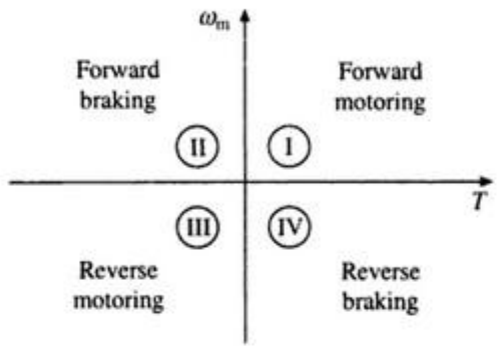
MODEL TEST PAPER

Q1. Explain speed torque conventions and multi quadrant operations.

Sol. A motor operate in 2 modes – Motoring and braking. In motoring, it converts electrical energy into mechanical energy which support its motion. In braking, it converts as a generator converting mechanical energy into electrical energy and thus opposes the motion. Motor can provide motoring & braking for both forward & reverse directions. Power developed by a motor is given by the product of speed & torque.



 The speed is assumed to be positive if the direction of rotation is anticlockwise or in such a way to cause an 'upward' or forward motion of the drive. For reversible drive positive direction of the speed can be assumed arbitrarily either clockwise or anticlockwise.

 The motor torque is positive if it produces increase in speed in the positive sense. The load torque is assigned the positive sign when it is directed against the motor torque.

 Plot of speed torque characteristics of the load/ motor for all four quadrant of operation is known as quadrant diagram.

Four Quadrant Operation

- Motor is driving a hoist consisting of a cage with or without load, a rope wound on to a drum to hoist the cage and a balance weight of magnitude greater than that of the empty cage but less than that of the loaded cage.
- The arrow in the figure indicates the actual directions of the motor torque, load torque and motion in four quadrants.
- The load torque of the hoisting mechanism is of active type and assumed to be constant due to negligible friction and windage for low speed hoist.

- Speed torque curve of the hoist is represented by vertical line passing through two quadrants. Loaded hoist characteristics in first and fourth and unloaded in second and third quadrants. Here T is motor torque and T1 is load torque.

- In the first quadrant the load torque acts in the opposite direction to that of rotation. Hence to drive the loaded hoist up, the motor developed torque must be in the direction of the rotation or must be positive. The power will also be positive so, this quadrant is known as **'forward motoring quadrant'.**
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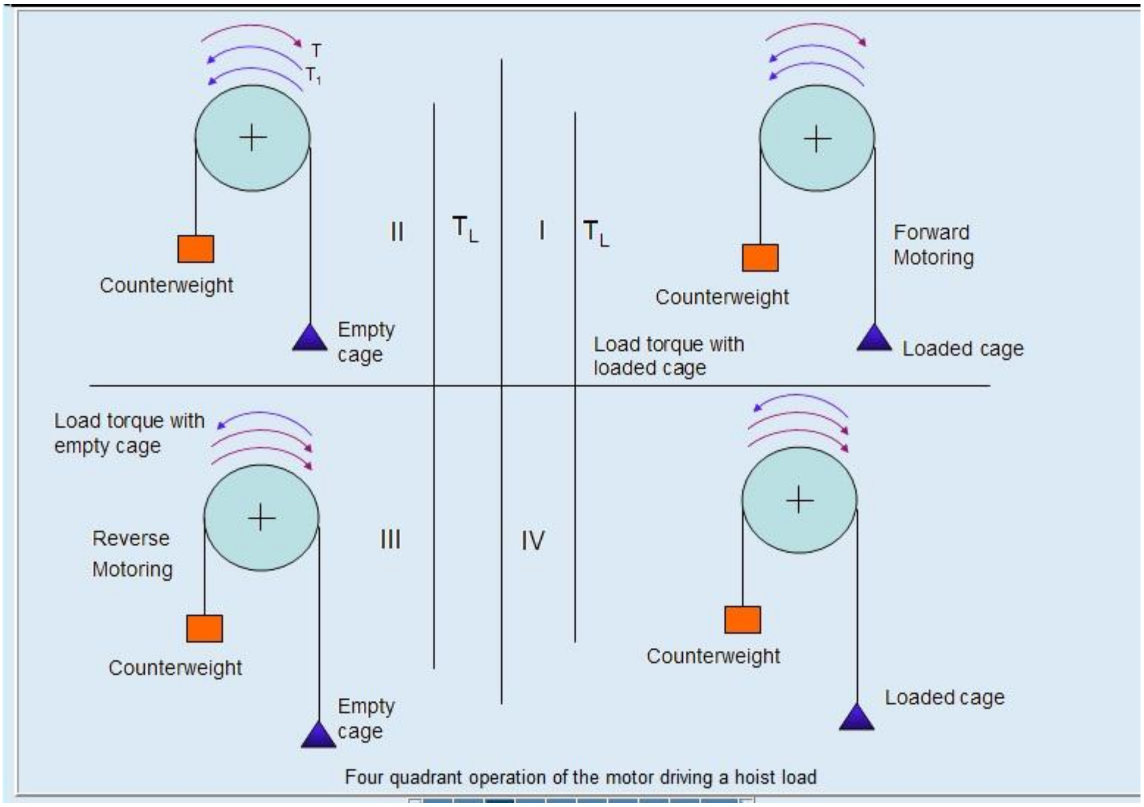
- The hoisting up of the unloaded cage is represented in the second quadrant. As the counterweight is heavier than the empty cage, the speed at which hoist moves upwards may reach a very high value. To avoid this, the motor torque must act in the opposite direction of rotation or motor torque must be negative. The power will be negative though the speed is positive, so this quadrant is known as **'forward braking quadrant'**.

- The third quadrant represents the downward motion of the empty cage. Downward journey will be opposed by torque due to counterweight and friction at the transmitting parts, move cage downwards the motor torque should must be in the direction of the rotation. Electric machine acts as a motor but in the reverse direction compared to first quadrant. The torque is negative as speed is increased I the negative direction, but the power is positive, this quadrant is known as **'Reverse motoring quadrant'**.

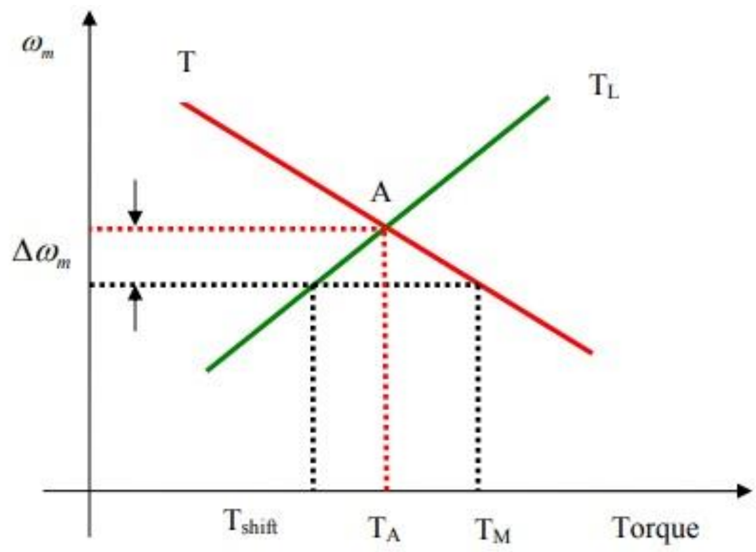
- Fourth quadrant has the downward motion of the loaded cage. As loaded cage has more weight than the balanced weight to limit the speed of the motion, motor torque must have opposite polarity with respect to rotation and acts as a brake. The motor torque sign is positive, but as speed has negative direction; the power will be negative, this quadrant is designated as **'Reverse braking quadrant'.**



2. what do you mean by steady state stability? Derive equivalent value of drive parameters.

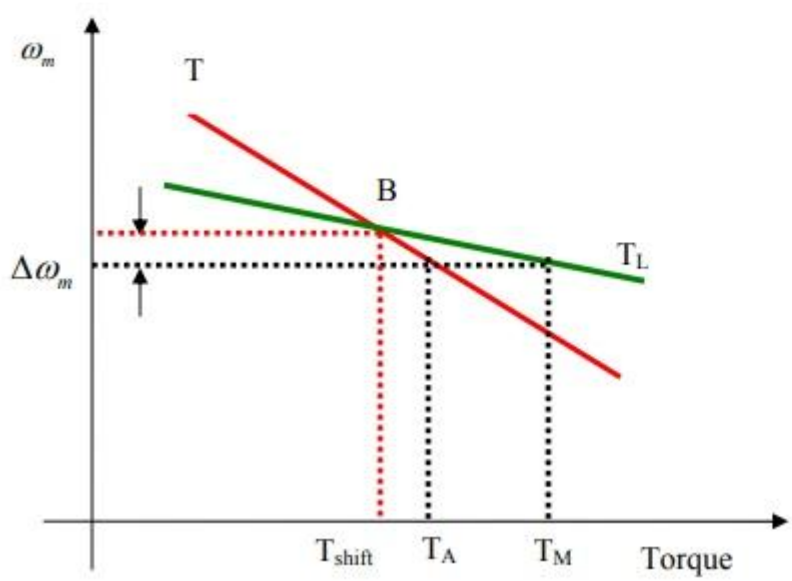
Steady State Stability:

Equilibrium speed of motor-load system can be obtained when motor torque equals the load torque. Electric drive system will operate in steady state at this speed, provided it is the speed of stable state equilibrium. Concept of steady state stability has been developed to readily evaluate the stability of an equilibrium point from the steady state speed torque curves of the motor and load system. In most of the electrical drives, the electrical time constant of the motor is negligible compared with the mechanical time constant. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation. Now, consider the steady state equilibrium point A shown in figure below.



The equilibrium point will be termed as stable state when the operation will be restored to it after a small departure from it due to disturbance in the motor or load. Due to disturbance a reduction of Δω m in speed at new speed, electrical motor torque is greater than the load torque, consequently motor will accelerate and operation will be restoring to point A. similarly an increase in Δω m speed caused by a disturbance will make load torque greater than the motor torque, resulting into deceleration and restoring of operation to point A.

Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure. A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B. Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B.



From the above discussions, an equilibrium point will be stable when an increase in speed causes load torque to exceed the motor torque. (i.e.) When at equilibrium point following conditions is satisfied.

$$\frac{dT_L}{d\omega_m} > \frac{dT}{d\omega_m} \text{-------------} (1)$$

Inequality in the above equation can be derived by an alternative approach. Let a small perturbation in speed, Δω m results in ΔT and ΔTl perturbation in T and Tl respectively. Therefore the general load torque equation becomes

$$(T + \Delta T) = (T_l + \Delta T_l) + \frac{Jd(\omega_m + \Delta\omega_m)}{dt}$$

$$= \; T + \Delta T = T_l + \Delta T_l + \frac{Jd\omega_m}{dt} + J\frac{d\Delta\omega_m}{dt} \text{----} (2)$$

The general equation is

$$T = T_l + J\frac{d\omega_m}{dt} \text{-------} (3)$$

Subtracting (3) from (2) and rearranging

$$J\frac{d\omega_m}{dt} = \Delta T - \Delta T_l \text{---------} (4)$$

From small perturbations, the speed –torque curves of the motor and load can be assumed to be straight lines, thus

$$\Delta T = \left(\frac{dT}{d\omega_m}\right)\Delta\omega_m -------(5)$$

$$\Delta T_l = \left(\frac{dT_l}{d\omega_m}\right)\Delta\omega_m -------(6)$$

Where $\frac{dT}{d\omega_m}$ and $\frac{dT_l}{d\omega_m}$ are respectively slopes of the steady state speed torque curves of motor and load at operating point under considerations. Substituting (5) and (6) in (4) we get,

$$J\frac{d\Delta\omega_m}{dt} + \left(\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m}\right)\Delta\omega_m = 0 -----(7)$$

This is a first order linear differential equation. If initial deviation in speed at t=0 be $(\Delta\omega_m)_0$ then the solution of equation (7) is

$$\Delta\omega_m = (\Delta\omega_m)_0 \exp\left\{-\frac{1}{J}\left(\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m}\right)t\right\} -----(8)$$

An operating point will be stable when $\Delta\omega_m$ approaches zero as t approaches infinity. For this to happen exponential term in equation (8) should be negative.

3. Explain various methods of control of dc motors.

Speed of a DC motor

We know, back emf E_b of a DC motor is the induced emf in the armature conductors due to the rotation of armature in magnetic field. Thus, magnitude of the E_b can be given by the EMF equation of a DC generator.

$$E_b = \frac{\Phi ZNP}{60A}$$

(where, P = no. of poles, Ø = flux/pole, N = speed in rpm, Z = no. of armature conductors, A = parallel paths)

thus, from the above equations

$$N = \frac{E_{b\,60A}}{\Phi ZP}$$

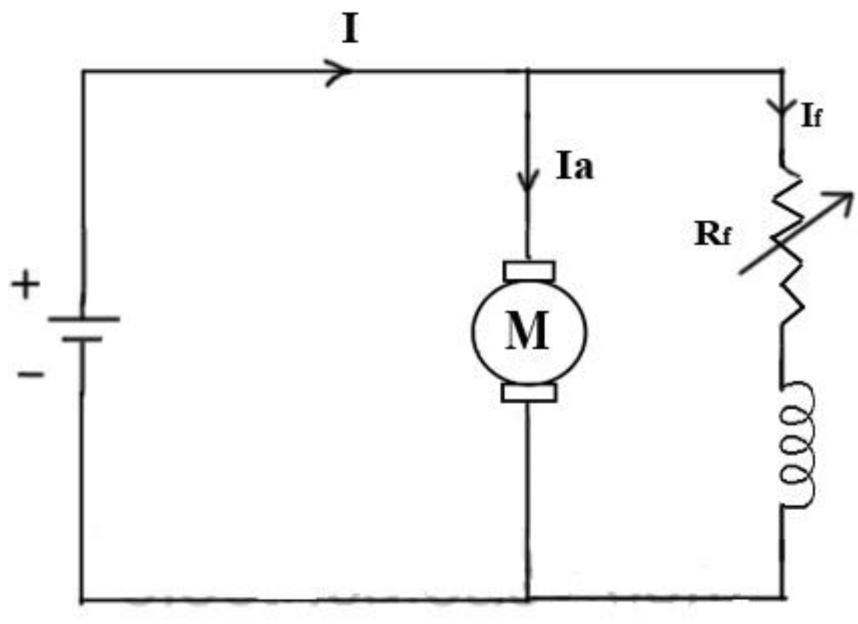
but, for a DC motor A, P and Z are constants

Therefore, $N \propto K\ {}^{E_b}/_{\text{Ø}}$ (where, K=constant)

This shows the speed of a dc motor is directly proportional to the back emf and inversely proportional to the flux per pole.

Speed control of Shunt motor

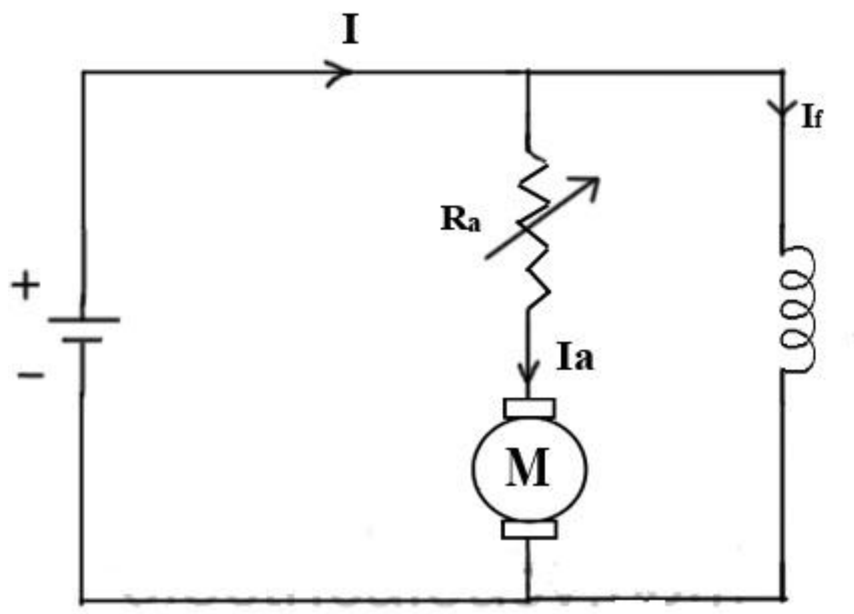
Flux control method: It is already explained above that the **speed of a dc motor** is inversely proportional to the flux per pole. Thus by decreasing the flux, speed can be increased and vice versa. To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram. Adding more resistance in series with the field winding will increase the speed as it decreases the flux. In shunt motors, as field current is relatively very small, I_{sh}^2R loss is small and, hence, this method is quite efficient. Though speed can be increased above the rated value by reducing flux with this method, it puts a limit to maximum speed as weakening of flux beyond the limit will adversely affect the commutation.



2. Armature control method: **Speed of a dc motor** is directly proportional to the back emf E_b and

$E_b = V - I_aR_a$.

That means, when the supply voltage V and the armature resistance R_a are kept constant, speed is directly proportional to the armature current I_a. Thus, if we add a resistance in series with the armature, I_a decreases and, hence, the speed also decreases. Greater the resistance in series with the armature, greater the decrease in speed.

