UNIT – I

SELECTION of MOTORS

1.1 INTRODUCTION

Motor control is required in large number of industrial and domestic applications such as transportation systems, rolling mills, paper machines, textile mills, machine tools, fans, pumps, robots, and washing machines. Systems employed for motion control are called *drives* and may employ any of the prime movers. Drives employing electric motors are known as electric drives.
Hence an Electric drive is defined as a form of machine equipment designed to convert electric energy into mechanical energy and provide control of these processes.

Nowadays, in electric power stations generating large amounts of electric energy for agriculture, industry, domestic needs, and electrified traction facilities and in driving all kinds of working machines, electric motor is essential, which is the predominant type of drive so the term electric drive being applied to it.

Electric drive becomes more popular because of its simplicity, reliability, cleanliness, easiness, and smooth control. Both AC and DC motors are used as electric drives; however, the AC system is preferred because:
o It is cheaper.
o It can be easily transmitted with low-line losses.
o It can be easy to maintain the voltage at consumer premises within prescribed limits.
o It is possible to increase or decrease the voltage without appreciable loss of power.

In spite of the advantages of AC motor, sometimes DC motor is used because:
o In some processes, such as electrochemical and battery charging, DC is the only type of power that is suitable.
o The speed control of DC motors is easy rather than AC; thus, for variable speed applications such as lift and Ward Leonard system, the DC motors are preferred.
o DC series motor is suited for traction work because of high starting torque.

1.2 BLOCK DIAGRAM OF ELECTRIC DRIVE:

Source:
1-φ and 3-φ, 50-Hz AC supplies are readily available in most locations. Very low power drives are generally fed from 1-φ source; however, the high power drives are powered from 3-φsource; some of the drives are powered from a battery.
Ex: Fork lifts trucks and milk vans.

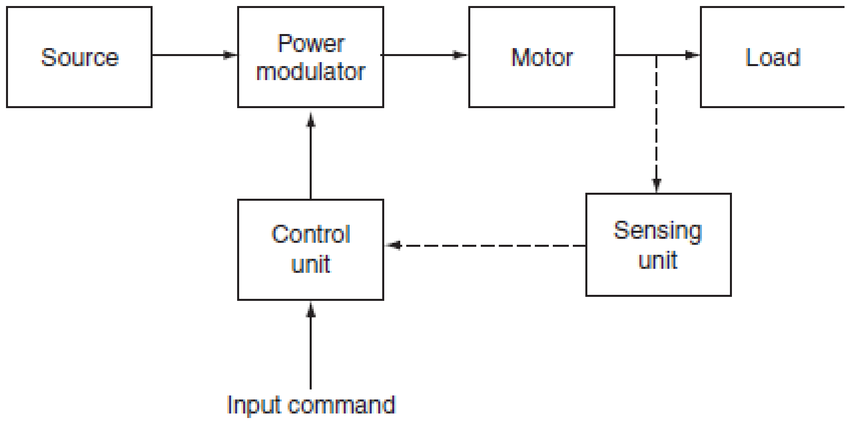


Fig. Block diagram of electric drive

Power modulator:

Power modulator performs the following functions:

o It modulates flow of power from the source to the motor is impart speed−torque characteristics required by the load.

o It regulates source and motor currents within permissible values, such as starting, braking, and speed reversal conditions.

o Selects the mode of operation of motor, i.e., motoring or braking.

o Converts source energy in the form suitable to the motor.

Electrical motors:

Motors commonly used in electric drives are DC motors, induction motors, synchronous motors, blushless DC motors, stepper motors, and switched reluctance motors, etc. In olden days, induction and synchronous motors were employed mainly for constant speed drives but not for variable speed drives, because of poor efficiency and are too expensive. But in nowadays, AC motors employed in variable speed drives due to the development of semiconductors employing SCRs, power transistors, IGBTs, and GTOs.

Load:

It is usually a machinery, such as fans, pumps, robots, and washing machines, designed to perform a given task, usually load requirements, can be specified in terms of speed and torque demands.

Control unit:

Control unit controls the function of power modulator. The nature of control unit for a particular drive depends on the type of power modulator used. When semiconductor converters are used, the control unit will consists of firing circuits. Microprocessors also used when sophisticated control is required.

Sensing unit:

Sensing unit consists of speed sensor or current sensor. The sensing of speed is required for the implementation of closed loop speed control schemes. Speed is usually sensed using tachometers coupled to the motor shaft. Current sensing is required for the implementation of current limit control.

Advantages of electric drive:

There are a number of inherent advantages that the electric drive possesses over the other forms of conventional drives are:

o They have comparatively long life than the mechanical drive.
o It is cleaner, as there are no flue gases, etc.
o It is more economical.
o They have flexible control characteristics.
o There is no need to store fuel or transportation.
o It requires less maintenance.
o Do not pollute environment.
o It is the reliable source of drive.
o Available in wide range of torque, speed, and power.
o High efficiency.
o Electric braking system is much superior and economical.
o Smooth speed control is easy.
o They can be started instantly and can immediately be fully loaded.
o They can operate in all the quadrants of speed torque plane.
o Being compactness, they require less space.
o They can be controlled remotely.

Disadvantages of electric drive:

The two inherit disadvantages of the electric drive system are:

o The non-availability of drive on the failure of electrical power supply.
o It cannot be employed in distant places where electric power supply is not available.

TYPES OF ELECTRIC DRIVES:

Depending on the type of equipment used to ran the electric motors in industrial purpose, they may be classified into three types. They are:

1. Group drives.
2. Individual drives.
3. Multi-motor drives.

Group drives:

Electric drive that is used to drive one or more than two machines from line shaft through belts and pulleys is known as group drive. It is also sometimes called the line shaft drive. This drive is economical in the consideration of the cost of motor and control gear. A single motor of large capacity cost is less than the total cost of a number of small motors of the same total capacity. In switch over from non-electric drive to electric drive, the simplest way is to replace the engine by means of motor and retaining the rest of power transmission system.

Advantages:

o The cost of installation is less. For example, if the power requirement of each machine is 10 HP and there are five machines in the group, then the cost of five motors will be more than one 50-HP motor.
o If it is operated at rated load, the efficiency and power factor of large group drive motor will be high.
o The maintenance cost of single large capacity motor is less than number of small capacity motors.
o It is used for the processes where the stoppage of one operation necessitates the stoppages of sequence of operations as incase of textile mills.
o It has overload capacity.

Disadvantages:

Even though group drive has above advantages, it suffers from the following disadvantages.
o If there is any fault in the main motor, all the machines connected to the motor will fail to operate; thereby, paralyzing a part of industry until the fault is removed.
o It is not possible to install any machine at a distant place.
o The possibility of the installation of additional machines in an existing industry is limited.
o The level of noise produced at the work site is quite large.
o The speed control of different machines using belts and pulleys is difficult.
o The flexibility of layout is lost due to line shaft, belts, and pulleys.

Individual drive:

In individual drive, a single electric motor is used to drive one individual machine. Such a drive is very common in most of the industries.

