = \frac{3}{60\pi} \times \frac{0.024}{0.2} \times \frac{1}{\left(\frac{0.048}{0.2}\right)^2 + (0.36)^2} \times V^2 = (0.0102)\,V^2$$

$$I_{st_2} = \frac{V}{\sqrt{\left(\frac{R_1 + R_2'}{k}\right)^2 + (X_1 + X_2')^2}}$$

$I_{st_2} =$ [redacted]

$= (2.311)\,V$

$$\frac{T_{st_2}}{T_{st_1}} = \frac{0.0102\,\cancel{V^2}}{2.897\times 10^{-3}\,\cancel{V^2}} = 3.52 \approx 3.5$$

$$\frac{I_{st_2}}{I_{st_1}} = \text{[redacted]}\ \frac{2.311\,\cancel{V}}{2.753\,\cancel{V}} = 0.839$$

$$\frac{T_{st_1}}{I_{st_1}} = (1.052\times 10^{-3})\,V$$

$$\frac{T_{st_2}}{I_{st_2}} = (4.413\times 10^{-3})\,V$$

Thus High torque to current ratio at low frequency can be obtained by variable frequency control.

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2008 Q A 3-ϕ, 1500 rpm induction motor is developing a torque of 3000 syn watts at input frq of 50Hz. If the motor torque is now reduced to 1500 syn watts. Determine the new value of stator frequency. The motor is operating in constant Hp region. Assume constant rotor frequency and neglect the effect of rotor resistance. (16M)

Ⓐ $$T_d = \frac{3}{\omega_s} \times \frac{R_2'}{s} \times \frac{V^2}{\left(R_1 + \frac{R_2'}{s}\right)^2 + (X_1 + X_2')^2}$$

Since the effect of Rotor Resistance is neglected

$T_d \propto \frac{1}{\omega_s}$, $T_1 = 3000$ syn watts at $f_1 = 50Hz$

$T_2 = 1500$ syn watts at $f_2 = ?$

$$\frac{T_2}{T_1} = \frac{\omega_1}{\omega_2} \Rightarrow \frac{\cancel{1500}^{1}}{\cancel{3000}_{2}} = \frac{\cancel{2\pi} \times 50}{\cancel{2\pi} \times f_2} \Rightarrow f_2 = 100 Hz.$$

2008 Q An inverter supplies a 6-pole, 3-ϕ, IM rated at 415V, 50Hz, Determine the approximate Voltages required of the inverter for motor speeds 600/800/1500/1800 rpm. (16M)

Ⓐ (V/f) ratio to be maintained constant $= \frac{V_{rated}}{f_{rated}} = \frac{415/\sqrt{3}}{50} \approx 4.8$

Rated frequency = 50Hz, Rated speed $= \frac{\cancel{120}^{20} \times 50}{\cancel{6}} = 1000$ rpm

① For 600 rpm, $f_1 = \frac{NP}{120} = \frac{600 \times 6}{\cancel{120}_{20}} = 30 Hz$

$V_1 = 4.8 f_1 = 4.8 \times 30 = 144 V$, $V_{1L} = 249.41V$

② For 800 rpm $f_2 = \frac{NP}{120} = \frac{800 \times 6}{\cancel{120}_{20}} = 40 Hz$

$V_2 = 4.8 f_2 = 192 V$, $V_{2L} = 332.55V$

③ For 1500 rpm; $f_3 = \frac{NP}{120} = \frac{1500 \times 6}{\cancel{120}_{20}} = 75Hz$

$V_3 = 4.8 \times 75 = 360V$, $V_{3L} = 623.53V$

④ For 1800 rpm, $f_4 = \frac{NP}{120} = \frac{1800 \times 6}{\cancel{120}_{20}} = 90Hz$

$V_4 = 4.8 \times 90 = 432V$, $V_{4L} = 748.24V$

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(2008) Q) A 400V, 50Hz star-connected induction motor is fed from a six step inverter which in turn fed from a six-pulse fully controlled rectifier. The ac supply mains are rated at 400V, 50Hz. what should be the firing angle of the rectifier to operate the motor at 50Hz under (V/f) control? (16M)

Ⓐ

$$\left.\begin{aligned} V_{L_1} &= \frac{\sqrt{6}}{\pi} V_d \\ V_d &= \frac{3V_{ml}}{\pi}\cos\alpha \end{aligned}\right\} \quad V_L = \frac{3\sqrt{6}}{\pi^2} V_{ml}\cos\alpha$$

$$\cos\alpha = \frac{V_L \pi^2}{3\sqrt{6}\, V_{ml}} = \frac{\pi^2 \times [illegible] \times 400}{3\sqrt{6} \times 400\sqrt{2}}$$

$$\cos\alpha = 0.948 \Rightarrow \alpha = 18.55^\circ.$$

Cyclo-Converter Control :-

→ cyclo converter allows Variable frequency and Variable Voltage supply to be obtained from fixed Voltage and frequency ac supply.

→ A low-frequency supply can be directly synthesized from a higher freq. source by suitable switching of the cycloconverter elements.

→ A major limitation of the cycloconverter is that, its output frequency is limited to one-Third of the input freq. If the input is 50Hz (or) 60Hz, the max output freq is around 20Hz, the neat result is being that the cycloconverter application is limited to low-speed drives. If the power-source is 400Hz, then clearly higher speeds are possible.

→ A 3-ϕ, 3-pulse cyclo converter along with the nature of its output Voltage waveform as shown below.

→ Because of low harmonic current when operating at low-frequencies, smooth motion is obtained at low speeds. Harmonic content is increases with freq making it necessary to limit the max output frequency to 40% of the source frequency. Thus max speed is restricted to 40% of syn. speed at the mains frequency. A motor with large leakage (reactance) inductance is used in order to minimize derating and torque-pulsations due to harmonics in motor current. The power factor is poor in this case.

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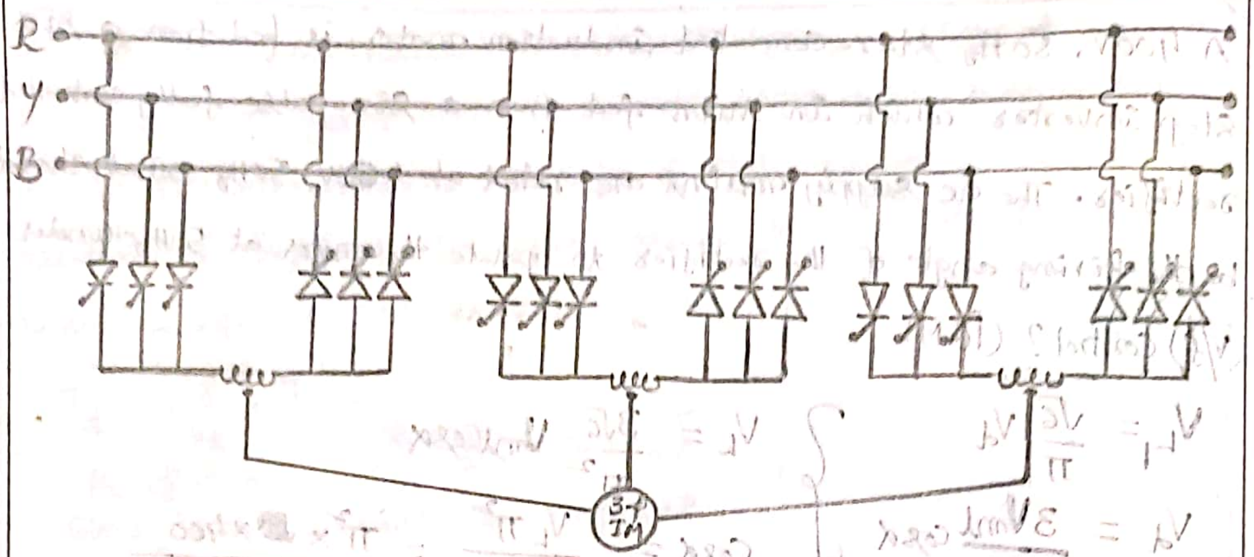


