ELECTRIC DRIVES

ELECTRICAL DRIVE

Multiple Choice Type Questions

1. A single motor which actuates several mechanisms or machines is called [WBUT 2009, 2013, 2017]
   a) group drive
   b) individual drive
   c) multi-motor drive
   d) active drive

Answer: (a)

2. Fourth quadrant operation of electric drive gives [WBUT 2015]
   a) forward motoring
   b) forward braking
   c) reverse braking
   d) reverse motoring

Answer: (c)

3. For multi-motor drives [WBUT 2015]
   a) current source inverters are used
   b) voltage source inverters are used
   c) both inverters are used
   d) none of these

Answer: (b)

4. The zone below base speed of an electric drive is known as [WBUT 2016]
   a) constant power zone
   b) constant torque zone
   c) constant voltage zone
   d) constant current zone

Answer: (b)

5. A crane is used to more material horizontally and vertically. The type of drive used is [WBUT 2016]
   a) multimotor
   b) group
   c) individual
   d) both (a) and (c)

Answer: (d)

6. A four quadrant operation requires [WBUT 2016]
   a) two full converters connected in series
   b) two full converters connected in parallel
   c) two full converters connected in back to back
   d) two semi-converters connected in back to back

Answer: (c)

7. Short time rating of an electric machine [WBUT 2017]
   a) is equal to the name plate rating
   b) is less than the name plate rating
   c) is greater than the name plate rating
   d) has no bearing to its name plate rating

Answer: (b)

Short Answer Type Questions

1. a) What do you mean by electric drives? **[WBUT 2007, 2013]**
b) What is group drive? Give examples. State advantages and disadvantages of such drive. **[WBUT 2007, 2013]**

Answer:

a) The electromechanical device which converts electrical energy into mechanical energy to impart motion to different machines and mechanism for various kinds of process control the device is termed as electric drive. Various functions performed by electric drives include

i) driving fans, ventilators, compressors and pumps
ii) lifting goods by hoists and cranes
iii) imparting motion to conveyors in factories, mines and ware houses, and
iv) running excavators and escalators, electric locomotives trains, cars, trolley, lifts and drum winders.

b) Group Drive

If a group of machines or mechanisms are required to be operated by a single motor which will first impart motion to one or more line shaft supported on bearings and then the motions are transmitted to the machines or mechanisms to drive the same with the help of pulleys and belts or gears which are fitted on the line shafts, then the system may be called as group electric drive.

Advantages:

1. Generally an induction type large single motor is used instead of a number of small motor for which cost is reduced.
2. Taking into account the diversity factor of the loads, the rating of the motor is reduced to some extent.
3. As the drive is an induction type, the motor can work at about full load thereby increasing the efficiency and power factor.

Disadvantages:

1. The major disadvantage is that in case of any fault in the motor, the entire process will be at stand still. If some of the machines are required to be kept in operative, the losses will increase thereby decreasing the efficiency and power factor.
2. It is difficult to add an extra machine to the main shaft.

2. What are the various factors that influence the choice of electric drives? **[WBUT 2016]**

Answer:

i) Steady state operation requirements: Nature of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations if any, ratings.

ii) Requirements related to source: Type of source, and its capacity, magnitude of voltage, voltage fluctuations, power factor, harmonics and their effect on other loads, ability to accept regenerative power.
iii) Transient operation requirements: Values of acceleration and deceleration, starting, braking and reversing performance.
iv) Capital and running cost, maintenance needs, life.
v) Space and weight restrictions if any.
vi) Environment and location
vii) Reliability.

Long Answer Type Questions

1. Write short note on Electrical drives and its components. [WBUT 2013, 2015]

Answer:

So far the parts of electrical drives are concerned it may be noted that the major parts are load, motor, power modulator, control unit and source.

Electrical motors commonly used in electrical drives are:

a) D.C. motors – shunt, series, compound and permanent magnet motors.
b) Induction motors – Squirrel cage, wound rotor and linear.
c) Synchronous motors – Wound field and permanent magnet.
d) Other types – Brushless dc motors; stepper motors, switched reluctance motors.

Previously, induction and synchronous motors were employed mainly in constant speed drives. Variable speed drives consisting these machines were either too expensive or had very poor efficiency. Consequently variable speed drive applications were dominated by dc motors. A.C motors are now employed in variable speed drives also due to development of semiconductor converters employing thyristors, power transistors, IGBTs and GTOs.

Brushless d.c. motor is somewhat similar to a permanent magnet synchronous motor, but has lower cost and requires simpler and cheaper converter. It is being considered for low power high-speed drives and for servo applications, as an alternative to d. c servomotors, which has been very popular so far. At low power levels, the coulomb friction between the brushes and commutator is objectionable, as it adversely affects the steady state accuracy of the drive. Stepper motor is also becoming popular for position control and switched reluctance motor drive for speed control.

DYNAMICS OF ELECTRICAL DRIVES

Multiple Choice Type Questions

1. In a fan motor the load torque is proportional to [WBUT 2006, 2007, 2010]

a) speed b) $(\text{speed})^2$ c) $\frac{1}{\text{speed}}$ d) $\frac{1}{(\text{speed})^2}$

Answer: (b)

2. In constant power drive [WBUT 2006, 2007, 2012]

a) torque is proportional to the speed
b) torque is proportional to the square of speed
c) torque is inversely proportional to the speed
d) torque is independent of speed

Answer: (c)

3. A typical active load is [WBUT 2007, 2016]

a) hoist b) blower c) pump d) lathe

Answer: (c)

4. A machine driving pulse torque load is equipped with a flywheel in order to [WBUT 2007]

a) equalize the current demand during the operation
b) equalize the torque requirement
c) reduce the mechanical overload
d) make the motor thermally suitable to drive the load

Answer: (b)

5. A motor driving a passive load is said to be steady state stable if [WBUT 2007, 2013]

a) $\frac{dT_L}{dW}-\frac{dT_M}{dW}=0$ b) $\frac{dT_L}{dW}-\frac{dT_M}{dW}<0$ c) $\frac{dT_L}{dW}-\frac{dT_M}{dW}>0$ d) all of these

Answer: (a)

6. A typical passive load is [WBUT 2008, 2017]

a) Hoist b) Friction c) Blower d) Pump

Answer: (b)

7. In constant torque drive [WBUT 2008, 2012, 2013, 2017]

a) power is proportional to the speed
b) power is proportional to the square of speed
c) power is inversely proportional to the speed
d) power is independent of speed

Answer: (a)

8. A drive has following parameters: [WBUT 2008]

$J = 10$ kg-m^2, $T_M = 100 - 0.1$ N, N-m

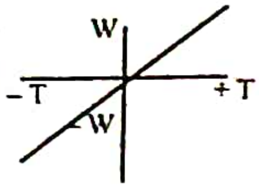
$T_L(\text{passive}) = 0.05$ N, N-m, where N is speed in rpm.

Then the steady state speed is

a) 700 rpm b) 800 rpm c) 667 rpm d) 680 rpm

Answer: (c)

9. The speed-torque curve of a fan type load is given by [WBUT 2009]

a)


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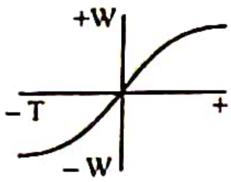

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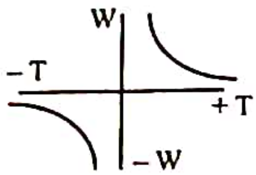

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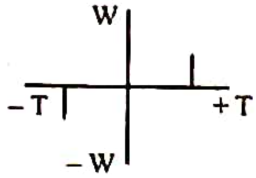


Answer: (c)

10. $\pm T_M = \pm T_L + J\dfrac{dW}{dt}$, if $T_M < T_L$, for active load, it means [WBUT 2009]

a) the drive will be accelerating
b) the drive will be decelerating
c) the drive will run at the same speed
d) the drive may accelerate or decelerate

Answer: (b)

11. The speed-torque curve of a separately exited motor is a [WBUT 2010]

a) hyperbola
b) straight line
c) circle
d) none of these

Answer: (b)

12. The zone of an electric drive below base speed is known as [WBUT 2011]

a) constant power cone
b) constant torque zone
c) constant voltage zone
d) none of these

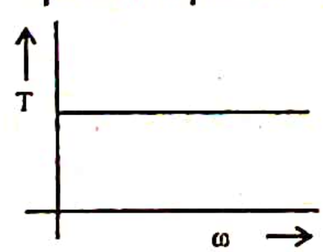
Answer: (b)

13. Second quadrant operation of electric drive gives [WBUT 2012]

a) forward motoring
b) forward braking
c) reverse braking
d) reverse motoring

Answer: (a)

14. The speed-torque curve of a fan-type load is given by [WBUT 2013, 2016]

a)


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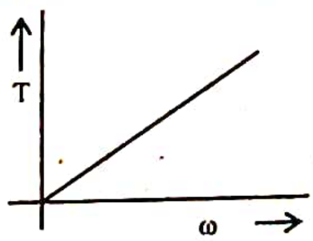
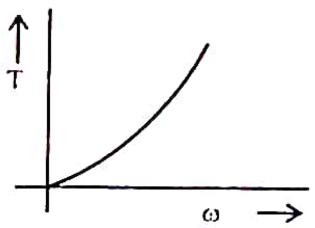
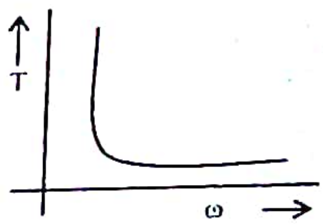


c) 

d) 

Answer: (c)

15. During lowering of an over hauling load, braking takes place is **[WBUT 2015]**
a) regenerative braking
b) dynamic braking
c) plugging
d) none of these

Answer: (a)

16. In fan type load, the torque (τ) varies with speed (w) as **[WBUT 2017]**

a) $\tau \propto w$
b) $\tau \propto w^2$
c) $\tau \propto \frac{1}{w}$
d) $\tau \propto \frac{1}{w^2}$

Answer: (b)

Short Answer Type Questions

1. A horizontal conveyer belt moving at a uniform velocity of 1 m/sec transports load at the rate of 50,000 kg/hour. The belt is 180 m long & is drive by a 960 rpm motor:
a) Determine the equivalent rotational inertia at the motor shaft.
b) Calculate the required braking torque of the motor shaft to stop the belt at a uniform rate in 10 sec. **[WBUT 2009]**

Answer:

a) Let J be the equivalent rotational inertia referred to the motor shaft.

$$\therefore \quad J = \frac{W_L}{g}\left(\frac{V}{\omega_m}\right)^2 = \frac{50000}{9.81} \times \left(\frac{1}{\frac{2\pi N}{60}}\right)^2$$

$$= 5096.84 \times \left(\frac{60}{2\pi \times 960}\right)^2 = 0.5043 \text{ Kg-m}^2.$$

b) Now, Braking Torque, $T_b = W_L + J \cdot t = 50000 + (0.5043 \times 10) = 50005.043$ N-m.

2. A weight of 500 kg is being lifted up to at a uniform speed of 1.5 m/s by a winch drive by a motor running at a speed of 1000 rpm. The moments of inertia of the motor and winch are 0.5 kg-m^2 and 0.3 kg-m^2 respectively. Calculate the motor torque and the equivalent moment of inertia referred to the motor shaft. In the absence of weight motor develops a torque of 100 N-m when running at 1000 rpm. **[WBUT 2010, 2016]**

Answer:

$J_m = 0.5\,\text{kg-m}^2$ $\quad J_w = 0.3\,\text{kg-m}^2$

$v_1 = 1.5\,\text{m/s}$ $\quad M_1 = 500\,\text{kg}$

$$\omega_m = \frac{1000\pi}{30}\,\text{rad./sec.}$$

$$\text{Equivalent moment of inertia} = J_m + J_w + M_1\left(\frac{v_1}{\omega_m}\right)^2$$

$$= 0.5 + 0.3 + 500\left(\frac{1.5\times 30}{1000\pi}\right)^2$$

$$= 0.8 + 0.1003 = 0.9003\,\text{kg-m}^2$$

Given $T_1 = 100\,\text{N-m}$ $\quad F_1 = 500\times 9.81\,\text{N}$

Assuming efficiency of the motor is $\eta = 0.95$

$$T_t = T_1 + \frac{F_1}{\eta}\left(\frac{v_1}{\omega_m}\right) = 100 + \frac{500\times 9.81}{0.95}\left(\frac{1.5\times 30}{1000\pi}\right)$$

$$= 100 + 73.994 = 173.994\,\text{N-m.}$$

3. A weight of 500 kg is being raised at a uniform speed of 1000 rpm. The moments of inertia of motor and the winch are 0.5 kg-m^2 and 0.3 kg-m^2 respectively. Calculate

i) the motor torque and

ii) the equivalent moment of inertia referred to the motor shaft.

In the absence of any weight the motor develops a torque of 100 N-m when running at 1000 rpm. [WBUT 2011]

Answer:

Given $J_m = 0.5\,\text{kg-m}^2$ $\quad J_w = 0.3\,\text{kg-m}^2$ $\quad M_1 = 500\,\text{kg}$ $\quad \omega_m = \frac{1000\pi}{30}\,\text{rad./sec.}$

Assuming, $v_1 = 1.5\,\text{m/s}$

Equivalent moment of inertia

$$= J_m + J_w + M_1\left(\frac{v_1}{\omega_m}\right)^2 = 0.5 + 0.3 + 500\left(\frac{1.5\times 30}{1000\pi}\right)^2 = 0.8 + 0.1003 = 0.9003\,\text{kg-m}^2$$

Given $T_1 = 100\,\text{N-m}$ $\quad F_1 = 500\times 9.81\,\text{N}$

Assuming efficiency of the motor is $\eta = 0.95$

$$T_t = T_1 + \frac{F_1}{\eta}\left(\frac{v_1}{\omega_m}\right) = 100 + \frac{500\times 9.81}{0.95}\left(\frac{1.5\times 30}{1000\pi}\right) = 100 + 73.994 = 173.994\,\text{N-m.}$$

4. With appropriate diagrams describe the four quadrant operation of a hoist drive. [WBUT 2011]

OR,

Describe with a neat diagram four quadrant operation of a motor driving a hoist load. **[WBUT 2013, 2015, 2016]**

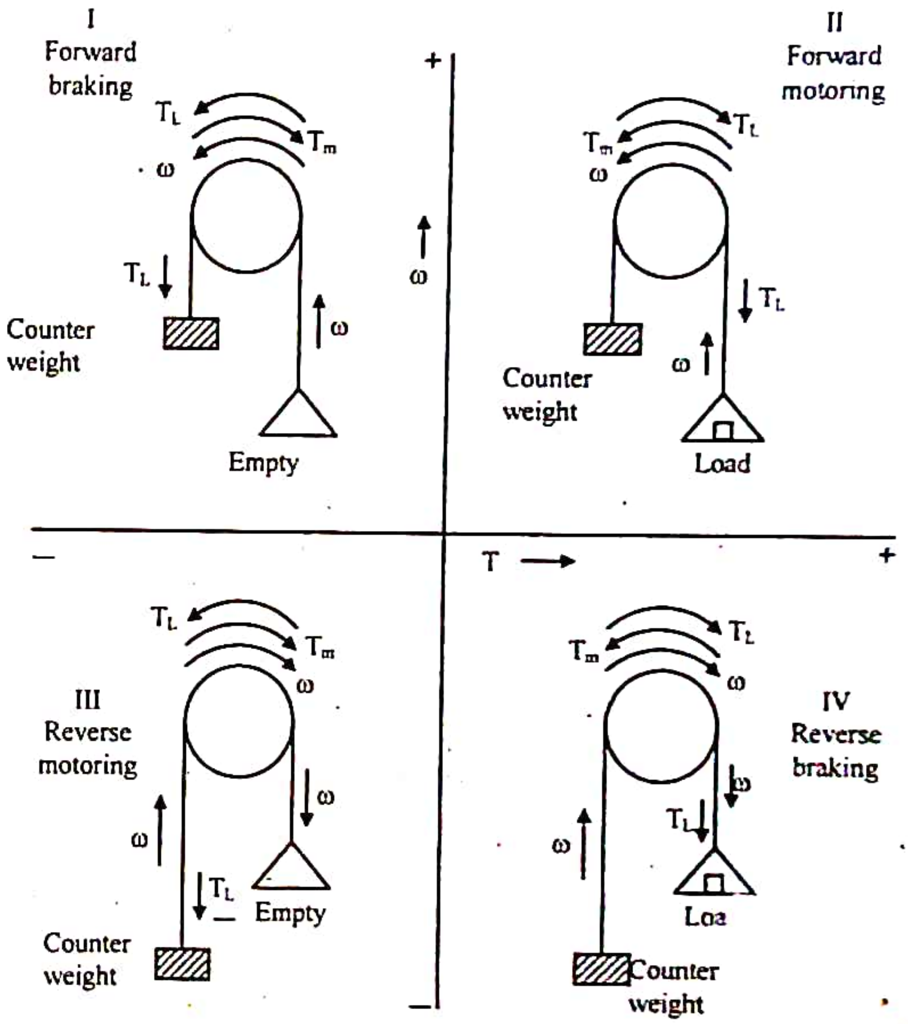
OR,

With the help of heat diagram, explain four quadrant operations of a motor driving a hoist load. **[WBUT 2017]**

Answer:

A motor drive capable of operating in both directions of rotation and of producing both motoring and regeneration is called a four-quadrant variable speed drive.

The four-quadrant operation of a hoist is shown by a quadrant diagram as under:



5. Discuss the effect of flywheel incorporated with an electric drive under shock loading condition. **[WBUT 2013]**

Answer:

Operation of Electric Drives incorporating Flywheel under Shock Loading Conditions

The machines like rolling mill, forging machine, electric press, etc. undergo shock loading during their operation. A simplified load diagram of a machine under shock loading condition is shown in figure (i).

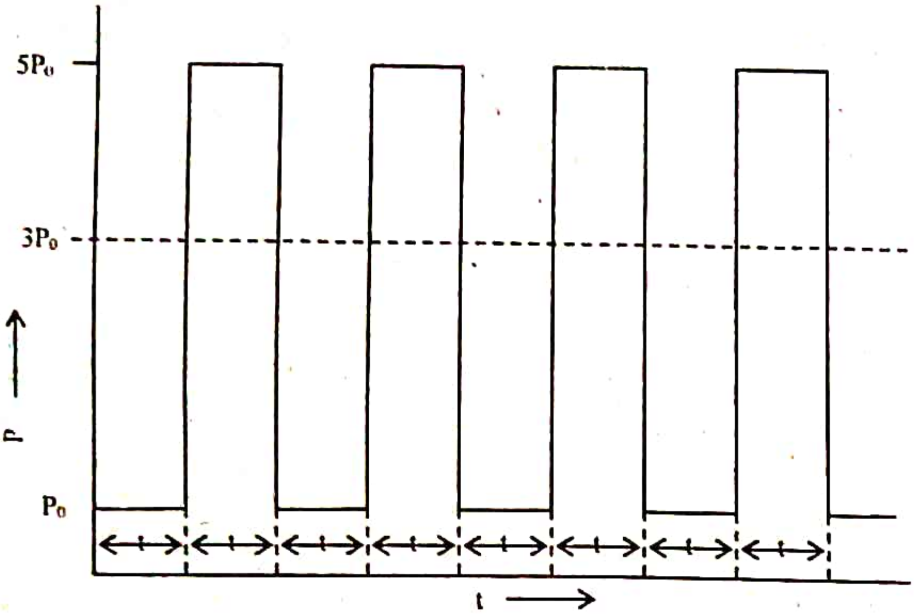


Fig: (i) Simplified load diagram of a machine under shock loading

Let it is assumed that sudden loading alternates with an idling period of equal duration. In such drives the losses are high and therefore efficiency is low. The size of the motor has to be increased to bear overloading. The problem can be overcome by fitting a flywheel to the shaft of the motor as the load is then shared by the flywheel. When a load is applied, the speed drops from ω_1 to ω_2 and the stored energy released by the flywheel to share the load with the motor is equal to $\frac{1}{2}J\left[(\omega_1)^2-(\omega_2)^2\right]$, which is flywheel inertia. When the load is off following the peak, the speed rises and stored energy in the flywheel increases to a new value depending upon the new speed. In this way the load on the motor is smoothed out, thus reducing the losses. This is called the *load equalization*. This can be illustrated with reference to the load diagram of fig: (i). The variable losses are proportional to (current)^2, i.e. (power)^2. For one cycle, the variable losses are

$$c5P_0^2t \cdot cP_0^2t = 26cP_0^2t$$

When the load on the motor is smoothed out, the average losses are

$$c3P_0^2(2t) = 18cP_0^2t$$

The energy saved per cycle is about 30%.

When the flywheel is incorporated, the motor selected can be of lower rating with lower overload capacity. Let us consider the load diagram of a rolling mill to illustrate how the load is shared between the motor and the flywheel, thus lowering the rating and the overload capacity of the motor.

The rolling mill operation consists of a number of passes per schedule. The rolling torque, i.e. load torque remains constant during a pass, but it varies from pass to pass. To find the division of load between the motor and the flywheel, a portion of the load diagram may be considered (fig: (ii)).

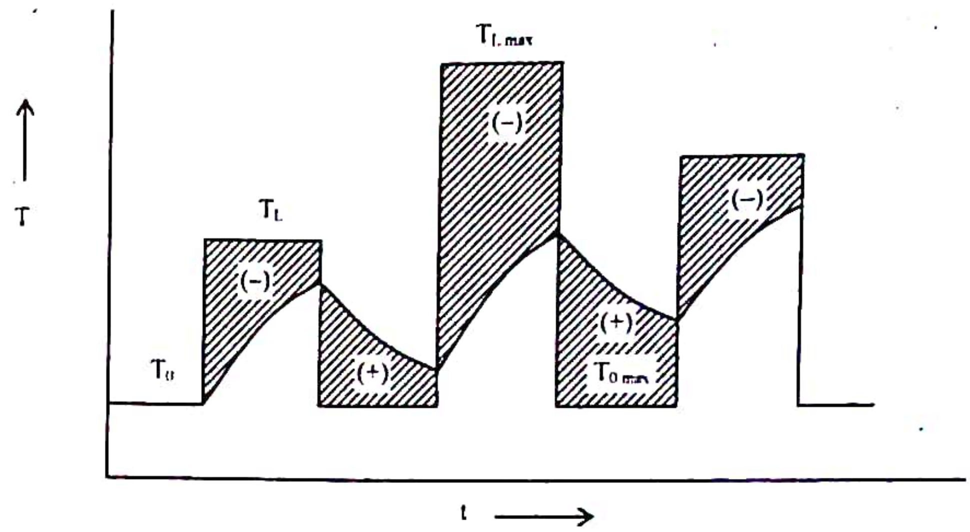


Fig: Load sharing between the motor and the flywheel of a rolling mill

With reference to Fig (ii) the torque equation of the motor during a pass., when the metal passes between the rolls of the mill at constant load torque T_L, can be written as

$$T = T_L\left(1 - e^{-\frac{t}{T_{em}}}\right) + T_0 e^{-\frac{t}{T_{em}}} \qquad \text{.... (1)}$$

When the metal is out of the rolls, we get

$$T = T_0\left(1 - e^{-\frac{t}{T_{em}}}\right) + T_L e^{-\frac{t}{T_{em}}} \qquad \text{.... (2)}$$

Where T_{em} is the electromechanical time constant.
In Fig: (ii) the shaded are bearing the (–) sign gives the energy supplied by the flywheel to the shaft and the area bearing the (+) sign gives the energy fed to the flywheel.
The size of the flywheel to the fitted to the shaft of the motor is determined based on the fact that the motor has to supply maximum torque equal to λT_{nom}. The maximum value of load torque in the load diagram may be considered for calculation of the size of the flywheel.

$$T = \lambda T_{nom} = (T_L)_{max}\left(1 - e^{-\frac{t}{T_{em}}}\right) + (T_0)_{max}\, e^{-\frac{t}{T_{em}}} \qquad \text{.... (3)}$$

Where

$(T_0)_{max}$ = Motor torque at the beginning of the maximum torque load period. Solving equation (3), we get

$$\frac{t_k}{T_{em}} = \log_e\left[\frac{(T_L)_{max} - (T_0)_{max}}{(T_L)_{max} - \lambda T_{nom}}\right] \qquad \text{.... (4)}$$

Now

$$T_{em} = \frac{J\omega_0 S_{nom}}{T_{nom}}$$

The expression of the required moment of inertia of the flywheel is

$$J = \frac{T_{nom} t_k}{\omega_0 s_{nom} \log_e \left[\frac{(T_L)_{max} - (T_0)_{max}}{(T_L)_{max} - \lambda T_{nom}} \right]} \quad \text{.... (5)}$$

It is seen from the above equation that the inertia of the flywheel is decorated by increasing s_{nom}. It may be borne in mind that a higher value of s_{nom} means higher losses and lower speed. Thus s_{nom} must lie between 10 – 15%.

6. Show that the torque to inertia ratios referred to the motor shaft and to the load shaft differ from each other by a factor of i, where i is the gear ratio.[WBUT 2014]

Answer:

Let us consider a motor driving two loads, one coupled directly to its shaft and other through a gear with n and n_1 teeth as shown in Fig. 1(a). Let the moment of inertia of motor and load directly coupled to its shaft be J_0, motor speed and torque of the directly coupled load be ω_m and T_{l0} respectively. Let the moment of inertia, speed and torque of the load coupled through a gear be J_1, ω_{m1} and T_{l1} respectively. Now,

$$\frac{\omega_{m1}}{\omega_m} = \frac{n}{n_1} = i_1 \quad \text{.... (1)}$$

where a_1 is the gear tooth ratio.

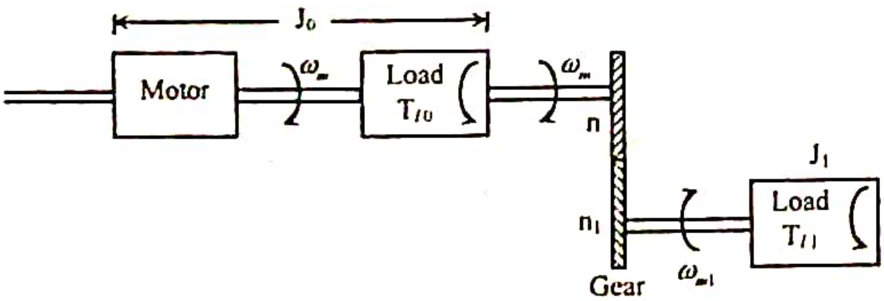
If the losses in transmission are neglected, then the kinetic energy due to equivalent inertia must be the same as kinetic energy of various moving parts. Thus

$$\frac{1}{2} J \omega_m^2 = \frac{1}{2} J_0 \omega_m^2 + \frac{1}{2} J_1 \omega_{m1}^2 \quad \text{.... (2)}$$

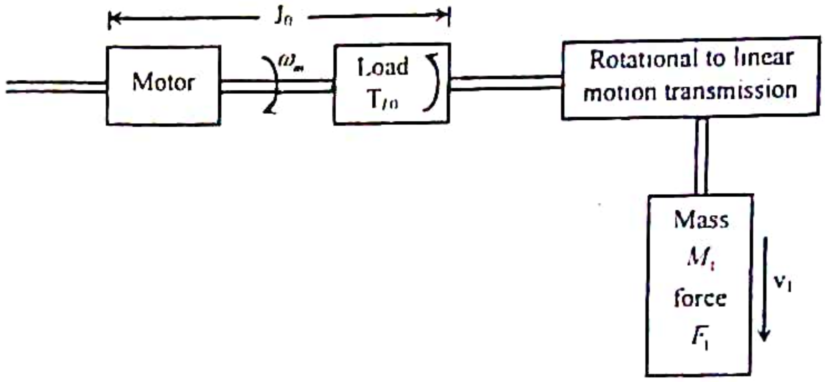
From eqs. (1) and (2)

$$J = J_0 + i_1^2 J_1 \quad \text{.... (3)}$$

Power at the loads and motor must be the same. If transimission efficiency of the gears be η_1, then



(a) Loads with rotational motion



(b) Loads with translational and rotational motion

Fig: 1 Motor load system with loads with rotational and linear motion

$$T_l\omega_m = T_{l0}\omega_m + \frac{T_{l1}\omega_{m1}}{\eta_1} \qquad \text{.... (4)}$$

where T_l is the total equivalent torque referred to motor shaft

From Eqs. (1) and (4)

$$T_l = T_{l0} + \frac{i_1 T_{l1}}{\eta_1} \qquad \text{.... (5)}$$

If in addition to load directly coupled to the motor with inertia J_0 there are m other loads with moment of inertias $J_1, J_2, \cdots\cdots, J_m$ and gear teeth ratios of $i_1, i_2, \cdots, i_n$, then

$$J = J_0 + i_1^2 J_1 + i_2^2 J_2 + \cdots + i_m^2 J_m \qquad \text{.... (6)}$$

If m loads with torques $T_{l1}, T_{l2}, \cdots\cdots, T_{lm}$ are coupled through gears with teeth ratios $i_1, i_2, \cdots, i_m$ and transmission efficiencies $\eta_1, \eta_2, \cdots \eta_m$, in addition to one directly coupled, then

$$T_l = T_{l0} + \frac{i_1 T_{l1}}{\eta_1} + \frac{i_2 T_{l2}}{\eta_2} + \cdots + \frac{i_m T_{lm}}{\eta_m} \qquad \text{.... (7)}$$

If loads are driven through a belt drive instead of fears, then, neglecting slippage, the equivalent inertia and torque can be obtained from Eqs. (6) and (7) by considering $i_1, i_2, \cdots, i_m$ each to be the ratios of diameters of wheels driven by motor to the diameters of wheels mounted on the load shaft.

7. Obtain the equilibrium point and determine their stability for motor and load having characteristics as $T_M = 1 + 2W_m$ and $T_L = 3\sqrt{W_m}$ respectively. [WBUT 2017]

Answer:

If the motor and the load torque are in dependent of time, the equation of motion will be:

$$J\frac{d\omega}{dt} = T_m - T_L$$

where J is the angular moment of inertia of the motor shaft and ω is the angular speed of the motor shaft.

Now if:

i) $T_{m(t)} > T_{L(t)}$ i.e., $(1+2W_m) > 3\sqrt{W_m}$ consequently $\frac{d\omega}{dt} > 0$ and therefore the speed of the drive increases.

ii) $T_{m(t)} < T_{L(t)}$ i.e., $(1+2W_m) < 3\sqrt{W_m}$ consequently $\frac{d\omega}{dt} < 0$ and therefore the speed of the drive decreases.

When $T_{m(t)} = T_{L(t)}$ i.e., $\frac{d\omega}{dt} = 0$, the drive attains steady state i.e., runs at a constant speed and in that case for steady state stability

$$T_m - T_L = 0$$

or, $$\left(1+2W_m - 3\sqrt{W_m}\right) = 0$$

8. Explain briefly the different components of load torque with their torque speed characteristics. **[WBUT 2017]**

Answer:

The different components of load torque are:

i) Friction torque (T_F): It will be present in the motor shaft and also in various parts of the load. T_F is equivalent value of various friction torque referred to the motor shaft. Variation of friction torque with speed is shown in Fig. 1.

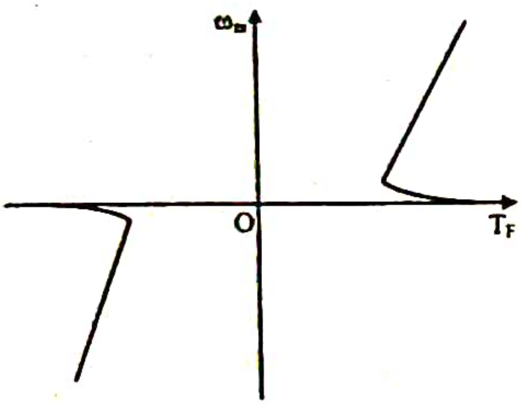


Fig: 1

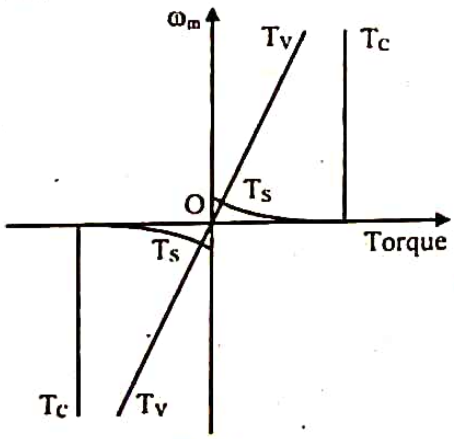


Fig: 2

Friction torque and its component

The value of friction torque at standstill is much higher than its value slightly above zero speed. Friction at zero speed is called striction or static friction. In order for drive to start, the motor torque should at least exceed striction. Friction torque can be resolved in three components as shown in Fig. 2. Component T_V which varies linearly with speed is called viscous friction and is given by

$$T_V = B\omega_m \quad \text{.... (1)}$$

where B is the viscous friction co-efficient.

Another component T_C. which is independent of speed is known as Coulomb friction. Third component T_S accounts for additional torque present at standstill. Since T_S is present only at standstill, it is not taken into account in the dynamic analysis.

ii) Windage torque (T_W): When a motor runs, wind generates a torque opposing the motion. This is known as windage torque and is proportional to speed squared. This is given by $T_W = C\omega_m^2$ .... (2)
where C is a constant.

iii) Torque required to the useful mechanical work (T):
Nature of this torque depends on particular application. It may be constant and independent of speed, it may be some function of speed; it may depend on the position or path followed by load. It may be time invariant or time variant. It may vary cyclically and its nature may also change with the load's mode of operation.
From the above discussion, we may write for finite speeds

$$T = T_L + B\omega_m + T_C + C\omega_m \quad .... (3)$$

Considering the value of only viscous frequency we may write,

$$T = J\frac{d\omega_m}{dt} + T_L + B\omega_m \quad .... (4)$$

If there is torsional elasticity, the coupling torque will be

$$T_e = K_e\theta_e \quad .... (5)$$

where, θ_e is the torsion angle of coupling (radians) and K_e the rotational stiffness.

Long Answer Type Questions

1. Deduce the condition for steady state stability of a motor load combination. Can this condition be applied for synchronous motor? [WBUT 2008]

OR,

Deduce a condition for steady state stability for drive system. Can the condition deduced be applied to synchronous motor drive? [WBUT 2009]

Answer:
Equilibrium speed of a motor-load system is obtained when motor torque equals the load torque. Drive will operate in steady-state at this speed of stable equilibrium. This concept has been developed to readily evaluate the stability of an equilibrium point from steady-state speed-torque curves of the motor and load, thus avoiding solution of differential equations valid for transient operation of drive.
As an example let us examine the steady state stability of equilibrium point A in Fig. (a). The equilibrium point will be termed as stable when the operation will be restored to it after a small departure from it due to a disturbance in the motor or load. Let the disturbance causes a reduction of Δw_m in speed. At new speed, motor torque is greater than the load torque, consequently motor will accelerate and operation will be restored to

A. Similarly an increase of Δw_m in speed caused by a disturbance will make load torque greater than the motor torque, resulting into deceleration and restoration of operation to pint A. Hence the drive is steady-state stable at point A. Let us now examine equilibrium point B which is obtained when the same motor drives another load. A decrease in speed causes the load torque to become greater than the motor torque, drive decelerated and operating point moved away from B. Similarly when working at B an increase in speed will make motor torque greater than the load torque, which will move the operating point away from B. Thus B is an unstable point of equilibrium. Similarly the stability of points C & D given in Fig. (c) & (d).

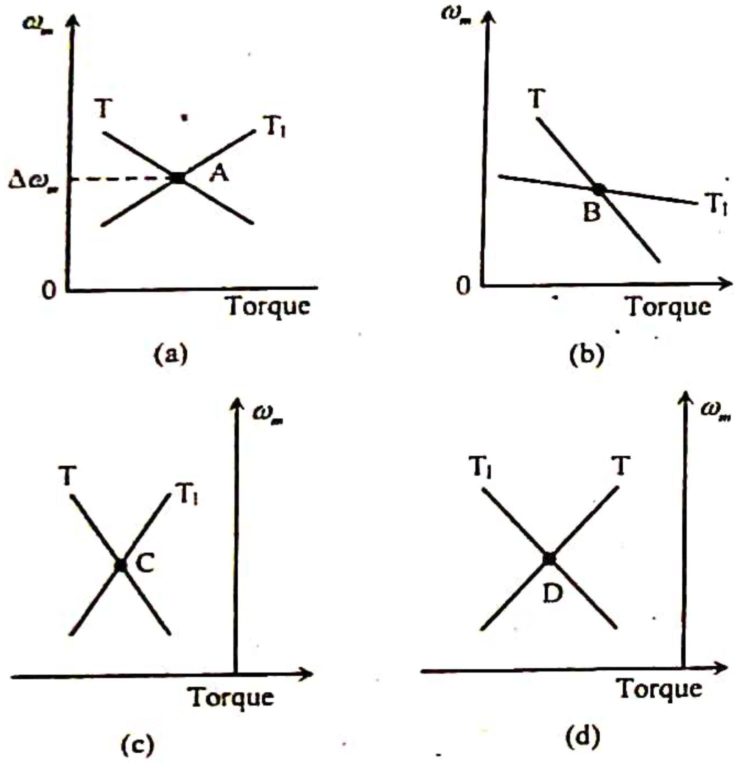


Fig: Prints A and C are stable and B and D are unstable

Above discussion suggest that an equilibrium point will be stable when an increase in speed causes load-torque to exceed the motor-torque.

$$\frac{dT_l}{dw_m} > \frac{dT}{dw_m} \qquad \text{.... (i)}$$

Inequality can be derived by an alternative approach from Eqn. (i). Let a small perturbation in speed, Δw_m results in ΔT and $\Delta T\ell$ perturbations in T & $T\ell$ respectively. Then from eqs.

$$(T+\Delta T) = (T\ell + \Delta T\ell) + J\frac{d(w_m + \Delta w_m)}{dt}$$

$$T + \Delta T = T\ell + \Delta T\ell + J\frac{dw_m}{dt} + J\frac{d\Delta w_m}{dt} \qquad \text{.... (ii)}$$

Subtracting

$$J\frac{d\ \Delta w_m}{dt} = \Delta T - \Delta T\ell \qquad \text{.... (iii)}$$

For small perturbations, the speed-torque curves of the motor and load can be assumed to be straight lines. Thus

$$\Delta T = \left(\frac{dT}{dw_m}\right)\Delta w_m \qquad \text{.... (iv)}$$

$$\Delta T\ell = \left(\frac{dT\ell}{dw_m}\right)\Delta w_m \qquad \text{.... (v)}$$

where $\left(\frac{dT}{dw}\right)$ & $\left(\frac{dT\ell}{dw_m}\right)$ are respectively slopes of the steady state speed-torque curves of motor & load at operating point under consideration.

Substituting (iv) & (v) in (iii) & rearranging he terms

$$J\frac{d\,\Delta w_m}{dt} + \left(\frac{dT\ell}{dw_m} - \frac{dT}{dw_m}\right)\Delta w_m = 0: \qquad \text{.... (vi)}$$

This is first order linear differential Eqns. If initial deviation in spe at $t = 0$ be (Δw_m) then the solution of Eqn. (n) will be

$$\Delta w_m = (\Delta w_m)\exp\left\{-\frac{1}{J}\left(\frac{dT\ell}{dw_m} - \frac{dT}{dw_m}\right)t\right\} \qquad \text{.... (vii)}$$

An operating point will be stable when Δw_m approaches zero as t approaches infinity. For this to happen the exponent in Eqn. (vii) must be negative. This yields the inequality: (i).

2nd Part:

In a steady state operation of a synchronous motor is a combination of equilibrium in which the electromagnetic torque is equal and opposite to the load torque. In the steady state, the rotor runs at a synchronous speed, thereby maintaining a constant value of the torque angle δ. If there is a certain change in the load torque, the equilibrium is disturbed and there is a resulting torque, which changes the speed of the motor.

When there is a sudden increase in a load torque the motor slows down temporarily and the torque angle δ is sufficiently increased to restore the torque equilibrium and the synchronous speed. Similarly, if the motor responds to a decreasing load torque by a temporary increase in speed and thereby, a reduction of the torque angle δ. The rotor swings or oscillates around synchronous speed and the new value of torque angle is required before reaching new equilibrium position (steady state).

2. A motor is used to drive a hoist. Motor characteristics are given by:

Quadrant I, II, and IV: $T = 200 - 0.2N$, Nm.

Quadrant II, III and IV: $T = -200 - 0.2N$, Nm where N is the speed in rpm.

When hoist is loaded, the net load torque $T_l = 100$ Nm and when it is unloaded, the net load torque $T_l = -80$ Nm. Obtain the equilibrium speeds for operation in all the four quadrants. **[WBUT 2017]**

Answer:

For steady state speed:

$$T - T_l = 0$$

When the hoist is loaded in quadrant I, II and IV.

$$200 - 0.2N - 100 = 0$$

or, $100 = 0.2N$

or, $N = \frac{1000}{2} = 500\,\text{RPM}$

When unloaded in quadrant II, III and IV

$$-200 - 0.2N - (-80) = 0$$

or, $-0.2N = 120$

or, $N = -\frac{1200}{2} = -600\,\text{RPM}$ (Reversing mode)

where N is the speed.

3. Write short note on Multiquadrant operation of electric drive. [WBUT 2010, 2012]

OR,

Write short note on Four quadrant operation of an electric motor drive **[WBUT 2011]**

Answer:

A motor drive capable of operating in both directions of rotation and of producing both motoring and regeneration is called **four quadrant variable speed drives.**

For multi-quadrant operation of drives the following conventions about the signs of torque and speed are useful.

1. Motor speed is considered positive when rotating in forward direction.
2. For drives which operate only in one direction, forward speed will be their normal speed.
3. In loads involving up and down motions, the speed of motor which causes upward motion is considered forward motion. For reversible drives, forward speed is chosen arbitrarily. Then the rotation in the opposite direction gives reverse speed which is assigned the negative sign.
4. Motor torque is taken negative if it produces retardation.
5. Load torque is opposite in direction to the positive motor torque.

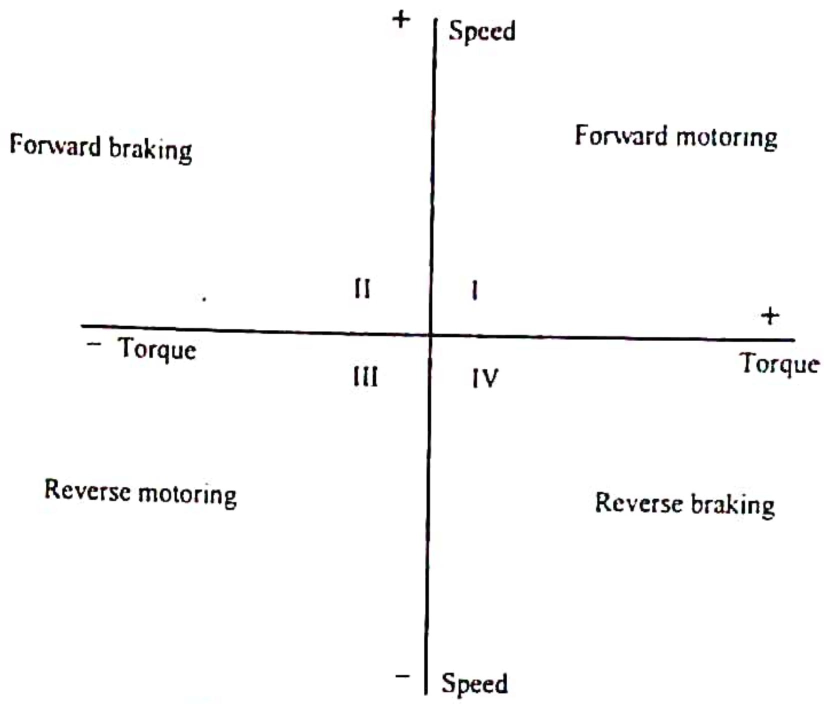


Fig: 1 Four-quadrant operation

Fig (1) as above shows the four-quadrant operation of drives. It may be observed from the above that: -

i. In quadrant I, power developed is positive which signifies that the machine works as a motor supplying mechanical energy and as such quadrant I is called forward motoring.
ii. Quadrant II represents braking operation, because in this part of the torque speed plane the direction of rotation is positive and the torque is negative. The machine operates as a generator developing a negative torque which opposes the motion.
iii. In the III quadrant, motor action is in the reverse direction and both speed and torque have negative values while the power is positive. In fact operation in quadrant III is similar to that in the first quadrant with direction of rotation reversed.
iv. In the fourth quadrant, the torque is positive and the speed is negative. This quadrant corresponds to braking in reverse motoring.

MOTOR POWER RATING

Multiple Choice Type Questions

1. Intermittent duty rating of an electric motor [WBUT 2008, 2014]
   a) is equal to name plate rating b) is less than name plate rating
   c) is greater than name plate rating d) has no bearing to its name plate rating

Answer: (a)

2. The power rating of electric motor for continuous duty & constant load having torque *T* in kgm & speed *N* in rpm is given by [WBUT 2009]
   a) $\frac{TN}{975\eta}$ b) $\frac{TN}{102\eta}$ c) $\frac{TN}{9.75\eta}$ d) $\frac{TN}{10.2\eta}$

Answer: (a)

3. The heating time constant of an electrical machine gives an induction of its [WBUT 2010, 2014, 2016]
   a) cooling b) rating
   c) overload capacity d) short time rating

Answer: (a)

4. Starting current of a motor is kept low [WBUT 2012]
   a) to avoid excessive heating
   b) to safeguard the life of the motor
   c) to reduce the fluctuation in supply voltage
   d) to reduce the acceleration time

Answer: (a)

Short Answer Type Questions

1. The temperature rise of a motor after operating for 30 minutes on full load is 20°C, after another 30 minutes on the same load the temperature rise becomes 30°C. Assuming that the temperature increases according to an exponential law, determine the find temperature rise and the time constant. [WBUT 2007, 2009]

Answer:

We know that the equation of temperature rise with time is given by the relation:

$\theta = \theta_m\left(1 - e^{-t/\lambda}\right)$ where $\theta, \theta_m, -t/\lambda$ have their usual meaning.

According to problem, $t_1 = 30$ minutes, $\theta_1 = 20°C$ and for the next 30 minutes i.e., after $(30+30) = 60$ minutes, (t_2) temperature rise is $30°C$ (θ_2).

So with this data and from the above equation it can be written as:

$$\frac{\theta_2}{\theta_1} = \frac{1 - e^{-t_2/\lambda}}{1 - e^{-t_1/\lambda}}$$

Putting the values, we get, $\frac{30}{20}=\frac{1-e^{-60/\lambda}}{1-e^{-30/\lambda}}$

Taking log in both sides, we have

$$\ln\left(\frac{30}{20}\right)=\ln\left(\frac{1-e^{-60/\lambda}}{1-e^{-30/\lambda}}\right)$$

$$\Rightarrow \quad 0.4054=\frac{60}{\lambda}-\frac{30}{\lambda}$$

$$\Rightarrow \quad 0.4054=\frac{30}{\lambda}$$

$$\Rightarrow \quad \lambda=\frac{30}{0.4054}=\text{time constant}$$

$$\Rightarrow \quad \lambda=\frac{30}{0.4054}=\text{time constant}=74$$

Again $\quad \theta=\theta_m\left(1-e^{-t/\lambda}\right)$

$$\Rightarrow \quad 20=\theta_m\left(1-e^{-30/74}\right)$$

$$\Rightarrow \quad \theta_m=\frac{20}{1-0.666}=\frac{20}{0.334}=60^\circ$$

$\therefore$ Final temperature rise will be 60° and time constant is 74 min.

2. The temperature rise of a motor when operating for 25 min on full-load is 25°C and becomes 40°C when the motor operates for another 25 min on the same load. Determine heating time constant and the steady state temperature rise.

[WBUT 2010, 2012, 2016]

Answer:

The equation of temperature rise with time is given by the relation

$$\theta=\theta_m\left(1-e^{-t/\lambda}\right)$$

$\theta, \theta_m, -t/\lambda$ have their usual meaning.

According to problem,

$t_1=25$ minutes $\qquad \theta_1=25^\circ$C

and for the next 25 minutes i.e. after $(25+25)=50$ minutes

$(t_2)=$ temperature rise is $\theta_2=40^\circ$ C

Using this data we can get

$$\frac{\theta_2}{\theta_1}=\frac{1-e^{-t_2/\lambda}}{1-e^{-t_1/\lambda}}$$

$$\frac{40}{25}=\frac{1-e^{-50/\lambda}}{1-e^{-25/\lambda}}$$

Taking log in both sides, we have

$$\ln\left(\frac{40}{25}\right)=\ln\left(\frac{1-e^{-50/\lambda}}{1-e^{-25/\lambda}}\right)=\frac{50}{\lambda}-\frac{25}{\lambda}=\frac{25}{\lambda}$$

$$\lambda=\frac{25}{\ln\left(\frac{40}{25}\right)}=53.19$$

Again $\theta=\theta_m\left(1-e^{-t/\lambda}\right)$

or, $25=\theta_m\left(1-e^{-25/\lambda}\right)$

$$\theta_m=\frac{25}{1-e^{-25/\lambda}}=\frac{25}{1-0.6249}=\frac{25}{0.3751}=66.65°\text{ C.}$$

Final temperature rise will be 66.65°C and time constant is 53.19.

3. A motor of smaller rating can be selected for a short time duty. Correct and/or justify. **[WBUT 2014]**

Answer:

In short time duty, time of motor operation is considerably less than the heating time constant and motor is allowed to cool down to the ambient temperature before it is required to operate again. If a motor with a continuous duty power rating of P_r, is subjected to a short time duty load of magnitude P_r, then the motor temperature rise will be far below the maximum permissible value θ_{per} and the motor will be highly underutilised (Fig. 1). Therefore, motor can be overloaded by a factor $K(K>1)$ such that the maximum temperature rise just reaches the permissible value θ_{per} as shown in (Fig. 1). When the duration of running period in a duty cycle with power KP_r is t_r, then

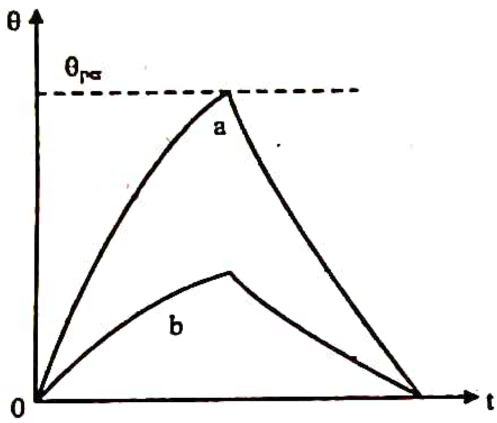


Fig: 1 θ vs. t curves for short time duty loads a — with power KP_r, b — with power P_r

$$\theta_{per}=\theta_m\left(1-e^{-t_r/\tau}\right) \quad \text{.... (1)}$$

or, $$\frac{\theta_{ss}}{\theta_{per}}=\frac{1}{1-e^{-t_r/\tau}} \quad \text{.... (2)}$$

Note that θ_{ss} is the steady state temperature rise which will be attained of motor delivers a power (KP_r) on continuous basis, whereas the permissible temperature rise θ_{per} is also the steady state temperature rise attained when motor operates with a power P_r on continuous basis. If the motor losses for powers P_r and (KP_r) be P_{1r} and P_{1s}, respectively, then

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{P_{1s}}{P_{1r}} = \frac{1}{1-e^{-t_r/\tau}} \qquad \text{.... (3)}$$

Let $\quad P_{1r} = p_c + p_{cu} = p_{cu}(\alpha + 1) \qquad \text{.... (4)}$

where $\quad \alpha = \dfrac{p_c}{p_{cu}} \qquad \text{.... (5)}$

and p_c is the load independent (constant) loss and p_{cu} the load dependent loss. Then

$$p_{1s} = p_c + p_{cu}\left(\frac{KP_r}{P_r}\right)^2 = p_c + K^2 p_{cu}$$

Substituting from Eqn. (5)

$$p_{1s} = p_{cu}(\alpha + K)^2 \qquad \text{.... (6)}$$

Substituting from Eqs. (4) and (6) into Eqn. (3) gives

$$\frac{\alpha + K^2}{\alpha + 1} = \frac{1}{1-e^{-t_r/\tau}}$$

or, $\quad K = \sqrt{\dfrac{1+\alpha}{1-e^{-t_r/\tau}} - \alpha} \qquad \text{.... (7)}$

Eqn. (7) allows the calculation of overloading factor K which can be calculated when constant and copper losses are known separately. When separately not known, total loss is assumed to be only proportional to (power)^2, i.e. α is assumed to be 0.
As already mentioned, K is subjected to the constraints imposed by maximum allowable current in case of dc motors and breakdown torque limitations in case of induction and synchronous motors.

4. A motor has a thermal heating time constant of 50 minutes. When the motor runs continuously on full load, its temperature rise is 100°C in 90 minutes.
a) Find the maximum steady state temperature.
b) How long will the motor take for its temperature to rise from 70°C to 95°C, if it is working on same load? [WBUT 2015]

Answer:

Heating time constant $\tau = 50$ min

$$\theta = \theta_{max}\left(1-e^{t/\tau}\right) = 100\left(1-e^{-90/50}\right) = 100(1-0.16) = 100 \times 0.84 = 84°\text{C}$$

a) Maximum steady state temperature

$$100 = \theta_{max}\left(1-e^{-90/50}\right)$$

$$\Rightarrow \quad \theta_{max} = \frac{100}{0.84} = 119.047°\text{ C.}$$

b) Time for temperature to rise from 70°C to 95°C is to be found out for 90 minutes rating of the motor.

For maximum temperature for 90 minutes rating $\theta_{max} = 119.047°$ C as found above

For temperature rise of 70°C

$$70 = 119.047\left(1 - e^{-t/70}\right)$$

where t is the time required to have the temperature rise of 70°C

$$\frac{70}{119.07} = \left(1 - e^{-t/70}\right)$$

$\Rightarrow \quad 1 - e^{-t/70} = 0.588$

$\Rightarrow \quad e^{-t/70} = 1 - 0.588 = 0.412$

$\Rightarrow \quad \log_e e^{-t/70} = \log_e 0.412$

$$-\frac{t}{70} = \log_e 0.412$$

$$t = -70\log_e 0.412 = -70 \times (-0.887) = 62.09 \text{ min}$$

The motor's temperature will therefore, rise from 70°C to 95°C in

$$(90 - 62.09)\text{min} = 27.91\text{min}.$$

5. What do you mean by 'classes of motor duty'? **[WBUT 2015, 2017]**

Answer:

Selection of motor is the prime criteria for electric drives. The motor rating from the stand point of over loading is considered to be selected properly, if its rated (full load) torque T_r is governed by the following relation: $T_r > \frac{T_{max}}{\lambda}$

where T_{max} is the maximum torque required to drive the equipments.

$t = -\frac{C}{A}\log_e\left[\frac{Q - A\tau}{Q - A\tau_o}\right]$ is the instantaneous torque overload capacity of the motor.

In D.C. motors, the maximum value of λ is restricted by the prerequisite of safe commutation, but for A.C. machines, it is determined by the maximum electro magnetic torque available. The value of λ for different types of motors are given below for ready reference:

λ For different types of motors

Table-I

Type of the motor	Value of λ
a) D.C. series and compound wound motors	3.5 – 4.0
b) General purpose D.C. motors	2.5
c) Squirrel cage and slip-ring induction motors (crane)	2.3 – 3.4
d) General purpose squirrel cage and slip-ring induction motors	1.7 – 2.7
e) Synchronous motor	2.0 – 2.7

Heating is also a prime point for selection of drive motor. The rating of the motor is selected, so that it never exceed the temperature limit of the pre-determined value, for several types of duty. The maximum permissible temperature of the motor determined by the class of insulation used in it.

The insulating materials used in electrical machines can be grouped into seven classes based on their thermal stability. The maximum temperatures as listed below are evolved for an ambient temperature of 35°C. So if the ambient temperature is less than 35°C, then the motor can operate with the larger load, than that stated in the nameplate and if the ambient temperature is greater than 35°C, the position will reverse.

6. What are the reasons for load equalization in an electric drive? State how is it achieved. [WBUT 2017]

Answer:

Load equalization in an electric drive is necessary to smoothen out the fluctuations in load otherwise during interval of peak load it will draw heavy current from the supply either producing large voltage drop in the distribution system or requiring cables and wires of heavy section. In this process, energy is stored during the interval of light load and given out during the interval of peak load. Thus power drawn from the supply mains remains almost constant.

Load equalization can be achieved by use of flywheel. During the light load period the flywheel accelerates and stores the excessive energy drawn from the supply and during peak load period the flywheel decelerates and supplies some of its stored energy to the load in addition to the energy supplied from the supply. Thus the load demand is reduced. The motors used for such load should have drooping speed-torque characteristics, so that speed may fall with the increase in load and enables the flywheel to give up its stored energy. For the load in which the motor have to run in the same direction and is not to be stopped and started frequently, flywheel may be mounted on the motor shaft. For a reversing drive, such as for colliery winder WARD LEONARD control system is generally used for reversing and speed control, so the flywheel can be mounted on motor generator set. The load torque required and motor torque developed as well as speed variations with time are shown in Fig. 1 below:

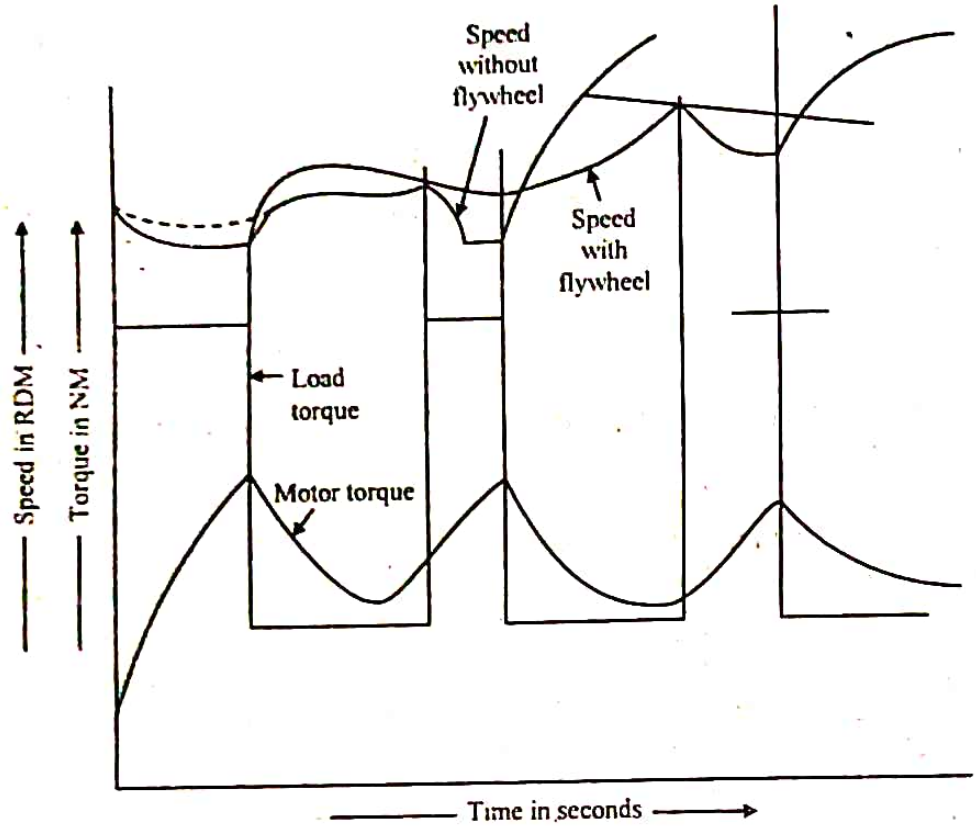


Fig: 1 Variation of speed, load torque and meter torque against time

7. A motor has a thermal heating time constant of 45 minutes. When the motor runs continuously on full load, its final temperature rise in 80°C. (i) What would be the temperature rise after 1 hour, if the motor runs continuously on full load? (ii) If the temperature rise on 1 hour is 80°C, find the maximum steady state temperature at this rating. [WBUT 2017]

Answer:

Refer to Question No. 4. (i) & (ii) of Long Answer Type Questions.

Long Answer Type Questions

1. a) "A motor of smaller rating can be selected for an intermittent periodic duty." Justify the statement by calculating the ratio of rated power P_r to P_x corresponding to duty cycle. [WBUT 2007, 2009, 2016]

b) A constant speed motor has the following duty cycle: [WBUT 2007]

Load rising linearity from 200 to 600 kW	:	4 min
Uniform load of 450 kW	:	2 min
Regenerative power returned to the supply reducing linearity from 450 kW to 0	:	3 min
Remains idle	:	4 min

Determine power rating of the motor, assuming loss to be proportional to (power)^2.

Answer:

a) Cooling and thermal capability of a motor are major criteria:

The intermittent ratings depend upon the cooling and thermal capability of a motor. The motor with intermittent rating are loaded with a train of identical duty cycles so that finally the rise and fall in temperature during each duty cycle are equal. For the evaluation of heating due to intermittent duty loads use is made of duty factor (ε) which is defined as the ratio of heating period to the period of whole cycle. Keeping these in mind a motor of smaller rating can be selected for a intermittent periodic duty which can be further corroborated if a case of a motor of rating P_r and duty factor ε_1 is considered for duty factor ε_2.

