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]

$J=10\text{ kg-m}^2$, $T_M=100-0.1N$, N-m

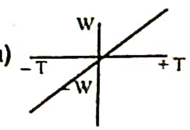
$T_L(\text{passive})=0.05N$, N-m, where N is speed in rpm.

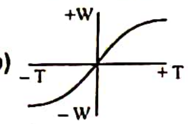
Then the steady state speed is

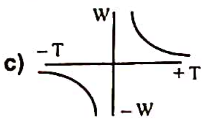
a) 700 rpm b) 800 rpm c) 667 rpm d) 680 rpm

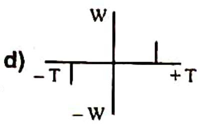
Answer: (c)

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

a) 

b) 

c) 

d) 

Answer: (c)

10. $\pm T_M=\pm T_L+J\frac{dW}{dt}$, 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

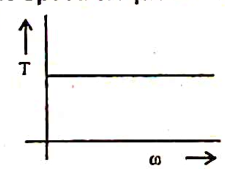
Answer: (b)

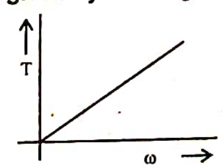
13. Second quadrant operation of electric drive gives [WBUT 2012]

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

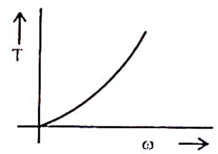
Answer: (a)

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

a) 

b) 

c)



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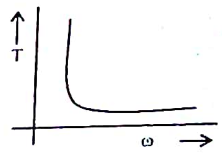


Answer: (c)

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:

$J_m = 0.5$ kg-m^2 $\quad J_w = 0.3$ kg-m^2
$v_1 = 1.5$ m/s $\quad M_1 = 500$ kg
$\omega_m = \frac{1000\pi}{30}$ 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 $T_1 = 100$ N-m $\quad F_1 = 500 \times 9.81$ 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 $J_m = 0.5$ kg-m^2 $\quad J_w = 0.3$ kg-m^2 $\quad M_1 = 500$ kg $\quad \omega_m = \frac{1000\pi}{30}$ rad./sec.

Assuming, $v_1 = 1.5$ 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 $T_1 = 100$ N-m $\quad F_1 = 500 \times 9.81$ 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]

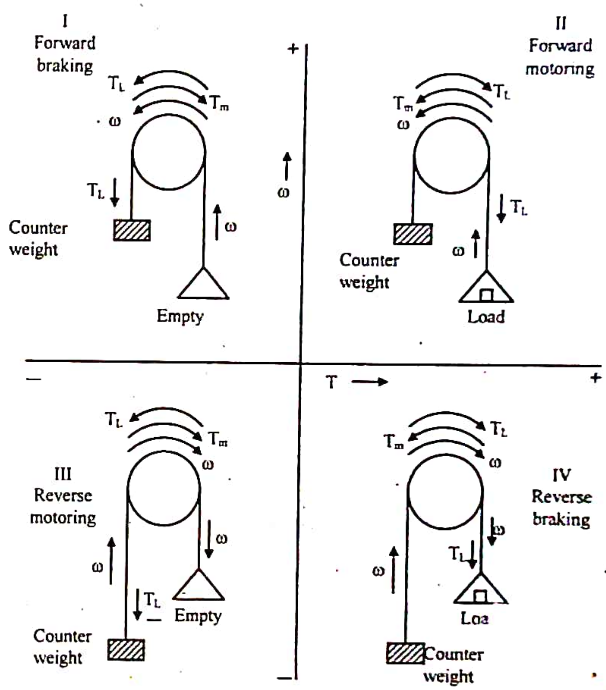
OR,

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

$$c5P_0^2t + cP_0^2t = 26cP_0^2t$$

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)).

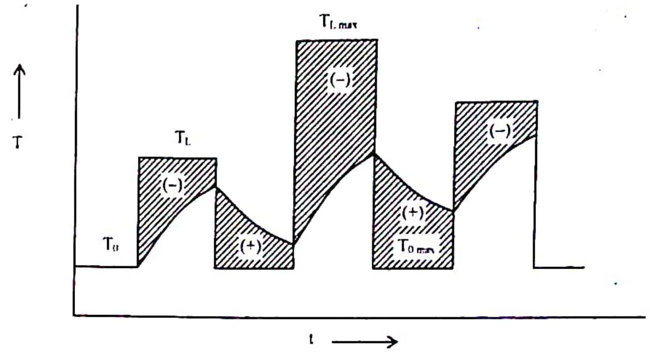


Fig: Load sharing between the motor and the flywheel of a rolling mill

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

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

When the metal is out of the rolls, we get

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

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.

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

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

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

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,

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

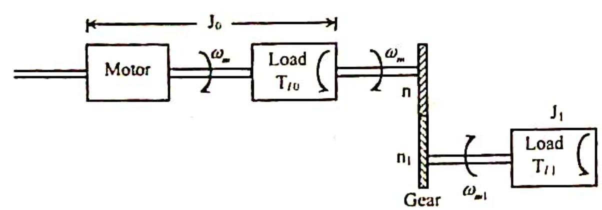
where a_1 is the gear tooth ratio.
If the losses in transmission are neglected, then the kinetic energy due to equivalent inertia must be the same as kinetic energy of various moving parts. Thus

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

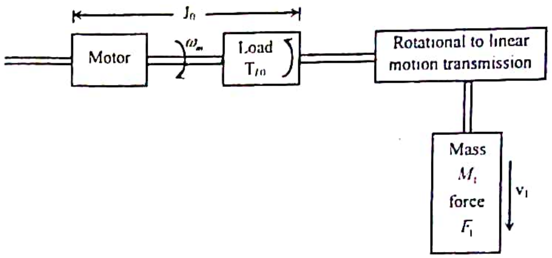
From eqs. (1) and (2)

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

Power at the loads and motor must be the same. If transmission 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

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

where T_l is the total equivalent torque referred to motor shaft

From Eqs. (1) and (4)

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

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

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

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

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

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.