output Voltage :-

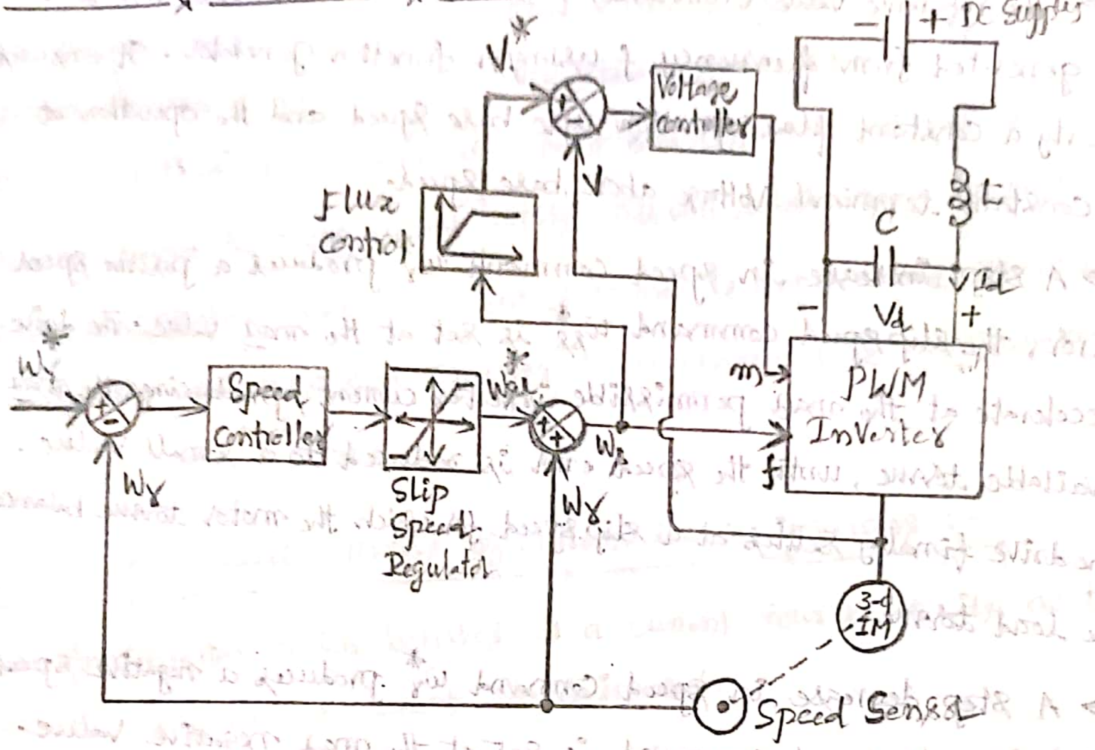
→ The power-circuit arrangement is shown above. It consists of three-dual converters each supplying one phase of the load. By switching each of the dual converters cyclically through all four quadrants of operation a waveform of perphase output voltage may be synthesized for each phase of the load. Each output waveform consists of segments of the waveforms of the input terminal voltage of the one dual converter.

→ Full Four quadrant operation is obtained by reversing the phase sequence of motor terminal voltage.

→ Since cycloconverter employs large no. of thyristors, it becomes acceptable only in large power drives.

→ cyclo converter drive has applications in high power drives requiring good dynamic response but only low speed operation. The low speed operation is obtained by feeding a motor with large pole numbers from a cyclo converter operating at low frequencies. These drives are called as gearless drives, because unlike conventional drives, the low speed operating of load is obtained without a reduction gear, thus eliminating the associated cost, space and maintenance.

Closed-loop Speed control of VSI & cyclo convertor IM Drives :-



→ A closed-loop speed controlled drive is shown in fig. It employs inner slip-speed loop with a slip limiter and outer speed loop.

→ For a given current slip-speed has a fixed value, the slip speed loop functions as an inner current loop.

→ To get the high-torque to current ratio the motor has to operate on the portion of speed torque curve between syn speed & the speed at which max torque occurs.

→ The drive uses PWM inverter fed from a DC supply, which has the capability of regenerative braking and four quadrant operation. Hence the drive scheme is however applicable to any VSI (or) cycloconverter drive having regenerative (or) dynamic braking capability.

→ The speed error is processed through a PI controller and a slip regulator. PI controller is used to get good steady-state accuracy, and to attenuate noise. The slip regulator sets the slip speed command W_{sl}^* whose max.

Value is limited to limit the inverter current to a permissible value.

→ The syn speed is obtained by adding actual speed ω_r and slip speed ω_{sl} determines the inverter frequency.

→ The reference value (command) of the machine terminal voltage V^* is generated from frequency f using a function generator. It ensures nearly a constant flux operation upto base speed and the operation at a constant terminal voltage above base speed.

→ A step increase in speed command ω_r^* produces a positive speed error, the slip speed command ω_{sl}^* is set at the max value. The drive accelerate at the max permissible inverter current, producing the max available torque, until the speed error is reduced to a small value. The drive finally settles at a slip speed for which the motor torque balances the load torque.

→ A step decrease in speed command ω_r^* produces a negative speed error, The slip speed command is set at the max negative value. the drive decelerates under regenerative braking, at the max permissible current and the max available braking torque, until the speed error is reduced to a small value. Now the operation shifts to motoring and the drive settles at the slip speed for which the motor torque equals the load torque.

→ The drive has fast response because the speed error is corrected at the max available torque. Direct control of slip speed assures the stable operation under all operating conditions.

→ For operation beyond the base speed, the slip speed limit of the slip regulator must be increased linearly with the freq until the breakdown value is reached. This is achieved by adding to the slip regulator output an additional slip speed signal, proportional to freq and of appropriate sign. For frequencies higher than the freq for which the breakdown torque is reached the slip speed limit is kept fixed near the breakdown value.

→ when fast response is required the max slip can be allowed to be equal to Smax, because induction motors can be allowed to carry several times the rated current during transient operations of short duration.

→ The inverter and its front end converter are built using semiconductor devices whose transient and steady state current ratings are same. Then the ratings of inverter and front end converter will have to be chosen several times the motor current rating. This will substantially increase the drive cost, when fast transient response is not required, current ratings of inverter and front end converter can be chosen to be marginally higher than that of motor.