The new power rating P_x for duty factor ε_2 is found by equating the equivalent power in both cases.

$$P_{eq}\left[\frac{P_r^2 t_{h_1}}{t_{h_1}+t_{\varepsilon_1}}\right]^{1/2}=\left[\frac{P_x^2 t_{h_2}}{t_{h_2}+t_{\varepsilon_2}}\right]^{1/2} \qquad \left[t_{h_1}, t_{h_2} \text{ are the heating period}\right]$$

But $\quad \varepsilon_1=\dfrac{t_{h_1}}{t_{h_1}+t_{\varepsilon_1}} \quad$ and $\quad \varepsilon_2=\dfrac{t_{h_2}}{t_{h_2}+t_{\varepsilon_2}}$

or, $\quad P_r^2\varepsilon_1=P_x^2\varepsilon_2$

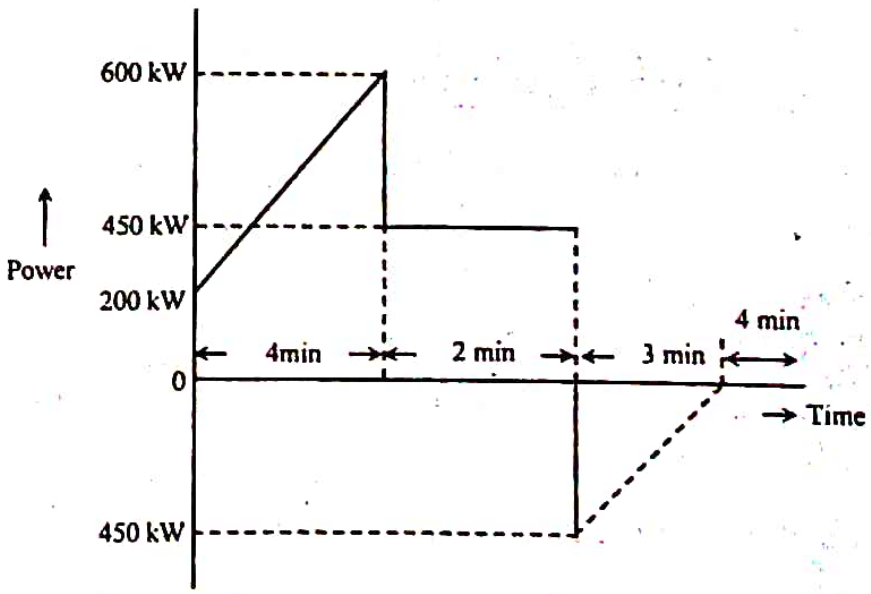
or, $\quad P_x=P_r\sqrt{\dfrac{\varepsilon_1}{\varepsilon_2}}$

Another formula that takes into account the constant losses may be used. This relationship is:-

$$P_x=P_r\sqrt{(K+1)\frac{\varepsilon_1}{\varepsilon_2}-K}$$

where $\quad K=$ ratio of constant losses to variable losses.

b)



The load diagram shown in the figure.

As loss is proportional to $(\text{Power})^2$ the equivalent rating of motor is given by the relation:

$$P_{eq} = \left[\frac{\frac{1}{3}\left(200^2 + 200\times600 + 600^2\right)\times4 + (450)^2\times2 + \frac{1}{3}(450)^2\times3 + 0\times4}{4+2+3+4}\right]^{1/2}$$

$$P_{eq} = \left[\frac{(\frac{1}{3}\times520{,}000\times4) + (202{,}500\times2) + \frac{1}{3}\times(202{,}500)\times3}{13}\right]^{1/2}$$

$$\doteq [100064.10]^{1/2} = 316.32\,\text{kW (Ans.)}$$

2. a) Explain equivalent current, torque & power methods to determine the motor rating for intermittent loads. **[WBUT 2009]**

Answer:

This method is based on approximation that the actual variable motor current can be replaced by an equivalent I_{eq}, which produces same losses in the motor as actual current. This equivalent current is determined as follows:

Motor loss p_l consists of two components-constant loss p_c which is independent of load and consists of core-loss and friction loss and load dependent copper loss. Thus for a fluctuating load Fig. (i) consisting of n values of motor currents $I_1, I_2, \cdots, I_n$ for durations $t_1, t_2, \cdots, t_n$ respectively, the equivalent current I_{eq} is given by

$$p_c + I_{eq}^2R = \frac{\left(p_c + I_1^2R\right)t_1 + \left(p_c + I_2^2R\right)t_2 + \cdots + \left(p_c + I_n^2R\right)t_n}{t_1 + t_2 + \cdots + t_n} \quad \text{.... (1)}$$

$$p_c + I_{eq}^2R = \frac{p_c\left(t_1 + t_2 + \cdots + t_n\right)}{t_1 + t_2 + \cdots + t_n} + \frac{\left(I_1^2t_1 + I_2^2t_2 + \cdots + I_n^2t_n\right)R}{t_1 + t_2 + \cdots + t_n}$$

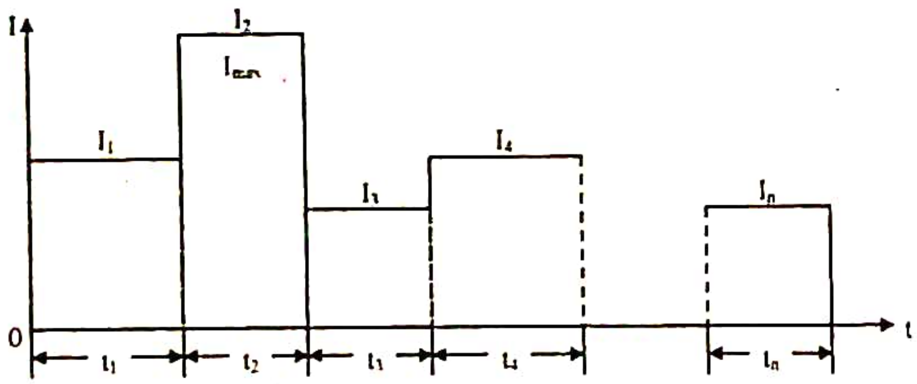


Fig: (i)

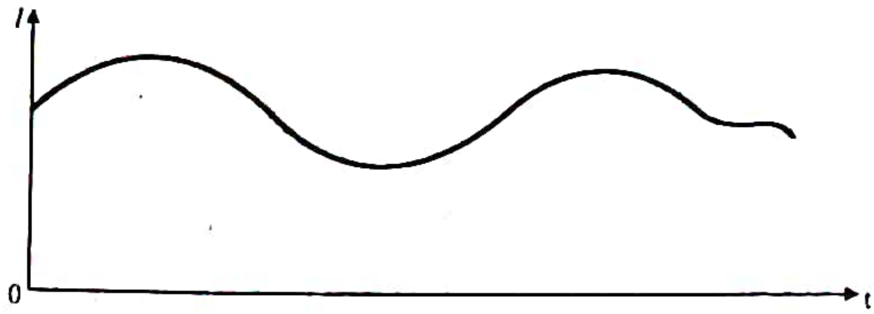


Fig: (ii) Load diagram of a fluctuating load

or, $$I_{eq} = \sqrt{\frac{I_1^2 t_1 + I_2^2 t_2 + \cdots + I_n^2 t_n}{t_1 + t_2 + \cdots + t_n}} \quad \text{.... (2)}$$

If the current varies smoothly over a period T Fig. (ii), Eqn. (2) can be written as

$$I_{eq} = \sqrt{\frac{1}{T}\int_0^T i^2 dt} \quad \text{.... (3)}$$

Integral $\int_0^T i^2 dt$ represents the area between i^2 vs. t curve and the time axis for duration 0 to T.

Implicit in above analysis is the assumption that heating and cooling conditions remain same. If motor runs at a constant speed throughout this operation, heating and cooling conditions will, in fact, remain same. If speed varies, constant losses will marginally change. However, if forced ventilation is used, heating and cooling conditions can still be assumed to remain same without much loss of accuracy. In self-ventilating machines, cooling conditions at low speeds will be poorer than at normal speed. Consequently Eqs. (2) and (3) should be used with caution.

After I_{eq} is determined, a motor with next higher current rating $(= I_{rated})$ from commercially available ratings is selected. Next, this rating is checked for its practical feasibility as follows:

D.C. Motor: This motor can be allowed to carry larger than the rated current for a short duration. This is known as short time overload capacity of the motor. A normally designed dc machine is allowed to carry up to 2 times the rated current (3 to 3.5 times the rated current in specially designed dc machines) because for higher currents sparking between the brushes and commutator reaches an unacceptable level. Let the ratio of maximum allowable current (or short time overload current capacity) to rated current be denoted by λ.

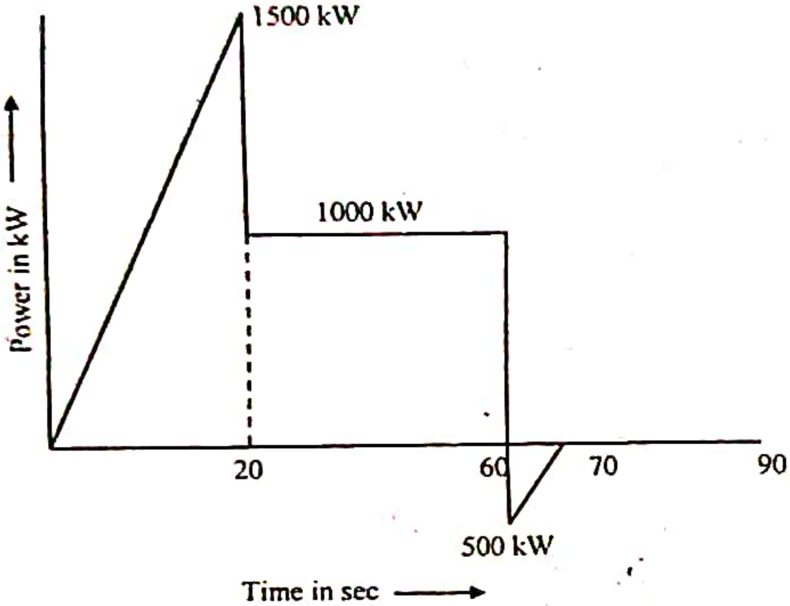
Then $$\lambda \geq \frac{I_{max}}{I_{rated}} \quad \text{.... (4)}$$

where I_{max} is the maximum value of current [Fig. (a) and (b)] and I_{rated} is the rated current of the motor. If condition (Eqn. 4) is not satisfied then the motor current rating is calculated from $I_{rated} \geq \frac{I_{max}}{\lambda}$.

b) A motor driving a mining equipment has to supply a load rising uniformly from zero to a maximum of 1500 kW in 20 seconds during acceleration period, 1000 kW for 50 seconds during the full-load period & during acceleration period of 10 seconds when regenerative braking takes place, the kW returned to the mains falls from an initial value of 500 kW to zero uniformly. The interval for decking before the next load cycle starts is 20 seconds. Estimate a suitable kW rating of the motor, based on rms power. [WBUT 2009, 2014]

Answer:

In order to solve the problem load (power) diagram is drawn below:



The power load diagram shows only the actual output power. It does not take into account the starting and braking losses as well as other losses.

Thus $$P_{eq} = \sqrt{\frac{\frac{(1500)^2 \times 20}{3} + (1000)^2 \times 50 + \frac{(500)^2 \times 10}{3}}{20+50+10+20}}$$

$$= \sqrt{\frac{15000000 + 50000000 + 833333.3333}{100}}$$

$$= \sqrt{\frac{65833333.33}{100}} = 811.377\,\text{kW}.$$

3. Mention & explain the factors on which the size & rating of a motor to be used as a drive element depend. [WBUT 2009, 2010]

Answer:

The factors upon which the size and rating of a motor to be used as a drive element depend upon the types of service conditions under which it is to run.

The motor rating from the stand point of overloading is considered to be selected properly, if its rated (full load) torque T_r is governed by the relating, $T_r > \frac{T_{max}}{\lambda}$ where

T_{max} is the maximum torque required to drive the equipments and λ is the instantaneous torque overload capacity of the motor. In D.C. motor, the maximum value of λ is restricted by the prerequisite of safe commutation, but for A.C. machine, it is determined by the maximum electromagnetic torque available. Heating is also a prime point for selection of drive motor. The rating of the motor is selected, so that it never exceed the temperature limit of the pre-determined value, for several types of duty. The maximum permissible temperature of the motor determined by the class of insulation used in it. From practical point of view, the service conditions under which the motor is to run is divided into three parts viz. (i) continuous service (ii) intermittent service and short term. For continuous service the motor will operate at steady load and the running period is of sufficient duration for the temperature rise to attain its steady state value.

The rating of the motor normally depend upon the types of service conditions under which it is to run. From practical point of view, it is divided into three parts,

i) Continuous service,
ii) Intermittent service,
iii) Short term.

For continuous service the motor will operate at steady load and the running period is of sufficient duration for the temperature rise to attain its steady state value. For example pumps, fans, compressors and conveyors. In fact they run continuously with constant load. The load curve for this service condition is shown in Fig. (a).

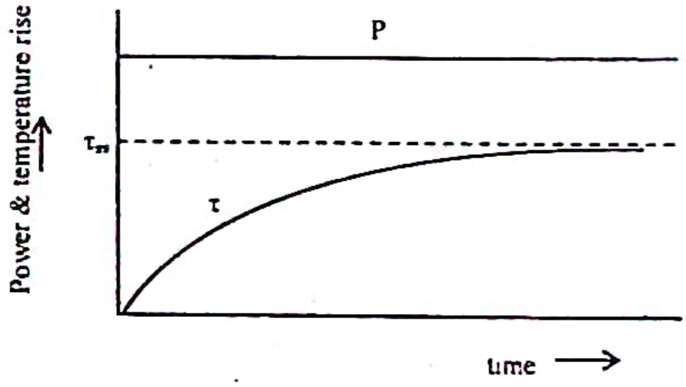


Fig: (a) For Continuous duty

But for intermittent service condition, the machine never reach it's steady state (temperature), during its working period. As the motor for that drives will operate under intermittent duty cycle i.e., (ON-OFF-ON-OFF), cranes, hoists etc. are subjected to intermittent duty. Fig. (b) shows the load curve for motors performing intermittent duty.

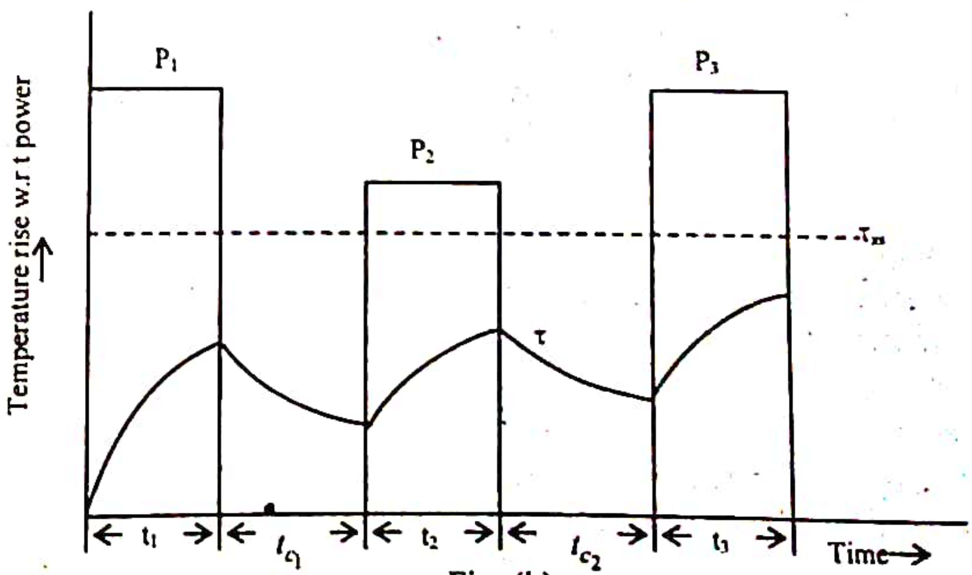


Fig: (b)

If a load curve for (total operating time t_{total}) intermittent duty cycle, is considered as shown in Fig. (b), then for that service condition, the motor will run for $t_{total} = [t_1 + t_2 + t_3]$ and total cooling time, $t_C = [t_{C_1} + t_{C_2}]$.

So the duty factor,

$$\varepsilon = \frac{t_{cy} \text{ or } t_{total}}{\text{Total time}} = \frac{[t_1 + t_2 + t_3]}{[t_1 + t_2 + t_3] + [t_{C_1} + t_{C_2}]}$$

ε for motors with intermittent duty ratings are 0.15, 0.25, 0.40. For crane duty factor is 0.25. With the motor on short time duty, the temperature rise does not reach its steady state value during the working period. The idle period between consecutive working period is of sufficient duration so that complete cooling can take place. Auxiliaries for several kinds of machine tools and also for cranes, hoists, etc. remain idle or keep running at no load for a long time after each working cycle for which Fig. (c) may be referred to.

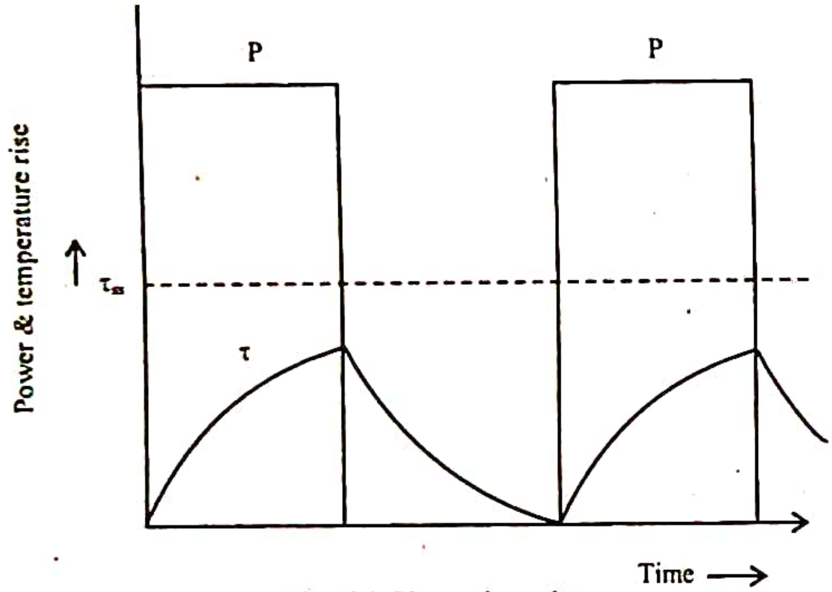


Fig: (c) Short-time duty

4. a) Derive the heating characteristics of an electric motor. Define heating time constant. **[WBUT 2013, 2016]**

b) A motor has a thermal heating time constant of 45 minutes. When the motor runs continuously at full load, its final temperature rise is 80°C.

(i) What would be the temperature rise after 1 hour, if the motor runs continuously of full load?

(ii) If the temperature rise in 1 hour rating is 80°C, find the maximum steady-state temperature at this rating.

(iii) How long will the motor take for its temperature to rise from 50°C to 80°C, if it is working at its 1 hour rating? **[WBUT 2013]**

Answer:

a) In a motor the various energy losses which occur are finally converted into heat. This causes an increase in temperature which depends upon (a) the heat absorbing capacity of the various parts of the motor and (b) the facility with which heat is conducted away or radiated or otherwise dissipated from the surface of the machine. In order to determine the variation of temperature rise (motor temperature minus the ambient temperature) with time; the following assumptions may be made:

1. Atmosphere has infinite thermal capacity and therefore its temperature don't change due to heat received from a radiating body (the motor).
2. The internal conductivity is infinite and as a result, all parts are at the same temperature.
3. The body is totally homogenous, i.e. the conductions for cooling are identical at all points on the surface of the body.
4. The heat losses, the emissivity and the heat capacity do not depend upon temperature.

With the above assumptions and denoting that:

$Q\,dt$ is the heat in calories produced in the motor during time dt, $A\tau\,dt$ is the amount of heat dissipated into the atmosphere in time dt for a temperature rise of τ and emissivity A (cal per sec per°C) and $C\,d\tau$ is the amount of heat necessary to raise the temperature of the motor having thermal capacity C (cal per °C) through $d\tau$(°C), then the heat balance equation can be written as:

$$Q\,dt = A\tau\,dt + C\,d\tau \qquad \text{.... (1)}$$

$$dt = \frac{C\,d\tau}{Q - A\tau}$$

The value of t is computed from the initial condition that at $t = 0$, the initial temperature rise is $\tau = \tau_o$

i.e.,
$$t = -\frac{C}{A}\log_e\left[\frac{Q - A\tau}{Q - A\tau_o}\right] \qquad \text{.... (2)}$$

The ratio

$$T_{H(Sec)} = \frac{C}{A} = \frac{\text{Cal per °C}}{\text{Cal per sec per °C}} \qquad \text{.... (3)}$$

where T_H is the thermal time constant which is numerically equal to the time for the motor temperature to reach its steady – state value, if no heat is dissipated in to the atmosphere.

To find out the temperature rise τ as a function of time,

$$-\frac{A}{C}t = \log_e\left[\frac{Q - A\tau}{Q - A\tau_o}\right]$$

$$e^{-\frac{A}{C}t} = \left[\frac{Q - A\tau}{Q - A\tau_o}\right]$$

or,
$$\tau = \frac{Q}{A}\left(1 - e^{-\frac{A}{C}t}\right) + \tau_o e^{-\frac{A}{C}t} \qquad \text{.... (4)}$$

At steady state i.e., $t = \infty$, then:

$$\tau = \tau_{SS} = Q/A$$

$$\therefore \quad \tau = \tau_{SS}\left(1 - e^{-t/T_H}\right) + \tau_o e^{-t/T_H} \qquad \text{.... (5)}$$

If at the initial stage of the heating process $\tau_o = 0$, then the equation for the temperature rise takes the form:

$$\tau = \tau_{SS}\left[1 - e^{-t/T_H}\right] \qquad \text{.... (6)}$$

The first term in the equation (5) shows the relationship between the temperature rise and time, if the motor is initially cold for which heating curve as shown in Fig. (1) curve [1] may be referred to. If no heat is produced, $\tau_{SS} = 0$, equation (6) then takes the form of $\tau = \tau_o e^{-t/T_H}$ as shown in Fig. (2) curve [1] may be referred to

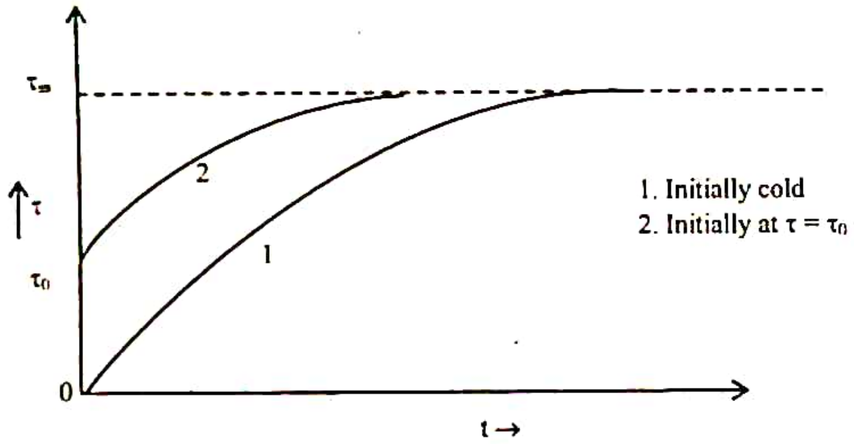


Fig: 1Temperature variation vs time heating

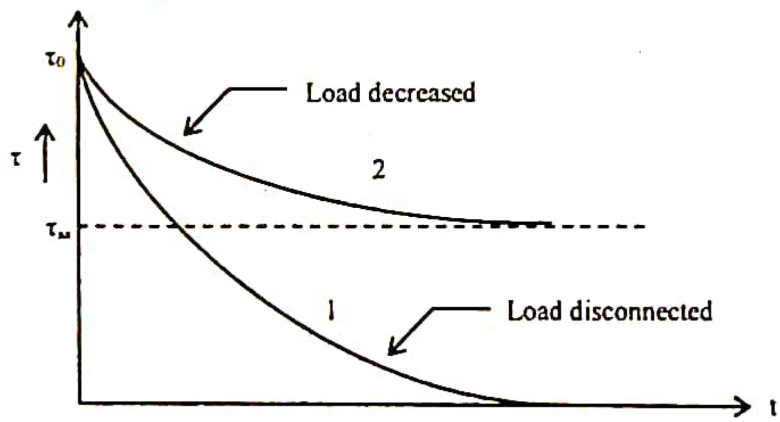


Fig: 2

Variation of temperature rise vs. time for cooling

Normally time constant T_H does not depend upon the motor load, but is determined by the parameters C and A, which depend on

i) Weight of the active parts of the machine in Kg. (G)
ii) Specific heat, cal per Kg per °C. (H)

iii) Cooling surface, m^2. (S)

iv) Specific heat dissipation or emissivity. Cal per sec per m^2 per °C. (λ)

So, C = G. H and A = S. λ

Now differentiating equation (6):

$$\frac{d\tau}{dt} = \frac{\tau_{SS}}{T_H} e^{-t/T_H}$$

Again from equation (6):

$$e^{-t/T_H} = \frac{\tau_{SS} - \tau}{\tau_{SS}}$$

So, $$\frac{d\tau}{dt} = \frac{\tau_{SS} - \tau}{T_H}$$

or, $$T_H = \frac{\tau_{SS} - \tau}{\left(\frac{d\tau}{dt}\right)} \qquad \text{.... (7)}$$

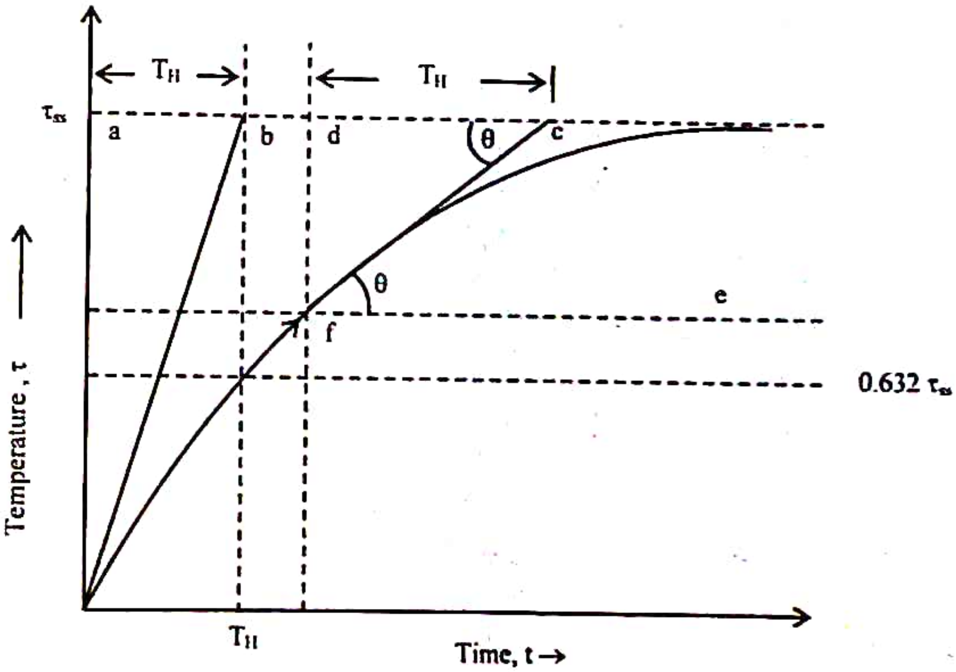


Fig: 3 Graphical determination of heating time constant

Now referring Fig (3) and considering triangle fdc

$$\tan \angle cfe = \cot \angle fcd = \frac{d\tau}{dt} = \frac{df}{dc} = \frac{\tau_{SS} - \tau}{dc}$$

$$dc = \frac{\tau_{SS} - \tau}{\left(\frac{d\tau}{dt}\right)}$$

So, $$T_H = dc \qquad \text{.... (8)}$$

Heating time constant is the time during which the motor will attain 63.2% of its final steady temperature.

b) Final temperature rise on continuous rating,

$$\theta_m = 80°\,C$$

Thermal time constant

$$T_h = 45 \text{ minutes} = \frac{45}{60} = 0.75 \text{ hour}$$

(i) Temperature rise after one hour (i.e., when $t = 1$ hour) can be found by using the following relation

$$\theta = \theta_m\left(1 - e^{-t/T_h}\right) = 80\left(1 - e^{-1/0.75}\right) = 58.9°\,C$$

Hence temperature rise after one hour 58.9°C (Ans.)

(ii) Let, $\theta_m{}' =$ maximum steady temperature rise at one hour

From given data:

$T_h = 0.75$ hour $\qquad \theta = 80°\,C \qquad t = 1$ hour

Now, $\theta = \theta_m{}'\left(1 - e^{-t/T_h}\right)$

$$\Rightarrow \quad 80 = \theta_m{}'\left(1 - e^{-1/0.75}\right)$$

$$\Rightarrow \quad \theta_m{}' = \frac{80}{\left(1 - e^{-1/0.75}\right)} = 108.7°\,C \qquad \text{(Ans.)}$$

Hence the maximum steady temperature rise at one hour rating $= 108.7°\,C$

(iii) Assuming initial temperature as 0°C, time taken to attain temperature of 80°C is one hour or 60 minutes.

Maximum temperature rise $\theta_m - 108.7°\,C$.

Let the time taken to attain temperature of 50°C from 0°C be t hours, then

$$50 = 108.7\left(1 - e^{-t/0.75}\right)$$

$$\Rightarrow \quad 1 - e^{-t/0.75} = \frac{50}{108.7}$$

$$\Rightarrow \quad e^{-t/0.75} = 1 - \frac{50}{108.7} = 1 - 0.4599$$

$$\Rightarrow \quad e^{-t/0.75} = 1 - 0.4599 = 0.5401$$

$$\Rightarrow \quad -\frac{t}{0.75} = \log_e 0.5401$$

$$\frac{t}{0.75} = -0.6160$$

$$\Rightarrow \quad t = 0.6160 \times 0.75 = 0.4620 \text{ hour} = 21.72 \text{ minutes.}$$

Hence, time taken to increase the temperature from 50°C to 80°C is 27.72 minutes.

5. a) Describe briefly the different methods for determination of motor power rating for variable load drives.
b) A drive has two loads. One has rotational motion. It is coupled to the motor through a reduction gear ratio a = 0.1 and efficiency is 90%. A load has moment of Inertia 10 kg-m^2 and torque 10 N-m. Other load has translation motion and consists of 1000 kg weight to be lifted upward at an uniform speed of 1.5 m/sec. Coupling between this load and the motor has a efficiency of 85%. Motor rating is $\omega_m = 1420$ and 0.2 kg-m^2. Determine equivalent inertia referred to the motor shaft and power developed by the motor. **[WBUT 2016]**

Answer:

a) Determination of Motor Rating

1. Continuous Duty

Maximum continuous power demand of the load is ascertained. A motor with next higher power rating from commercially available ratings is selected. Obviously, motor speed should also match load's speed requirements. It also necessary to check whether the motor can fulfill starting torque requirement and can continue to drive load in the face of normal disturbances in power supply system; the latter is generally assured by the transient and steady-state reserve torque capacity of the motor.

2. Equivalent Current, Torque and Power Methods for Fluctuating and Intermittent Loads

Refer to Question No. 2.a) of Long Answer Type Questions.

Induction and Synchronous Motor: In case of induction and synchronous motors, for stable operation, maximum load torque should be well within the breakdown torque of the motor. If motor current rating selected based on Eqs. (2) and (3) violates this constraint, the motor rating is selected to satisfy breakdown torque constraint. In case of induction motors with normal design, the ratio of breakdown to rated torque varies from 1.65 to 3 and for synchronous motors 2 to 2.25 (for special types up to 3.5). If the ratio of breakdown to rated torque is denoted by λ' then the motor torque rating is chosen based on

$$I_{\text{rated}} \geq \frac{I_{\max}}{\lambda'} \quad \text{.... (5)}$$

When the load has high torque pulses, selection of motor rating based on this will be too large.

Load equalization by mounting a flywheel on the motor shaft must then be considered.

Equivalent current method assumes 'constant losses', to remain constant for all operating points. Therefore, this method should be carefully employed when these losses vary. It is also not applicable to motors with frequency (or speed) dependent parameters of the equivalent circuit, e.g. in deep bar and double squirrel-cage rotor motors the rotor winding resistance and reactance vary widely during starting and braking making this method inapplicable.

When torque is directly proportional to current, as for example in dc separately excited motor, then from Eqn. (2).

$$T_{eq} = \sqrt{\frac{T_1^2 t_1 + T_2^2 t_2 + \cdots + T_n^2 t_n}{t_1 + t_2 + \cdots + t_n}} \quad \text{.... (6)}$$

Equation (6) can be employed to directly ascertain the motor torque rating.

When motor operates at nearly fixed speed, its power will be directly proportional to torque. Hence, for nearly constant speed operation, power rating of the motor can be obtained directly from:

$$P_{eq} = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + \cdots + P_n^2 t_n}{t_1 + t_2 + \cdots + t_n}} \quad \text{.... (7)}$$

3. Short Time Duty

In short time duty, time of motor operation is considerably less than the heating time constant and motor is allowed to cool down to the ambient temperature before it is required to operate again. If a motor with a continuous duty power rating of P_r, is subjected to a short time duty load of magnitude P_r, then the motor temperature rise will be far below the maximum permissible value θ_{per} and the motor will be highly underutilised (Fig. 2). Therefore, motor can be overloaded by a factor $K(K>1)$ such that the maximum temperature rise just reaches the permissible value θ_{per} as shown in (Fig. 2). When the duration of running period in a duty cycle with power KP_r is t_r, then

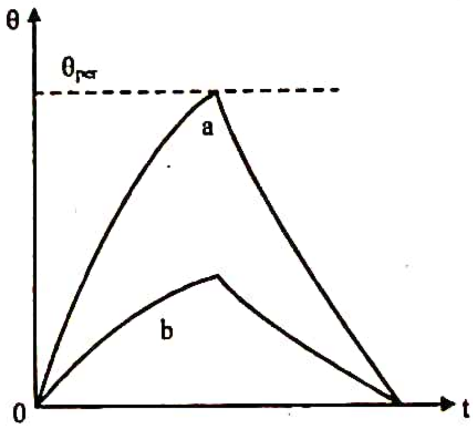


Fig: 2 θ vs. t curves for short time duty loads a — with power KP$_r$, b — with power P$_r$

$$\theta_{per} = \theta_m \left(1 - e^{-t_r/\tau}\right) \quad \text{.... (8)}$$

or,
$$\frac{\theta_{ss}}{\theta_{per}} = \frac{1}{1 - e^{-t_r/\tau}} \quad \text{.... (9)}$$

Note that θ_{ss} is the steady state temperature rise which will be attained of motor delivers a power (KP_r) on continuous basis, whereas the permissible temperature rise θ_{per} is also the steady state temperature rise attained when motor operates with a power P_r on continuous basis. If the motor losses for powers P_r and (KP_r) be P_{1r} and P_{1s}, respectively, then

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{P_{1s}}{P_{1r}} = \frac{1}{1-e^{-t_r/\tau}} \quad ....(10)$$

Let $\quad P_{1r} = p_c + p_{cu} = p_{cu}(\alpha+1) \quad ....(11)$

where $\quad \alpha = \dfrac{p_c}{p_{cu}} \quad ....(12)$

and p_c is the load independent (constant) loss and p_{cu} the load dependent loss. Then

$$p_{1s} = p_c + p_{cu}\left(\frac{KP_r}{P_r}\right)^2 = p_c + K^2 p_{cu}$$

Substituting from Eqn. (3.21)

$$p_{1s} = p_{cu}(\alpha+K)^2 \quad ....(13)$$

Substituting from Eqs. (11) and (13) into Eqn. (10) gives

$$\frac{\alpha+K^2}{\alpha+1} = \frac{1}{1-e^{-t_r/\tau}}$$

or, $\quad K = \sqrt{\dfrac{1+\alpha}{1-e^{-t_r/\tau}} - \alpha} \quad ....(14)$

Eqn. (14) allows the calculation of overloading factor K which can be calculated when constant and copper losses are known separately. When separately not known, total loss is assumed to be only proportional to (power)^2, i.e. α is assumed to be 0.

As already mentioned, K is subjected to the constraints imposed by maximum allowable current in case of dc motors and breakdown torque limitations in case of induction and synchronous motors.

4. Intermittent Periodic Duty

During a period of operation, if the speed changes in wide limits, leading to changes in heating and cooling conditions, methods of equivalent current, torque or power, described in the previous section cannot be employed. This section describes methods useful for such cases.

Let us consider a simple intermittent load, where the motor is alternately subjected to a fixed magnitude load P_r' of duration t_r and standstill condition of duration t_s (Fig. 3). As motor is subjected to a periodic load, after the thermal steady-state is reached the temperature rise will fluctuate between a maximum

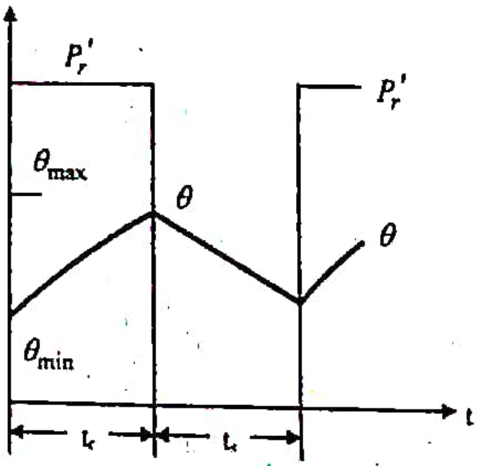


Fig: 3. Intermittent periodic load

value θ_{max} and a minimum value θ_{min}. For this load, the motor rating should be selected such that $\theta_{max} < \theta_{per}$, where θ_{per} is the maximum permissible temperature rise of the motor.

Temperature at the end of working (or running) interval will be given by

$$\theta_{max} = \theta_{ss}\left(1-e^{-t_r/\tau_r}\right)+\theta_{min}e^{-t_r/\tau_r} \qquad \text{.... (15)}$$

and fall in temperature rise at the end of standstill interval t_s will be

$$\theta_{min} = \theta_{max}e^{-t_s/\tau_s} \qquad \text{.... (16)}$$

where τ_r and τ_s are the thermal time constants of motor for working and standstill intervals.

Combining Eqns. (15) and (16) yields

$$\frac{\theta_{ss}}{\theta_{max}} = \frac{1-e^{-\{(t_r/\tau_r)+(t_s/\tau_s)\}}}{1-e^{-t_r/\tau_r}} \qquad \text{.... (17)}$$

For full utilisation of motor, $\theta_{max} = \theta_{per}$. Further θ_{per} will be the motor temperature rise when it is subjected to its continuous rated power P_r. Ratio θ_{ss}/θ_{max} will be proportional to losses and that would take place for two values of load. If losses for load values P_r and P_r' be denoted by p_{1r} and p_{1s}, then

$$\frac{\theta_{ss}}{\theta_{per}} = \frac{p_{1s}}{p_{1r}} \qquad \text{.... (18)}$$

From Eqs. (14), (16), (17) and (18), overloading factor $K = \left(P_r'/P_r\right)$ is given by

$$K = \sqrt{(\alpha+1)\frac{1-e^{-\{(t_r/\tau_r)+(t_s/\tau_s)\}}}{1-e^{-t_r/\tau_r}}-\alpha} \qquad \text{.... (19)}$$

K can be determined from Eqn. (19) subject to maximum current limitation of dc motors and breakdown torque constraints of induction and synchronous motor. As explained earlier, when constant and copper losses are not available separately, α is replaced by zero in Eqn. (19).

b) Given;

$J_0 = 0.2\,\text{kg-m}^2$ $\qquad$ $n_1 = 0.9$

$i_1 = 0.1$ $\qquad$ $n_1' = 0.85$

$J_1 = 10\,\text{kg-m}^2$ $\qquad$ $T = 10\,\text{N-m}$

$V = 1.5\,\text{m/s}$; $\qquad$ $G = 1000\,\text{kg}$

$\omega = (1420 \times \pi/30) = 148.7\,\text{rad/sec}$

The total moment of inertia referred to the motor shaft

$$J = J_0 + i_1^2 J_1 M_1 \left(\frac{v_1}{\omega_m}\right)^2$$

$$J = 0.2 + (0.1)^2 \times 10 + 1000\left(\frac{1.5}{148.7}\right)^2 = 0.4\,\text{kg-m}^2$$

$$T_L = \frac{i_1 T_{L1}}{\eta_1} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right)$$

$$T_L = \frac{0.1\times 10}{0.9} + \frac{1000\times 9.81}{0.85}\left(\frac{1.5}{148.7}\right) = 117.53\,\text{N-m}$$

6. a) Explain continuous duty, short time duty and intermittent duty with necessary graph showing variation of load torque *vs.* time and temperature *vs.* time for each.
[WBUT 2017]

Answer:

Te nominal duty of a drive motor is the duty corresponding to the service conditions and performance marked on its name plate. There are three types of duties viz.:

i) **Continuous duty:** It is that duty when the on-period is so long that the motor attains a steady state temperature rise. Continuous duty motors are employed to drive fans, compressors, generators etc. and they may be in operation for many hours and even days in succession.

The heating and cooling curves as also the duty cycle of continuous duty motors are shown below in Fig. (a) and Fig. (b) respectively.

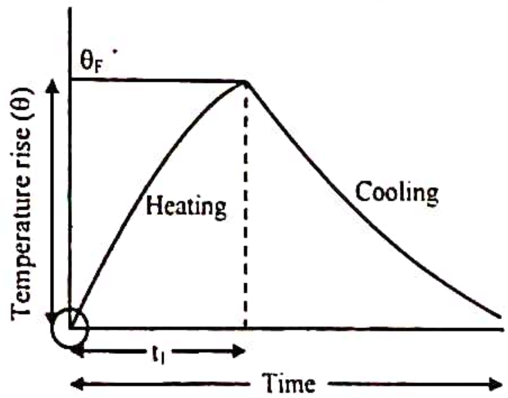


Fig: (a)

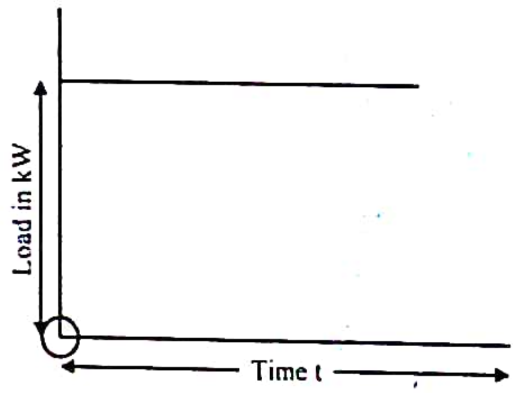


Fig: (b) Continuous duty cycle

ii) **Short time duty:** The short time duty motor operates at a constant load for some specified periods which is then followed by a period of rest. The period of run (or load) is so short that machine cannot its steady temperature rise while the period of rest is too long that the motor temperature drops to the ambient temperature. Short time duty motors are used in navigation-lock gates, railway turntables, bascule bridges etc. The heating and cooling curves for short time duty motors and short time duty cycle are shown in Fig. (c) and (d) respectively.

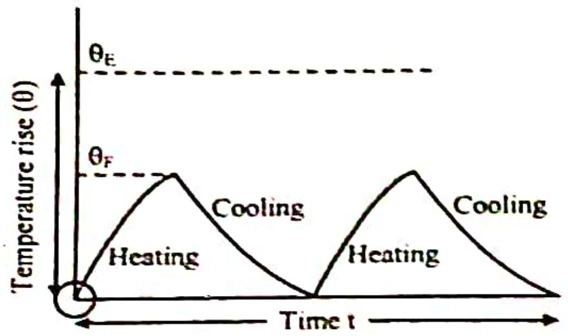


Fig: (c) For short time duty motor

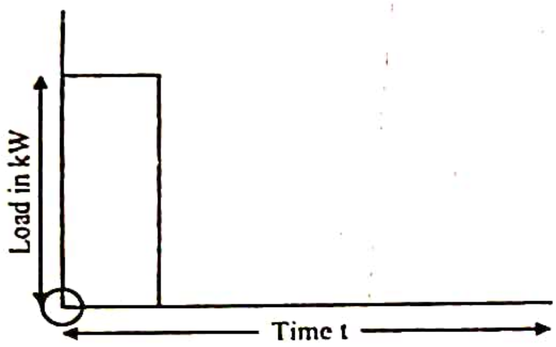


Fig: (d) Short time duty cycle

iii) **Intermittent duty cycle:** On intermittent duty the period of constant loads and rest with machine de-energized alternate. Intermittent duty motors are employed in cranes, hoists, lifts, rolling mills, some metal working machines.
Heating and cooling curves and duty cycle for intermittent duty motors are shown in Fig. (e) and Fig. (f) respectively.

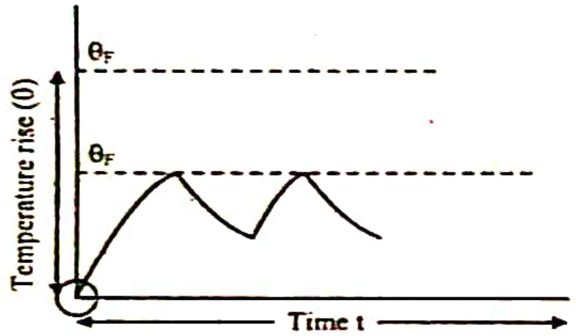


Fig: (e) For intermittent periodic duty motor

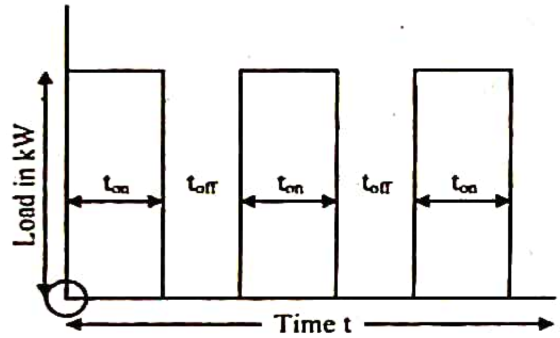


Fig: (f) Intermittent duty cycle

b) A motor driving a colliery winding equipment has to deliver a load, having the following characteristics:

i) rising uniformly from zero to a maximum of 2000 kW in 20 seconds, during the acceleration period
ii) 1000 kW for 40 seconds during the full-speed periods
iii) during the deceleration period of 10 seconds, when regenerative braking is taking place, the power returned to the supply falls from an initial value of 330 kW to zero
iv) remains idle for another 10 seconds before next cycle starts.

Draw the load (power) diagram and find the rating of the motor using equivalent power method. **[WBUT 2017]**

Answer:

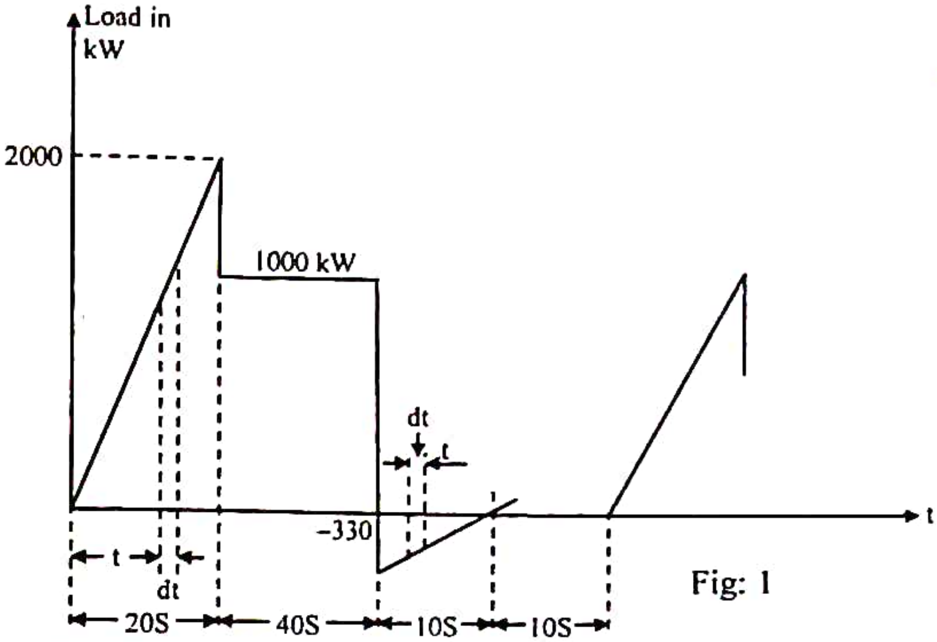


Fig: 1

The variation of load power over a duty cycle of 80 seconds is illustrated in Fig. (1) as above. The r.m.s. value of this cycle gives the kW rating of a continuous rated motor.

The slope of the load time curve during acceleration is $\frac{2000}{20}$ kW/sec and that during deceleration is $\frac{330}{10}$ kW/sec. At any time 't' measured from the zero of the load time curve, the load kW is $\left(\frac{2000}{20}t\right)$kW and $\left(\frac{330}{10}t\right)$kW respectively during acceleration and deceleration periods.

The r.m.s. value is therefore given by,

$$\text{r.m.s. power} = \left[\frac{1}{80}\left\{\int_0^{20}\left(\frac{2000}{20}t\right)^2 dt + (1000)^2 \times 40 + \int_0^{10}\left(\frac{330}{10}t\right)^2 dt + 0 \times 10\right\}\right]^{1/2}$$

$$= \left[\frac{1}{80}\left\{\int_0^{20}(100)^2 t^2\,dt + (1000)^2 \times 40 + \int_0^{10} 33t\,dt\right\}\right]^{1/2}$$

$$= \left[\frac{1}{80}\left\{(100)^2 \frac{t^3}{3}\Bigg|_0^{20} + (1000)^2 \times 40 + 33 \cdot \frac{t^2}{2}\Bigg|_0^{10}\right\}\right]^{1/2}$$

$$= \left[\frac{1}{80}\left\{\frac{(100)^2}{3}(20)^3 + (1000)^2 \times 40 + \frac{33}{2}\cdot(10)^2\right\}\right]^{1/2}$$

$$= \left[\frac{1}{80}\left\{26.67 \times 10^6 + 40 \times 10^6 + 1650\right\}\right]^{1/2} = \left[\frac{1}{80}\left\{66.67 \times 10^6\right\}\right]^{1/2} = \left[833.4 \times 10^3\right]^{1/2}$$

$\Rightarrow$ r.m.s. power, $P_{rms} = 912.91\,\text{kW}$ **(Ans.)**

STARTING OF ELECTRIC DRIVES

Short Answer Type Questions

1. Derive the expression for energy required to start an induction motor against constant load torque. What should be the relative magnitude of the load torque w.r.t. the inherent starting torque of the motor? [WBUT 2011, 2012, 2014]

Answer:

In induction motor for calculating the shaft power output P_{sh}, the core loss is subtracted from the internal mechanical power developed at the same time when friction, windage and stray load losses are subtracted.

If θ_2 is the time phase angle between E_2 and I_2 in the rotor circuit, power transferred (P_g) across the airgap from stator to rotor is

$$P_g = \frac{E_2}{Z_2} \cdot I_2 \cdot \frac{r_2}{s} = I_2^2 \cdot \frac{r_2}{s} = \frac{1}{s} \times \text{ (total rotor ohmic loss, } P_r)$$

But, $\quad P_g = \omega_s T_e$

Total ohmic loss,

$$P_r = sP_g = s\omega_s T_e \qquad \text{.... (1)}$$

The motor torque balance equation is:

$$T_e = Jp\omega_r + D\omega_r + T_L$$

It is assumed that the motor is connected to a pure inertia load whose total moment of inertia, including motor and load is J kgm^2.

For simplicity, the rotational losses i.e., friction torque $D\omega_r$ is neglected, the torque balance equation becomes: -

$$T_e = Jp\omega_r = J\frac{d}{dt}\left[\omega_s(1-s)\right]$$

$$= -\omega_s J\frac{ds}{dt} \qquad \text{.... (2)}$$

Substitution of T_e from equation (2) in equation (1) gives

$$P_r = -\omega_s^2 J_s^2 \frac{ds}{dt}$$

Total energy dissipated in the rotor circuit, as slip changes from s_1 to s_2, is given by

$$W_r = \int_{t_1}^{t_2} P_r\, dt = \int_{s_1}^{s_2} \left(-\omega_s^2 J\right) s ds = \frac{J\omega_s^2}{2}\left(s_1^2 - s_2^2\right) \text{ Joules.}$$

At starting with constant load, the rotor frequency is equal to the supply frequency f. At normal rotor speed, the rotor frequency equal to s_f, is very small. From stand still $s = 1$

to negligible slip $s_2(0)$, the total energy loss appearing as heat in the rotor is equal to $\frac{1}{2}J\omega_s^2$ is the kinetic energy stored in the rotating mass. Thus total energy taken by an induction motor from the ac source is equal to $J\omega_s^2$.

Since the total energy loss appearing as heat in rotor and is equal to $\frac{1}{2}J\omega_s^2$ Joules is independent of the accelerating time and is equal to the kinetic energy of the rotating mass, the load torque with respect to inherent starting torque will be $-\omega_s J\frac{ds}{dt}$.

2. Deduce the expression for energy lost during starting of Induction motor with no load.

[WBUT 2016]

Answer:

Three-phase induction motor

In a 3-phase induction motor, torque developed is given by,

$$T = \frac{3}{\omega_s}\left(I_2^2\frac{R_2}{s}\right) \quad \text{....(1)}$$

Neglecting load and friction torques, we have

$$T = J\frac{d\omega}{dt} = -J\omega_s\frac{ds}{dt} \quad \text{....(2)}$$

$$\omega = \omega_s(1-s)$$

The energy loss in the rotor of the induction motor when the slip changes from s_1 to s_2 is given by,

$$W = 3\int_{t_1}^{t_2} I_2^2 R_2 dt \quad \text{....(3)}$$

The slips are s_1 & s_2.

From (1), (2), and (3), we have

$$W = 3I_2^2R_2 = -J\omega_s^2 s\frac{ds}{dt}$$

$$W = -J\omega_s^2\int_{s_1}^{s_2} s.ds$$

i.e., $$W = \frac{1}{2}J\omega_s^2\left(s_1^2 - s_2^2\right) \text{ joules} \quad \text{....(4)}$$

At the time of starting the slip changes from 1 to 0 and so the energy lost in the rotor circuit is given by,

$$W_{start} = \frac{1}{2} J \omega_s^{\ 2} \text{joules} \qquad \text{.... (5)}$$

The Eqn. (4) indicates that the total energy lost in the rotor circuit depends on the moment of inertia of the rotating masses and initial and final speeds and does not depend on the rotor circuit resistance. This does not mean that the total energy lost is independent of rotor circuit resistance. The total energy lost depends on the stator and rotor resistances.

We know that $\dfrac{\text{Stator copper loss}}{\text{Rotor copper loss}} = \dfrac{R_1}{R_2}$

The total energy lost in the motor when the speed changes is given by,

$$W_{motor} = 3\int_{t_1}^{t_2} I_2^2 \left(R_1 + R_2\right) dt \text{.....................since } I_1 = I_2$$

Following the same procedure of deriving W, we can write the energy lost in the motor,

$$W_{motor} = \frac{1}{2} J \omega_s^2 \left(s_1^2 - s_2^2\right)\left(1 + \frac{R_1}{R_2}\right) \qquad \text{.... (6)}$$

At starting $\left(s_1 = 1\,;\, s_2 = 0\right)$

$$W_{motor} = \frac{1}{2} J \omega_s^{\ 2} \left(1 + \frac{R_1}{R_2}\right) \qquad \text{.... (7)}$$

When the motor starts under a load torque of T_{load} we can write

$$T_{motor} - T_{load} = J\frac{d\omega}{dt}$$

or, $$dt = \frac{J d\omega}{T_{motor} - T_{load}}$$

Again, $d\omega = -\omega_s ds$

$\therefore$ $$W = 3\int_{t_1}^{t_2} I_2^2 R_2 dt$$

$$= \omega_s \int s T_{motor}\, dt$$

$$= -J\omega_s^{\ 2} \int_{s_1}^{s_2} \frac{T_{motor}}{T_{motor} - T_{load}} s \cdot ds$$

or, $$W = -J\omega_r^2 \int_{s_1}^{s_2} \left[1 + \frac{T_{load}}{T_{motor} - T_{load}}\right] s \cdot ds \qquad \text{.... (8)}$$

Equation (8) shows that the energy lost in starting of an induction motor on load is much more than that on no load.

again when the motor is started using direct on line starter T_{max} will be high at rated voltage and so the energy lost will be minimum. In the reduced voltage starting $V < V_{rated}$ and so the energy losses will be more. The energy loss during starting is wasted as heat in stator and rotor windings of squirrel-cage motor and in external circuit resistance added to the rotor of a wound rotor induction motor. Whereas the external resistance added to the motor is more compared to stator and rotor resistances to have a low operating temperature, a higher resistance added to the rotor circuit will cause the starting time to increase.

Long Answer Type Questions

1. Deduce the expression of loss of energy during starting of a separately excited D.C. motor. [WBUT 2008, 2014]

OR,

Derive the expression for loss of energy during starting of a separately excited *dc* motor. Discuss the result. [WBUT 2012]

Answer:

In a separately excited D.C motor, loss of energy during starting is obtained form the equation $A_L = \int_0^{t_{st}} i^2 R dt$ .... (1)

The KVL equation during starting of the motor in one step is

$$V = E + ir$$

$$i^2 R = V_i - E_i \quad = \omega_o T - \omega T \qquad \text{.... (2)}$$

The motor is started without load. Friction is neglected

$$T = J\frac{d\omega_m}{dt}$$

$$dt = \frac{J}{T} d\omega_m \qquad \text{.... (3)}$$

Substituting he quantities of Eqns. (2) & (3) in Eqn. (1), we have

$$A_L = \int_{\omega_{in}}^{\omega_{fin}} J(\omega_o - \omega_m) d\omega_m \qquad \text{.... (4)}$$

If started form rest $\omega_{in} = 0$ & $\omega_{fin} = \omega_o$

$$A_L = \frac{1}{2} J\omega_o^2 \qquad \text{.... (5)}$$

It shows that the energy loss in the motor during starting is equal to the stored energy in this rotating parts at steady state speed irrespective of the armature circuit resistance, the number of steps in the starting resistance, the resistance of each step and starting time. The work done by the motor in storing kinetic energy in its rotating parts is given by

$$A_{mech} = \int_0^{w_o} J w_m \frac{d\omega_m}{dt} dt = \int_0^{w_o} J d\omega_m d\omega_m = \frac{1}{2} J\omega_0^2 \qquad \text{.... (6)}$$

∴ The amount of electrical energy drawn by the motor during starting is equal to double the kinetic energy stored in it. That is

$$A_{elec} = A_L + A_{mech} = J\omega_o^2 \qquad .... (7)$$

Now when the motor is started up with const. load

$$\therefore \quad i^2R = T(\omega_o - \omega_m) \quad = (T_L + T_J)(\omega_0 - \omega_m)$$

$$T_J = J\frac{d\omega_m}{dt}$$

Thus, energy loss during starting is

$$A_L = \int_0^{t_{st}} i^2 R dt = \int_0^{\omega_L} J(\omega_o - \omega_m) d\omega_m + \int_0^{t_{st}} T_L(\omega_o - \omega_m) dt$$

$$= J\left[\omega_o\omega_L - \frac{1}{2}\omega_L^2\right] + T_L\left[\omega_o t_{St} - \int_0^{t_{St}} \omega_m dt\right] \qquad .... (8)$$

The first part of Eqn. (8) represents the energy loss in armature circuit due to acceleration, whereas the second part represents the loss in the armature circuit on account of load carried by the motor.

2. Deduce an expression for the energy lost during starting of DC shunt motor with constant load torque T_L. **[WBUT 2009]**

Answer:

In a D.C motor, $V = E_b + I_a R_a$

or, $\quad I_a R_a = V - E_b = V - k\omega$

This expression is also suitable for separately excited motor,

The equation of motion at no load is given by,

$$T_{motor} = kI_a = \frac{Jd\omega}{dt}$$

or, $\quad \left(I_a = \frac{J}{k}\frac{d\omega}{dt}\right)$

Hence, $\quad I_a^2 R_a = I_a\left(I_a R_a\right) = \frac{J}{k}\frac{d\omega}{dt}(V - k\omega)$

or, $\quad I_a^2 R_a = \frac{JV}{k}\frac{d\omega}{dt} - \frac{J\omega d\omega}{dt}$

As $I_a R_a$ is negligible at no load, $V = k\omega_0$ at no load (ω_0 is the no-load speed of the motor)

$$\therefore \quad I_a^2 R_a dt = J\omega_0 d\omega - J\omega d\omega$$

The energy absorbed (W) by the armature for a change in speed from ω_1 to ω_2 time t_1 to t_2 is given by,

$$W = \int_{t_1}^{t_2} I_a^2 R_a dt = J\omega_0 \int_{\omega_1}^{\omega_2} d\omega - J\int_{\omega_1}^{\omega_2} \omega d\omega$$

or, $$W = J\omega_0\left(\omega_2 - \omega_1\right) - \frac{J}{2}\left(\omega_2^2 - \omega_1^2\right)$$

Hence the energy change when the motor changes speed from rest to no-load speed ω_0 will be: $W_{start} = J\omega_0^2 - \frac{J}{2}\omega_0^2$

or, $$W_{start} = \frac{J\omega_0^2}{2} \text{ joule}$$

$= KE$ absorbed by the armature in acceleration in accelerating from standstill to no-load speed.