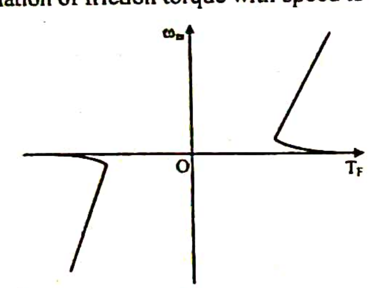


Fig: 1

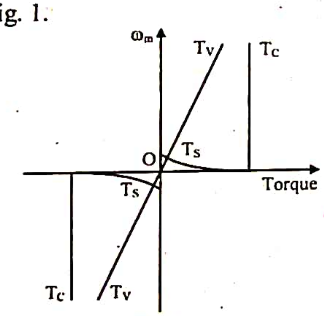


Fig: 2

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

$$T_c = K_c\theta_c \quad .... (5)$$

where, θ_c is the torsion angle of coupling (radians) and K_c 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).

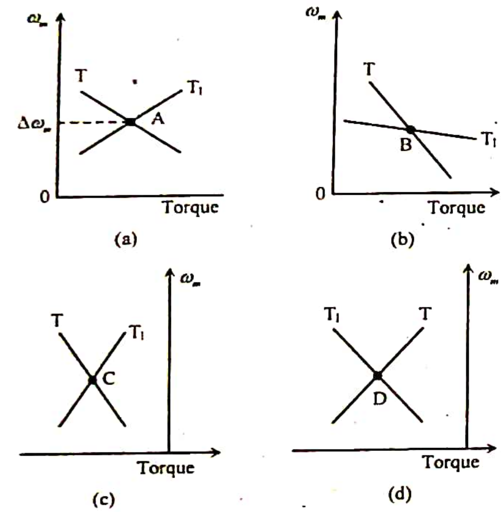


Fig: Prints A and C are stable and B and D are unstable

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

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

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.

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

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

Subtracting

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

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

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

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

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

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

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

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

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.

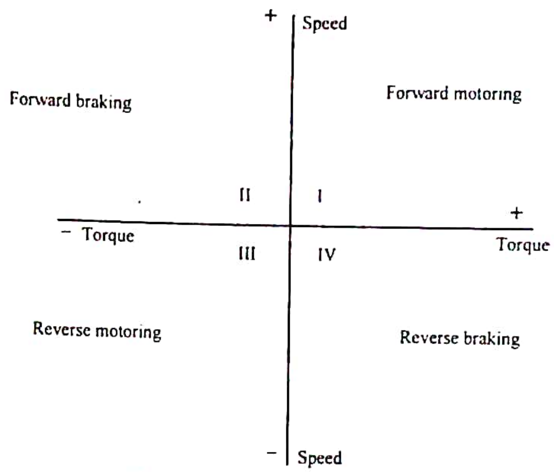


Fig: 1 Four-quadrant operation

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

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

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

∴ 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 $\qquad \theta_1=25°C$

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

$(t_2)=$ temperature rise is $\theta_2=40°$ 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

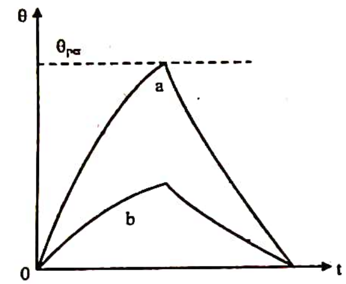


Fig: 1 θ vs. t curves for short time duty loads a — with power KP_r, b — with power P_r

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

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

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

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

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

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

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

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

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

or, $\quad K = \sqrt{\dfrac{1+\alpha}{1-e^{-t_r/\tau}} - \alpha} \quad$ .... (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 $(\text{power})^2$, 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: $T_r > \dfrac{T_{max}}{\lambda}$

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

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

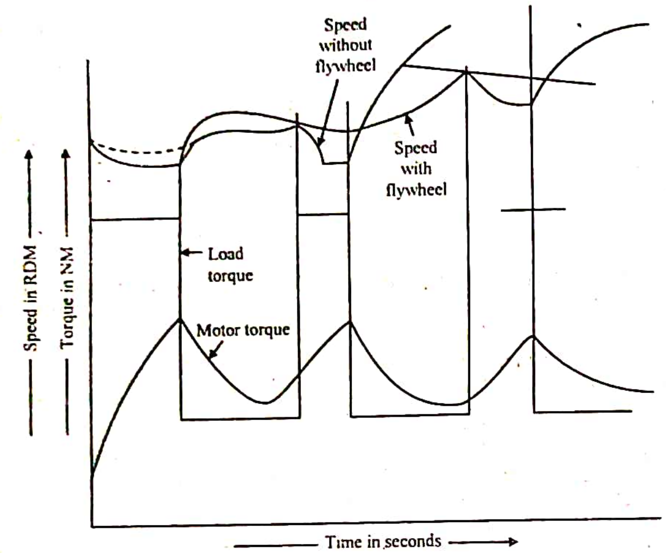


Fig: 1 Variation of speed, load torque and meter torque against time

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

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

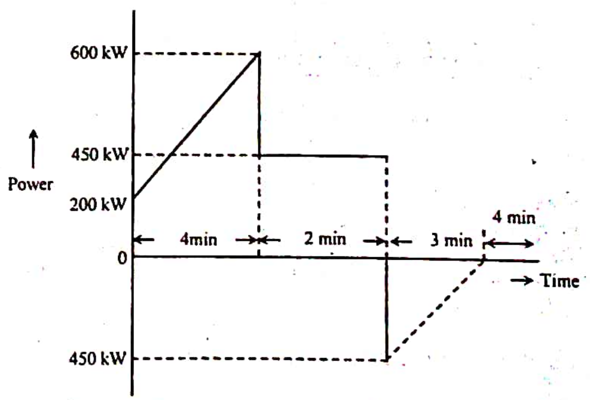
or, $P_x=P_r\sqrt{\dfrac{\varepsilon_1}{\varepsilon_2}}$

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 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:

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

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

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

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

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

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

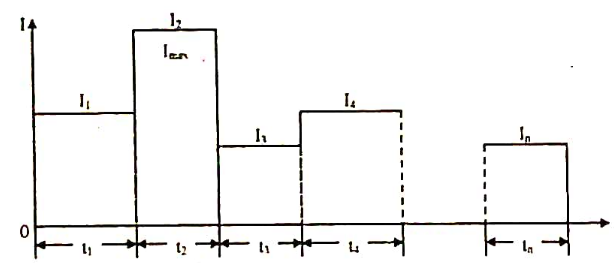


Fig: (i)

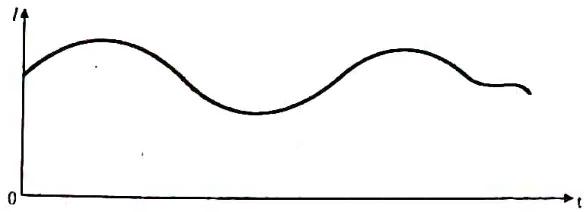


Fig: (ii) Load diagram of a fluctuating load

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

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

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

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.