Advantages:

o It is more clean and safety.
o Machines can be located at convenient places.
o If there is a fault in one motor, the output and operation of the other motors will not be effected.
o The continuity in the production of the industry is ensured to a higher degree.
o Individual drive is preferred for new factories, as it causes some saving in the cost.

Disadvantages:

o Initial cost will be high.
o Power loss is high.

Multi-motor drive:

In multi-motor drives, several separate motors are provided for operating different parts of the same machine.

Ex: In traveling cranes, three motors are used for hoisting, long travel, and cross-travel motions.Multi-motor drive is used in complicated metal cutting machine tools, rolling mills, paper making machines, etc.

CHOICE OF MOTORS:

The selection of the driving motor for a given service depends upon the conditions under which it has to operate. Due to the universal adoption of electric drive, it has become necessary for the manufacturer to manufacture motors of various designs according to the suitability and the use in various designs according to the suitability and the use in various classes of industry. This has resulted into numerous types of motors. For this reason, the selection of motor itself has become an important and tedious process. The conditions under which an electric motor has to operate and the type of load it has to handle, determine its selection.

While selecting a motor, the following factors must be taken into consideration:

(a) Cost:

1. initial cost and
2. running cost.

(b) Electric characteristics:

1. starting characteristics,
2. running characteristics,
3. speed control characteristics, and
4. braking characteristics.

(c) Mechanical characteristics:

1. type enclosure and bearings,
2. arrangement for the transmission of power,
3. noise, and
4. cooling.

(d) Size and vetting of motors:

1. requirements for continuous, Intermittent, or variable load cycle and
2. overload capacity.

(e) Type of drive:

1. the drive is for one or more machines and
2. the type of transmission through gears, belts, etc.

(f) Nature of supply.

From the above, it is seen that a large number of factors are to be considered in making the choice of an electric motor for a given drive. The motor selected must fulfill all the necessary load requirements and at the same time, it should not be very costly if it has to be a commercial success. The factors motioned above will be individually discussed in the following sections to bring home to the reader the importance of each. While making the final choice of the motor, a satisfactory compromise may have to be made in some cases on account of the conflicting requirements.

CHARACTERISTICS OF DC MOTOR:

The performance and, therefore, suitability of a DC motor are determined from its characteristics. The important characteristics of DC motor are:

1. *Torque vs. armature current characteristics* (*T vs. I*a):

This characteristic curve gives relation between torque developed in the armature (T) and armature current (I_a). This is also known as *electrical characteristic.*

2. *Speed vs. armature current characteristics (N vs. I*a):

This characteristic curve gives relation between speed (N) and armature current (I_a). This is also known as *speed characteristics.*

3. *Output (HP) vs. armature current characteristics (HP vs. I*a):

The horse power of the motor is dependent on the shaft torque, so its characteristics follows *shaft torque characteristic.*

4. *Speed vs. T characteristics (N vs. T):*

This characteristic gives relation between speed (N) and torque (T) developed in the armature. This curve may be derived from the two characteristics mentioned in characteristics (i) and (ii) above. Characteristics (i), (ii), and (iii) are called *starting characteristics,* and (iv) is known as *running characteristics.*

While discussing motor characteristics, the following relations should always be kept in mind.

$$T \propto \phi I_a \quad \text{and} \quad N \propto \frac{E_b}{\phi},$$

where T_a is the torque developed in the armature in N-m, I_a is the armature current in ampere, E_b is the back emf in volts, and φ is the flux in weber.

Characteristics of shunt motor:

The field winding connected across the armature terminals called as *shunt motor* as shown in Fig.. Rated voltage is applied across the field and armature terminals.

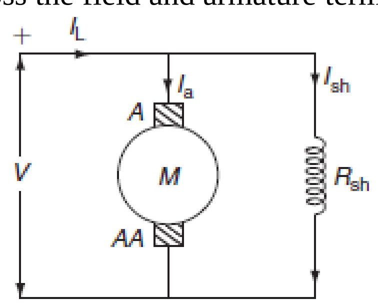


Fig. DC shunt motor

Starting characteristics:

The study of starting characteristics of a motor is essential to know the starting torque necessary to accelerate the motor from standstill position is also to require to overcome the static friction and the standstill load or, to provide load torque.

Torque vs. armature current (T Vs Ia):

In the expression for the torque of a DC motor, torque is directly proportional to the product of flux per pole (φ) and armature current (Ia):

$$\therefore T \propto \phi I_a$$

Since, in case of a DC shunt motor, the flux per pole (φ) is considered to be constant.

$$\therefore T \propto I_a.$$

So, the torque is proportional to armature current and is practically a straight line passing through the origin as shown if Fig.

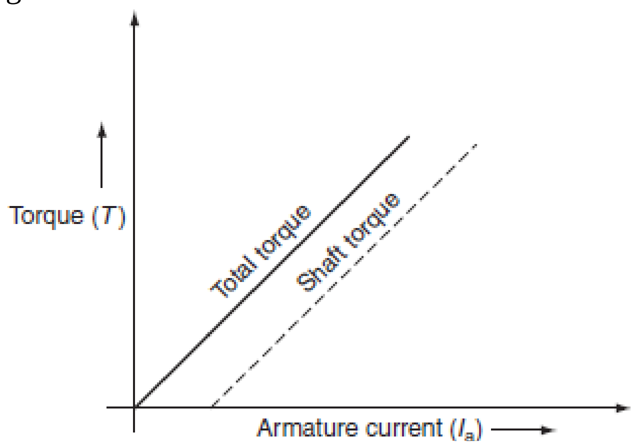


Fig. Torque vs. armature current characteristics

To generate high starting torque, this type of motor requires a large value of armature current at starting. This may damage the motor, hence DC shunt motors can develop moderate starting torque and hence suitable for such applications where starting torque requirement is moderate.

Speed vs. armature current (N Vs Ia):

In shunt motor, the applied voltage ‘ V' is kept constant, the field current will remain constant, and hence the flux will have maximum value on no load due to the armature reaction; if load on the motor increases, the flux will be slightly decrease. By neglecting the armature reaction, the flux is almost constant.

From the speed equation of DC shunt motor:

$$N \propto \frac{E_b}{\phi},$$

where $E_b = V - I_a R_a$

$$\therefore N \propto \frac{V - I_a R_a}{\phi}.$$

Since, for DC shunt motor, the flux per pole is considered to be constant.So,

$$\therefore N \propto V - I_a R_a.$$

So, as the load on the motor increases, the armature current increases and hence $I_a R_a$ drop also increases. For constant supply, the voltage (V-$I_a R_a$) decreases and hence the speed reduces.

Hence, as armature current increases, the speed of the DC motor decreases. The variation of speed with armature current is shown in Fig.