The energy loss at starting, when the motor is started with a constant load torque T_{load} is calculated as follows:

$$T_{motor} = kJ_a = T_{load} + \frac{Jd\omega}{dt}$$

$$I_a^2 R_a = \frac{JV}{k}\frac{d\omega}{dt} - \frac{J\omega d\omega}{dt} + \frac{V}{k}\left(T_{load}\right) - T_{load}\omega$$

The energy lost, when the motor speed changes from ω_1 to ω_2, is given by,

$$W = \int_{t_1}^{t_2} I_a^2 R_a dt$$

$$= \frac{JV}{k}\int_{\omega_1}^{\omega_2} d\omega - j\int_{\omega_1}^{\omega_2} \omega d\omega + \frac{V}{k}T_{load}\int_{t_1}^{t_2} dt - T_{load}\int_{t_1}^{t_2} \omega(t)dt$$

$$= \frac{JV}{k}\left(\omega_2 - \omega_1\right) - \frac{J}{2}\left(\omega_2^2 - \omega_1^2\right) + \frac{V}{k}T_{load}\left(t_2 - t_1\right) - T_{load}\int_{t_1}^{t_2} \omega(t)dt$$

Now substituting ω_0 (the no load speed) for $\frac{V}{k}$, the energy lost at starting on no-load when the speed changes from 0 to ω_r is given by,

$$W_{start} = J\omega_0\omega_r - \frac{J}{2}\omega_r^2 + T_{load}\omega_0 t_{st} - T_{load}\int_0^{t} \omega(t)dt$$

or, $$W_{start} = J\left(\omega_0\omega_r - \frac{\omega_r^2}{2}\right) + T_{load}\left[\omega_0 t_{st} - \int_0^{t} \omega(t)dt\right]$$

This equation shows that the energy lost during starting depends on the accelerating time and on the speed variation with time during acceleration.

3. a) Discuss the effects of starting on power supply, motor and load. [WBUT 2017]

Answer:

If we first consider D.C. motor drive viz. series, shunt or compound motor, it is known that the motor draws large starting current from the supply mains and such heavy in rush of starting current taken by the motor may result in (a) detrimental sparking at the commutator (b) damage to the armature winding and deterioration of the insulation due to overheating and (c) large dips in the power supply. In view of this, the armature current must be limited to a value that can be commutated safely, by inserting a suitable external resistance in the armature circuit. as the motor accelerates back emf is generated in the armature and this decreases the armature current to a small value. Thus the external resistance in the armature circuit should be gradually decreased, as the armature accelerates. If this additional resistance is left in the armature circuit, it would result in (i) reduced operating speed of the motor and (ii) additional energy loss and therefore reduced efficiency.

Further, during starting of shunt and compound motor, the field excitation must be kept maximum because a large field current would result in low operating speed resulting less heating of the armature during starting. Since field current is kept at its maximum permissible value, the armature current during starting would be minimum for a given load torque.

In case of A.C. motors viz. the polyphase induction motor, it is started either with full voltage or with reduced voltage across its stator terminals. Though the reduced voltage starting has the advantage of reducing the starting current yet it produces an objectionable reduction on the starting torque on account of the fact that the motor torque is proportional to the square of the applied voltage.

b) Explain methods to reduce the energy loss during starting. **[WBUT 2017]**

Answer:

The energy loss in starting resistance of d.c. motors can be eliminated by employing an adjustable voltage system, thus dispensing with the external starting resistance. That the adjustable voltage method is energy efficient and illustrated in Fig. (1).

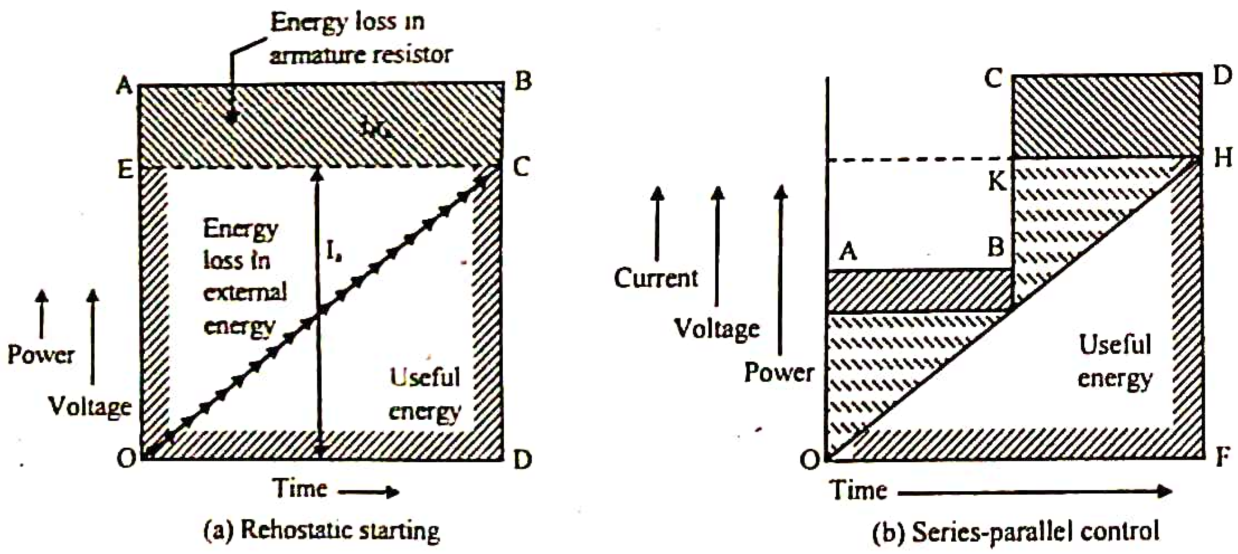


Fig: 1 Energy losses in D.C. motor

The supply voltage V is constant. If the armature current i_a is assumed to be constant during the starting period then the (a) Input power remains constant as represented by AB

[Fig1.(a)] (b) Speed of rotation back emf, and useful power increase linearly with time as represented by OC.

In rheostatic starting, the various related energies may be accounted for as under:

a) Energy input = Area ABDO
b) Energy output = Area OCDO
c) Energy loss in the external resistance = Area OECO
d) Energy loss in the armature resistance = Area ABCE.

It is clear from Fig. 1(a) that in rheostatic starting of d.c. shunt motors, the energy loss is very high and this is eliminated to a large extent by step by step variation of supply voltage as in adjustable voltage control or series parallel control. Energy saving in series parallel control is shown in Fig. 1(b). The supply voltage and field excitation are assumed to be constant. Initially the armature are connected in series and then in parallel. The voltage across each armature is equal to $\frac{V}{2}$ in series connection and V in parallel connection.

The armature current remains constant to develop constant torque and thereby constant acceleration. The supply voltage remaining constant the input power in parallel connection is double of that in series connection. In Fig. 1(b), AB and CD represent the measure of input power and current in series and parallel connection respectively. The back emf increases along OFH. The useful energy is given by the area OHK. The energy loss in series parallel starting is reduced to half of that incurred in rheostatic starting.

The energy loss decreases as the number of steps increases.

The energy loss is reduced when an induction motor is started by smooth variation of supply frequency under constant Volts/Hz operation. Both induction and d.c. shunt motors have exactly identical torque speed characteristics.

BRAKING OF ELECTRIC DRIVES

Multiple Choice Type Questions

1. Regenerative braking in a squirrel cage induction motor takes place when [WBUT 2007, 2014]
   a) the overhauling load drives the rotor at a speed greater than synchronous speed
   b) the stator frequency is reduced so that synchronous speed is below the rotor speed
   c) both (a) and (b)
   d) none of these

Answer: (a)

2. In case of power failure, while a crane is in operation, the preferred electrical braking technique is [WBUT 2007, 2014]
   a) regenerative b) dynamic c) counter current d) none of these

Answer: (b)

3. Regenerative braking is a [WBUT 2008]
   a) first quadrant (T-ω) operation
   b) second quadrant operation
   c) multiquadrant operation
   d) third quadrant operation

Answer: (b)

4. The slip of an induction motor during *d.c.* rheostatic braking is [WBUT 2008, 2017]
   a) s b) $2-s$ c) $1-s$ d) none of these

Answer: (a)

5. Field control of a DC shunt motor gives [WBUT 2009]
   a) constant torque drive
   b) constant kW drive
   c) constant speed drive
   d) variable load drive

Answer: (b)

6. The regenerative braking is not possible in [WBUT 2009, 2013]
   a) DC series motor
   b) induction motor
   c) DC shunt motor
   d) DC separately excited motor

Answer: (a)

7. The loss in energy during starting with m equal steps of voltage can be expressed as [WBUT 2009]
   a) $\frac{1}{2}J\omega_0^2$ b) $\frac{1}{2m}J\omega_0^2$ c) $\frac{m}{2}J\omega_0^2$ d) $\frac{1}{2m^2}J\omega_0^2$

Answer: (a)

8. Most efficient braking is [WBUT 2010]
   a) dynamic braking
   b) regenerating braking
   c) both (a) & (b)
   d) none of these

Answer: (a)

9. In plugging of an electric motor effectively we apply [WBUT 2011]
   a) a reverse voltage on the armature
   b) double voltage on the armature
   c) zero voltage on the armature
   d) zero magnetisation current

Answer: (a)

10. The slip *s* for plugging is [WBUT 2012]
   a) $s-1$
   b) $2s-1$
   c) $2-s$
   d) $2+s$

Answer: (c)

11. To get the speed higher than the base speed of a dc shunt motor [WBUT 2012, 2014]
   a) armature voltage control is used
   b) field control is used
   c) armature resistance control is used
   d) frequency control is used

Answer: (b)

12. During dynamic braking employed for DC series motors, [WBUT 2016]
   a) armature current is reversed
   b) field winding is reversed
   c) field current direction is unchanged
   d) both (a) and (c)

Answer: (d)

13. The magnetizing reactance of an induction motor during *dc* dynamic braking, increases with [WBUT 2017]
   a) increasing rotor speed
   b) decreasing rotor speed
   c) independent of rotor steed
   d) depends on the way the stator windings are connected during braking

Answer: (a)

14. For an electric locomotive in the downward direction in a hilly region, the economical braking system will be [WBUT 2017]
   a) counter-current braking
   b) dynamic braking
   c) regenerative braking
   d) mechanical braking

Answer: (c)

15. Which braking is not possible in series motor? [WBUT 2017]
   a) Regenerative braking
   b) Dynamic braking
   c) Counter-current braking
   d) Rheostatic braking

Answer: (a)

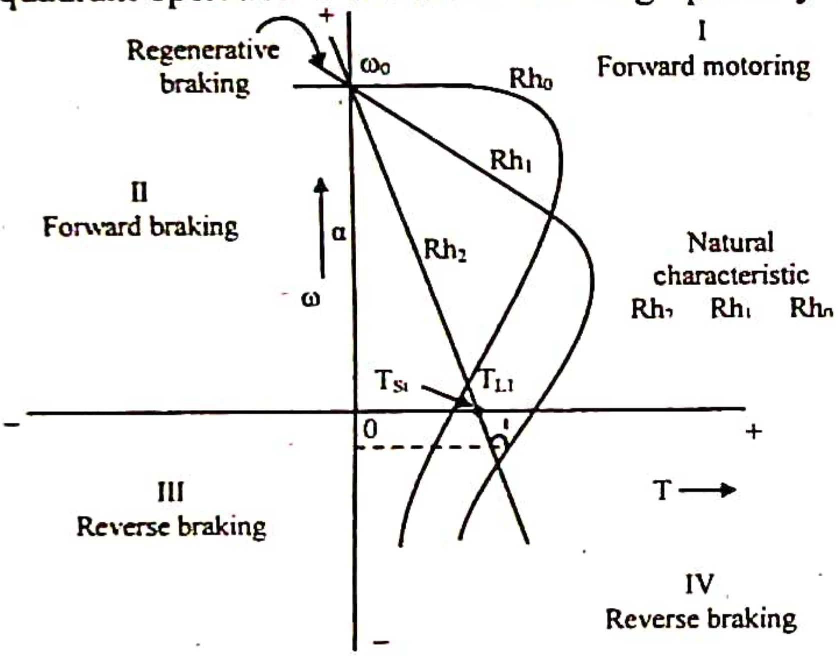
Short Answer Type Questions

1. Explain, how regenerative braking is done in a 3-phase induction motor. Show graphically the four-quadrant operation of the motor. [WBUT 2006, 2012]

Answer:

In regenerative braking of a 3- phase induction motor, the rotor speed of the motor must exceeds the synchronous speed of the motor.

So far the procedural part is concerned it may be mentioned that when the number of poles of a pole changing induction motor is changed in the ratio 1 : 2, for example, four-pole to eight pole, regenerative braking takes place immediately after the change over, till the lower steady state speed is reached. Under such a situation, the machine acts as induction generator returning energy to the supply and taking only the reactive power for excitation. When the rotor speed exceeds the synchronous speed, the slip become negative. The four-quadrant operation of the motor shown graphically below:



The regenerative braking characteristic as shown above is the continuation of the motoring characteristic into the upper part of quadrants II/IV. The maximum regenerative braking torque is higher than the maximum motoring torque.

2. With appropriate characteristic curves explain the dynamic braking operation of a *dc* series motor. [WBUT 2011]

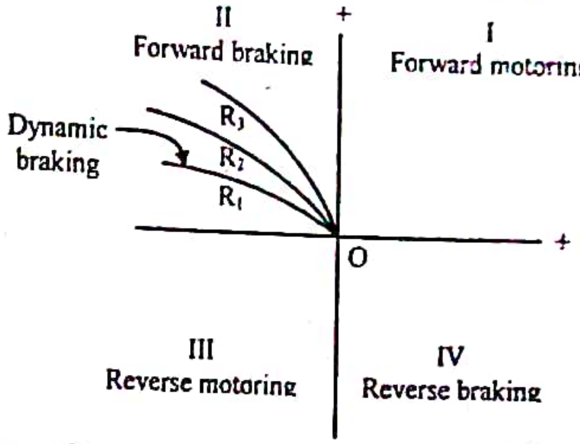
Answer:

In a dynamic braking of d.c. series motor with self-excitation, the supply to the motor is switched off and then the armature circuit including the series field winding is connected across a resistor ensuring that the excitation is not reversed during the change over.

The dynamic braking torque is

$$T_{db} = \frac{(k\phi)^2 \omega}{R_a + R_{se} + R_{db}}.$$

Here the flux ϕ is dependent on the armature current I_a. When braking is initiated, the current is high, thus, resulting in increased value of flux, and the torque is also high, being approximately proportional to square of the current. The speed torque characteristics for dynamic braking are in the second quadrant as shown below:



At this instant, the driven unit may experience objectionable shocks due to a large value of braking torque. The machine now runs as a self-excited generator.

3. Describe the regenerative breaking operation of an 3-phase induction motor.
[WBUT 2013]

Answer:

Regenerative braking

An induction motor is subjected to regenerative braking, if the rotor speed exceeds the synchronous speed of the motor. Under regenerative braking, the machine acts as an induction generator returning energy to the supply and taking only the reactive power for excitation. When the rotor speed exceeds the synchronous speed, the slip becomes negative. The regenerative braking characteristic is the continuation of the motoring characteristic into the upper part of quadrants II/V as shown in Fig. below. The maximum regenerative braking torque is higher than the maximum motoring torque.

When the number of poles of a pole-changing induction motor is changed in the ratio 1: 2, for example, four-pole to eight-pole regenerative braking takes place immediately after the changeover, till the lower steady state speed is reached.

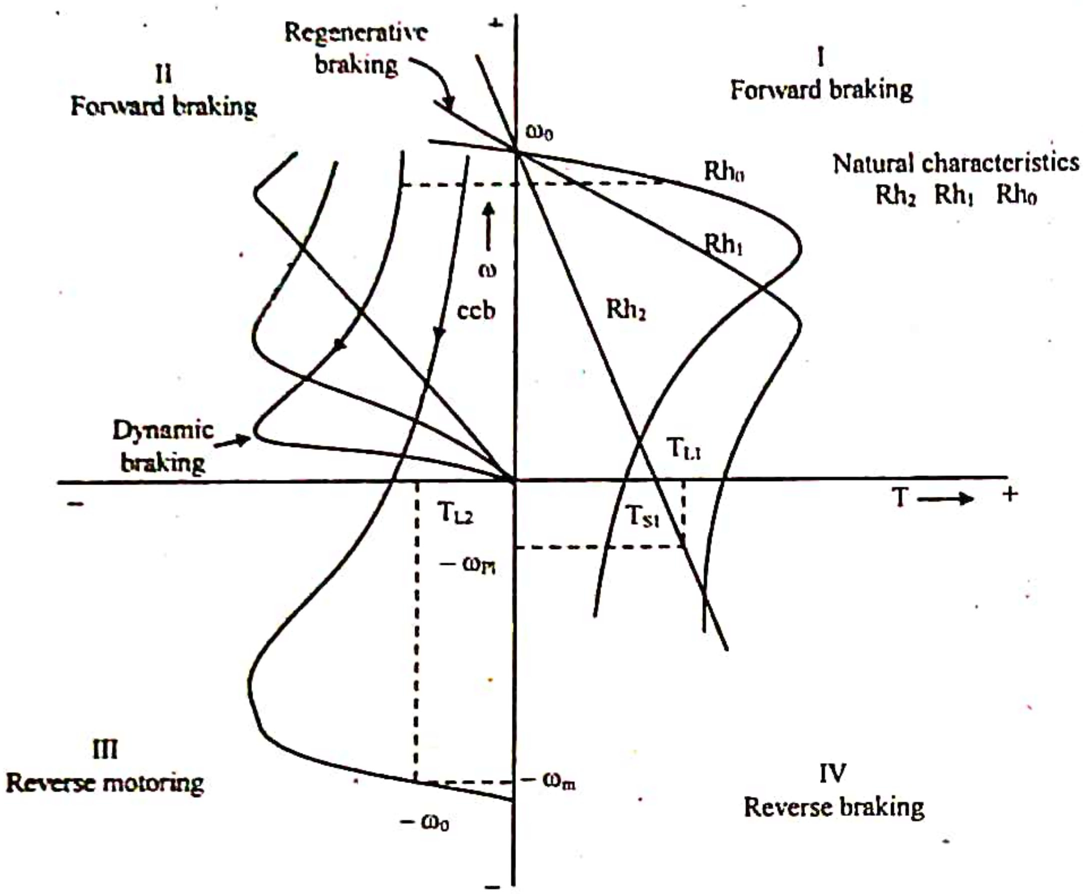


Fig: Typical speed-torque characteristics of induction motor under different operating conditions.

4. How does the braking resistance control the dynamic braking torque in dc separately excited motor? How to employ dynamic braking in dc series motors?
[WBUT 2014]

Answer:
1st Part:
Rheostatic or dynamic braking

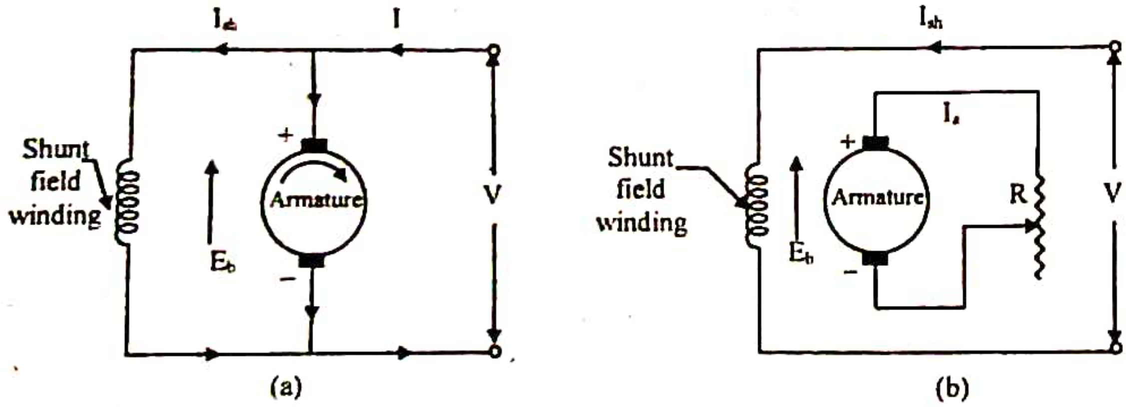


Fig: 1 Rheostatic or dynamic braking

In this method of electric braking of shunt motors, the armature of the shunt is disconnected from the supply and is connected across a variable resistance R as shown in

Fig. 1(b). The field winding is, however, left connected across the supply undisturbed. The braking effect is controlled by varying the series resistance R.

2nd Part:

Fig. 1 shows dynamic braking scheme for a d.c. motor. During braking the motor is used as a separately excited d.c. generator and the series field winding is connected to a low voltage high current converter.

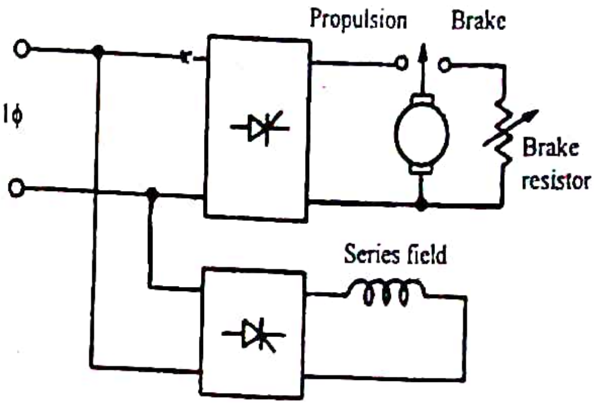


Fig: 1 Dynamic braking for a d.c. motor

5. Describe with suitable diagram plugging operation of DC machine. [WBUT 2015]

Answer:

Plugging or counter current braking for Shunt motor

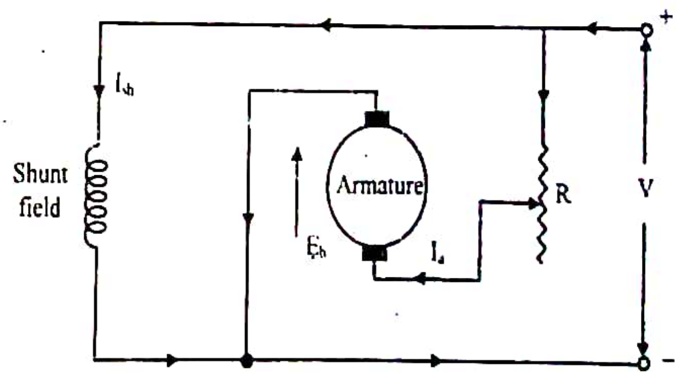


Fig: 1 Plugging or counter-current braking

- In this method, connection to the armature terminals are reversed so that motor tends to run in the opposite direction. (Fig. 1). Due to reversal of armature connections, applied voltage V & E_b start acting in the same direction around the circuit. In order to limit the armature current to reasonable value, it is necessary to insert a resistor in the circuit while reversing armature connection.
- This method is commonly used in controlling:
  (i) Printing presses
  (ii) Rolling mills
  (iii) Machine tools
  (iv) Elevators etc

- As compare to rheostatic braking, plugging gives better braking torque.

(i) Plugging for Series Motor

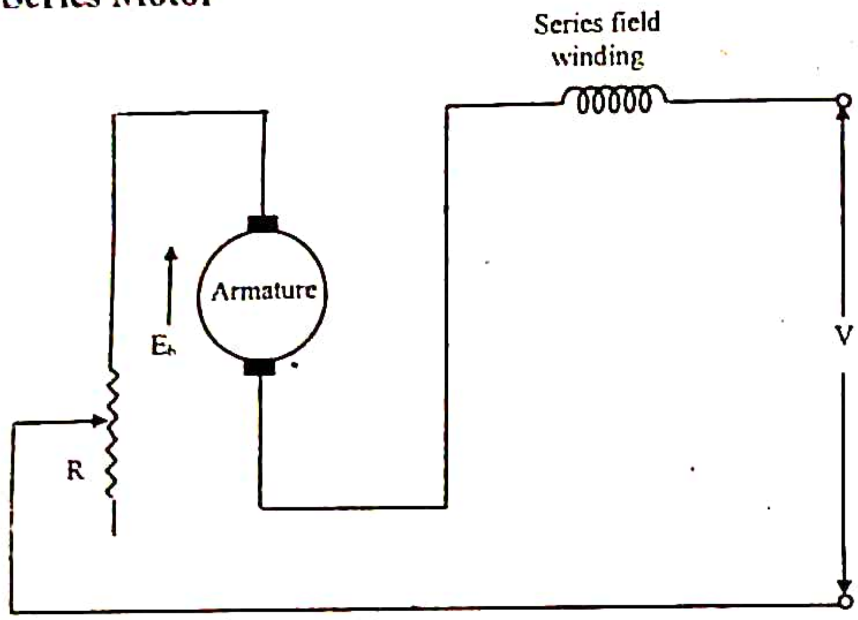


Fig: 2 Plugging

In this method (as in the case of shunt motors) the connections of the armature are reversed and a variable resistance R is put in series with the armature as shown in Fig. (2) above.

6. Describe with suitable diagram dynamic braking operation of Induction Machine. **[WBUT 2015]**

Answer:

The speed of an induction motor can be controlled by injecting D.C voltage in its stator winding. A variable resistance may be used in the rotor (in case of a slip ring induction motor) for dissipating the required amount of power. Now-a-days thyristor bridges are used for supplying D.C which is controllable in nature. With the help of controlled D.C from a thyristors bridge the dynamic braking can be achieved in a more effective manner. The connection diagram for scheme is shown in Fig. 5.10.

- 3-phase A.C is stepped down to lower voltage and fed to a 3-phase thyristor bridge which serves as the rectifier.
- This D.C is filtered by an L.C filter for minimizing the ripples.
- Ripple free D.C is then fed to the stator winding of the induction motor as shown in Fig.

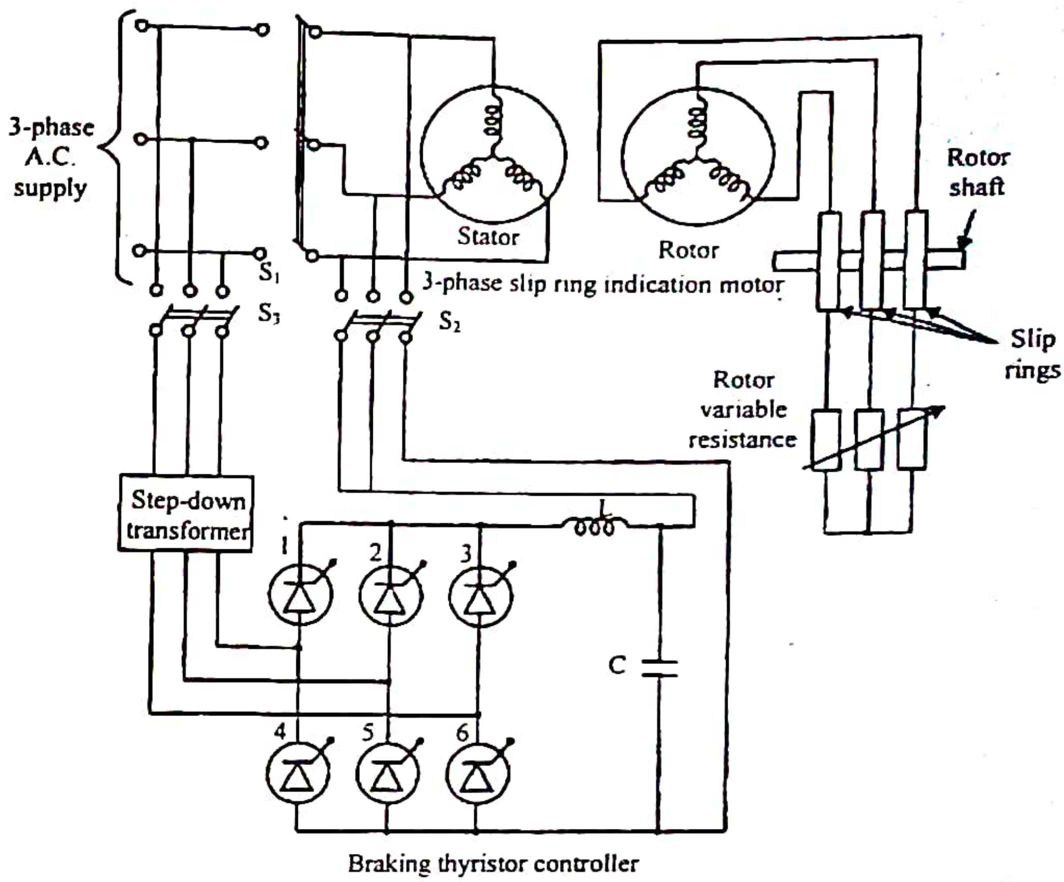


Fig: Dynamic braking of a 3-phase slip ring induction motor

It is to be noted that while feeding D.C to the stator the 3-phase A.C input must be disconnected. A.C is disconnected with the help of S_1 and D.C is disconnected with the help of S_2. Since, the input A.C voltage is stepped down to a lower value, the thyristor converter may be of lower voltage rating.

Long Answer Type Questions

1. a) With the help of relevant torque speed characteristics, discuss regenerative braking and reverse current braking of an induction motor. **[WBUT 2007]**

b) A 400 V, 3-phase, 50 Hz, 4 pole cage type induction motor has the following parameters: $r_1 = r_2' = 0.1\Omega$, $x_1 = x_2' = 0.4\Omega$, $x_m = 14\Omega$

That motor was operating on full load slip 0.05 when the two stator terminals were suddenly interchanged. Calculate the primary current and the braking torque immediately after application of plugging. Assume approximate equivalent circuit.

[WBUT 2007, 2010]

Answer:

a) *i) Plugging (or counter current braking)*

It is known that plugging can be achieved in an induction motor merely by reversing two of the three phases which cause reversal of the direction of rotating magnetic field. At the

instant of switching the motor to the plugging position the motor runs in the opposite direction to that of the field and the relative speed is approximately twice [(2-s) times] of synchronous sped i.e. the slip (s) is very nearly equal to two, being equal to (2-s). So voltage induced in the rotor will be twice of normally induced voltage at stand still and the winding must be provided with the additional insulation to withstand this much voltage. During plugging, the motor acts as a brake and it absorbs kinetic energy from the still revolving load causing its speed to fall. The heat developed in the rotor during braking period are all out three times the heat developed during starting period.
In case of squirrel cage motor, energy is dissipated only within the machine where as in case of wound rotor motor. This energy is dissipated also in the external resistance added in the rotor circuit for this purpose.

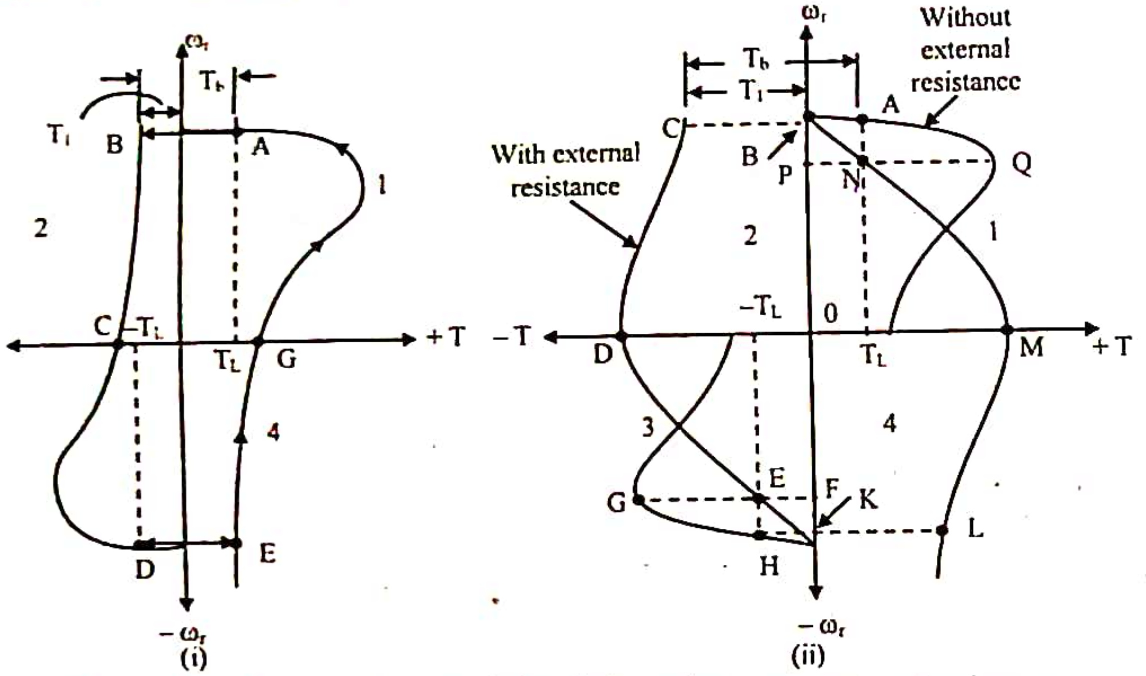


Fig: (a) Speed-torque characteristics during plugging of (i) squirrel-cage motor and (ii) wound-rotor motor

ii) Regenerative braking

When the load, forces the motor to run above synchronous speed, Regenerative braking takes place. When rotor speed, as when lowering of load in a crane or a hoist becomes more than rotating field speed, the slip becomes negative. The negative slip means that the induction machine will operate as an induction generator in the 2nd quadrant as shown in Fig. (b) below and returns power to the supply lines. The power delivered to the supply is given by the product of regenerative braking torque and the corresponding rotor speed.

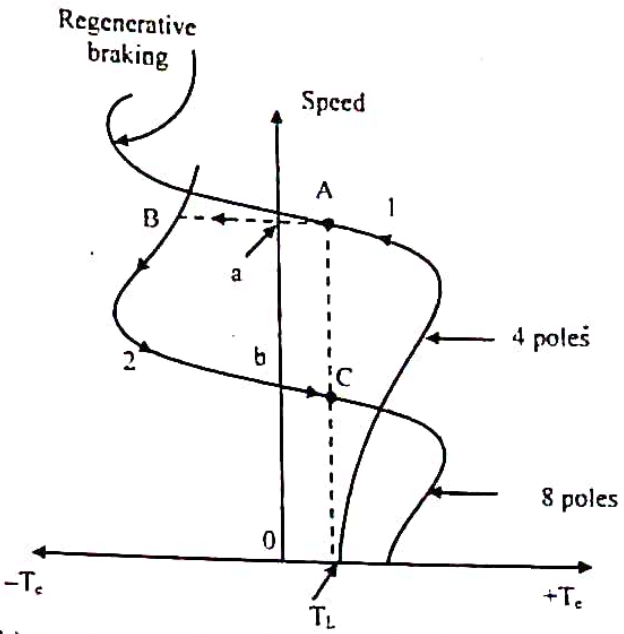


Fig: (b) regenerative braking of polyphase induction motor

The Fig. (b) shows that the amount of power returned to the supply line depends upon how far is the rotor speed above synchronous speed when rotor speed falls synchronous speed. When rotor speed falls to synchronous speed, the regenerative braking comes to an end.

In case of squirrel cage induction motor, stable speed is obtained at a speed considerable in excess of synchronous speed and the regenerative braking cannot be applied unless the motor is specially designed to withstand the excessive speed.

b) Data given:

$$r_1 = r_2' = 0.1\Omega,\quad x_1 = x_2' = 0.4\Omega,\quad x_m = 14.0\Omega,\quad f = 50\,\text{Hz},\quad p = 4$$

$$V_{ph} = \frac{400}{\sqrt{3}} = 230\,\text{V},\qquad N_s = \frac{120f}{p} = \frac{120\times 50}{4} \doteq 1500\,\text{rpm}$$

$$\omega_s = \frac{2\pi}{60}N_s = \frac{2\pi\times 1500}{60} = 157.1\ \text{rad/s}$$

Magnetizing Current

$$I_m = \frac{V_{ph}}{jX_m} = \frac{230 + j0\cdot 0}{0\cdot 0 + j14} = -j16.43 = 16.43\angle -90^\circ\,\text{A}$$

$$s = 0.05,\ 2 - s = 2 - 0.05 = 1.95,\ \frac{r_2'}{2-s} = \frac{0.1}{1.95} = 0.0513\Omega$$

$$Z = \left(r_1 + \frac{r_2'}{2-s}\right) + j\left(x_1 + x_2'\right) = \left(0.1 + 0.0513\right) + j\left(0.4 + 0.4\right)$$

$$= 0.1513 + j0.8 = 0.8142\angle 79.3^\circ\,\Omega$$

Rotor current referred to the stator

$$I_2' = \frac{V_{ph}}{Z} = \frac{230\angle 0^\circ}{0.8142\angle 79.3^\circ} = 282.5\angle -79.3\text{A}$$

Primary current $= I_1 = I_m + I_2' = 16.43\angle -90^\circ + 282.5\angle -79.3^\circ = 299.0\angle -79.88\text{A}$

Braking torque

$$T_b = \frac{3(I_2')^2}{\omega_s} \cdot \frac{r_2'}{2-s} = \frac{3\times(282.5)^2 \times 0.0513}{157.1} = 78.19\text{N - m.}$$

2. a) With the help of relevant torque-speed characteristics, discuss different methods of braking of D.C. shunt motor. **[WBUT 2008, 2010, 2012]**

Answer:

The different types/methods of braking of DC shunt motor is discussed below with their torque-speed characteristics.

1. Regenerative Braking:

In a regenerative braking, generated energy is supplied to the source, for which following condition should be satisfied.

$E > V$ and negative I_a .... (1)

Field flux cannot be increased substantially beyond rated value because of saturation. For a source of fixed voltage of rated value regenerative braking is possible only for speeds higher than rated and with a variable voltage source it is also possible below rated speeds. The speed-torque characteristic is show below in fig. 'a' for a DC shunt motor.

In actual supply system when the machine regenerates its terminal voltage rises. Consequently the regenerated power flows into the loads connected to the supply and the source is relieved from supplying this much amount of power. This braking is therefore possible only when there are loads connected to the line and they are in need of power more or equal to the regenerated power. When the capacity of the loads is less than the regenerated power, all the regenerated power will not be absorbed by the loads and remaining power is supplied to capacitors in line and the line voltage will rise to dangerous values leading to insulation breakdown. Hence regenerative braking should be used where there are enough loads to absorb the regenerated power. The speed torque characteristics can be calculated from

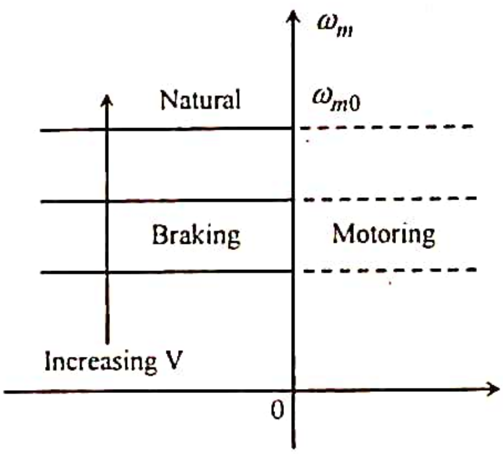


Fig: (a)

$$E = K_e\phi\omega_m$$

$$\omega_m = \frac{V}{K_e\phi} - \frac{Ra}{(K_e\phi)^2}\times T.$$

2. Dynamic Braking:

In dynamic braking, when motor armature is disconnected from the source and connected across a resistance say R_B, dynamic braking takes place. The generated energy is dissipated in R_B & R_a. In Fig.(b_1) the speed-torque curves are shown & transition from motoring to braking. As speed falls, sections are cut out to maintain a high average torque, as shown in Fig.(b_2) for a shunt motor. During braking, shunt motor can be converted as self excited generator. This permits braking even when supply fails.

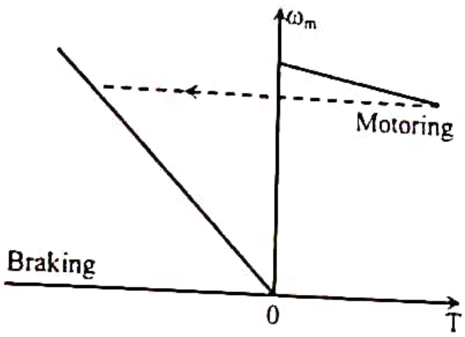


Fig: (b_1)

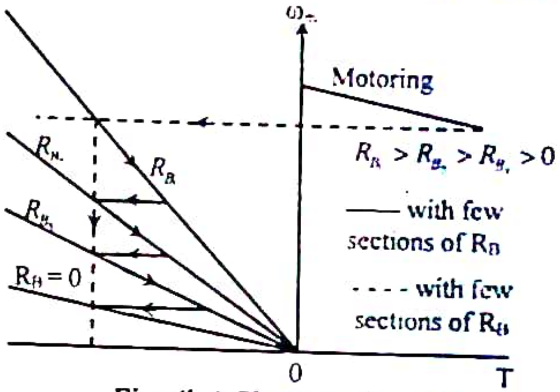


Fig: (b_2) Shunt motor with variable armature resistance

Dynamic braking speed-torque curves

The characteristics are obtained from

$$\omega_m = \frac{V}{K} - \frac{R_a}{K_2} T \text{ and } \omega_m = \frac{V}{\sqrt{K_e K_J}} \cdot \frac{1}{\sqrt{T}} - \frac{R_a}{K_e K_J} \quad \text{for } V = 0$$

3. Plugging:

In plugging, the supply voltage of a shunt motor is reversed so that it assists the back emf in forcing armature current in reverse direction. A resistance R_B is also connected in series with armature to limit the current. In fig.(A) a particular case of plugging for motor rotation in reverse direction arises, when a motor connected for forward motoring, is driven by an active load in the reverse direction. Here again back emf & applied voltage act in the same direction. However, the direction of torque remains positive in fig. (B): This type of situation arises in crane & hoist applications & the braking is then called counter- torque braking.

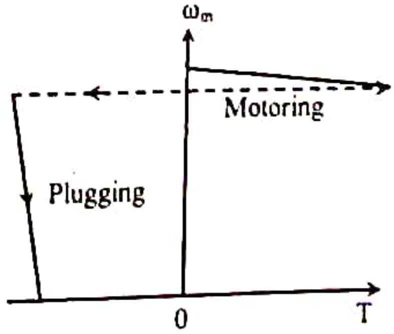


Fig: A Plugging speed torque curves

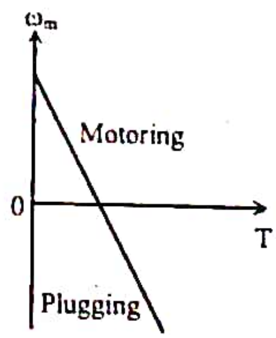
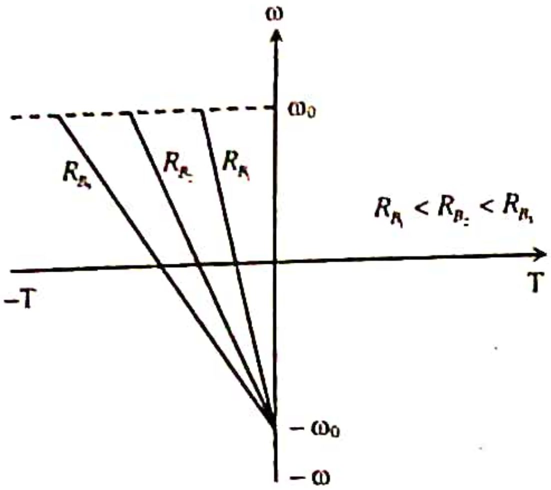


Fig: B Counter torque braking



Speed torque curves can be calculated from

$$\omega_m = \frac{V}{K} - \frac{R_a}{K^2}T \text{ and } \omega_m = \frac{V}{\sqrt{K_e K_f}} \cdot \frac{1}{\sqrt{T}} - \frac{R_a}{K_e K_f}$$

By replacing V and $-V$ are shown above.

b) A 500 V D.C. shunt motor taking an armature current of 240 A, while running at 800 rpm, is braked by disconnecting the armature from the supply & closing it on a resistance of 2.02 Ω, the field excitation remaining constant. The armature has a resistance of 0.5 Ω. Calculate the initial braking current. [WBUT 2008, 2010]

Answer:

Data given:

500V d.c. shunt motor

$I_a = 240A \qquad R_a = \cdot 5\Omega$

$R_b = 2.02\Omega$

Now, $E_b = 500 - (240 \times \cdot 5) = 500 - 120 = 380\text{V}$

In dynamic braking, it is known that:

$$\frac{V + E_b}{2I_b} = R_a + R_b$$

$$\Rightarrow \quad \frac{500 + 380}{2I_b} = 0 \cdot 5 + 2.02$$

$$\Rightarrow \quad \frac{880}{2I_b} = 2.52$$

$$\Rightarrow \quad I_b = \frac{880}{2 \times 2.52} = 174.6 \text{ Amp}$$

3. A 220 V, 150 A, 875 rpm *dc* separately excited motor has an armature resistance of 0.06 Ω. It is fed from a single-phase fully controlled converter with an *ac* source voltage of 220 V, 50 Hz. Assuming continuous conduction, calculate

[WBUT 2009, 2016]

i) firing angle for motor torque, 750 rpm.
ii) firing angle for rated motor torque, (– 500) rpm.
iii) Motor speed for $\alpha = 160°$ & rated torque.

Answer:

220 V, 875 r.p.m. 150 A separately excited d.c. motor

$$R_a = 0.06\Omega$$

At rated operation $E = 220 - (150 \times 0.06) = 220 - 9 = 211$ V

i) E at 750 r.p.m.

$$E = \frac{750}{875} \times 211 = 180.857 \text{ V}$$

$$V_a = E + I_a R_a = 180.857 + (150 \times 0.06) = 180.857 + 9 = 189.857 \text{ V}$$

Now, $\frac{2V_m}{\pi} \cos\alpha = V_a$

or, $\frac{2 \times 220\sqrt{2}}{\pi} \cos\alpha = 189.857 \text{ V}$

or, $\cos\alpha = \frac{189.857 \times \pi}{2 \times 220\sqrt{2}} = 0.9580$

or, $\alpha = 16.667°$

ii) At -500 r.p.m.

$$E = \frac{-500}{875} \times 211 = -120.571 \text{ V}$$

Since $V_a = E + I_a R_a$

$$V_a = -120.571 + 1.50 \times 0.06 = -111.571 \text{ V}$$

Now, $\frac{2V_m}{\pi} \cos\alpha = V_a$

or, $\frac{2 \times 220\sqrt{2}}{\pi} \cos\alpha = -111.571$

or, $\cos\alpha = -\frac{111.571 \times \pi}{2 \times 220\sqrt{2}} = -0.5630$

or, $\alpha = 124.26°$

iii) At $\alpha = 160°$

$$V_a = \frac{2V_m}{\pi} \cos\alpha = \frac{2 \times 220}{\pi} \cos 160° = -186.218 \text{ V}$$

Since $V_a = E + I_a R_a$

or, $-186.218 = E + (150 \times 0.06)$

or, $E = -186.218 - 9 = -195.218$ V

$$\text{Speed} = \frac{-195.218}{211} \times 875 = -809.557 \text{ r.p.m.}$$

Rated torque $\quad K = \dfrac{E}{\omega_m} = \dfrac{-195.218}{-809.557} \times \dfrac{60}{2\pi} = 2.303$

Torque $\quad T = KI_a = 2.303 \times 150 = 345.45\,\text{N-m}$

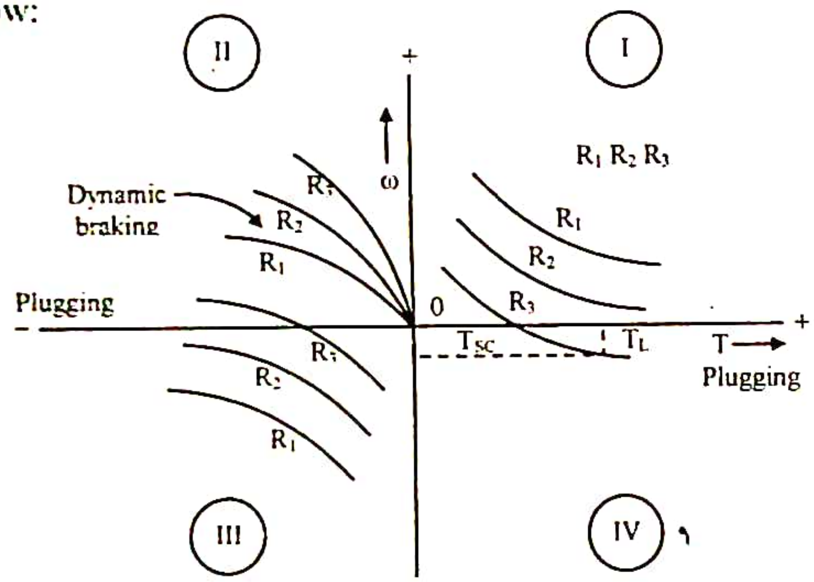
$$I_a = \frac{V_a - E}{R_a} = \frac{-186.218 - (-195.218)}{0.06} = 150\ \text{A}.$$

4. a) Draw the speed-torque characteristics for dynamic braking operation of *d.c.* series motor. Why does torque become zero at finite speed? [WBUT 2010, 2013]

Answer:

1st Part:

The speed torque characteristics for dynamic braking are in the second quadrant of the figure shown below:



In the second quadrant i.e. at this instant, the driven unit may experience objectionable shocks due to large value of braking torque and the machine runs as a self-excited generator.

2nd Part:

Operation in quadrant II represents braking because in this part of the torque-speed curve the direction of rotation is positive and the torque is negative. The machine operates as a generator developing a negative torque, which opposes motion. In III quadrant, which corresponds to the motor action in the reverse direction both speed and torque are negative value while the power is positive.

b) A 230 V separately excited *d.c.* motor takes 50 A at a speed of 800 rpm. It has armature resistance of 0.4 Ω. This motor is controlled by a chopper with an input voltage of 230 V and frequency of 500 Hz. Assuming continuous conduction throughout, calculate the speed torque characteristic for

i) motoring operation at duty ratios of 0.3 and 0.6

ii) regenerative braking operation at duty ratios 0.7 and 0.4.

[WBUT 2010, 2013]

Answer:

Given data:

$$E_a = 230\text{ V} \qquad I_a = 50\text{ A} \qquad N_1 = 800\text{ r.p.m.}$$

$$R_a = 0.4\,\Omega \qquad E_0 = \delta E_a$$

i) For $\delta = 0.3$

$$E_0 = (0.3)(230)$$

$$E_0 = 69\text{ V}$$

$$E_{b1} = E_a - I_a R_a = 230 - (50 \times 0.4) = 210\text{ V}$$

$$E_{b2} = E_0 - I_a R_a = 69 - (50 \times 0.4) = 49\text{ V}$$

$$\frac{E_{b1}}{E_{b2}} = \frac{N_1}{N_2}$$

$$N_2 = \frac{E_{b2}}{E_{b1}} \times N_1 = \frac{49}{210} \times 800 = 186\text{ r.p.m.}$$

For $\delta = 0.6$

$$E_0 = \delta E_a = (0.6) \times 230 = 138\text{ V}$$

$$E_{b1} = E_a - I_a R_a = 230 - (50 \times 0.4) = 210\text{ V}$$

$$E_{b2} = E_0 - I_a R_a = 138 - (50 \times 0.4) = 118\text{ V}$$

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}}$$

$$N_2 = \frac{18}{210} \times 800 = 449.5\text{ r.p.m.}$$

ii) Regenerative braking operation

For $\delta = 0.7$

$$E_0 = \delta E_a$$

$$E_0 = (0.7 \times 230) = 161\text{ V}$$

$$E_{b1} = E_a - I_a R_a = 230 - (0.4 \times 50) = 210\text{ V}$$

$$E_{b2} = E_0 + I_a R_a = 161 + (50 \times 0.4) = 181\text{ V}$$

$$N_2 = \frac{E_{b2}}{E_{b1}} \times N_1 = \frac{181}{210} \times 800 = 689.5\text{ r.p.m.}$$

For $\delta = 0.4$

$$E_0 = \delta E_a = (0.4) \times 230 = 92\text{ V}$$

$$E_{b1} = E_a - I_a R_a = 230 - (50 \times 0.4) = 210\text{ V}$$

$$E_{b2} = E_0 + I_a R_a = 92 + (50 \times 0.4) = 112\text{ V}$$

$$\frac{N_1}{N_2} = \frac{E_{b2}}{E_{b1}}$$

$$N_2 = \frac{112}{210} \times 800 = 426.6 \text{ r.p.m.}$$

5. Describe regenerative braking operation of DC machine. **[WBUT 2015]**

Answer:

Refer to Question No. 6 of Long Answer Type Questions.

6. Write short note on Regenerative braking for dc motor. **[WBUT 2014]**

Answer:

Regenerative Braking of DC Shunt motor

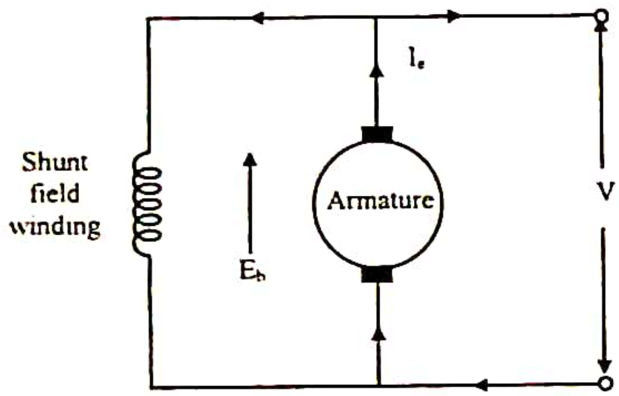


Fig: 1 Regenerative braking

Regenerative braking method is used when the load on the motor has overhauling characteristics as in the lowering of the case of a hoist or downgrade motion of an electric train. Regeneration takes place when E_b becomes greater than V. This happens when the overhauling load acts as a prime mover and so drives the machine as a generator. Consequently, direction of I_a, and hence of armature torque is reversed and speed falls until E_b becomes less than V. It is obvious that during slowing down of the motor, power is returned to the line which may be used for supplying another train on an upgrade thereby relieving the power house a part of its load. In this context Fig. shown above may be referred to.

As protective measure, it is necessary to have some type of mechanical brake in order to hold the load in the event of a power failure.

Regenerative braking of Series motor

In a series motor regenerative braking is not possible without modification because reversal of I_a would also mean reversal of the field and hence of E_b.

This method, however is used with special arrangements in traction motors.

DC MOTOR DRIVES (RECTIFIER AND CHOPPER FED)

Multiple Choice Type Questions

1. The ripple frequency is twice the supply frequency in the case of [WBUT 2006, 2007, 2010, 2014]

   a) single phase half-wave converter
   b) single phase dual converter
   c) three phase full converter
   d) three phase semi-converter

Answer: (b)

2. The free wheeling diode is needed with inductive load in [WBUT 2006, 2014]

   a) single phase half converter drive only
   b) single phase semi-converter drive only
   c) single phase full converter drive and single phase dual converter drive
   d) both single phase half converter drive and single phase full converter drive

Answer: (b)

3. Which operation is not possible for semi-converter fed D.C. drive system? [WBUT 2008]

   a) II nd quadrant (V-I)
   b) III rd quadrant
   c) IV th quadrant
   d) All of these

Answer: (c)

4. In a thyristor *d.c.* chopper, which type of commutation results in best performance? [WBUT 2010]

   a) voltage commutation
   b) current commutation
   c) load commutation
   d) none of these

Answer: (a)

5. In case of a 3-phase full controlled converter the ripple frequency on the *dc* side is (if the *ac* side supply frequency is taken to be *f*) [WBUT 2011]

   a) *f* b) 2*f* c) 3*f* d) 6*f*

Answer: (d)

6. In a dual converter, the circulating current [WBUT 2015]

   a) increases the response time but allows smooth reversal of load current
   b) decreases the response time but does not allow smooth reversal of load current
   c) improves the speed of response and also allows smooth reversal of load current
   d) make performance of the converter worse

Answer: (c)

7. In constant torque operation of DC motor [WBUT 2015]
   a) field flux is proportional to speed
   b) field flux is inversely proportional to speed
   c) field flux is proportional to square of speed
   d) field flux remains constant

Answer: (a)

8. The ripple frequency is six times of the supply frequency in case of [WBUT 2015]
   a) single phase full converter
   b) three phase semi converter
   c) three phase full converter
   d) single phase semi converter

Answer: (c)

9. In constant torque operation of DC motor [WBUT 2015]
   a) field flux is proportional to speed
   b) field flux is inversely proportional to speed
   c) field flux is proportional to square of speed
   d) field flux remains constant

Answer: (a)

10. The regenerative breaking is not possible in [WBUT 2016]
   a) DC series motor
   b) Induction motor
   c) DC shunt motor
   d) DC separately excited motor

Answer: (a)

11. For a single phase half controlled converter fed *dc* drive, the possible quadrant operation is [WBUT 2017]
   a) 2nd quadrant
   b) 3rd quadrant
   c) 4th quadrant
   d) 1st quadrant

Answer: (a)

Long Answer Type Questions

1. Derive mathematically the (a) torque *vs.* current and (b) torque *vs.* speed characteristics of dc series motor. Draw the characteristics and explain practical significance. [WBUT 2006, 2012]

Answer:

a) *Derivation of torque vs. current characteristics of series motor*

During steady state operation of the motor, the voltage equation is given by:

$$V = E_b + I_a R \qquad \text{.... (1)}$$

where a) V = input voltage. b) E_b = back emf c) R is the total resistance in the armature circuit and d) I_a armature current and in a series motor, the flux 'ϕ' .depends upon armature current. Again it is known that back emf generated i.e. $E_b = \frac{\phi ZN}{60} \times \left(\frac{P}{A}\right)$ where Z = total number of armature conductor, A = number of parallel path in armature,

ϕ = flux/pole, P = number of poles, N = speed of the armature in rpm.
Now equation (1) may be written as:

$$E_b = V - I_a R$$

or, $$\phi N\left(\frac{ZP}{60A}\right) = V - I_a R \qquad \text{.... (2)}$$

when expressed in angular velocity ω in radian/sec, then equation (2) may be expressed as

$$\phi \frac{\omega}{2\pi}\left(\frac{ZP}{60A}\right) = V - I_a R$$

or, $$\omega = \frac{V - I_a R}{K\phi} \qquad \left[\text{As } \frac{ZP}{120\pi A} \text{ is constant it is denoted by K}\right] \qquad \text{.... (3)}$$

The motor torque may be expressed as $T = K\phi I_a$. As already stated that in a series motor, the flux ϕ depends upon armature current and if, for simplification $\phi - I_a$ relationship is assumed to be linear, then $\phi = K_1 I_a$. Now

$$T = K\phi I_a$$

$$= KK_1 (I_a)^2$$

i.e., $$I_a = \sqrt{\frac{T}{KK_1}}$$

b) *Derivation of Torque Versus speed characteristics*
Using equation (3), it can be obtained as:

$$\omega = \frac{V}{K\phi} - \frac{I_a R}{K\phi} = \frac{V}{KK_1 I_a} - \frac{R}{KK_1}$$

$$= \frac{V}{\sqrt{KK_1}} \cdot \frac{1}{\sqrt{T}} - \frac{R}{KK_1}$$

$$= \frac{A}{\sqrt{T}} - B \qquad \text{......(4)}$$

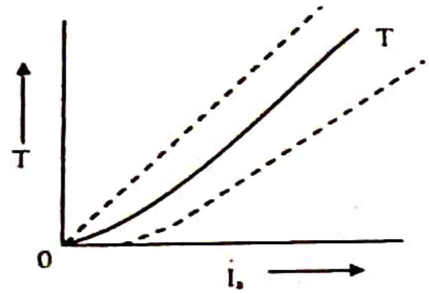
If the flux is assumed to be constant due to saturation of the magnetic circuit, then

$$\omega = \frac{V}{K\phi} - \frac{I_a R}{K\phi}$$

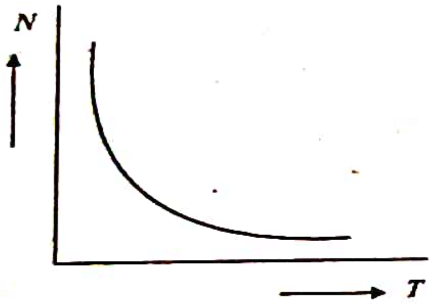
$$= C - DT \qquad (\because T \propto I_a) \qquad \text{... (5)}$$

where C and D are constants.

Characteristics and explanation
T/I_a Characteristics
In case of series motor, before saturation $T \propto I_a^2$ and as such at light loads, I_a and hence ϕ is small. But as I_a increases, T increases as the square of the current.



Hence T/I_a curve is a parabola as shown above. After saturation, ϕ is almost independent of I_a, hence $T \propto I_a$ only. So the characteristics is a straight line. So it can be concluded that (prior to magnetic saturation), on heavy loads, a series motor exerts a torque proportional to I_a^2. Hence a D.C. series motor cannot be used without any load and to be used where high starting torque is required.
Torque vs. speed or mechanical characteristics



From the above it may be seen that when speed is high, torque is small and vice versa.

2. Explain the principle of operation of chopper fed drives. **[WBUT 2008]**

Answer:
Chopper is commonly known as D.C-to-D.C converter and in order to explain the chopper fed drives, the chopper circuit for motoring mode as shown below may be referred to. This chopper circuit is termed as step down chopper. There are two types of chopper fed drives.

One-quadrant chopper-fed drive
In the armature circuit of a d.c. separately excited motor, chopper can be utilized for speed control provided the field current is kept constant. Since the speed is proportional to the output voltage which is variable is controlled by ON time T_{ON}, the time period T is being kept constant in this case. The field is supplied from a transistor chopper with the diode (FWD) connected across the field and the high inductance of the field produces continuous current in the field circuit. In this case, the output voltage and with the;

current through the motor are both positive, the motoring torque produced is positive with the result that the motor rotates in the forward direction. In view of this, this chopper is suitable for one quadrant (quadrant I) only. This can also be used for sped control of d.c. series motors. However, for operation in quadrant-III (reverse motoring), it must be connected in the reverse direction to the armature with the direction of field current remaining the same. In this case, for continuous current in armature circuit particularly during OFF period, the inductance of the armature must be sufficient and the chopping frequency of the chopper to be high.