Control of induction motors by current source inverters :-

→ An inverter which behaves as a current source at its ac terminals is called a current source inverter.

→ Inverter because of large internal impedance, the terminal voltage of a current source inverter changes substantially with a change in load.

→ If it is used in a multi-motor drive, a change in load on any motor affects other motors. Hence, current source inverters are not suitable for multi-motor drives.

→ Since, the inverter current is independent of load impedance, it has inherent protection against short-circuits across its terminals.

→ Rotor current is given by $I_2' = \dfrac{X_m I_1}{\sqrt{\left(\frac{R_2'}{s}\right)^2 + (X_m + X_2')^2}}$

$$T = \frac{3}{\omega_s} \times (I_2')^2 \left(\frac{R_2'}{s}\right) = \frac{3}{\omega_s} \times \frac{I_1^2 X_m^2}{\left(\frac{R_2'}{s}\right)^2 + (X_m + X_2')^2} \times \frac{R_2'}{s}$$

$$I_m^2 = \left[\frac{\left(\frac{R_2'}{s}\right)^2 + (X_2')^2}{\left(\frac{R_2'}{s}\right)^2 + (X_m + X_2')^2}\right] I_1^2 = \left[\frac{(R_2'/sf)^2 + (2\pi L_2')^2}{(R_2'/sf)^2 + (2\pi L_m + 2\pi L_2')^2}\right] I_1^2$$

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→ Motor Speed–Torque curves for various values of I_1 and natural Speed–Torque curve, which corresponds to the operation at rated constant flux as shown in fig ⓐ.

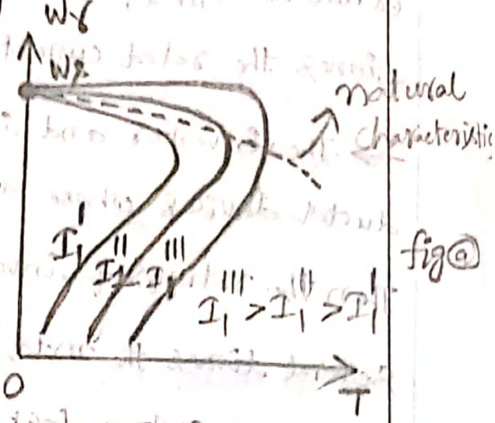


fig ⓐ

→ For a given I_1 operation above natural characteristics takes place for flux higher than the rated and operation of motor below the natural characteristics takes place for flux below the rated value.

→ But rated flux operation is preferred.

→ As the flux is maintained at rated value ie at rated I_m, the relationship between I_1 and (Sf) is as shown in fig ⓑ, when freq is changed to control the speed.

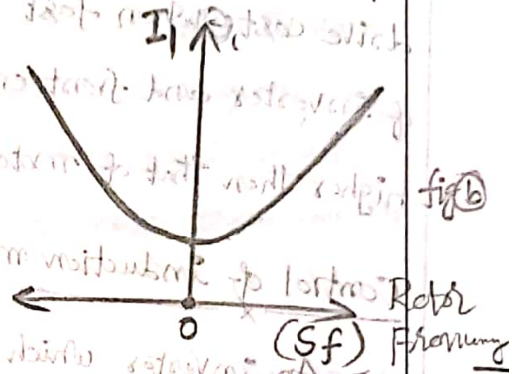


fig ⓑ

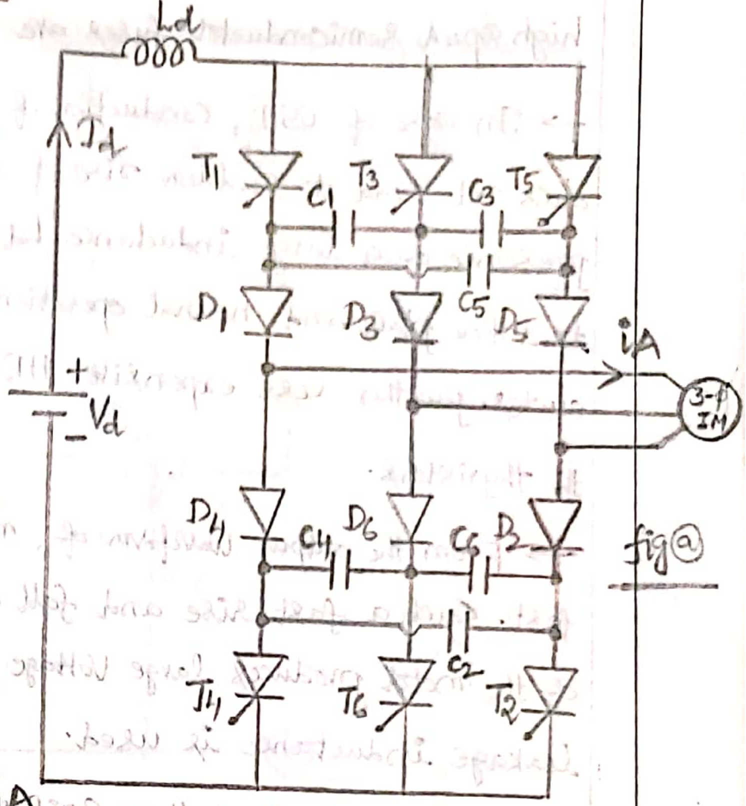
→ When operating at a constant flux, the operating points are located mostly on the part of speed–Torque curve, which gives unstable operation with most of loads. **Hence** closed-loop speed control is mandatory.

→ Since motor has to operate at constant flux, its steady state behavior is identical to that with variable freq variable voltage source (VFVS). Thus at a given slip speed (or rotor freq), the motor draws a constant current and develops a constant torque at all freq. So the motor operates in constant torque mode from zero to base speed.

→ At base speed, either rated machine voltage is reached (or) VFCS voltage saturates. In either case machine operates at a constant terminal voltage above base speed, providing constant power mode. Variable freq current supply is provided by current source inverter.

current Source Inverter Control :-

→ A thyristor current source inverter is shown in fig(a). Diodes and capacitors (D_1-D_6 & C_1-C_6) provide the commutation of thyristors (T_1-T_6), which are fired with a phase diff. of 60° in sequence of their numbers.

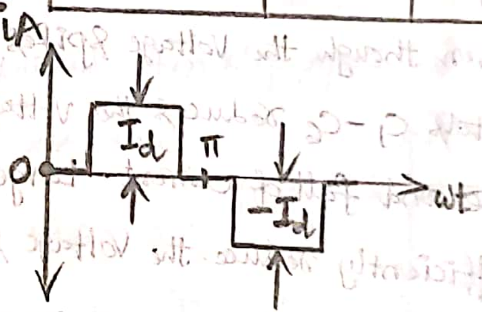


fig(a)

→ fig(b) shows the nature of output current waveform. Inverter behaves as a current source due to the presence of large inductance Ld in dc-link.

→ The fundamental component of motor phase current is given by

$$I_1 = \frac{\sqrt{6}}{\pi} I_d$$



fig(b)

→ For a given speed, torque is controlled by varying the dc link current I_d by changing the value of V_d.