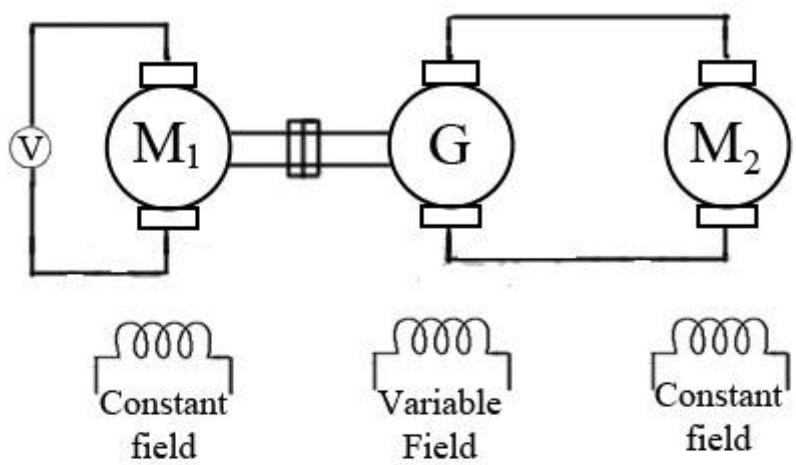


3. Voltage Control Method:

a) **Multiple voltage control**: In this method, the shunt field is connected to a fixed exciting voltage and armature is supplied with different voltages. Voltage across armature is changed with the help of a suitable switchgear. The speed is approximately proportional to the voltage across the armature.

b) **Ward-Leonard System**:

This system is used where very sensitive **speed control of motor** is required (e.g electric excavators, elevators etc.). The arrangement of this system is as shown in the figure at right.M_2 is the motor whose speed control is required.M_1 may be any AC motor or DC motor with constant speed.G is a generator directly coupled to M_1.
In this method, the output from the generator G is fed to the armature of the motor M_2 whose speed is to be controlled. The output voltage of the generator G can be varied from zero to its maximum value by means of its field regulator and, hence, the armature voltage of the motor M_2 is varied very smoothly. Hence, very smooth **speed control of the dc motor** can be obtained by this method.



Speed control of series motor

1. Flux control method

- <u>Field divertor</u>: A veritable resistance is connected parallel to the series field as shown in fig (a). This variable resistor is called as divertor, as the desired amount of current can be diverted through this resistor and hence current through field coil can be decreased. Hence, flux can be decreased to the desired amount and speed can be increased
- <u>Armature divertor</u>: Divertor is connected across the armature as in fig (b). For a given constant load torque, if armature current is reduced then flux must increase. As, $Ta \propto ØIa$ This will result in an increase in current taken from the supply and hence flux Ø will increase and subsequently **speed of the motor** will decrease.
- <u>Tapped field control</u>: As shown in fig (c) field coil is tapped dividing number of turns. Thus we can select different value of Ø by selecting different number of turns.
- <u>Paralleling field coils</u>: In this method, several speeds can be obtained by regrouping coils as shown in fig (d).
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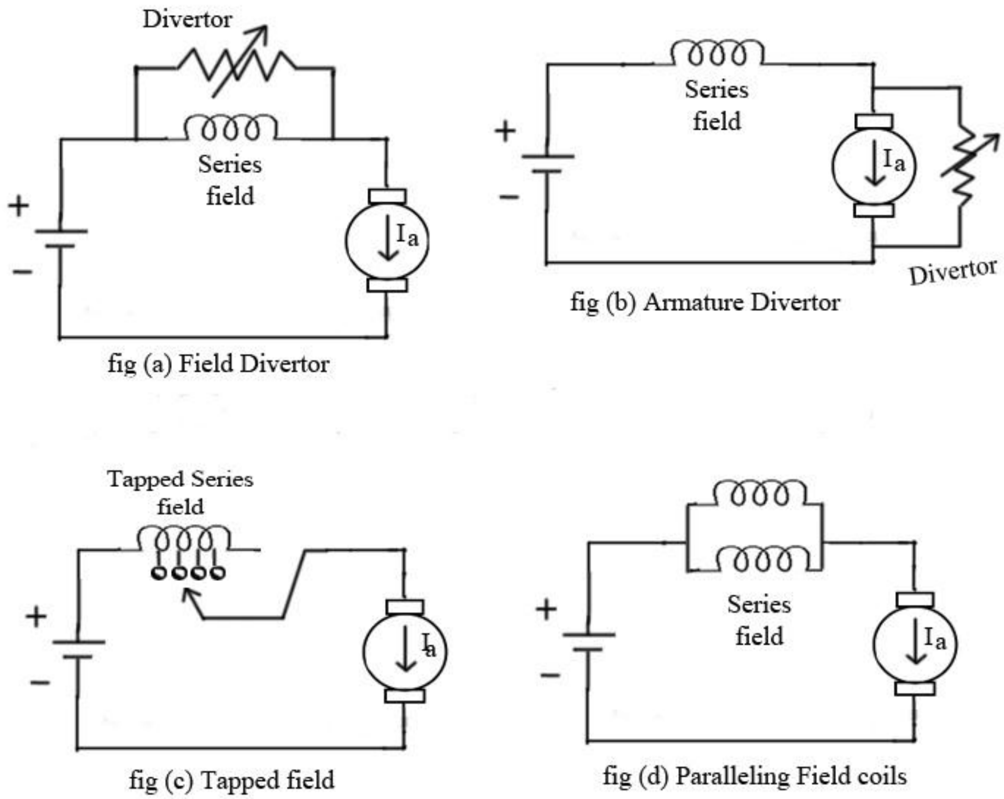


2.Variable resistance in series with armature

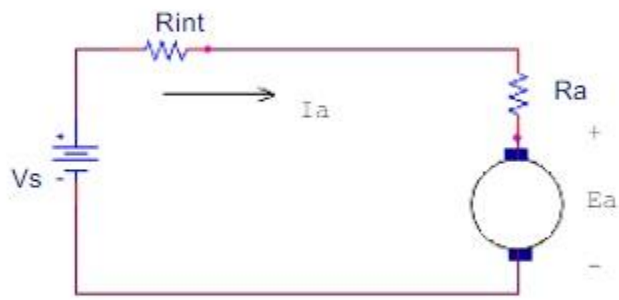
By introducing a resistance in series with the armature, voltage across the armature can be reduced. And, hence, speed reduces in proportion with it.

3. Series-parallel control

This system is widely used in electric traction, where two or more mechanically coupled series motors are employed. For low speeds, the motors are connected in series, and for higher speeds the motors are connected in parallel.
When in series, the motors have the same current passing through them, although voltage across each motor is divided. When in parallel, the voltage across each motor is same although the current gets divided.

4. A 220V, 200 A, 800 rpm dc separately excited motor has an armature resistance of 0.06Ω.The motor armature is fed from a variable voltage source with an internal resistance of 0.04Ω . Calculate internal voltage of the variable voltage source (VVS) when the motor is operating in motoring at 50% of the rated motor torque and 400 rpm.

Sol. We know that the motor torque,Tm is proportional to the armature current, Ia. The motorspeed, N is proportional to the back emf, E



The motor armature current at 50% of the rated motor torque is

$$Ia = 0.5 \times 200 = 100A$$

The back emf at the rated speed and the rated torque is

$$E = Va - IaRa = 220 - 200 \times 0.06 = 208 \text{ V}$$

The back emf at 400 rpm is

$$E = \frac{N_2}{N_1} \times E = \frac{400}{800} \times 208 = 104 \text{ V}$$

Internal voltage of VVS is

$$V_{int} = E + I_a(R_a + R_{int}) = 104 + 100(0.06 + 0.04) = 114\,V.$$

5. A DC motor with a separately excited field winding is considered. The rated armature voltage is UN = 600 V, rated torque TN = 420 Nm, rated speed N = 1600 r/min, and maximum speed Nmax = 3200 r/min. The losses are omitted.

(a) The flux factor kf is kept constant at its rated value. When the armature voltage is varied from 0 to UN, the speed varies from 0 to N. Determine the rated armature current IN.

(b) A load is to be driven in the speed range from N to Nmax by weakening the flux factor while the armature voltage is kept constant at UN Determine the torque available at maximum speed, if the rated armature current IN is not exceeded.

Sol. The losses are omitted, i.e., Ra = 0 holds. Hence, the steady-state equations of the DC motor are

(a) Let us first calculate the rated rotor speed in radians per second:

$$\omega_N = 2\pi n_N = 2\pi \cdot \frac{1600 \text{ r/min}}{60 \text{ s/min}} = 167.6 \text{ rad/s}$$

The rated flux factor is

$$k_{fN} = \frac{U_N}{\omega_N} = \frac{600 \text{ V}}{167.6 \text{ rad/s}} = 3.58 \text{ Vs}$$

The rated armature current is

$$I_N = \frac{T_N}{k_{fN}} = \frac{420 \text{ Nm}}{3.58 \text{ Vs}} = 117.3 \text{ A}$$

(b) The maximum rotor speed in radians per second is

$$\omega_{max} = 2\pi n_{max} = 2\pi \cdot \frac{3200 \text{ r/min}}{60 \text{ s/min}} = 335.1 \text{ rad/s}$$

The flux factor at the maximum speed is

$$k_f = \frac{U_N}{\omega_{max}} = \frac{600 \text{ V}}{335.1 \text{ rad/s}} = 1.79 \text{ Vs}$$

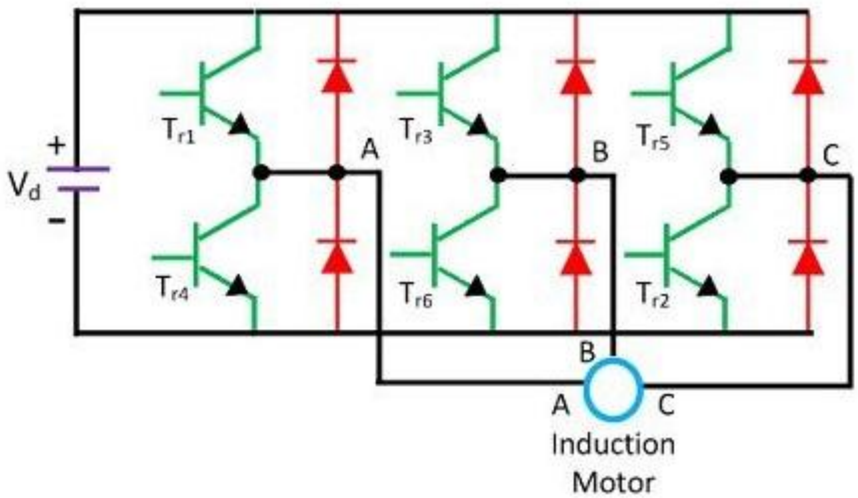
The torque at the maximum speed is

$$T_M = k_f I_N = 1.79 \text{ Vs} \cdot 117.3 \text{ A} = 210 \text{ Nm}$$

The same result could be obtained as $T_M = (n_N/n_{max})T_N$, i.e. the torque reduces inversely proportionally to the speed in the field-weakening region.

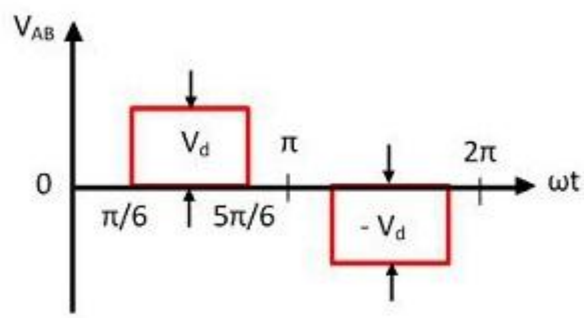
6. Discuss voltage source inverter (VSI) fed Induction motor drives.

Sol. The voltage source inverter is defined as the inverter which takes a variable frequency from a DC supply. The input voltage of the voltage source inverter remains constant, and their output voltage is independent of the load. The magnitude of the load current depends on the nature of the load impedance.

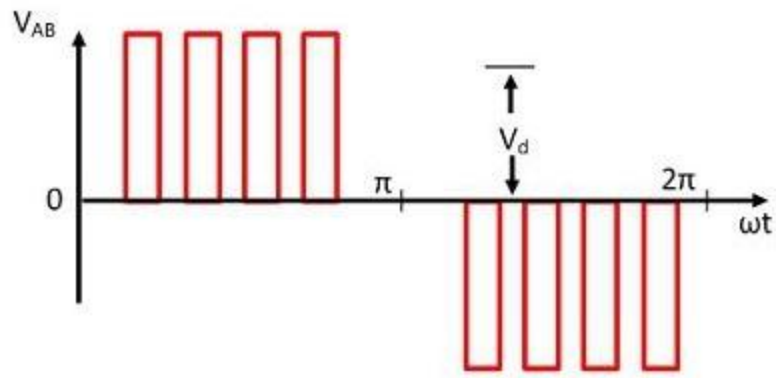


The voltage source inverter use self-commutated device like MOSFET, IGBT, GTO, etc. It is operated as a stepped-wave inverter or a pulse width modulation. When the voltage source inverter is operated as a stepped-wave inverter, then the transistor is switched in the sequence of their number with a time difference of T/6.

The each of the transistors is kept on for the duration of T/2, where T is the period for one cycle. The waveform of the line voltage is shown in the figure below. The frequency of the inverter is varied by varying T, and the output voltage of the inverter is varied by varying DC input voltage.

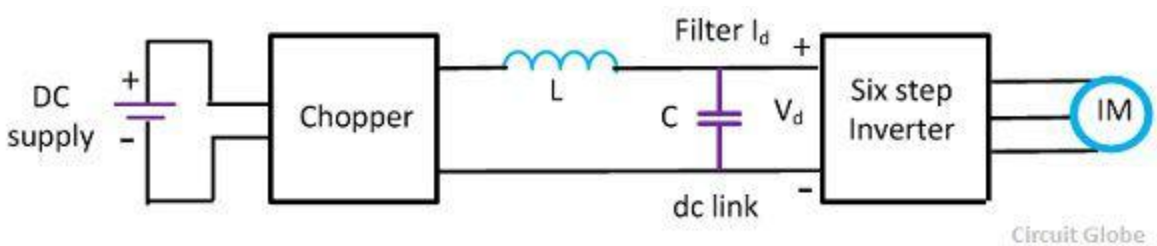


Stepped wave inverter line voltage waveform

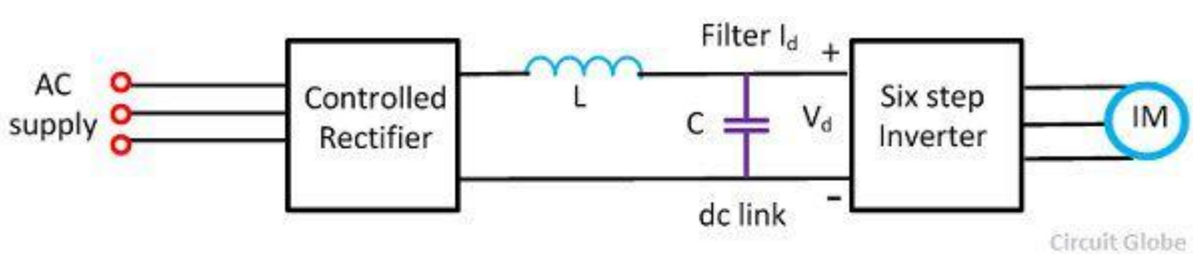


PWM inverter line voltage waveform

When the supply is DC, then the variable DC input is obtained by connecting a chopper between DC supply and inverter.



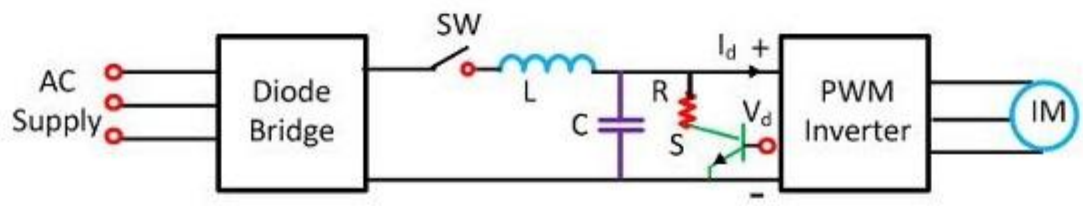
When the supply is AC, then the DC input voltage is obtained by connecting the controlled rectifier between the AC supply and inverter shown in the figure below.The capacitor C filter out the harmonics in DC link voltage.



The main drawback of the VSI induction motor drive is the large harmonics of the low frequency in the output voltage. The harmonics increases the loss in the motor and cause the jerky motion of the rotor at low speed.