Two/Four quadrant Chopper fed drive

The transistorized chopper drive for two quadrant operation with two transistors along with two diodes and for four quadrant operation four transistors along with four diodes are shown in Fig. (a) and Fig. (b) below:

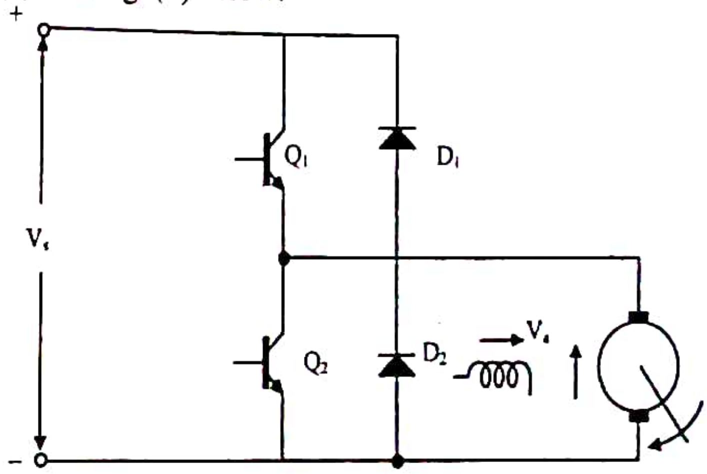


Fig: (a) Two-quadrant dc chopper-fed drive

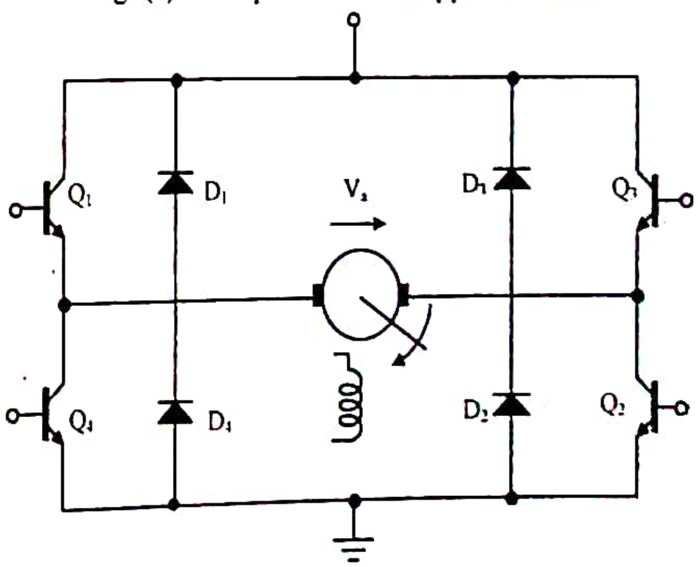


Fig: (b) Four-quadrant dc chopper-fed drive

Referring to Fig. (a) i.e., for two-quadrant operation, transistor Q_1 and diode D_2 as (FWD) function as a chopper circuit for operation in quadrant I. Similarly, transistor Q_2 and diode D_1 act as a chopper circuit for operation in quadrant II. In case of four-quadrant operation, the circuit diagram as shown in Fig. (b) may be referred to. When the transistors Q_1 and Q_2 are turned on together, it is ON time. During OFF time, either Q_1 or Q_2, or both Q_1 and Q_2 can be turned off. In case of quadrant II operation i.e. forward regenerative braking with the transistors Q_1, Q_2 and Q_3 being off, the transistor Q_4 is turned on. The current flows through Q_4 and D_2. When Q_4 is turned off, the current flows through D_1 and D_2, thus returning energy to the supply. Similarly for quadrant III (reverse motoring), both the transistors Q_1 and Q_2 can first be turned on and then turned off, with the current passing through the diodes D_1 and D_2. In case of quadrant IV operations, only the transistor Q_3 can be turned off and then off with other transistors Q_1, Q_3 and Q_4 remaining off.

3. a) Explain a *dc* chopper-based scheme for bi-directional speed control of *dc* separately excited motor. Draw the circuit diagram and clearly show how the four quadrants of drive operation can be handled by this scheme. [WBUT 2011]

OR,

How can a separately excited dc motor be controlled using a chopper? [WBUT 2013]

Answer:

In the armature circuit of a d.c. separately excited motor, chopper can be used for speed control. The transistorised chopper drive for bi-directional speed control the circuit diagram is shown below:

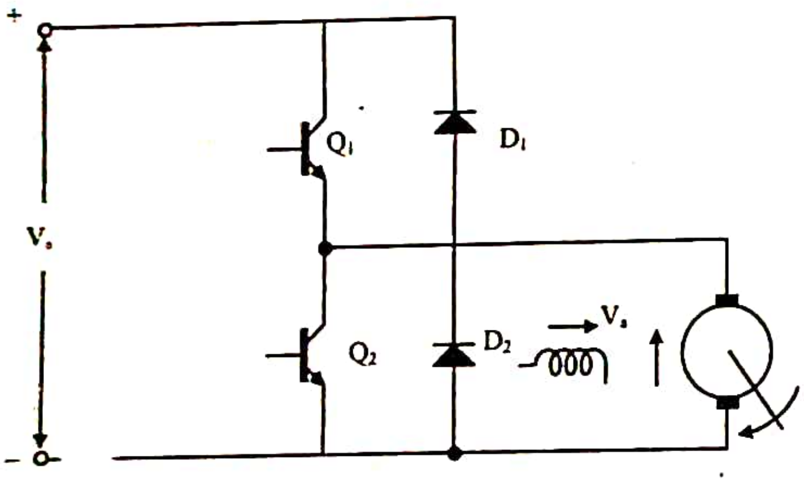


Fig: 1 Two-quadrant dc chopper-fed drive

For two-quadrant operation, transistor Q_1 and diode D_2 as (FWD) function as a chopper circuit for operation in quadrant I. Similarly, transistor Q_2 and diode D_1 act as a chopper circuit for operation in quadrant II.

For four-quadrant operation four transistors along with four diodes are shown below: -

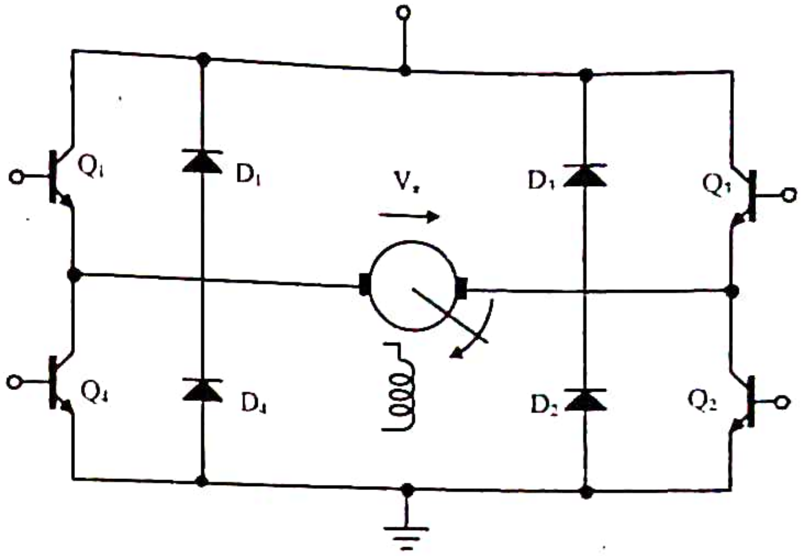


Fig: 2 Four-quadrant dc chopper-fed drive

In case of four-quadrant operation, the circuit diagram as shown in Fig. 2 may be referred to. When the transistors Q_1 and Q_2 are turned on together, it is ON time. During OFF time, either Q_1 or Q_2, or both Q_1 and Q_2 can be turned off. In case of quadrant II operation i.e. forward regenerative braking with the transistors Q_1, Q_2 and Q_3 being off, the transistor Q_4 is turned on. The current flows through Q_4 and D_2. When Q_4 is turned off, the current flows through D_1 and D_2, thus returning energy to the supply. Similarly for quadrant III (reverse motoring), both the transistors Q_1 and Q_2 can first be turned on and then turned off, with the current passing through the diodes D_1 and D_2. In case of quadrant IV operations, only the transistor Q_3 can be turned off and then off with other transistors Q_1, Q_3 and Q_4 remaining off.

b) A 220 V, 150 A, 875 rpm *dc* separately excited motor has an armature resistance of $r_a = 0.06\Omega$. It is fed from a signal phase full-controlled converter with an *ac* source side voltage of 200 V, 50 Hz. Assuming continuous current in the armature, calculate
i) firing angle for a motor torque of 650 Nm
ii) motor speed at firing angle of 120°.
Draw the waveforms for
iii) armature terminal voltage and
iv) v_{AK} for any one of the thyristors. **[WBUT 2011]**

Answer:

i) $$V_a = E_b + I_a R_a$$

$$\Rightarrow \quad V_a = K_a \phi N + I_a R_a$$

$$\Rightarrow \quad 220 = \left(K_a \phi \times 2\pi \times \frac{875}{60} \right) + (150 \times 0.06)$$

$$\Rightarrow \quad K_a \phi = \frac{211 \times 60}{2\pi \times 875} = 2.304$$

For torque 650 N-m

$$I_{a_2} = \frac{T}{K_a\phi} = \frac{650}{K_a\phi} = \frac{650}{2.304} = 282.118\text{ A}$$

$$V_a = E_b + I_a R_a$$

$$\Rightarrow \quad \frac{2V_m}{\pi}\cos\alpha = 211 + \left(I_{a_2} \times 0.06\right)$$

$$\Rightarrow \quad \frac{2\sqrt{2}\times 200}{\pi}\cos\alpha = 211 + (282.118 \times 0.06)$$

$$\Rightarrow \quad \cos\alpha = \frac{(227.927)}{2\sqrt{2}\times 200}\times\pi = \frac{227.927\times 3.14}{2\sqrt{2}\times 200}$$

$$\Rightarrow \quad \alpha = \cos^{-1}\left(\frac{227.927\times 3.14}{2\sqrt{2}\times 200}\right)$$

$$\Rightarrow \quad \alpha = 0^\circ.$$

ii) $\alpha = 120^\circ$

$$V_a = \frac{2V_m}{\pi}\cos\alpha$$

$$= \frac{2V_m}{\pi}\cos 120^\circ = \frac{2\times 200\sqrt{2}}{\pi}\times\left(-\frac{1}{2}\right) = \frac{200\sqrt{2}}{\pi} = -89.8089\text{ V}$$

$$V_a = E + I_a R_a$$

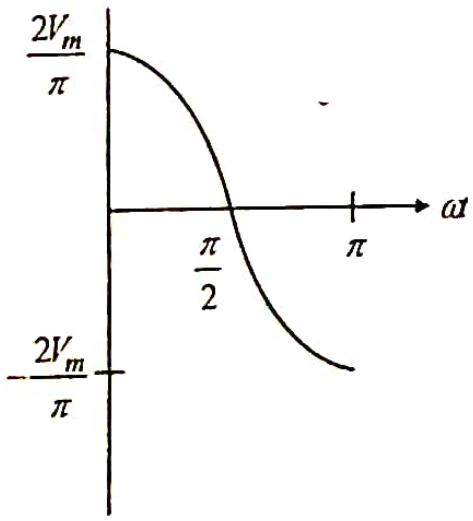
$$-89.8089 = E + (150\times 0.06)$$

$$E = -98.8089$$

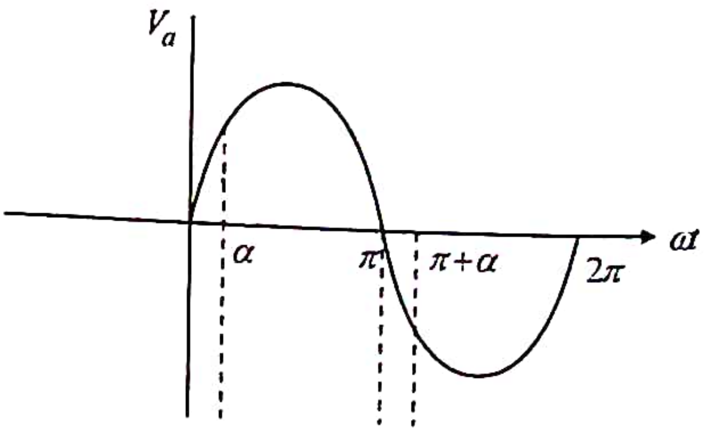
$$\text{Speed} = \frac{-98.8089}{211}\times 875 = -409.256\text{ N-m.}$$

Negative sign indicates that the motor runs in braking condition.

iii)



iv) For continuous conduction



4. A 250V, 1000 rpm, 80A dc separately excited motor has an armature resistance of 0.1Ω. It is braked by plugging from an initial speed of 1000 rpm. Calculate
- **i) Resistance to be placed in armature circuit to limit braking current to 1.5 times of the full load value**
- **ii) Braking torque**
- **iii) Torque when the speed has fallen to zero. [WBUT 2012]**

Answer:

$V = 250\ \text{V} \qquad I_{FL} = 80\ \text{A} \qquad R_a = 0.1\Omega$

$$I_b = \text{Braking current} = 80\ \text{A}$$

$$I_{aFL} = I_{FL} = 80\ \text{A}$$

At full load

$$E_b = V - I_{aFL}R_a = 250 - (80 \times 0.1) = 250 - 8 = 242\ \text{V}$$

At the time of plugging the total voltage around the circuit is

$$V_T = V + E_b = 250 + 242 = 492\ \text{V}$$

$$\therefore \quad R_T = \frac{V_T}{I_b} = \frac{492}{80} = 6.15\Omega$$

i) Braking current is 1.5 times of full load value

Braking current

$$I_b = 1.5 \times 80 = 120\ \text{A}$$

At full load

$$E = V - I_{aFL} \times R_a = 250 - (120 \times 0.1) = 250 - 12 = 238\ \text{V}$$

At the time of plugging the total voltage around the circuit is

$$V_T = V + E_b = 250 + 238 = 288\ \text{V}$$

$$R_T = \frac{V_T}{I_b} = \frac{488}{120} = 4.0667\Omega$$

$$R_b = \text{Braking resistance} = R_T - R_a = 4.0667 - 0.1 = 3.9667\Omega.$$

ii) The braking torque will be produced at 1000 r.p.m.

$$I_a = \frac{V + E_b}{R + R_a} = 80\,\text{A}$$

$$T_b = \frac{E_b I_a}{\frac{2\pi N}{60}} = \frac{288 \times 80}{\frac{2\pi \times 1000}{60}} = \frac{288 \times 80 \times 60}{2\pi \times 1000} = 220.127388\,\text{N-m.}$$

iii) Torque when the speed has fallen to zero

$$T_b = K_4 + K_5 N$$

In this case

$$T_b = K_4$$

$$K_4 = \frac{1}{2\pi}\left(\frac{\phi ZP}{A}\right)\left(\frac{V}{R + R_a}\right)$$

$$\left[E_b = \frac{\phi PNZ}{60A};\quad 288 = \frac{\phi P \times 1000 Z}{60A};\frac{\phi PZ}{A} = \frac{288 \times 60}{1000}\right].$$

$$= \frac{1}{2\pi} \times \frac{288 \times 60}{1000} \times \frac{250}{3.9667 + 0.1}$$

$$= \frac{1}{2\pi} \times \frac{288 \times 6}{100} \times \frac{250}{4.0667} = \frac{288 \times 15}{2\pi \times 4.0667} = 169.1538\,\text{N-m.}$$

5. A 200 V, 875 rpm, 150 A, separately excited dc motor has an armature resistance of 0.06 Ω. It is fed from a single phase full controlled rectified with a source voltage of 220 Volt, 50 Hz. Assuming continuous conduction, calculate.
i) firing angle for rated motor torque and 750 rpm
ii) motor speed for firing angle of 160° and at rated torque. [WBUT 2012, 2017]

Answer:

i) To obtain firing angle

Let us first calculate the value of $K_a\phi$ under rated conditions. Under rated conditions $N = 875$ r.p.m. Hence rated angular speed will be

$$\omega_{\text{rated}} = N \times \frac{2\pi}{60} = 875 \times \frac{2\pi}{60} = 91.629\ \text{rad/sec}$$

Hence at rated speed, back emf will be

$$E_b = K_a\phi\omega_{\text{rated}} = 91.629 \times K_a\phi$$

Now $\quad V_a = E_b + I_a R_a$

Under rated conditions

$$V_a = 200\,\text{V},\ E_b = E_{b(\text{rated})} = 91.629 \times K_a\phi$$

$$I_a = 150\,\text{A}$$

Hence above equation becomes

$$200 = 91.629 \times K_a\phi + 150 \times 0.06$$

$$K_a\phi = 2.0845 \text{ Volt-sec/rad}$$

Now $N = 750$ r.p.m. Hence angular speed will be

$$\omega = N \times \frac{2\pi}{60} = 750 \times \frac{2\pi}{60} = 78.54 \text{ rad/sec}$$

$$E_b = K_a\phi\omega = 20845 \times 78.54 = 163.71 \text{ Volts.}$$

At rated torque

$$I_a = 150 \text{ A}$$

$$V_a = E_b + I_a R_a$$

$$\frac{2V_m}{\pi}\cos\alpha = 163.71 + 150 \times 0.06$$

i.e., $$\frac{2\sqrt{2} \times 220}{\pi}\cos\alpha = 172.71$$

$\Rightarrow$ $$\cos\alpha = \frac{172.71 \times \pi}{2\sqrt{2} \times 220} = 0.874186$$

or, $$\alpha = 29.057°$$

ii) To obtain motor speed

At rated torque $I_a = 150$ A and

$$V_a = E_b + I_a R_a$$

$$\frac{2V_m}{\pi}\cos\alpha = E_b + I_a R_a$$

Putting values we get

$$\frac{2\sqrt{2} \times 220}{\pi}\cos 160° = E_b + 150 \times 0.06$$

$\Rightarrow$ $$\frac{2\sqrt{2} \times 220}{\pi}(-0.9339) = E_b + 9$$

$\Rightarrow$ $$E_b + 9 = -184.5196$$

$\Rightarrow$ $$E_b = -185.664 - 9 = -194.664$$

Since $$E_b = K_a\phi\omega$$

$\therefore$ $$\omega = \frac{E_b}{K_a\phi} = \frac{-194.664}{2.0845} = -93.3864 \text{ rad/sec}$$

$$N = \omega \times \frac{60}{2\pi} = -93.3864 \times \frac{60}{2\pi} = 892.226 \text{ r.p.m.}$$

The negative speed indicates that the motor operates in braking region.

6. a) A 220 V, 50 A, 1500 rpm separately excited motor with armature resistance of 0.5 ohm is fed from a 3-phase fully controlled rectifier. A variable ac source has line voltage of 440 V, 50 Hz. A star/delta connected transformer is used to feed the

converter so that motor terminal voltage equals rated voltage when converter firing angle is 0°
(i) Calculate turns ratio of the transformer.
(ii) Determine firing angle when (a) motor is running at 1200 rpm and at rated torque, (b) motor is running at 800 rpm and at twice the rated torque. [WBUT 2014]

Answer:

For a 3-ϕ fully controlled converter,

$$V_a = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

$$V_m = \frac{V_a\pi}{3\sqrt{3}\cos\alpha} = \frac{V_a\pi}{3\sqrt{3}} \quad [\because \alpha = 0]$$

$$= \frac{220\times\pi}{3\sqrt{3}} = 133\text{ V}$$

Given that $V_L = 440\text{ V}$

$$V_{ph} = \frac{440\times\sqrt{2}}{\sqrt{3}} = 359.2\text{ V}$$

(i) $\text{Turn's ratio} = \frac{359.2}{133} = 2.7$

(ii) At 1500 rpm,

$$E_b = 220 - 0.5\times 50 = 195\text{ V}$$

At 1200 rpm,

$$E_b = \frac{1200}{1500}\times 195 = 156\text{ V}$$

$$V_a = 156 + 0.5\times 50 = 181\text{ V}$$

$$\therefore \quad V_a = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

$$\cos\alpha = \frac{V_a\pi}{3\sqrt{3}V_m} = \frac{181\times\pi}{3\sqrt{3}\times 133}$$

$$\cos\alpha = 0.8228$$

$$\therefore \quad \alpha = 34.64°$$

(iii) At 800 rpm, $E_b = \frac{-800}{1500}\times 195 = -104\text{ V}$

(iv) Here the torque is twice the armature current

$$\therefore \quad V_a = E_b + I_aR_a = -104 + 2\times 50\times 0.5 = -54\text{ V}$$

$$V_a = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha$$

$$\cos\alpha = \frac{\pi V_a}{3\sqrt{3}V_m} = \frac{-\pi\times 54}{3\sqrt{3}\times 133}$$

$$\cos\alpha = -0.2454$$
$$\therefore \quad \alpha = 104.20°$$

b) Explain 4-quadrant operation of dc motor controlled by dual converter operating in non-circulating mode. **[WBUT 2014]**

Answer:

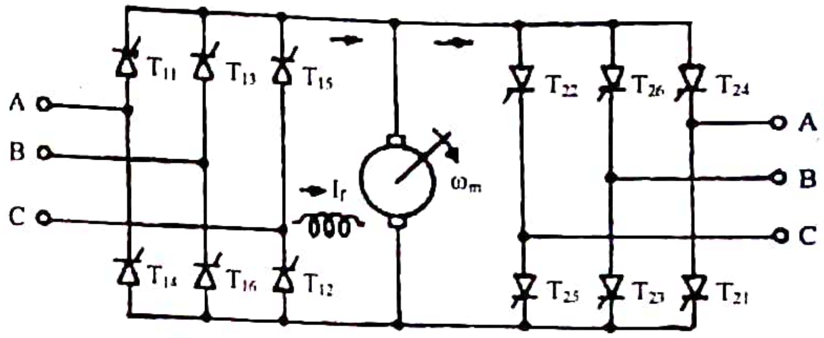


Fig: 1 Non-circulating current mode

In the non-circulating current mode, only one bridge is operated at a time. So, when the motor is to be stopped (braked), the firing pulses to the thyristors in the bridge (#1) conducting at that time are withdrawn. Then, after waiting for one full cycle, the firing pulses are fed to the thyristors in the bridge (#2) to bring it to the conducting state for the braking operation. As two bridges must not conduct simultaneously, it must be made sure that the thyristors in the outgoing bridge (#1) are off, before bringing the incoming bridge (#2) to conduction state. For this purpose, we have to wait for one full cycle, so that no short circuit takes place due to two bridges conducting at the same time. The only limitation in this mode is the time delay, needed to bring the incoming bridge to conducting state.

7. 230 Volt, 1200 rpm, 200A separately excited motor has an armature resistance of 0.06 ohm. Armature is fed from a three phase dual converter with circulating control. The available ac supply has line-line voltage of 440 Volt with supply frequency 50 Hz. When motor operates in forward motoring, converter A works as a rectifier and converter B as an inverter. Determine firing angles of converters A and B for

i) Motoring operation at 90% of rated motor torque and 900 rpm speed

ii) Braking operation at 120% of rated motor torque and 1000 rpm speed. **[WBUT 2015]**

Answer:

i) At 1200 rpm $E = 230 - (200 \times 0.06) = 230 - 12 = 218\,\text{V}$

At 900 rpm $\quad E = \dfrac{900}{1200} \times 218 = \dfrac{3}{4} \times 218 = 163.5\,\text{V}$

For a 3-phase fully controlled rectifier

$$V_m = \frac{\pi}{3} \times \frac{V_a}{\cos\alpha}$$

α = firing angle

For rated motor terminal voltage $\alpha = 0°$

$$V_m = \frac{\pi}{3} \times \frac{230}{\cos 0°} = 0.5 \times 230 = 115\text{ V}$$

Since $\quad V_a = \frac{3}{\pi} V_m \cos\alpha$

$$\cos\alpha = \frac{\pi}{3} \times \frac{V_a}{V_m} = \frac{\pi}{3} \times \frac{175.5}{115} = 0.763$$

$$\alpha = \cos^{-1}(0.763) = 40.26°$$

ii) E at 1000 rpm $= \frac{1000}{1200} \times 218 = 181.66\text{ V}$

For braking operation

$$V_a = E - I_a R_a = 181.66 - (200 \times 0.6) = 181.66 - 12 = 169.66\text{ V}$$

$$\therefore \qquad \cos\alpha = \frac{\pi}{3} \times \frac{V_a}{V_m} = \frac{0.5 \times 169.66}{115} = 0.7376$$

$$\alpha = \cos^{-1}(0.7376) = 42.46° \qquad \textbf{(Ans.)}$$

8. A 230 Volt, 960 rpm and 60 Amp separately excited dc motor has an armature resistance of 0.1 ohm and field resistance of 20 ohm.
The motor armature is fed from two quadrant chopper capable of operating in first quadrant and second quadrant with dc source voltage of 300 Volt. The motor field circuit is fed from first quadrant chopper with dc source voltage of 300 Volt. Speeds below rated value are controlled by armature voltage control with full field flux and speeds above rated are controlled by field control at rated armature voltage. Assume continuous conduction.
i) Calculate duty cycle of chopper connected to motor armature and duty ratio of chopper connected to motor field circuit for motoring operation at 750 rpm and 1.2 times rated torque.
ii) Calculate duty cycle of chopper connected to motor armature and duty ratio of chopper connected to motor field circuit for forward braking operation at 800 rpm speed and 75% of rated torque.
iii) Calculate duty ratio of chopper connected to motor field circuit for motoring operation at 1000 rpm speed and rated torque. [WBUT 2015]

Answer:

i) At rated operation

$$E = 230 - (60 \times 0.1) = 224\text{ V}$$

E at 750 r.p.m. $= \frac{750}{960} \times 224 = 175\text{ V}$

Motor terminal voltage

$$V_t = E + I_a R_a = 175 + (60 \times 0.1) = 175 + 6 = 181\text{ V}$$

Duty ratio $\delta = \frac{181}{230} = 0.786$

ii) E at 800 r.p.m. $= \frac{800}{960} \times 224 = 186.66$ V

In case of braking operation

$$V = E - I_a R_a = 186.66 - (60 \times 0.1) = 186.66 - 6 = 180.66 \text{ V}$$

Duty ratio $\delta = \frac{180.66}{230} = 0.785$

iii) $E = 224$ V for which at rated field current speed = 960 rpm. Assuming linear magnetic circuit, E will be inversely proportional to field current. Field current as a ratio of its rated value $= \frac{960}{1000} = 0.96$

9. Write short notes on the following:
a) Chopper fed drives **[WBUT 2009, 2014]**

OR,

DC chopper based electric drives. **[WBUT 2011]**

OR,

Chopper fed *dc* drive **[WBUT 2017]**
b) Three phase Rectifier fed dc drive **[WBUT 2015]**

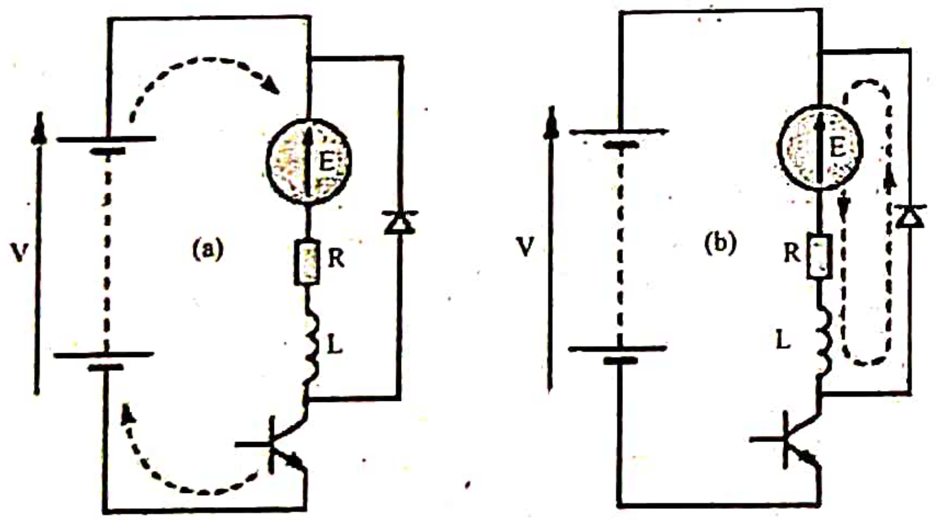
Answer:

a) 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 basic operation of a single-switch chopper was discussed in topic 2, where it was shown that the average output voltage could be varied by periodically switching the battery voltage on and of for varying intervals. The principal difference between the thyristor-controlled rectifier and the chopper is that in the former the motor current always lows through the supply, whereas in the latter, the motor current only flows from the supply terminals for part of each cycle. A single-switch chopper using a transistor, MOSFET or IGBT can only supply positive voltage and current to a d.c. motor, and is therefore restricted to quadrant 1 motoring operation. When regenerative and/or rapid speed reversal is called for, more complex circuitry is required, involving two or more power switches, and consequently leading to increased cost. Many different circuits are used and it is not possible to go into detail here, though it should be mentioned that the chopper circuit discussed in topic 2 only provides an output voltage in the range $0 < E$, where E is the battery voltage, so this type of chopper is only suitable if the motor voltage is less than the battery voltage. Where the motor voltage is greater than the battery voltage, a 'step-up' chopper using an additional inductance as an intermediate energy store is used.

Performance of chopper-fed d.c. motor drives

It is known that the d.c. motor performed almost as well when fed from a phase-controlled rectifier as it does when supplied with pure d.c. 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. Typical waveforms of armature voltage and current are shown in Fig. 1(c): these are drawn with the assumption that the switch is ideal. A chopping frequency of around 100 Hz, as shown in Fig. 1, is typical of medium and large chopper drives, while small drives often use a much higher chopping frequency, and thus have lower ripple current. As usual, we have assumed that the speed remains constant despite the slightly pulsating torque, and that the armature current is continuous.

The shape of the armature voltage waveform reminds us that when the transistor is switched on, the battery voltage V is applied directly to the armature, and during this period the path of the armature current is indicated by the dotted line in Fig. 1(a). For the remainder of the cycle the transistor is turned 'of' and the current freewheels through the diode, as shown by the dotted line in Fig. 1(b). When the current is freewheeling through the diode, the armature voltage is clamped at (almost) zero. The speed of the motor is determined by the average armature voltage, (V_{dc}), which in turn depends on the proportion of the total cycle.



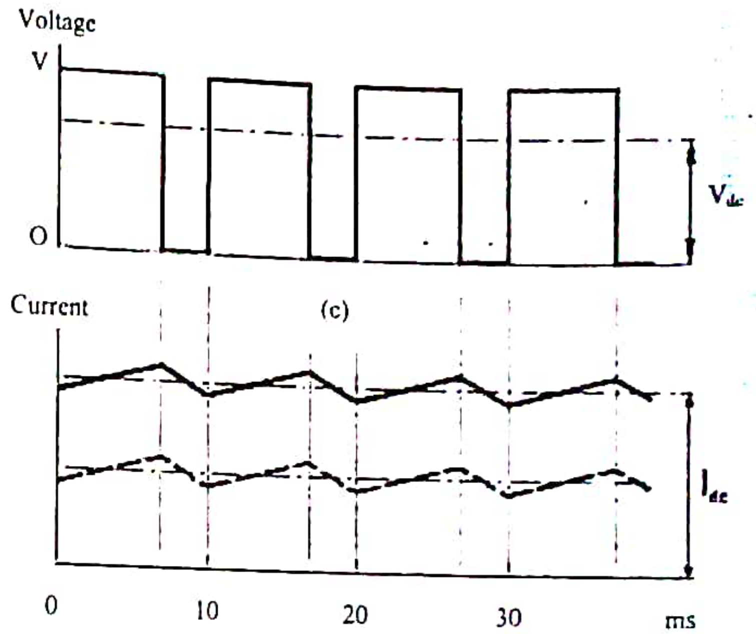


Fig: 1

b) Three-phase half controlled bridge rectifier

The action of three phase half controlled bridge rectifiers is almost similar to the case of single-phase type.

In this type the thyristors are fired at delay angle α from the natural commutation and the diodes are naturally commutated. The power circuit having three diodes and three thyristors with d.c. motor load is shown in Fig.1(a) and the voltage and current waveforms are shown in Fig. 1(b) below:

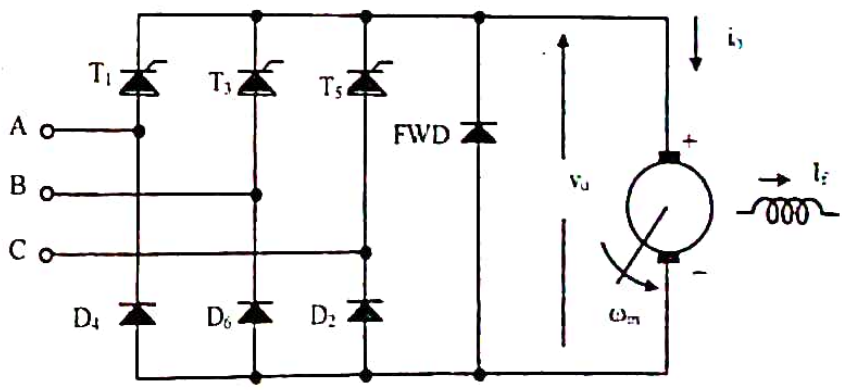


Fig: 1 (a) power circuit with dc motor load

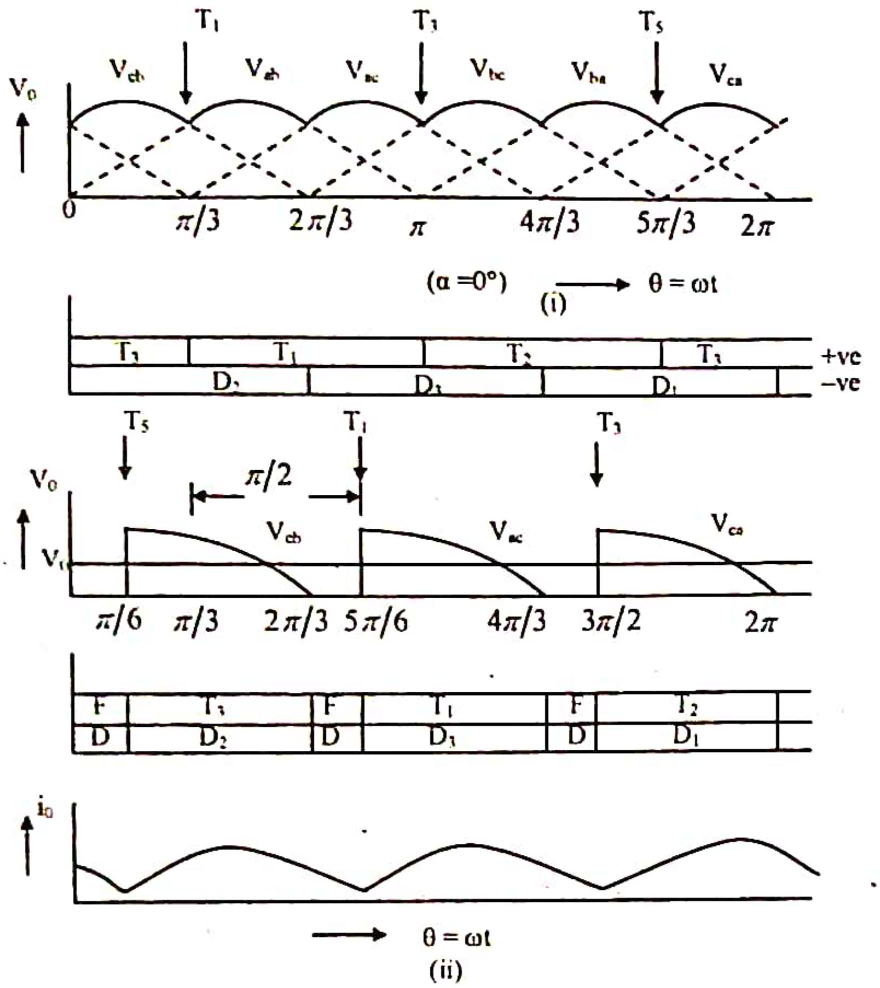


Fig: 1(b) voltage (i) α = 90° and current (α = 90°) waveforms
for continuous load current

Now if Fig. 1(b) (i) and 1(b) (ii) are referred to it may be seen that:

a) The voltage waveform for the diode bridge or thyristor bridge Fig. [1b(i)] for $\alpha = 0°$. where the thyristor T_1 is fired at $\theta = 60°$ with thyristor T_1 and diode D_6 conducting (T_5 going off) for $60°$ when commutation occurs from D_6 to D_2.

b) At $\theta = 180°$, the thyristor, T_3 is fired with T_1 going off. If $\alpha = 90°$, T_1 is fired at $\theta = 150°$, with T_1 and D_2 conducting for $90°(\theta = 240°)$, when free wheeling diode (FD) takes over, as the instantaneous voltage goes negative T_3 is fired at $270°$ with T_3 and D_4 conducting. This is shown in Fig. [1(ii)].

The output voltage having continuous current will be given by the equation $V_{dc} = 1.35V_L(1 + \cos\alpha)$ for $\pi > \alpha > 0$.

If $\alpha < \pi/3$, the voltage waveform will be continuous and when $\alpha > \pi/3$, it will be discontinuous.

Three-phase full controlled bridge rectifier

This type of thyristor drive circuits are used for armature voltage control with a view to change the speed of D.C. shunt motors and the field is fed from a diode bridge. The bridge circuits are used for high power drives and the average current in the thyristors is less than rated motor current because the thyristors conduct for about one third of the cycle. The power circuits having six thyristors with d.c. motor load is shown in Fig. 2(a) and the waveform in Fig. 2(b).

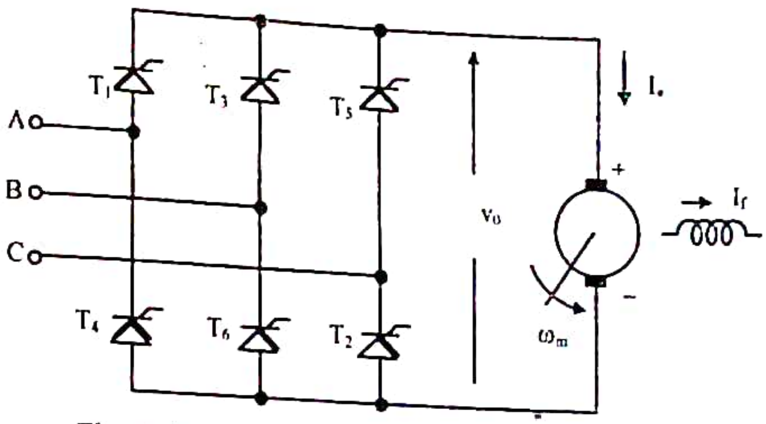


Fig: 2(a) power circuit with dc motor load

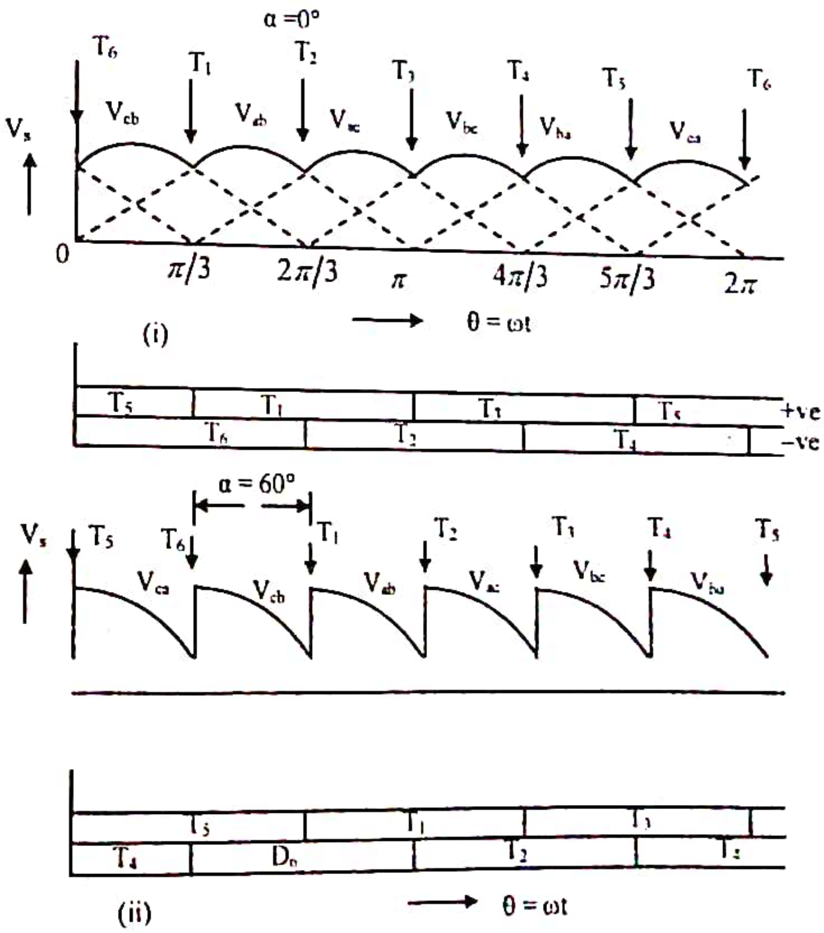


Fig: 2(b) voltage (i) $\alpha = 0°$ (ii) $\alpha = 60°$ and current ($\alpha = 60°$) waveforms for continuous load current

In this system, the thyristors are fired in sequence with delay angle α, with each thyristor conducting for angle 120°. Two thyristors conduct at a time. If thyristor T_1 is triggered, the thyristors T_1 and T_6 start conducting, with thyristor T_5 going off. Prior to this, the thyristors, T_5 and T_6 are conducting. Similarly when thyristor T_2 is triggered after a delay of 60° from the instant T_1 is triggered, the thyristors, T_1 and T_2 start conducting, with thyristor, T_6 going off. This sequence is repeated at an interval of 60°.

Now, if $\alpha < \pi/2$, the output voltage is positive.

If $\alpha > \pi/2$, the output voltage is negative.

The output voltage equation with continuous current can be expressed as:

$$V_{dc} = 1.35V_L \cos\alpha \text{ for } \pi > \alpha > 0.$$

Special feature:

Except for large delay in motoring mode, the current is mostly continuous.

INDUCTION MOTOR DRIVES

Multiple Choice Type Questions

1. A three phase induction motor having a combination of diode rectifier & line commutated inverter in rotor circuit, can give [WBUT 2008]
   a) speed below synchronous speed only
   b) speed above synchronous speed only
   c) both sub- & super-synchronous speed
   d) no change in speed.

Answer: (a)

2. The motor having slip energy recovery scheme can be braked by means of [WBUT 2009]
   a) regenerative braking
   b) plugging
   c) dc dynamic braking
   d) all the methods of (a), (b) & (c)

Answer: (d)

3. A current source inverter fed induction motor is inherently unstable when it operates in [WBUT 2009]
   a) open loop
   b) closed loop
   c) a variable frequency supply keeping air gap flux constant
   d) a variable frequency supply keeping stator flux constant

Answer: (b)

4. For increasing the speed of an induction motor, the frequency of the supply is increased by 20%. In order to operate the motor at the same flux condition, the supply voltage must [WBUT 2009, 2016]
   a) remain constant
   b) be reduced by 10%
   c) be reduced by 20%
   d) be increased by 20%

Answer: (d)

5. In V/f control of an induction motor the peak torque [WBUT 2011, 2017]
   a) can be reduced at will
   b) will remain almost constant with speed
   c) can be increased with speed
   d) none of these

Answer: (b)

6. The term 'slip power recovery' is associated with [WBUT 2011]
   a) dc shunt motors
   b) 3-phase slip-ring induction motors
   c) 3-phase cage rotor induction motors
   d) both (b) and (c)

Answer: (b)

7. PWM switching schemes are used in inverter based drives in order to [WBUT 2011]

a) get output power greater than input power
b) reduce harmonic content in the load current and hence torque
c) reduce input side power density
d) none of these

Answer: (b)

8. Induction generator runs at [WBUT 2012]

a) super synchronous
b) sub-synchronous
c) synchronous speed
d) none of these

Answer: (a)

9. A three phase induction motor is started by means of a star/delta starter. The starting current is [WBUT 2012]

a) three times the current with DOL
b) $1/3$ times the current with DOL
c) $\sqrt{3}$ times the current with DOL
d) $1/\sqrt{3}$ times the current with DOL

Answer: (d)

10. Average output voltage from three phase full control converter is [WBUT 2012]

a) $\frac{3V_m}{\pi}\cos\alpha$
b) $\frac{3V_m}{\pi}(1+\cos\alpha)$
c) $\frac{V_m}{3\cdot\pi}\cos\alpha$
d) $\frac{V_m}{3\cdot\pi}(1+\cos\alpha)$

Answer: (a)

11. A fully controlled line commutated converter operates as an inverter [WBUT 2012]

a) in the range of firing angles $0 \le \alpha \le 90°$
b) in the range of firing angles $90° \le \alpha \le 180°$
c) in the range of firing angles $90° \le \alpha \le 180°$ with a suitable *dc* source in the load
d) when it supplies RLE load

Answer: (b)

12. The slip s for reversal of any induction motor is [WBUT 2013]

a) $s-1$
b) $1-s$
c) $2-s$
d) $1-2s$

Answer: (c)

13. Stator voltage control of Induction motor is suitable for applications where [WBUT 2013]

a) torque demand reduces with speed
b) torque demand increases with speed
c) torque demand reduces with increase of speed
d) torque demand increases with reduction of speed

Answer: (a)

14. For slip power recovery method for a positive P_r where $P_r = P_g - P_m$, the induction motor will run at a speed [WBUT 2013]

a) higher than the rated speed
b) lower than the rated speed
c) at the rated speed
d) none of these

Answer: (b)

15. A three-phase induction motor operates at a constant rotor frequency when the stator frequency is varied from zero to rated value. The torque developed by the motor is [WBUT 2013]

a) constant from zero to rated speed
b) proportional to speed
c) proportional to square of speed
d) inversely proportional to speed

Answer: (a)

16. The speed of an induction motor can be varied by means of variable frequency supply from a static power converter. A simultaneous voltage variation is also effected in order to [WBUT 2014]

a) avoid saturation and provide optimum torque capability
b) the torque pulsations decrease if supplied from variable voltage supply
c) to limit the peak value of stator current
d) to minimize the additional losses

Answer: (b)

17. A three phase induction motor having a combination of diode rectifier and line commutated inverter in the rotor circuit can give [WBUT 2014]

a) speeds below synchronous speed only
b) speeds above synchronous speed only
c) both sub and super synchronous speeds
d) speeds varying from 0 to 50% of synchronous speed

Answer: (a)

18. A three-phase induction motor operates at a constant rotor frequency when the stator frequency is varied from zero to rated value. The torque developed by the motor is [WBUT 2015]

a) constant from zero to rated speed
b) proportional to speed
c) inversely proportional to speed
d) proportional to cube of speed

Answer: (a)

19. A three phase line commutated converter, when operating in the inverter mode [WBUT 2015]

a) draws both real and reactive power from ac supply
b) delivers both real and reactive power to ac supply
c) delivers real power to ac supply but draws reactive power from ac supply
d) delivers real power to dc side but draws reactive power from dc side

Answer: (c)

20. PWM Control, when applied to a three phase voltage source inverter, introduces [WBUT 2015]

a) low order harmonic voltage on the dc side
b) low order harmonic voltages on the ac side
c) higher order harmonic voltages on the ac side
d) higher order harmonic voltages on the dc side

Answer: (a)

21. For slip power recovery method for negative Pr, where $Pg = Pr + Pm$, the induction motor will run at [WBUT 2015]

a) sub synchronous speed
b) synchronous speed
c) super synchronous speed
d) none of these

Answer: (a)

22. The range of slip of regenerative braking of a polyphase induction motor remains between [WBUT 2016]

a) $s = 1$ to $s = s_m$
b) $s = 1$ to $s = -s_m$
c) $s = s_m$ to $s = 0$
d) $s = 0$ to $s = -s_m$

where s_m is the slip at maximum torque.

Answer: (d)

23. For slip power recovery method of speed control, power is injected to the rotor of the induction motor. The induction motor will run at a speed [WBUT 2016]

a) higher than rated speed
b) lower than the rated speed
c) at the rated speed
d) of zero speed

Answer: (b)

24. In case of rotor resistance control of induction motor drives, for the same torque [WBUT 2016]

a) speed falls with an increase in rotor resistance
b) speed increased with an increase in rotor resistance
c) speed falls with fall in rotor resistance
d) speed increases with fall in rotor resistance

Answer: (a)

Short Answer Type Questions

1. Discuss the plugging operation of 3-phase wound rotor induction motor. Why usually an external resistance is inserted in the rotor circuit during this operation? [WBUT 2006]

OR,

Explain, how regenerative braking is done in a 3-phase induction motor. Show graphically the four quadrant operation of the motor. What is the slip during plugging of an induction motor? [WBUT 2012]

Answer:

The plugging operation of a 3 phase wound rotor induction motor involves interchanging of any two-supply terminals with insertion of external resistance into the rotor circuit. This will result the reversal of the direction of rotation of the rotating magnetic field with respect to the rotation of the motor. The electromagnetic torque developed, provides the braking action and the motor should be disconnected from the supply when the speed drops to zero. Otherwise, the motor would continue to run in the opposite direction in reverse motoring mode.

If 'S' be the slip for the motoring operation with respect to the forward rotating field, then the corresponding slip after reversal of the rotating magnetic field will be (2- s).

$$\text{s(during motoring)} = \frac{\omega_S - \omega_r}{\omega_S}$$

$$\omega_r = (1-s)\omega_S$$

$$\text{Slip during plugging, } s_{pl} = \frac{-\omega_S - \omega_r}{-\omega_S} = \frac{\omega_s + \omega_r}{\omega_S} = 2 - s$$

The counter current braking or plugging condition can also be set up, when the load torque exceeds the stalling torque. The rotor rotates in the direction opposite to that of the rotating magnetic field.

External resistance is inserted in the rotor circuit during this operation in order to limit the plugging current and to develop the plugging torque.

2. Why VVVF method of speed control of 3-phase induction motor is preferable to the frequency control method? Draw typical speed-torque curves for both the methods. **[WBUT 2006, 2010, 2015, 2016]**

Answer:

The variable voltage, variable frequency method of speed control of 3-phase induction motor is preferable to the frequency control method, because of the fact that:

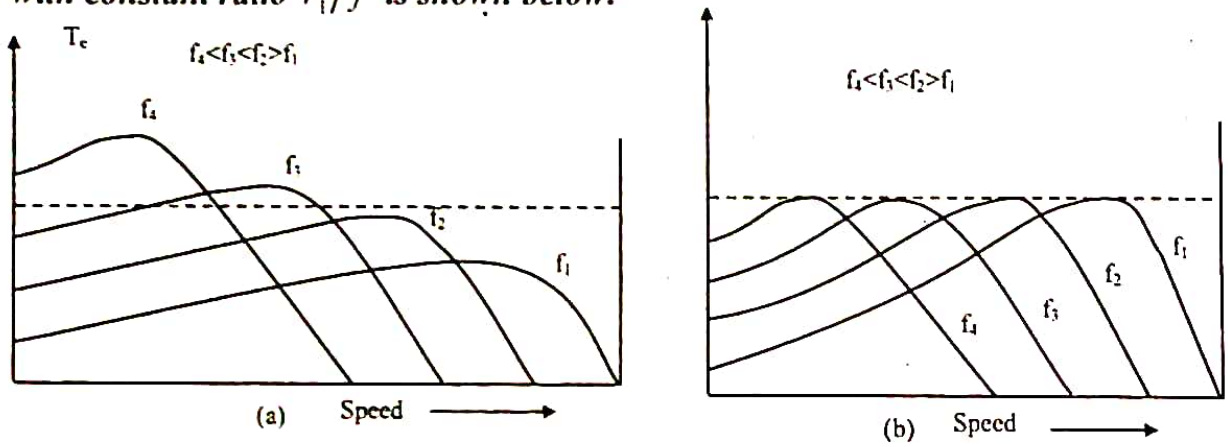
i) In frequency control method ,supply voltage V_1 or V_e is kept constant and the starting torque is inversely proportional to

$$f^3\left[T_{est} = \frac{mP}{16\pi^2}\left(\frac{V_e}{f}\right)^2 \cdot \frac{1}{f} \cdot \frac{1}{(L_e + \ell_2)^2} r_2\right]$$

Further, with constant V_1 or V_e, the maximum torque is inversely proportional to $f^2\left[T_{em} = \frac{mP}{16\pi^2}\left(\frac{V_e}{f}\right)^2 \frac{1}{L_e + \ell_2}\right]$. With reduction in frequency for constant V_1, the air gap flux increases and the induction motor magnetic circuit gets saturated which is highly undesirable.

ii) In case VVVF method, when the ratio $\frac{V_1}{f}$ is kept constant, starting torque is inversely proportional to f and the maximum torque remains unaltered. However, at lower values of frequencies, the effect of resistances cannot be neglected as compared to reactances. This has the effect of reducing the magnitude of maximum torque at lower frequencies.

Induction motor torque-speed curves (a) with variable frequency and constant V_1 and (b) with constant ratio V_1/f is shown below:



3. Explain with appropriate diagram the operation of a static Scherbius drive. **[WBUT 2011]**

OR,

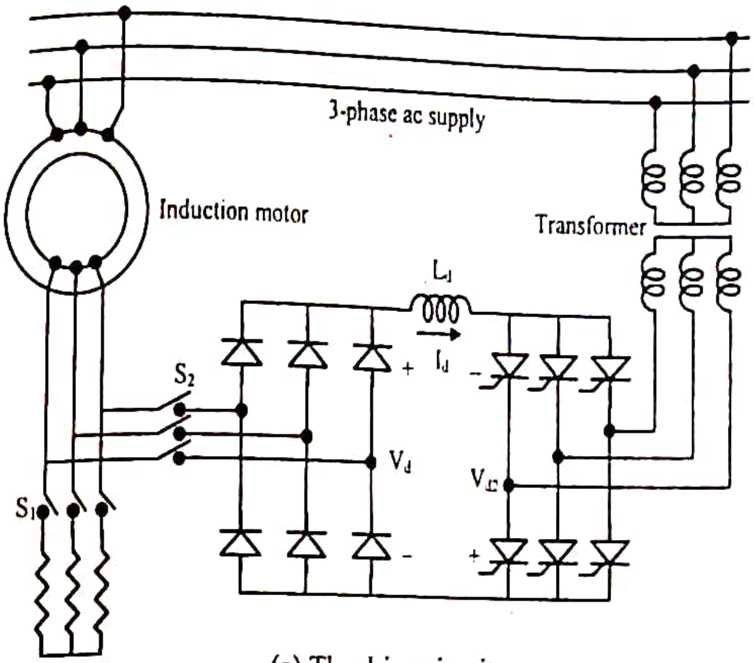
Explain the principle of slip power recovery scheme of controlling the speed of induction motor, using static Scherbius Drive. **[WBUT 2015]**

Answer:

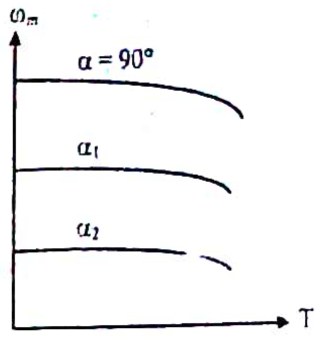
It provides the speed control of a wound rotor motor below synchronous speed. A portion of rotor ac power is converted into dc by a diode bridge. The controlled rectifier working as an inverter converts it back to ac and feeds it back to the ac source. Power fed back (i.e. P_r) can be controlled by controlling inverter counter emf V_{d2}, which in turn is controller by controlling the inverter firing angle. The dc link inductor is provided to reduce ripple in dc link current I_d.

Since slip power is fed back to the source, unlike rotor resistance control where it is wasted in resistors, drive has a high efficiency. The drive has higher efficiency than stator voltage control by ac voltage controllers because of the same reasons.

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, drive has a poor power factor throughout the range of its operation.



(a) The drive circuit



(b) Speed-torque curves

Fig: Static Scherbius drive

From Fig. (a), neglecting stator and rotor drops

$$V_{d1} = \frac{3\sqrt{6}}{\pi}\frac{sV}{n} \qquad \text{.... (i)}$$

and $$V_{d2} = \frac{3\sqrt{6}}{\pi}\frac{V}{m}\cos\alpha \qquad \text{.... (ii)}$$

where α is the inverter firing angle and n and m are respectively, the stator to rotor turns ratio of motor and source side to converter side turns ratio of the transformer. Neglecting drop across inductor $V_{d1} + V_{d2} = 0$

Substituting from equations (i) and (ii) yields

$$s = -\frac{n}{m}\cos\alpha = -a\cos\alpha \qquad \text{.... (iii)}$$

where $a = n/m$.

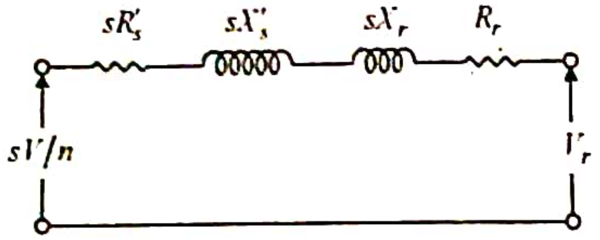
Maximum value of α is restricted to 165° for safe commutation of inverter thyristors. Slip can be controlled from 0 to $0.966a$ when α is changed from 90° to 165°. By appropriate choice of a, required speed range can be obtained.

Transformer is used to match the voltages V_{d1} and V_{d2}. At the lowest speed required from the drove, V_{d1} will have the maximum value V_{d1m} given by $V_{d1m} = Vs_{max}/n$ where s_{max} 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 165° i.e.

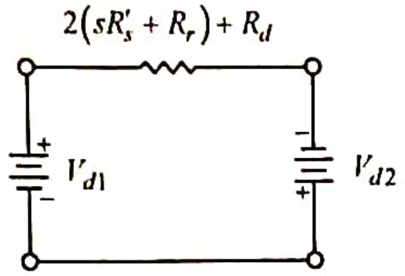
$$\frac{V}{m}\cos 165° + \frac{Vs_{max}}{n} = 0$$

$$m = -\frac{n\cos 165°}{s_{max}} = -0.966\frac{n}{s_{max}}.$$

Such a choice of m ensures inverter operation at the highest firing angle at the lowest motor speed, giving highest power factor $\left[PF = \frac{I_1}{I_{rms}}\cos\phi_1 = \mu\cos\phi_1\right]$ 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.



(c) Equivalent circuit of the motor referred to the rotor



(d) Equivalent circuit of the drive

Fig: Motor and drive equivalent circuits

Figure (c) shows equivalent circuit of motor referred to the rotor, neglecting magnetizing branch. Derivation of equation [Power consumed per phase $= \frac{P_{AB}}{3} = 0.5R(1-\delta)I_r^2$] shows that when referred to dc link, resistance $(sR_s' + R_r)$ will be $2(sR_s' + R_r)$. This gives approximate dc equivalent circuit of the drive Fig. (d), where V_{d1} and V_{d2} are given in equation (i) and (ii). R_d is the resistance of dc link inductor. Equivalent circuit ignores the commutation overlap in the diode bridge. Now

$$I_d = \frac{V_{d1} + V_{d2}}{2(sR_s' + R_r) + R_d} = \frac{\frac{3}{\pi}\sqrt{6}V\left(\frac{s}{n} + \frac{\cos\alpha}{m}\right)}{2(sR_s' + R_r) + R_d} \quad \text{.... (iv)}$$

If rotor copper loss is neglected

$$sP_g = |V_{d2}|I_d \quad \text{.... (v)}$$

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

Now $$T = \frac{P_g}{\omega_{ms}} = \frac{|V_{d2}|I_d}{s\omega_{ms}} \quad \text{.... (vi)}$$

The nature of speed torque curves is shown in Fig. (b).

The drive has applications in fan and pump drives, which require speed control in a narrow range only. If maximum slip is denoted by s_{max}, then power ratings of diode bridge, inverter and transformer can be just s_{max} times the motor power rating [equation (v)]. 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.

Drive is started by resistance control with S_1 closed and S_2 open [figures (a) and (b)]. When speed reaches within control range of the drive, S_2 is closed to connect diode bridge and inverter is activated. Now S_1 is opened to remove the resistances.

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 a closed loop speed control. A close loop speed control scheme with inner current control is shown in Fig. (e).

This drive is widely used in medium and high power (up to around to 10 MW) fan and pump drives, because of high efficiency and low cost.