→ When supply is ac a controlled rectifier is connected between the supply and inverter.

→ When supply is dc, a chopper is incorporated between the supply and inverter.

→ The max value of dc output voltage of fully-controlled rectifier & chopper are chosen so that the motor terminal voltage saturates at rated value.

→ The major advantage of CSI is its reliability. In case of VSI a commutation failure cause two devices in the same leg to conduct. This connects conducting devices directly across the source. Consequently current through the devices rises to dangerous values. So expensive high speed semiconductor fuses are required to protect the devices.

→ In case of CSI, conduction of two devices in the same leg does not lead to sudden rise of current through them due to the presence of a large inductance L_d. This allows time for commutation to takes place and normal operation to get restored in subsequent cycles. Further less expensive HRC fuses are good enough to protect the thyristors.

→ From the output waveform of, motor current rise and fall are very fast. Such a fast rise and fall of current through the leakage inductance of the motor produces large voltage spikes. Therefore a motor with low leakage inductance is used.

→ Even though the voltage spikes have large values the commutation capacitors $C_1 - C_6$ reduces the voltage spikes, by reducing the rate of rise and fall of current. Large value of capacitors is required to sufficiently reduce the voltage spikes.

→ Large commutation capacitors have the advantages that cheap converter grade thyristors can be used, but they reduces the freq. range of the inverter, and therefore speed range of the drive.

→ Due to large value of inductor L_d and capacitors, the CSI drive is expensive and has more weight & volume.

closed-loop speed control of CSI Drives :-

→ A closed loop CSI Drive is as shown in below fig@.

→ Speed command ω_r^* and actual speed ω_r are compared by. substracting ω_r from ω_r^* produces the speed error.

→ The speed error processed through a PI controller and slip regulator. The slip regulator sets the slip speed command ω_{sl}^*.

→ The syn speed is obtained by adding ω_r, ω_{sl}^* determines the inverter frequency.

CC → current controller

FC → Firing Circuit

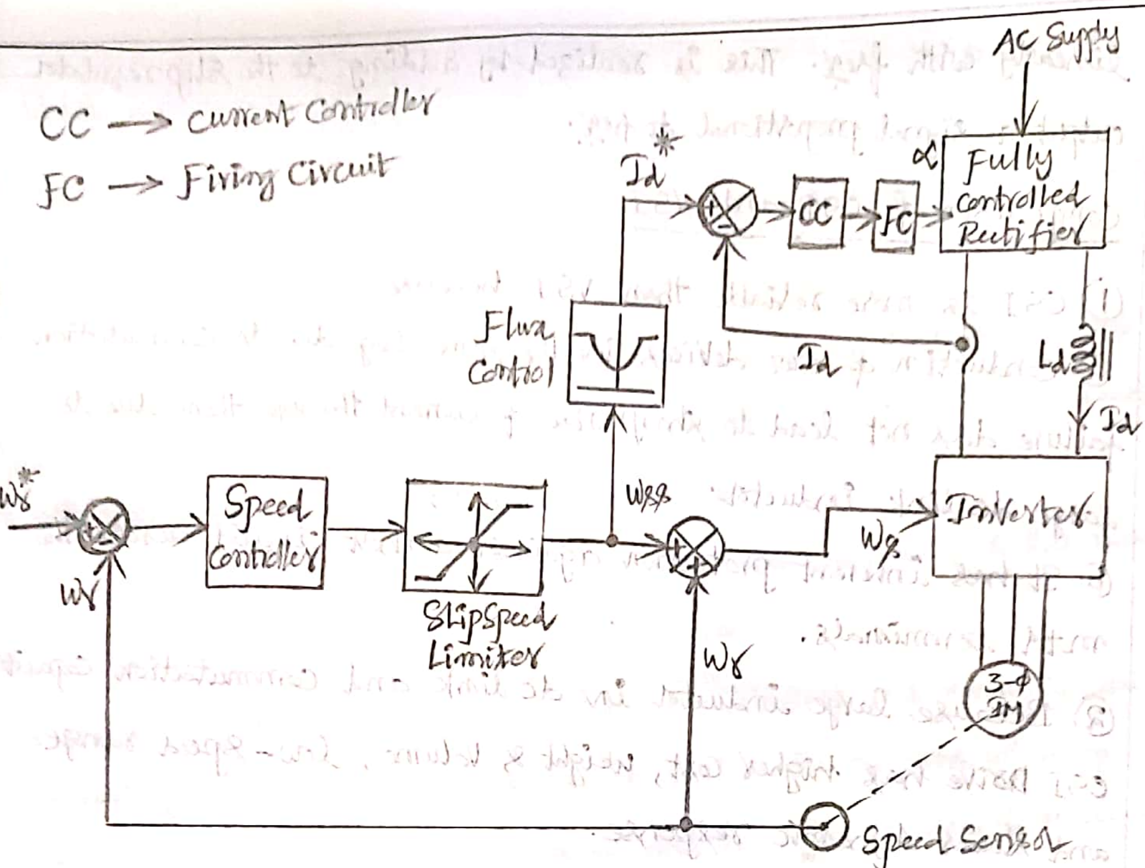


fig ⓐ

→ Constant flux operation is obtained when slip speed ω_{sl}^* and I_1 have the relationship is shown in below fig ⓑ.

→ Since I_d is proportional to I_1 according to $I_1 = \frac{\sqrt{6}}{\pi} I_d$, a relation similar to fig ⓑ exists between ω_{sl}^* and I_d for constant flux operation.

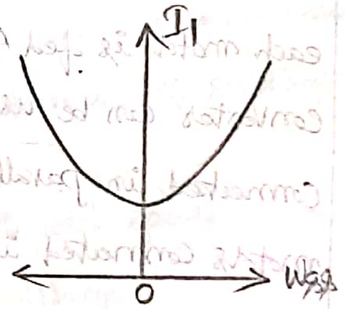


fig ⓑ

→ Based on the value of ω_{sl}^*, the flux control block produces a reference current I_d^* which through a closed-loop current control adjusts the dc link control I_d to maintain a constant flux.

→ The limit imposed on the output of the slip regulator limits I_d at the inverter rating. Any speed collection in speed error is carried out at the max permissible inverter current and max available torque giving the fast transient response and current protection.

→ Beyond base speed, machine terminal Voltage saturates, flux control and closed loop control of I_d operation is ineffective. To operate the drive upto rated inverter current, the slip speed limit of the slip regulator must increase

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linearly with freq. This is realized by adding to the slip regulator output a signal proportional to freq.

Comparison of CSI and VSI :-

① CSI is more reliable than VSI because

ⓐ Conduction of two devices in the same leg due to commutation failure does not lead to sharp rise of current through them due to large dc link inductor.

ⓑ It has inherent protection against a short circuit across the motor terminals.

② Because large inductor in dc link and commutation capacitors CSI Drive has higher cost, weight & volume, low-speed range and slower dynamic response.