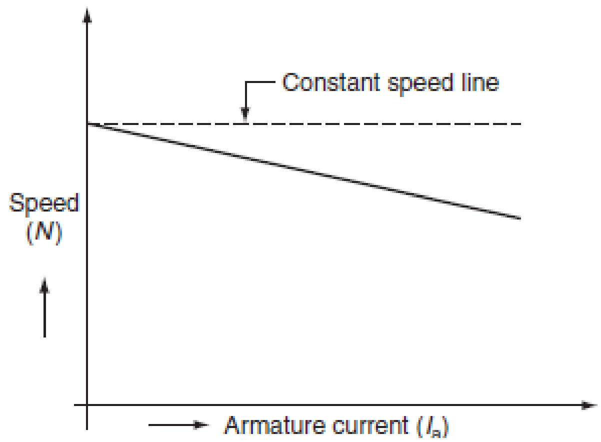


Fig. Speed vs. armature current characteristics

Output vs. armature current:

The output of the motor is dependent on the shaft torque. If the armature current increases, the output of the motor gradually increases. The variation of output with the armature current is shown in Fig.

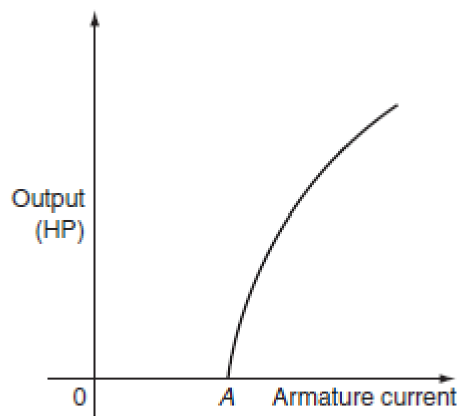


Fig. Armature current and HP characteristics

Running characteristics:

Speed-torque characteristics (N vs. T):

These characteristics can be derived from its staring characteristics of (i) and (ii). During the steady-state operation of the motor, the voltage equation of the armature circuit is given by:

$$V = E_b + I_a R_a$$

where V is the applied voltage, E_b is the back emf of motor, I_a is the armature current, and R_a is the armature resistance.

The back emf of motor can be expressed as:

$$E_b \propto \varphi N$$

$$\therefore E_b = K\,\varphi\,N,$$

$$N = \frac{E_b}{K\phi}.$$

where K is the constant, Substituting E_b from Equation in above equation:

$$\text{Speed, } N = \frac{V - I_a R_a}{K\phi}.$$

The torque of the motor is directly proportional to product of flux and armature current.

$$\therefore T \propto \phi I_a$$

$$= K\,\phi\,I_a$$

$$I_a = \frac{T}{K\phi}$$

$$N = \frac{V}{K\phi} - \frac{T}{(K\phi)^2} \times R_a.$$

Since, the shunt motor flux is constant, the speed of the motor is:

$$N = \frac{V}{K_1} - \frac{T}{K_1^2} R_a,$$

where $K_1 = K\varphi$.

When V and R_a are kept constant, the speed torque characteristic is a *straight line.*

If the load on the motor increases, thus the torque increases and hence the speed of the motor decreases.

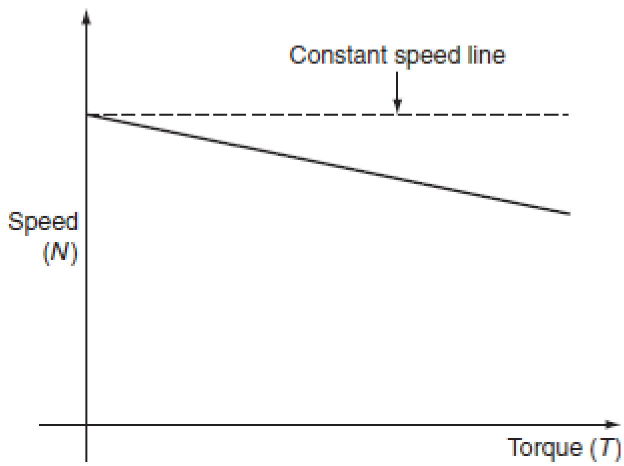


Fig. Speed and torque characteristics

Characteristics of DC series motor

In case of series motor, the field windings are connected in series with armature terminals as shown in Fig. Since, the field winding is connected in series with the armature winding, the load current (I_L) is equals to the armature current (I_a) or the series field current (I_{se}).

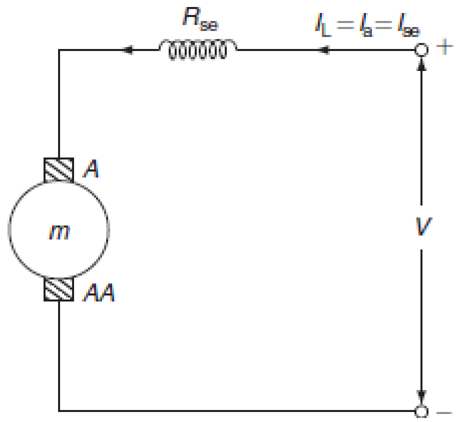


Fig. DC series motor

From Figure, $\therefore I_L = I_a = I_{se}$.

Starting characteristics:

Torque vs. armature current (T Vs Ia*):*

In case of DC motors, torque is directly proportional to the product of flux per pole (φ) and armature current (I_a).

$$\therefore T \propto \varphi I_a.$$

Up to the saturation point, the flux is proportional to the field current and hence the armature current:

$$\text{i.e., } \varphi \propto I_{se} \propto I_a.$$

Therefore, the torque is proportional to the square of the armature current.

$$\therefore T \propto I_a^2 \left(\because I_a = I_{se}\right).$$

Hence, the curve drawn in Fig; the torque and the armature currents are parabolas, up to saturation point. After saturation, the flux (φ) is almost independent of the excitation current and so the torque is proportional to the armature current, i.e., $T \propto I_a$. Hence the characteristics become a straight line. The variation of torque with the armature current is shown in Fig.

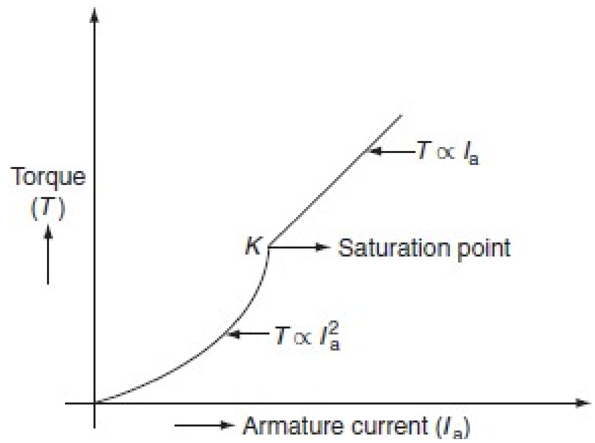


Fig. Torque and armature current

Speed vs. armature current:
From the speed equation of DC series motor, the speed is directly proportional to the back emf and is inversely proportional to flux:

$$N \propto \frac{E_b}{\phi}$$

where $E_b = V - I_a R_{se}$.
When the armature current increases, the voltage drop in the armature resistance and the field resistance increases, but under the normal conditions, the voltage drop is small and it is negligible.
Hence, $V = E_b$ and it is constant:

$$\therefore \; N \propto \frac{1}{\phi} \propto \frac{1}{I_a}$$

$$\therefore N \propto \frac{1}{I}$$

This relation shows the variation of speed with the armature current and it will be a *rectangular hyperbola*, which is shown in Fig.