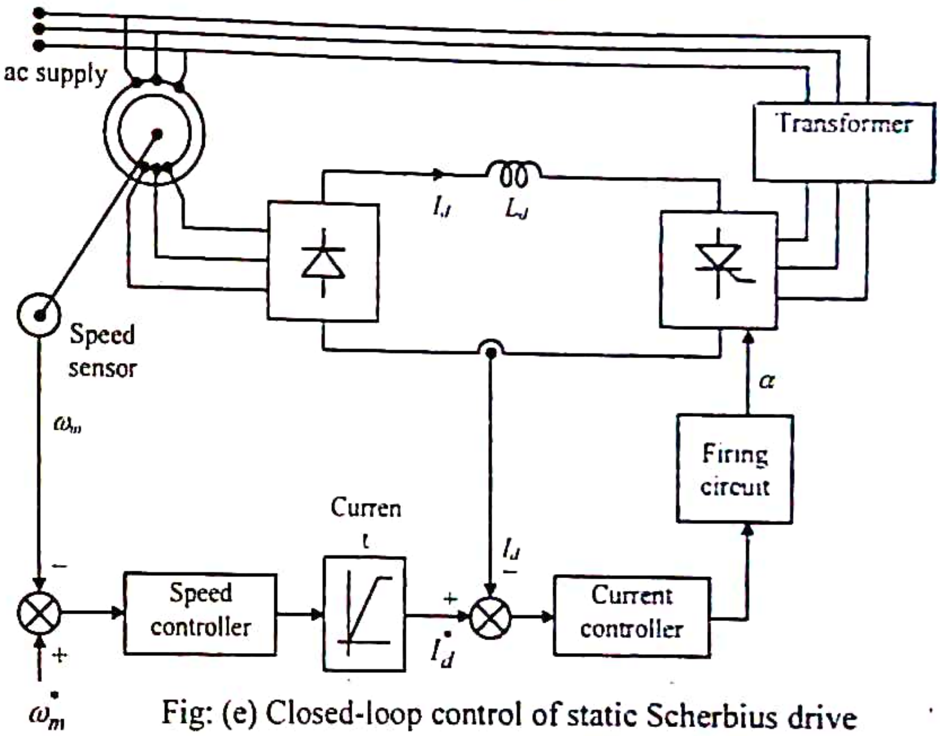


Fig: (e) Closed-loop control of static Scherbius drive

Long Answer Type Questions

1. a) Explain the method of speed control of induction motors using a variable frequency supply. **[WBUT 2006, 2008]**

b) A star connected squirrel-cage induction motor has the following ratings and parameters:

400V, 50Hz, 4-pole, 1410 rpm, $R_s = 2\Omega$, $R'_r = 3\Omega$, $X_s = X'_r = 3.5\Omega$. It is controlled by a current source inverter at a constant flux. Calculate **[WBUT 2006, 2012, 2014]**

i) motor torque, speed when operating at 30 Hz and rated slip speed

ii) inverter frequency for rated motor torque at a speed of 1250 rpm

Answer:

a) There are three basic types of variable frequency supply:

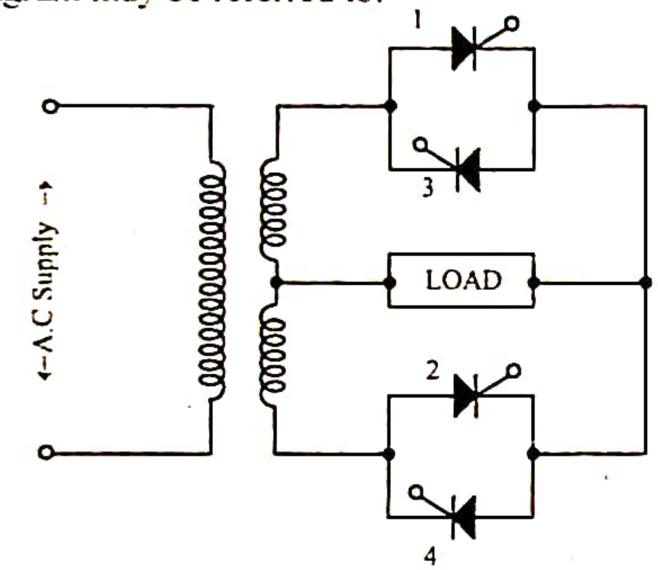
i) variable frequency motor alternator set ii) d.c. link inverter and iii) cycloconverter. Now a days, the variable frequency motor alternator set is being largely replaced by solid state static frequency changers which are of two types i.e.

i) rectifier inverter type and

ii) cycloconverter type.

In rectifier, inverter type, supply frequency input is first converted into d.c. by using diode or thyristor bridge. This direct voltage, after being filtered, is then converted into desired frequency a.c. output using static inverters. In the latter type, i.e. in a cycloconverter, supply frequency input is converted directly into the desired frequency output. In cycloconverter type the power is handled once, it is, therefore, more efficient than the rectifier inverter type in which power is handled twice. The only draw back of the cycloconverter type is that its output frequency range is from zero to about one half of the supply frequency; whereas for the rectifier inverter (or d.c. link converter) type a wide frequency range from zero to about 2 to 3 KHz can be obtained.

Here the basic principle of the single phase cycloconverter is explained for which the following circuit diagram may be referred to:



The above circuit diagram shows two pairs of thyristors connected in inverse parallel. If thyristor 1 and 2 are fired in alternate half cycles, an output of positive is obtained. On the other hand, if thyristors 3 and 4 are fired in alternate half cycle, an output of negative polarity is obtained. So, by proper firing of the positive and negative group of thristors, output of any desired voltage and frequency can be obtained.

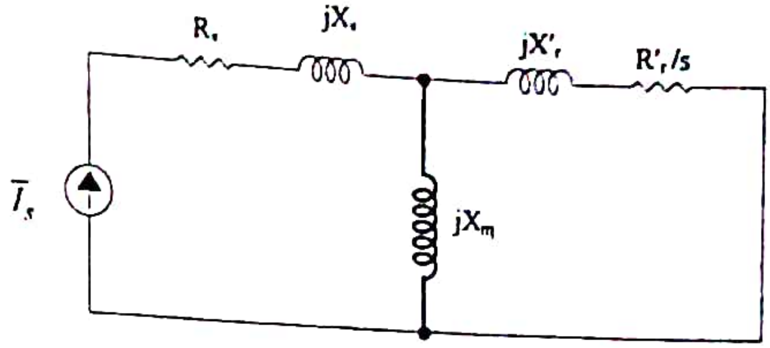
b) Synchronous speed $n_S = \dfrac{120f}{P} = \dfrac{120 \times 50}{4} = 1500$ rpm

$\therefore \qquad \omega_S = 50\pi$ rad/sec.

full load slip, $s_f = \dfrac{1500-1410}{1500} = 0.06$

full load slip speed = 1500 – 1410 = 90 r. p. m.

The equivalent fig. of induction motor is



where R_S = Stator resistance

R_s = Rotor resistance

X_S = Stator inductance

X_r = Rotor inductance

X_m = magnetizing impedance

Z_{eq} = Total equivalent impedance

$$= R_S + j\,X_S + \frac{j\,X_m\left(R_r'/s + jX_r\right)}{R_r'/s + j(X_m + X_r)}$$

$$= 2 + j3.5 + \frac{j\,X_m\left(\frac{3}{0.06} + j\,3.5\right)}{\frac{3}{0.06} + j(X_m + 3.5)}$$

As X_m is not mentioned so we can consider here X_m is very large compare to with the rotor impedance.

$$\therefore \qquad Z_{eq} = R_S + j\,X_S + \frac{j\,X_m\left(\frac{R_r'}{s} + j\,X_r'\right)}{\frac{R_r'}{s} + j(X_m + X_r')}$$

$$Z_{eq} = R_S + j\,X_S + \frac{R_r'}{s} + j\,X_r' \quad \text{[if } X_m \text{ is very large]}$$

$$= R_S + \frac{R_r'}{s} + j(X_s + X_r') = 2 + \frac{3}{0.06} + j(3.5 + 3.5)$$

$$= 2 + 50 + j7 = 52 + j7$$

$$\therefore \qquad |Z_{eq}| = 52.47$$

$$\therefore \text{Full load stator current } I_{sf} = \frac{V_{pk}}{|Z_{ye}|} = \frac{400/\sqrt{3}}{52.47} = \frac{230.9}{52.47} = 4.40\text{ A}$$

As X_m is considered very high full load stator current is equal to the full load rotor current.

$$\therefore \text{ Full load Torque } T_F = \frac{3}{\omega_S}\left[I_r^{\,2} \times \frac{R_r'}{s}\right] = \frac{3}{50\pi} \times \left[(4.4)^2 \times \frac{3}{0.06}\right]$$

$$= \frac{9}{50\pi} \times (4.4)^2 \times \frac{1}{0.06} = 18.496 \text{ N-m.}$$

(i) As Motor torque depends on the rated slip speed which remains constant so when operating at 30 Hz also

Torque $= T_F = 18.496$ N-m (Ans.)

and stator current $I_{S_f} = 4.4$ A. (Ans.)

At 30 Hz synchronous speed $= \frac{30}{50} \times 1500 = 900$ r p m.

Full load slip speed = 90 r. p. m. = constant

$\because$ Motor speed = 900 – 90 = 810 r p m. (Ans.)

(ii) At rated motor torque, slip speed and I_S will be same as at 50 Hz operation.

Therefore, $I_S = 4.4$ A, slip speed = 90 r.p.m.

$\therefore$ Synchronous speed = 1250 + 90 = 1340 r.p.m. when motor speed is 1250 r.p.m.

$\therefore$ Inverter frequency $= \frac{1340}{1500} \times 50 = 44.66$ Hz (Ans.)

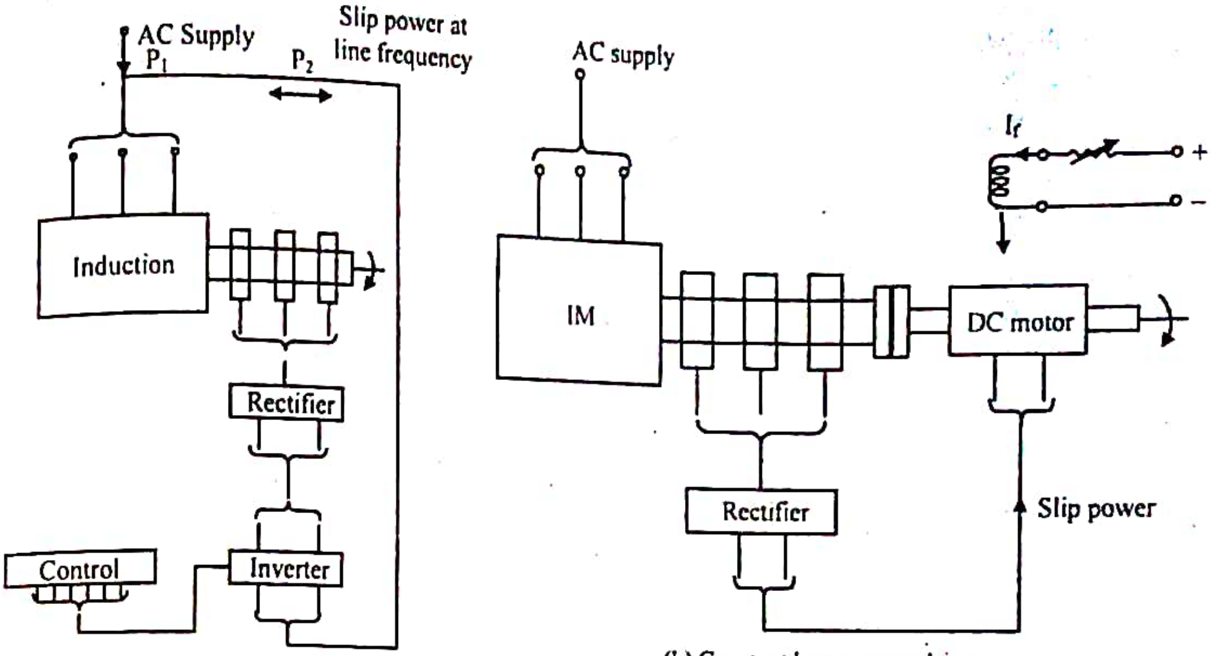
2. Explain the principle of slip power recovery scheme of controlling the speed of induction motor. [WBUT 2007, 2009]

OR,

With the help of relevant diagram explain slip power recovery scheme of three-phase induction motor for speed control below synchronous speed. [WBUT 2017]

Answer:

In static Kramer drive, slip power recovery takes place. For speed control below synchronous speed, the slip power is pumped back to the supply, where for speed above synchronous speed additional slip power is injected into the rotor circuit. Kramer control scheme utilizing slip power recovery for constant torque and constant horsepower operations may be seen from Fig. 1(a) and 1(b) respectively.



(a) Constant torque

(b) Constant horsepower drive

Fig: 1 Slip-power Recovery, Kramer Method

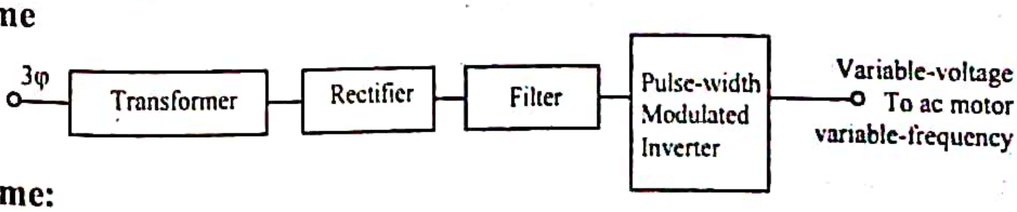
3. Explain the principle of operation of VVVF control of induction motor.
[WBUT 2007, 2008, 2010]

Answer:

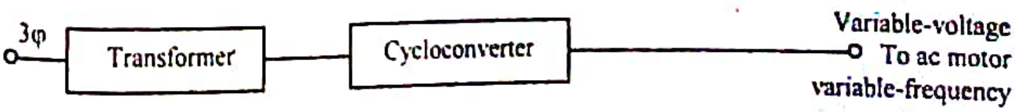
In VVVF Control of induction motor, variable frequency input requires that voltage to frequency ratio remains constant in order to maintain the flux constant. As the inverter frequency is varied, the voltage must be varied to maintain voltage to frequency (V/f) ratio constant. But this type of control requires two to three stages which results in higher losses and lower efficiency. Further, for low value of frequency, the element of the filter circuit increase in size and weight which results in their high cost and low efficiency. Moreover the low values of d.c. input voltage, the voltage across the commutating capacitor decreases, thus reducing a circuit turn-off time for thyristors for constant load current. The output voltage can also be varied by control within the inverter.

Generally there are two schemes of speed control of induction motor by variable-voltage variable frequency method.

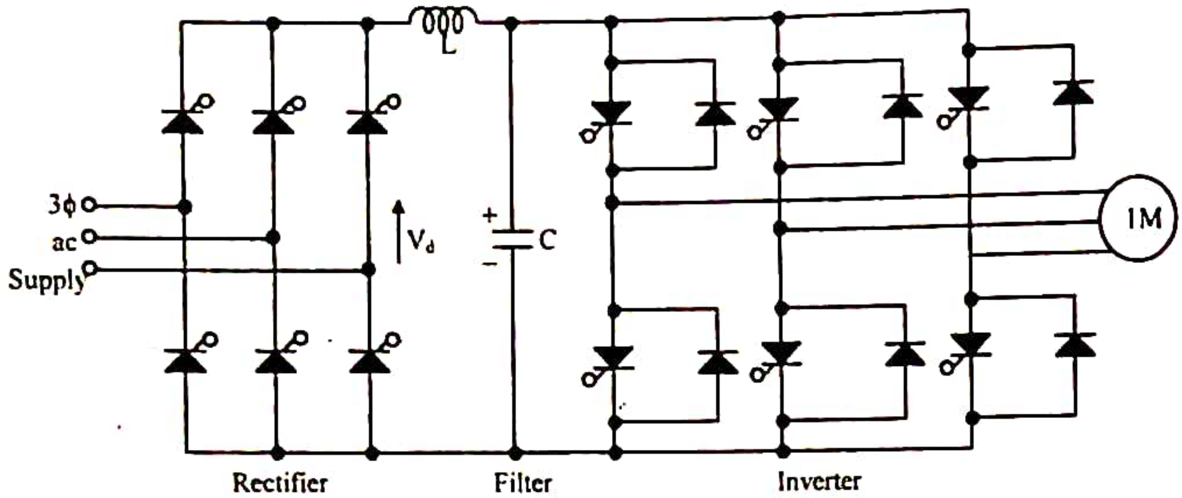
1st scheme



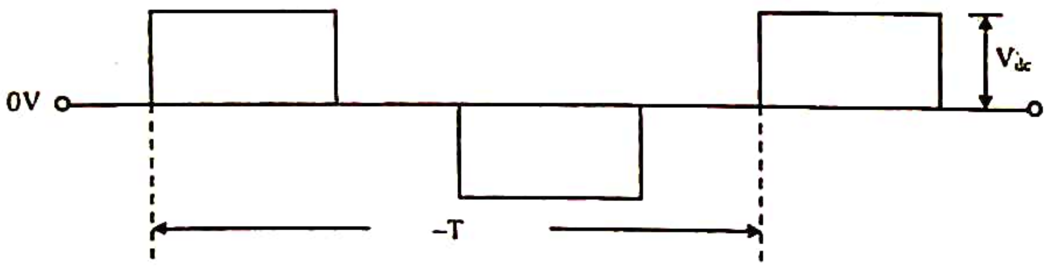
2nd scheme:



In the 1st scheme a three-phase bridge converter a.c to variable d.c voltage which is impressed at the input of a force commutated bridge inverter. The inverter generates a variable-voltage variable-frequency power supply to control the speed of the motor, the capacitor C as in the Fig. shown below supplies stiff voltage supply to the inverter and the inverter output voltage waves are not affected by nature of load. The inductance L is of large value to prevent discontinuity in output voltage and smooth the ripple.



The induced stator phase emf is given by $V = 4.44\phi fT$ where V is the applied voltage, f the applied frequency, ϕ the air gap flux and T the number of turns in the stator winding.
In order to achieve constant torque operation below base speed, flux ϕ has to be kept constant and for keeping ϕ constant, the ratio $\frac{V}{f}$ has to be kept constant. Thus to control the speed of a.c induction motor, below the rated value, not only frequency has to be decreased but also voltage has to be decreased in the same proportion.
The inverter of six thyristors connects each phase to positive and negative DC bus. Each thyristor is on for 180° and the switching sequence produces a 3ϕ output voltage. The waveform at the output is a six-step waveform as shown below in Fig.



The output frequency is controlled by inverter and amplitude V_{dc} is controlled by the phase controlled bridge. The shape of waveform is same at all frequencies.
The inverter can also be used as a Pulse Width Modulator (PWM) but this requires a control logic.
It may however be mentioned that in the cycloconverter method, the DC link is not necessary. But the frequency variation attainable is limited to 1/3 of supply frequency.

4. a) Discuss with relevant diagrams, the principle of speed control of induction motor, above and below synchronous speed by feeding energy to the source.
[WBUT 2008]

Answer:

As induction motor drives require variable voltage variable frequency power supply with const. volt/Hz ratio to keep the flux constant in the motor, this results const. frequency operation at speeds below base speed. Above base speed the input voltage is kept constant, resulting in const. horse power operation. The flux in the motor decreases as frequency is increased.

i) Stator voltage and frequency variation for speed control of IM:

It is known that the torque developed in a $3-\phi$ IM motor is proportional to the square of the supply voltage & the slip at max torque is independent of supply voltage. The torque-speed characteristics of $3\phi - IM$ for varying supply voltage is shown below.

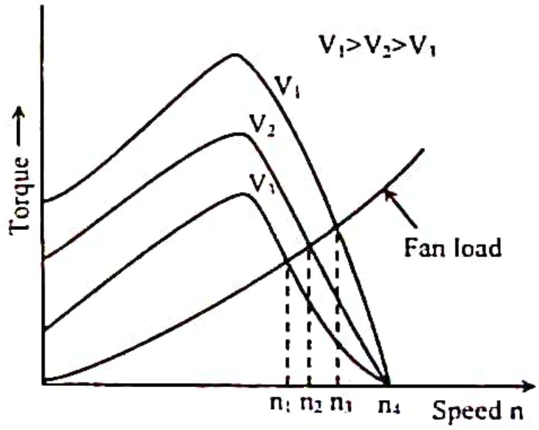


Fig: (a) Torque-speed characteristics of terminal voltage

From Fig. 'a' it may be seen that for a given load, the speed of the motor can be varied with a small range by this method. Since the operation at voltages higher than the rated voltage is not permissible, this method also allows speed control only below the normal rated speed.

The synchronous speed of an IM is given by $N_S = \dfrac{120f}{P}$. Varying supply frequency the speed can be controlled. The variable frequency control allows good running and transient performance to be obtained from cage induction motor.

ii) Constant voltage/Hz operation for speed control of IM:

It is known that *emf* induced/phase of an IM is expressed as

$$E = 4.44 K_w \phi_m \text{ if } T_{Ph} \text{ with usual rotation} \quad ...(1)$$

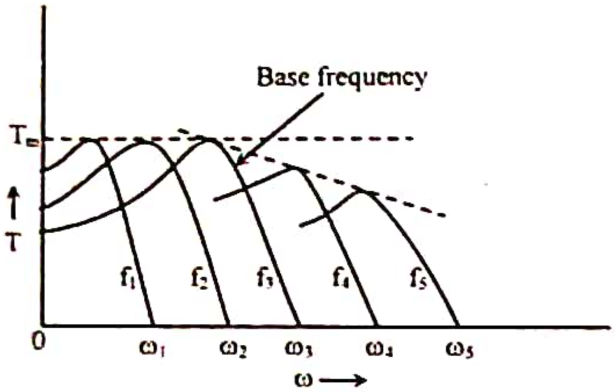
Neglecting drop in stator impedance and as induced *emf* E is nearly equal to the applied voltage 'V' from Eqn. (1) it can be written as $V/f = 4.44\ K_w\ \phi_w T_{Ph}\ (\mathrm{V/Hz})$

If supply frequency is change, V will also change to maintain the same air gap flux.

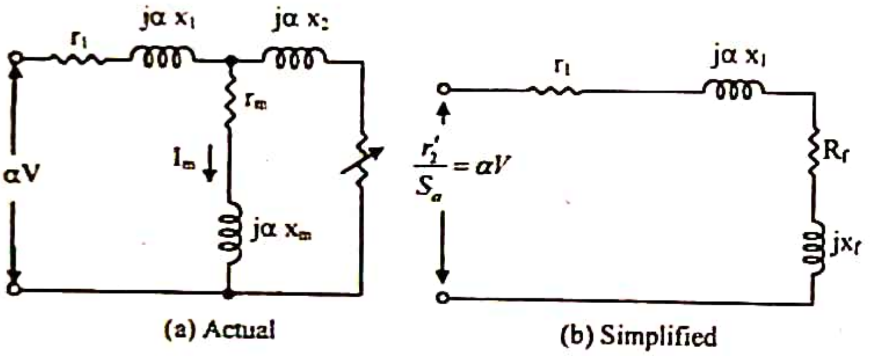
However when the voltage increases above rated value R when the input frequency goes above base frequency, only constant voltage with variable frequency is used for speed control. Under this condition both flux & maximum torque decrease as the frequency is increased.

$$T_m = \frac{3}{2\omega_S(x_1 + x_2)}\left(\frac{V}{\alpha}\right)^2 \text{ when } \alpha = \frac{\text{Supply frequency}}{\text{base frequency}}$$

x_1, x_2' are the equivalent circuit parameters V = Input voltage. with $\alpha > 1$ as frequency is higher than base frequency, both maximum torque and flux is given by V/f ratio, decrease with the increase of frequency as shown in Fig. below.



Torque-speed characteristics of the induction motor under variable frequency supply



Equivalent circuit of the induction motor under variable frequency supply at constant air gap flux

b) The rotor of an 8-pole, 50 Hz, 3-phase induction motor has a resistance of 0.2 Ω per phase & runs at 730 rpm. If the load torque remains unchanged, calculate the additional rotor resistance that will reduce its speed by 10%. Neglect stator impedance. **[WBUT 2008]**

Answer:

P = 4 $f = 50$ Hz, $3\phi I/M$, $N = 730$ r.p.m.

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{4} = 750 \text{ r.p.m.}$$

Slip $s = \frac{N_S - N}{N_S} = \frac{750-730}{750} = \frac{20}{750} = \frac{2}{75}$

The motor torque is given by $T = \frac{KsR_2}{R_2^2 + (sX_2)^2}$

Since X_2 is not given so we assume $T = \frac{K_S R_2}{R_2^2} = \frac{K_S}{R_2}$

In the first case $T_1 = \frac{Ks_1}{R_2}$

Second case $T_2 = \frac{Ks_2}{(R_2 + r)}$ [Let r resistance is added]

$r \rightarrow$ external rotor resistance

Load Torque remains unchanged

$$T_1 = T_2$$

$$\therefore \quad \frac{Ks_1}{R_2} = \frac{Ks_2}{R_2 + r}$$

$$\rightarrow \quad \frac{s_1}{s_2} = \frac{R_2}{R_2 + r} \quad = s_1 = \frac{2}{75} = 0 \cdot 0266$$

$$N_2 = 730 - 10\% \ of \ 730 = 730 - 73 = 657 \ r.p.m$$

$$s_2 = \frac{750 - 657}{750} = 0.124$$

$$\frac{s_1}{s_2} = \frac{R_2}{R_2 + r}$$

$$\Rightarrow \quad \frac{0 \cdot 0266}{0 \cdot 124} = \frac{0 \cdot 2}{0 \cdot 2 + r}$$

$$\Rightarrow \quad \frac{2 + r}{0 \cdot 2} = \frac{0 \cdot 124}{0 \cdot 0266}$$

$$\Rightarrow \quad 0 \cdot 2 + r = \frac{0 \cdot 124}{0 \cdot 0266} \times 0 \cdot 2 = 0 \cdot 9323$$

$$\Rightarrow \quad r = \cdot 7323 \Omega$$

5. a) Explain with relevant circuit diagram and torque-speed characteristics, the principle of Rheostatic braking applied to induction motor. [WBUT 2009]

Answer:

The speed of an induction motor can be controlled by injecting D.C voltage in its stator winding. A variable resistance may be used in the rotor (in case of a slip ring induction motor) for dissipating the required amount of power. Now-a-days thyristor bridges are used for supplying D.C., which is controllable in nature. With the help of controlled D.C from a thyristors bridge the dynamic braking can be achieved in a more effective manner.

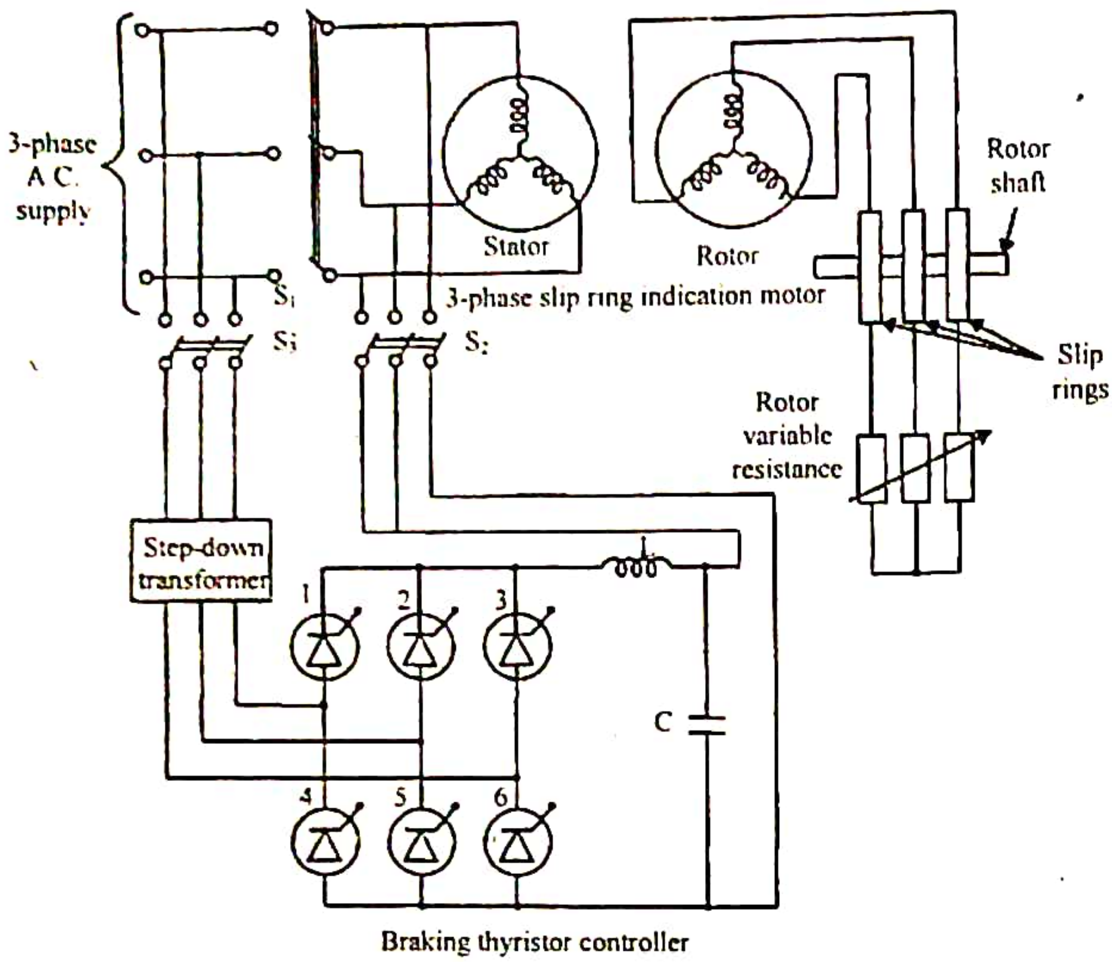


Fig: (i) Dynamic braking of a 3-phase slip ring induction motor

The connection diagram for scheme is shown in Fig. (i).

- 3-phase A.C is stepped down to lower voltage and fed to a 3-phase thyristor bridge, which serves as the rectifier.
- This D.C is filtered by an L.C filter for minimizing the ripples.
- Ripple free D.C is then fed to the stator winding of the induction motor as shown in Fig. (i).

It is to be noted that while feeding D.C to the stator the 3-phase A.C input must be disconnected. A.C is disconnected with the help of S_1 and D.C is disconnected with the help of S_2. Since, the input A.C voltage is stepped down to a lower value, the thyristor converter may be of lower voltage rating.

The torque vs. speed characteristics, which lie in the lower side of the quadrant II as shown in the Fig. (ii).

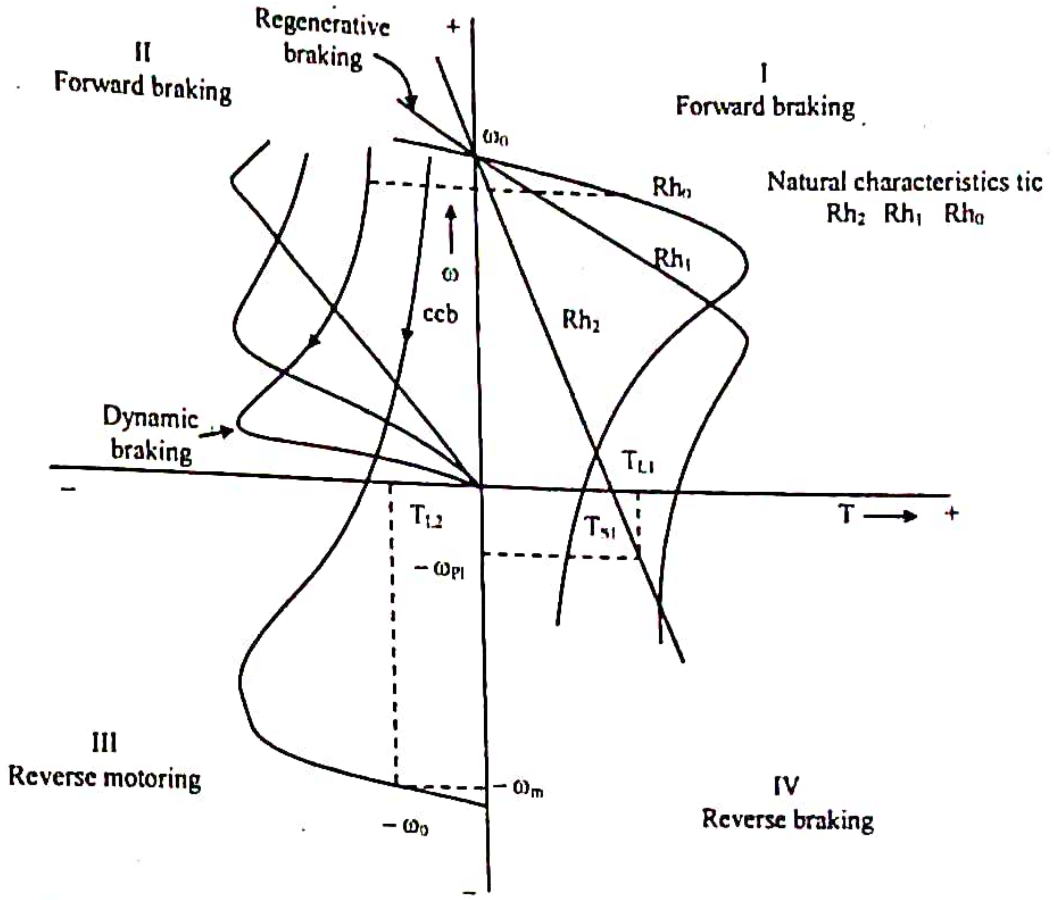


Fig: (ii) Typical speed-torque characteristics of induction motor under different operating conditions.

b) A 3-phase star connected, 400 V, 50 Hz, 4-pole induction motor has the following equivalent circuit parameters referred to stator in ohms per phase: $R_1 = 0.8$, $R_2 = 0.3$, $X_1 = X_2 = 2$, $X_m = 48$. An external resistance of 2Ω per phase referred to stator has been inserted in the rotor circuit in order to brake the motor at 1440 rpm by means of *dc* rheostatic braking. Determine the initial braking torque.

[WBUT 2009]

Answer:

3-ϕ, star connected 400 V, 50 Hz 4 pole induction motor

$$R_1 = 0.8\Omega,\ R_2 = 0.3\Omega,\ X_1 = X_2 = 2\Omega,\ X_m = 48\Omega$$

$$\text{slip} = \frac{1500-1440}{1500} = \frac{60}{1500} = 0.04$$

voltage/phase

$$V_1 = \frac{400}{\sqrt{3}} = 230.95\,\text{V}$$

Synchronous speed

$$\omega_S = 2\pi\left(\frac{50\times 2}{4}\right) = 50\pi \text{ rad./sec.}$$

For negligible no-load current, the air-gap flux is proportional to $\bar{E}_2$ which is given by .

$$\bar{E}_2 = \frac{\bar{Z}_2}{\bar{Z}_1 + \bar{Z}_2}\bar{V}_1$$

$$\bar{Z}_1 = R_1 + jX_1 = 0.8 + j2\,\Omega$$

$$\bar{Z}_2 = \frac{R_2}{s} jX_2 = \frac{0.3}{0.04} + j2 = 7.5 + j2$$

$$\bar{Z}_1 + \bar{Z}_2 = (7.5 + 0.8) + j(2+2) = 8.3 + j4\,\Omega$$

$$\bar{E}_2 = \frac{7.5 + j2}{8.3 + j4} \times 230.95$$

$$E_2 = \sqrt{\frac{7.5^2 + 2^2}{8.3^2 + 4^2}} \times 230.95 = \sqrt{\frac{60.25}{84.89}} \times 230.95 = 194.56657\text{ V}$$

Rotor current under dynamic braking is given

$$I_2 = \frac{E_2}{\sqrt{\left(\frac{R_2}{2.5}\right)^2 + X_2^2}} = \frac{194.566}{\sqrt{\left(\frac{0.3}{1.96}\right)^2 + 2^2}} = \frac{194.566}{\sqrt{4.023427738}} = \frac{194.566}{2.0058} = 97\text{ Amp.}$$

$I_1 = I_2$ because no load current is neglected

From d.c. excitation is given by

$$I_{dc} = \sqrt{\frac{3}{2}} I_2 = \sqrt{\frac{3}{2}} \times 97 = 118.8\text{ A}$$

Dynamic braking torque $= \dfrac{3}{\omega_S} I_2^2 \cdot \dfrac{R_2}{(2-s)} = \dfrac{3}{50\pi}(97)^2 \times \dfrac{0.3}{1.96} = 27.5188\text{ N-m.}$

When external resistance of 2Ω is inserted in rotor circuit rotor current during dynamic braking

$$I_2 = \frac{194.566}{\sqrt{[(0.3+2)/1.96]^2 + 2^2}}$$

$$= \frac{194.566}{\sqrt{(2.3/1.96)^2 + 2^2}} = \frac{194.566}{\sqrt{5.37703}} = \frac{194.566}{2.3188} = 83.9\text{ Amp}$$

Dynamic braking torque $= \dfrac{3}{50\pi}(83.9)^2 \dfrac{2.3}{1.96} = 157.87\text{ N-m}$

D.C. excitation, $I_{dc} = \sqrt{\dfrac{3}{2}} I_2 = \sqrt{\dfrac{3}{2}}(83.9) = 102.756\text{ Amp.}$

6. A three phase, 400 V, 50 Hz, 6 pole, 960 rpm, star-connected wound rotor induction motor has following constants referred to the stator:

$r_1 = 0.5$ **ohm,** $r_2' = 0.7$ **ohm,** $x_1 = x_2' = 1.5$ **ohm**

The motor drives a fan load at 960 rpm. The stator to rotor turns ratio is 2. Calculate the resistance required to be connected in each phase of the rotor circuit to reduce the speed to 600 rpm. **[WBUT 2010]**

Answer:

$$\text{Synchronous speed} = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 \text{ rpm} = 104.72 \text{ rad./sec.}$$

$$\text{Full load torque } T_F = \frac{3}{\omega_{ms}}\left[\frac{V^2 R_r'/s}{(R_r'/s)^2 + X_r'^2}\right] = \frac{3}{104.72}\left[\frac{400^2 \times 0.5/0.04}{\left(\frac{0.5}{0.04}\right)^2 + 1.5^2}\right]$$

$$= \frac{3}{104.72}\left[\frac{2{,}000{,}000}{156.25 + 2.25}\right] = \frac{3}{104.72} \times \frac{2{,}000{,}000}{158.5}$$

$$= 361.486 \text{ N-m.}$$

$$T_L = KN^2$$

$$K\left[N_s(1-s)\right]^2 = T$$

$$K\left[1000(1-0.04)\right]^2 = T$$

$$K = \frac{361.486}{[1000 \times 0.96]^2} = 3.922 \times 10^{-4}$$

Therefore at speed 600 r.p.m

$$T_L = K \times (600)^2 = 3.922 \times 10^{-4} \times (600)^2 = 141.205 \text{ N-m}$$

$$s = \frac{1000 - 600}{1000} = \frac{400}{1000} = \frac{4}{10} = 0.4$$

In equilibrium

$$T = T_L$$

$$\frac{3}{\omega_{ms}} \times \frac{V^2 (R_r' + R_e)/s}{\left(\frac{R_r' + R_e}{s}\right)^2 + X_r'^2} = T_L$$

$R_e \rightarrow$ is the external resistance

Substitution of parameter values in above equation we get

$$\frac{3}{104.72} \times \frac{400^2 (R_e + 0.5)/0.4}{\left(\frac{R_e + 0.5}{0.4}\right)^2 + 1.5^2} = 141.205$$

$$\Rightarrow \quad \frac{400^2(R_e+0.5)/0.4}{\left(\frac{R_e+0.5}{0.4}\right)^2+1.5^2}=\frac{141.205\times104.72}{3}$$

$$\Rightarrow \quad \frac{400{,}000(R_e+0.5)}{\left(\frac{R_e+0.5}{0.4}\right)^2+1.5^2}=4{,}928.99$$

$$\Rightarrow \quad \frac{R_e+0.5}{\left(\frac{R_e+0.5}{0.4}\right)^2+1.5^2}=\frac{4928.99}{400{,}000}$$

$$\Rightarrow \quad \frac{X}{\left(\frac{X}{0.4}\right)^2+1.5^2}=0.01232$$

$$\Rightarrow \quad \frac{X}{\frac{X^2}{0.16}+2.25}=0.01232$$

$$\Rightarrow \quad 0.01232\left(\frac{X^2}{0.16}+2.25\right)=X$$

$$\Rightarrow \quad \frac{X^2}{0.16}+2.25=\frac{1}{0.01232}X$$

$$\Rightarrow \quad X^2+(2.25\times0.16)-12.9X=0$$

$$\Rightarrow \quad X^2-12.9X+0.36=0$$

$$X=\frac{12.9\pm\sqrt{(12.9)^2-4\times(0.36)}}{2\cdot1}$$

$$=\frac{12.9\pm\sqrt{12.9^2-1.44}}{2}=\frac{12.9\pm\sqrt{164.97}}{2}=\frac{12.9\pm12.84}{2}$$

$$X=\frac{12.9+12.84}{2}=\frac{25.74}{2}=12.87$$

$$R_e+0.5=12.87$$

$$R_e=12.37$$

$$X=\frac{12.9-12.84}{2}=\frac{0.1}{2}=0.05$$

$$R_e=0.05-0.5$$

$$=-0.45\Omega$$

Since the other value is unfeasible

$$R_e=12.37\Omega$$

Rotor referred value of external resistance $=\frac{12.37}{2^2}=3.09\Omega$.

7. a) Explain with relevant circuit diagrams and characteristics how V/f control is achieved in induction motor drives.
b) Can this method be applied for both wound rotor and cage rotor motors?
c) What may be the difficulty faced in principle, while implementing V/f at starting or at low speeds? How can this be overcome?
d) Can this method be applied to synchronous motors also? Justify.
e) Which method of speed control is valid only for wound rotor I.M. and which one only for cage motor I.M.?
[WBUT 2011]

Answer:

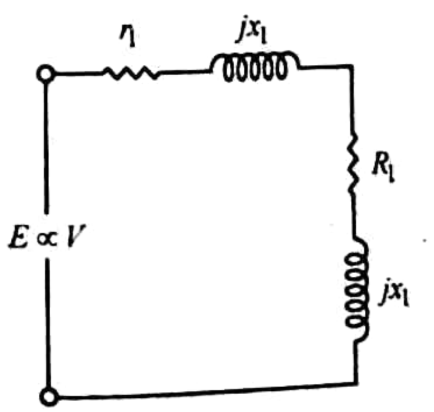
a) V/f control is achieved in induction motor drive by varying the supply frequency. The emf per phase of an induction motor is given by $E = 4.444K_{\omega}\phi_m T_{ph}$ volts with usual notations.

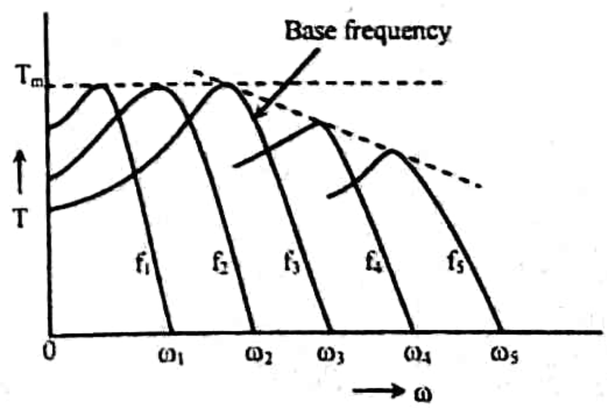
The induced emf E is nearly equal to the applied voltage V (neglecting drop in stator impedance. Then we can write

$$\frac{V}{f} = 4.44K_{\omega}\phi_m T_{ph} \text{ (V/Hz)}$$

When the frequency is reduced, the applied voltage also must be reduced proportionately so as to maintain constant flux, otherwise the core will get saturated resulting in exercise iron loss and magnetizing current. The maximum torque also remains constant under this condition. This type of control (Constant $\frac{V}{f}$) is used for speed control below the base frequency (line frequency 50 Hz).

As the voltage increase above rated value, when the input frequency goes above base frequency, only constant (rated) voltage with variable frequency (frequency control) is used for speed control under the condition, both flux and maximum torque decrease as the frequency is increased. This method is used very rarely and can only be used in cases where preferably squirrel cage induction motor happens to be the only load on the generators in which case the supply frequency could be controlled by controlling the speed of the prime-movers of the generators. Simplified connection diagram in the shape of equivalent circuit and the torque speed characteristics is shown below: -





Torque-speed characteristics

b) The variable frequency control allows good running and transient performance to be obtained from a cage induction motor.

c) The difficulty faced in principle while implementing V/f at starting or low speeds are saturation and losses. In order to avoid saturation and to minimise losses the motor is operated at rated air gap flux by varying terminal voltage with frequency so as to maintain (V/f) ratio constant at the rate value.

d) Yes. The method (V/f) ratio can be applied to synchronous motor also as the voltage to frequency ratio is proportional to flux. Therefore, a constant voltage to frequency (V/f) ratio is maintained for frequencies below base (or rated frequency) and the ratio is increased at low speed to take into account the stator resistance drop. This may be termed variable-voltage-variable frequency (VVVF) control.

e) Rotor resistance variation method is suitably valid for speed control of wound rotor induction motor.
For cage induction motor pole changing method appears to be acceptable for which design arrangement has to be made accordingly.

8. a) Explain with proper circuit diagram and characteristic curves etc. the static Krămer drive. **[WBUT 2011]**

Answer:

Refer to Question No. 2 of Long Answer Type Questions.

b) What is its effect on the overall power factor? **[WBUT 2011]**

Answer:

The effect on the power factor can be explained keeping in view the fact that when the secondary current advances, the power factor increases due to the horizontal component of the injected emf. If the emf is injected at an angle $180° > \beta > 0°$, both the speed and power factor are controlled.

c) A *y*-connected cage rotor induction motor has the following parameters as given below (per phase): **[WBUT 2011]**
$r_1 = 2\Omega, r_2' = 3\Omega, x_1 = x_2' = 6.5\Omega$ **and** $x_m = 55\Omega$**, where symbols have their usual significance. The ratings are 400 V, 50 Hz, 4 pole and its rated speed is 1430 rpm. If** V/f **control is effected, calculate**

i) the motor torque, speed and current when the inverter frequency is 30 Hz and slip is rated

ii) inverter frequency and stator current at rated torque and motor speed of 1300 rpm.

Answer:

y connected cage rotor Induction Motor

$$r_1 = 2\Omega,\ r_2' = 3\Omega,\ x_1 = x_2' = 6.5\Omega,\ x_m = 55\Omega$$

400 V, 50 Hz, 4 pole 1430 r.p.m.

Synchronous speed

$$n_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 \text{ r.p.m.}$$

$$\therefore \quad \omega_s = 50\pi \text{ rad/sec.}$$

Full load slip

$$s_f = \frac{1500 - 1430}{1500} = \frac{70}{1500} = 0.0466$$

Full load slip speed $= 1500 - 1430 = 70$ r.p.m.

The equivalent circuit of induction motor

r_1 = Stator resistance

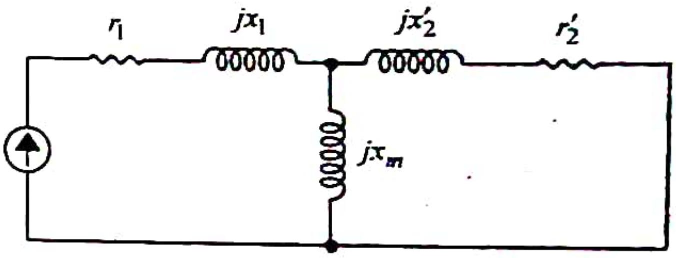
r_2' = Rotor resistance

x_1 = Stator inductance

x_2' = Rotor inductance

x_m = Magnetizing impedance

Z_{eq} = Total equivalent impedance



$$= r_1 + jx_1 + \frac{jX_m\left(r_2'/s + jx_2'\right)}{\frac{r_2'}{s} + j\left(x_m + x_2'\right)} = 2 + j6.5 + \frac{j55\left(\frac{3}{0.046} + j6.5\right)}{\frac{3}{0.046} + j(55 + 6.5)}$$

$$= 2 + j6.5 + \frac{j55(65.217 + j6.5)}{65.217 + j61.5}$$

$$= 2 + j6.5 + \frac{j55(65.217 + j6.5)(65.217 - j61.5)}{(65.217 + j61.5)(65.217 - j61.5)}$$

$$= 2 + j6.5 + \frac{j55\left(65.217^2 + j6.5 \times 65.217 - j61.5 \times 65.217 + 6.5 \times 61.5\right)}{65.217^2 + 61.5^2}$$

$$= 2 + j6.5 + \frac{j55(4253.257089 + j423.9105 - j4010.8455 + 399.75)}{4253.257089 + 3782.25}$$

$$= 2 + j6.5 + \frac{j55(4653.007089 - j3586.935)}{8035.507089}$$

$$= 2 + j6.5 + j55\left[\frac{4653.007089}{8035.507089} - j\frac{3586.935}{8035.507089}\right]$$

$$= 2 + j6.5 + j31.848069 - j^2 24.5521$$

$= 2 + 24.5521 + j38.348069$
$= 26.5521 + j38.348069$
$\left| Z_{eq} \right| = \sqrt{26.5521^2 + 38.348069^2} = 46.6432\,\Omega$

Full load stator current

$$I_{sf} = \frac{400/\sqrt{3}}{46.64} = 4.9516\text{ A}$$

Full load torque

$$T_F = \frac{3}{\omega_s}\left[I_r^2 \times \frac{r_2'}{s}\right] = \frac{3}{50\pi}\left[4.9516^2 \times \frac{3}{0.046}\right] = \frac{3}{50\pi}\left[4.9516^2 \times 65.217\right] = 30.5543\text{ N-m.}$$

i) As motor torque depends on the rated slip speed which remains constant so when operating at 30 Hz also torque $= T_F = 30.5543$ N-m.

Stator current $I_{sf} = 4.9516$ A

At 30 Hz synchronous speed $= \frac{30}{50} \times 1500 = 900$ r.p.m.

Full load slip speed = 90 r.p.m. = constant

$\therefore$ Motor speed $= 900 - 90 = 810$ r.p.m.

ii) At rated motor torque, slip speed and I_s will be same as at 50 Hz operation.

Therefore,

$$I_s = 4.9516\text{ A}$$

Slip speed = 90 r.p.m.

$\therefore$ Synchronous speed $= 1300 + 90 = 1390$ r.p.m.

When motor speed is 1300 r.p.m.

$\therefore$ Inverter frequency $= \frac{1390}{1500} \times 50 = 46.333$ Hz.

9. With the help of torque-speed characteristics discuss the different methods of braking an induction motor in appropriate details. [WBUT 2011]

Answer:

i) Plugging (or counter current braking)

Plugging can be achieved in an induction motor merely by reversing two of the three phases which cause reversal of the direction of rotating magnetic field. At the instant of switching the motor to the plugging position the motor runs in the opposite direction to that of the field and the relative speed is approximately twice [(2-s) times] of synchronous sped i.e. the slip (s) is very nearly equal to two, being equal to (2-s). So voltage induced in the rotor will be twice of normally induced voltage at stand still and the winding must be provided with the additional insulation to withstand this much voltage. During plugging, the motor acts as a brake and it absorbs kinetic energy from the

still revolving load causing its speed to fall. The heat developed in the rotor during braking period are all out three times the heat developed during starting period.
In case of squirrel cage motor, energy is dissipated only within the machine where as in case of wound rotor motor. This energy is dissipated also in the external resistance added in the rotor circuit for this purpose.

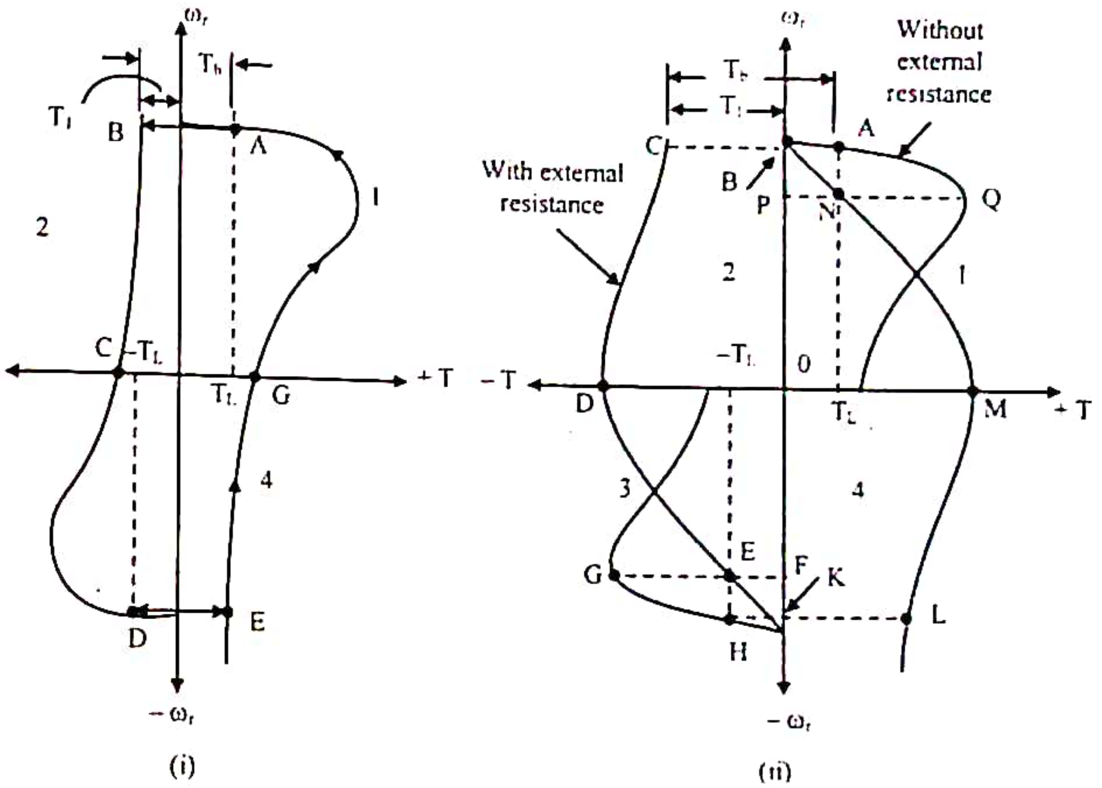


Fig: (a) Speed-torque characteristics during plugging of (i) squirrel-cage motor and (ii) wound-rotor motor

ii) Dynamic (or Rheostatic braking)

The Rheostatic braking with a poly phase induction motor can be obtained by disconnecting the stator winding from the a.c supply and exciting it from a, d, c source to produce a stationary d.c. field. For details refer chapter on "Starting & Braking of Electric Motors".

iii) Regenerative braking

Regenerative braking takes place when the load forces the motor to run above synchronous speed. When rotor speed, as when lowering of load in a crane or a hoist becomes more than rotating field speed, the slip becomes negative. The negative slip means that the induction machine will operate as an induction generator in the 2nd quadrant as shown in Fig. (b) below and returns power to the supply lines. The power delivered to the supply is given by the product of regenerative braking torque and the corresponding rotor speed. The Fig. (b) shows that the amount of power returned to the supply line depends upon how far is the rotor speed above synchronous speed when rotor speed falls synchronous speed. When rotor speed falls to synchronous speed, the regenerative braking comes to an end.

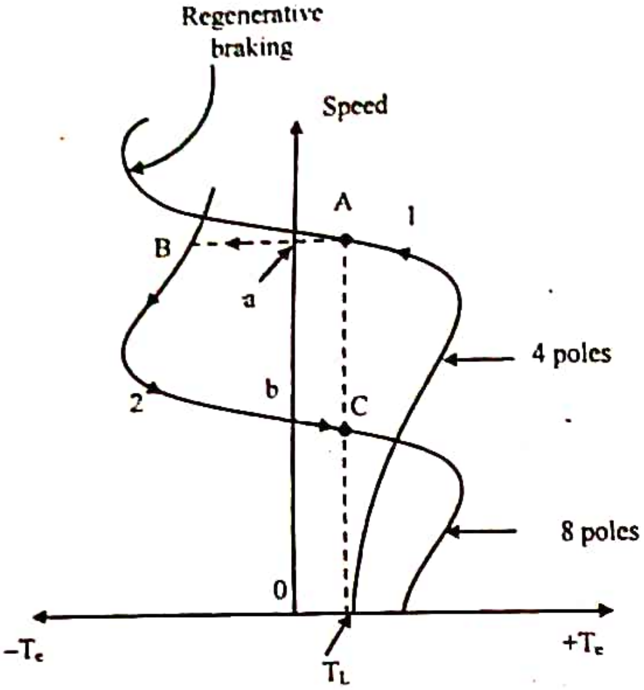


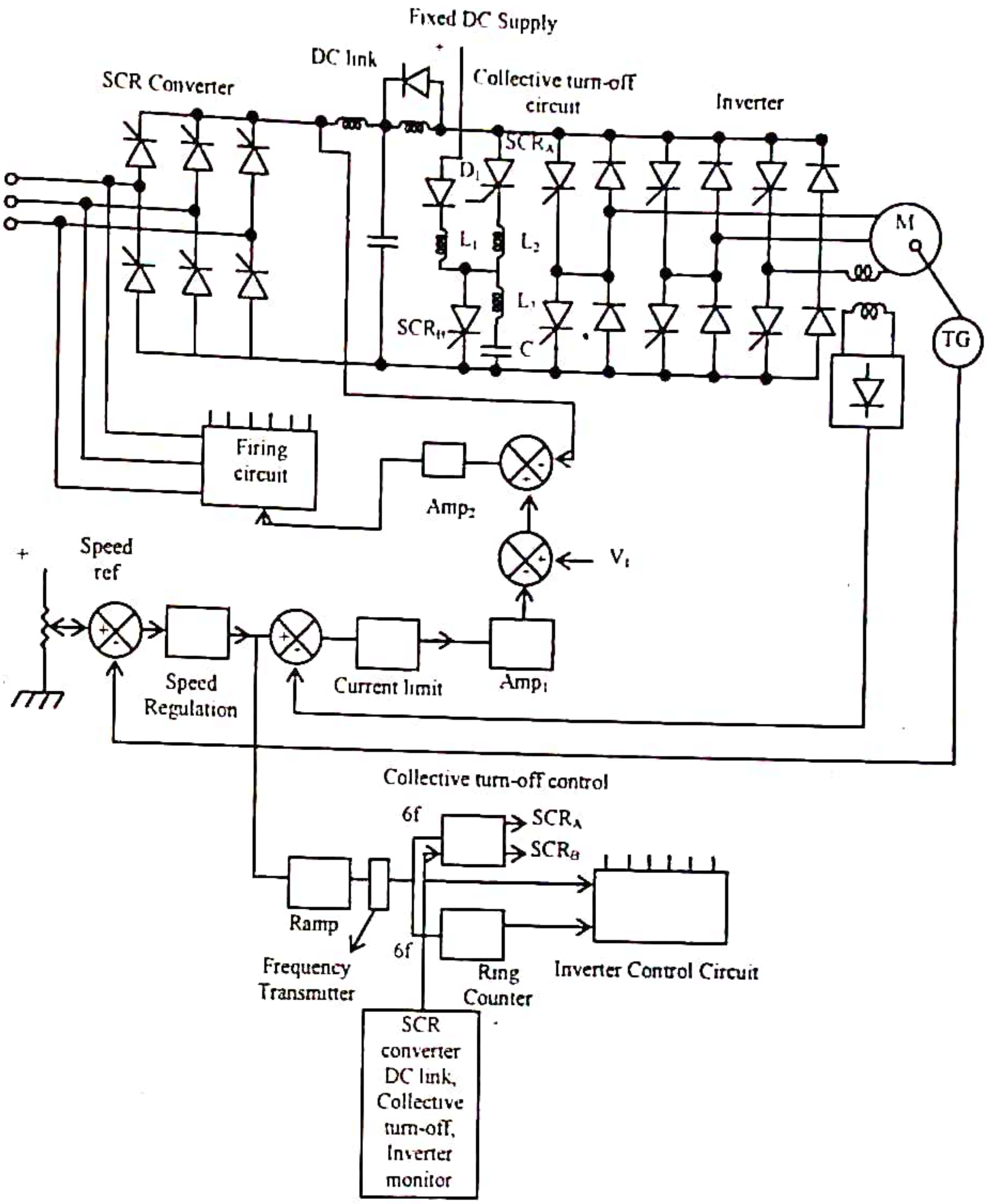
Fig: (b) regenerative braking of polyphase induction motor

In case of squirrel cage induction motor, stable speed is obtained at a speed considerable in excess of synchronous speed and the regenerative braking cannot be applied unless the motor is specially designed to withstand the excessive speed.

10. Draw and explain the scheme for closed-loop speed control of a three phase induction motor by V/F control drive. **[WBUT 2012, 2014, 2016]**

Answer:

In a closed loop system, speed control of a three-phase induction motor is made easy by monitoring the actual air-gap flux and control it by adjusting and ensuring a proper V/f ratio. If the rotor frequency f_2 and the air-gap flux are maintained constant, the rotor current also remains constant and consequently, so does the stator current since it is the vector sum of the magnetising and the rotor currents. Therefore if f_2 and ϕ are kept constant, in a feedback control system, the stator current consequently remains constant developing a constant torque at all the speeds of the motor. On the other hand, if the stator current is controlled in the feedback loop and also the air-gap flux, the rotor frequency automatically adjust itself. Again, if the stator current and rotor frequency are directly controlled, the air-gap flux is controlled automatically. The system in which the rotor frequency is controlled directly is called controlled slip system. A schematic six-step variably frequency dc link inverter with feedback controlled circuit is shown below in Figure.



Schematic diagram of closed loop control of variable dc link(V/f=constant) inverter for speed control of IM

In the above scheme the converter is a dc link using a 3-phase controlled rectifier. The variable voltage is smoothed by an LC filter. The inverter is fed from the variable voltage of the converter and thus V/f requirement is achieved.

11. Compare VSI and CSI drives. Show that a variable frequency induction motor drive develops at all frequencies the same torque for a given slip-speed when operating at constant flux. A Y-connected squirrel cage induction motor has the following ratings and parameters: 400V, 50Hz, 4pole, 1370rpm, $R_s = 2\Omega$, $R_r' = 3\Omega$, $X_s = X_r' = 3.5\Omega$, $X_m = 55\Omega$, where symbols have their usual meanings. It is controlled by CSI at a constant flux. Calculate

i) Motor torque, speed and stator current when operating at 30 Hz and rated slip speed

ii) Inverter frequency and stator current for rated motor torque and motor speed for 1200 rpm. **[WBUT 2012]**

Answer:

1st Part:

i) Current source inverter (CSI) is more reliable than voltage source inverter (VSI) because a) conduction of two devices in the same lag due to commutation failure does not lead to sharp rise of current through them and b) it has inherent protection against a short-circuit across motor terminals.

ii) Because of large inductance in the dc link and large inverter capacitors, CSI drives has higher cost, weight and volume, lower speed range and slower dynamic response.

iii) 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 number of motors connected in parallel.