③ The CSI drive is not suitable for multi-motor drives. Hence each motor is fed from its own inverter and rectifier. A single converter can be used to feed a number of VSI motor systems, connected in parallel. A single VSI can similarly feed a no. of motors connected in parallel.

Rotor Resistance Control :-

Introduction :- (Slip-Ring Induction Motor)

→ The wound-rotor motor has a number of disadvantages compared to squirrel cage induction motor such as higher cost, weight, volume & inertia and frequent maintenance due to the presence of brushes & slip rings.

→ The control of a wound-rotor motor from the rotor allows cheaper drives to be obtained for a few specific applications.

→ The rotor winding is designed to have a low resistance so that running efficiency is high and the full-load slip is low.

→ In a wound-rotor motor, the improved starting performance is obtained by connecting an external resistance in series with the rotor winding.

→ The increase in the rotor resistance does not affect the value of maximum torque but increases the slip at max torque occurs.

→ When high starting torque is needed, the rotor resistance can be chosen to obtain the max. torque at standstill. This also decreases the starting current substantially.

→ External resistances can be decreased, as the rotor speeds up, making the max torque available throughout accelerating (period) range.

→ Since most of the rotor cu losses occurs in the external resistors, the rotor temperature rise during starting is substantially lower than it would be if resistance were incorporated in the rotor winding as in the case of squirrel cage motors. This allows optimum use of the motor torque capability. Hence, the wound rotor motor is widely used in applications requiring frequent starting & braking with large motor torques.

Introduction :- (Rotor Resistance Control).

→ Speed - Torque characteristics for rotor resistance control is shown in below fig@

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→ Effective Value of resistance across terminals A and B (R_{AB}) is Varied by Varying duty cycle of Transistor T_r, which in turn Varies rotor circuit resistance.

→ Inductance L_d is added to reduce ripple and discontinuity in the dc link current I_d.

→ Rotor current waveform is shown in fig ⓒ, when ripple is neglected. Thus rms rotor current is given by $I_r = \sqrt{\frac{2}{3}} I_d$

→ Resistance between terminals A and B will be zero when transistor is ON and it will be 'R' when it is off.

∴ Average Value of resistance $= R_{AB} = (1-\delta)R$

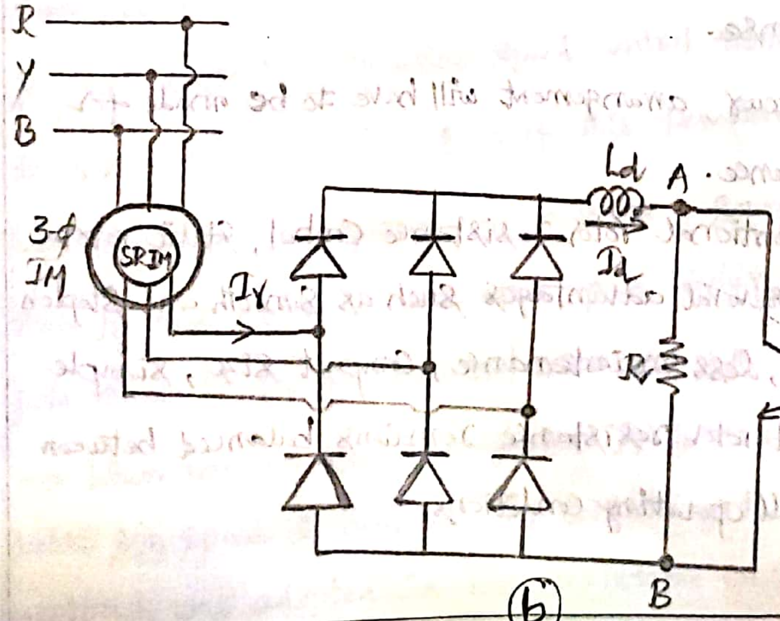
where $\delta = \frac{t_{ON}}{T}$ = Duty ratio

power consumed by $R_{AB} = P_{AB} = I_d^2 R_{AB} = I_d^2 (1-\delta)R = \frac{3}{2} I_r^2 (1-\delta)R$

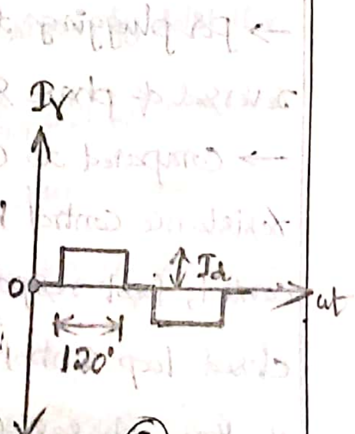
perphase power consumed by $R_{AB} = \frac{P_{AB}}{3} = 0.5\, I_r^2 (1-\delta)R$

→ The above equation is suggests that the rotor circuit resistance perphase is increased by $0.5R(1-\delta)$. Thus total rotor circuit resistance perphase $= R_{rT} = R_r + 0.5R(1-\delta)$

R_{rT} can be Varied from R_r to $(R_r + 0.5R)$ as δ is changed from 1 to 0.

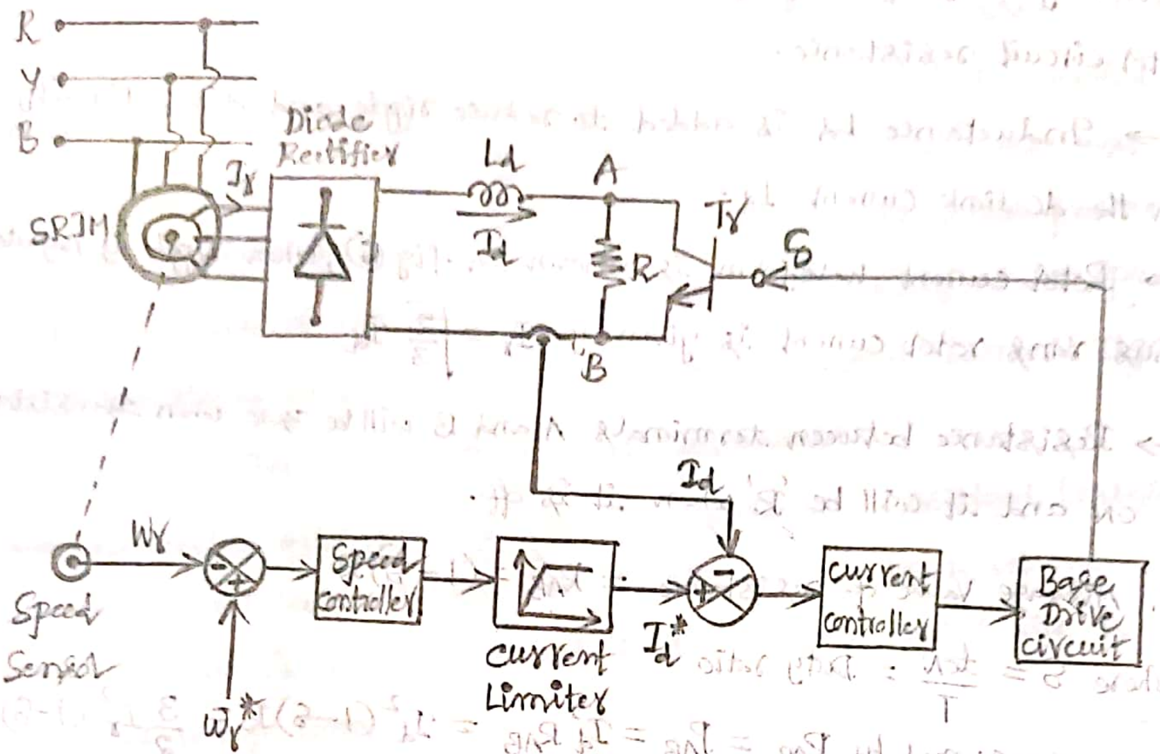


ⓑ



ⓒ

closed Loop Speed control of Static-Rotor Resistance Control :-



→ A closed loop speed control scheme with inner current control loop is shown above.