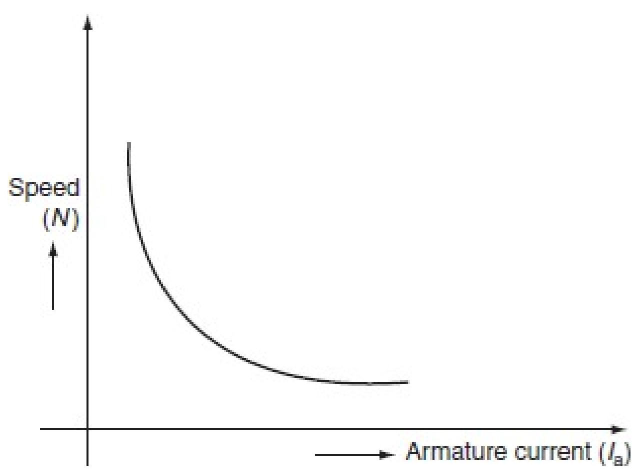


Fig. Speed and armature current

Running characteristics:

Speed-torque characteristics:

These characteristics can be derived its starting characteristics. It is also known as *mechanical characteristic.*

In case of series motors:

$$T \propto \phi I_a \propto I_a^2 \text{ and}$$

$$N \propto \frac{1}{I_a}.$$

As the torque of a DC machine is directly proportional to armature current and flux, the speed will be inversely proportional to the square root of the torque, i.e., from the above two relations:

But at higher loads, the flux becomes saturated and the torque will be proportional to armature current, so the speed can be represented as:

The speed–torque characteristics of a DC series motor is shown in Fig.

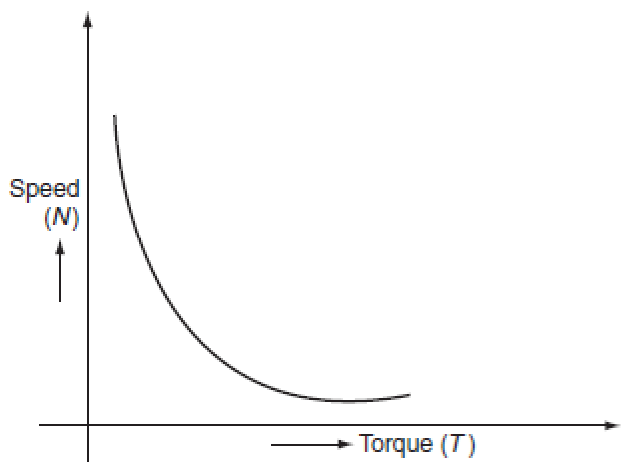


Fig. 1.10 Speed–torque characteristics

Hence, the series motors are best suited for services where the motor is directly coupled to the load such as whose speed falls with the increase in load torque.

Characteristics of DC compound wound motors:

Compound motors have both series. If the series field excitation aids with the shunt excitation, then the motor is said to be *cumulatively compounded.* If the series field opposes the shunt field excitation, it is known as *differential compound motor.*

The characteristics of such motors lie in between shunt and series motors.

Cumulative-compound motor:

Since, the series field aids with the shunt field winding, the flux is increased, as load is applied to the motor, and due to this reason, the motor speed slightly decreases. Such machines are used where series characteristics are required. Due to the shunt field, the winding speed will not become excessively high, but due to the series field winding, it will be able to take heavy loads. Compound wound motors have the greatest application with loads that require high starting torques or pulsating load.

Differential-compound motors:

In this motor, the series field opposes the shunt field and the flux is decreased, as load is applied to the motor. This results in the motor speed that is almost constant or even increasing with increase in load.

The speed-armature current and the torque–armature current characteristics of both the cumulative and the differential compound motors are shown in Figs.

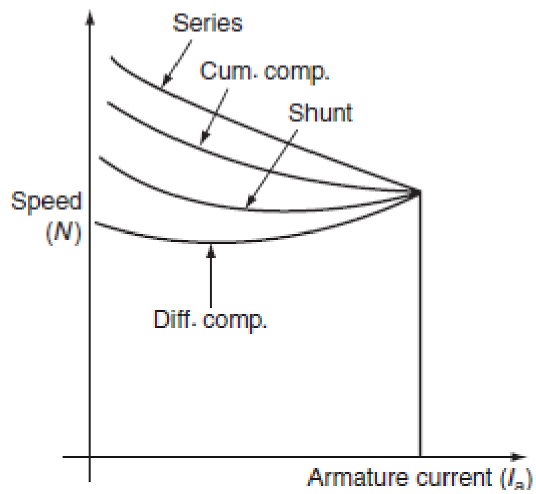


Fig. Speed and armature current characteristics

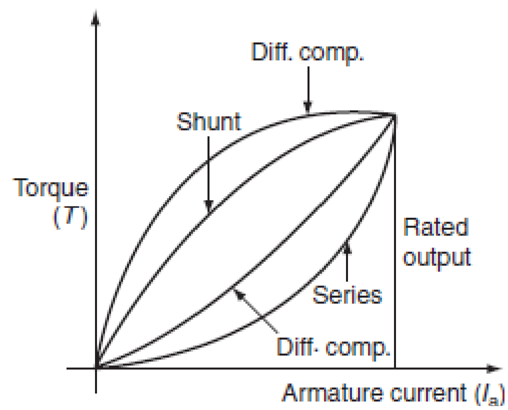


Fig. Torque and armature current characteristics

THREE-PHASE INDUCTION MOTOR:

Three-phase induction motors are simple in design, rugged in construction with the absence of commentator, and reliable in service. Besides this, they have low initial cost, simple maintenance, easy operation, and simple control gear for starting and speed control. The speed–torque characteristics of the induction motor are quite important in the selection of the induction motor drive. These characteristics can be effectively determined by means of the equivalent circuit of the induction motor. The simplified equivalent circuit of induction motor is shown in Fig

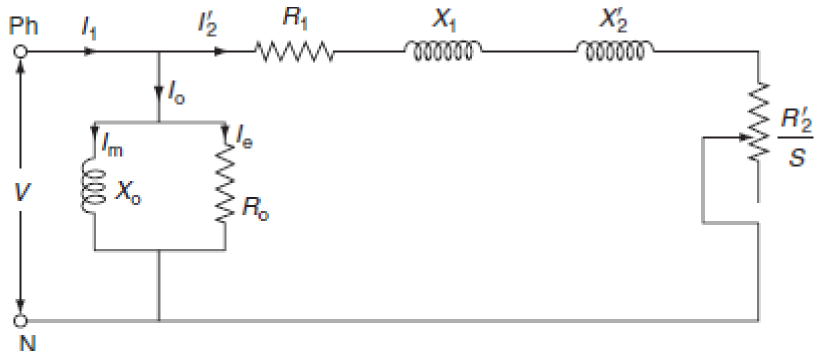


Fig. Equivalent circuit of induction motor

In Fig , V is the applied voltage per phase, R_1 and X_1 are the stator resistance and leakage reactance per phase, $R_{2'}$ and $X_{2'}$ are the rotor resistance and leakage reactance per phase, R_0 and X_0 are the resistance and reactance per phase of the magnetizing branch, and is $I_{2'}$ the rotor current per phase.