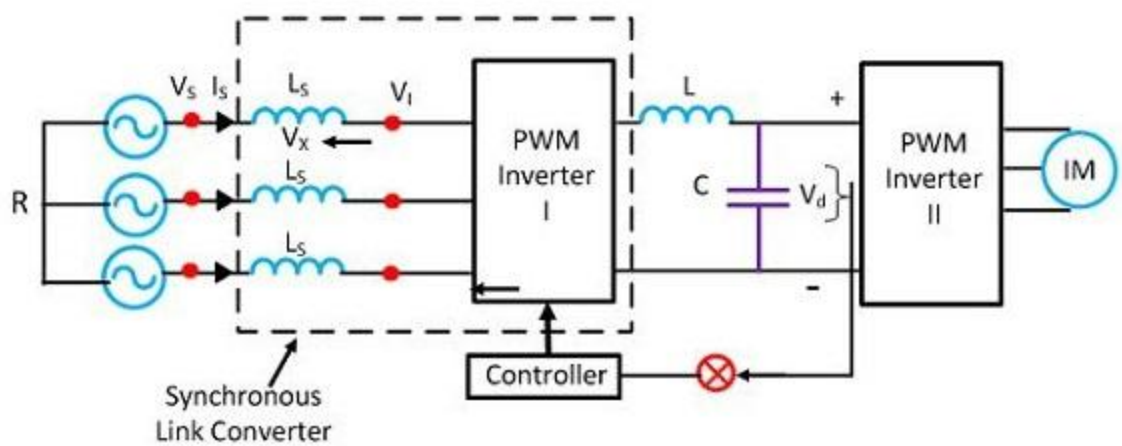
7. Discuss the dynamic braking and regenerative braking of VSI fed Induction motor drives.

Dynamic Braking: In dynamic braking, the switch SW and a self-commutated switch in series with the braking resistance R are connected across the DC links. When the operation of the motor is shifted from motoring to braking switch SW is opened. The energy flowing through the DC link charges the capacitors and its voltage rises.



Dynamic braking of VSI controlled induction motor drive

Regenerative Braking: Let us consider the regenerative braking of pulse width modulation of inverter drive. When the operation shift from motoring to braking, the DC link current I_d reverse and flows into the DC supply feeding the energy to the source.Thus the drive already has the regenerative braking capability.



VSI Induction motor drive with regenerative braking capability

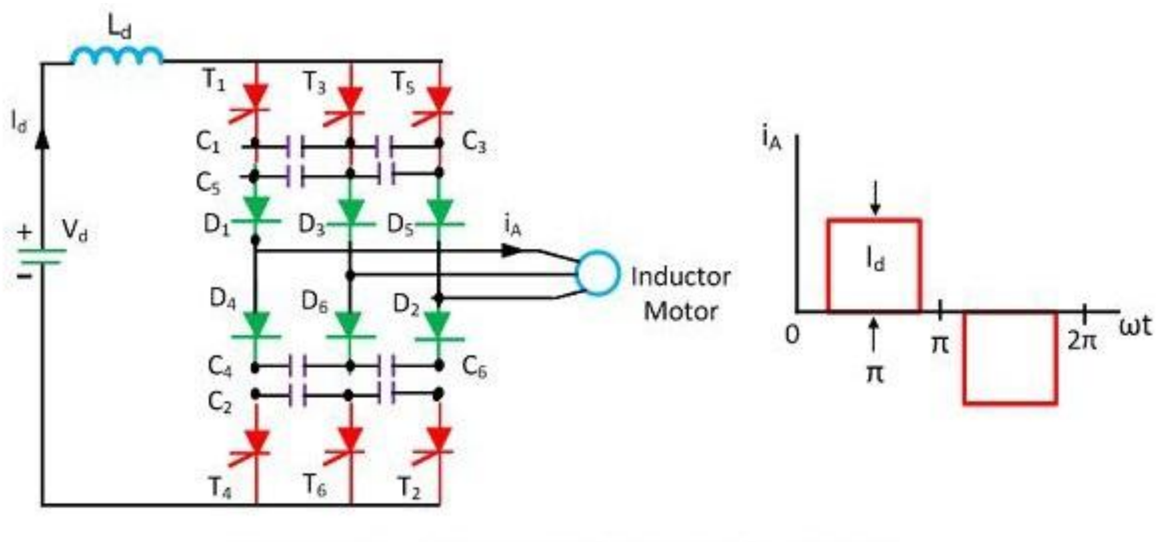
In regenerative braking the, the power supply to the DC link must be transferred to the AC supply. When the operation shift from motoring to braking, the DC link current I_d reverse, but the V_d remain in the same direction. Thus, for regenerative braking, a converter is required for converting the DC voltage and direct current in either direction.

8. Explain the Current source inverter control of Induction motor drive.

Definition: The current source inverter converts the input direct current into an alternating current. In current source inverter, the input current remains constant but this input current is adjustable. The current source inverter is also called current fed inverter. The output voltage of the inverter is independent of the load. The magnitude and nature of the load current depends on the nature of load impedance.

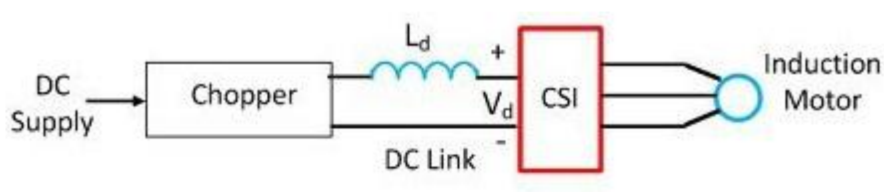
Current Source Inverter Control

A thyristor current source inverter is shown in the figure below. The diodes D_1-D_6 and capacitor C_1-C_6 provide commutation of thyristor T_1-T_6, which are fired with a phase difference of 60º in the sequence of their number. It also shows the nature of the output current waveform. The inverter act as a current source due to large inductance L_D in DC link. The fundamental component of motor phase current is shown in the figure below.



Current source inverter fed induction motor drive

The torque is controlled by varying DC link current I_d by changing the value of V_d. When the supply is AC, a controlled rectifier is connected between the supply and inverter. When the supply is, DC a chopper is interposed between the supply and inverter.



Current source inverter of DC motor drive

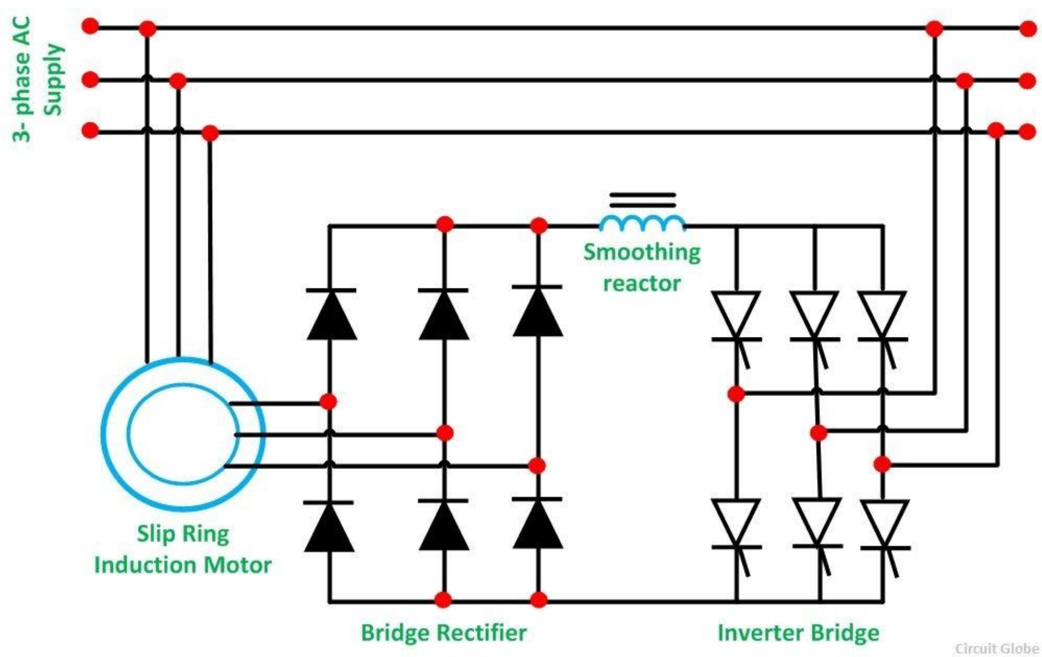
The major advantage of current source inverter is its reliability. In the case of current source inverter a commutation failure in the same leg does not occur due to the presence of a large inductance Ld.

In an induction motor, the rise and fall of current are very fast. This rise and fall of current provide large motor spikes. Therefore a motor of low leakage inductance is used. The commutation capacitance C_1-C_6 reduce the voltage spikes by reducing the rate of rising and fall of the current. A large value of capacitance is required to sufficiently reduced the voltage spikes.

9. Explain slip energy recovery of an induction motor drive.

Slip Energy Recovery is one of the methods of controlling the speed of an **Induction motor.** This method is also known as **Static Scherbius Drive**. In the rotor resistance control method, the slip power in the rotor circuit is wasted as I^2R losses during the low-speed operation. The efficiency is also reduced. The slip power from the rotor circuit can be recovered and fed back to the AC source so as to utilize it outside the motor. Thus, the overall efficiency of the drive system can be increased.

The figure below shows the connection and method for recovering the **slip energy** and **power recovery** of an Induction Motor.



The **basic principle** of the **slip power recovery** is to connect an external source of the EMF of the slip frequency of the rotor circuit. The slip energy recovery method provides the speed control of a **slip ring induction motor** below its synchronous speed. A portion of rotor AC power (slip power) is converted into DC by a diode bridge.

The **smoothing reactor** is provided to **smoothen** the rectified current. The output of the rectifier is then connected to the DC terminals of the inverter. The inverter inverts the DC power to the

AC power and feeds it back to the AC source. The inverter is a controlled rectifier operated in the **inversion mode**.

This method of speed control is used in large power applications where the variation of speed over a wide range involves a large amount of slip power.

10. Explain static rotor resistance control of Induction motor drive.

Rotor Resistance Control is also one of the methods by which we can control the speed of the **Induction motor**. The speed of the wound induction motor can be controlled by connecting an external resistance in the rotor circuit through slip rings. This method is not applicable to cage rotor induction motor.

As we know that the maximum torque is independent of the rotor resistance, yet the accurate location of the maximum torque τ_{max} is dependent on it. The larger the value of the resistance, larger will be the value of the slip at which the maximum torque occurs.

If the resistance of the motor is increased, then the pull out speed of the motor decreases. But the maximum torque remains constant. Thus, by **Rotor Resistance Control** method, the speed control is provided by the rated speed to the lower speeds. This method of speed control is very simple. It is possible to have a large starting torque, low starting current and large values of the pullout torque at a small value of slip.

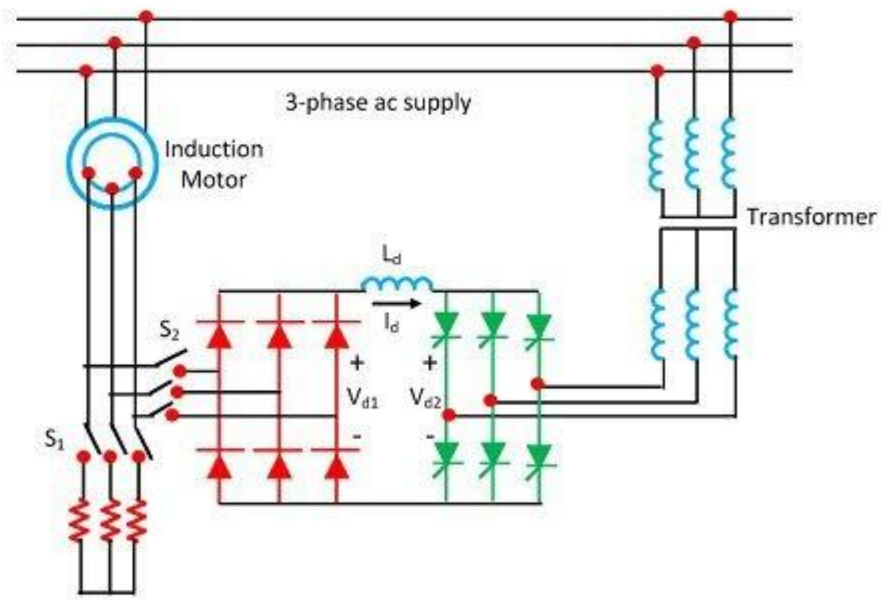
The **Major Disadvantages** of the rotor resistance control method are that the efficiency is low because of the additional losses present in the resistors connected in the rotor circuit. The efficiency is greatly reduced at low speeds because of the higher value of the slip. This method of speed control is used in **Cranes, Ward Leonard** drives and other intermittent load applications because of the **low cost** and **high torque capability** at the lower speed.

This speed control method can also be used in fans or pump drives, where speed variation over a small range near the maximum or top speed is required.

11. Explain static scherbius drive with necessary derivation.

The Static Scherbius Drive provides the speed control of a wound rotor motor below synchronous speed. The portion of rotor AC power is converted into DC by a diode bridge. The controlled rectifier works as an inverter and converts the DC power back into AC and feeds it back to the AC source. This drive has the ability of flow the power both in the positive as well as the negative direction of the injected voltage. This increases the operating condition of the drive.

The feedback power is controlled by controlling the inverter counter emf V_{d2}, which is controlled by controlling the inverter firing angle. The DC link inverter reduced the ripple in DC link current I_d. The slip power of the drive is fed back to the source due to which the efficiency of the drive increases.



Static scherbius drive

The drive input power is the difference of the DC input power and the power fed back. Reactive input power is the sum of the motor and input reactive power.Thus, the drive has poor power factor throughout the range of its operation.

$$V_{d1} = \frac{3\sqrt{6}}{\pi} \times \frac{sV}{n} \ldots\ldots\ldots\ldots equ(1)$$

$$V_{d2} = \frac{3\sqrt{6}}{\pi} \times \frac{V}{m} cos\alpha \ldots\ldots equ(2)$$

Where α is the inverter firing angle and n, and m are respectively the stator to the rotor turn ratio of motor and source side to convert side turns ratio of the transformer. The neglecting drop across the inductor.

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

Substituting the equation (1) and (2) in the above equation we get

$$\frac{3\sqrt{6}sV}{\pi n} + \frac{3\sqrt{6}Vcos\alpha}{\pi m} = 0$$

$$\frac{3\sqrt{6}V}{\pi}\left(\frac{s}{n} + \frac{cos\alpha}{m}\right) = 0$$

$$\frac{s}{n} = -\frac{cos\alpha}{m}$$

$$s = \frac{n}{m}cos\alpha = -acos\alpha \ldots\ldots.equ(3)$$

where a = n/m

The maximum value of alpha is restricted to 165º for safe commutation of inverter thyristor. The slip can be controlled from 0 to 0.966α when α is changed from 90º to 165º.The appropriate speed range can be obtained by choosing the appropriate value of α.

The transformer is used to match the voltage from V_{d1} and V_{d2}. At the lowest speed required from the drive, V_{d1} will have the maximum value V_{d1m}, and it is given by

$$V_{d1m} = {}^{V_{smax}}/_{n}$$

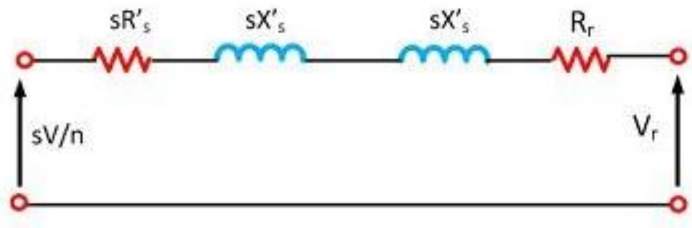
Where S_m is the value of slip at the lowest speed. If α is restricted to 165, m is chosen such that the inverter voltage has a value V_{d1m} when α is 165º, i.e.,

$$\frac{V}{m}cos165^\circ + \frac{Vs_{max}}{n}$$

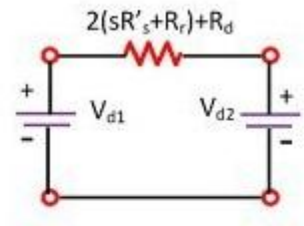
$$m = \frac{-ncos165^\circ}{s_{max}} = -0.966\frac{n}{s_{max}}$$

The value of m determines the highest firing angle at the lower motor speed. It also gives the highest firing angle and the lowest reactive power at the lowest speed.

Considered the circuit of the motor, which is neglecting the magnetizing branch. When referred to DC link, resistance ($sR_s + R_r$) will be $2(sR'_s + R_r)$. This gives the equivalent circuit of the drive, where V_{d1} and V_{d2} are given. $R_d$is the resistance of the DC link inductor.



Equivalent circuit of motor



Equivalent circuit of drive

Motor and drive equivalent circuit

$$\frac{V}{m}cos165° + \frac{Vs_{max}}{n}$$

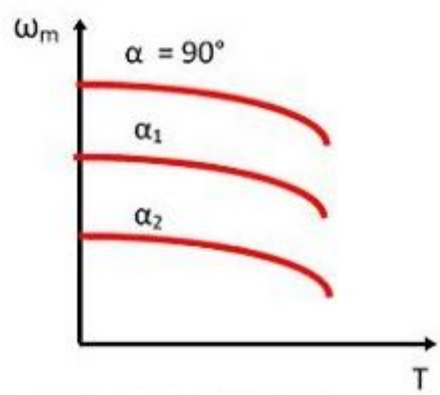
$$m = \frac{-ncos165°}{s_{max}} = -0.966\frac{n}{s_{max}}$$

If rotor copper loss is neglected

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

$$T = \frac{P_g}{\omega_{ms}} = \frac{|V_{d2}|I_d}{s\omega_{ms}} \dots\dots\dots. equ(6)$$

The nature of the speed torque curve is shown in the figure below.