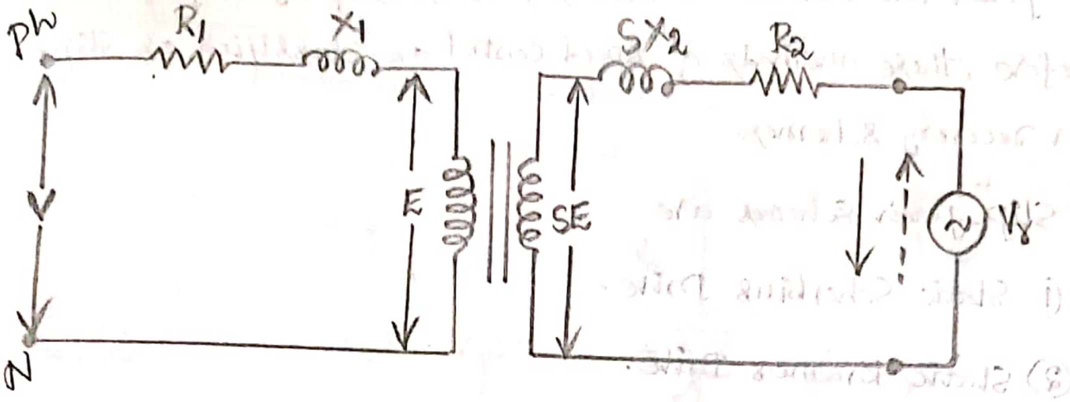
→ Rotor current I_r, and hence I_d has a constant value at the max torque point both during motoring and braking (plugging).

→ If the current limiter is made to saturate at this current, the drive will accelerate and decelerate at the max torque, giving very fast transient response.

→ For plugging to occur, arrangement will have to be made for reversal of phase sequence.

→ Compared to conventional rotor resistance control, static rotor resistance control has several advantages such as smooth and stepless control, fast response, less maintenance, compact size, simple closed-loop control and rotor resistance remains balanced between the three phases for all operating conditions.

Slip Power Recovery (or) Slip Energy Recovery (SER):-



→ Figure shows an equivalent circuit of a wound-rotor induction motor with voltage V_r injected into its rotor, assuming stator to rotor turns ratio unity.

→ When rotor cu losses are neglected $P_m = P_g - P_r$

where P_r = Power absorbed by the source (V_r).

→ The magnitude of P_r and sign of P_r can be controlled by controlling the magnitude & phase of V_r.

→ When P_r is zero, motor runs on its natural speed characteristics

→ A positive P_r will reduce P_m and therefore motor will run at a lower speed for the same torque. When P_r is made equal to P_g, then P_m and conseruently speed will be zero. Thus variation of P_r from 0 to P_g will allow speed control from synchronous speed to zero speed. polarity of V_r of this operation is shown by solid line.

→ When P_r is negative, V_r acts as a source P_m will be larger than P_g and motor will run at a speed higher than synchronous speed polarity of V_r for speed control above the syn speed shown by dotted line.

→ When rotor cu loss is neglected P_r is equal to SP_g. Speed control below syn speed is obtained by controlling the slip-power. The same approach was adopted in rotor resistance control.

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→ In contrast to the rotor resistance control, instead of wasting power in external resistors, it is usefully employed here. Therefore, these methods of speed control are classified as slip-power recovery schemes.

→ Slip-power schemes are

① Static Scherbius Drive.

② Static Kramer Drive.

Static Scherbius Drive :-

→ It provides the speed control of a wound rotor motor below sync speed. A portion of rotor ac power is converted into dc by a diode bridge.

→ The controlled rectifier working as an inverter converts it back to ac and feeds it back to the ac source.

→ Power fed back (P_r) can be controlled by controlling inverter counter emf V_{d2}, which in turn controlled by controlling the inverter firing angle.

→ The dc link inductor is provided to reduce ripple in dc link current I_d.

→ Since slippower is fed back to the source, unlike rotor resistance control where it is wasted in resistors, drive has a high efficiency.

→ Drive input power is the difference between motor input power and the power fed back.

→ Reactive input power is the sum of motor and inverter reactive powers. Therefore the drive has a poor PF throughout the range of its operation.

→ Neglect the stator and rotor drops,

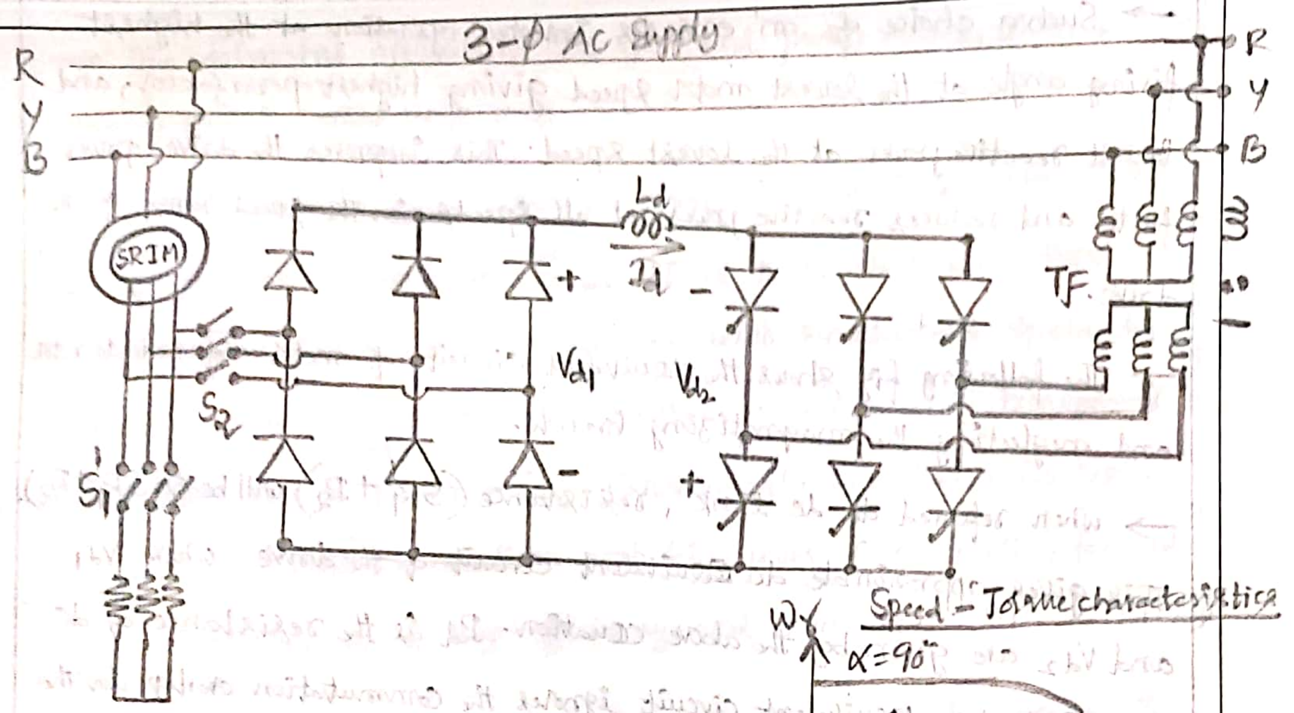
$$V_{d1} = \frac{3\sqrt{6}}{\pi} \frac{sV}{n}$$