From the equivalent circuit of induction motor, as shown in Fig. 1.13, the rotor current referred to the stator is given by:

$$I_2' = \frac{V}{\sqrt{\left(R_1 + \frac{R_2'}{S}\right)^2 + (X_1 + X_2')^2}}.$$

If the induction motor is rotating at slip is then:

Induced emf of rotor = SE_2.

Rotor resistance = R_2.

Rotor reactance = SX_2.

Rotor current /phase

$$I_2 = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

Torque equation:

The torque produced in the induction motor is mainly depends on the magnitude of rotor current, the power factor of the rotor circuit, and the part of rotating magnetic field that interacts with the rotor.

$$\therefore T \propto E_2 I_2 \cos\phi_2.$$

Substituting the values of I_2 and $\cos\varphi_2$

$$T \propto E_2 \times \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} \times \frac{R_2}{\sqrt{R^2 + (SX_2)^2}}$$

$$\therefore T \propto \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

$$T = \frac{KSE_2^2 R_2}{R_2^2 + (SX_2)^2},$$

where 'K' is proportionality constant,

$$\therefore T = \frac{3}{2\pi N_s} \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}, \qquad ($$

where N_s is synchronous speed in rps at standstill slip $S = 1$; therefore, the expression for starting torque may be obtained by putting $S = 1$.

$$\therefore T_s = \frac{KE_2^2 R_2}{R_2^2 + X_2^2},$$

Condition for maximum torque:

The torque developed by the motor under running condition mainly depends on slip at which motor is running.

Therefore, the torque will be maximum when:

$$\frac{dT}{dS} = 0; \qquad \text{where } T = \frac{KSE_2^2 R_2}{R_2^2 + (SX_2)^2}.$$

By differentiating torque w.r.t. 'S' we get:

$$\frac{dT}{dS} = \frac{(KSE_2^2 R_2)\frac{d}{dS}(R_2^2 + S^2 X_2^2) - (R_2^2 + S^2 X_2^2)\frac{d}{dS}(KSE_2^2 R_2)}{(R_2^2 + S^2 X_2^2)^2}$$

$$\therefore KS_m E_2^2 (2S_m X_2^2) - (R_2^2 + S_m{}^2 X_2^2) = 0$$

$$2S_m{}^2 X_2^2 - (R_2^2 + S_m{}^2 X_2^2) = 0$$

$$R_2 = S_m X_2$$

$$S_m = \frac{R_2}{X_2} \qquad (8.17)$$

Above equation reveals that the slip 'S_m' at which maximum torque will be developed by the induction motor.

Now, the maximum torque corresponding to slip $S_m = R_2/X_2$ is given by:

$$T_{max} = \frac{K \times \frac{R_2}{X_2} \times R_2 \times E_2^2}{R_2^2 + \frac{R_2^2}{X_2^2} \times X_2^2}$$

$$= \frac{KE_2^2}{2X_2}. \tag{8.18}$$

Torque ratios

The performance of motor is estimated in terms of the ratios of different torques such as fullload, starting, and maximum torques.

Ratio of full-load torque to maximum torque

Let,

S_f = full-load slip of the motor

S_m = slip corresponding to maximum torque

According to the torque, the equation of motor is:

$$\text{Full-load torque } T_{fl} \propto \frac{S_f E_2^2 R_2}{R_2^2 + (S_f X_2)^2}.$$

$$\text{Maximum torque } \mathrm{T_m} \propto \frac{S_m E_2^2 R_2}{R_2^2 + (S_m X_2)^2}.$$

$$\therefore \frac{T_{FL}}{T_m} = \left[\frac{S_f E_2^2 R_2}{R_2^2 + (S_f X_2)^2}\right]\left(\frac{R_2^2 + (S_m X_2)^2}{S_m E_2^2 R_2}\right)$$

$$= \frac{S_f}{S_m}\left[\frac{\left(\frac{R_2}{X_2}\right)^2 + {S_m}^2}{\left(\frac{R_2}{X_2}\right)^2 + {S_f}^2}\right].$$

$$\text{We know that } \frac{R_2}{X_2} = S_m$$

$$\therefore \frac{T_{FL}}{T_m} = \frac{S_f}{S_m}\left[\frac{2{S_m}^2}{{S_f}^2 + {S_m}^2}\right]$$

$$= \frac{2 S_f S_m}{{S_f}^2 + {S_m}^2}.$$

Ratio of starting torque to maximum torque

$$\frac{T_{st}}{T_m} = \frac{KE_2^2 R_2}{R_2^2 + X_2^2} \times \frac{2X_2}{KE_2^2}$$

$$= \frac{2(R_2/X_2)}{(R_2/X_2)^2 + 1}$$

$$= \frac{2S_m}{S_m^{\ 2} + 1}.$$

Torque–speed and torque–slip characteristics

The torque–speed and torque–slip characteristics are shown in Fig. (a) and (b). According to the torque equation of motor:

$$T \propto \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}.$$

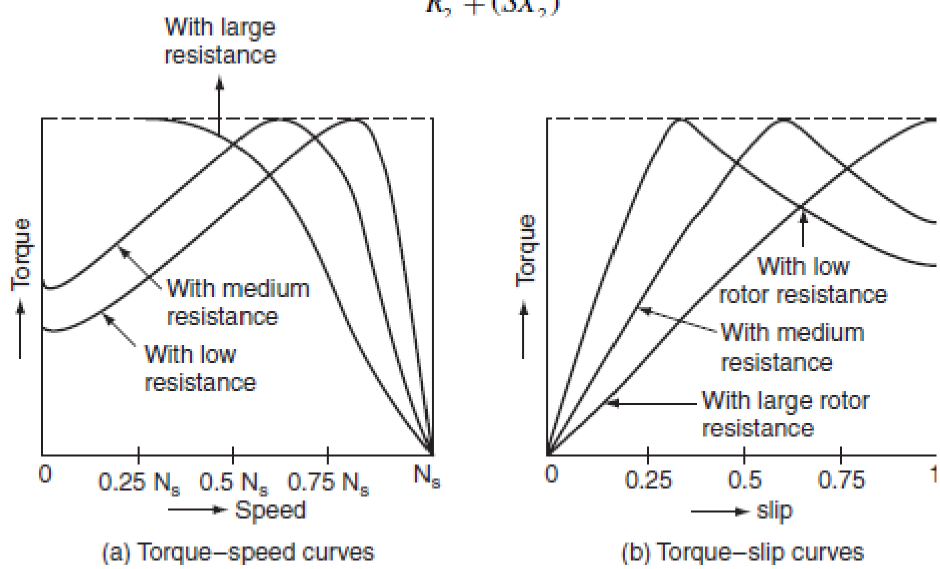


Fig. (a) Torque-speed characteristics and (b) torque–slip characteristics

But for constant supply voltage, E_2 is also constant:

$$\text{i.e.,}\ T \propto \frac{SR_2}{R_2^2 + (SX_2)^2}.$$

From the above expression, it is evident that, when torque is zero, slip $S = 0$ in low-slip region, slip is very very small, so that (SX_2) is so small compared to R_2; hence, it can be neglected.

$$T \propto \frac{SR_2}{R_2^2} \propto S.$$

Therefore, torque T is proportional to slip ‘S’ if rotor resistance R_2 is constant. That is speeds nearer to synchronous speeds, the torque–speed, and torque–slip curves are approximately straight lines.