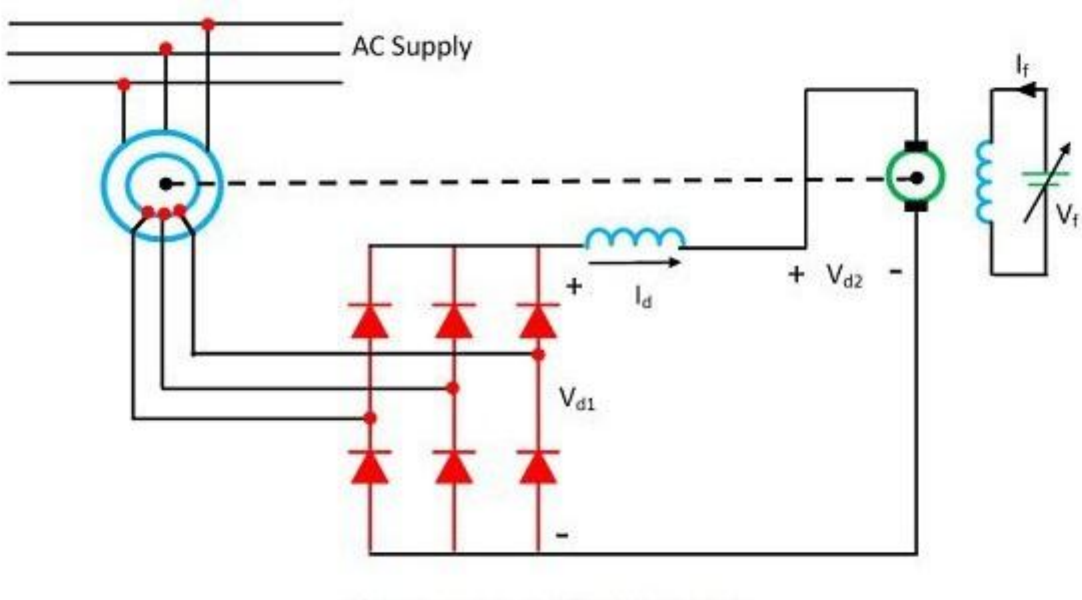


Speed Torque Curves

The drive has application in pump drive which requires the speed control in the narrow range only. The drive is widely used in medium and high power fan and pump drives, because of high efficiency and low cost.

12. Explain closed loop control of static Kramer drive.

Definition: The static Kramer-drive is the method of controlling the speed of an induction motor by injecting the opposite-phase voltage in the rotor circuit. The injected voltage increases the resistance of the rotor, thus controlled the speed of the motor. By changing the injected voltage, the resistance and speed of an induction motor are controlled.

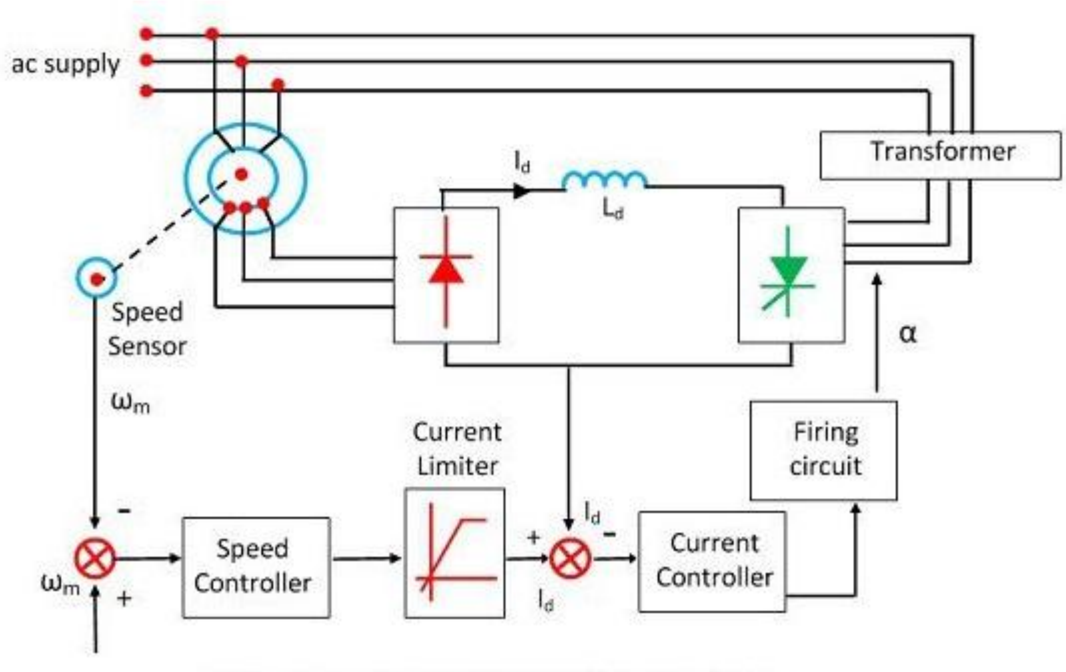


Static Kramer drive

The static Kramer-drive converts the slip power of an induction motor into AC power and supply back to the line. The slip power is the air gap power between the stator and the rotor of an induction motor which is not converted into mechanical power. Thus, the power is getting wasted. The static Kramer drives fed back the wasted power into the main supply. This method is only applicable when the speed of the drive is less than the synchronous speed.

Static Kramer Drive Working

The rotor slip power is converted into DC by a diode bridge. This DC power is now fed into DC motor which is mechanically coupled to an induction motor. The torque supplied to the load is the total sum of the torque produced by the induction and DC motor drive.



Closed loop control of static Kramer drive

The figure shown below represents the variation of V_{d1} and V_{d2} with a speed of two values of DC motor field current. When the value of V_{d1} is equal to the value of V_{d2} then the steady state operation of the drive is obtained, i.e., at A and B for field current of I_{f1} and I_{f2}.

The speed control is possible only when speed is less or half of the synchronous speed. When the large range speed is required, the diode bridge is replaced by the thyristor bridge. The relationship between the V_{d1} and the speed can be altered by controlling the firing angle of thyristor amplifier. Speed can now be controlled up to stand still.

13. Write different types of braking and explain any three of them

When it comes to controlling an electric machine by electric drivers braking is a very important term because it helps to decrease the speed of the motor according to will and necessity. Braking of induction motors can be classified mainly in three types

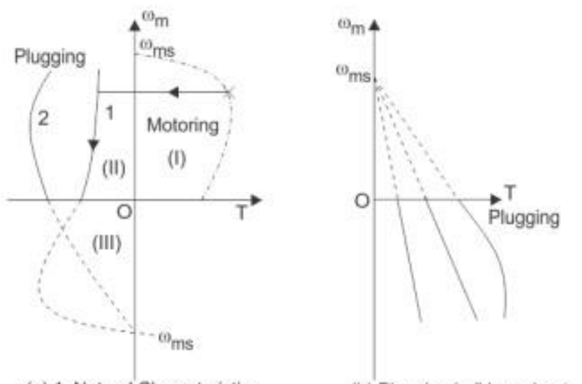
- Regenerative braking.
- Plugging or reverse voltage braking
- Dynamic braking which can be further classified
- AC dynamic braking

- Self-excited braking using capacitors
- DC dynamic braking
- Zero sequence braking

To explain that regeneration braking for induction motor, we can take help of the equation

$$P_{in} = 3NI_sCos\theta_s$$

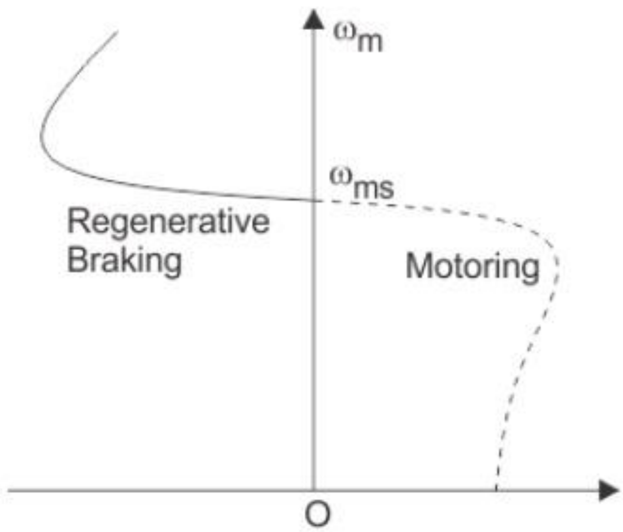
Here, θ_s is the phase angle between the stator voltage and stator current, the simple words whenever this phase angle exceeds 90° (i.e θ_s>90°) regenerative braking can take place. To explain this more clearly and easily we can say that whenever the speed of the rotor exceeds synchronous speed, regeneration braking occurs. That is because whenever the rotor rotates at a speed more than synchronous speed there is a reverse field occurs which opposes the normal rotation of the motor and therefore braking takes place. Main disadvantage of this type of braking is that the speed of the motor has to exceed synchronous speed which may not be possible every time. To acquire regenerative braking at a lower speed than synchronous speed, variable frequency source can be used.



(a) 1: Natural Characteristic
2: With external resistance rotor

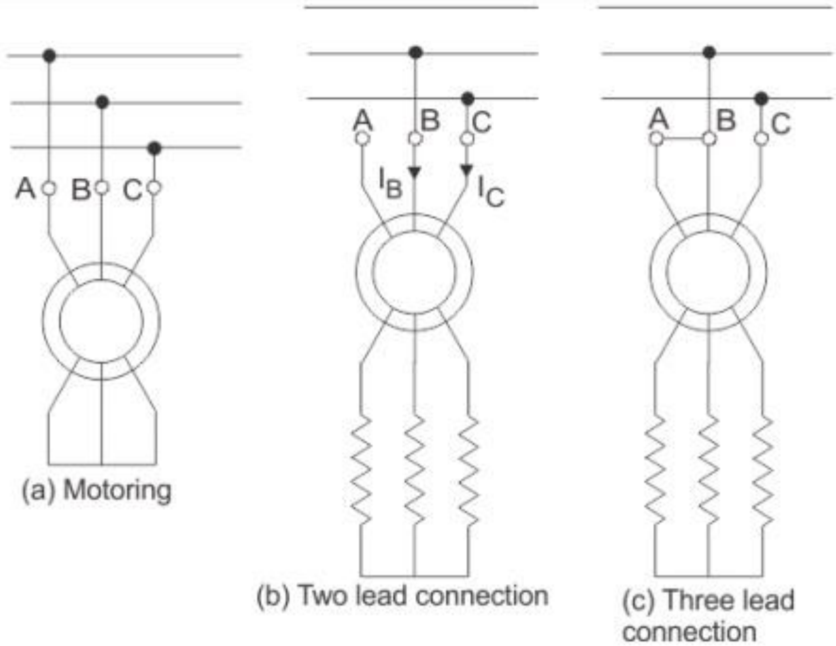
(b) Plugging in IV quadrant with large external resistance in rotor

Plugging of induction motors is done by interchanging any two of the supply terminals. When the terminals are reversed the operation of the machine changes from motoring to plugging. From technical point of view and for better understanding it can be said that the slip changes from‘s’ to (2-s), which indicates that due to reversal of the terminals the torque also changes its direction and braking occurs.



Regenerative Braking

The first classification of dynamic braking of induction motors is AC dynamic braking any one of the supply phase is disconnected from the supply and then it is either kept open or connected with the other phase. The first type is known as two lead connection and the second one is known as three lead connection. To understand this braking method clearly we can assume the system to be a single phase system. Now the motor can be considered to be fed by positive and negative sequence voltages. That's why when the rotor resistance is high the net torque is negative and braking can be acquired.



Sometimes capacitors are kept permanent by connected across the supply terminals of the motor. This is called self-excited braking using capacitors of induction motors. This type of braking works mainly by the property of the capacitors to store energy. Whenever the motor is disconnected from the supply the motor starts to work as a self-excited induction generator, the power comes from the capacitors connected across the terminals. The values of the capacitor are so chosen that they are sufficient to make the motor work as an induction generator after being disconnected from the supply. When the motor works as an induction generator the produced torque opposes the normal rotation of the motor and hence braking takes place.

14. Write a brief note on variable speed drives. Also state the reasons behind its use.

Sol. Variable Speed Drives (VSDs), also known as adjustable speed drives, are large industrial electric motors whose speed can be adjusted by means of an external controller. They are used in process control and help saving energy in plants that use many powerful electric motors.

The use of adjustable speed in process control matches the motor speed to the required tasks and may compensate for changes in the process's variables. The use of adjustable speed for saving energy is exemplified by the adjusting the speed of a cooling fan motor to match the temperature of the machinery parts it is cooling.

VSDs are effective in energy savers in pump and fan applications; "they enhance process operations, particularly where flow control is involved. VSDs provide soft-start capabilities, which decrease electrical stresses and line voltage sags associated with full voltage motor start-ups, especially when driving high-inertia loads

Adjustable frequency drives are a specific type of VSDs; they are controlling the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electrical power supplied to the motor.

Reasons behind it’s use:

1 - Reduce Energy Consumption and Energy Costs

If you have an application that does not need to be run at full speed, then you can cut down energy costs by controlling the motor with a variable frequency drive, which is one of the benefits of Variable Frequency Drives. VFDs allow you to match the speed of the motor-driven equipment to the load requirement. There is no other method of AC electric motor control that allows you to accomplish this.

Electric motor systems are responsible for more than 65% of the power consumption in industry today. Optimizing motor control systems by installing or upgrading to VFDs can reduce energy consumption in your facility by as much as 70%. Additionally, the utilization of VFDs improves product quality, and reduces production costs. Combining energy efficiency tax incentives, and utility rebates, returns on investment for VFD installations can be as little as 6 months.

2 - Increase Production Through Tighter Process Control

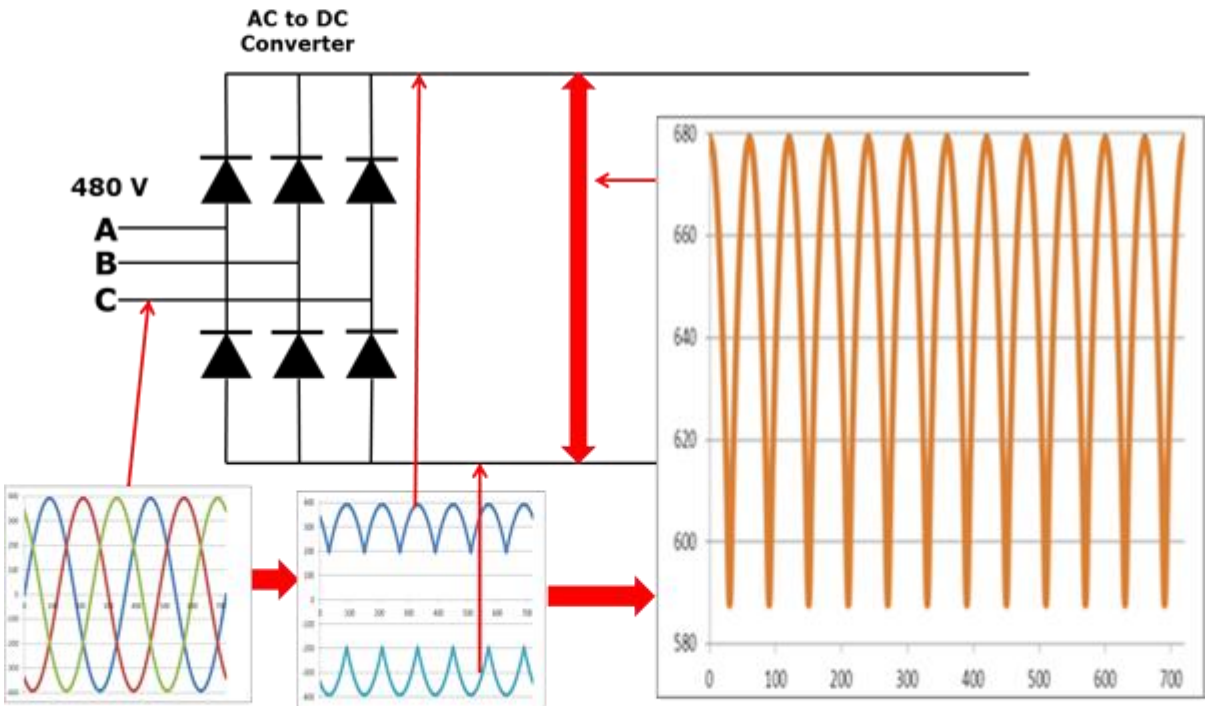
By operating your motors at the most efficient speed for your application, fewer mistakes will occur, and thus, production levels will increase, which earns your company higher revenues. On conveyors and belts you eliminate jerks on start-up allowing high through put.