2nd Part:

The torque-slip relationship of a 3-phase induction motor can be represented as under: –

$$T = \frac{3p}{2\pi}\left(\frac{E_1}{f_1}\right)^2 \times \frac{f_2 R_2}{\left[(R_{1s} + R_2)^2 + s^2 (X_1 + X_2)^2\right]} \qquad \text{.... (1)}$$

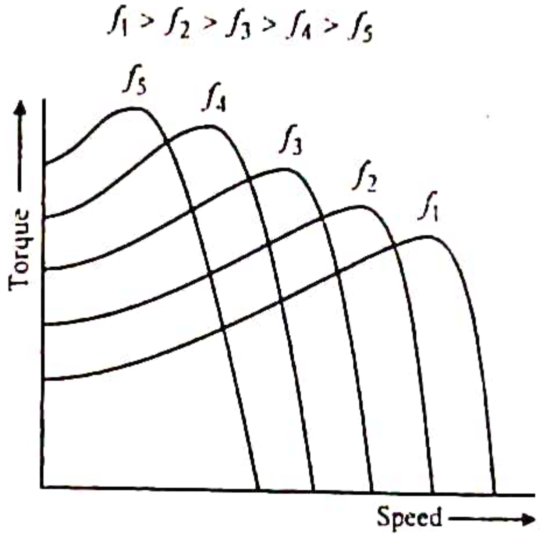
where p = number of pole pairs

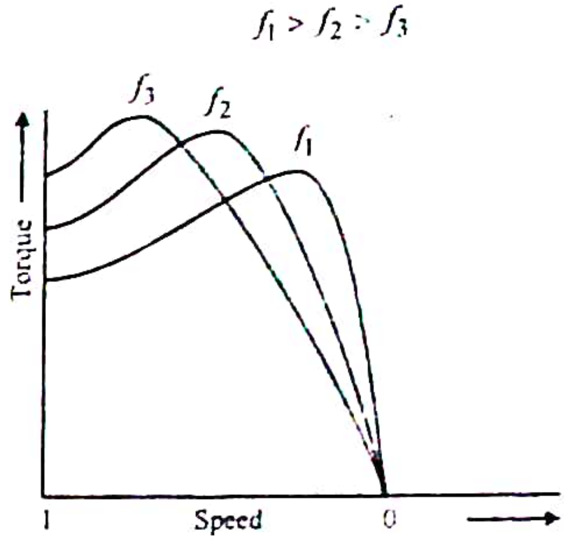
f_1 = stator frequency

E_1 = stator voltage

f_2 = rotor frequency = sf_1

In order to maintain a high torque through out the control range, the air-gap flux should be constant, i.e., E_1/f_1 should be constant. The speed torque characteristics for various supply frequencies.





In variable frequency control, the speed torque characteristics remain high hardness and at higher frequencies the maximum torque remains almost the same. However, at lower frequencies the stator resistance becomes comparable to or even larger than the stator leakage reactance reducing the air-gap flux considerably. The stator voltage drop becomes an important factor and the maximum torque decreases.

If we now write the equation for maximum or break down torque as under:

$$T_{max} = \frac{3E_1^2}{2\omega_s\left[R_1 \pm \sqrt{R_1^2 + (X_1 + X_2)^2}\right]}$$

Then at higher frequencies, $(X_1 + X_2)^2 >> R_1$

and $$T_{max} = \frac{3E_1^2}{3\omega_s(X_1 + X_2)} \qquad \text{.... (2)}$$

Since ω and $(X_1 + X_2)$ are proportional to f_1

$$T_{max} \simeq K\left(\frac{E_1}{f_1}\right)^2 \qquad \text{.... (3)}$$

The above equation suggests that if E_1/f_1 is maintained constant T_{max} also remains constant, while at lower frequencies R_1 becomes comparable to $X_1 + X_2$ and T_{max} decreases.

Last Part:

$R_s = 2\Omega \qquad R_r' = 3\Omega \qquad X_s = X_r' = 3.5\Omega$

$X_m = 55\Omega$

Synchronous speed $\quad n_s = \dfrac{120f}{P} = \dfrac{120 \times 50}{4} = 1500$ r.p.m.

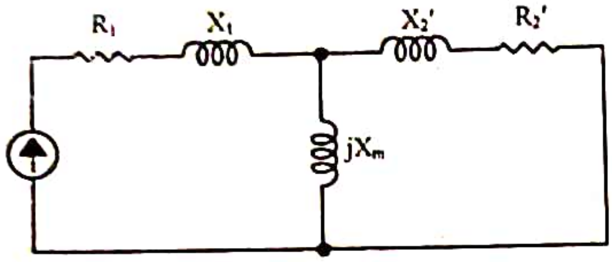
$\omega_s = 50\pi$ rad/sec.

Full load slip

$$s_f = \frac{1500-1370}{1500} = \frac{130}{1500} = 0.0866$$

Full load slip speed $1500-1370=130$ r.p.m.

The equivalent circuit of induction motor



Z_{eq} = Total equivalent impedance

$$= R_1 + jX_1 + \frac{jX_m\left(\frac{R_2'}{s}+jX_2'\right)}{\frac{R_2}{s}+j\left(X_m+X_2'\right)}$$

$$=2+j3.5+\frac{j55\left(\frac{3}{0.086}+j3.5\right)}{\frac{3}{0.086}+j(55+3.5)}$$

$$=2+j3.5+\frac{j55(34.8837+j3.5)}{34.8837+j58.5}$$

$$=2+j3.5+\frac{j55(34.8837+j3.5)(34.8837-j58.5)}{(34.8837+j58.5)(34.8837-j58.5)}$$

$$=2+j3.5+\frac{j55\left[34.8837^2+j(35\times34.8837)-(34.8837\times j58.5)+(3.5\times58.5)\right]}{(34.8837)^2+(58.5)^2}$$

$$=2+j3.5+\frac{j55[1216.87252+j122.09295-j2040.69645+204.75]}{1216.8725+3422.25}$$

$$=2+j3.5+\frac{j55\left[(1216.87252+204.75)+j(122.09295-2040.09648)\right]}{4639.1225}$$

$$=2+j3.5+\frac{j55[1421.6225-j1918.6035]}{4639.1225}$$

$$=2+j3.5+j\frac{55\times1421.6225}{4639.1225}+\frac{55\times1918.6035}{4639.1225}$$

$$=2+j3.5+j16.8543+22.7463$$

$= 24.7463 + j20.3543$

$Z_{eq} = \sqrt{24.7463^2 + 20.3543^2} = 32.047\angle 34.0798\,\Omega.$

Full load stator current

$$I_{sf} = \frac{400/\sqrt{3}}{32.047} = 7.21\text{ A}$$

Full load rotor current

$$I'_{rf} = I_{sf}\left[\frac{jX_m}{(R'_r/S_r) + j(X'_r + X_m)}\right] = 7.21\left[\frac{j55}{\frac{3}{0.0867} + j(58.5)}\right] = 5.865\text{ A}$$

Full load torque, $T_F = \frac{3}{\omega_s}\left[I_{rf}^2 \times \frac{R'_2}{s}\right] = \frac{3}{50\pi}\left[5.865 \times \frac{3}{0.086}\right] = \frac{3}{50\pi}[1813.3988] = 22.73\text{ N-m}$

i) As motor torque depends on the rated slip speed which remains constant so when operating at 30 Hz also torque $T_F = 22.73$

Stator current $= I_{sf} = 7.21$ A

At 30 Hz synchronous speed $= \frac{30}{50} \times 1500 = 900$ r.p.m.

Full load slip speed $= 130$ r.p.m. = constant

$\therefore$ Motor speed $= 900 - 130 = 770$ r.p.m.

ii) At rated motor torque, slip speed and I_s will be same as at 50 Hz operation.

Therefore, $I_s = 7.21$ A

Slip speed $= 130$ r.p.m.

Synchronous speed $= 1200 + 130 = 1330$ r.p.m.

When motor speed is 1290 r.p.m.

$\therefore$ Inverter frequency $= \frac{1330}{1500} \times 50 = \frac{133}{150} \times 50 = 44.33$ Hz.

12. a) When plugging is employed for stopping an induction motor, why is it necessary to disconnect it from supply when speed reaches close to zero?
b) Explain the principle of slip power recovery scheme of controlling the speed of induction motor, using static Scherbius Drive. [WBUT 2013]

Answer:

a) When plugging is employed for stopping the induction motor, the braking torque is produced by interchanging any two supply terminals, so that the direction of rotation of the rotating magnetic field is reversed with respect to the rotation of the motor. The electromagnetic torque developed provides the braking action and brings the rotor to a quick stop. If the rotor is of slip ring type, external resistance may be inserted into the rotor circuit to limit the plugging current. The motor is disconnected from the supply at the time when the speed drops to zero. Otherwise the motor would continue to run in the opposite direction in reverse motoring mode.

b) *Refer to Question No. 3 of Short Answer Type Questions.*

13. a) A 2.8 kW, 440 Volt, 50 Hz, 4 pole 1390 rpm, delta connected squirrel cage induction motor has following parameters referred to the stator:
$R_s = 3\Omega,\ R_r' = 6\Omega,\ X_s = 4.5\Omega,\ X_r' = 5.5\Omega,\ X_m = 75\Omega$. **Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated voltage. Calculate motor terminal voltage, current and torque at 1230 rpm.** **[WBUT 2015, 2017]**

Answer:

$$T = \frac{3}{\omega_{ms}} \times \frac{V^2 R_r'/s}{\left(R_s + \frac{R_r'}{s}\right)^2 + \left(X_s + X_r'\right)^2}$$

$$\text{Synchronous speed} = \frac{120f}{p} = \frac{120\times 50}{4} = 1500\text{ rpm} = 50\pi\text{ rad/sec}$$

At full load

$$s = \frac{1500-1390}{1500} = \frac{110}{1500} = 0.073$$

At full load

$$T = \frac{3}{50\pi}\times\frac{440^2\times\frac{6}{0.073}}{\left(3+\frac{6}{0.073}\right)^2 + (4.5+5.5)^2} = \frac{3}{50\pi}\times\frac{440^2\times 82.19}{(3+82.191)^2+10^2}$$

$$= \frac{3}{50\pi}\times\frac{440^2\times 82.19}{85.191^2+10^2} = \frac{3}{50\pi}\times\frac{440^2\times 82.19}{7257.639+100}$$

$$= \frac{3}{50\pi}\times\frac{440\times 440\times 82.19}{7357.639} = 41.32\text{ N-m.}$$

For a fan load torque is proportional to (speed)^2.

Thus $T_L = K(1-s)^2$

At full load

$$T = T_L$$

$$K(1-0.073)^2 = 41.32$$

$$\Rightarrow \quad K = \frac{41.32}{0.927^2} = \frac{41.32}{0.927\times 0.927} = 48.08$$

Hence $T_L = 48.08(1-s)^2$ .... (1)

At 1230 rpm

$$s = \frac{1500-1230}{1500} = \frac{270}{1500} = 0.18$$

At this speed from Eqn. (1) we get

$$T_L = 48.08(1-0.18)^2 = 48.08 \times 0.82^2 = 32.32\,\text{N-m}$$

Since $T = T_L$

$\therefore$ $T = 32.32\,\text{N-m}$

Now $$\frac{3}{50\pi} \times \frac{V^2 \times \dfrac{6}{0.18}}{\left(3+\dfrac{6}{0.18}\right)^2 + (5.5+4.5)^2} = 32.32$$

$$\Rightarrow \quad \frac{3}{50\pi} \times \frac{V^2 \times 33.33}{(3+33.33)^2 + 100} = 32.32$$

$$\Rightarrow \quad \frac{V^2 \times 33.33}{36.33^2 + 100} = 32.32 \times \frac{50\pi}{3}$$

$$\Rightarrow \quad \frac{V^2 \times 33.33}{1320.11 + 100} = 32.32 \times \frac{50\pi}{3}$$

$$\Rightarrow \quad \frac{V^2 \times 33.33}{1420.11} = 32.32 \times \frac{50\pi}{3}$$

$$\Rightarrow \quad V^2 = \frac{1691.41 \times 1420.11}{33.33} = 72{,}066.996$$

$$\Rightarrow \quad V = 268.452\ \text{V}$$

$$\bar{I}_t' = \frac{268.452}{\left(3+\dfrac{6}{0.18}\right) + j10} = \frac{268.452}{36.33 + j10} = \frac{268.452(36.33 - j10)}{(36.33 + j10)(36.33 - j10)}$$

$$= \frac{268.452(36.33 - j10)}{36.33^2 - j^2 100} = \frac{268.452(36.33 - j10)}{36.33^2 + 100} = \frac{268.452(36.33 - j10)}{1420.11}$$

$$= \frac{268.452 \times 36.33}{1420.11} - j\frac{268.452 \times 10}{1420.11} = 6.867 - j1.89\ \text{A}$$

$$\bar{I}_m = \frac{V}{jX_m} = \frac{268.452}{j75} = \frac{268.452 \times j75}{j^2 75^2} = \frac{268.452 \times j75}{-75^2} = -j3.579\ \text{A}$$

$$\bar{I}_s = \bar{I}_t' + \bar{I}_m = 6.867 - j1.89 - j3.579 = 6.867 - j5.469$$

$$= \sqrt{6.867^2 + 5.469^2}\tan^{-1}\frac{5.469}{6.867} = \sqrt{6.867^2 + 5.469^2}\tan^{-1}(0.796)$$

$$= \sqrt{47.155 + 29.909}\angle -38.534° = \sqrt{77.0649}\angle -38.534° = 8.778\angle -38.534°\ \text{A}$$

Line current $= \sqrt{3} \times 8.778 = 15.2039$ Amp **(Ans.)**

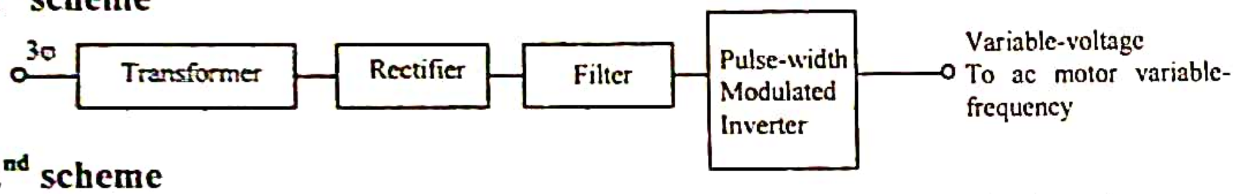
b) Explain with suitable diagram variable voltage and variable frequency control of three phase induction motor. **[WBUT 2015]**

Answer:

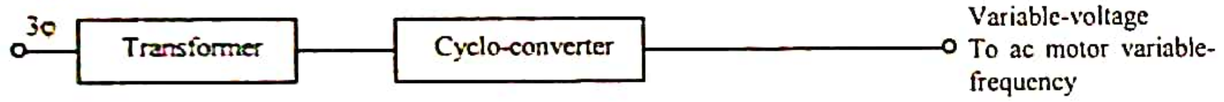
It is needless to mention that for induction motor, variable frequency input requires that voltage to frequency ratio remains constant in order to maintain the flux constant. As the inverter frequency is varied, the voltage must be varied to maintain voltage to frequency (V/f) ratio constant. But this type of control requires two to three stages which results in higher losses and lower efficiency. Further, for low value of frequency, the element of the filter circuit increase in size and weight which results in their high cost and low efficiency. More-over the low values of d.c. input voltage, the voltage across the commutating capacitor decreases, thus reducing a circuit turn-off time for thyristors for constant load current. The output voltage can also be varied by control within the inverter.

Generally there are two schemes of speed control of induction motor and synchronous motor by variable-voltage variable frequency method.

1st scheme



2nd scheme



Here the 1st scheme is discussed. To begin with, it may be told that in this method a three-phase bridge converter a.c to variable d.c voltage which is impressed at the input of a force commutated bridge inverter. The inverter generates a variable-voltage variable-frequency power supply to control the speed of the motor, the capacitor C as in the Fig. (i) supplies stiff voltage supply to the inverter and the inverter output voltage waves are not affected by nature of load. The inductance L is of large value to prevent discontinuity in output voltage and smooth the ripple.

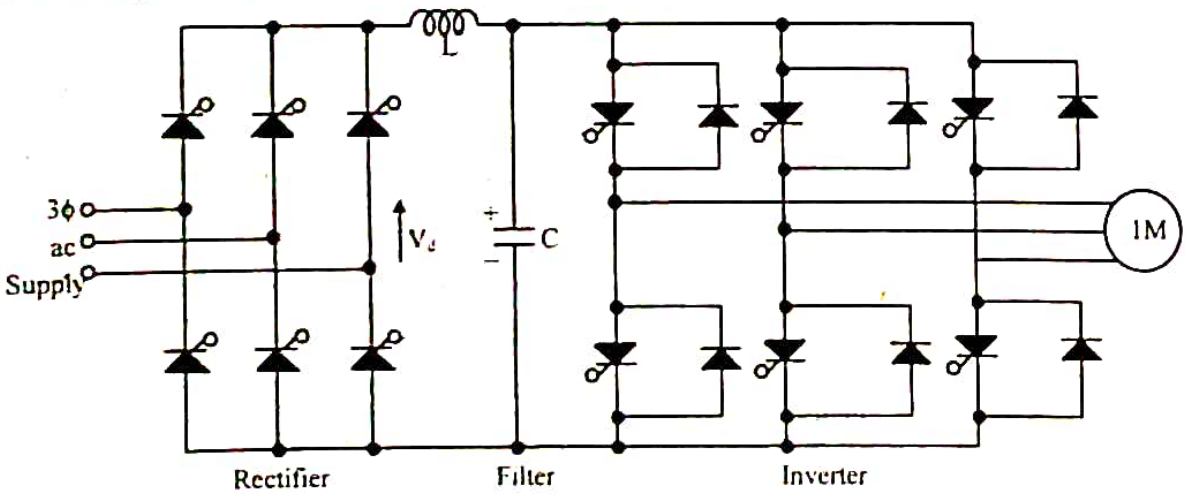


Fig: (i)

The induced stator phase emf is given by $V = 4.44\phi f T$
where V is the applied voltage, f the applied frequency, ϕ the air gap flux and T the number of turns in the stator winding.
In order to achieve constant torque operation below base speed, flux ϕ has to be kept constant and for keeping ϕ constant, the ratio $\frac{V}{f}$ has to be kept constant. Thus to control the speed of a.c induction motor, below the rated value. not only frequency has to be decreased but also voltage has to be decreased in the same proportion.
The inverter of six thyristors connects each phase to positive and negative DC bus. Each thyristor is on for 180° and the switching sequence produces a 3ϕ output voltage. The waveform at the output is a six-step waveform as shown below in Fig. (ii).

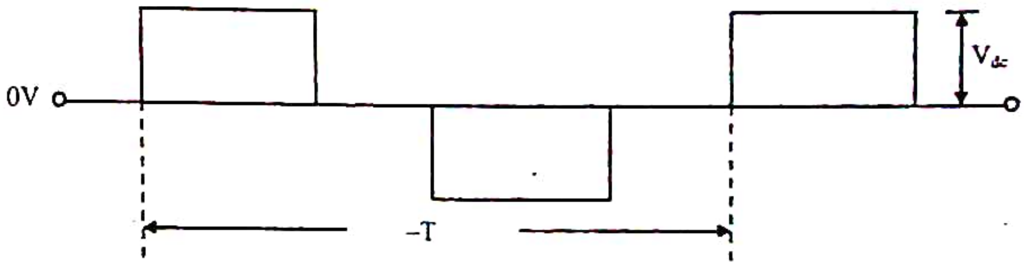


Fig: (ii)

The output frequency is controlled by inverter and amplitude V_{dc} is controlled by the phase controlled bridge. The shape of waveform is same at all frequencies.
The inverter can also be used as a Pulse Width Modulator (PWM) but this requires a control logic.
In the cycloconverter method, the DC link is not necessary. But the frequency variation attainable is limited to 1/3 of supply frequency.

14. a) With the help of relevant circuit diagram explain different methods of dynamic braking for a polyphase induction motor.
b) A 3-phase, 440V, 50 Hz, 6 pole, Y-connected IM has the following parameters referred to the stator: Rs = 0.5 Ω, Rr' = 0.6 Ω, Xs = Xr'= 1 Ω, Stator to rotor ratio is 2. The motor is running on no load. The plugging is used to stop the motor.
i) Determine the maximum braking current and initial and final braking torque when no external braking resistance is used.
ii) Calculate the additional braking resistor to be inserted into the rotor circuit so as to limit the maximum braking current to twice the rated value. The motor has a rated speed of 940 rpm. **[WBUT 2016]**

Answer:

a) The speed of an induction motor can be controlled by injecting D.C voltage in its stator winding. A variable resistance may be used in the rotor (in case of a slip ring induction motor) for dissipating the required amount of power. Now-a-days thyristor bridges are used for supplying D.C which is controllable in nature. With the help of controlled D.C from a thyristors bridge the dynamic braking can be achieved in a more effective manner.

The connection diagram for scheme is shown in Fig. 1.

- 3-phase A.C is stepped down to lower voltage and fed to a 3-phase thyristor bridge which serves as the rectifier.
- This D.C is filtered by an L.C filter for minimizing the ripples.
- Ripple free D.C is then fed to the stator winding of the induction motor as shown in Fig. 1.

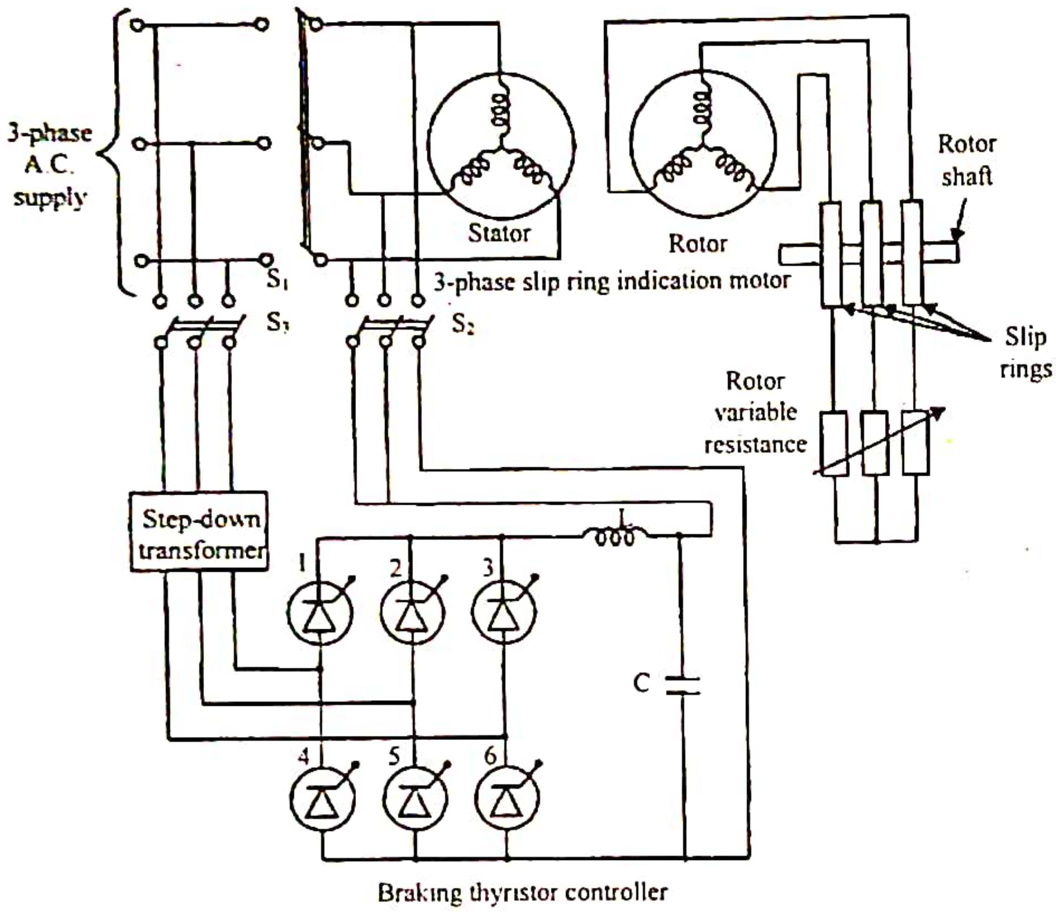


Fig: 1 Dynamic braking of a 3-phase slip ring induction motor

It is to be noted that while feeding D.C to the stator the 3-phase A.C input must be disconnected. A.C is disconnected with the help of S_1 and D.C is disconnected with the help of S_2. Since, the input A.C voltage is stepped down to a lower value, the thyristor converter may be of lower voltage rating.

b) $R_s = 0.5\Omega$ $\qquad$ $R_r = 0.6\Omega$ $\qquad$ $X_s = X_r' = 1\Omega$

$R_s + R_r' = 0.5 + 0.6 = 1.1\Omega$

Pole pairs $P = \dfrac{6}{2} = 3$

$N_s = 1000$ r.p.m. $\qquad$ $\omega_s = 104.72$ rad/sec $\qquad$ $N_m = 925$ r.p.m.

$$N_s = \frac{400}{\sqrt{3}} = 231 \text{ V}$$

$$s_1 = \frac{1000-925}{1000} = 0.075$$

$$\frac{R_r'}{s} = \frac{0.6}{0.075} = 8$$

$$I_1 = \frac{V_s}{\sqrt{\left(R_s + \frac{R_r'}{s_1}\right)^2 + \left(X_s + X_r'\right)^2}} = \frac{231}{\sqrt{\left(0.5 + \frac{0.6}{0.075}\right)^2 + (2)^2}}$$

$$= \frac{231}{\sqrt{(8.5)^2 + (2)^2}} = \frac{231}{8.731} = 26.46 \text{ Amp.}$$

$$T_1 = \frac{3(I_1)^2 \cdot \left(\frac{R_r'}{s_1}\right)}{\omega_s} = \frac{3\cdot(26.46)^2 \cdot 8}{104.72} = 160.166 \text{ N-m}$$

Plugging

$$s_{pl} = 2 - s_1 = 2 - 0.075 = 1.925$$

$$\frac{R_r'}{s_{pl}} = \frac{0.6}{1.925} = 0.3116$$

Initial braking (plugging) current

$$I_{pl} = \frac{231}{\sqrt{\left(R_s + \frac{R_r'}{s_{pl}}\right)^2 + \left(X_s + X_r'\right)^2}} = \frac{231}{\sqrt{(0.5 + 0.3116)^2 + (2)^2}}$$

$$= \frac{231}{\sqrt{(0.8116)^2 + 4}} = \frac{231}{\sqrt{4.8116}} = \frac{231}{2.19} = 107.44 \text{ A}$$

Therefore

$$\frac{I_{pl}}{I_1} = \frac{107.44}{26.46} = 4.06$$

Initial braking torque

$$T_{pl} = \frac{3(I_{pl})^2 \cdot \left(\frac{R_r'}{s_{pl}}\right)}{\omega_s} = \frac{3 \times (107.44)^2 \times (0.3116)}{104.72} = 103.04 \text{ N-m}$$

Therefore

$$\frac{T_{p'}}{T_1} = \frac{103.04}{160.166} = 0.6433$$

In the next case

$$N_2 = -940 \text{ r.p.m.}$$

$$s_{p'} = \frac{N_s - N_2}{N_s} = \frac{1000-(-940)}{1000} = \frac{1940}{1000} = 1.94$$

As the maximum braking torque is at speed N_2, we have

$$2 \cdot \frac{R_r' + R_e'}{s_{p'}'} = \sqrt{(R_s)^2 + (X_s + X_r')^2}$$

$$\Rightarrow \quad 2 \cdot \frac{0.6 + R_e'}{1.925} = \sqrt{(0.5)^2 + (2)^2}$$

$$\Rightarrow \quad 2 \cdot (0.6 + R_e') = \sqrt{0.25+4} \times 1.925$$

$$\Rightarrow \quad 0.6 + R_e' = \frac{2.061 \times 1.925}{2} = 1.984$$

or, $\quad R_e' = 1.984 - 0.6 = 1.384\,\Omega$

$$R_e = \frac{R_e'}{4} = \frac{1.384}{4} = 0.346$$

$$s_{p'} = 1.925$$

$$\frac{R_r' + R_e'}{s_{p'}} = \frac{0.6 + 1.384}{1.925} = \frac{1.984}{1.925} = 1.03$$

Maximum braking current with external resistance $R_e = (0.346)\,\Omega$ inserted in rotor circuit

$$I_{p'}'' = \frac{V_s}{\sqrt{\left(R_s + \frac{R_r' + R_e}{s_{p'}}\right)^2 + (X_s + X_r')^2}} = \frac{231}{\sqrt{\left(0.5 + \frac{0.6+0.364}{1.925}\right)^2 + (2)^2}}$$

$$= \frac{231}{\sqrt{\left(0.5 + \frac{0.964}{1.925}\right)^2 + 4}} = \frac{231}{\sqrt{5.00155}} = \frac{231}{2.236} = 103.309 \text{ A}$$

15. a) What are the advantages of static rotor resistance control over conventional methods of rotor resistance control. **[WBUT 2017]**

Answer:

The major advantages of static rotor resistance control over conventional methods of rotor resistance control are:

1. Speed control of induction motor of bigger sizes say 100-200 kW is easy in this process and by this system speed adjustment in the range from 15 to 30% below or above is possible.
2. Variation of delay angle permits power flow in both directions and smooth speed control is achieved.
3. The slip power from the rotor circuit can be recovered and feed back to the ac source so as to utilise it outside the motor.
4. There will be negligible power loss particularly at low speed which automatically improve the motor efficiency.

b) Discuss the methods of *ac* dynamic braking operation of an induction motor. **[WBUT 2017]**

Answer:

AC dynamic braking of the induction motor is achieved by disconnecting the stator windings from ac supply and connecting it to the dc supply. When the machine is motoring, the stator magnetic field is stationary as it is fed from dc supply and the rotor continues to rotate in this stationary field. Alternating current is thus induced in the rotor windings. This current produces a rotating magnetic field, which rotates at the same speed as the rotor, but in the direction opposite to that of the rotor such that it becomes stationary with respect to the stator. The rotor current therefore, flows in the direction opposite to that corresponding to the motoring action. Hence, a braking torque is produced.

Initially, the frequency of the rotor current corresponds to nearly the synchronous speed. The relative speed between the stationary magnetic field and the rotating rotor at any speed is given by $(1-S)\omega_S = S\omega_S$.

Therefore, as the speed drops, the frequency will also reduce and become zero at standstill. When the motor accelerates, the rotor frequency decreases and comes to zero at synchronous speed. The conditions in the rotor during dynamic braking are very similar to those when the motor accelerates from the standstill. The magnitude of the braking torque depends upon dc excitation, the rotor speed and the rotor resistance.

16. Write short notes on the following:

a) V/f control of Induction Motor **[WBUT 2010, 2012]**

b) Disadvantages and advantages of inverter fed AC drives **[WBUT 2011]**

c) Armature voltage control *vs* rotor resistance control methods of speed control in W.R.I.M. **[WBUT 2011]**

d) Vector control of Induction motor **[WBUT 2013, 2016]**

e) Induction motor speed control by rotor resistance control **[WBUT 2014]**

f) Current Source Inverter fed Induction Motor drive **[WBUT 2015]**

Answer:

a) V/f control of Induction Motor:

Refer to Question No. 5 of Long Answer Type Questions.

b) Disadvantages and advantages of inverter fed A.C. drive:

1. In case of voltage source inverter fed drive for example 3-phase induction motor, when fed from this type of inverter with pulse width modulated wave, it gives low harmonic content and therefore, low pulsation of the torque, where as for stepped waveform. harmonic gives rise to increased pulsation of the torque in the induction motor.
2. In voltage source inverters, the output voltage is controlled by input voltage, which is kept constant, while the output current is maintained constant, but it can be adjusted. For this purpose a high value of inductance is connected in series with the source to keep the current constant. The output voltage waveform is governed by load impedance.
3. Current source inverter fed drive is generally considered to be more reliable as the chances of commutation failure compared to voltage source inverter is minimal. Regeneration is also possible. The presence of a large inductance L_d in the d.c. link makes the current constant. The torque is controlled by link current I_d, which is obtained by varying the input voltage V_d, using a full controlled bridge rectifier or chopper.

c) Armature voltage control vs rotor resistance control methods of speed control in W.R.I.M.:

Armature voltage control vs. rotor resistance control methods of speed control in wound rotor induction motor (WRIM)

Stator Voltage Variation:

Although the torque developed in an induction motor at any slip is approximately proportional to the applied voltage, for an ordinary induction motor operating with constant torque. the range of speed control obtained is small, which may be seen from Fig. 1(a).

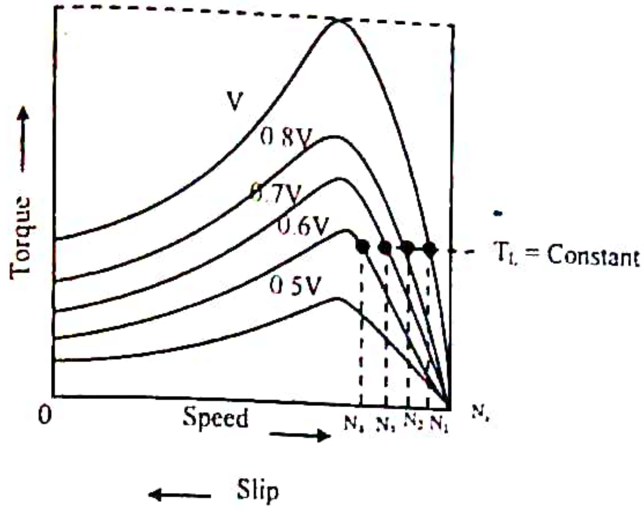


Fig: 1(a) Low rotor resistance, constant load torque

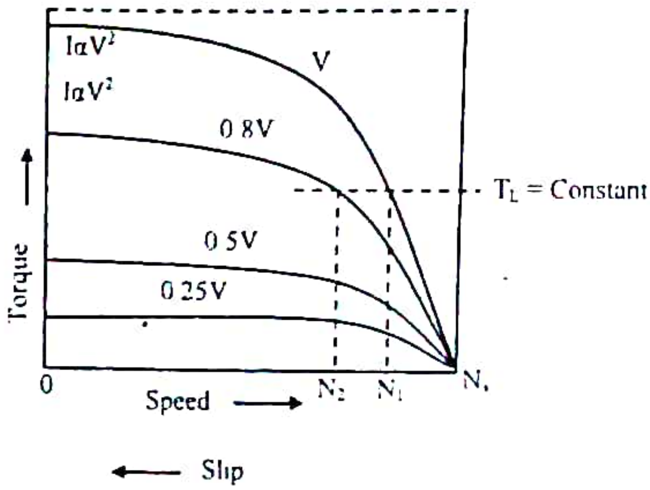


Fig: 1(b) High rotor resistance constant load torque

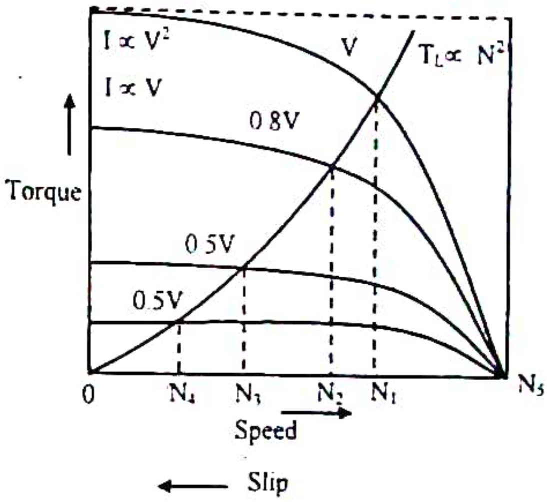


Fig: 1(c) High rotor resistance fan type load ($T_L \propto N^2$)

However, a continuous control of speed of an induction motor may be obtained by step less adjustment of voltage, if its rotor resistance is high in which cause high resistance, constant load torque curve as shown in Fig. 1(b) may be referred to. The major draw back in this case is that the torque per ampere is small at low speed.

It may however be noted that in a pump drive or in a pump fan, the load torque varies as the square of the speed and the power requirement for these drives decreases rapidly with the decrease in speed thereby removing the difficulties is as stated/mentioned. The situation may be understood by referring Fig. 1(c).

Rotor Resistance Variation:

Where the motors drive loads with intermittent type duty, such as cranes, ore or coal unloaders, skip hoists, mine hoists lifts etc. slip ring induction motors with speed control by variation of resistance in the rotor circuit are frequently used.

The speed is controlled in steps. The same resistance can be used for starting the motor. High starting torque, low starting current and large pullout torque are obtained. Excessive power loss at low speeds is one of its major shortcomings. The torque-speed characteristics [Fig. 1(d)] loose hardness considerably at low speeds.

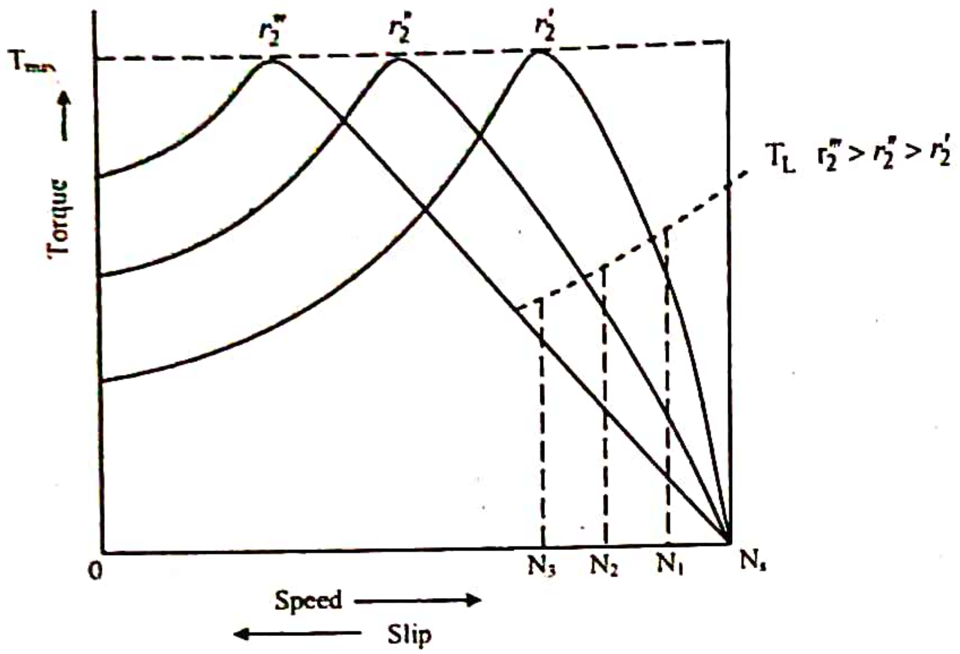


Fig: 1(d) Speed control of slip-ring indication motors by variation of rotor resistance

The range of speed control is limited to 2:1 to 3:1. This method of speed control is employed for a motor-generator set with a flywheel (Ilgner set) used as an automatic skip regulator under shock loading conditions.

d) Vector Control:

This method is used for speed control of ac, both induction and synchronous motors. In closed loop control, either stator voltage or stator current is regulated by the error in speed but in magnitude only. The phase angle of the current is regulated by the error in speed, but in magnitude only. The phase angle of the current with respect to the flux is not considered. This is termed scalar control. But the stator current can be decomposed into two components in respect of rotor flux, the magnetizing and torque producing components which are separately controlled. The transient response improves to a great extent using this method of vector or field oriented control as this scheme resembles that of a normal dc motor in which field excitation and armature voltage are separately controlled.

The stator currents (phase) of the induction motor are decomposed into d- and q-axes components using a three-phase to two-phase transformation, with the rotor flux being available only along the d-axis which is taken as the reference. The quadrature component of flux is zero. The system is now decoupled. Two controllers are used, one of them computes the magnetizing components from the error in flux between the reference value (as set or may be rated) and the measured/observed or computed one, while the other controller is used to determine the torque producing component from the error between the set value of torque and the measured value. The phase angle θ

between the a-phase stator current and the rotor flux on the d-axis must be computed properly so as to determine the phase currents in the stator to be fed to the motor, from the two components using a two-phase to three-phase transformation. The dynamic performance of the closed loop system is superior to that of a system with scalar controller. The main problem is to either measure the flux directly using search coils, or estimate the flux indirectly using the motor model from terminal voltages and current. The first one is known as direct method, the second type is called the indirect method. In the direct method flux observer has been used recently to estimate the rotor flux from the system (motor) model and use it to control the motor speed. This eliminates the need for search coils or Hall effect sensors. In the indirect method, the variation of rotor resistance affects the machine model, though various methods have been proposed to compensate this effect. With the advent of different types of processors PCs, it is now possible to design and then, implement a vector control scheme for speed control of ac (induction/synchronous) motors.

e) Induction motor speed control by rotor resistance control:

Refer to Question No. 14(c) of Long Answer Type Questions.

f) Current Source Inverter:

Speed control of AC motor

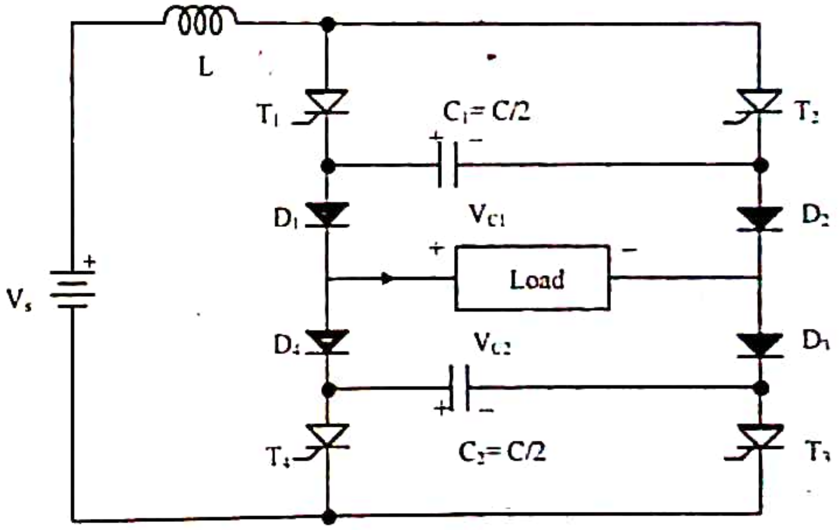


Fig: 1 Single-phase current source inverter
(Auto-sequential commutation)

A single-phase current source inverter is shown above and in this case the input current is maintained constant, but it can be adjusted. Two modes of operations may be followed.

Mode I: It is initially assumed that the thyristor pair T_2 & T_4 is conducting and current passes through the load and the diodes D_2 & D_4. The capacitors are charged to the same voltage, with the polarity such that the right hand plates are positive, and the left hand plates negative.

The other thyristor pair T_1 & T_3 is now gated. The conducting thyristor pair T_2 & T_4 is turned off by the application of reverse voltages across the capacitors. The diodes D_2 & D_4 continue to conduct and both the capacitors are charged through the load and the diodes D_2 & D_4 and thyristors T_1 & T_3. As the direction of current shows, the capacitors are charged linearly by the load current, assumed to be constant. The voltages decreases. The other diode D_1 & D_3 are initially reverse biased. But as the voltages across capacitors decrease with the polarity as shown earlier, the two diodes D_1 & D_3 are forward biased, when the capacitor voltages become zero and then the polarity reverses with the charging current as shown.

Mode II: Now all the four diodes $D_1 - D_2$ are conducting. The diodes D_2 & D_3 are forward biased with the capacitor voltages reducing to zero. The current passes through two paths. The load is now connected across the two capacitors in parallel. Due to the inductance in the load circuit, the current through the capacitors becomes zero after some time. This current also passes through the diodes D_2 & D_4 . At the same time the current in the diodes D_1 & D_3 increases thus reversing the load current. When the capacitor current reaches zero, the diodes D_2 & D_4 are OFF and the load current reaches the constant value in the reverse direction. The current path is now through T_1 D_1 load, D_3 & T_3. The capacitor voltage is now fully reversed with the polarity set so as to be ready for commutating the thyristor pair T_2 & T_4 when the pair is gated ON.

When the question of current source inverter-fed drive arises, the presence of a large inductance (L_d) in the DC link makes the current constant. There the chances of commutation failure compared to voltage source inverter is minimum. In this context the following points to be remembered:

i) Regeneration is also possible.
ii) Closed loop operation is required.
iii) For regenerative braking the machine runs as a generator when the inverter frequency is reduced.
iv) The torque is controlled by link current which is obtained by varying the input voltage using a full controlled bridge rectifier or chopper.

SYNCHRONOUS MOTOR DRIVES

Multiple Choice Type Questions

1. Cycloconverters have typical application in [WBUT 2011]
   a) synchronous motor drives
   b) *dc* motor drives
   c) brushless *dc* motor drives
   d) stepper motor drives

Answer: (a)

2. The frequency of voltage generated by an alternator having 4 poles and rotating at 1800 rpm is [WBUT 2012]
   a) 60 Hz
   b) 7200 Hz
   c) 120 Hz
   d) 450 Hz

Answer: (a)

3. By self control of a synchronous motor we mean that [WBUT 2014]
   a) elimination of torque ripple
   b) the speed of the motor is varied in steps
   c) the speed of the motor is a function of input frequency
   d) the input frequency is controlled from the speed of the motor

Answer: (c)

4. When operated with variable frequency, a synchronous motor has an advantage over an induction motor in [WBUT 2014]
   a) that it is free from torque oscillations
   b) that it has very good efficiency
   c) that the line power factor can be improved by varying excitation
   d) that in certain cases the inverter can be of simpler configuration due to the possible load commutation

Answer: (c)

5. In self controlled synchronous Motor drive, where Load Commutated Inverter is used, synchronous Motor is necessary to operate at [WBUT 2015]
   a) lagging pf
   b) unity pf
   c) leading pf
   d) none of these

Answer: (b)

Short Answer Type Questions

1. Explain the principle of operation of self-controlled synchronous motor drive. [WBUT 2007, 2008]

OR,

Describe with suitable diagram the "self-controlled mode" of speed control operation of a synchronous motor using load commutated inverter. [WBUT 2014, 2015]

OR,

Write short note on Self control of synchronous motor [WBUT 2016]

Answer:

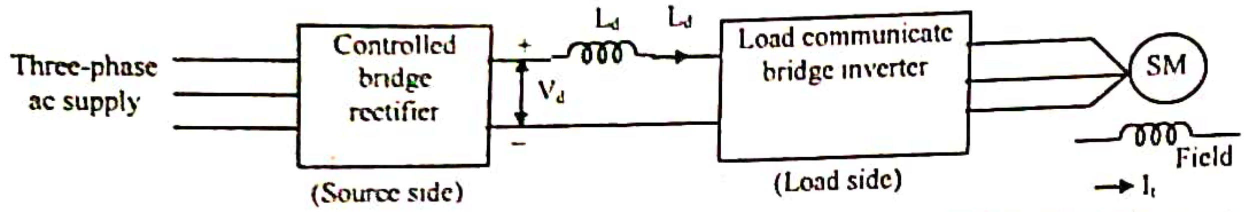


Fig: Self-controlled synchronous motor drive using load commutated thyristor inverter

Here a schematic diagram is shown above & it is meant for a SCM drive with load commutated thyristor inverter. In this system there are two three phase bridge rectifiers, one connected on the source side and the other on the load side. Source side converter is used to obtain dc output voltage from a.c. input supply behaving like a line commutated converter with $0 < \alpha < \frac{\pi}{2}$, the other inverter is connected on the load side for obtaining three phase ac output which is to be fed to the motor, acting like a load commutated inverter with $\pi/2 < \alpha < \pi$. In the latter case, the thyristors are commutated by the application of motor induced voltages with input power factor taken as leading & the duty angle α is measured by comparison of induced voltages in the same way as in case of line voltage in a line commutated converter.

So far its braking operation is concerned the operation changes from acting as converters on load side to inverter and converter on the source side to inverter resulting changes of delay angle accordingly and the firing pulses are obtained either by comparison of motor terminal voltages or by rotor position sensor. The problem of operation at low speed is overcome by operating the source side converter as inverter in pulse mode as the load side inverter frequency is low compared to high frequency on high speed operation.

2. Discuss the methods of speed control of synchronous motor. [WBUT 2017]

Answer:

The speed control of synchronous motor can be done by input frequency variation for which synchronous motors are fed from a variable frequency source such as voltage source inverter in view of the fact that control strategy in general is that voltage to frequency ratio is proportional to flux. Therefore, a constant voltage to frequency $\left(\frac{V}{f}\right)$ is maintained for frequencies below base (or rated) frequency, and the ratio is increased at low speeds to take into account the stator resistance drop. This may be termed variable voltage variable frequency (VVVF) control. This also results in a constant pull out torque at all frequencies. Similarly, for frequencies above base frequency, a constant voltage is applied which results in decrease of flux, and also developed torque.

Otherwise a voltage higher than rated value is needed to keep flux constant, which may not be permitted in mast cases. For this case, the motor may be operated in two modes:

a) True synchronous mode
b) Self-controlled mode

i) In true synchronous mode, the motor is supplied from a variable frequency inverter (voltage source) with constant $\frac{V}{f}$ ratio. The frequency is slowly increased such that the difference between the synchronous speed and the rotor speed is small and the machine speed increases at a slow rate to keep pace with the change in input frequency or synchronous speed.

ii) In the self-controlled mode, the stator supply frequency is changed with the rotor speed which remains always at synchronous speed, as the rotor portion is sensed and accordingly. The switching sequence of devices in the inverter, used for the stator, is determined by the control circuit.

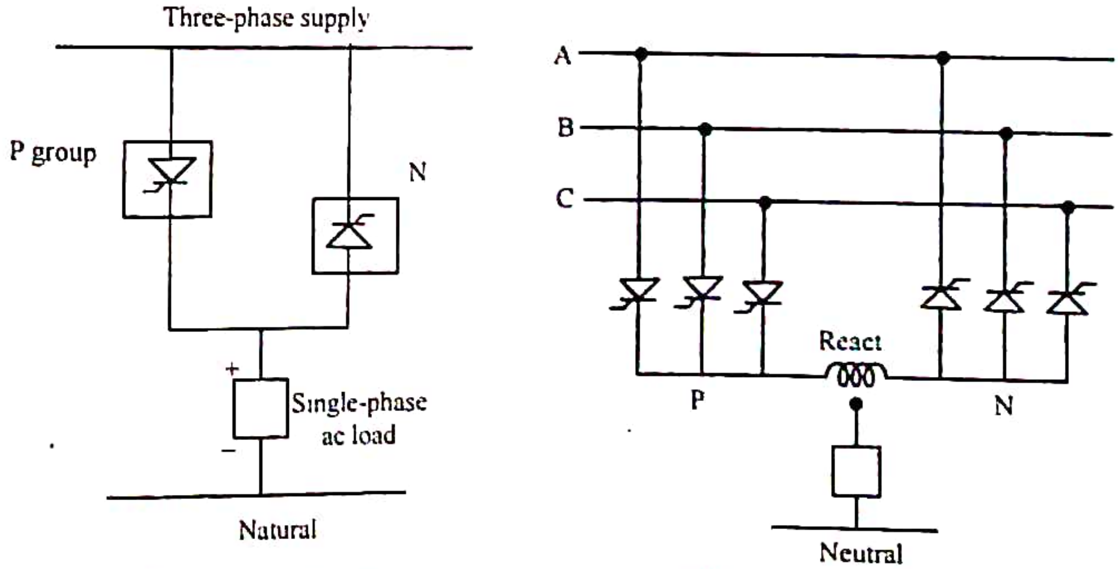
Long Answer Type Questions

1. Explain how cycloconverter can be used to control the speed of synchronous motor drives. **[WBUT 2007, 2009, 2010, 2014]**

Answer:

Cyclo converter is suitable for low speed drives including synchronous motor and in fact it converts power at low frequency from line frequency supply. These types of control are cost effective only for large power drives as larger numbers of thyristors are needed. The output voltage at low frequency contains less harmonics resulting smooth operation. In order to restrict the harmonic contents with the increase in frequency resulting Jerky motion normally, the frequency is limited to $1/3$rd of input frequency.

A schematic diagram and basic circuit configuration with inter group reactors for a 3-phase to single phase cycloconverter is shown below in Fig. (i) and (ii) respectively:



(i) Schematic diagram

(ii) Basic circuit configuration with inter-group reactor

Fig: 3-phase to single phase cycloconverter

In fact under this scheme, two three phase half wave circuits are connected in parallel load work as a dual converter scheme. One group is termed as positive conducts when the polarity of output voltage is positive and the other may be termed as negative group conducts for the negative half of the output voltage.
The voltage waveforms for half cycle of output is shown in Fig. below.

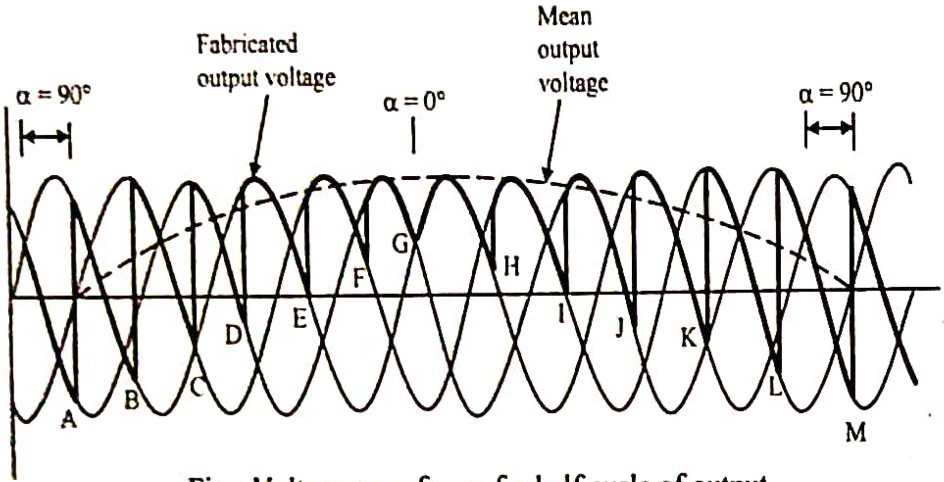


Fig: Voltage waveforms for half cycle of output

It may be seen from Fig that the delay angle α at the point is 90° and the firing angle is gradually reduced till it reaches the point G, where the output voltage increases to maximum. In between the points B to G, the firing angle is $90° > \alpha > 0°$. The firing angle is again increased to 90° when the voltage is reduced from maximum value to zero. The negative half of the waveform is generated, when the other group (N-group) is conducting. The firing angle in this case varies from 90° to 180° and again decreases to 90°. If the load power factor is lagging, the load current lags the voltage. For the case, when the current is negative and voltage positive, the current flows through the N-group and also for the next half when the current is positive and voltage negative, thyristors in the P-group conduct.
It is to be noted that in case of three phase to three phase cyclo converter, it will have six bridge circuits each having six thyristors i.e. two thyristors bridge circuits per phase are needed.

2. A 400 kW, 3-phase, 33 kV, 50 Hz unity power factor, 4-pole, star connected synchronous motor has the following parameters:
$\Omega_a = 0,\ X_s = 13\Omega$, rated field current = 10 A. The machine is controlled by variable frequency control at a constant $\frac{v}{f}$ ratio.
Calculate the torque & field current for rated armature current, 900 rpm & 0.8 leading power factor. **[WBUT 2008]**

Answer:
Data given:
400 KW 3ϕ, 33KV,50Hz, unity $p.f$
4 pole, star connected

$$R_a = 0\ X_s = 13\Omega$$

$I = 10\text{ A}$

900 r. p. m. and ·8 leading p.f.

At rated operation

$$3V\, I_S \cos\phi = P_m$$

$$\Rightarrow \quad 3\times\frac{33,000}{\sqrt{3}} I_S \times 1 = 400\times 10^3$$

$$\Rightarrow \quad I_S = \frac{400\times 1000}{\sqrt{3}\times 33,000} = \frac{400}{\sqrt{3}\times 33} = 6.998\text{A} \approx 7\text{A}$$

$$E = \bar{V} - I_S(jX_S) = \frac{33,000}{\sqrt{3}} - 13\angle 90 \;\times 7\cos^{-1}1$$

$$= 19052 - 91\angle 90 \;= \sqrt{19052^2 + 91^2}\;\; \tan^{-1}\frac{91}{19052}$$

$$= 19052.7762\;\angle -2736$$

Synchronous speed

$$N_S = \frac{120f}{P} = \frac{120\times 50}{4} = 1500\text{ r.p.m.}$$

$$\text{Frequency } f' = \frac{900}{1500}\times 50 = 30\text{ Hz}$$

$$\text{V} = \frac{33,000}{\sqrt{3}}\times\frac{30}{50} = 11,431.53\text{V}$$

$$X_S = \frac{900}{1500}\times 13 = \frac{3}{5}\times 13 = \frac{39}{5} = 7.8\Omega$$

$$E = V - I_S(jX_S)$$

$$= 11,431.53 - 7(\cos^{-1}\cdot 8\times 7.8\angle 90\;)$$

$$= 11,431.53 - (7\angle 36.87\;\times 7.8\angle 90\;)$$

$$= 11,431.53 - 54.6\angle 126.87$$

$$= 11,431.53 - 54.6[\cos 126.87^\circ + j\sin 126.87^\circ]$$

$$= 11,431.53 - 54.6[-\cdot 600 + j\cdot 799]$$

$$= 11,431.53 - [-32.76 + j43.6]$$

$$= 11,431.53 + 32.76 - j\;43.6$$

$$= 11464.29 - j43.6$$

$$= \sqrt{11464.29^2 + 43.6^2}\;\;\tan^{-1}\left(\frac{-43.6}{11,464}\right)$$

$$= 11464.08\angle -.2179\;\;V$$

At rated field current & 900 r.p.m

$$E = 19052 \times \frac{900}{1500} = 11{,}431.2V$$

Field current $= \frac{11464.08}{11431.2} \times 10 = 10.028$ A

Power input $= 3VI_S \cos\phi$

$$P_m = 3 \times 11{,}431 \times 7 \times \cdot 8 = 192040.8 \text{ W} = 192 \text{ KW}$$

Motor speed $= \frac{900}{60} \times 2\pi = 94.2857$rad/sec

Torque $= \frac{192040.8}{94.2} = 2036.796$ N- m

3. a) Explain why VVVF control drive is better than either variable voltage or variable frequency control drive.
b) Give a short description of different schemes of VVVF control drive.
c) Describe the 180 deg conduction mode operation of 3-phase VSI. [WBUT 2013]

Answer:

a) In a variable voltage control drive, for a given load, the speed of the motor can be varied within a small range. Since the operation at voltages higher than the rated voltage is not permissible. This method allows speed control only below the normal rated speed. In a variable frequency control drive, say for induction motor, the variable frequency is obtained by the converters like a) voltage source inverter, b) current source inverter, c) cyclo converter. But in VVVF control, variable frequency input requires that voltage to frequency ratio remains constant in order to maintain the flux constant. As the inverter frequency is varied, the voltage must be varied to maintain voltage to frequency ratio constant. As such VVVF control drive is better.

b) In a PWM technique the output voltage of the inverter comprises of number of pulses of varying periods in any cycle. With the advent of the fast switching devices such as power transistors and MOSFET pulse width modulation technique are being increasingly used in voltage source or current source inverters using modulation schemes as (a) multiple pulse (b) sinusoidal modulation. In the multiple pulse method, the pulses are of equal width and the number of pulses per cycle is varied. In sinusoidal pulse width modulation method the cross over point to switch on and off. The devices are determined by comparing the sinusoidal reference waveform with the triangular carrier waveform having frequency n times the reference frequency as shown in the Fig. below. The pulse width are unequal, smaller at the beginning and end of each half cycle, increasing in width as the midpoint in each half cycle is gradually approached.