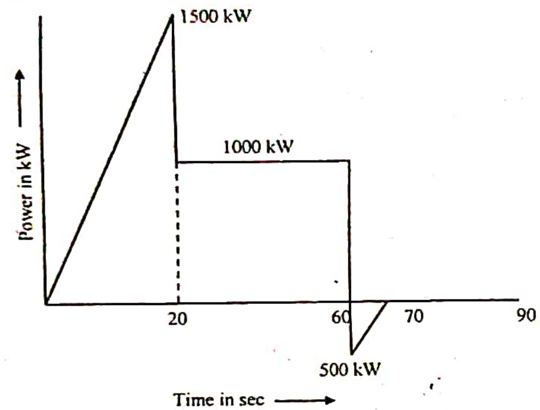
Then $$\lambda \geq \frac{I_{max}}{I_{rated}} \quad \ldots (4)$$

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).

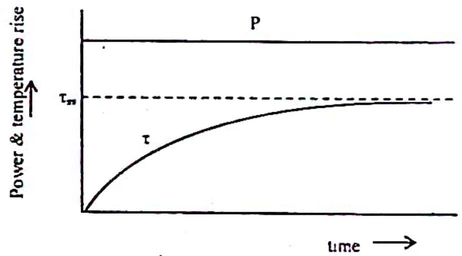


Fig: (a) For Continuous duty

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.

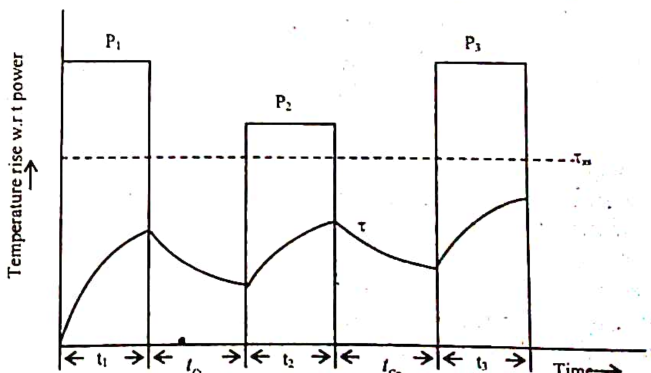


Fig: (b)

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,

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

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.

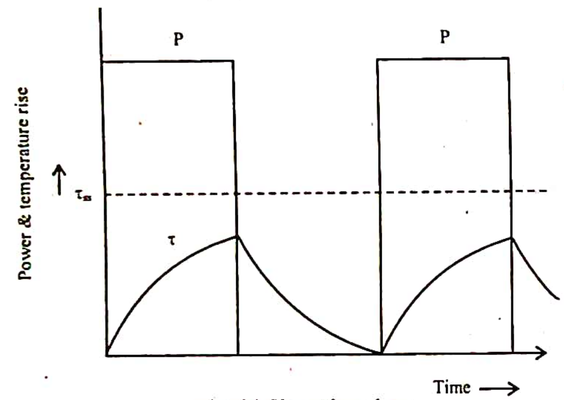


Fig: (c) Short-time duty

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

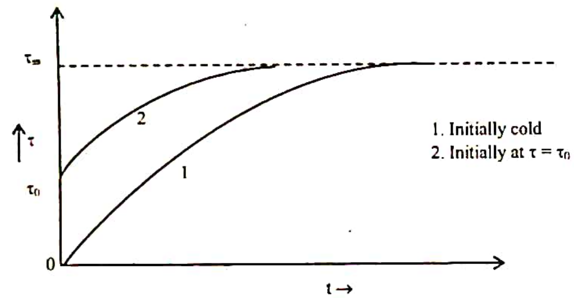


Fig: 1Temperature variation vs time heating

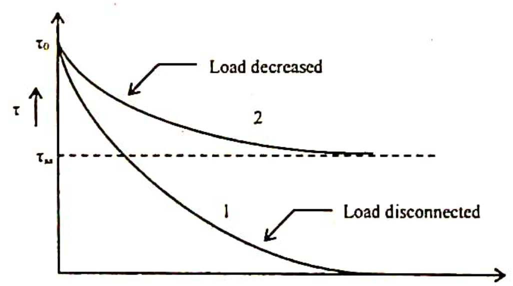


Fig: 2

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

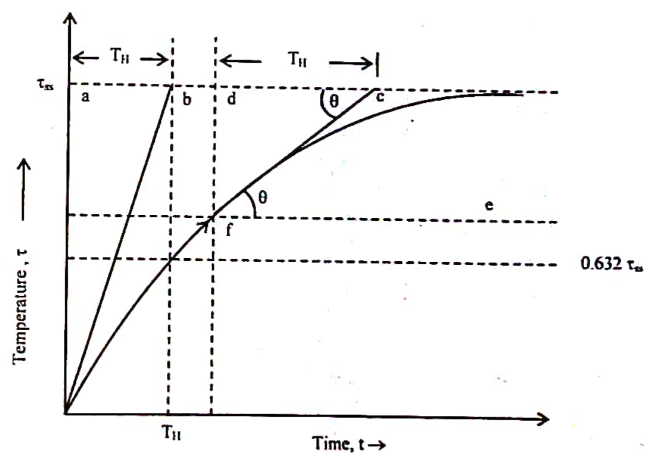


Fig: 3 Graphical determination of heating time constant

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

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,

$$\theta_m=80°\text{ C}$$

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

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

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

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

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

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

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

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

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

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

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

$\quad \dfrac{t}{0.75}=-0.6160$

$\Rightarrow \quad t=0.6160\times0.75=0.4620\text{ hour}=21.72\text{ minutes}.$

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

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

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).