3 - Extend Equipment Life and Reduce Maintenance

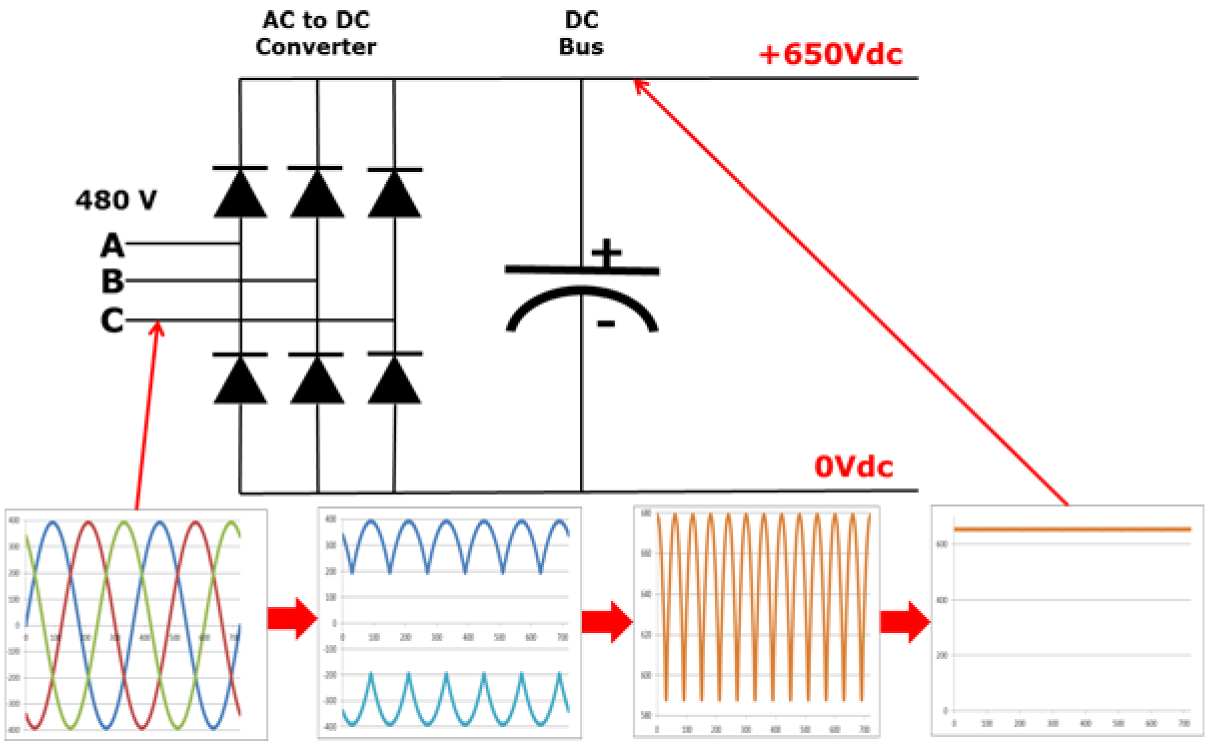
Your equipment will last longer and will have less downtime due to maintenance when it’s controlled by VFDs ensuring optimal motor application speed. Because of the VFDs optimal control of the motor’s frequency and voltage, the VFD will offer better protection for your motor from issues such as electro thermal overloads, phase protection, under voltage, overvoltage, etc.. When you start a load with a VFD you will not subject the motor or driven load to the “instant shock” of across the line starting, but can start smoothly, thereby eliminating belt, gear and bearing wear. It also is an excellent way to reduce and/or eliminate water hammer since we can have smooth acceleration and deceleration cycles.

Q 15. How does a Variable Frequency Drive work.

Sol. The first stage of a Variable Frequency AC Drive, or VFD, is the Converter. The converter is comprised of six diodes, which are similar to check valves used in plumbing systems. They allow current to flow in only one direction; the direction shown by the arrow in the diode symbol. For example, whenever A-phase voltage (voltage is similar to pressure in plumbing systems) is more positive than B or C phase voltages, then that diode will open and allow current to flow. When B-phase becomes more positive than A-phase, then the B-phase diode will open and the A-phase diode will close. The same is true for the 3 diodes on the negative side of the bus. Thus, we get six current “pulses” as each diode opens and closes. This is called a “six-pulse VFD”, which is the standard configuration for current Variable Frequency Drives.

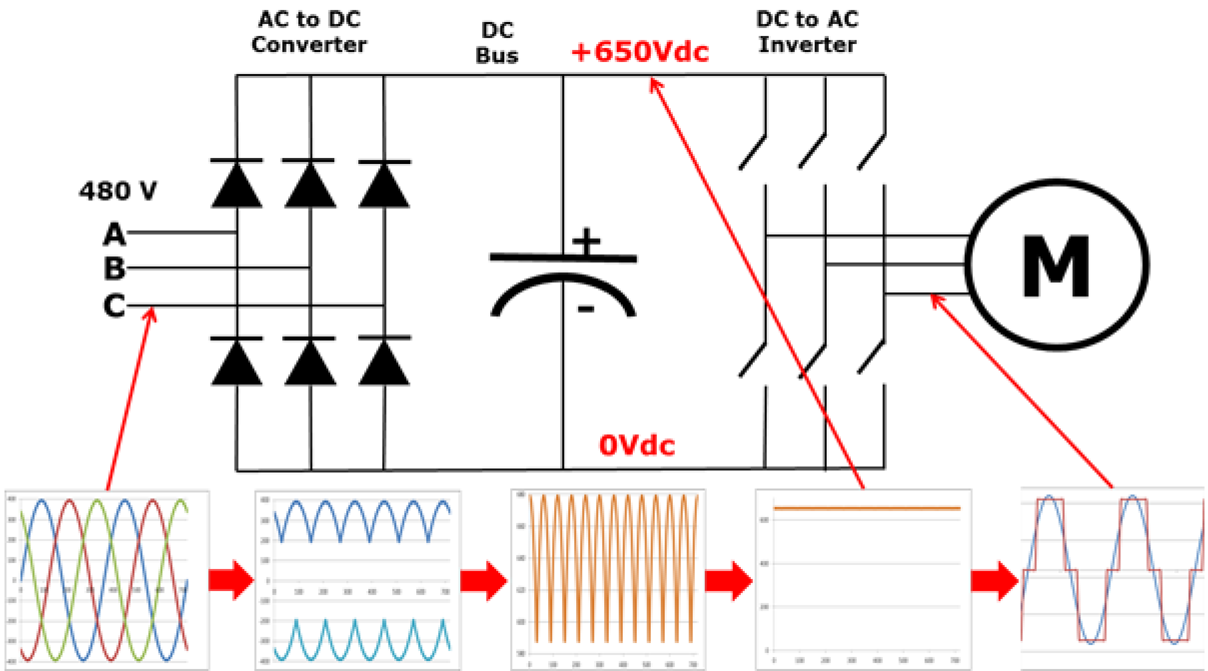


Let us assume that the drive is operating on a 480V power system. The 480V rating is “rms” or root-mean-squared. The peaks on a 480V system are 679V. As you can see, the VFD dc bus has a dc voltage with an AC ripple. The voltage runs between approximately 580V and 680V.

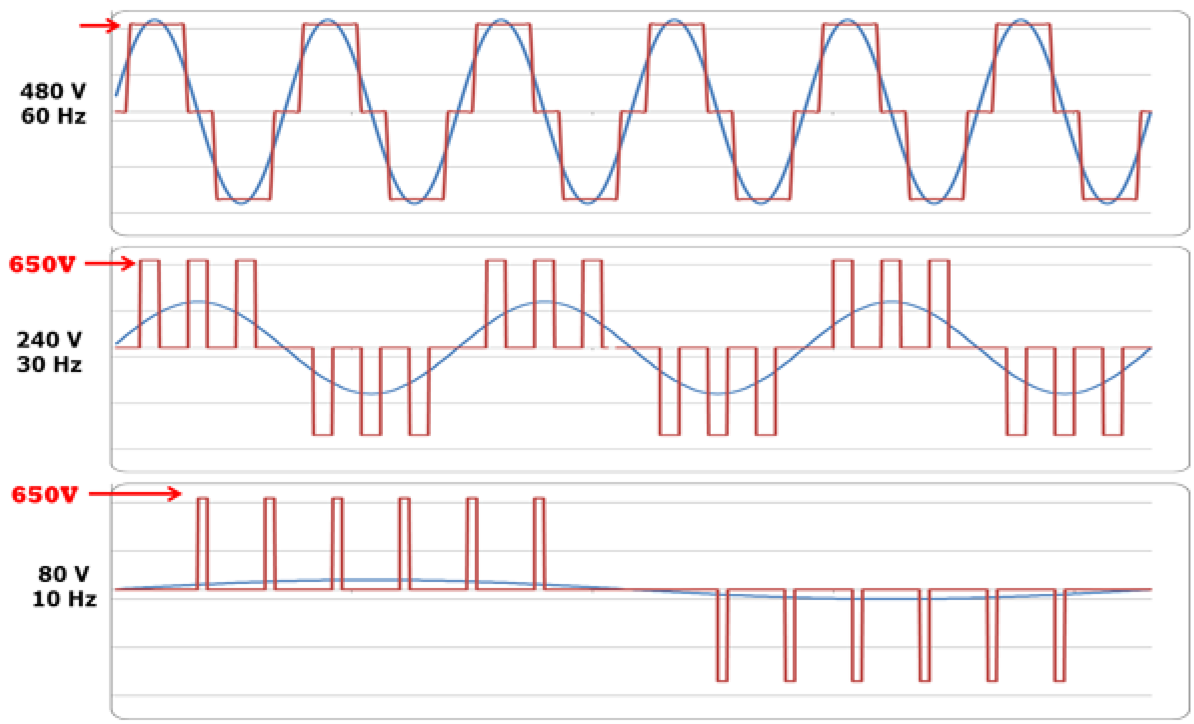


We can get rid of the AC ripple on the DC bus by adding a capacitor. A capacitor operates in a similar fashion to a reservoir or accumulator in a plumbing system. This capacitor absorbs the ac ripple and delivers a smooth dc voltage. The AC ripple on the DC bus is typically less than 3 Volts. Thus, the voltage on the DC bus becomes “approximately” 650VDC. The actual voltage will depend on the voltage level of the AC line feeding the drive, the level of voltage unbalance on the power system, the motor load, the impedance of the power system, and any reactors or harmonic filters on the drive.

The diode bridge converter that converts AC-to-DC, is sometimes just referred to as a converter. The converter that converts the dc back to ac is also a converter, but to distinguish it from the diode converter, it is usually referred to as an “inverter”. It has become common in the industry to refer to any DC-to-AC converter as an inverter.



When we close one of the top switches in the inverter, that phase of the motor is connected to the positive dc bus and the voltage on that phase becomes positive. When we close one of the bottom switches in the converter, that phase is connected to the negative dc bus and becomes negative. Thus, we can make any phase on the motor become positive or negative at will and can thus generate any frequency that we want. So, we can make any phase be positive, negative, or zero.



Notice that the output from the VFD is a "rectangular" wave form. VFD's do not produce a sinusoidal output. This rectangular waveform would not be a good choice for a general purpose distribution system, but is perfectly adequate for a motor.

If we want to reduce the motor frequency to 30 Hz, then we simply switch the inverter output transistors more slowly. But, if we reduce the frequency to 30Hz, then we must also reduce the voltage to 240V in order to maintain the V/Hz ratio (see the VFD Motor Theory presentation for more on this). How are we going to reduce the voltage if the only voltage we have is 650VDC?

This is called Pulse Width Modulation or PWM. Imagine that we could control the pressure in a water line by turning the valve on and off at a high rate of speed. While this would not be practical for plumbing systems, it works very well for VFD's. Notice that during the first half cycle, the voltage is ON half the time and OFF half the time. Thus, the average voltage is half of 480V or 240V. By pulsing the output, we can achieve any average voltage on the output of the VFD.

16. What is the current status of DC and AC drives.

Sol. In the past induction and synchronous motor drives were mainly used in fixed speed applications. Variable speed applications were dominated by dc motor drives. Emergence of thyristors in 1957 lead to the development of variable speed induction motor drives in late sixties which were efficient and could match the performance of dc drives. Consequently, because of the advantages of squirrel-cage induction motors over dc motors, it was predicted that induction motor drives will replace dc drives in variable speed applications. However, following hurdles forbidden for the prediction to come true:

- Although squirrel-cage induction motor was cheaper than dc motor, the converter and control circuit of an induction motor drive was very expensive compared to those for a dc drive. Therefore, total cost of an induction motor drive was significantly higher than that of a dc drive.
- While the technology of dc drives was well established, that of ac was new.
- AC drives were not as reliable as DC.
- Developments in linear and digital ICs, and VLSIs were helpful in improving the performance and reliability of ac drives. But then these developments also led to similar improvements in dc drives.

Improvement in thyristor capabilities, availability of power transistors in early seventies and that of GTOs and IGBTs in late seventies and late eighties respectively; reduction in cost of thyristors, power transistors and GTOs; developments of VLSIs and microprocessors; and improvement in control techniques of converters have resulted into reduction in cost, simple controllers, and improvement in performance and reliability for ac drives. Although even now majority of variable speed applications employ dc drives, the ac drives are preferred over dc drives in a number of applications with the result, ac drive applications are growing. Induction motor drives find applications in low to high power applications and synchronous motor drives are employed in very high power (megawatts) and medium power drives. The permanent magnet-synchronous motor and brushless dc motor drives are being considered for replacing dc servo motors for fractional hp range. As the trend exists, applications of ac drives will continue to grow. However, dc drives will also continue to be used for quite some time.

17. How do you define passive and active load torques? What are the components of load torque.

Sol. Classification of Load Torques:

Various load torques can be classified into two broad categories-

1. Active Load torques
2. Passive Load torques

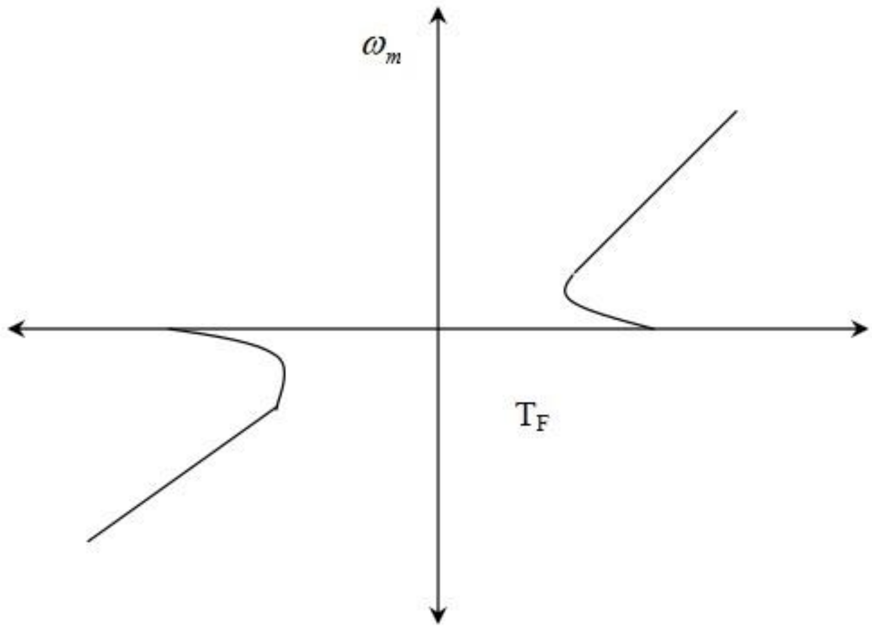
Active Load Torques:
Load torques which have the potential to drive the motor under equilibrium conditions are called active load torques. Load torques usually retain sign when the drive rotation is changed.
Eg: Torque due to force of gravity
Torque due tension
Torque due to compression and torsion etc

Passive Load torques:
Load torques which always oppose the motion and change their sign on the reversal of motion are called passive load torques
Eg: Torque due to friction, cutting etc.

Components of Load Torques:
The load torque T_1 can be further divided into following components
i) Friction Torque (TF):
Friction will be present at the motor shaft and also in various parts of the load. TF is the equivalent value of various friction torques referred to the motor shaft.

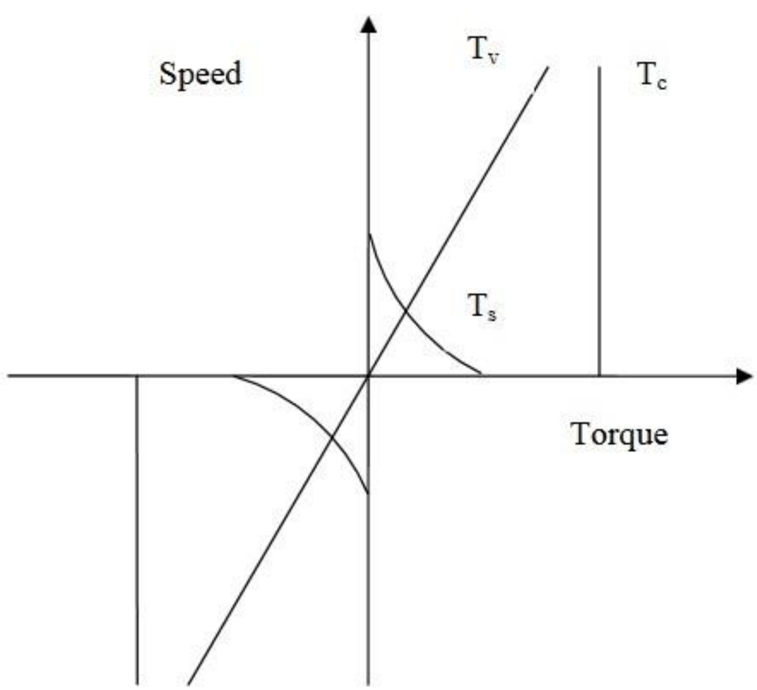
(ii) Windage Torque (TW):
When motor runs, wind generates a torque opposing the motion. This is known as windage torque.