$$V_{d2} = \frac{3\sqrt{6}}{\pi} \frac{V}{m} \cos\alpha$$

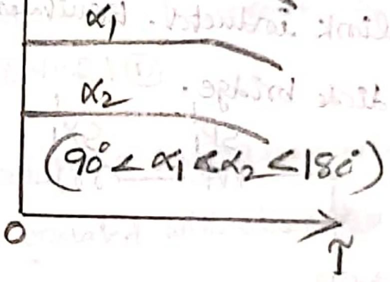
α = Inverter firing angle, n = Stator to rotor turns ratio of motor

m = Source side to converter side turns ratio of the transformer.

V = phase voltage of the motor



Speed – Torque characteristics



→ Neglecting the drop across inductor

$$\therefore V_{d1} + V_{d2} = 0$$

$$\frac{3\sqrt{6}}{\pi}\frac{SV}{n} + \frac{3\sqrt{6}}{\pi}\frac{V}{m}\cos\alpha = 0$$

$$S = -\frac{n}{m}\cos\alpha = -a\cos\alpha, \text{ where } a = n/m.$$

→ Max Value of 'α' is restricted to 165° for safe commutation of inverter thyristors. Slip can be controlled from 0 to 0.966a when α is changed from 90 to 165°. By appropriate choice of 'a', required speed range can be obtained.

→ Transformer is used to match the Voltages V_{d1} and V_{d2}.

→ The lowest speed required from the drive V_{d1} will have the max value

$$(V_{d1})_{max} = \frac{VS_{max}}{n} \qquad S_{max} = \text{Slip at the lowest speed.}$$

If 'α' is restricted to 165°, 'm' is chosen such that the inverter Voltage has a value $(V_{d1})_{max}$ when α is 165°

$$\frac{VS_{max}}{n} + \frac{V}{m}\cos 165^\circ = 0$$

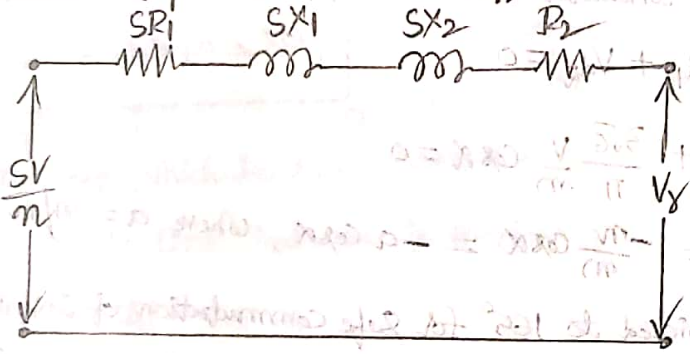
$$m = -\frac{n\cos 165^\circ}{S_{max}} = -0.966\frac{n}{S_{max}}$$

→ Such a choice of 'm' ensures inverter operation at the highest firing angle at the lowest motor speed giving highest powerfactor, and lowest reactive power at the lowest speed. This improves the drive power factor and reduces reactive power at all speeds in the speed range of the drive.

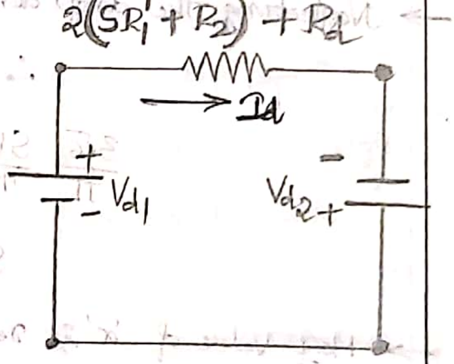
→ The following fig shows the equivalent circuit of motor referred to rotor and neglecting the magnetizing branch.

→ when referred to dc link, resistance $(SR_1' + R_2)$ will be $2(SR_1' + R_2)$ This gives approximate dc equivalent circuit of the drive, where V_{d1} and V_{d2} are given by the above equation. R_d is the resistance of dc link inductor. Equivalent circuit ignores the commutation overlap in the diode bridge.

ⓐ Equivalent circuit of the motor as ref. to rotor



ⓑ Equivalent circuit of the Drive



$$\rightarrow \text{Dc link current } I_d = \frac{V_{d1} + V_{d2}}{2(SR_1' + R_2) + R_d} = \frac{\frac{3\sqrt{6}}{\pi} V\left(\frac{S}{n} + \frac{\cos\alpha}{m}\right)}{2(SR_1' + R_2) + R_d}$$