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

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:

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

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

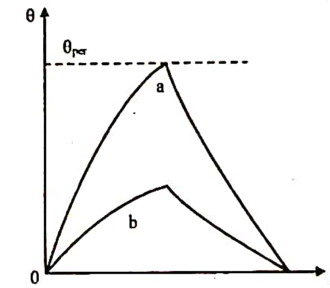


Fig: 2 θ vs. t curves for short time duty loads
a — with power KP$_r$, b — with power P$_r$

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

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

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

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

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

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

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

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

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

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

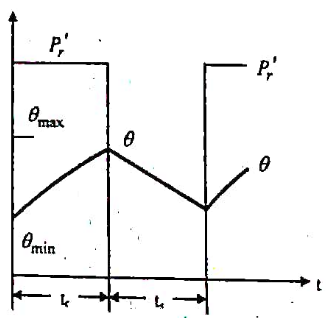


Fig: 3. Intermittent periodic load

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;

$J_0 = 0.2\,\text{kg-m}^2$	$\eta_1 = 0.9$
$i_1 = 0.1$	$\eta_1' = 0.85$
$J_1 = 10\,\text{kg-m}^2$	$T = 10\,\text{N-m}$
$V = 1.5\,\text{m/s}$;	$G = 1000\,\text{kg}$

$\omega = (1420 \times \pi/30) = 148.7$ 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.

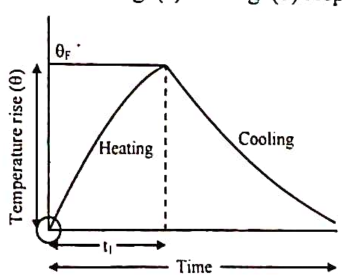


Fig: (a)

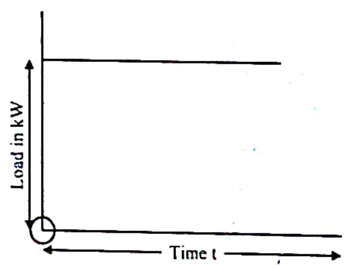


Fig: (b) Continuous duty cycle

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.

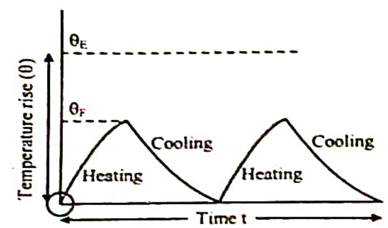


Fig: (c) For short time duty motor

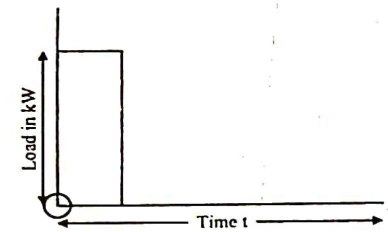


Fig: (d) Short time duty cycle

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.

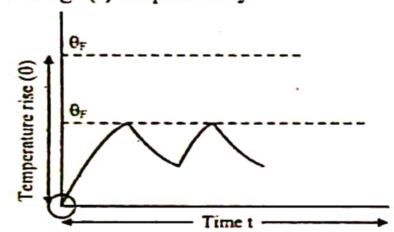


Fig: (e) For intermittent periodic duty motor

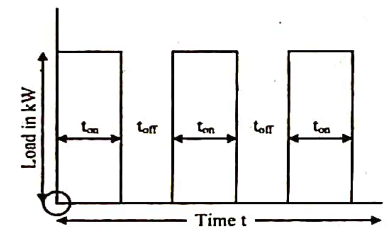


Fig: (f) Intermittent duty cycle

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:

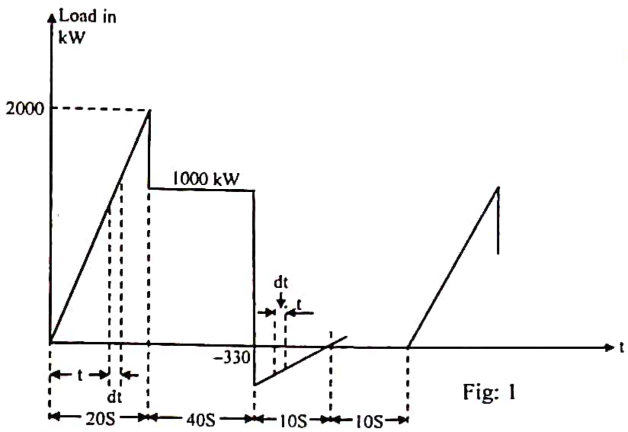


Fig: 1

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,

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

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

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

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

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

$\Rightarrow$ r.m.s. power, $P_{rms} = 912.91$ 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, $P_g = \omega_s T_e$

Total ohmic loss,

$$P_r = sP_g = s\omega_s T_e \quad \ldots (1)$$

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: -

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

$$= -\omega_s J\frac{ds}{dt} \quad \ldots (2)$$

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

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

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

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,

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

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 on the rotor circuit resistance. The total energy lost depends on the stator and rotor resistances.

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

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

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

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

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

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

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

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

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

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

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, $$W = -J\omega_r^2\int_{t_1}^{t_2}\left[1+\frac{T_{load}}{T_{motor} - T_{load}}\right]s\cdot ds \quad \text{.... (8)}$$

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

$$V = E + ir$$

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

The motor is started without load. Friction is neglected

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

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

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

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

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

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

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

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

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

$$A_{ele} = A_L + A_{mech} = J\omega_o^2 \quad \text{.... (7)}$$

Now when the motor is started up with const. load

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

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

Thus, energy loss during starting is

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

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

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,

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

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

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

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

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

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:

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

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

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

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

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

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

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,

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

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

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).

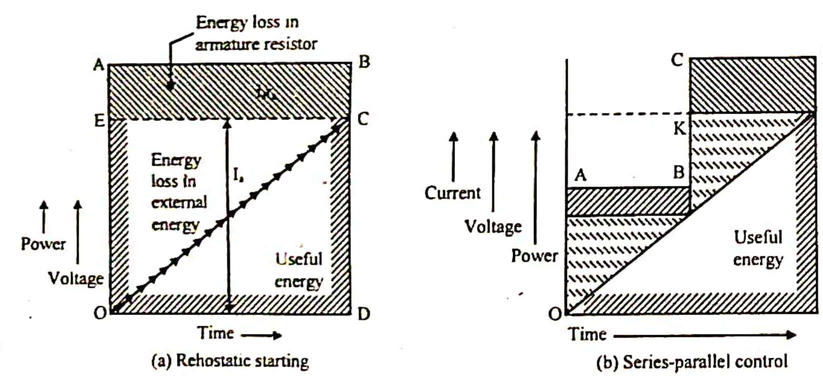


Fig: 1 Energy losses in D.C. motor

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)