(iii) Torque required to do useful mechanical work:
Nature of this torque depends upon particular application. It may be constant and independent of speed. It may be some function of speed, it may be time invariant or time variant, its nature may also change with the load’s mode of operation.
Value of friction torque with speed is shown in figure below :



Its value at stand still is much higher than its value slightly above zero speed. Friction at zero speed is called stiction or static friction. In order to start the drive the motor should at least exceed stiction.

Friction torque can also be resolved into three components



Component Tv varies linearly with speed is called VISCOUS friction and is given by

$$T_v = B\omega_m$$

Where B is viscous friction co-efficient. Another component TC, which is independent of speed, is known as COULOMB friction. Third component Ts accounts for additional torque present at stand still. Since Ts is present only at stand still it is not taken into account in the dynamic analysis. Windage torque, TW which is proportional to speed squared is given by

$$T_w = C\omega_m^{\ 2} \qquad \text{C is a constant}$$

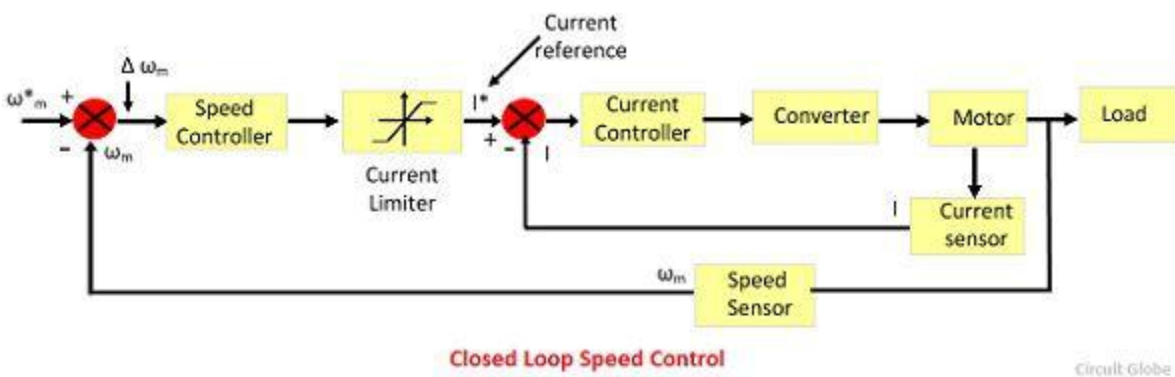
From the above discussions, for finite speed

$$T_l = T_L + B\omega_m + T_C + C\omega_m^{\ 2}$$

18. Explain the operation of a closed – loop speed control scheme with inner current control loop.

Closed-Loop Speed Control

The block diagram of the closed loop speed control system is shown in the figure below. This system used an inner control loop within an outer speed loop. The inner control loop controls the motor current and motor torque below a safe limit.



Consider a reference speed ω*m which produces a positive error Δ ω*m. The speed error is operated through a speed controller and applied to a current limiter which is overloaded even for a small speed error. The current limiter set current for the inner current control loop. Then, the drive accelerates, and when the speed of the drive is equal to the desired speed, then the motor torque is equal to the load torque. This, decrease the reference speed and produces a negative speed error.

When the current limiter saturates, then the drive becomes de-accelerate in a braking mode. When the current limiter becomes desaturated, then the drive is transferred from braking to motoring.

19. What is braking? What are the types of braking for DC motor.

The term braking comes from the term brake. We know that brake is an equipment to reduce the speed of any moving or rotating equipment, like vehicles, locomotives. The process of applying brakes can be termed as braking.

Types of Braking

Brakes are used to reduce or cease the speed of motors. We know that there are various types of motors available (DC motors, induction motors, synchronous motors, single phase motors etc.) and the specialty and properties of these motors are different from each other, hence this braking method also differs from each other. But we can divide braking in to three parts mainly, which are applicable for almost every type of motors.

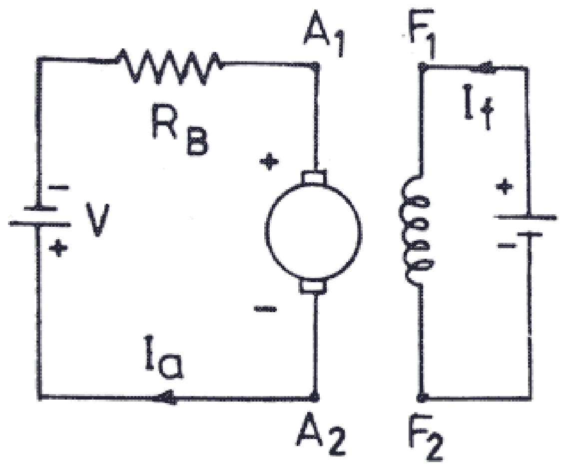
- Regenerative Braking.
- Plugging type braking.
- Dynamic braking.

Regenerative Braking

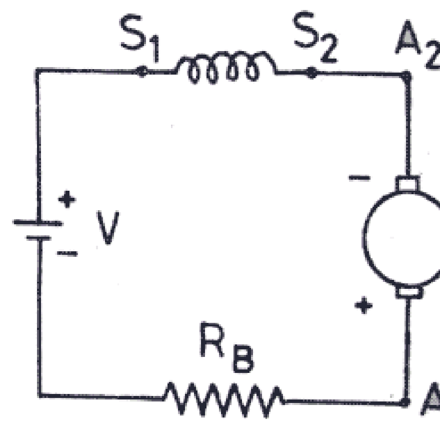
Regenerative braking takes place whenever the speed of the motor exceeds the synchronous speed. This baking method is called regenerative braking because here the motor works as generator and supply itself is given power from the load, i.e. motors. The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, only then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place. The only disadvantage of this **type of braking** is that the motor has to run at super synchronous speed which may damage the motor mechanically and electrically, but regenerative braking can be done at sub synchronous speed if the variable frequency source is available.

Plugging

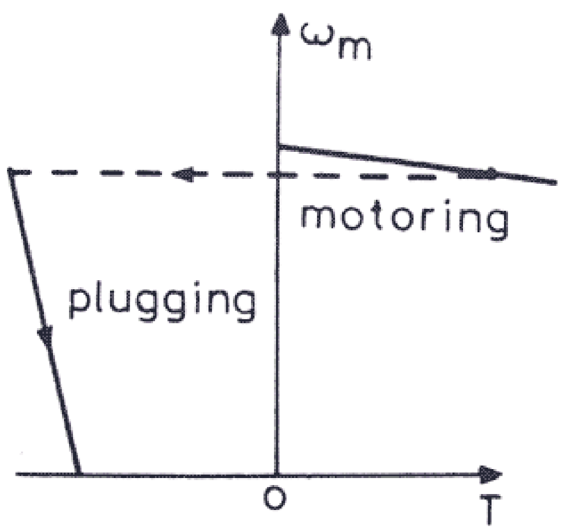
Another type of braking is **Plugging type braking**. In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases. During plugging external resistance is also introduced into the circuit to limit the flowing current. The main disadvantage of this method is that here power is wasted.



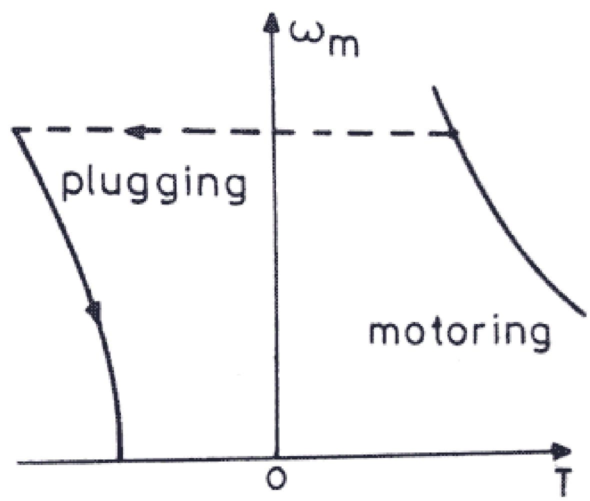
Separately excited



Series



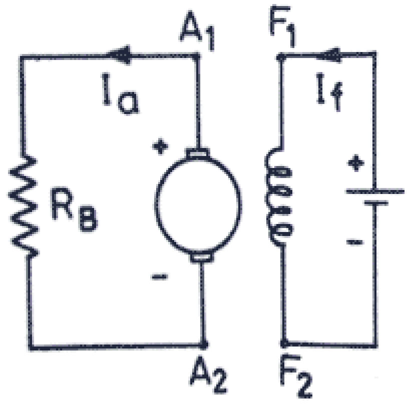
Separately excited



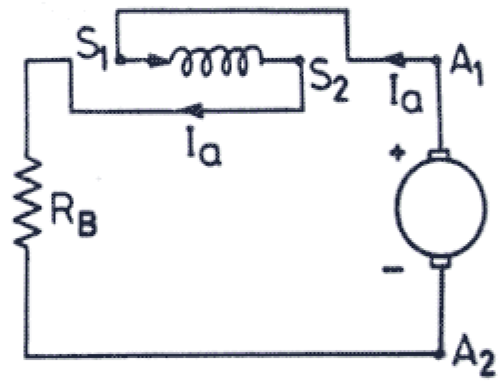
Series

Dynamic Braking

Another method of reversing the direction of torque and braking the motor is **dynamic braking**. In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance. When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self-excited generator. When the motor works as a generator the flow of the current and torque reverses. During braking to maintain the steady torque sectional resistances are cut out one by one.



Separately excited motor



Series motor

20. Explain chopper controlled DC drives. What are the advantages of chopper control?

Chopper fed DC drives

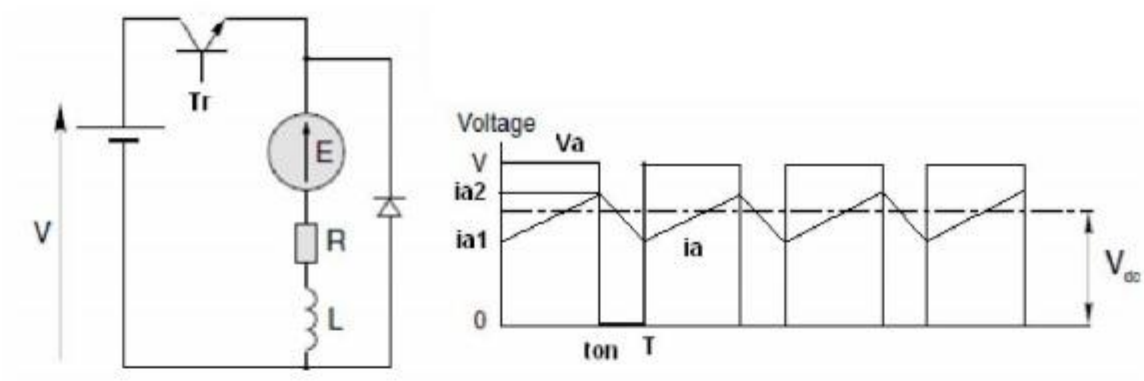
A chopper is a static device that converts fixed DC input voltage to a variable dc output voltage directly o A chopper is a high speed on/off semiconductor switch which connects source to load and disconnects the load from source at a fast speed. o Choppers are used to get variable dc voltage from a dc source of fixed voltage. Self-commutated devices such as MOSFET's, Power transistors, IGBT's, GTO's and IGCT's are used for building choppers because they can be commutated by a low power control signal and do not need communication circuit and can be operated at a higher frequency for the same rating. Chopper circuits are used to control both separately excited and Series circuits.

Chopper Controlled Separately Excited DC motor

If the source of supply is D.C. (for example in a battery vehicle or a rapid transit system) a chopper-type converter is usually employed. The chopper-fed motor is, if anything, rather better than the phase-controlled, because the armature current ripple can be less if a high chopping frequency is used.

Motoring Mode of Operation

A transistor is used to chop the DC input voltage in to pieces and chopped DC voltage is given to the motor as shown in the figure. Current limit control is used in chopper. In current limit control, the load current is allowed to vary between two given limits (i.e. Upper and lower limits). The ON and OFF times of the transistor is adjusted automatically, when the current increases beyond the upper limit the chopper is turned off, the load current free wheels and starts to decrease. When the current falls below the lower limit the chopper is turned ON. The current starts increasing if the load. The load current and voltage waveforms are shown in the figure. By assuming proper limits of current, the amplitude of ripple can be controlled.



The lower the current ripple, the higher the chopper frequency. By this switching losses increase. Discontinuous conduction avoid in this case. The current limit control is superior one.

Duty Interval

During the ON period of the chopper (i.e) duty interval $0 < t < t_{ON}$, motor terminal voltage V_a is a source voltage V and armature current increases from i_{a1} to i_{a2}. The operation is describe by,

$$R_a I_a + L_a \frac{di_a}{dt} + E = V \quad 0 \le t \le t_{ON} \quad (2.54)$$

In this interval the armature current increases from I_{a1} to I_{a2} since the motor is connected to the source during this interval, it is called as duty cycle.

Free Wheeling Interval

Chopper T_r is turned off at $t=t_{ON}$. Motor current free wheels through the diode D and the motor terminal voltage is zero. During interval $t_{ON} \le t \le T$. Motor operation during this interval is known as free wheeling interval and is described by

$$R_a I_a + L_a \frac{di_a}{dt} + E = 0 \quad t_{ON} \le t \le T$$

During this interval current decreases from i_{a2} to i_{a1}

Duty cycle (or) Duty Ratio:

Duty cycle is defined as the ratio of duty interval t_{ON} to chopper period T is called Duty cycle (or) Duty Ratio.

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$$\delta = \frac{\text{Duty Interval}}{\text{Chopper Period}} = \frac{t_{ON}}{T}$$

From fig.

$$V_a = \frac{1}{T}\int_0^{t_{ON}} V dt$$

Solving the above,

$$V_a = \frac{V}{T}\int_0^{t_{ON}} dt = \frac{V}{T}\left[t\right]_0^{t_{ON}} = V\frac{t_{ON}}{T}$$

$$V_a = \delta V$$

Then the speed of the chopper drive can be obtained as

$$V_a = E + I_a R_a$$

Substituting V_a from equation (2.59) in the above equation we get,

$$\delta V = E + I_a R_a$$

Substituting $E = K\omega_m$ we get

$$I_a = \frac{\delta V - K\omega_m}{R_a}$$

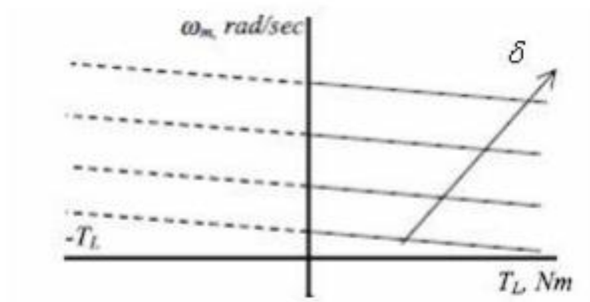
From above equation we get

$$\omega_m = \frac{\delta V}{K} - \frac{I_a R_a}{K}$$

Substituting $T = K\varphi I_a$ in above equation we get

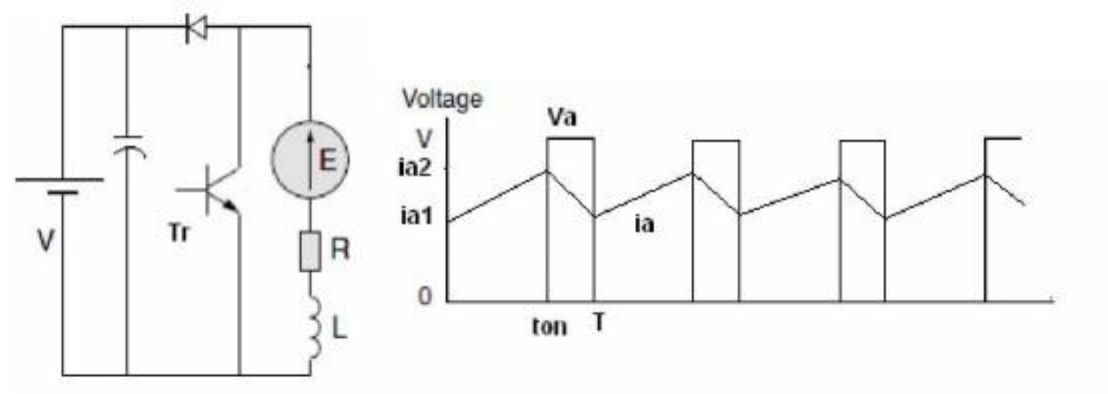
$$\omega_m = \frac{\delta V}{K} - \frac{R_a}{K^2 \varphi} T$$

The torque speed characteristics of chopper fed separately excited DC motor is shown in the fig.