In high-slip region, the slip value approaches to unity. Here, it can be assumed that R_2^2 is very

ery small as compared to $(SX_2)^2$; hence, it can be neglected.

$$T \propto \frac{SR_2}{S^2 X_2^2}.$$

When slip increases, the torque increases to its maximum value when $S = R_2/X_2$. The maximum torque is also known as pullout or breakdown torque. Beyond this, if slip further increases torque is inversely proportional to slip if R_2 and X_2 are constant.
This means that the torque–speed and the torque–slip curves are approximately straight lines.
Above Figure shows the torque speed and the torque–slip curves for the different values of rotor resistance.

SPEED CONTROL OF DC MOTORS:
In practical applications, a motor may be required to perform a number of desirable jobs conforming different load conditions and speed requirements. The availability of DC motors to adjustment of their operating speed over wide ranges and by a variety of methods is one of the important reasons for the strong competitive position of DC machinery in the industrial applications.
The natures of speed control required by different industrial drives are:
o Some drives require a continuously variable speed over the range from zero to full speed, such drives are known as *variable-speed drives.*
o Some drives require only two to three fixed speeds over a region, such drives are known as*multi-speed drives.*
o In some cases, speed is needed for adjusting or setting up the work on driven machine only for a few revolutions per minute. Such a speed is known as *creeping speed.*

For example, crane or hoist requires same torque at all speeds, while a fan or centrifugal pump requires a torque proportional to the square of the speed. For most of the drives, however, a control of speed within ±25% of the normal speed is required. The speed and torque of a DC motor can be expressed by the following relationships.

$$N \propto \left(\frac{V - I_a R_a}{\phi}\right) \qquad (8.19)$$

$$T \propto \phi I_a,$$

where V is the terminal voltage in volts, I_a is th armature current in ampere, R_a is the armature resistance in ohm, φ is the flux per pole in *wb*, TV is the speed of DC motor in rpm, and T is the torque in N-m.

Therefore, the speed of DC motors can be regulated by varying φ, R, or V. The speed of DC motors can be controlled by the following methods:
1. Field control or flux control method.

2. Armature control method.
3. Applied voltage control.

Speed control of DC shunt motors:

Speed of DC shunt motor can be controlled by varying the flux, armature resistance, and applied voltage to the armature terminals.

Various methods of controlling the speed of the shunt motor is given as follows.

Field control method:

The speed adjustment of the DC shunt motors by field control may be obtained by one of the following methods.

1. Field rehostatic control method.
2. Reluctance control method.
3. Field voltage control.

Field-rehostatic control method

In this method, speed control is obtained by controlling the field current or flux by means of a variable resistance inserted in series with the shunt filed winding. The external resistance (R_e) connected in series with the field winding is shown as shunt field regulator. The method of regulating the speed by varying the flux or field current in the shunt field winding is known as flux control method. Circuit diagram illustrating the speed control of a shunt motor is shown in Fig.

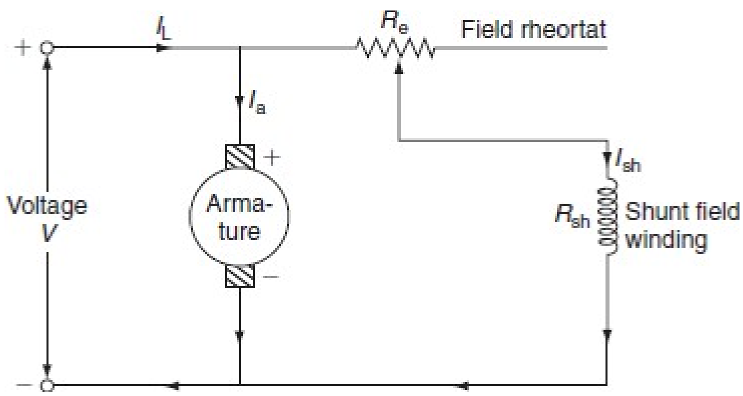


Fig. Field-rehostatic control of shunt motor

The variation of external resistance '*R*e' in the filed reduces the field current and hence the flux '*φ*' also reduces. The reduction in flux will also results in an increase in the speed. For DC shunt motor, speed is inversely proportional to field flux (φ). Since in this method of speed control, flux can be only reduced. Consequently, the motor runs at a speed higher than the normal speed. For this reason, this method of speed control is used to give motor speeds above normal or to correct for a fall in speed due to load.

Reluctance control:

In this method of speed control, the motor must be constructed with special mechanical features so that the reluctance of the magnetic circuit can be changed, which makes the motor more expensive. Hence, the variable reluctance type of motor is seldom used.

Field voltage control:

This method requires a variable voltage for the field circuit; such a variable supply can be obtained by means of an adjustable electronic rectifier.
The speed adjustment of the DC shunt motors by armature control may be obtained by one of the following methods.

1. Armature rehostatic control method.
2. Armature diverter method or potential devider method.

Armature rheostat control method:

In armature or rehostatic control method of speed, a variable rehostatic or resistance connected in series with the armature is known as controller resistance. The circuit diagram of the armature control method is shown in Fig.

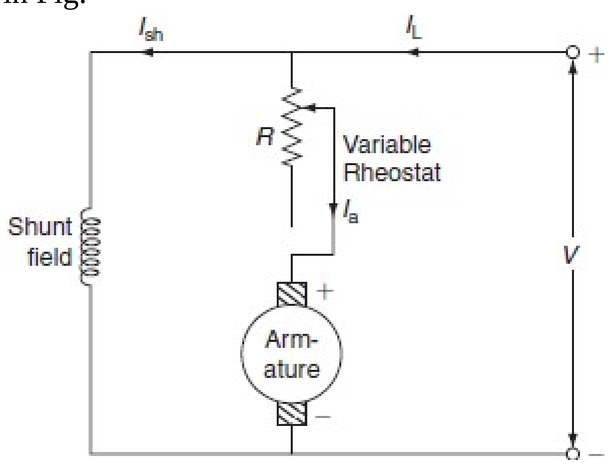


Fig. Armature rheostatic control of shunt motor

The speed is directly proportional to the voltage applied across the armature. Voltage across the armature can be controlled by changing resistance connected in series with it. As the controller resistance is increased, the potential difference across the armature is decreased thereby decreasing the armature speed. There is a particular load current at which the speed would be zero is called stating current. The main disadvantage of this method is speed up to zero is not possible, as it requires large rehostat in series with the armature that is practically impossible.

Armature diverter method or potential devider method

The main disadvantage of the above method can be overcome by connecting a rheostat in a potential devider arrangement as shown in Fig.