If Rotor cu loss is neglected $SP_g = |V_{d2}| I_d$

$$P_g = \frac{|V_{d2}| I_d}{S}$$

$$T = \frac{P_g}{\omega_s} = \frac{|V_{d2}| I_d}{S\omega_s}$$

→ Drive is started by resistance control with S_1 closed and S_2 open

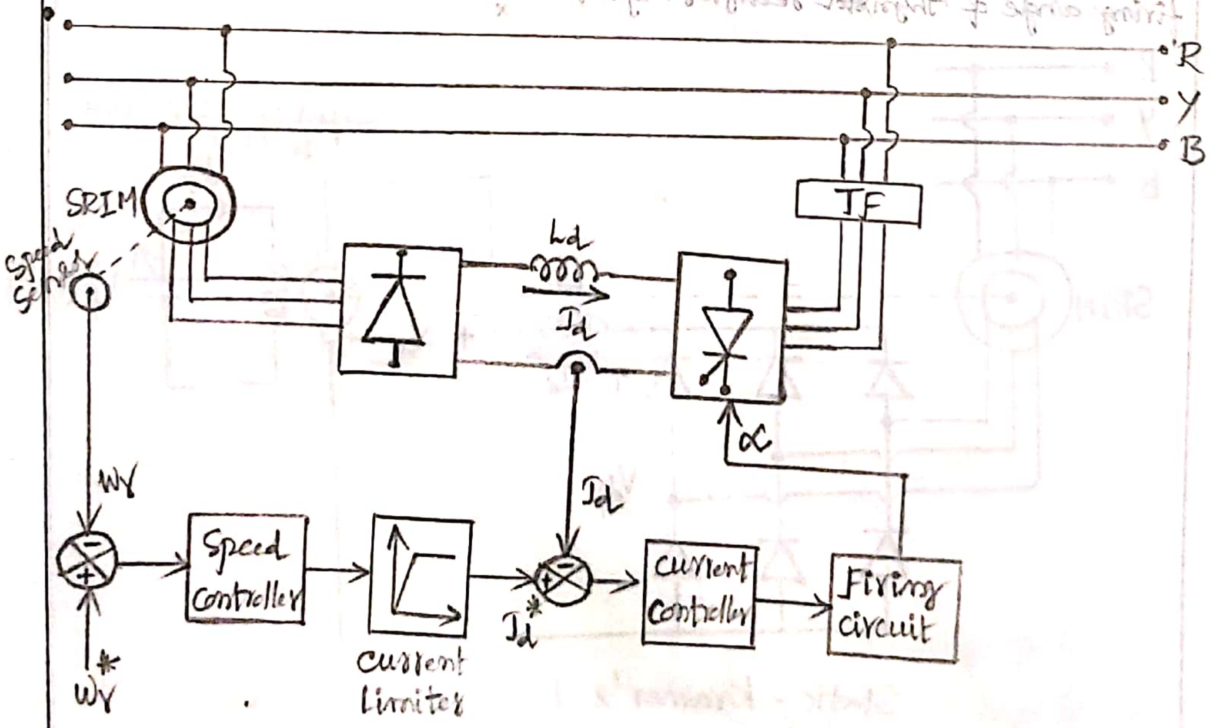
→ when the speed reaches within control range S_1 is opened and S_2 closed to connect diode bridge and inverter is activated

→ The drive has applications in fan and pump drives, which require speed control in narrow range only.

→ If max. slip is S_{max}, then the power rating of diode bridge, inverter and transformer can be just S_{max} times the motor power rating. For example, when speed is to be reduced below synchronous speed by only 20%, power ratings of diode bridge, inverter and transformer will be just 20% of motor power rating. Consequently drive has a low cost. This drive is used in medium and high power (upto 10MW) fan and pump drives because of high efficiency and low cost.

→ In fan and pump drives braking is not required, because the fluid pressure provides adequate braking torque.

→ To maintain constant fluid flow with variations in pressure head and the nature of pumped fluid, the drive is operated with closed loop speed control. A closed-loop speed control scheme with inner current control is shown in below fig.



TF – Transformer.

→ This drive provides a constant torque control. Constant power control is obtained by Static Kramer's drive.

Static Kramer Drive :-

→ The drive circuit is shown in fig ⓐ. Rotor slip power is converted into dc by a diode bridge. The dc power is now fed to dc motor mechanically coupled induction motor.

→ Torque supplied to load is sum of torque produced by induction and dc motors.

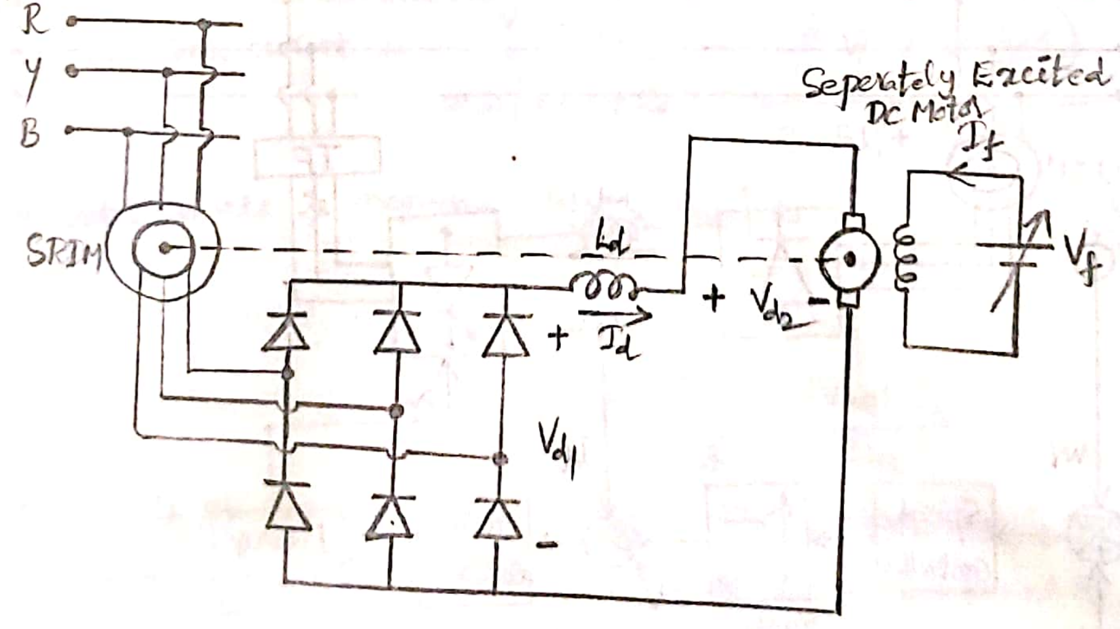
→ Speed control is obtained by controlling field current of dc motor.

→ fig ⓑ shows variations of V_{d_1}, V_{d_2} with speed for two values of dc motor field current. The steady state operation is obtained when $V_{d_1} = V_{d_2}$ ie at A and B for field currents I_{f_1} and I_{f_2}.

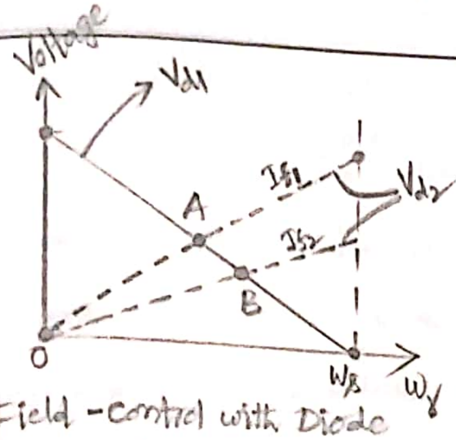
→ Speed control is possible from syn speed to around half of syn speed.

→ when larger speed range is required, diode bridge is replaced by a thyristor bridge.

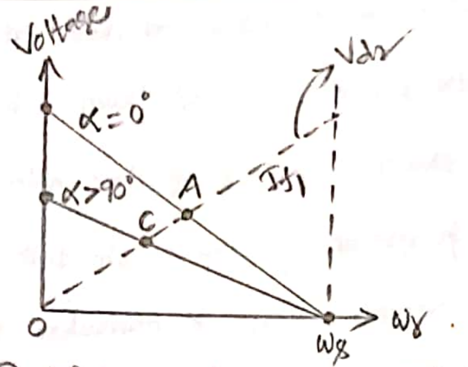
→ Now relationship between V_{d_1} and speed can be altered by controlling firing angle of thyristor rectifier. Speed can now be controlled upto standstill.



Static-Kramer's Drive circuit.



ⓑ Field -control with Diode Bridge



© Firing Angle control of Thyristor Bridge with Constant Motor field.