Regenerative Braking Mode

Regenerative braking operation by chopper is shown in the fig. Regenerative braking of a separately excited motor is fairly simple and can be carried out down to very low speeds.



In regenerative mode, the energy of the load is fed back to the supply system. The DC motor works as a generator during this mode. As long as the chopper is ON the
mechanical energy is converted in to electrical energy by the motor, now working as a generator, increases the stored magnetic energy in the armature circuit. When chopper is switched off, a

large voltage appears across the motor terminals this voltage is more than that of the supply voltage V and the energy stored in the inductance and energy supplied by the machine is fed back to the supply system. When the voltage of the motor fall to V, the diodes in the line blocks the current flow preventing any short circuit of the load can be supplied to the source. Very effective braking of motor is possible up to extreme small speeds.

Energy Storage Interval

The stored energy and energy supplied by the machine is fed to the source. The interval $0 < t < t_{ON}$ is now called energy storage interval and interval $t_{ON} \le t \le T$ is the duty interval.

Here duty ratio $\delta = \frac{T - t_{ON}}{T}$

From figure 2.21

$$V_a = \frac{1}{T}\int_{t_{ON}}^{T} V dt = \frac{V}{T}\int_{t_{ON}}^{T} dt = \frac{V}{T}\left[t\right]_{t_{ON}}^{T} = \frac{V}{T}(T - t_{ON})$$

$$V_a = V\frac{T - t_{ON}}{T} = V\left(1 - \frac{t_{ON}}{T}\right)$$

Therefore the speed torque relations under braking operation is given as

$$\omega_m = \frac{(1-\delta)V}{K} - \frac{R_a}{K^2\varphi}T$$

Chopper control of DC series motor

Motoring control of series motor

The main drawback in the analysis of a chopper controlled series motor arises due to the nonlinear relationship between the induced voltage E and armature current Ia, because of the saturation in the magnetization characteristic. At a given motor speed, the instantaneous back emf E changed between E1 and E2 as Ia changes between Ia1 and Ia2 as shown in figure.

Regenerative Braking of DC series Motor

With chopper control, regenerative braking of series motor can also be obtained. During regenerative braking, series motor functions as a self-excited series generator. For self excitation current flowing through the winding (field) should assist residual magnetism. Therefore when changing from motoring to braking connection, when armature current reverses field current should flow in the same direction. This is achieved by reversing the field with respect to armature when changing from motoring to braking operation.

The speed of this drive ω_m can be derived from the following equation

$$E = V_a + I_a R_a \qquad \text{but } V_a = \delta V$$

$$\therefore E = \delta V + I_a R_a \qquad K_a \omega_m = \delta V + I_a R_a$$

$$\omega_m = \frac{\delta V \pm I_a R_a}{K_a}$$

The speed – torque characteristics gives unstable operation with most loads shown in figure.Therefore regenerative braking of series motor is difficult.

Advantages of Chopper Circuits

Chopper circuits have several advantages over phase controlled converters

1. Ripple content in the output is small. Peak/average and rms/average current ratios are small. This improves the commutation and decreases the harmonic heating of the motor.
2. The chopper is supplied from a constant dc voltage using batteries. The problem of power factor does not occur at all. The conventional phase control method suffers from a poor power factor as the angle is delayed.
3. Current drawn by the chopper is smaller than in phase controlled converters.
4. Chopper circuit is simple and can be modified to provide regeneration and the control is also simple.

21. Explain the starting methods of an Induction Motor.

Starting of an Induction Motor

A three phase Induction Motor is Self Starting. When the supply is connected to the stator of a three-phase induction motor, a rotating magnetic field is produced, and the rotor starts rotating and the induction motor starts. At the time of starting, the motor slip is unity, and the starting current is very large.

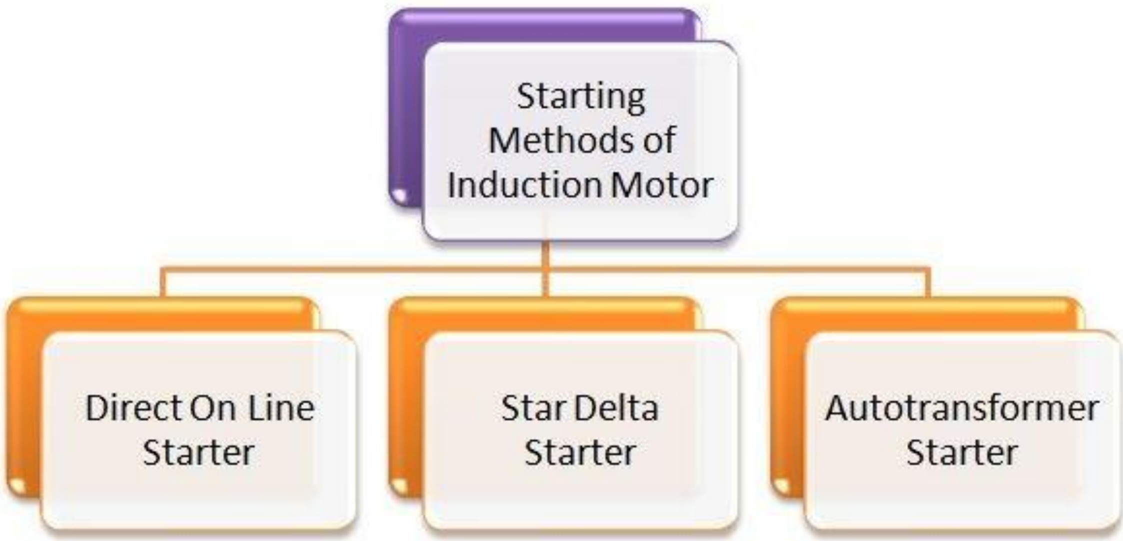
The purpose of a starter is not to just start the motor, but it performs the two main functions. They are as follows.

- To reduce the heavy starting current
- To provide overload and under voltage protection.

The three phase induction motor may be started by connecting the motor directly to the full voltage of the supply. The motor can also be started by applying a reduced voltage to the motor when the motor is started.

The torque of the induction motor is proportional to the square of the applied voltage. Thus, a greater torque is exerted by a motor when it is started on full voltage than when it is started on the reduced voltage.

There are three main methods of **Starting of Cage Induction Motor**. They are as follows.



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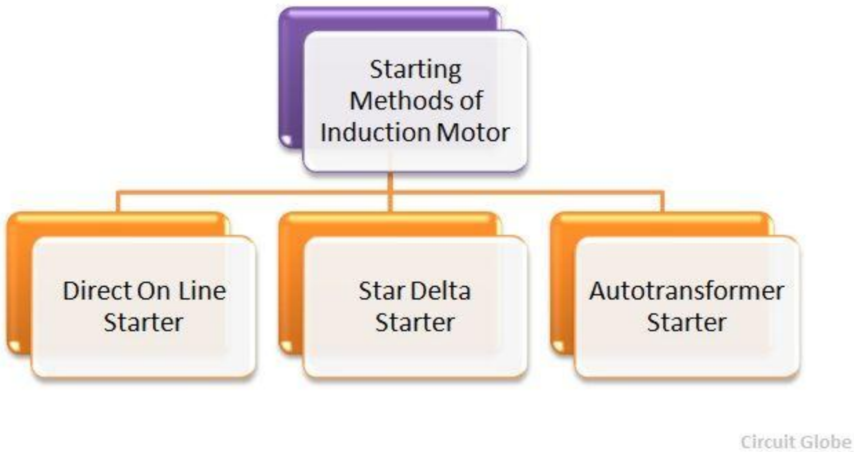


Direct on line starter

The direct on line starter method, of an induction motor is simple and economical. In this method, the starter is connected directly to supply voltage. By this method small motors up to 5 kW rating is started to avoid the supply voltage fluctuation.

Star delta starter

The star delta starter method of starting three phase induction motors is very common and widely used among all the methods. In this method, the motor runs at delta connected stator windings.

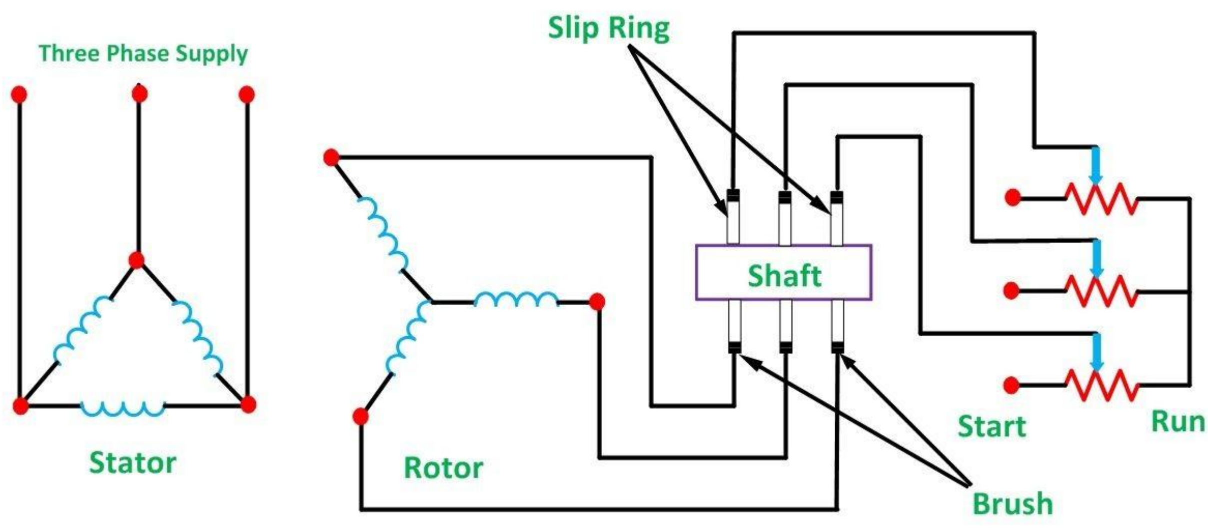
Auto transformer starter

The Auto transformer is used in both the type of the connections, i.e., either star connected or delta connected. The auto transformer is used to limit the starting current of the induction motor.

The above three starters are used for cage rotor induction motor.

Slip Ring Induction Motor Starter Method of Starting Induction Motor

In the **Slip Ring Induction Motor** starter, the full supply voltage is connected across the starter. The connection diagram of the slip ring starter induction motor is shown below.



Full starting resistance is connected and thus the supply current to the stator is reduced. The rotor begins to rotate, and the rotor resistances are gradually cut out as the speed of the motor increases. When the motor is running at its rated full load speed, the starting resistances are cut out completely, and the slip rings are short-circuited.

22. What are various speed control methods of Induction Motor.

Different speed control methods of induction motor are explained below:

Induction Motor Speed Control from Stator Side

1. **By Changing the Applied Voltage:**

   From the torque equation of induction motor,

$$T = \frac{k_1 s E_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}} = \frac{3}{2\pi N_s} \frac{sE_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

   Rotor resistance R_2 is constant and if slip s is small then $(sX_2)^2$ is so small that it can be neglected. Therefore, $T \propto sE_2^2$ where E_2 is rotor induced emf and $E_2 \propto V$ Thus, $T \propto sV^2$, which means, if supplied voltage is decreased, the developed torque decreases. Hence, for providing the same load torque, the slip increases with decrease in voltage, and consequently, the speed decreases. This method is the easiest and cheapest, still rarely used, because

- large change in supply voltage is required for relatively small change in speed.

- large change in supply voltage will result in a large change in flux density, hence, this will disturb the magnetic conditions of the motor.

2. **By Changing the Applied Frequency:**

Synchronous speed of the rotating magnetic field of an induction motor is given by

$$Ns = \frac{120\ f}{P} \quad (RPM)$$

where, f = frequency of the supply and P = number of stator poles. Hence, the synchronous speed changes with change in supply frequency. Actual speed of an induction motor is given as N = Ns (1 - s). However, this method is not widely used. It may be used where, the induction motor is supplied by a dedicated generator (so that frequency can be easily varied by changing the speed of prime mover). Also, at lower frequency, the motor current may become too high due to decreased reactance. And if the frequency is increased beyond the rated value, the maximum torque developed falls while the speed rises.

3. **Constant V/F Control of Induction Motor:**

This is the most popular method for controlling the speed of an induction motor. As in above method, if the supply frequency is reduced keeping the rated supply voltage, the air gap flux will tend to saturate. This will cause excessive stator current and distortion of the stator flux wave. Therefore, the stator voltage should also be reduced in proportional to the frequency so as to maintain the air-gap flux constant. The magnitude of the stator flux is proportional to the ratio of the stator voltage and the frequency. Hence, if the ratio of voltage to frequency is kept constant, the flux remains constant. Also, by keeping V/F constant, the developed torque remains approximately constant. This method gives higher run-time efficiency. Therefore, majority of AC speed drives employ constant V/F method (or variable voltage, variable frequency method) for the speed control. Along with wide range of speed control, this method also offers 'soft start' capability.

4. **Changing The Number of Stator Poles:**

From the above equation of synchronous speed, it can be seen that synchronous speed (and hence, running speed) can be changed by changing the number of stator poles. This method is generally used for squirrel cage induction motors, as squirrel cage rotor adapts itself for any number of stator poles. Change in stator poles is achieved by two or more independent stator windings wound for different number of poles in same slots. For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles.
For supply frequency of 50 Hz

i) synchronous speed when 4 pole winding is connected, Ns = 120*50/4 = 1500 RPM
ii) synchronous speed when 6 pole winding is connected, Ns = 120*50/6 = 1000 RPM

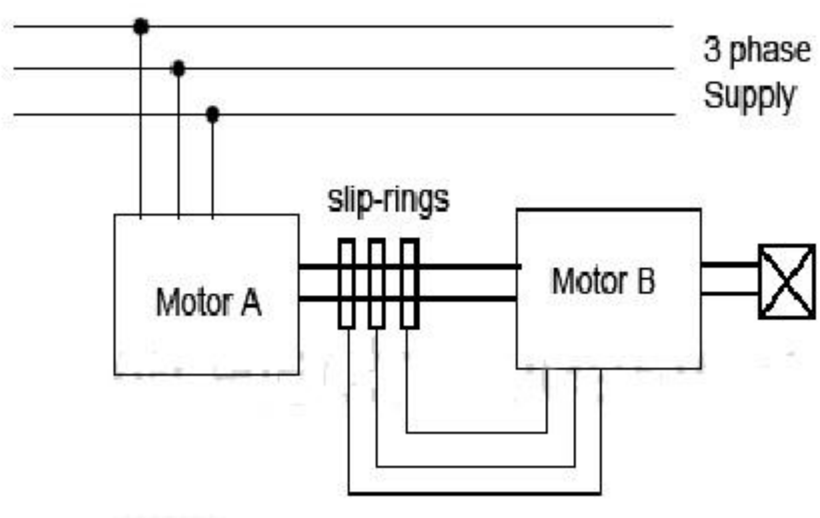
Speed Control from Rotor Side:

1. Rotor Rheostat Control:

This method is similar to that of armature rheostat control of DC shunt motor. But this method is only applicable to slip ring motors, as addition of external resistance in the rotor of squirrel cage motors is not possible.

2. Cascade Operation

In this method of speed control, two motors are used. Both are mounted on a same shaft so that both run at same speed. One motor is fed from a 3phase supply and the other motor is fed from the induced emf in first motor via slip-rings. The arrangement is as shown in following figure.



Motor A is called the main motor and motor B is called the auxiliary motor.