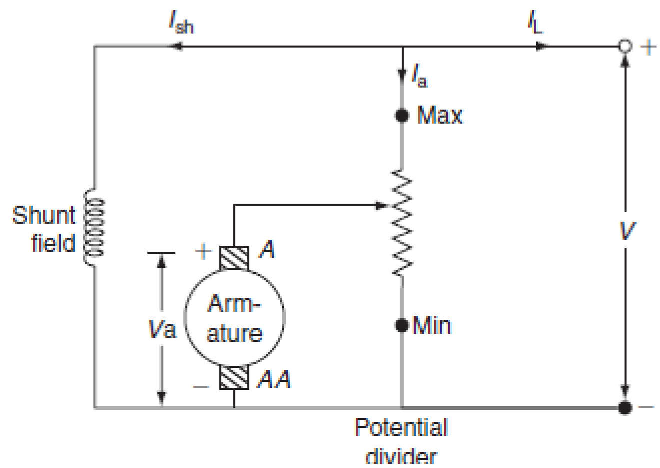


Fig. Potential divider method of shunt motor

When the variable rehostat is at minimum position, the voltage across the armature is zero. If rehostat is moved toward maximum position, the voltage across the armature increases then speed also increases. The variation of speed with the armature voltage is shown in Fig.

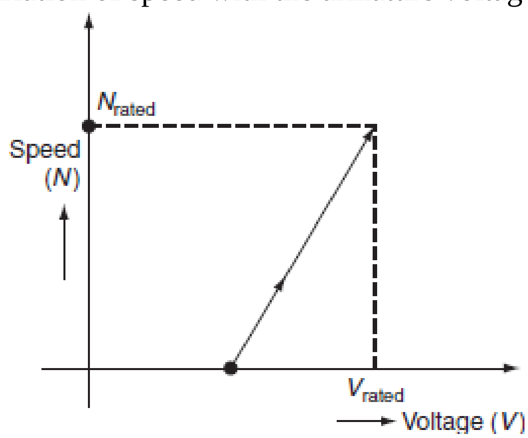


Fig. Speed-voltage characteristics

Speed control of DC series motor

The speed control of DC series motor can be obtained by changing the series field current, flux, or voltage applied across the armature. The methods of the speed control of the series motor are:

1. Field control method.
2. Armature control method.

Field control method

In the series motor, the variation of flux can be brought about by diverting the current flowing through the series field winding by any one of the following methods.

Field diverter's method:

In this method, the series field winding is shunted by a variable resistor 'R' known as series field divertor. Any desired amount of current can be passed through the divertor by adjusting its resistance. Hence, the flux can be controlled, i.e., decreased, and consequently the speed of the motor is increased.

The arrangement of field diverter and the speed-armature current characteristics with change in resistance '*R*' is shown in Figs. (a) and (b).

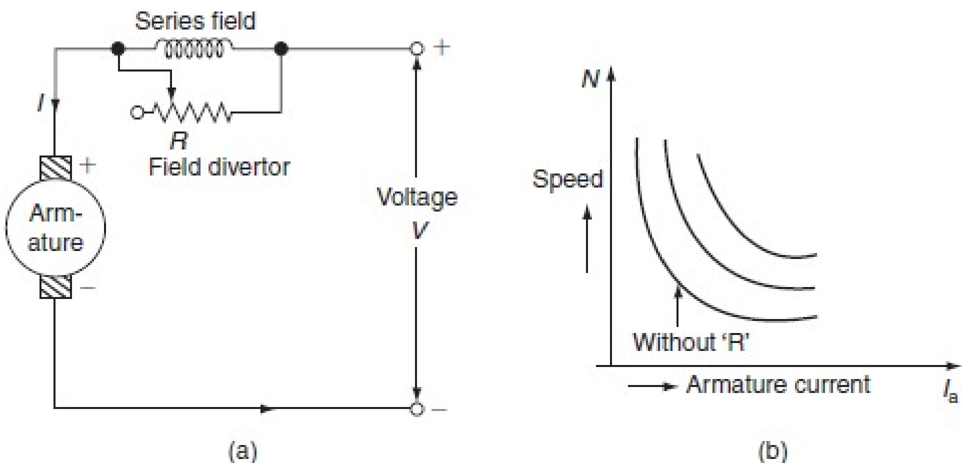


Fig. (a) Field diverter method of speed control and (b) Speed-current characteristics

Armature diverter method:

In this method, the armature of the motor is shunted with an external variable resistance (*R*) as shown in Fig. 8.20 is known as armature diverter.

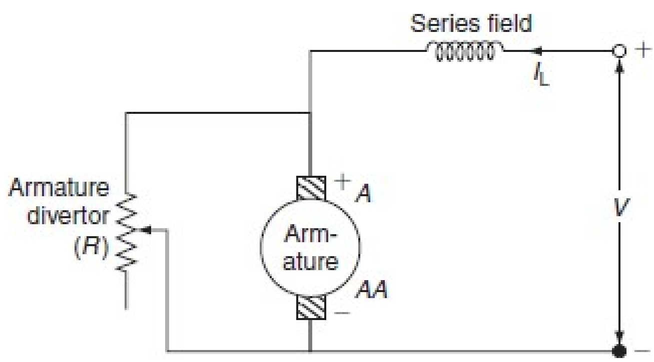


Fig. Armature diverter method of speed control

For a given constant load torque, if armature current is reduced due to armature divertor then flux (φ) must increase ($\therefore T \propto I_a$). So that, the motor reacts by drawing more current from the supply. So, the current through field winding increase, so the flux increases and the speed of the motor reduces.

This method of speed control is used to have the speed below the normal value.

Tapped filed method:

In this method, the flux change is achieved by providing a number of tapings from the field winding, which are brought out side as shown in Fig.

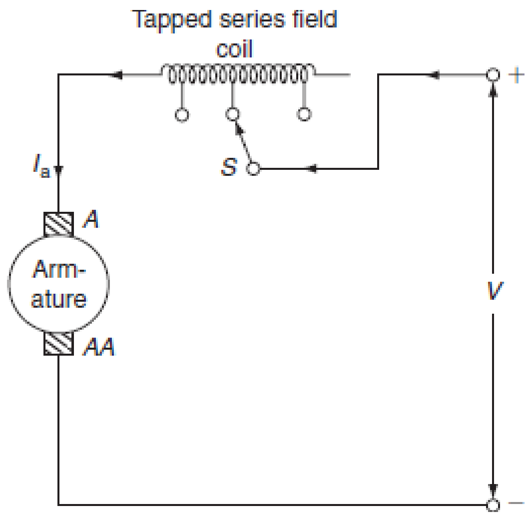


Fig. Tapped field speed control

As shown in Fig, the selector switch ‘SW’ is provided to select number of turns. So, the net mmf will change. This will cause the change in the speed of DC series motor.

This method is used in electric traction.

Series-parallel connection of field coils:

In this method of speed control, several speeds can be obtained by grouping the several field coils as shown in Figs. (a) and (b). This method is used generally in case of fan motors.