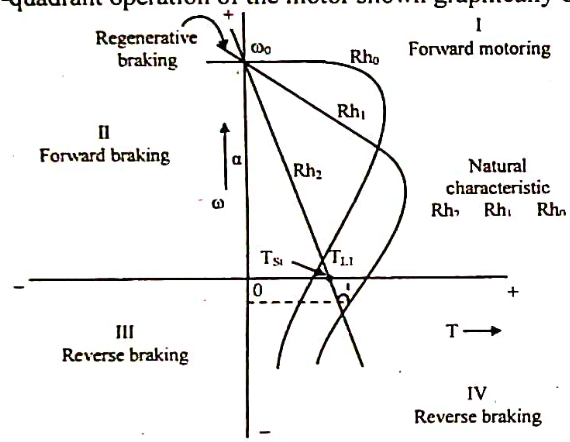
Short Answer Type Questions

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]

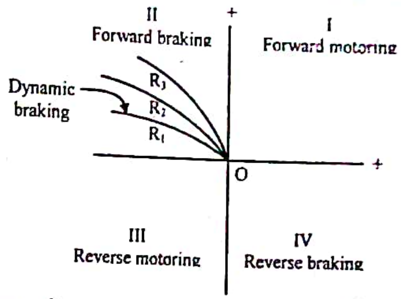
Answer:

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.

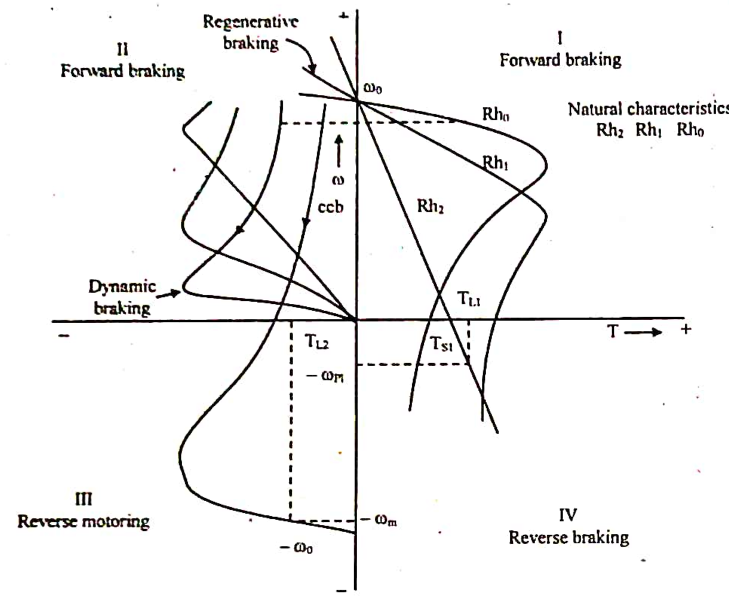


Fig: Typical speed-torque characteristics of induction motor under different operating conditions.

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

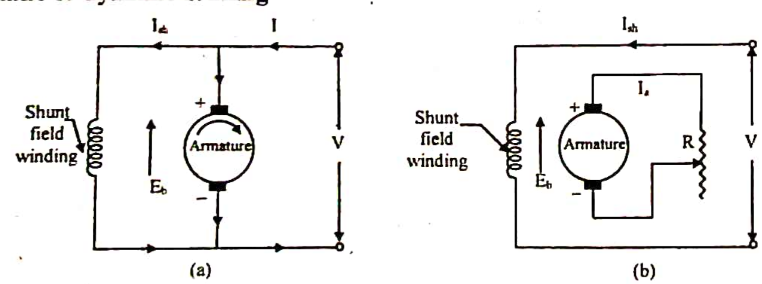


Fig: 1 Rheostatic or dynamic braking

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.

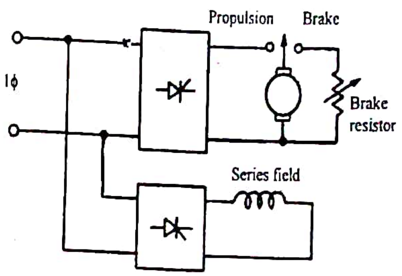


Fig: 1 Dynamic braking for a d.c. motor

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

Answer:

Plugging or counter current braking for Shunt motor

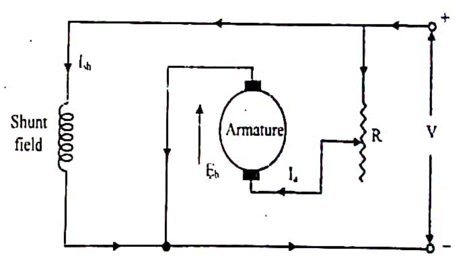


Fig: 1 Plugging or counter-current braking

- 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

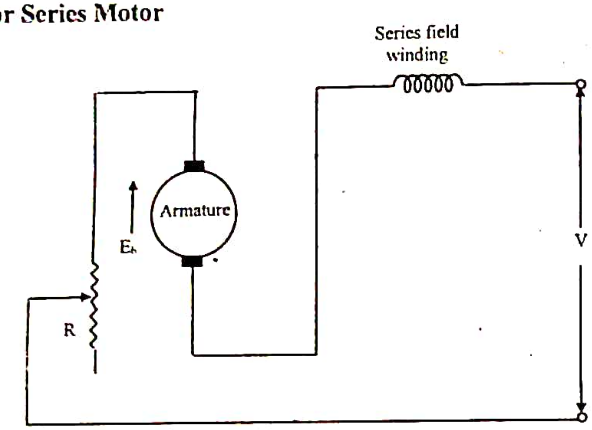


Fig: 2 Plugging

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.