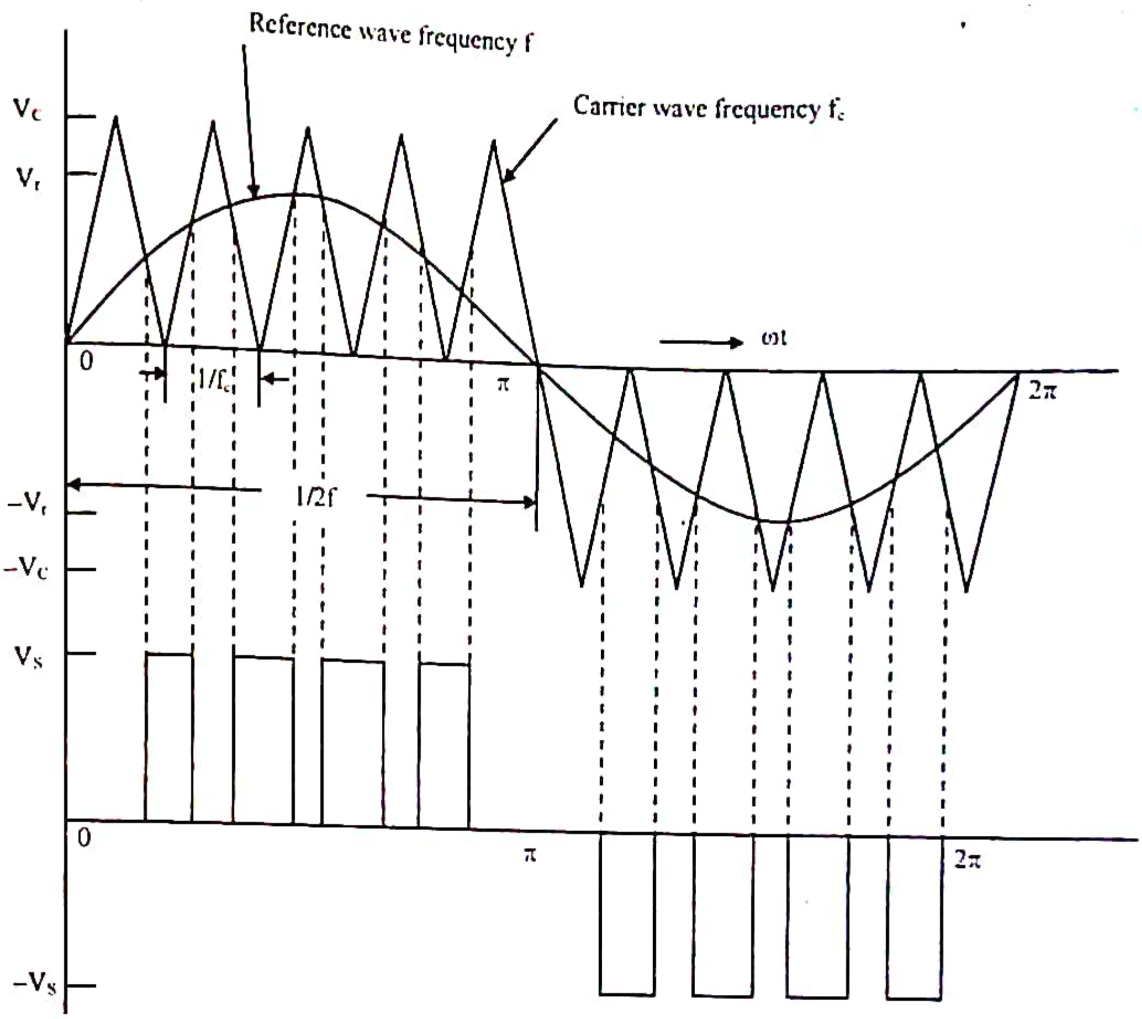
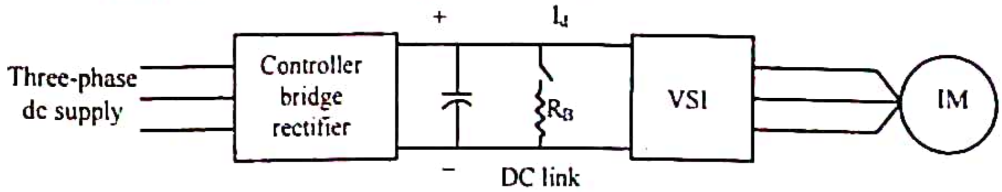


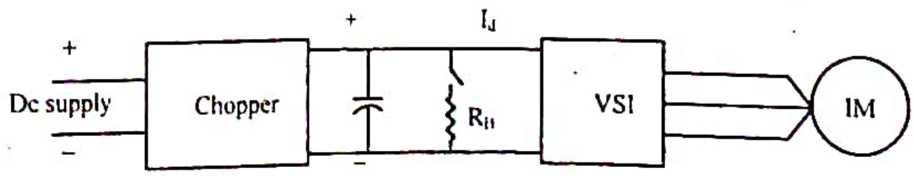
Fig: Inverter voltage waveforms

1. Voltage source inverter (VSI) – fed drive

The output waveform of a voltage source inverter can be either a simple stepped wave or a pulse width modulated wave. The later type gives low harmonic content and therefore, low pulsation of the torque, if the three-phase induction motor is fed from this type of inverter. For stepped waveform type, harmonics give rise to increased pulsation of the torque in an induction motor. The inverter frequency is controlled by the firing signals applied to the switching devices, such as transistors.



(a) Chopper



(b) Chopper

Fig: DC link inverter (voltage source) fed induction motor

The above Fig. shows DC link inverter (voltage source) fed induction motor. In both these cases the output voltage or d.c input voltage to the inverter is varied so as to maintain V/f ratio constant in order to keep flux constant at rated values in A.C motors, the method can be used or starting and also speed control of induction motor.
When the question of braking is concerned, either the full-controlled converter needs to be replaced by a dual converter or the chopper by a two-quadrant chopper, in which case the power from the dc link inverter can be transferred to respective sources, to enable regenerative braking to take place. An inverter with variable frequency is used such that the frequency can be reduced so as to break the induction motor. Dynamic braking is obtained by switching on a resistance R_b across the dc link. In this case, first the dc link voltage is sensed and as it exceeds a specified value, the resistance R_b is switched on to provide dynamic braking.

2. Current Source Inverter

Speed control of AC motor

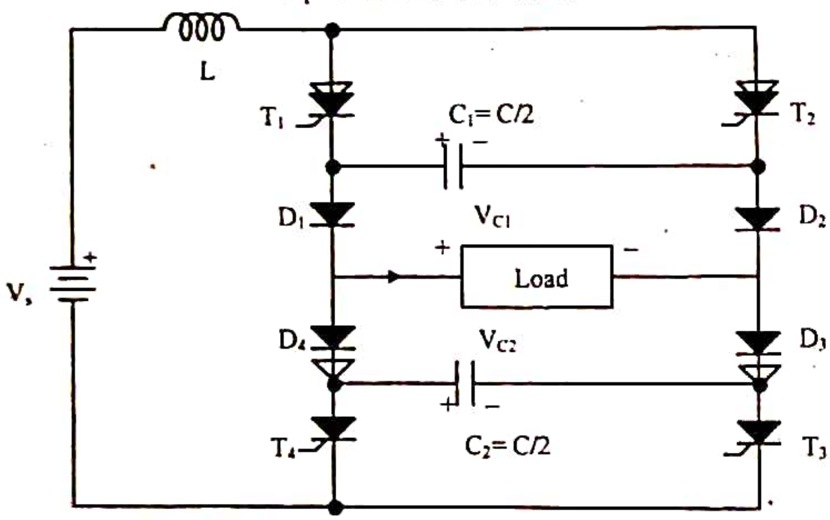


Fig: Single-phase current source inverter
(Auto-sequential commutation)

A single-phase current source inverter is shown above and in this case the input current is maintained constant, but it can be adjusted. Two modes of operations may be followed.

Mode I: It is initially assumed that the thyristor pair T_2 & T_4 is conducting and current passes through the load and the diodes D_2 & D_4. The capacitors are charged to the same voltage, with the polarity such that the right hand plates are positive and the left hand plates negative.
The other thyristor pair T_1 & T_3 is now gated. The conducting thyristor pair T_2 & T_4 is turned off by the application of reverse voltages across the capacitors. The diodes D_2 & D_4 continue to conduct and both the capacitors are charged through the load and the diodes D_2 & D_4 and thyristors T_1 & T_3. As the direction of current shows, the capacitors are charged linearly by the load current, assumed to be constant. The voltage

decreases. The other diode D_1 & D_3 are initially reverse biased. But as the voltages across capacitors decrease with the polarity as shown earlier, the two diodes D_1 & D_3 are forward biased, when the capacitor voltages become zero and then the polarity reverses with the charging current as shown.

Mode II: Now all the four diodes $D_1 - D_2$ are conducting. The diodes D_2 & D_3 are forward biased with the capacitor voltages reducing to zero. The current passes through two paths. The load is now connected across the two capacitors in parallel. Due to the inductance in the load circuit, the current through the capacitors becomes zero after some time. This current also passes through the diodes D_2 & D_4. At the same time the current in the diodes D_1 & D_3 increases thus reversing the load current. When the capacitor current reaches zero, the diodes D_2 & D_4 are OFF and the load current reaches the constant value in the reverse direction. The current path is now through $T_1 D_1$ load, D_3 & T_3. the capacitor voltage is now fully reversed with the polarity set so as to be ready for commutating the thyristor pair T_2 & T_4 when the pair is gated ON.

When the question of current source inverter-fed drive arises, the presence of a large inductance (L_d) in the DC link makes the current constant. There the chances of commutation failure compared to voltage source inverter is minimum. In this context the following points to be remembered:

i) Regeneration is also possible.
ii) Closed loop operation is required.
iii) For regenerative braking the machine runs as a generator when the inverter frequency is reduced.
iv) The torque is controlled by link current which is obtained by varying the input voltage using a full controlled bridge rectifier or chopper.

c) In the rotor resistance control, it is stated that the slip power is transferred via air gap and is dissipated in the resistance R_e i.e. it is wasted in the form of I^2R loss. Thereby reducing the efficiency of the drive system. 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 basic principle of slip power recovery is to connect an external source of emf frequency to the rotor circuit.

When an emf of slip frequency at an angle β is injected into the secondary circuit of an induction motor, the stator and rotor current position can be represented by a phasor diagram as shown in Fig. below:

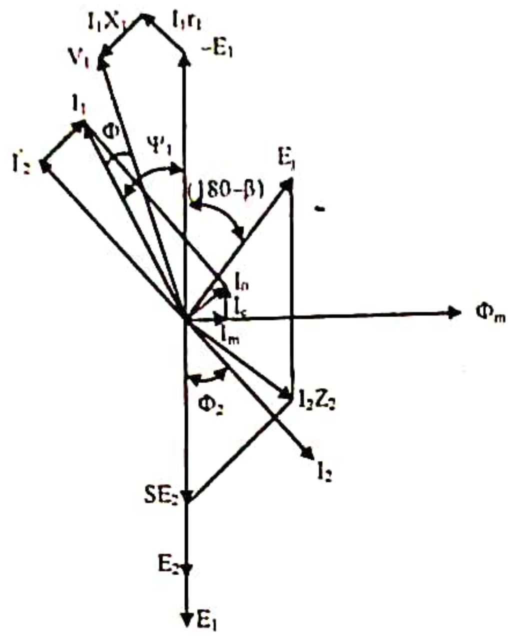


Fig: Phasor diagram when an emf of slip frequency at an angle β is injected

Now, the power input to the induction motor is

$$P_1 = V_1 I_1 \cos\phi_1 = E_1 I_1 \cos\Psi_1 + I_1^2 r_1$$

Resolving currents on E_1 we have

$$I_1 \cos\Psi_1 = I_c + I_2' \cos\phi_2$$

Multiplying by E_1, we get

$$E_1 I_1 \cos\Psi_1 = E_1 I_c + E_1 I_2' \cos\phi_2$$

or, $P_1 = I_1^2 r_1 + E_1 I_c + E_1 I_2' \cos\phi_2$

=(Stator copper loss) + (Iron loss)

+ (Power transferred to the secondary circuit)

Resolving emfs on I_2 we get

$$sE_2 \cos\phi_2 = I_2 r_2 + E_j \cos(180° - \beta + \phi_2)$$

Multiplying by I_2 we obtain

$$sE_2 I_2 \cos\phi_2 = I_2^2 r_2 + E_j I_2 \cos(180° - \beta + \phi_2)$$

Referring to the stator side, we have

$$sE_1 I_2' \cos\phi_2 = I_2'^2 r_2' + E_j' I_2' \cos(180° - \beta + \phi_2)$$

Adding $(1-s) E_1 I_2' \cos\phi_2$ we get

$$E_1 I_2' \cos\phi_2 = I_2'^2 r_2' + E_j' I_2' \cos(180° - \beta + \phi_2) + (1-s) E_1 I' \cos\phi_2$$

∴ Power transferred to the secondary circuit

$P_2 =$ Rotor copper loss + slip power + Mechanical power output

The air gap P_2 is nearly constant. If the losses are neglected the mechanical power output and the slip can be varied by regulating the slip power or injected voltage E_j at slip frequency sf.

The phasor diagrams for injected emfs at different β angles are also drawn and shown in Fig. below:

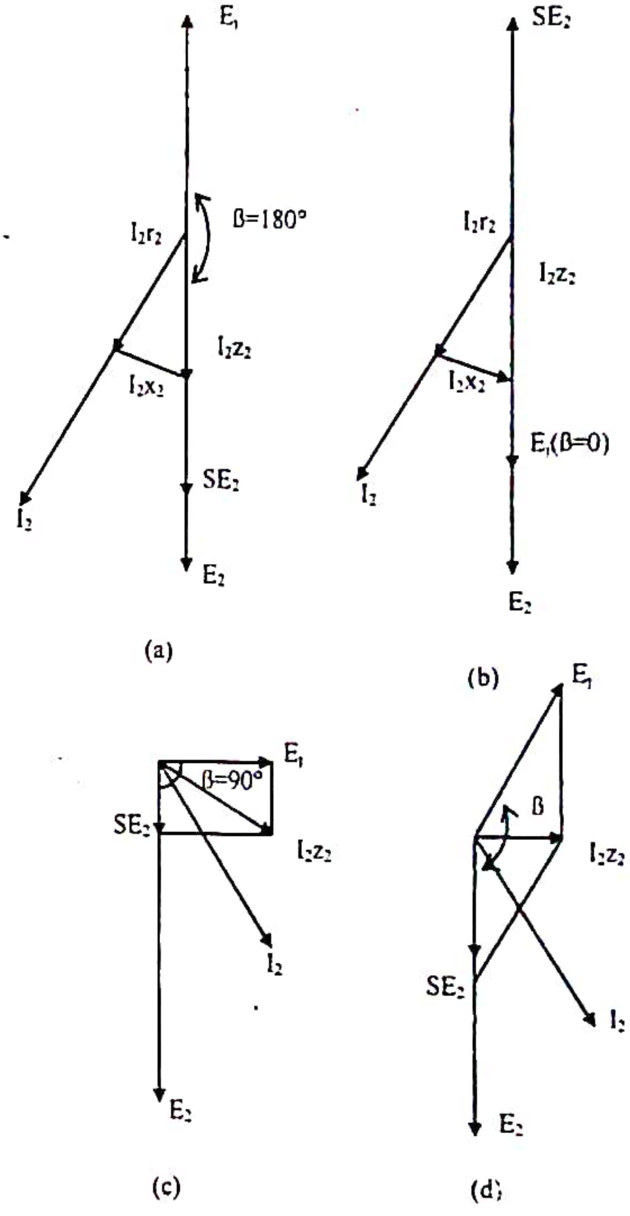


Fig: Phasor diagrams for injected emf at different β angles

Case: 1

The angle of injection of emf β is equal to 180° [Fig. (a)].

If (I_2Z_2) is negligibly small, then $SE_2 = E_j$ or, $S = \dfrac{E_j}{E_2}$

Hence the speed can be controlled over a wide range below synchronous speed by varying the injected emf.

Case: 2

When the slip frequency emf is injected into the secondary circuit in phase with the stand still induced emf E_2 at $\beta = 0$ Fig. (b), then under this condition, the emf equation is given by:-

$$I_2 Z_2 = SE_2 + E_j \qquad (S = \text{negative})$$

If $(I_2 Z_2)$ is assumed to be negligibly small, then $S = -\frac{E_j}{E_2}$

Hence the speed can be controlled above synchronous speed upto nearly double of the synchronous speed.

Case: 3

If the emf is injected into the rotor circuit at an angle $\beta = 90°$ i.e. Fig. (c), then the motor speed does not change but the secondary current advances and the power factor increases due to the horizontal component of the component of the injected emf.

Case: 4

When the emf is injected at an angle $180° > \beta > 0°$ [Fig. (d)], both the speed and power factor are controlled.

4. Explain the variable frequency control of synchronous motor drive. [WBUT 2013]

Answer:

Input frequency variation:

In this method, the control strategy adopted is the same as that of induction motor i.e. a constant voltage to frequency (V/f) ratio is maintained for frequencies below rated (base) frequency and the ratio is increased at low speeds to take into account the stator resistance drop, which may be termed as variable voltage variable frequency (VVVF) control resulting a constant pull out torque at all frequencies.

In case the frequencies are above the base frequency, a constant voltage is to be applied which will cause decrease of flux and also developed torque, otherwise, a voltage higher than rated value is needed to maintain the flux as constant, which is in general not permitted. Under this situation the motor may be operated in two modes viz. (i) true synchronous mode and (ii) self controlled mode.

i) True synchronous mode:

In this mode, the motor is supplied from a variable frequency inverter (voltage source) with constant V/f ratio. The frequency is slowly increased in a manner that the difference between the synchronous speed and the rotor speed is small and the machine speed increases at a slow rate to keep pace with the change in input frequency or synchronous speed.

Use: i) This type of control can be used both for speed control, starting as well as braking which occurs when the rotor speed is more than the synchronous speed. It is capable of regeneration.

ii) Such drives using reluctance or permanent magnet type motors can be used for multi-machine drive in textile and paper mills fed by one voltage source inverter only, where accurate tracking of motor speeds is required.

Limitation

Slow rate of change in frequency

ii) Self controlled mode

In the self controlled mode, the stator supply frequency is changed with the rotor speed, which remains always at synchronous speed, as the rotor position is sensed and accordingly, the switching sequence of devices in the inverter, used for the stator, is determined by the control circuit. So the rotor is always in step with input frequency and cannot pull out as in the earlier case. The motor does not require a damper winding. This is termed dc 'brushless' motor and the input supply is dc voltage in the case of inverter. The input voltage (d.c.) is varied to control the speed. Other type of ac 'brushless' motors can be implemented using a cycloconverter, which produces low output frequency for motors required to be run at low speed. Thus, cycloconverters are suitable for high power; low speed drives used for cement kilns and mine-hoists, including other special applications. The firing pulses are obtained by rotor position sensors (optical or Hall Effect type) or by comparison of motor terminal voltages.

SPECIAL TYPE DRIVES

Long Answer Type Questions

1. Write short notes on the following:
a) Stepper motor [WBUT 2007, 2010, 2012]
b) Solar & battery powered drive [WBUT 2009, 2013, 2017]

Answer:

a) Stepper motor:

- A stepper motor is an incremental motion machine (i.e. the motor which turns in discrete movement called the steps). It does not rotate continuously as a conventional motor does.
- The stepper motor is a special type of synchronous motor which is designed to rotate through a specific number of degrees for each electrical pulse received by its control unit. Typical steps are 2°, 2.5°, 5°, 7.5° and 15° per pulse. These motors are built to follow signals as rapid as 1200 pulses per second and with equivalent power ratings up to several kW.
- The stepper motor is used in digitally controlled position control system in open loop mode. The input command is in the form of a train of pulses to turn a shaft through a specified angle.
- A stepper motor consists of a slotted stator having multi-pole, multi-phase winding and a rotor structure carrying no winding. They typically use three and four phase windings, the number of poles depends upon the required angular change per input pulse.
- The rotors may be of the permanent magnet or variable reluctance type.
- Stepper motors operate with an external drive logic circuit. When a train of pulse is applied to the input of the drive circuit, the circuit supplies currents to the stator windings of the motor to make the axis of the air-gap field around in coincidence with the input pulses. The rotor follows the axis of air-gap magnetic field by virtue of the permanent magnet torque and/or the reluctance torque, depending upon the pulse rate and load torque (including inertia effects).

1. Permanent-magnet stepper motor:

- Fig. below shows the phases or stacks of a 2-phase, 4-pole permanent magnet stepper motor.

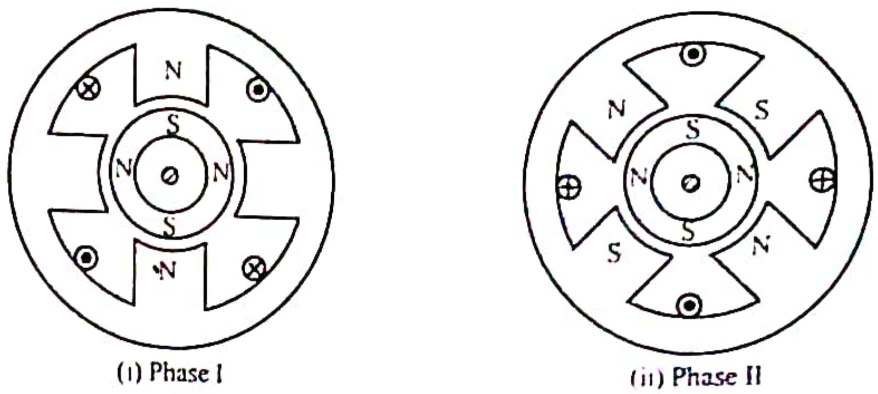


Fig: Permanent-magnet stepper motor

- The rotor is made of ferrite or rare-earth material which is permanently magnetized.
- The stator stack of phase II is staggered from that of phase I by an angle of 90°.
- When the phase 'I' is excited, the rotor is aligned as shown in Fig. (i). If now the phase 'II' is also excited, the effective stator poles shift anti-clockwise by 22.5° [Fig.(ii)] causing the rotor to move accordingly. Now, keeping the phase 'II' still energized, if the phase 'I' is now de-energized, the rotor will move another step of 22.5°. The reversal of phase 'I' winding current will produce a further forward movement of 22.5°, and so on. It can be easily observed/visualized as to how the direction of movement can be reversed.
- Each phase is provided with double coils to simplify the switching arrangement (which is electronically accomplished).

2. *Variable-reluctance stepper motor:*

- A variable-reluctance stepper motor has no permanent magnet on the rotor and the rotor employed is a Ferro-magnetic multi-toothed one.
- The large differences in magnetic reluctances that exist between the direct and quadrature axes developed the torque. The stationary field developed by the direct current in some stator coils tends to develop a torque which causes the rotor to move to the position where the reluctance of the flux path is minimum. Steeping angle, irrespective of the type of stepper motor is given as:

$$\alpha = \frac{360°}{\text{Number of phases} \times \text{number of poles}} = \frac{360°}{np} \qquad \text{.... (1)}$$

3. *Hybrid stepper motor:*

- This is in fact is a permanent-magnet stepper motor with constructional features of toothed and stacked rotor adopted from the variable-reluctance motor.
- The stator has only one set of winding-excited poles which interact with the two rotor stacks.
- The permanent-magnet is placed axially along the rotor in the form of an annular-cylinder over the motor shaft.

- The stacks at each end of the rotor are toothed. So all the teeth on the stack at one end of the rotor acquire the same polarity while the teeth of the stack at the other end of the rotor acquire the opposite polarity. The two sets of the teeth are displaced from each other by one half of the tooth pitch (also called pole pitch).
- The primary **advantage** of the hybrid motor is that if stator excitation is removed, the rotor continues to remain locked into the same position, as before removal of excitation. This is due to the reason that the rotor is prevented to move in either direction by torque because of the permanent magnet excitation.
- Typical step angles for stepper motors are 15°, 7.5°, 2° and 0.72°. The choice of the angle depends upon the angular resolution required for application.

Advantages:

The stepper motor (a position control device) entails the following advantages:

1. Compatibility with digital systems.
2. The angular displacement can be precisely controlled without any feedback arrangement.
3. No sensors are needed for position and speed sensing.
4. It can be readily interfaced with microprocessor (or computer based controller).

Applications:

Stepper motors have a wide range of applications, mentioned below:

- Paper feed motors in typewriters and printers.
- Positioning of print heads.
- Pens in XY-plotters.
- Recording heads in computer disc drives.
- Positioning of worktables and tools in numerically controlled machining equipment.
- Also employed to perform many other functions such as metering, mixing, cutting, blending, stirring etc, in several commercial, military and medical applications.

b) Solar & battery powered drive:

Solar Drive

In order to give an example of its application solar powered pump drives are discussed here. To begin with, it will be beneficial to have a discussion on motors suitable for pump drives.

For low power application (<1kW) permanent magnet dc motor is generally preferred because of its higher part load efficiency. A motor rated around 400 W may have full load efficiency in the range of 77-86% and half-load efficiency in 68-86%. By comparison, typical induction motors of similar power ratings would have efficiencies in the range of 25-65%. Because of high efficiency of dc motors, the solar panel can have smaller power rating. Therefore, although a permanent magnet dc motor is more expensive than induction motor, the dc drive has much lower cost compared to the induction motor drive. The main problem with dc motor is that it requires the change of brushes after 200 to 400 hrs, and if this is not done, some motors can suffer irreparable damage. Certain dc motors are being offered with claimed brush life of about 10,000 hrs. and these would be better for this type of application. The brushless dc motor is also being used to overcome the problem of frequent brush replacement.

For rating higher than 1 kW three-phase squirrel-cage induction motor is preferred because of high efficiency, maintenance free operation and long life.

A simple scheme of solar pump drive using a permanent magnet is shown in Fig. (1). The solar panel directly feeds the motor and one can connect the solar cells to form a low voltage-high-current or low-current-high-voltage unit. A low current-high-voltage arrangement is preferred because of lower proportion of losses in the motor and solar panel. However, a dc voltage more than 80 volts may present a serious electrocution hazard and should be avoided. Since the solar cells themselves regulate the maximum output current no starter is required for the dc motor.

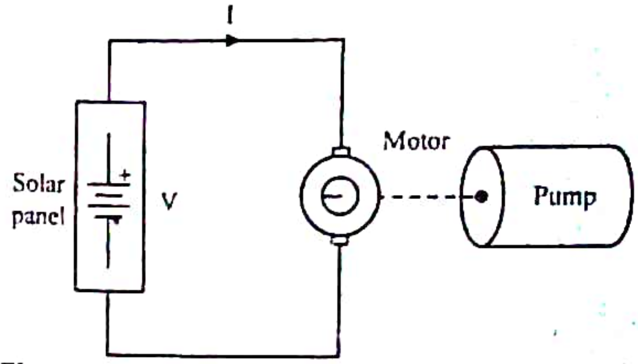


Fig: 1 Solar pump drive employing permanent magnet dc motor

Battery Powered Drive

These are popularly known as electric vehicles. Although several batteries and fuel cells have been developed, only available at affordable price is the lead acid battery. Therefore, electric vehicles are generally powered by lead acid batteries. Series and separately excited dc motors, permanent magnet dc motor, brushless dc motor and induction motor have been used in electric vehicles. The advantages of electric vehicles (EV) over the internal combustion vehicles (ICV) are:

(i) Less pollution.

(ii) Quieter operation.

(iii) Less maintenance: The electric drive being simple requires hardly any maintenance. Unlike ICV, EV has no water cooling system to maintain, no filters, belts, or hoses to replace, or no oil to change.

(iv) More reliable: Due to the presence of fuel injectors, compressors, pumps and valves, water cooling system, filters, an internal combustion engine is lot more complex compared to an electric drive, and therefore, less reliable.

The disadvantages are:

(i) More expensive.

(ii) EV cannot go nearly as far on a single charge as comparable ICV can go in a tank of fuel.

(iii) It takes much longer to recharge electric vehicle's battery than it does to fill a petrol tank.

Voltage employed have typical values of 6V, 12V, 24V, 48V and 110V. Higher voltage yields a motor with less weight, volume and cost, but then battery cost becomes high.

INDUSTRIAL APPLICATIONS

Multiple Choice Type Questions

1. For application in cranes [WBUT 2009, 2010]
   a) differentially compounded motors are suitable
   b) cumulatively compounded motors are suitable
   c) *dc* shunt motors are suitable
   d) *dc* series motors are suitable

Answer: (d)

2. In tram cars the electric motor used is [WBUT 2011]
   a) a *dc* separately excited motor
   b) a *dc* series motor
   c) a squirrel cage induction motor
   d) a synchronous motor

Answer: (b)

3. In our domestic 230 V ceiling fans, the motor used is [WBUT 2011]
   a) 3-phase induction motor
   b) 1-phase conventional induction motor
   c) 1-phase hub-type induction motor
   d) synchronous motor

Answer: (c)

4. The regulator of our domestic ceiling fans effectively cause [WBUT 2011]
   a) rotor resistance control
   b) armature voltage control through variation of series resistance
   c) *ac* 1-phase variac type voltage control
   d) none of these

Answer: (b)

5. The motor most suited to crane application is [WBUT 2011]
   a) *dc* series motor
   b) *dc* shunt motor
   c) 1-phase induction motor
   d) stepper motor

Answer: (a)

6. For application in cranes [WBUT 2012]
   a) dc shunt motors are suitable
   b) dc series motor are suitable
   c) induction motors are suitable
   d) synchronous motors are suitable

Answer: (b)

Long Answer Type Questions

1. Write short notes on the following:
a) Drive for paper mills **[WBUT 2009, 2016]**
b) Drive for textile mills **[WBUT 2010, 2012, 2015, 2017]**
c) Drive for cement mill **[WBUT 2013]**

Answer:

a) Drive for paper mills:

In a paper industry, the drives are required for (i) Pulp making, and (ii) Paper making.
In the pulp making process, the logs of wood are either ground in mechanical grinders or else they are chemically treated with alkalis and simultaneously beaten up to turn them into soft pulp. In the mechanical method of pulp making, the electrical power requirement is very high because the wood is hard. Since the mechanical grinders operate at a constant speed of about 200 – 300 rpm, the motors can be started on no load. Thus synchronous motors are used for these drives. These motors normally run at 1000 – 1500 rpm and gears are used to reduce the speed to 200 – 300 rpm.
In the chemical method of pulp making, the logs of wood are continuously beaten by the beaters at the time of treatment with alkali. The power requirement of the beater motors is less than those of grinder motors but these motors require high starting torque. Therefore, slip ring induction motors with gears are used to drive these beaters at about 150 – 200 rpm.

b) Drive for textile mills:

The textile industry requires special types of drives for
(i) weaving and (ii) spinning.

(i) Weaving: The motors used in weaving mills must have good cooling capacity to keep their temperatures within limits in the presence of large power losses. The rating of the motors and the cooling facility must be properly selected because these motors are used in conditions where high moisture content is present along with cage induction motors with high rotor resistance, totally enclosed, fan cooled and having high temperature insulation are used to drive looms. For light fabrics like cotton, silk, nylon etc. small motors of less than 1 hp may be sufficient. For heavy fabrics such as wool, the rating of these motors may be 2-3 hps. These motors are normally run at 750 – 1000 rpm.

(ii) Spinning: The spinning mills use one of the following three types of drives:
(a) A 4-pole or 6-pole squirrel cage induction motor.
(b) A pole amplitude 4/6 or 6/8 poles induction motor.
(c) Two separate motors to be runs at 1500/1000 or 1000/750 rpm. But whatever may be the types of motor used, the motor must be started with controlled torque.

c) Drive for Cement Mills:
Call for a starting torque of about 250% in addition to the speed control feature. The commonly used drives are:

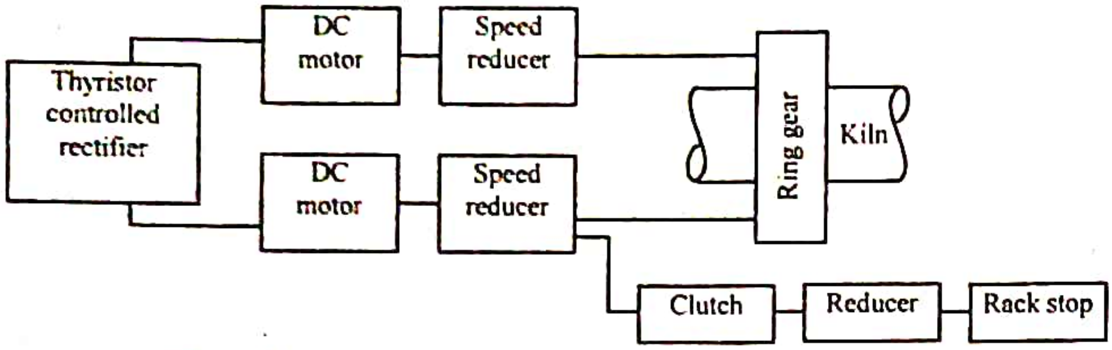


Fig: 1 Layout of twin-motor klin drive for cement plant

(i) Slip ring induction motor
(ii) Three phase shunt wound commutator motor
(iii) Cascade control AC motor
(iv) Ward Leonard controlled DC motor
(v) DC motor with transformer step switch control.

SPEED TORQUE CHARACTERISTICS OF D.C. MOTORS & INDUCTION MOTORS

Multiple Choice Type Questions

1. To get speed higher than the base speed of a d.c. shunt motor [WBUT 2006, 2008, 2017]
   a) armature voltage control is used
   b) field control is used
   c) armature resistance control is used
   d) none of these

Answer: (b)

2. Speed control by varying the armature voltage offers [WBUT 2007, 2010, 2014]
   a) constant power drive
   b) variable power drive
   c) constant torque drive
   d) variable torque drive

Answer: (c)

Long Answer Type Questions

1. Derive mathematically the (a) torque vs. current and (b) torque vs. speed characteristics of d.c. series motor. Draw the characteristics and explain practical significance. [WBUT 2006, 2012]

Answer:

a) Derivation of torque vs current characteristics of series motor

During steady state operation of the motor, the voltage equation is given by:

$$V = E_b + I_a R \qquad \text{.... (1)}$$

where a) V = input voltage, b) E_b = back emf c)R is the total resistance in the armature circuit and d) I_a armature current and in a series motor, the flux 'ϕ' depends upon armature current. Again it is known that back emf generated i.e. $E_b = \frac{\phi ZN}{60} \times \left(\frac{P}{A}\right)$ where Z = total number of armature conductor, A = number of parallel path in armature, ϕ = flux/pole, P = number of poles, N = speed of the armature in rpm.

Now equation (1) may be written as:-

$$E_b = V - I_a R$$

or, $$\phi N\left(\frac{ZP}{60A}\right) = V - I_a R \qquad \text{.... (2)}$$

when expressed in angular velocity ω in radian/sec, then equation (2) may be expressed as

$$\phi\frac{\omega}{2\pi}\left(\frac{ZP}{60A}\right)=V-I_aR$$

or, $$\omega=\frac{V-I_aR}{K\phi} \quad \left[\text{As } \frac{ZP}{120\pi A} \text{ is constant it is denoted by K}\right] \quad \text{.... (3)}$$

The motor torque may be expressed as $T=K\phi I_a$. As already stated that in a series motor, the flux ϕ depends upon armature current and if, for simplification $\phi-I_a$ relationship is assumed to be linear, then $\phi=K_1I_a$. Now

$$T=K\phi I_a=KK_1(I_a)^2$$

i.e., $$I_a=\sqrt{\frac{T}{KK_1}}$$

b) Derivation of Torque vs speed characteristics

Using equation (3), it can be obtained as:

$$\omega=\frac{V}{K\phi}-\frac{I_aR}{K\phi}=\frac{V}{KK_1I_a}-\frac{R}{KK_1}$$

$$=\frac{V}{\sqrt{KK_1}}\cdot\frac{1}{\sqrt{T}}-\frac{R}{KK_1}$$

$$=\frac{A}{\sqrt{T}}-B \quad \text{....(4)}$$

If the flux is assumed to be constant due to saturation of the magnetic circuit, then

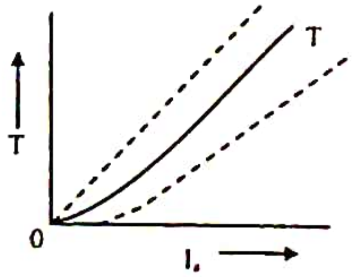
$$\omega=\frac{V}{K\varphi}-\frac{I_aR}{K\varphi}=C-DT\ (\because T\propto I_a) \quad \text{.... (5)}$$

where C and D are constants.

Characteristics and explanation

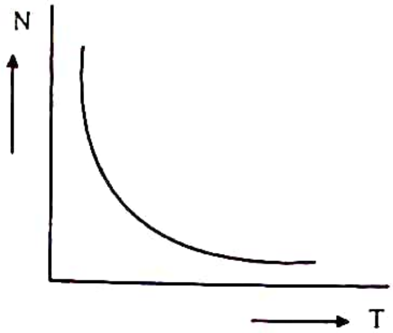
T/I_a Characteristics

In case of series motor, before saturation $T\propto I_a^2$ and as such at light loads, I_a and hence ϕ is small. But as I_a increases, T increases as the square of the current.



Hence T/I_a curve is a parabola as shown above. After saturation, ϕ is almost independent of I_a, hence $T \propto I_a$ only. So the characteristics is a straight line. Sot it can be concluded that (prior to magnetic saturation), on heavy loads, a series motor exerts a torque proportional to I_a^2. Hence a D.C. series motor cannot be used without any load and to be used where high starting torque is required.

Torque vs. speed or mechanical characteristics



From the above it may be seen that when speed is high, torque is small and vice versa.

SPEED CONTROL OF D.C. SHUNT MOTOR BY WARD LEONARD METHOD & BUCK BOOST METHOD

Multiple Choice Type Questions

1. The characteristics of drive for crane hoisting and lowering is [WBUT 2013]
   a) smooth movement
   b) precise control
   c) fast speed control
   d) all of these

Answer: (d)

2. When smooth and precise speed control over a wide range is desired, the motor preferred is [WBUT 2013]
   a) synchronous motor
   b) squirrel cage induction motor
   c) wound rotor induction motor
   d) dc motor

Answer: (d)

Short Answer Type Questions

1. State the advantages & disadvantages of Ward-Leonard drive system. [WBUT 2008]

Answer:

Advantages of Ward-Leonard drive system

i) Very fine speed control over the whole range from zero to normal speed in both directions can be obtained. Speed regulation is good.

ii) It has inherent regenerative braking capacity and uniform acceleration can be obtained.

iii) The lagging reactive volt-amperes of a plant can be neutralized by using an over excited synchronous motor. The overall power factor of the plant also improves.

Disadvantages of Ward-Leonard drive system

i) High initial cost and low efficiency because of an additional M-G set.

ii) Costly foundation and more floor area required.

iii) The drive produces noise and required frequent maintenance.

Long Answer Type Questions

1. Explain with schematic diagram, the principle of operation of Buck-boost method of speed control of D.C motor. [WBUT 2007]

OR,

Write short note on Buck-boost method of speed control of dc motor. [WBUT 2013, 2015]

Answer:

Buck-Boost Method of Speed Control of D.C. Shunt Motors

The method is economical because of the reduced size of the Motor-Generator set and is similar in principle to Ward-Leonard control with the advantages and disadvantages being nearly the same.

The schematic diagram of Buck-Boost method of speed control is shown in Fig. 1:

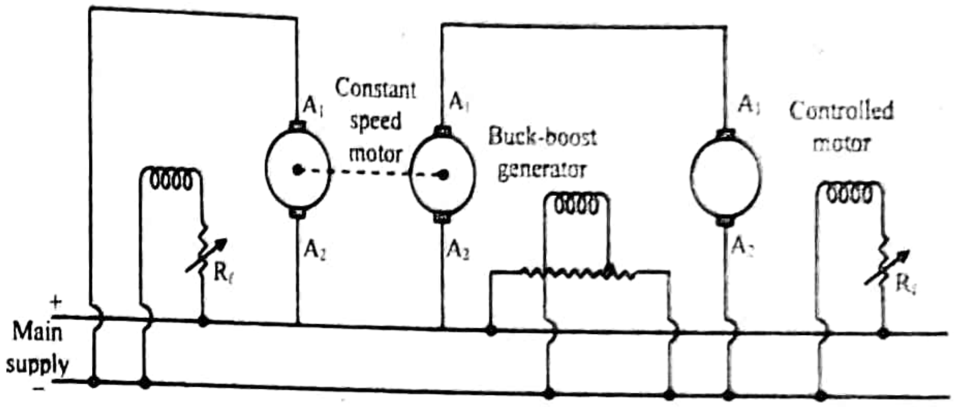


Fig1: Schematic diagram of buck-boost method of speed control of dc shunt motors

It may be seen from Fig (1) above that a varibale voltage generator (Buck-Boost) driven by a constant speed motor is connected in series with the d.c. supply.

At starting, the generator is excited in a direction such that its outpout voltage is in series buck with the dc supply. The potentiometer is adjusted such that the permissible starting current flows through the armature of the controlled dc motor, whose speed depends upon its field excitation (current) and hence, the output voltage of the generator. As the field current is decreased with the help of the potentiometer, the bucking voltage of a generator decreasses too and the net voltage appearing across the motor increases, thus increasing its speed. When the excitatin current of the generator is reuceded to zero, the motor runs at half the rated (base) speed. Beyond this point (mid-point of the potentioneter), the field current is incresed in the opposite direction. The polarity of the generator now reverses, connecting it in series boost with the dc supply. The rated (base) speed is obtained, when the booster voltage is increased by adjustment of its excitation current with the help of the potentiometer such that rated voltage is applied across the motor. The motor field excitation is always at rated value. Beyond the rated (base) speed, the motor speed is controlled by variation of field excitation. The speed control takes place in two modes: (a) armature voltage control and (b) field excitation (current) control.

2. Explain the operation of Ward-Leonard drive system with suitable diagram. Mention the advantages and disadvantages of it. **[WBUT 2012, 2015, 2017]**

Answer:

Ward Leonard Method

By Ward Leonard method, speed can be controlled over a wide range in either direction. The schematic diagram is shown in Fig. (1) below:

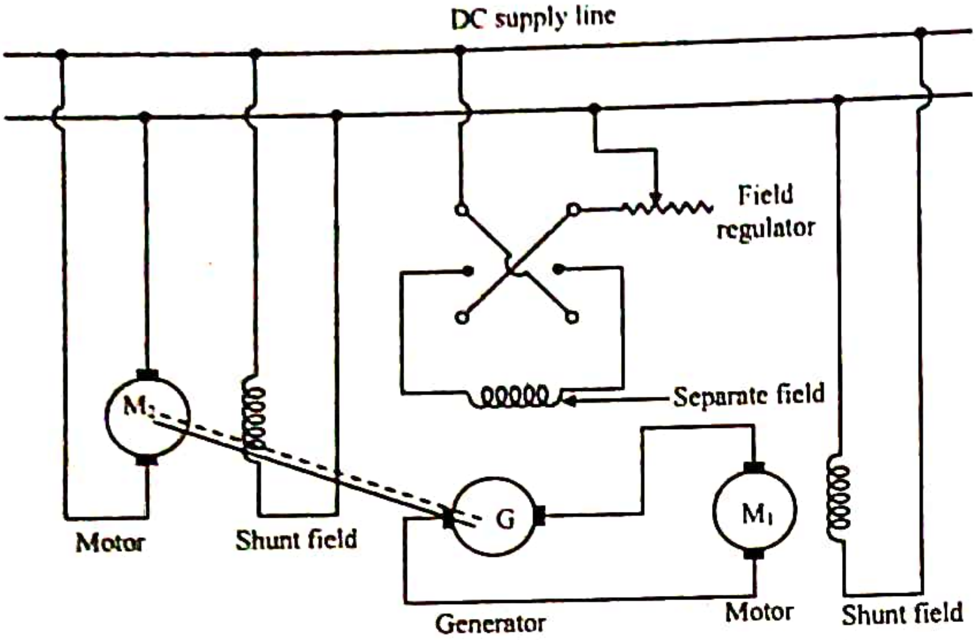


Fig: 1 schematic diagram of the ward-Leonard method of speed control of d.c. shunt motor

In the above figure, the machine M_1 is the motor whose speed is to be controlled. There are two more machines, a motor M_2 and a generator G, which are mechanically coupled together. The motor M_2 gets the supply from the line and its output is coupled to the generator, i.e. M_2 acts as the prime-mover to G.

The field of the generator 'G' is supplied from the line through a regulator. So flux of 'G' is controlled, which will control its generated e.m.f.

It is known that generated emf, $E_g = \frac{P\phi ZN}{60A}$

This voltage is given as input to the motor M_1 and hence the speed is indirectly controlled.

i.e., $N_{M_1} \propto \frac{V - I_a R_a}{\phi}$

In this case since flux is not controlled, it is a constant,

Therefore, $N_{M_1} \propto V_{M_1}$ where $V_{M_1} \propto E_{gG} \propto \phi_G$

This method will give a very sensitive control of speed but this is of costly because of using two machines to control the speed of the third machine.

Also ***Refer to Question No. 1 of Short Answer Type Questions.***

SOFT-START

Short Answer Type Questions

1. What do you mean by soft start? **[WBUT 2007, 2010]**

Answer:

When a 3-phase a.c regulator using back-to-back connection of thyristors or triacs in the supply lines for phase control operation is used, then the system is termed as soft start of a 3-phase induction motor.

At start, 180° delay is provided. Phasing forward is controlled at a pre-determined rate or by monitoring acceleration so that the starting process is without mechanical or electrical shock. The current limit controller may be incorporated to maintain the starting current at preset value. However, it may be noted that the frequency must remain constant. Soft starters can have soft stop included for no extra cost. Soft stop is the opposite of soft start. The voltage is gradually reduced, reducing the torque capacity of the motor. The reduction of available torque causes the motor to begin to stall when the shaft torque of the motor is less than the torque that is required by the load. As the torque is reduced, the speed of the load will reduce to the point where the load torque equals the shaft torque. Typically, the soft stop used is an open loop voltage ramp. but there are some torque control soft stop systems that use torque feedback to provide better control over the deceleration of the motor.

Open loop soft stop performance is very dependent on the characteristics of the motor and driven load. On larger machines this can be very non linear and provide poor performance.

Soft stop effectively adds inertia to the load and extends the braking time. It should only be applied to installations where the stopping time is too short and needs to be extended. Soft stop does not provide any measure of braking.

ELECTRIC TRACTION

Multiple Choice Type Questions

1. The common method of speed control used in 25 kV, 50 Hz, 1-phase traction system is [WBUT 2006, 2008]
   a) tap changing control
   b) reducing current method
   c) series parallel method
   d) none of these

Answer: (c)

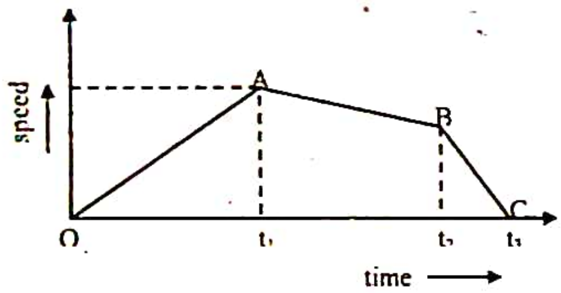
2. In case of series parallel control of two identical d.c. motor, the capacity of each motor is [WBUT 2007]
   a) half of the capacity of the load
   b) twice the capacity of the load
   c) equal to the capacity of the load
   d) none of these

Answer: (a)

3. The value of co-efficient of adhesion will be high when rails are [WBUT 2008]
   a) greased b) wet c) sprayed with oil d) none of these

Answer: (d)

4. The speed time curve for a local train is shown in figure below. [WBUT 2008]



In this *AB* represents
   a) coasting b) acceleration c) braking d) regeneration

Answer: (a)

5. For application in traction [WBUT 2015]
   a) dc series motors are suitable
   b) dc shunt motors are suitable
   c) dc compound motors are suitable
   d) synchronous motors are suitable

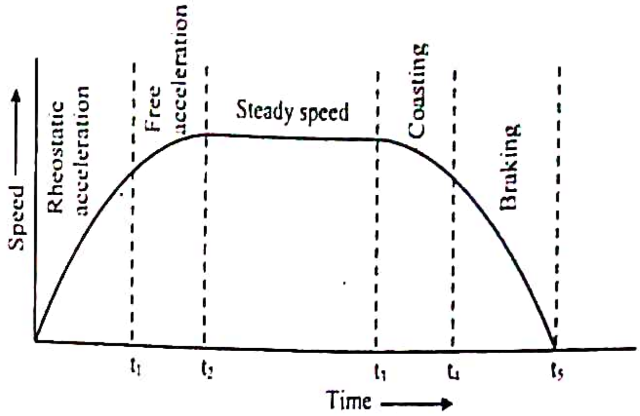
Answer: (a)

Short Answer Type Questions

1. With approximate speed-time curves explain the operation of a traction drive related to urban train services. [WBUT 2011]

Answer:

In electric traction related to urban train services frequent start, stop and high-speed schedules are required. In general, while moving from one station to another, the motion of the train may be represented by speed time curve as under:



1. During rheostatic acceleration, the starting resistance is cut out step-by-step so as to maintain constant current and constant acceleration.
2. At instant t_1, all starting resistance has been cut out. The train continues to accelerate up to the instant t_2, when balancing or steady speed is reached.
3. The train runs freely at steady speed in this section.
4. When the train approaches a stop, the power supply to the traction motors is switched off. The speed falls, but the train continues to run due to momentum. The duration is called the coasting.
5. First the electric brake and then the mechanical brake is applied to stop the train.

Long Answer Type Questions

1. a) What are the characteristics that a traction motor should possess? How does a d.c. series motor fit into such requirement? **[WBUT 2006, 2008]**

Answer:

The characteristics of a traction motor are

1. The traction motors must be capable of withstanding voltage fluctuations and interruptions of power supply and must be amenable to simple speed control methods.
2. Power to weight ratio of the traction motor should be high so that it occupies less space.
3. High tractive effort at starting.
4. It should be possible to overload the motor for a short period.
5. Ability of traction motors to apply; regenerative braking during descent.
6. Coefficient of adhesion should be high.
7. Traction equipments should be robust and steady enough to withstand continuous vibrations, dust and humid environment.

Type of motors suitable to meet the requirement of electric traction:

The major requirements of electric traction as stated above are met by d.c. series motors which provide sufficient tractive effort to set the train in motion for optimal run between the stops from the point of view of energy consumptions. It will not be out of place to mention that while moving from one station to another, the motion of the train may be of the following types:

1) During rheostatic acceleration, the starting resistance is cut out step-by-step so as to maintain constant current and constant acceleration.
2) At the instant say t_1, all starting resistance has to be cut out. The train continues to accelerate up to the instant say t_2, when balancing or steady speed is reached.
3) The train runs freely at steady speed in this section.
4) When the train approaches a stop, the power supply to the traction motors is switched off. The speed falls, but the train continues to run due to momentums. This duration is called the coasting period.
5) First the electric brake and then the mechanical brake is applied to stop the train.

Now if the total resistance offered by the windage and friction to the motion of the train along with the series motor characteristic is represented graphically, it will be as under:

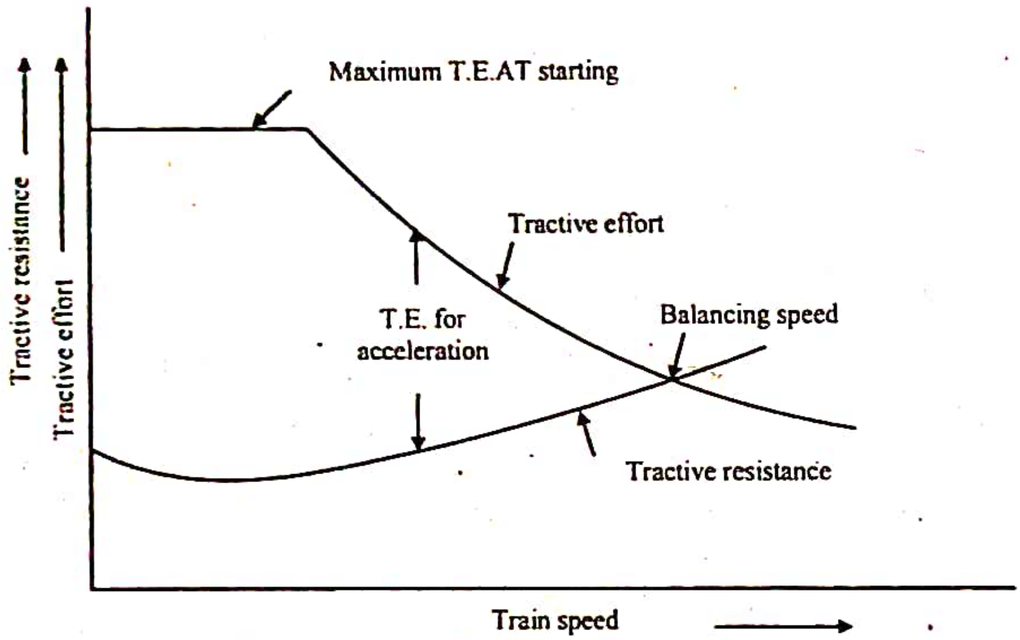


Fig: 1

It may be observed from the above Fig. (1) that:

1. The maximum tractive effort is produced at starting when the motor is separately excited.
2. The difference between the TE offered by the motor and the tractive resistance is the force available for accelerating the train.
3. As the train gains speed, TE gradually decreases and eventually the balancing speed is reached.

All these lead to conclude that a series motor offers the best speed torque characteristic for electric motor.

b) What is series-parallel control for starting two d.c. series motor that will ultimately operate in parallel? What are its advantages compared to those of the rheostatic starting of individual motor? **[WBUT 2006, 2008]**

Answer:

Series-Parallel control of two identical d.c. series motor in electric traction system

When two or more similar series motors are employed in pairs, as in electric traction, speed control can be obtained by combining series resistance with series and parallel connections, as illustrated in Fig. (1), then the method is called Series-Parallel Control.

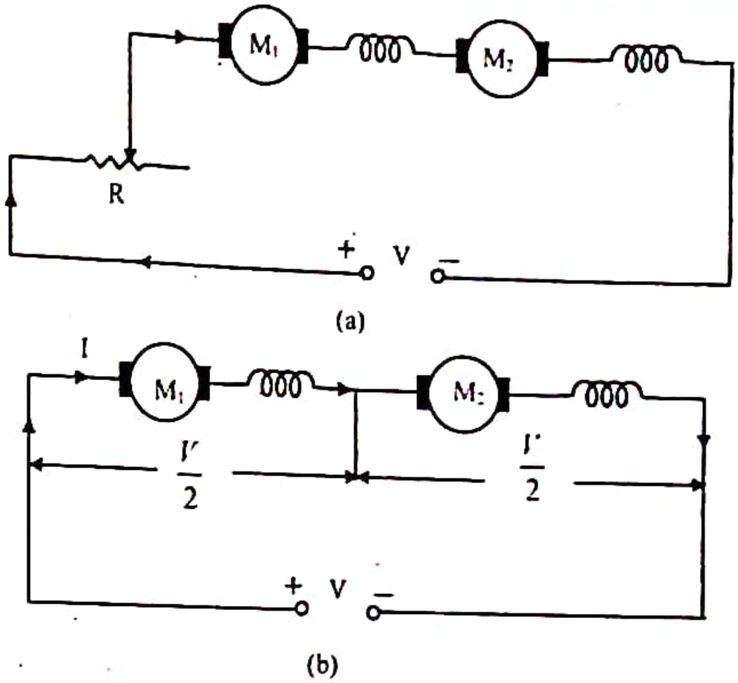
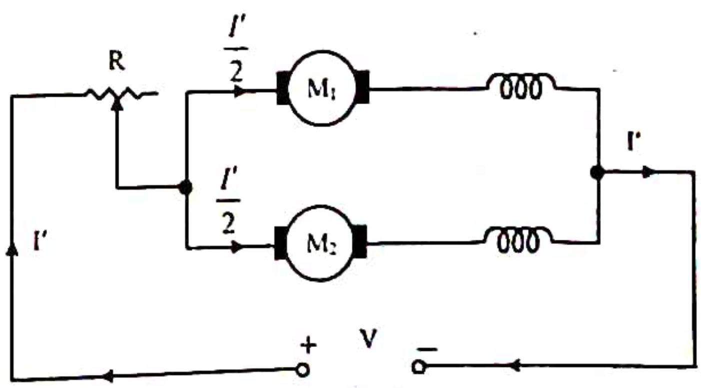


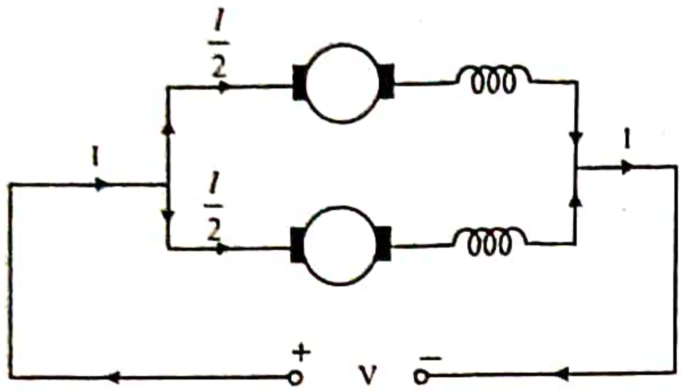
Fig: 1

The machines are started up in series with each other and a starting or control resistance as illustrated in Fig. 1(a). The additional resistance is gradually cut-out the controller as the motors attain speeds and finally the control resistance is totally removed, then each motor has one half of the line voltage across it, as shown in Fig. 1(b). This is the first running position. In this position for any given value of armature current, each motor will run at half of its normal speed.

Since there is no external resistance in the circuit, hence there is no waste of energy and so motors operate at anefficiency nearly equal to that obtainable with full line voltage across the terminal of each motor.



(c)



(d)

Fig: 1

If it is required to increase the speed of the combination, two motors are connected in parallel. and in series with a variable resistance R, as shown in Fig. 1(c). This resistance is gradually cut out as the motors attain the speed and finally when this resistance is totally removed from the circuit, as illustrated in Fig. 1(d), the second running position is obtained. In this position each motor is connected across the full line voltage. If the line voltage is taken as V volts and line current 1 amperes, then:-

i) When motor are connected in series and are in running position.

Voltage across each motor $= \frac{V}{2}$

Current through each motor = I

$$\text{Speed} \propto \frac{\text{Voltage}}{\text{Current}}$$

$$\propto \frac{V}{2I} \qquad \text{.... (1)}$$

$$\text{Torque} \propto \phi I \propto I^2 \qquad \text{.... (2)}$$

(Since $\phi \propto I$, assuming unsaturated field)

ii) When motors are connected in parallel and are in running position

Voltage across each motor = V

Current through each motor $= \frac{1}{2}$

$$\text{Speed} \propto \frac{\text{Voltage}}{\text{Current}}$$

$$\propto \frac{V}{I/2} \propto \frac{2V}{I} \qquad \text{.... (3)}$$

$$\text{Torque} \propto \text{Flux} \times \text{current} \propto (\text{current})^2 \propto \left(\frac{I}{2}\right)^2 \propto \frac{I^2}{4} \qquad \text{.... (4)}$$

Comparing Eqns. (1) and (3) for the speeds of motors we observe that speeds of the motors when running in parallel is 4 times that while running in series. But from Eqns. (2) and (4) of torque we observe that torque of the motor when running in series is 4 times that while running in parallel.

Switching Sequence:

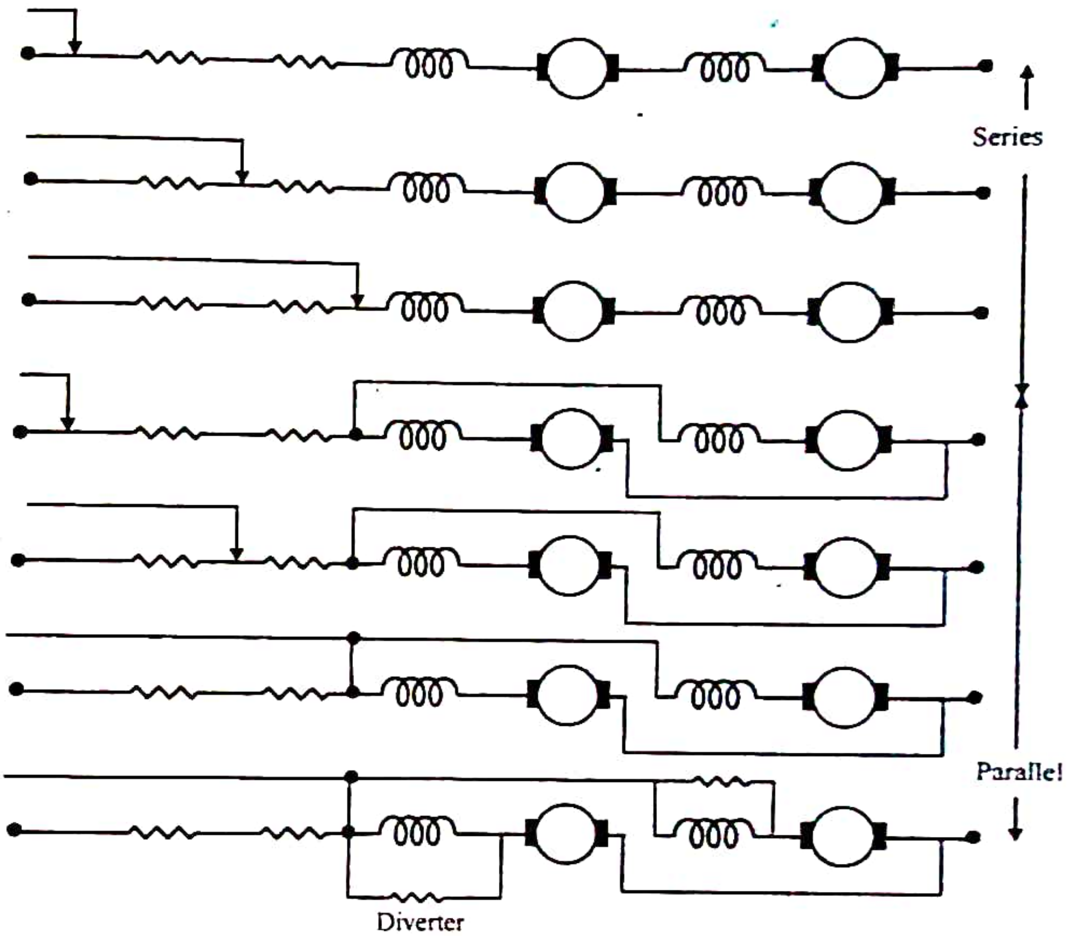


Fig: 2 A diagram of connections illustrating the switching sequence is given

Advantages

There are several advantages of this method of speed control. It is more economical than providing each motor with a separate starting resistance or by connecting the motors permanently in parallel with only single starting resistance. It reduces the starting and braking time by reducing the overall moment of inertia. because in this control system two motors, each rated for half the required load capacity are used. It provides higher reliability of operation. It is more convenient to use two motors of smaller size than one of the larger size in view of space limitations. Finally it provides two speeds without wastage of power.

2. Write short notes on the following:

a) Traction motor control **[WBUT 2007]**

b) Series parallel control of D.C. motor **[WBUT 2008, 2014]**

c) EMU. **[WBUT 2008]**

Answer:

a) Traction motor control:

Although the speed of traction motors is controlled by the combined series-parallel method, and rheostatic method which dealing with speed control of d.c. motors, there may be different arrangements of motor connections yielding different speeds. This is mainly due to the reason that for long distance trains, acceleration and braking periods are negligible compared to running time and on the other hand, free running is almost absent for suburban trains.