Let, N_{s1} = frequency of motor A

N_{s2} = frequency of motor B

P_1 = number of poles stator of motor A

P_2 = number of stator poles of motor B

N = speed of the set and same for both motors

f = frequency of the supply

Now, slip of motor A, $S_1 = (N_{s1} - N) / N_{s1}$.

frequency of the rotor induced emf in motor A, $f_1 = S_1 f$
Now, auxiliary motor B is supplied with the rotor induce emf

therefore, $N_{s2} = (120f_1) / P_2 = (120S_1 f) / P_2$.

now putting the value of $S_1 = (N_{s1} - N) / N_{s1}$

$$N_{s2} = \frac{120f(N_{s1} - N)}{P_2 N_{S1}}$$

At no load, speed of the auxiliary rotor is almost same as its synchronous speed.
i.e. $N = N_{s2}$.
from the above equations, it can be obtained that

$$N = \frac{120f}{P_1 + P_2}$$

With this method, four different speeds can be obtained
1. when only motor A works, corresponding speed = .Ns1 = 120f / P_1
2. when only motor B works, corresponding speed = Ns2 = 120f / P_2
3. if cumulative cascading is done, speed of the set = N = 120f / ($P_1 + P_2$)
4. if differential cascading is done, speed of the set = N = 120f ($P_1 - P_2$)

3. By Injecting EMF in Rotor Circuit:

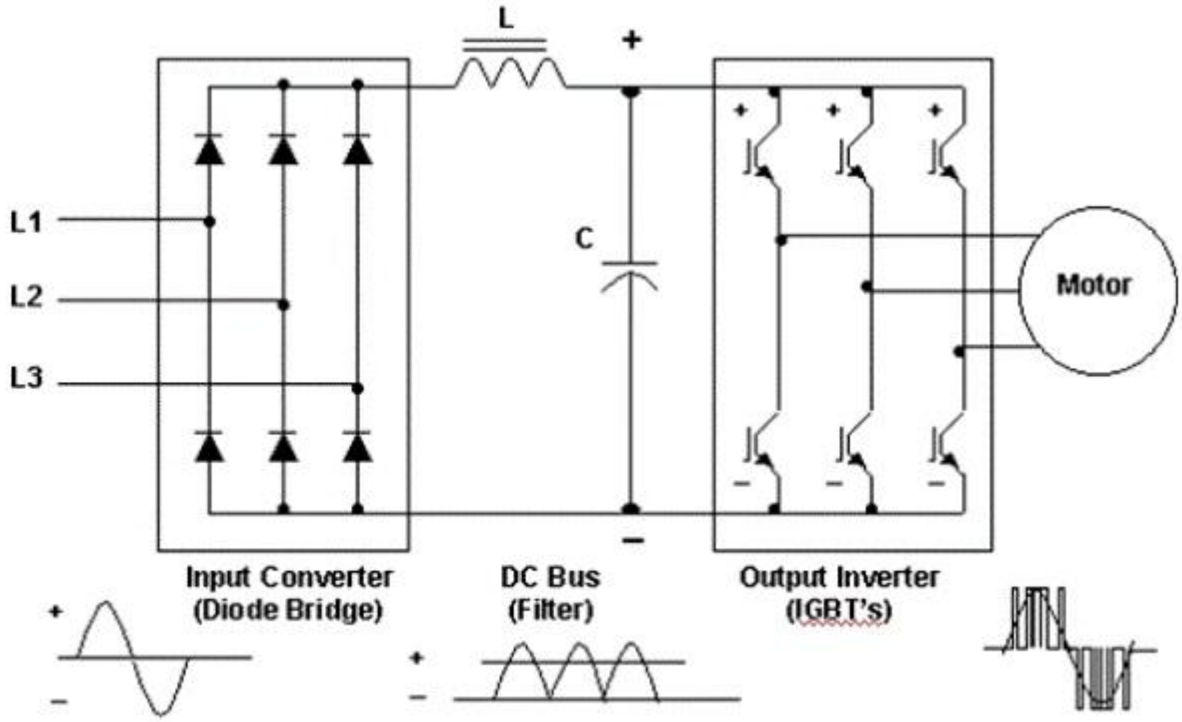
In this method, speed of an induction motor is controlled by injecting a voltage in rotor circuit. It is necessary that voltage (emf) being injected must have same frequency as of the slip frequency. However, there is no restriction to the phase of injected emf. If we inject emf which is in opposite phase with the rotor induced emf, rotor resistance will be increased. If we inject emf which is in phase with the rotor induced emf, rotor resistance will decrease. Thus, by changing the phase of injected emf, speed can be controlled. The main advantage of this method is a wide range of speed control (above normal as well as below normal) can be achieved. The emf can be injected by various methods such as Kramer system, Scherbius system etc.

23. Explain variable frequency drive(VFD), it's working and the merits of using VFD. Also, mention it's applications.

It is interesting to know that the first A.C. drive (400 HP) based on thyratron cycloconverter-fed WRIM was installed in 1932 by F.E. Alexanderson of General Electric in the Logan Power Station of Pacific Gas and Electric Company. From then industrial drives have evolved rapidly by dedicated effort of many scientists and engineers all over the world resulting in development of advanced drive technology such as **Variable Frequency Drive**(VFD).**VFD** is a power electronics based device which converts a basic fixed frequency, fixed voltage sine wave power (line power) to a variable frequency, variable output voltage used to control speed of induction motor(s). It regulates the speed of a three phase induction motor by controlling the frequency and voltage of the power supplied to the motor.

$$Ns = \frac{120\,f}{P}$$

Since the number of pole is constant the speed N_s can be varied by continuously changing frequency.



Working of Variable Frequency Drive

Any **Variable Frequency Drive** or VFD incorporates following three stages for controlling a three phase induction motor.

Rectifier Stage
A full-wave power diode based solid-state rectifier converts three-phase 50 Hz power from a standard 220, 440 or higher utility supply to either fixed or adjustable DC voltage. The system may include transformers for high voltage system.

Inverter Stage

Power electronic switches such as IGBT, GTO or SCR switch the DC power from rectifier on and off to produce a current or voltage waveform at the required new frequency. Presently most of the voltage source inverters (VSI) use pulse width modulation (PWM) because the current and voltage waveform at output in this scheme is approximately a sine wave. Power Electronic switches such as IGBT; GTO etc. switch DC voltage at high speed, producing a series of short-width pulses of constant amplitude. Output voltage is varied by varying the gain of the inverter. Output frequency is adjusted by changing the number of pulses per half cycle or by varying the period for each time cycle.

The resulting current in an induction motor simulates a sine wave of the desired output frequency. The high speed switching action of a PWM inverter results in less waveform distortion and hence decreases harmonic losses.

Control System

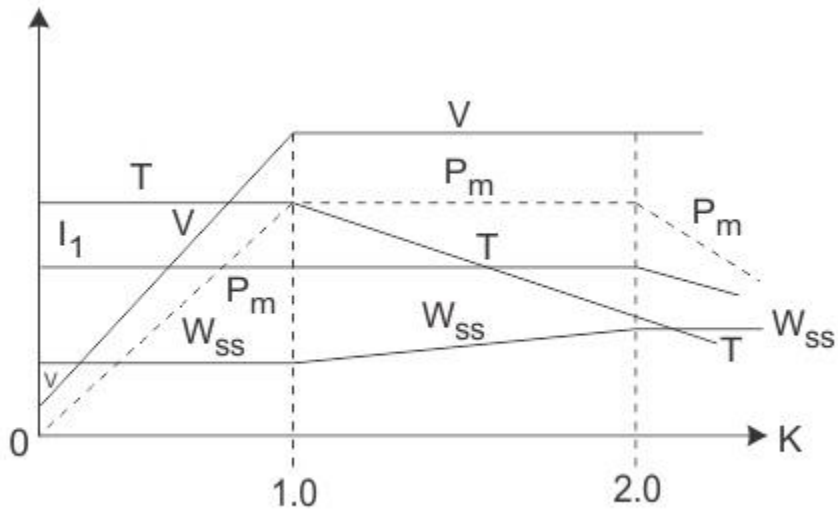
Its function is to control output voltage i.e. voltage vector of inverter being fed to motor and maintain a constant ratio of voltage to frequency (V/Hz). It consists of an electronic circuit which receives feedback information from the driven motor and adjusts the output voltage or frequency to the desired values. Control system may be based on SPWM (Sine Wave PWM), SVPWM (Space Vector modulated PWM) or some soft computing based algorithm.

Induction Motor Characteristic under Variable Frequency Drive

In an induction motor induced in stator, E is proportional to the product of the slip frequency and the air gap flux. The terminal voltage can be considered proportional to the product of the slip frequency and flux, if stator drop is neglected. Any reduction in the supply frequency without a change in the terminal voltage causes an increase in the air gap flux which will cause magnetic saturation of motor. Also the torque capability of motor is decreased. Hence while controlling a motor with the help of VFD or Variable Frequency Drive we always keep the V/f ratio constant. Now define variable ‘K’ as,

$$K = \frac{f}{f_{rated}}$$

For operation below K < 1 i.e. below rated frequency we have constant flux operation. For this we maintain constant magnetization current I_m for all operating points. For K > 1 i.e. above rated frequency we maintain terminal voltage Vrated constant. In this field is weakened in the inverse ratio of per unit frequency ‘K’. For values of K = 1 we have constant torque operation and above that we have constant power application.



V(Terminal Voltage), T(Torque), P_m(Power), I_1(Stator Current) and W_{ss} vs. K plot

Merits of using Variable Frequency Drives

Energy Saving

Primary function of VFD in industry is to provide smooth control along with energy savings. The variable speed motor drive system is more efficient than all other flow control methods including valves, turbines, hydraulic transmissions, dampers, etc. Energy cost savings becomes more pronounced in variable-torque ID fan and pump applications, where the load's torque and power is directly proportional to the square and cube of the speed respectively.

Increased Reliability

Adjustable speed motor-drive systems are more reliable than traditional mechanical approaches such as using valves, gears, louvers or turbines to control speed and flow. Unlike mechanical control system they don't have any moving parts hence they are highly reliable.

Speed Variations

Beyond energy saving, applications such as crushers, conveyors and grinding mills can use the motor and VFD's packages to provide optimal speed variations. In some crucial applications, the operating speed range can be wide, which a motor supplied with a constant frequency power source cannot provide. In the case of conveyors and mills, a VFD and motor system can even provide a "crawl" speed foe maintenance purposes eliminating the need for additional drives.

Soft Starting

When Variable Frequency Drives start large motors, the drawbacks associated with large inrush current i.e. starting current (winding stress, winding overheating and voltage dip on connected bus) is eliminated. This reduces chances of insulation or winding damage and provides extended motor life.

Extended Machine Life and Less Maintenance

The VFD's greatly reduce wear to the motor, increase life of the equipment and decrease maintenance costs. Due to optimal voltage and frequency control it offers better protection to the motor from issues such as electro thermal overloads, phase faults, over voltage, under voltage etc. When we start a motor (on load) with help of a VFD, the motor is not subjected to "instant shock" hence there is less wear and tear of belt, gear and pulley system.

High Power Factor

Power converted to rotation, heat, sound, etc. is called active power and is measured in kilowatts (kW). Power that charges builds magnetic fields or charges capacitor is called reactive power and is measured in kVAR. The vector sum of the kW and the kVAR is the Apparent Power and is measured in KVA. Power factor is the ratio of kW/KVA. Typical AC motors may have a full load power factor ranging from 0.7 to 0.8. As the motor load is reduced, the power factor becomes low. The advantage of using VFD's is that it includes capacitors in the DC Bus itself which maintains high power factor on the line side of the Variable Frequency Drive. This eliminates the need of additional expensive capacitor banks.

Applications of Variable Frequency Drive:

1. They are mostly used in industries for large induction motor (dealing with variable load) whose power rating ranges from few kW to few MW.
2. **Variable Frequency Drive** is used in traction system. In India it is being used by Delhi Metro Rail Corporation.
3. They are also used in modern lifts, escalators and pumping systems.
4. Nowadays they are being also used in energy efficient refrigerators, AC's and Outside-air Economizers.

24. Explain Voltage source inverter (VSI) fed synchronous motor drive.

Three combinations are possible to provide a variable voltage variable frequency supply to synchronous motor fed from VSI:

- Square wave inverter
- PWM inverter
- Chopper with square wave inverter

a) Square wave inverter

Here the dc link voltage is variable i.e. the voltage control is obtained to the inverter using phase controlled rectifier Fig (a) and (c). The disadvantage of this method is that the commutation is difficult at very low speeds. Hence is applicable since for medium to high speed application. Since the output voltage is a square wave, the inverter is called variable voltage inverter (or) square wave inverter.

b) PWM inverter

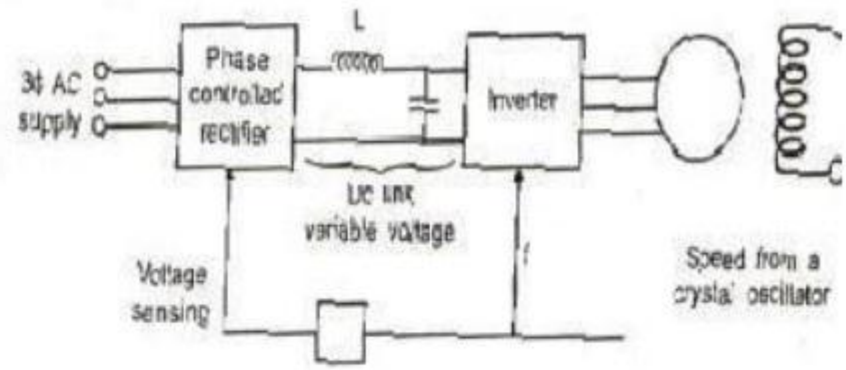
The second method is to have voltage control within the inverter itself using the principles of PWM Fig (b) & (d). Here the dc link voltage is constant. Here diode rectifier is used on the line side. It doesn't have difficulties in commutation at low speeds. It has wide range of speed applications (even till zero speeds)

c) Chopper with square wave inverter

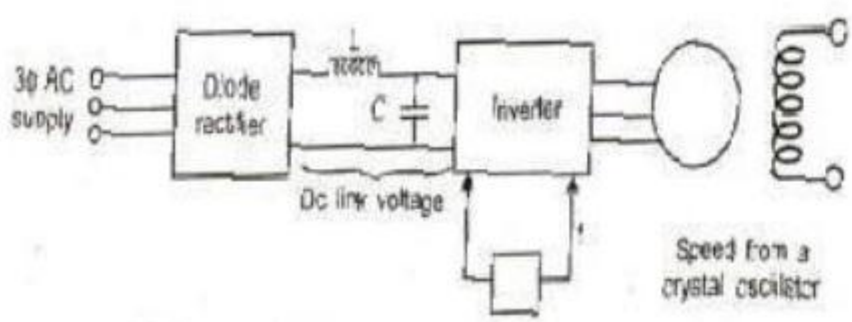
The third method is to include a dc chopper in between the diode rectifier and the inverter. It has many advantages through it seem to the complex circuitry. Here 3 simple converters are used and is possible to reduce the link inductance by having synchronous control of the chopper.

Generally, a VSI fed synchronous motor drive has:

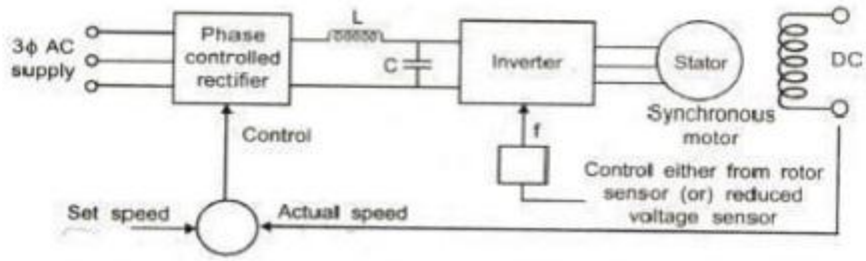
- Reasonable efficiency
- Converter cost is high
- Multi motor operation is possible
- Open loop (separate) control may pose stability problem at low speeds. CL mode is very stable
- PWM drive has better dynamic response than square wave drive



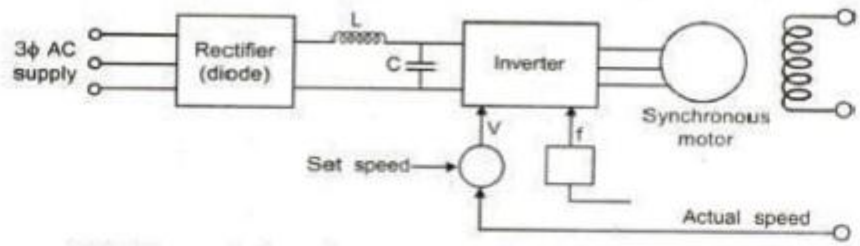
(a) Separate control of SM fed from square wave inverter



(b) Separate control of SM fed from PWM inverter



(c) Self control of synchronous motor fed from square wave inverter



(d) Self control of synchronous motor fed from a PWM inverter

25. What are the methods employed for braking of synchronous motor.

The methods that are employed for Braking of Synchronous Motor are:

- Regenerative braking while operating on a variable frequency supply
- Rheostatic braking
- Plugging

Regenerative braking

When the motor operates as a variable speed drive motor utilizing a variable frequency supply, it can be regeneratively braked and all the K.E. returned to the mains. As in an induction motor, regeneration is possible if the synchronous speed is less than the rotor speed. The input frequency is gradually decreased to achieve this at every instant. The KE. of the rotating parts is returned to the mains. The braking takes place at constant torque. With a CSI and cycloconverter, regeneration is simple and straightforward. With VSI an additional converter is required on the line side.

Rheostatic or dynamic braking

A Braking of Synchronous Motor is switched on to a three-phase balanced resistive load after disconnecting it from the mains, keeping the excitation constant. To achieve greater braking torque for effective braking, the excitation may be increased. The terminal voltage and current (change) decrease as the speed decreases. At very low speeds the resistance effect becomes considerable. The value of resistance affects the speed at which the maximum torque occurs. It can ideally be made to occur Just before the stopping of the motor.

The braking current at any instant is given by

$$I_{br} = \frac{E}{\sqrt{r_1^2 + (\omega L_s)^2}}$$

Where

$E=\omega L_{af} I_f/\sqrt{2}$ is the induced voltage.

In the above equations

r_1 = stator resistance per phase

L_s = synchronous inductance per phase

L_{af} = mutual inductance between armature and field

I_f = field current

The braking torque

$$= \frac{3 I_{br}^2 r_1}{\omega} = K \frac{\omega}{r_1^2 + (\omega L_s)^2}$$

The speed at which the T_{br} is maximum can be obtained as $\omega_m = r_1/L_s$.. By proper choice of r_1, the maximum braking torque can be made to occur just before stopping.

Plugging

The Braking of Synchronous Motor by plugging has serious disadvantages. Very heavy braking current flows causing line disturbances. The torque is also not effective. However, if the motor is synchronous induction type it can be braked effectively by plugging only if the machine is working as an induction motor.