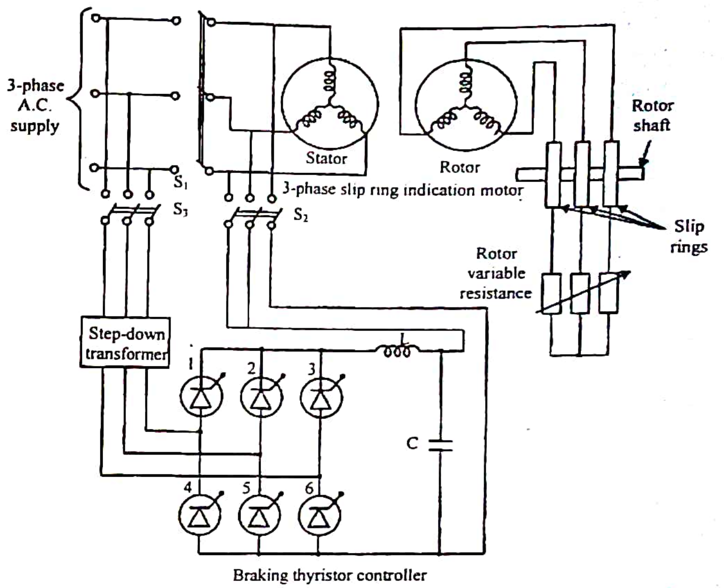


Fig: Dynamic braking of a 3-phase slip ring induction motor

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.

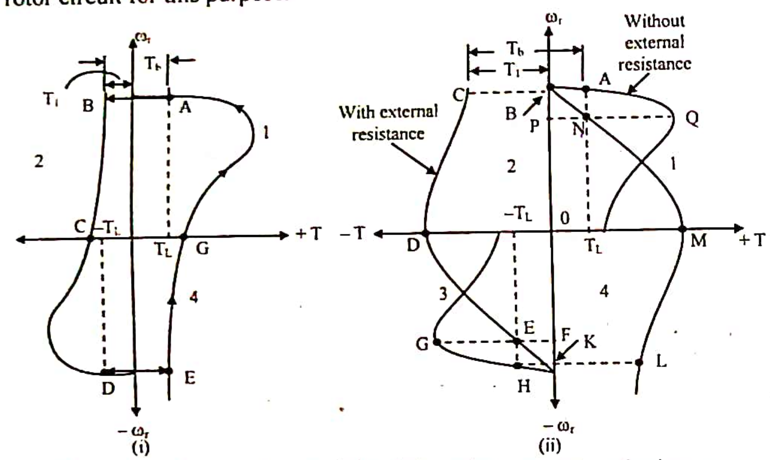


Fig: (a) Speed-torque characteristics during plugging of (i) squirrel-cage motor and (ii) wound-rotor motor

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.

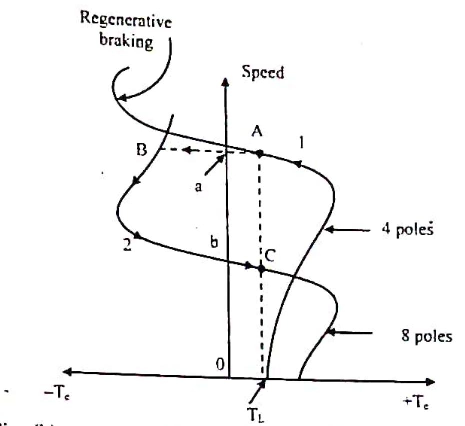


Fig: (b) regenerative braking of polyphase induction motor

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:

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

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

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

Magnetizing Current

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

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

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

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

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

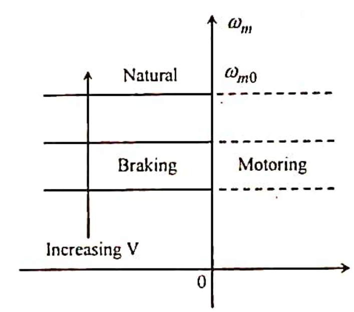


Fig: (a)

$$E = K_e\phi\omega_m$$

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

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.

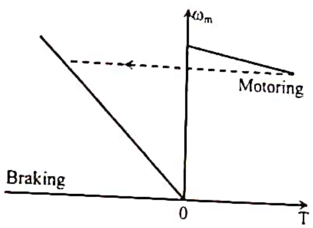


Fig: (b_1)

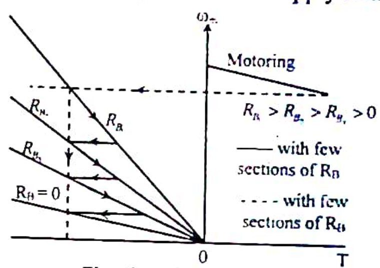


Fig: (b_2) Shunt motor with variable armature resistance

Dynamic braking speed-torque curves

The characteristics are obtained from

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

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.

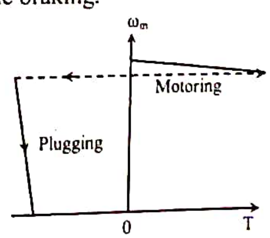


Fig: A Plugging speed torque curves

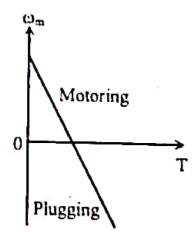
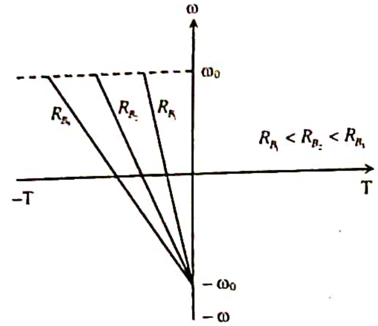


Fig: B Counter torque braking



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

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, $\frac{2 \times 220\sqrt{2}}{\pi} \cos\alpha = 189.857$ 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 $K = \frac{E}{\omega_m} = \frac{-195.218}{-809.557} \times \frac{60}{2\pi} = 2.303$

Torque $T = KI_a = 2.303 \times 150 = 345.45$ N-m

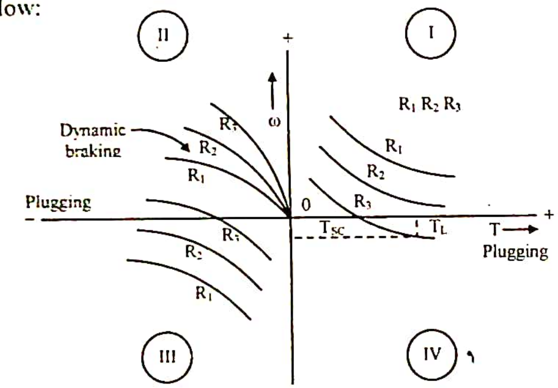
$$I_a = \frac{V_a - E}{R_a} = \frac{-186.218 - (-195.218)}{0.06} = 150 \text{ A}.$$

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:

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

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

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

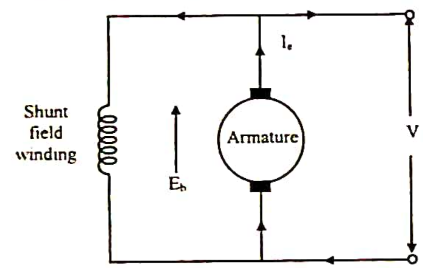


Fig: 1 Regenerative braking

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:

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

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

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

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 $\phi = K_1 I_a$. 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:

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

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

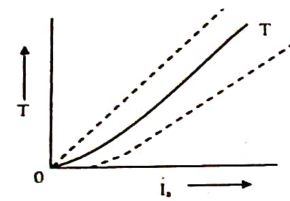
$$= \frac{A}{\sqrt{T}} - B \quad \text{......(4)}$$

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

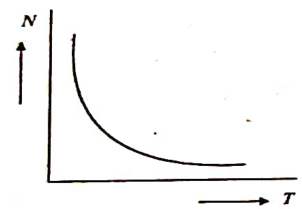
$$\omega = \frac{V}{K\phi} - \frac{I_a R}{K\phi}$$
$$= C - DT \quad (\because T \propto I_a) \quad \text{... (5)}$$

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. 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:

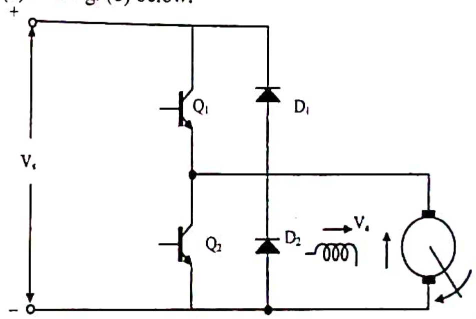


Fig: (a) Two-quadrant dc chopper-fed drive

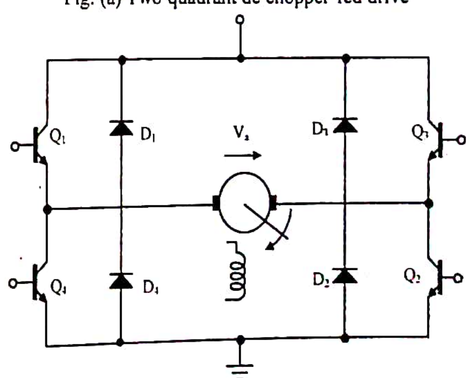


Fig: (b) Four-quadrant dc chopper-fed drive

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:

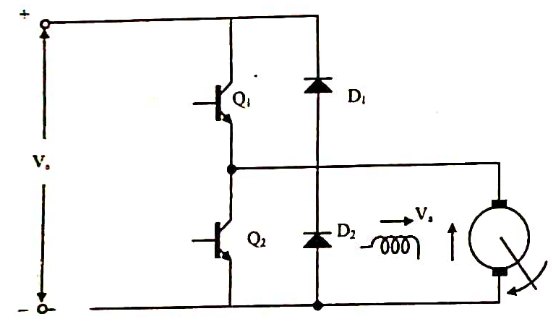


Fig: 1 Two-quadrant dc chopper-fed drive

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: -

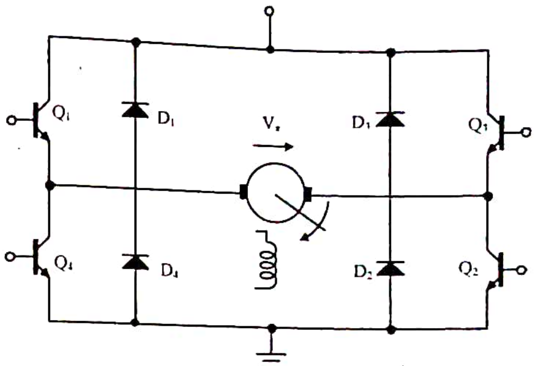


Fig: 2 Four-quadrant dc chopper-fed drive

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) $V_a = E_b + I_a R_a$

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

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

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

For torque 650 N-m

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

$$V_a = E_b + I_a R_a$$

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

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

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

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

$$\Rightarrow \quad \alpha = 0°.$$

ii) $\alpha = 120°$

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

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

$$V_a = E + I_a R_a$$

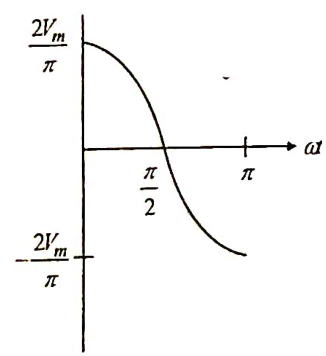
$$-89.8089 = E + (150 \times 0.06)$$

$$E = -98.8089$$

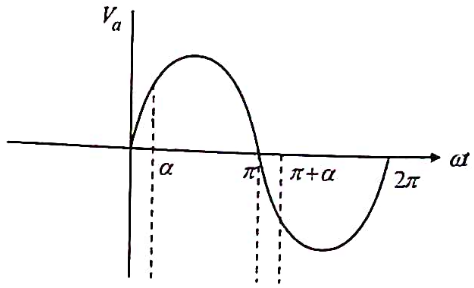
$$\text{Speed} = \frac{-98.8089}{211} \times 875 = -409.256\text{ N-m.}$$

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:

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

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

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

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 $V_L = 440$ V

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

(i) 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,

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

$$V_a = 156 + 0.5 \times 50 = 181 \text{ V}$$

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

$$\cos\alpha = \frac{V_a\pi}{3\sqrt{3}V_m} = \frac{181 \times \pi}{3\sqrt{3} \times 133}$$

$$\cos\alpha = 0.8228$$

$\therefore$ $$\alpha = 34.64°$$

(iii) At 800 rpm, $E_b = \frac{-800}{1500} \times 195 = -104$ V

(iv) Here the torque is twice the armature current

$\therefore$ $$V_a = E_b + I_a R_a = -104 + 2 \times 50 \times 0.5 = -54 \text{ V}$$

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

$$\cos\alpha = \frac{\pi V_a}{3\sqrt{3}V_m} = \frac{-\pi \times 54}{3\sqrt{3} \times 133}$$

$\cos\alpha = -0.2454$

$\therefore \quad \alpha = 104.20°$

b) Explain 4-quadrant operation of dc motor controlled by dual converter operating in non-circulating mode. **[WBUT 2014]**

Answer:

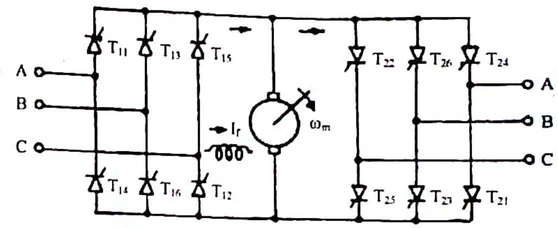


Fig: 1 Non-circulating current mode

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 $\quad E = \frac{900}{1200} \times 218 = \frac{3}{4} \times 218 = 163.5\text{ V}$

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

$$V_a = E - I_a R_a = 181.66 - (200 \times 0.6) = 181.66 - 12 = 169.66\text{ V}$$

$$\therefore \quad \cos\alpha = \frac{\pi}{3} \times \frac{V_a}{V_m} = \frac{0.5 \times 169.66}{115} = 0.7376$$

$$\alpha = \cos^{-1}(0.7376) = 42.46° \quad \textbf{(Ans.)}$$

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]**

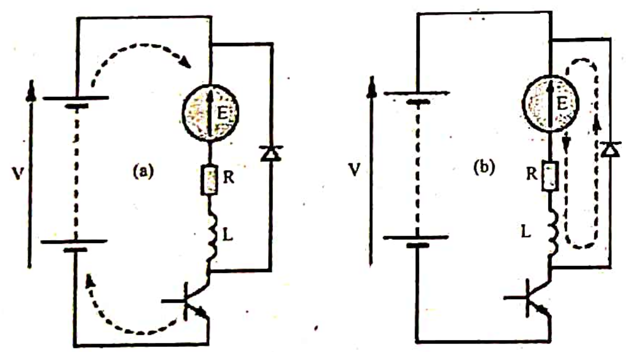
Answer:

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.



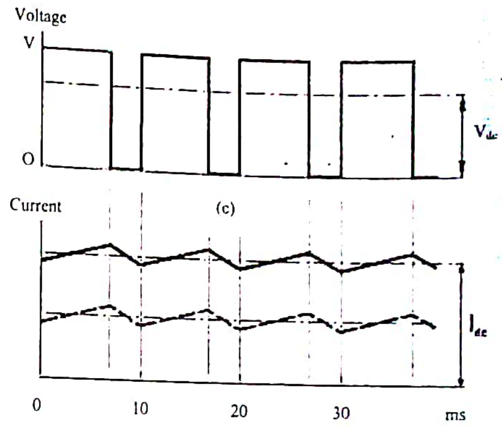


Fig: 1

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:

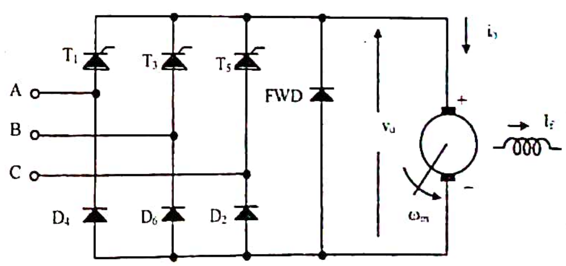


Fig: 1 (a) power circuit with dc motor load

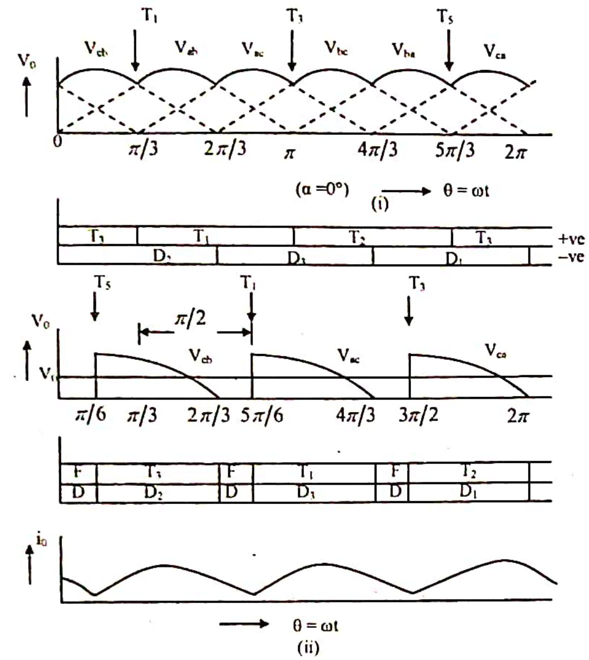


Fig: 1(b) voltage (i) α = 90° and current (α = 90°) waveforms for continuous load current

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).

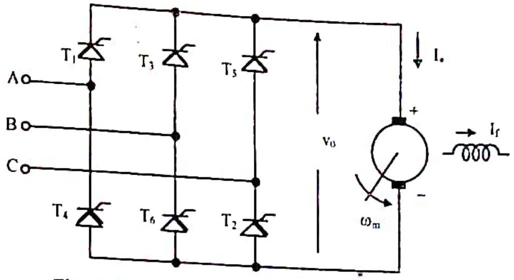


Fig: 2(a) power circuit with dc motor load

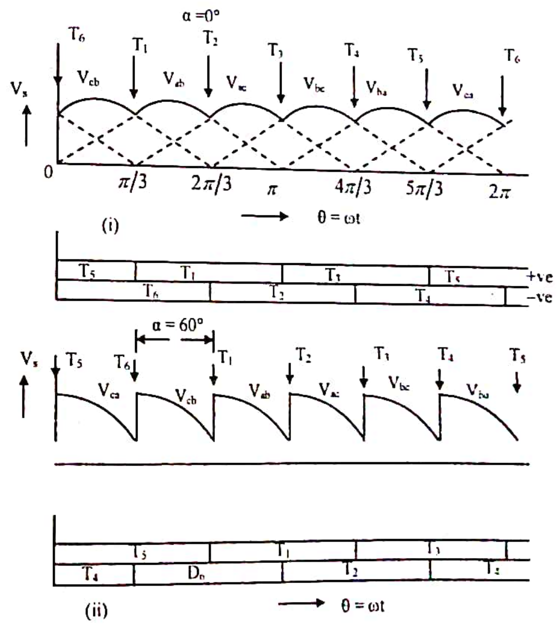


Fig: 2(b) voltage (i) α = 0° (ii) α = 60° and current (α = 60°) waveforms for continuous load current

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.