In general, in electric traction, four or six identical motors are used and constant horsepower operation takes place. There are separate notches of the master controller for different speeds. Accelerating resistance is used for adjustable voltage control of d.c. traction motors placed under the carriage. For getting various speeds, transformer output voltages are also adjusted with the help of on load tap changers.

By way of giving an example, it may be mentioned that a six motor locomotive having each motor rated for half the line voltage may undertake the following connections:

i) Three sets connected in parallel yielding full speed.

ii) Three sets connected in series yielding one-third full speed.

Series-Parallel control of two identical d.c. series motor in electric traction system:
Refer to Question No. 1. (b) of Long Answer Type Questions.

b) Series parallel control of D.C. motor:

When two or more similar series motors are employed in pairs (mechanically coupled) as in electric traction, speed control can be obtained by combining series resistance with series & parallel connection as shown in fig. (a) & (b).

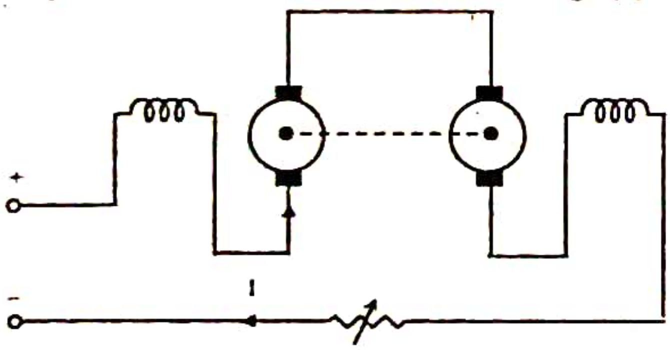


Fig: (a) Series connection

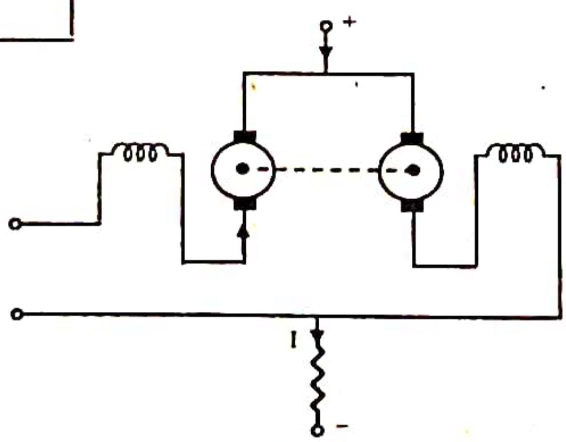


Fig: (b) Parallel connection

In this method the size of each motor as well as connection the moment of inertia is the decreased, thus shortening the time of starting & braking. The capacity of each motor is approximately half of the capacity of the load.

When intermediate speeds are required, a series resistance to be inserted in the armature circuit. In order to utilize full motor capacity, speed control has to be done at const. output torque. The total torque characteristics of a pair of series motor is shown below fig. (c).

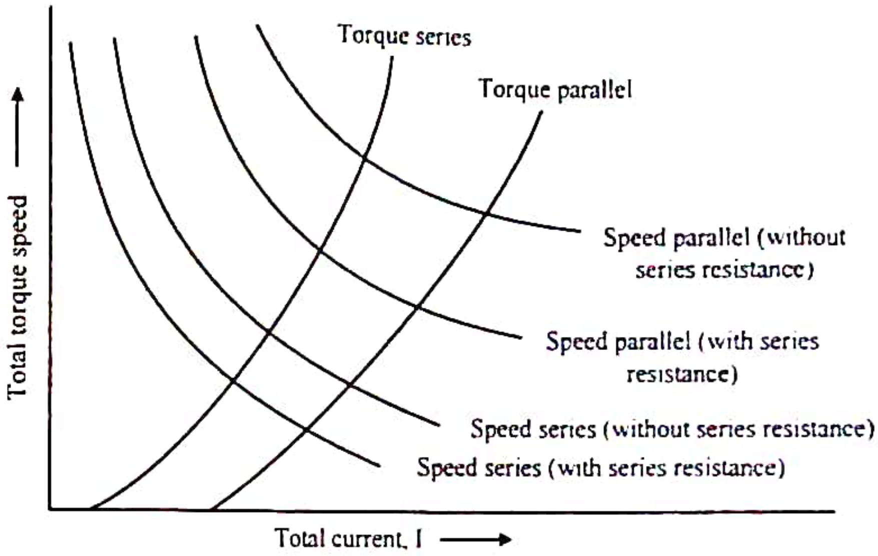


Fig: (c) Total characteristics of a pair of series motors

Uses of these drives:

1) Ladle cranes
2) Electric trains
3) Trolley cars
4) Blast furnace Skip Hoists etc.

c) EMU:

The suburban trains or local trains are driven by motor coaches. instead of locomotives. Each motor coach is equipped with an electric drive with its control in driver's cabin and a pantograph collector. Usual pattern is to use motor coaches and trailer coaches in the ratio 1: 2. In high speed trains the ratio may be increased to 1:1. The trains employing motor coaches and trailer coaches are also known as electrical multiple unit (EMU) trains. Such an arrangement provides the flexibility in train size. During light traffic periods, one or two units, each consisting of one motor coach and two trailer coaches form a train. During rush hours, number of such units are coupled together. Each unit is provided with local and remote control equipment, so that all the motor coaches of a train can be controlled from the driver's cabin of the front motor coach.

MICROPROCESSOR-BASED CONTROLLER FOR DC MOTOR DRIVES

Multiple Choice Type Questions

1. The advantage of PWM inverter over a Voltage Source Inverter is [WBUT 2013]
   a) higher order harmonics are eliminated inherently
   b) lower order harmonics are eliminated inherently
   c) harmonics are not introduced into the circuit
   d) both higher and lower order harmonics are introduced

Answer: (b)

MISCELLANEOUS

Long Answer Type Questions

1. Write short notes on the following:
a) Brushless DC motors **[WBUT 2009]**
b) Switched Reluctance motor. **[WBUT 2014, 2016]**

Answer:

a) A brush less dc motor is a motor drive system that combines into one unit poly phase ac synchronous motor, solid-state inverter and a rotor position sensor. The solid-state inverter uses transistors for low power drives and thyristors for high power drives. It is also viewed as "Inside - out" d.c. motor because its construction is opposite to that of a conventional d .c motor. It has a permanent magnet field poles on the rotor and poly phase armature winding on the stator. The function of mechanical commutator in a conventional d c motor is now performed by electronic commutator. Rotor position sensor monitors the shaft position and sends the control signals for turning on the controlled switches of the inverter in an appropriate sequence.

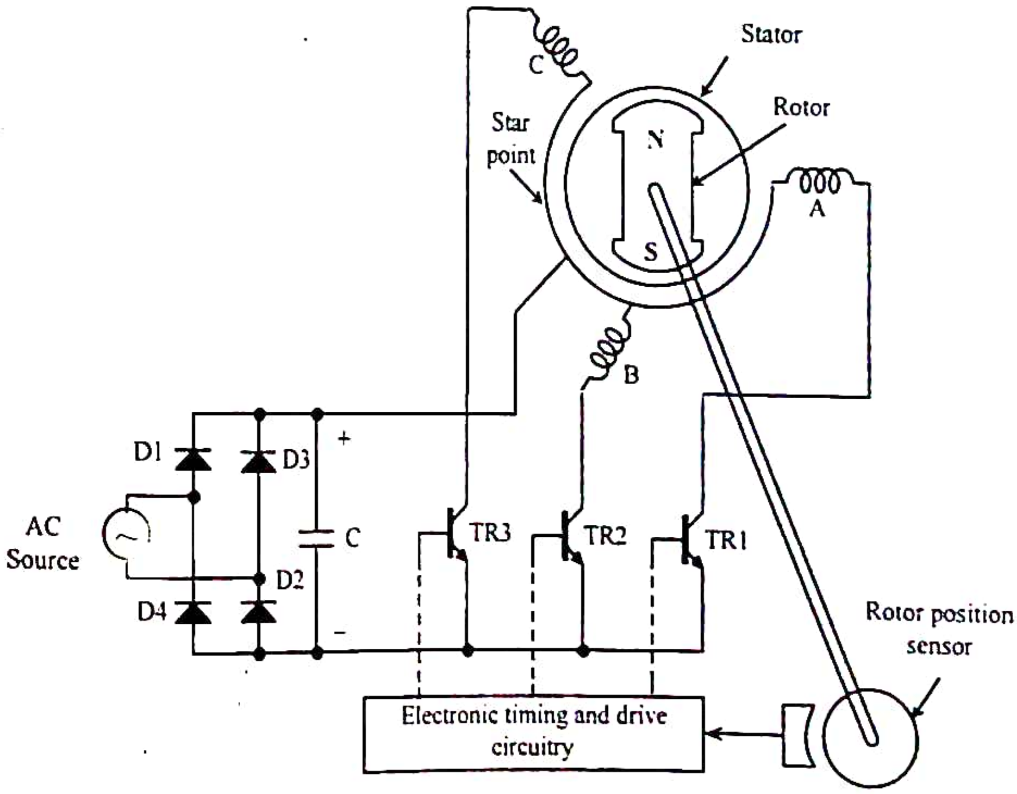


Fig: (i) 3-phase 3-pulse brushless dc motor

The above Fig. (i) shows a 3-phase, 3-pulse brush less d c motor along with its electronic controller, and the stator has 3ϕ winding connected in star. The neutral is connected to positive terminal of d c supply. Full-bridge diode converts ac to dc and the capacitor C serves as a filter circuit.

When transistor TR_1 is turned on, phase A is energized and when TR_2 is on, phase B is energized and so on. If the phase windings are energized in sequence ABC, the rotor rotates clockwise and with sequence ACB, the rotor revolves anti clockwise.
The commonly used rotor position sensors are Hall effect sensor and electro-optical sensor, which consists of a light emitting diode (LED), Phototransistor and a shaft mounted slotted wheel.

Operating Principle

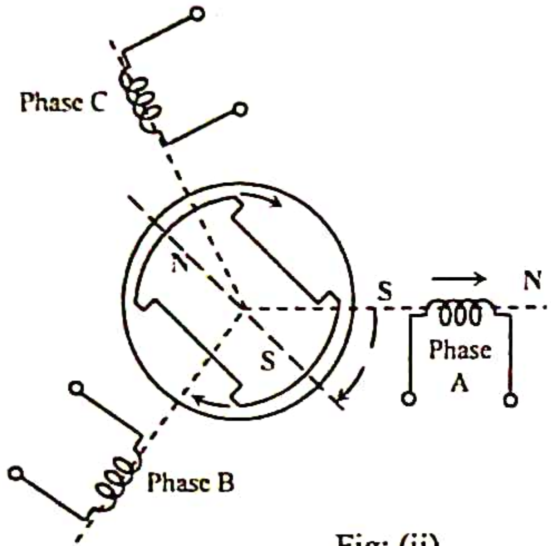


Fig: (ii)

In order to understand the basic operating principle of a brush less DC motor Fig. (ii) as above may be referred to.
When phase A is energized, South (S) and North (N) poles of the stator are created as shown. The South pole of stator repels the south pole of rotor and attracts North pole (N) of rotor there by producing clock-wise torque, the magnitude of which is given by: –

$$T_c = K_1\phi_s\phi_r\sin\theta \quad \text{.... (1)}$$

where ϕ_s, ϕ_r represent stator and rotor field flux, θ = torque angle and K_1 = torque constant. As ϕ_r is produced by permanent magnet, the strength of rotor field flux is constant. As stator current is constant, the stator field flux will also be constant. In view of this, the Eqn. (1) may be written as

$$T_{ea} = KI_a\sin\theta \quad \text{.... (2)}$$

where I_a is the constant stator current in phase A.
The Eqn. (2) shows that torque developed by phase A varies sinusoidally with torque angle θ, which may be seen from Fig. (iii) below:

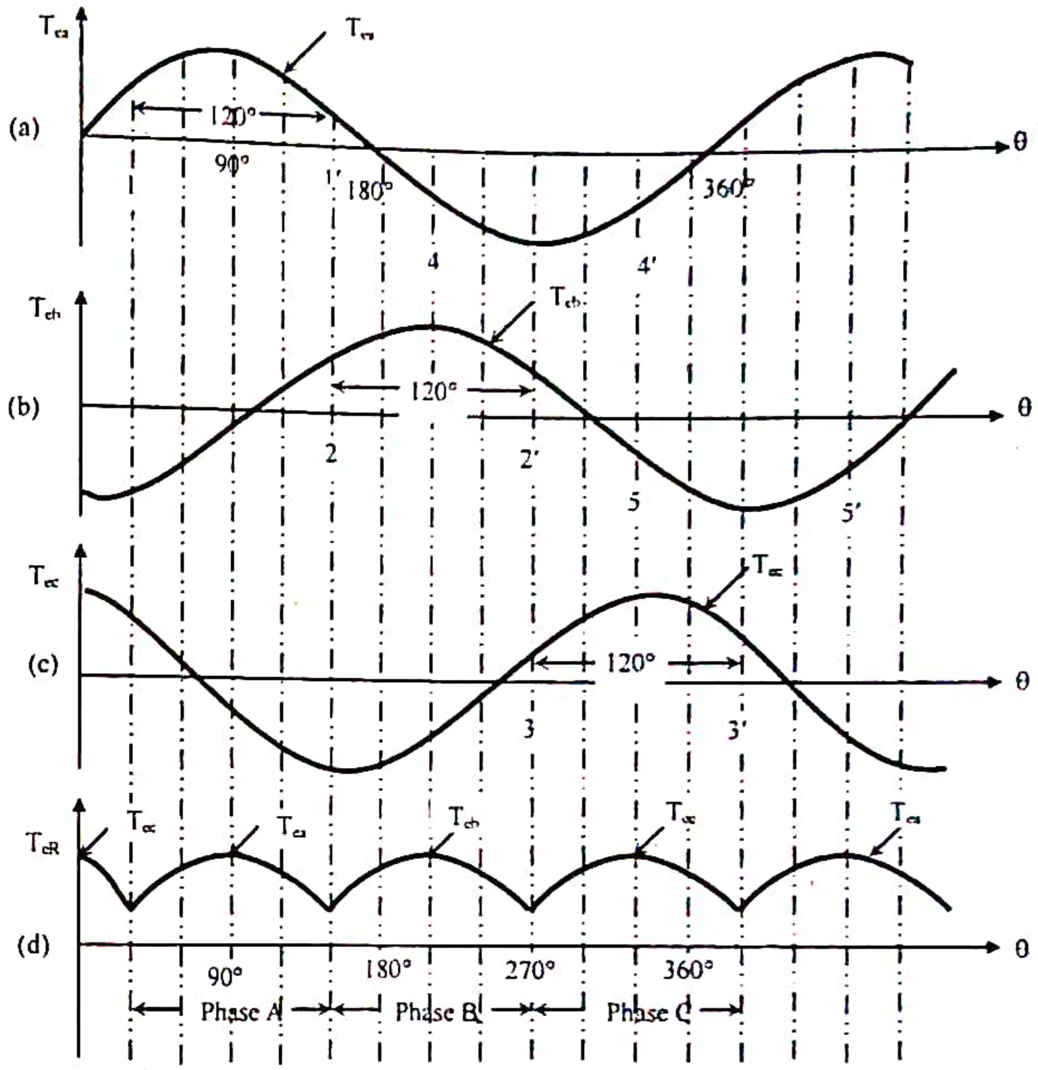


Fig: (iii)

Fig (a) shows torque developed by phase A which varies sinusoidally with torque angle θ.

Fig (b) shows displacement of the axis of phase winding B by 120° from phase A axis Resulting shifting of the developed torque T_{eb} by phase B by 120° from Torque T_{ea}.

Fig (c) shows the developed torque by Phase C sketched as Tec

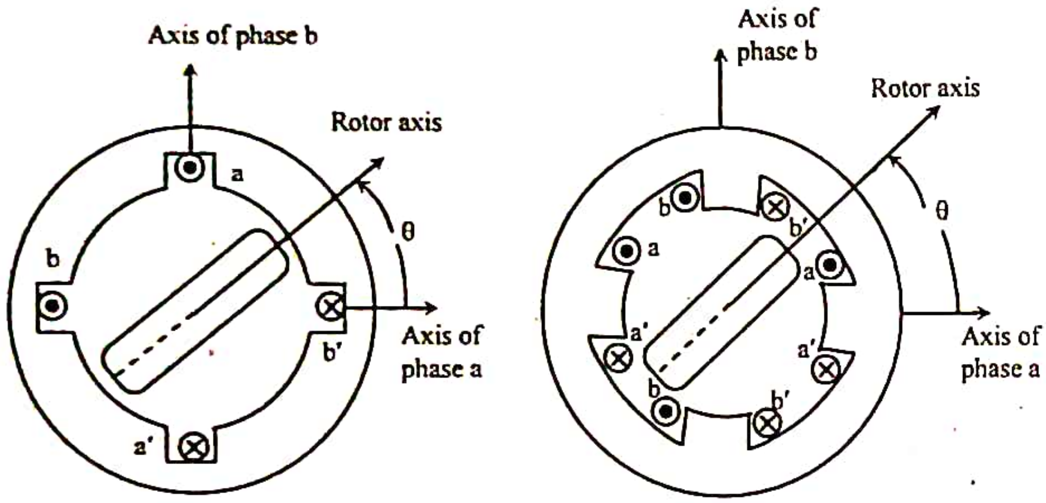
Fig (d) shows the positive torque developed Sketched as T_{ea}

[from instant 1 (θ = 30°) to instant 1′ (θ = 150°)]

In fact for the operation of this motor as a brush less d.c. motor, phase winding 'A' is energized through transistor TR_1 of Fig. (i) from instant $1(\theta = 30°)$ to instant I'' $(\theta = 150°)$ so that positive torque T_{ea} is developed which may be seen from Fig. (iii)(d).

b) Switched Reluctance motor:
Switched reluctance motor is also known as variable-reluctance motor (VRM). The name switched reluctance motor is just to indicate that switching inverter is required to drive a VRM. It has concentrated windings on stator poles and no winding on the rotor teeth and should not be confused with synchronous motor which in fact has cylindrical stator with distributed windings and salient pole rotor with concentrated field winding. It is designed for continuous rotation and required a rotor position sensor. Further, it can be operated from unidirectional drive circuits resulting reduction of cost of micro and power electronics. As these motors can be manufactured with a large number of stator and rotor teeth, they give large torque per unit volume.

Construction



(a) (b)

Fig: 1

These motors may be of i) single salient construction as shown in Fig. 1(a) above consisting of a non-salient stator and a two pole salient rotor which has no winding but the cylindrical stator has two phase winding and ii) doubly salient construction as shown in Fig. 1(b) consisting of four salient poles on stator and the rotor has two salient poles with no winding. The concentrated windings on radially opposite poles are connected in either series or parallel to result in two phases winding on stator. This shows that both motors of Fig. (4) have two-phase stator winding and a two pole salient rotor.

Principle of Operation

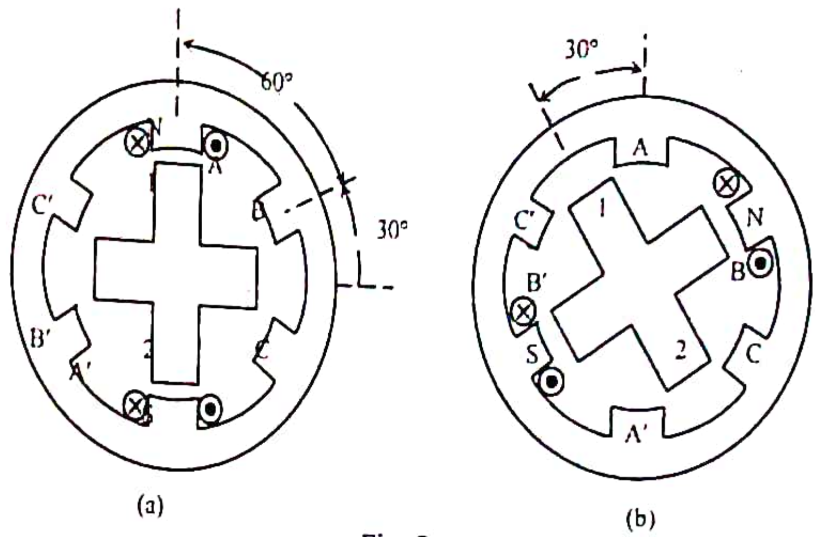


Fig: 2

With phase winding 'A' excited, the rotor orientation is shown in Fig. 2(a) and the flux linkages are maximized with phase A. When phase winding A is de-energized and phase winding B is excited, the rotor moves counter clockwise (CCW) so as to maximize the flux linkages with phase B Fig. 2(b). For further counter clockwise rotation, phase winding B is de-energized and phase winding C is energized. In fact, the phase current to stator phases are switched on and off in synchronism with rotor position so that continuous rotor position is achieved and a steady average torque is developed. The synchronization of the switching of phase windings with the rotor position is essential for continuous rotor rotation for which purpose, a shaft mounted sensor of the Hall effect type or electro optical type is a must.

Torque Production

Inductance of each stator phase winding varies with rotor position; it is maximum when axis of stator phase winding coincides with the rotor axis. The reluctance torque developed in variable reluctance motor under the assumption of magnetic linearity, can be expressed as $E_e = \frac{1}{2} i^2 \frac{dL}{d\theta}$ where i is the instantaneous value of exciting current in the phase winding and L is the self inductance of the phase winding. The sign of the torque is however dependent upon the variation of inductance with rotor position θ. Inductance variation of stator phase winding with respect to θ and torque angle characteristics are shown in Fig, 3(a) and 3(b).

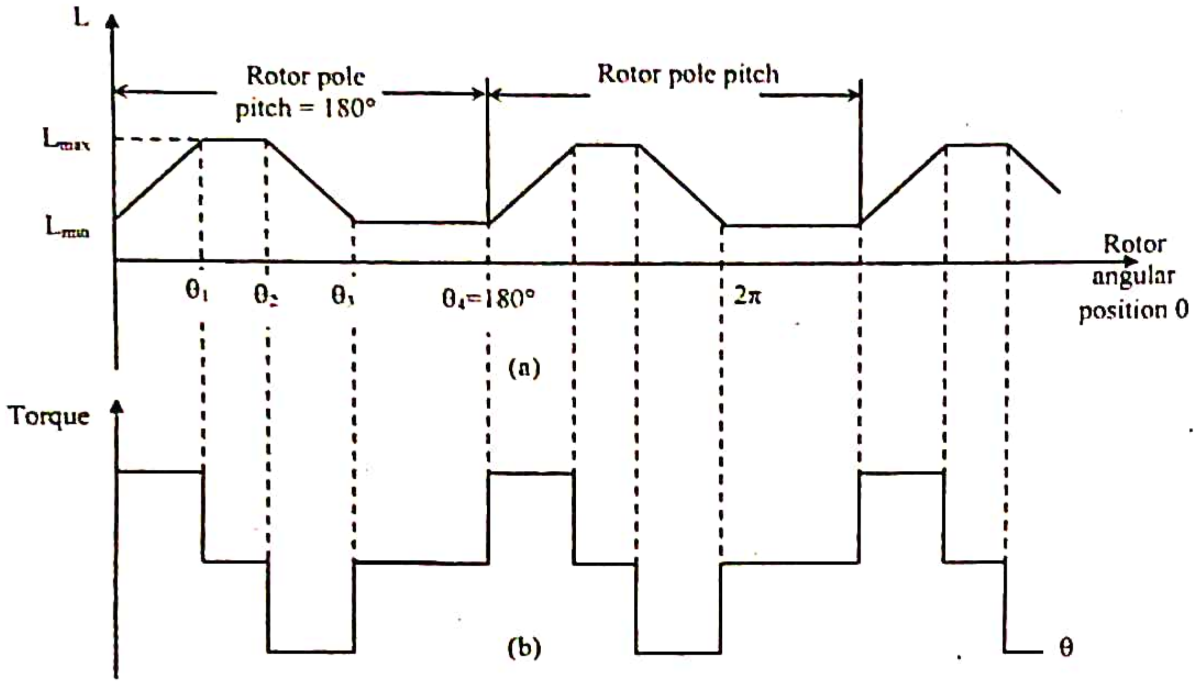


Fig: 3

It may be observed from Fig. 3(a) that the variation of inductance from L_{min} to L_{max} is linear. The variation of reluctance torque is rotor angular position as shown in Fig. 3(b) for a constant stator current in the phase winding. It may be observed further that reluctance torque is positive when $\frac{dL}{d\theta}$ is positive and torque is negative for negative value of $\frac{dL}{d\theta}$.

No reluctance torque is produced when L is constant. Operation of motor for the condition of negative torque leads to regenerative process of VRM drive system. This shows that torque in VRM can be controlled by shifting the switching "ON" and "OFF" instants of the phase windings during the cycle of inductance variation.

Operating Mode

In variable reluctance motors, there are two types of operating modes viz.:

i) Single pulse mode also called high speed mode
ii) Pulse width operation mode (PWM) also called low speed mode.

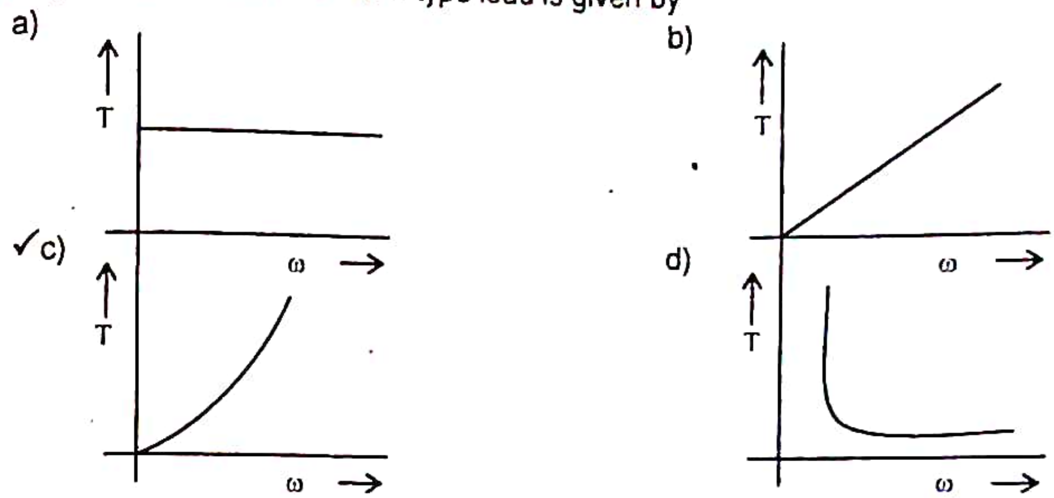
QUESTION 2013

Group – A

(Multiple Choice Type Questions)

1. Choose the correct alternatives for any *ten* of the following:

i) The speed-torque curve of a fan-type load is given by



ii) For a constant torque drive, power will be

✓a) directly proportional to the speed
b) inversely proportional to the speed
c) independent of speed
d) directly proportional to the square of the speed

iii) The slip s for reversal of any induction motor is

a) $s-1$ b) $1-s$ ✓c) $2-s$ d) $1-2s$

iv) A single motor which actuates several mechanisms or machines is called

✓a) group drive b) individual drive c) multi-motor drive d) active drive

v) Stator voltage control of Induction motor is suitable for applications where

✓a) torque demand reduces with speed
b) torque demand increases with speed
c) torque demand reduces with increase of speed
d) torque demand increases with reduction of speed

vi) For slip power recovery method for a positive P_r where $P_r = P_g - P_m$, the induction motor will run at a speed

a) higher than the rated speed ✓b) lower than the rated speed
c) at the rated speed d) none of these

vii) A motor driving a passive load is said to be steady state stable if

✓a) $\frac{dT_L}{d\omega} - \frac{dT_M}{d\omega} = 0$ b) $\frac{dT_L}{d\omega} - \frac{dT_M}{d\omega} < 0$

c) $\frac{dT_L}{d\omega} - \frac{dT_M}{d\omega} > 0$ d) all of these

viii) A three-phase induction motor operates at a constant rotor frequency when the stator frequency is varied from zero to rated value. The torque developed by the motor is

✓a) constant from zero to rated speed
b) proportional to speed
c) proportional to square of speed
d) inversely proportional to speed

ix) The advantage of PWM inverter over a Voltage Source Inverter is

a) higher order harmonics are eliminated inherently
✓b) lower order harmonics are eliminated inherently
c) harmonics are not introduced into the circuit
d) both higher and lower order harmonics are introduced

x) When smooth and precise speed control over a wide range is desired, the motor preferred is

a) synchronous motor
b) squirrel cage induction motor
c) wound rotor induction motor
✓d) dc motor

The regenerative braking is not possible in case of

✓a) dc series motor
b) induction motor
c) dc shunt motor
d) dc separately exited motor

The characteristics of drive for crane hoisting and lowering is

a) smooth movement
b) precise control
c) fast speed control
✓d) all of these

Group – B

(Short Answer Type Questions)

2. What are the advantages and disadvantages of group electric drive over individual electric drive?
See Topic: ELECTRICAL DRIVE, Short answer Type Question No. 1(b).

3. Discuss the effect of flywheel incorporated with an electric drive under shock loading condition.
See Topic: DYNAMICS OF ELECTRICAL DRIVES, Short Answer Type Question No. 5.

4. Describe with a neat diagram four quadrant operation of a motor driving a hoist load.
See Topic: DYNAMICS OF ELECTRICAL DRIVES, Short answer Type Question No. 4.

5. How can a separately excited dc motor be controlled using a chopper?
See Topic: DC MOTOR DRIVES (RECTIFIER AND CHOPPER FED), Long answer Type Question No. 3(a).

6. Describe the regenerative breaking operation of an 3-phase induction motor.
See Topic: BRAKING OF ELECTRIC DRIVES, Short Answer Type Question No 3.

Group – C

(Long Answer Type Questions)

7. a) Explain why VVVF control drive is better than either variable voltage or variable frequency control drive.
b) Give a short description of different schemes of VVVF control drive.
c) Describe the 180 deg conduction mode operation of 3-phase VSI.
See Topic: SYNCHRONOUS MOTOR DRIVES, Long Answer Type Question No. 3.

8. a) Derive the heating characteristics of an electric motor. Define heating time constant.
b) A motor has a thermal heating time constant of 45 minutes. When the motor runs continuously at full load, its final temperature rise is 80°C.
(i) What would be the temperature rise after 1 hour, if the motor runs continuously of full load?
(ii) If the temperature rise in 1 hour rating is 80°C, find the maximum steady-state temperature at this rating.
(iii) How long will the motor take for its temperature to rise from 50°C to 80°C, if it is working at its 1 hour rating?
See Topic: MOTOR POWER RATING, Long Answer Type Question No. 4.

9. a) Draw the speed torque characteristic for dynamic braking operation of dc series motor. Why does torque become zero at finite speed?
b) A 230 V separately excited dc motor takes 50A at a speed of 800 rpm. It has armature resistance of 0.4Ω. This motor is controlled by a chopper with an input voltage of 230 V and frequency of 500 Hz. Assuming continuous conduction throughout, calculate the speed-torque characteristics for:
(i) Motoring operation at duty ratios of 0.3 and 0.6
(ii) Regenerative braking operation at duty ratios of 0.7 and 0.4.
See Topic: BRAKING OF ELECTRIC DRIVES, Long Answer Type Question No. 4.

10. a) When plugging is employed for stopping an induction motor, why is it necessary to disconnect it from supply when speed reaches close to zero?
b) Explain the principle of slip power recovery scheme of controlling the speed of induction motor, using static Scherbius Drive.
c) Explain the variable frequency control of synchronous motor drive.
a) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 12(a).
b) See Topic: INDUCTION MOTOR DRIVES, Long answer Type Question No. 12(b).
c) See Topic: SYNCHRONOUS MOTOR DRIVE, Long Answer Type Question No. 4.

11. Write short notes on any *three* of the following:
   a) Electrical drives and its components
   b) Buck-boost method of speed control of dc motor
   c) Solar and Battery powered drives
   d) Drive for cement mill
   e) Vector control of Induction motor.
a) See Topic: ELECTRICAL DRIVE, Long Answer Type Question No. 1.
b) See Topic: SPEED CONTROL OF D.C. SHUNT MOTOR BY WARD LEONARD METHOD & BUCK BOOST METHOD, Long answer Type Question No. 1.
c) See Topic: SPECIAL TYPE DRIVES, Long answer Type Question No. 1(b).
d) See Topic: NDUSTRIAL APPLICATIONS, Long Answer Type Question No. 1(c).
e) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 16(d).

QUESTION 2014

Group – A
(Multiple Choice Type Questions)

1. Answer any ten questions.

i) In case of power failure, while a crane is in operation, the preferred electrical braking technique is
a) regenerative ✓b) dynamic c) counter current d) none of these

ii) To get speed higher than the base speed of DC shunt motor
a) armature voltage control is used ✓b) field control is used
c) armature resistance control is used d) frequency control is used

iii) Speed control by varying the armature voltage offers
a) constant power drive ✓b) constant torque drive
c) variable power drive d) variable torque drive

iv) Intermittent duty rating of electric motor
✓a) is equal to name plate rating b) is less than name plate rating
c) is greater than name plate rating d) has no bearing to its name plate rating

v) The heating time constant of an electrical machine gives an indication of its
✓a) cooling b) rating
c) overload capacity d) short time rating

vi) The speed of an induction motor can be varied by means of variable frequency supply from a static power converter. A simultaneous voltage variation is also effected in order to
a) avoid saturation and provide optimum torque capability
✓b) the torque pulsations decrease if supplied from variable voltage supply
c) to limit the peak value of stator current
d) to minimize the additional losses

vii) A three phase induction motor having a combination of diode rectifier and line commutated inverter in the rotor circuit can give
✓a) speeds below synchronous speed only
b) speeds above synchronous speed only
c) both sub and super synchronous speeds
d) speeds varying from 0 to 50% of synchronous speed

viii) A Regenerative braking in a squirrel cage induction motor takes place when
✓a) the overhauling load drives the rotor at a speed greater than synchronous speed
b) the stator frequency is reduced so that synchronous speed is below the rotor speed
c) both (a) and (b)
d) none of these

ix) By self control of a synchronous motor we mean that

a) elimination of torque ripple

b) the speed of the motor is varied in steps

✓c) the speed of the motor is a function of input frequency

d) the input frequency is controlled from the speed of the motor

x) The ripple frequency is twice the supply frequency in the case of

a) single phase half wave converter

✓b) single phase dual converter

c) three phase full converter

d) three phase semiconverter

xi) The free wheeling diode is needed with inductive load in

a) single phase half converter drive only

✓b) single phase semi converter drive only

c) single phase full converter drive and single phase dual converter drive

d) both single phase half converter drive and single phase full converter drive

xii) When operated with variable frequency, a synchronous motor has an advantage over an induction motor in

a) that it is free from torque oscillations

b) that it has very good efficiency

✓c) that the line power factor can be improved by varying excitation

d) that in certain cases the inverter can be of simpler configuration due to the possible load commutation

Group – B

(Short Answer Type Questions)

2. How does the braking resistance control the dynamic braking torque in dc separately excited motor? How to employ dynamic braking in dc series motors?

See Topic: BRAKING OF ELECTRIC DRIVES, Short Answer Type Question No. 4.

3. Derive the expression for energy required to start an induction motor against constant load torque. What should be the relative magnitude of the load torque w.r.t. the inherent starting torque of the motor?

See Topic: STARTING OF ELECTRIC DRIVES, Short Answer Type Question No. 1.

4. Show that the torque to inertia ratios referred to the motor shaft and to the load shaft differ from each other by a factor of i, where i is the gear ratio.

See Topic: DYNAMICS OF ELECTRICAL DRIVES, Short Answer Type Question No. 6.

5. A motor of smaller rating can be selected for a short time duty. Correct and/or justify.

See Topic: MOTOR POWER RATING, Short Answer Type Question No. 3.

6. The temperature rise of a motor after operating for 30 minutes on full load is 20°C, after another 30 minutes on the same load the temperature rise becomes 30°C. Assuming that the temperature increases according to an exponential law, determine the final temperature rise and the time constant.

See Topic: MOTOR POWER RATING, Short Answer Type Question No. 1.

Group – C
(Long Answer Type Questions)

7. a) A 220 V, 50 A, 1500 rpm separately excited motor with armature resistance of 0.5 ohm is fed from a 3-phase fully controlled rectifier. A variable ac source has line voltage of 440 V, 50 Hz. A star/delta connected transformer is used to feed the converter so that motor terminal voltage equals rated voltage when converter firing angle is 0°
(i) Calculate turns ratio of the transformer.
(ii) Determine firing angle when (a) motor is running at 1200 rpm and at rated torque, (b) motor is running at 800 rpm and at twice the rated torque.
b) Explain 4-quadrant operation of dc motor controlled by dual converter operating in non-circulating mode.
See Topic: DC MOTOR DRIVES (RECTIFIER AND CHOPPER FED), Long Answer Type Question No. 6.

8. a) Deduce the expression of loss of energy during starting of a separately excited DC motor.
b) A motor driving a mining equipment has to supply à load rising uniformly from zero to a maximum of 1500 kW in 20 seconds during acceleration period, 1000 kW for 50 seconds during the full-load period and during acceleration period of 10 seconds when regenerative braking takes place, the kW returned to the mains falls from an initial value of 500 kW to zero uniformly. The interval for decking before the next load cycle starts is 20 seconds. Estimate a suitable kW rating of the motor, based on rms power.
a) See Topic: STARTING OF ELECTRIC DRIVES, Long Answer Type Question No. 1.
b) See Topic: MOTOR POWER RATING, Long Answer Type Question No. 2 (b)..

9. a) Draw and explain the scheme for closed-loop speed control of a three phase induction motor by V/F control drive.
See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 10.

b) A star connected squirrel-cage induction motor has the following rating and parameters: 400 V, 50 Hz, 4-pole, 1410 rpm, $R_r = 2\Omega$, $R_r' = 3\Omega$, $X_s = X_r' = 3.5\Omega$. It is controlled by a current source inverter at a constant flux. Calculate (i) motor torque, speed when operating at 30 Hz and rated slip speed (ii) Inverter frequency for rated motor torque at a speed of 1250 rpm.
See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 1 (b).

10. a) Describe with suitable diagram the "self-controlled mode" of speed control operation of a synchronous motor using load commutated inverter.
b) Explain how cyclo-converter can be used to control the speed of synchronous motor drives.
a) See Topic: SYNCHRONOUS MOTOR DRIVES, Short Answer Type Question No. 1.
b) See Topic: SYNCHRONOUS MOTOR DRIVES, Long Answer Type Question No. 1.

11. Write short notes on any *three* of the following:
   a) Induction motor speed control by rotor resistance control
   b) Regenerative braking for dc motor
   c) Series-parallel speed control technique for DC series motor
   d) Chopper fed drives
   e) Switched Reluctance motor

a) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 16 (e).
b) See Topic: BRAKING OF ELECTRIC DRIVES, Long Answer Type Question No. 6.

c) See Topic: ELECTRIC TRACTION, Long Answer Type Question No. 2 (b).
d) See Topic: DC MOTOR DRIVES (RECTIFIER AND CHOPPER FED), Long Answer Type Question No. 9.a).
e) See Topic: MISCELLANEOUS, Long Answer Type Question No. 1 (b).

QUESTION 2015

Group – A
(Multiple Choice Type Questions)

1. Answer any ten questions:

i) Fourth quadrant operation of electric drive gives
a) forward motoring
b) forward braking
✓c) reverse braking
d) reverse motoring

ii) In constant torque operation of DC motor
✓a) field flux is proportional to speed
b) field flux is inversely proportional to speed
c) field flux is proportional to square of speed
d) field flux remains constant

iii) The ripple frequency is six times of the supply frequency in case of
a) single phase full converter
b) three phase semi converter
✓c) three phase full converter
d) single phase semi converter

iv) A three-phase induction motor operates at a constant rotor frequency when the stator frequency is varied from zero to rated value. The torque developed by the motor is
✓a) constant from zero to rated speed
b) proportional to speed
c) inversely proportional to speed
d) proportional to cube of speed

v) For application in traction
✓a) dc series motors are suitable
b) dc shunt motors are suitable
c) dc compound motors are suitable
d) synchronous motors are suitable

vi) For slip power recovery method for negative Pr, where $Pg = Pr + Pm$, the induction motor will run at
✓a) sub synchronous speed
b) synchronous speed
c) super synchronous speed
d) none of these

vii) In a dual converter, the circulating current
a) increases the response time but allows smooth reversal of load current
b) decreases the response time but does not allow smooth reversal of load current
✓c) improves the speed of response and also allows smooth reversal of load current
d) make performance of the converter worse

viii) During lowering of an over hauling load, braking takes place is
✓a) regenerative braking
b) dynamic braking
c) plugging
d) none of these

ix) PWM Control, when applied to a three phase voltage source inverter, introduces
✓a) low order harmonic voltage on the dc side
b) low order harmonic voltages on the ac side
c) higher order harmonic voltages on the ac side
d) higher order harmonic voltages on the dc side

x) For multi-motor drives
a) current source inverters are used
✓b) voltage source inverters are used
c) both inverters are used
d) none of these

xi) A three phase line commutated converter, when operating in the inverter mode
a) draws both real and reactive power from ac supply
b) delivers both real and reactive power to ac supply
✓c) delivers real power to ac supply but draws reactive power from ac supply
d) delivers real power to dc side but draws reactive power from dc side

xii) In self controlled synchronous Motor drive, where Load Commutated Inverter is used, synchronous Motor is necessary to operate at
a) lagging pf
✓b) unity pf
c) leading pf
d) none of these

Group – B
(Short Answer Type Questions)

2. Describe with suitable diagram plugging operation of DC machine.
See Topic: BRAKING OF ELECTRIC DRIVES, Short Answer type Question No. 5.

3. A motor has a thermal heating time constant of 50 minutes. When the motor runs continuously on full load, its temperature rise is 100°C in 90 minutes.
a) Find the maximum steady state temperature.
b) How long will the motor take for its temperature to rise from 70°C to 95°C, if it is working on same load?
See Topic: MOTOR POWER RATING, Short Answer Type Question No. 4.

4. Describe with suitable diagram dynamic braking operation of Induction Machine.
See Topic: BRAKING OF ELECTRIC DRIVES, Short Answer Type Question No. 6.

5. Describe with neat diagram four quadrant operation of a motor driving hoist load.
See Topic: DYNAMICS OF ELECTRIC DRIVES, Short Answer Type Question No. 4.

6. Why variable voltage frequency method of speed control of three phase induction motor is preferable over fixed voltage variable frequency control method? Explain with typical speed-torque curves for both the methods.
See Topic: INDUCTION MOTOR DRIVES, Short Answer Type Question No. 2.

Group – C
(Long Answer Type Questions)

7. a) 230 Volt, 1200 rpm, 200A separately excited motor has an armature resistance of 0.06 ohm. Armature is fed from a three phase dual converter with circulating control. The available ac supply has line-line voltage of 440 Volt with supply frequency 50 Hz. When motor operates in forward

motoring, converter A works as a rectifier and converter B as an inverter. Determine firing angles of converters A and B for

i) Motoring operation at 90% of rated motor torque and 900 rpm speed

ii) Braking operation at 120% of rated motor torque and 1000 rpm speed.

b) Explain the operation of Ward-Leonard drive system with suitable diagram. Mention the advantages and disadvantages of it.

a) See Topic: DC MOTOR DRIVES (RECTIFIER & CHOPPER FED), Long Answer Type Question No. 7.

b) See Topic: SPEED CONTROL OF D.C SHUNT MOTOR BY WARD LEONARD METHOD & BUCK BOOST METHOD, Long Answer Type Question No. 2.

8. a) A 2.8 kW, 440 Volt, 50 Hz, 4 pole 1390 rpm, delta connected squirrel cage induction motor has following parameters referred to the stator:

$R_s = 3\Omega,\ R_r' = 6\Omega,\ X_s = 4.5\Omega,\ X_r' = 5.5\Omega,\ X_m = 75\Omega$. Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated voltage. Calculate motor terminal voltage, current and torque at 1230 rpm.

b) Describe regenerative braking operation of DC machine.

c) What do you mean by 'classes of motor duty'?

a) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 13 (a).

b) See Topic: BRAKING OF ELECTRIC DRIVES, Long Answer Type Question No. 5.

c) See Topic: MOTOR POWER RATING, Short Answer Type Question No. 5.

9. a) Explain the principle of slip power recovery scheme of controlling the speed of induction motor, using static Scherbius Drive.

b) Describe with suitable diagram the self-controlled synchronous motor drive using load-commutated inverter.

a) See Topic: INDUCTION MOTOR DRIVES, Short Answer Type Question No. 3.

b) See Topic: SYNCHRONOUS MOTOR DRIVES, Short Answer Type Question No. 1.

10. a) A 230 Volt; 960 rpm and 60 Amp separately excited dc motor has an armature resistance of 0.1 ohm and field resistance of 20 ohm.

The motor armature is fed from two quadrant chopper capable of operating in first quadrant and second quadrant with dc source voltage of 300 Volt. The motor field circuit is fed from first quadrant chopper with dc source voltage of 300 Volt. Speeds below rated value are controlled by armature voltage control with full field flux and speeds above rated are controlled by field control at rated armature voltage. Assume continuous conduction.

i) Calculate duty cycle of chopper connected to motor armature and duty ratio of chopper connected to motor field circuit for motoring operation at 750 rpm and 1.2 times rated torque.

ii) Calculate duty cycle of chopper connected to motor armature and duty ratio of chopper connected to motor field circuit for forward braking operation at 800 rpm speed and 75% of rated torque.

iii) Calculate duty ratio of chopper connected to motor field circuit for motoring operation at 1000 rpm speed and rated torque.

b) Explain with suitable diagram variable voltage and variable frequency control of three phase induction motor.

a) See Topic: DC MOTOR DRIVES (RECTIFIER & CHOPPER FED), Long Answer Type Question No. 8.

b) See Topic: **INDUCTION MOTOR DRIVES, Long Answer Type Question No. 13 (b).**

11. Write short notes on any three of the following:
    a) Three phase Rectifier fed dc drive
    b) Drive for Textile Mills
    c) Current Source Inverter fed Induction Motor drive
    d) Electric drives and its components
    e) Buck-boost method of speed control of dc motor.

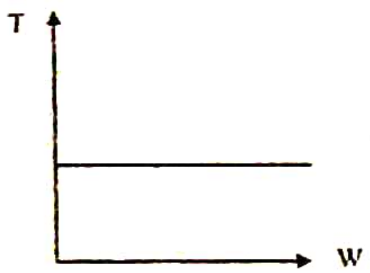
a) See Topic: DC MOTOR DRIVES, Long Answer Type Question No. 9.b).
b) See Topic: INDUSTRIAL APPLICATIONS, Long Answer Type Question No. 1 (b).
c) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 16 (f).
d) See Topic: ELECTRIC DRIVES, Long Answer Type Question No. 1.
e) See Topic: SPEEDCONTROL OF D.C SHUNT MOTOR BY WARD LEONARD METHOD& BUCK BOOST METHOD, Long Answer Type Question No. 1.

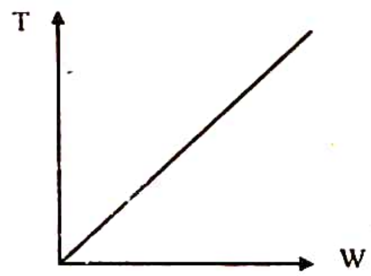
QUESTION 2016

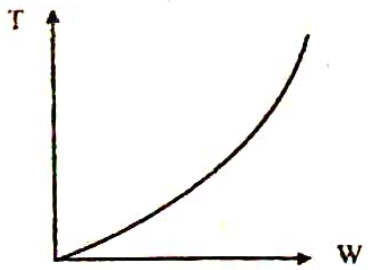
Group – A
(Multiple Choice Type Questions)

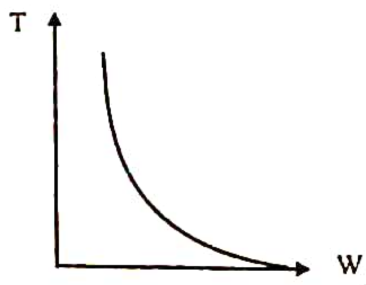
1. Choose the correct alternatives for any *ten* of the following:

i) The speed torque characteristics of a fan type load is given by

a)


b)


✓c)


d)


ii) The range of slip of regenerative braking of a polyphase induction motor remains between
a) $s = 1$ to $s = s_m$
b) $s = 1$ to $s = -s_m$
c) $s = s_m$ to $s = 0$
✓d) $s = 0$ to $s = -s_m$
where s_m is the slip at maximum torque.

iii) For slip power recovery method of speed control, power is injected to the rotor of the induction motor. The induction motor will run at a speed
a) higher than rated speed
✓b) lower than the rated speed
c) at the rated speed
d) of zero speed

iv) The heating time constant of an electrical machine gives an indication of its
✓a) cooling
b) rating
c) overload capacity
d) short time ratting

v) The zone below base speed of an electric drive is known as
a) constant power zone
✓b) constant torque zone
c) constant voltage zone
d) constant current zone

vi) A crane is used to more material horizontally and vertically. The type of drive used is
a) multimotor
b) group
c) individual
✓d) both (a) and (c)

vii) The regenerative breaking is not possible in
✓a) DC series motor
b) Induction motor
c) DC shunt motor
d) DC separately excited motor

viii) For increasing the speed of an induction motor, the frequency of the supply is increased by 20%. In order to operate the motor at the same flux, the supply
a) remain constant
b) be reduced by 10%
c) be reduced by 20%
✓d) be increased by 20%

ix) In case of rotor resistance control of induction motor drives, for the same torque
✓a) speed falls with an increase in rotor resistance
b) speed increased with an increase in rotor resistance
c) speed falls with fall in rotor resistance
d) speed increases with fall in rotor resistance

x) A typical active load is
a) Hoist
b) Blower
✓c) Pump
d) Fan

xi) During dynamic braking employed for DC series motors,
a) armature current is reversed
b) field winding is reversed
c) field current direction is unchanged
✓d) both (a) and (c)

xii) A four quadrant operation requires
a) two full converters connected in series
b) two full converters connected in parallel
✓c) two full converters connected in back to back
d) two semi-converters connected in back to back

Group – B
(Short Answer Type Questions)

2. A weight of 500 kg is being lifted up at a uniform speed of 1.5 m/s by a winch driven by motor running at a speed of 1000 rpm. The moment on inertia of the motor and winch are 0.5 kgm^2 and 0.3 kgm^2 respectively. Calculate the motor torque and the equivalent moment of inertia referred to the motor shaft. In the absence of weight motor develops a torque of 100 Nm when running at 1000 rpm.

See Topic: DYNAMICS OF ELECTRICAL DRIVES, Short Answer Type Question No. 2.

3. "A motor of smaller rating can be selected for intermittent duty." Justify the statement with proper analysis.
See Topic: MOTOR POWER RATING, Long Answer Type Question No. 1.a).

4. Deduce the expression for energy lost during starting of Induction motor with no load.
See Topic: STARTING OF ELECTRICAL DRIVES, Short Answer Type Question No. 2.

5. With appropriate diagram, discuss the four quadrant operation of a hoist drive.
See Topic: DYNAMICS OF ELECTRICAL DRIVES, Short Answer Type Question No. 4.

6. Why VVVF method of speed control of a polyphase induction motor is preferable over frequency control method? Draw the relevant torque-frequency characteristics.
See Topic: INDUCTION MOTOR DRIVES, Short Answer Type Question No. 2.

Group – C
(Long Answer Type Questions)

7. a) What are the various factors that influence the choice of electric drives?
b) Derive the heating and cooling characteristics of an electric motor.
c) The temperature rise of motor when operating for 25 min on full load is 25°C and becomes 40°C when the motor operates for another 25 min on the same load. Determine heating time constant and the steady state temperature rise.
a) See Topic: ELECTRICAL DRIVE, Short Answer Type Question No. 2
b) See Topic: MOTOR POWER RATING, Long Answer Type Question No. 4.a).
c) See Topic: MOTOR POWER RATING, Short Answer Type Question No. 2.

8. a) With the help of relevant circuit diagram explain different methods of dynamic braking for a polyphase induction motor.
b) A 3-phase, 440V, 50 Hz, 6 pole, Y-connected IM has the following parameters referred to the stator: $R_s = 0.5\ \Omega$, $R_r' = 0.6\ \Omega$, $X_s = X_r' = 1\ \Omega$, Stator to rotor ratio is 2.
The motor is running on no load. The plugging is used to stop the motor.
i) Determine the maximum braking current and initial and final braking torque when no external braking resistance is used.
ii) Calculate the additional braking resistor to be inserted into the rotor circuit so as to limit the maximum braking current to twice the rated value. The motor has a rated speed of 940 rpm.
a) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 14.a).
b) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 14.b).

9. a) Draw and explain the scheme for closed loop speed control of a three-phase induction motor by V/f control.
b) A 220V, 150 A, 875 rpm separately excited motor has an armature resistance of 0.06 ohm. It is fed from a single phase fully controlled converter with an ac source voltage of 220V, 50 Hz. Assuming continuous conduction, calculate –
(i) firing angle of converter for motor speed of 750 rpm.
(ii) firing angle for rated motor torque (–500) rpm.
(iii) motor speed and torque for $\alpha = 160°$.
a) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 10.
b) See Topic: BRAKING OF ELECTRICAL DRIVES, Long Answer Type Question No. 3.

10. a) Describe briefly the different methods for determination of motor power rating for variable load drives.
b) A drive has two loads. One has rotational motion. It is coupled to the motor through a reduction gear ratio a = 0.1 and efficiency is 90%. A load has moment of Inertia 10 kg-m^2 and torque 10 N-m. Other load has translation motion and consists of 1000 kg weight to be lifted upward at an uniform speed of 1.5 m/sec. Coupling between this load and the motor has a efficiency of 85%. Motor rating is $\omega_m = 1420$ and 0.2 kg-m^2. Determine equivalent inertia referred to the motor shaft and power developed by the motor.

a) See Topic: MOTOR POWER RATING, Long Answer Type Question No. 5.a).
b) See Topic: MOTOR POWER RATING, Long Answer Type Question No. 5.b).

11. Write the short notes any *three* of the following:
a) Self control of synchronous motor
b) Vector control of Induction motor
c) Drive for paper mills
d) Switched reluctance motor

a) See Topic: SYNCHRONOUS MOTOR DRIVES, Short Answer Type Question No. 1.
b) See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 14.d).
c) See Topic: INDUSTRIAL APPLICATIONS, Long Answer Type Question No. 1.a).
d) See Topic: MISCELLANEOUS, Long Answer Type Question No. 1.b).

QUESTION 2017

Group – A
(Multiple Choice Type Questions)

1. Choose the correct alternatives for any *ten* of the following:

i) To get speed higher than the base speed of a *dc* shunt motor, the method of control to be used is
a) armature voltage control ✓b) field control
c) armature resistance control d) frequency control

ii) A typical passive load is
a) Hoist b) Pump c) Blower ✓d) Friction

iii) The magnetizing reactance of an induction motor during *dc* dynamic braking, increases with
✓a) increasing rotor speed
b) decreasing rotor speed
c) independent of rotor steed
d) depends on the way the stator windings are connected during braking

iv) The slip of an induction motor during *dc* rheostatic braking is
✓a) s b) $1-s$ c) $2-s$ d) $s+1$

v) In constant torque drive
✓a) power is proportional to speed b) power is proportional to square of speed
c) power is inversely proportional to speed d) power is independent to speed

vi) For a single phase half controlled converter fed *dc* drive, the possible quadrant operation is
✓a) 2nd quadrant
b) 3rd quadrant
c) 4th quadrant
d) 1st quadrant

vii) For an electric locomotive in the downward direction in a hilly region, the economical braking system will be
a) counter-current braking
b) dynamic braking
✓c) regenerative braking
d) mechanical braking

viii) In v/f control of an induction motor, the maximum torque
a) can be reduced at will
✓b) will remain almost constant with speed
c) can be increased with speed
d) none of these

ix) Short time rating of an electric machine
a) is equal to the name plate rating
✓b) is less than the name plate rating
c) is greater than the name plate rating
d) has no bearing to its name plate rating

x) In fan type load, the torque (τ) varies with speed (w) as
a) $\tau \propto w$
✓b) $\tau \propto w^2$
c) $\tau \propto \frac{1}{w}$
d) $\tau \propto \frac{1}{w^2}$

xi) A motor which actuates several mechanisms in a machine is called
✓a) group drive
b) individual drive
c) multi-motor drive
d) active drive

xii) Which braking is not possible in series motor?
✓a) Regenerative braking
b) Dynamic braking
c) Counter-current braking
d) Rheostatic braking

Group – B
(Short Answer Type Questions)

2. What are the reasons for load equalization in an electric drive? State how is it achieved.
See Topic: MOTOR POWER RATING, Short Answer Type Question No. 6.

3. Obtain the equilibrium point and determine their stability for motor and load having characteristics as $T_M = 1 + 2W_m$ and $T_L = 3\sqrt{W_m}$ respectively.
See Topic: DYNAMICS OF ELECTRICAL DRIVES, Short Answer Type Question No. 7.

4. A motor has a thermal heating time constant of 45 minutes. When the motor runs continuously on full load, its final temperature rise in 80°C. (i) What would be the temperature rise after 1 hour, if the motor runs continuously on full load? (ii) If the temperature rise on 1 hour is 80°C, find the maximum steady state temperature at this rating.
See Topic: MOTOR POWER RATING, Short Answer Type Question No. 4.i) & ii).

5. Explain briefly the different components of load torque with their torque speed characteristics.
See Topic: DYNAMICS OF ELECTRICAL DRIVES, Short Answer Type Question No. 8.

6. Discuss the methods of speed control of synchronous motor.
See Topic: SYNCHRONOUS MOTOR DRIVES, Short Answer Type Question No. 2.

Group – C
(Long Answer Type Questions)

7. a) With the help of heat diagram, explain four quadrant operations of a motor driving a hoist load.
See Topic: DYNAMICS OF ELECTRICAL DRIVES, Short Answer Type Question No. 4.

b) A motor is used to drive a hoist. Motor characteristics are given by:
Quadrant I, II, and IV: $T = 200 - 0.2N$, Nm.
Quadrant II, III and IV: $T = -200 - 0.2N$, Nm where N is the speed in rpm.
When hoist is loaded, the net load torque $T_l = 100$ Nm and when it is unloaded, the net load torque $T_l = -80$ Nm. Obtain the equilibrium speeds for operation in all the four quadrants
See Topic: DYNAMICS OF ELECTRICAL DRIVES, Long Answer Type Question No. 2.

c) What do you mean by 'classes of motor duty'?
See Topic: MOTOR POWER RATING, Short Answer Type Question No. 5.

8. a) Explain the operation of Ward-Leonard drive system with suitable diagram. Mention the advantages and disadvantages of it.
See Topic: SPEED CONTROL OF D.C. SHUNT MOTOR BY WARD LEONARD METHOD & BUCK BOOST METHOD, Long Answer Type Question No. 2.

b) A 200 V, 875 rpm, 150 A, separately excited *dc* motor has an armature resistance of 0.06 Ω. It is fed from a single phase full controlled rectifier with a source voltage of 220 volt, 50 Hz. Assuming continuous conduction, calculate

i) firing angle for rated motor torque and 750 rpm
ii) motor speed for firing angle of 160° and at rated torque.

See Topic: DC MOTOR DRIVES (RECTIFIER AND CHOPPER FED), Long Answer Type Question No. 5.

9. a) What are the advantages of static rotor resistance control over conventional methods of rotor resistance control.
See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 15.a).

b) Discuss the methods of *ac* dynamic braking operation of an induction motor.
See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 15.b).

c) A 2.8 kW, 440 volt, 50 Hz, 4 pole, 1390 rpm, delta connected squirrel cage induction motor has following parameters referred to the stator:

$R_s = 3\Omega,\ R_r' = 6\Omega,\ X_s = 4.5\Omega,\ X_r' = 5.5\Omega,\ X_m = 75\Omega$. Motor speed is controlled by stator voltage control. When driving a fan load, it runs at rated speed and at rated voltage. Calculate motor terminal voltage, current and torque at 1230 rpm. 2+5+8
See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 13.a).

10. a) Explain continuous duty, short time duty and intermittent duty with necessary graph showing variation of load torque *vs.* time and temperature *vs.* time for each.
See Topic: MOTOR POWER RATING, Long Answer Type Question No. 6.a).

b) A motor driving a colliery winding equipment has to deliver a load, having the following characteristics:

i) rising uniformly from zero to a maximum of 2000 kW in 20 seconds, during the acceleration period
ii) 1000 kW for 40 seconds during the full-speed periods
iii) during the deceleration period of 10 seconds, when regenerative braking is taking place, the power returned to the supply falls from an initial value of 330 kW to zero
iv) remains idle for another 10 seconds before next cycle starts.

Draw the load (power) diagram and find the rating of the motor using equivalent power method.
See Topic: MOTOR POWER RATING, Long Answer Type Question No. 6.b).

11. a) Discuss the effects of starting on power supply, motor and load.
See Topic: STARTING OF ELECTRIC DRIVES, Long Answer Type Question No. 3.a).

b) Explain methods to reduce the energy loss during starting.
See Topic: STARTING OF ELECTRIC DRIVES, Long Answer Type Question No. 3.b).

c) With the help of relevant diagram explain slip power recovery scheme of three-phase induction motor for speed control below synchronous speed.
See Topic: INDUCTION MOTOR DRIVES, Long Answer Type Question No. 2.

12. Write short notes on the following:
a) Drive for textile mills
b) Solar and battery powered drive
c) Chopper fed *dc* drive.

a) See Topic: INDUSTRIAL APPLICATIONS, Long Answer Type Question No. 1.b).
b) See Topic: SPECIAL TYPE DRIVES, Long Answer Type Question No. 1.b).
c) See Topic: DC MOTOR DRIVES (RECTIFIER AND CHOPPER FED), Long Answer Type Question No. 9.a).