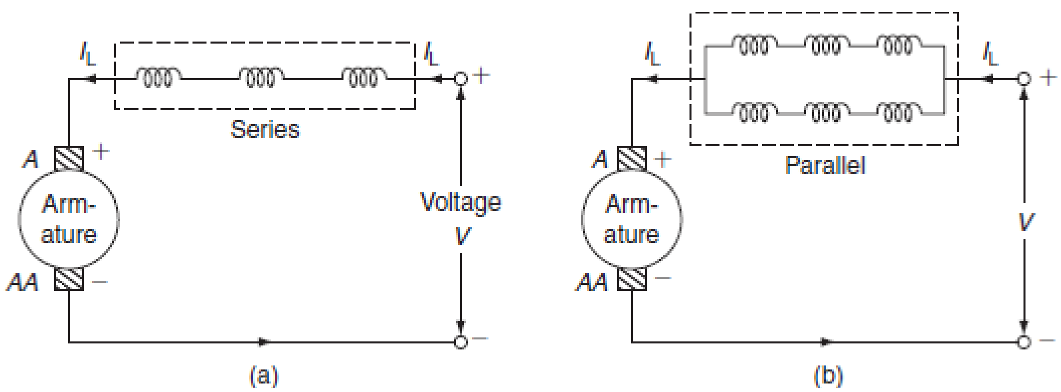


Fig. Series–parallel connection of field winding

If the field coils are arranged in series, or parallel, the mmf produced by the coils changes; hence, the flux produced also changes. Hence, the speed is controlled.

Armature control method:

Armature resistance control method is the most common method employed for DC series motor. The arrangement and speed-current characteristics of series motor is shown in Figs. (a) and (b).

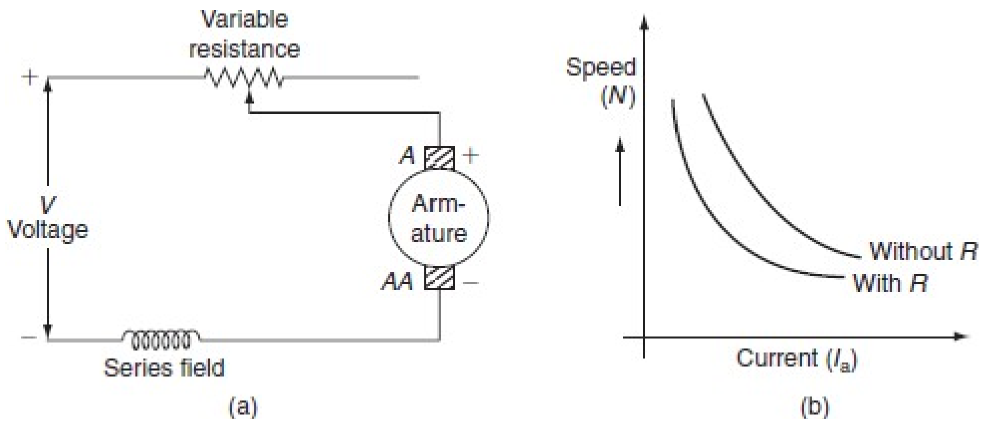


Fig. (a) Armature control method and (b) Speed-current characteristics

By increasing the resistance in series with the armature, voltage drop across this resistance occurs. So that, the voltage applied across the armature terminals can be decreased. As the speed is directly proportional to the voltage across the armature, the speed reduces.

Ward–Leonard method of speed control:

The speed control of DC motor accomplished by means of an adjustable voltage generator is called the Ward−Leonard system. If it is desired to have wide and very sensitive speed control, then this system is more generally used. The system is as shown in Fig

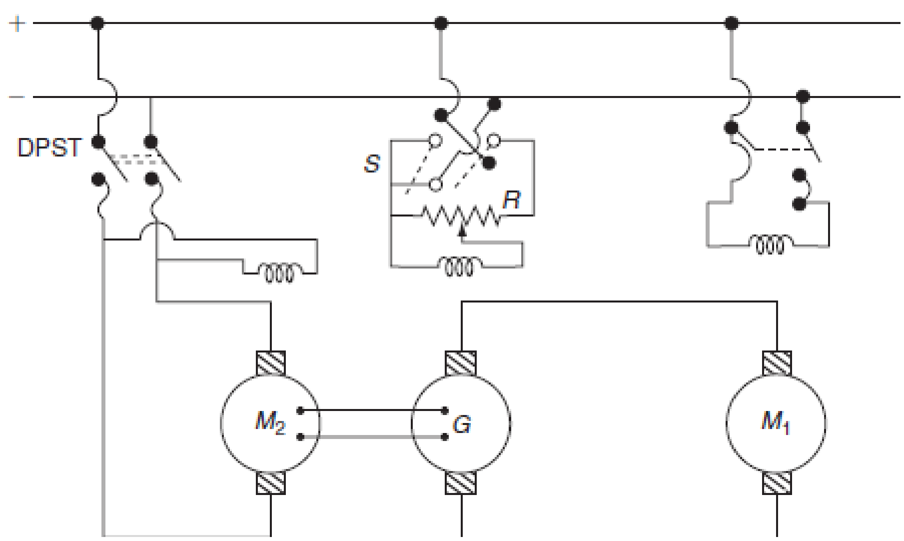


Fig. Ward−Leonard speed control system.

In Fig, R is the potential devider, M_1 is the main motor whose speed is to be controlled, G is the separately excited generator that feeds the armature of the motor M_1, M_2 is the driving motor that drive generator and main motor, and S is a double-throw switch. M_1 is the main motor whose speed control is required. The field winding of this motor is permanently connected to DC supply and armature is fed from variable voltage so that the motor can run at any desired speed. To provide this variable, the voltage motor generator set is used, in which the generator is directly coupled to a constant speed motor.

The field circuit of this generator is separately excited from the available DC supply through a reversing switch and a potential divider '*R*' so that its excitation can be varied from zero to maximum in both the directions. Thus, the generator output voltage can be varied from zero to maximum value. The polarity of generating voltage will be reversed with the help of reversing switch; thus, the change of the direction of the motor M_1 can be achieved.

This system is commonly employed for elevators, hoists, and main drive in steel mills, as this method can give unlimited speed control in either direction. Since the generator voltage can be varied gradually from zero, no extra starting equipment is required to start up the main motor smoothly. The important feature of the Ward–Leonard system is its regenerative action. The modified Ward–Leonard is called Ward–Leonard–Ilgner system in which a flywheel is used in addition to motor-generator set, whose function is to reduce fluctuations in the power demand from the supply circuit. When the main motor M_1 becomes suddenly overloaded, the driving motor M_2 slows down, thus allowing the inertia of the flywheel to supply a part of the overload. However, when the load is suddenly thrown of the main motorM_1, then M_2 speeds up thereby again stores energy in the flywheel.

Advantages of Ward–Leonard system:

o A wide range of speed from standstill to high speed in either direction.

o Starting without any extra starting equipment.

o Extremely good speed regulation at any speed.

Disadvantages:

o High capital cost due to the motor generator set.

o The efficiency of this method is not so high.

SPEED CONTROL OF INDUCTION MOTORS:

A three-phase induction motor is practically a constant-speed motor as the DC shunt motor. The speed control of DC shunt motor can be achieved easily, but it is difficult to achieve the smooth speed control of the induction motor because the performance of the induction motor in terms of its power factor, efficiency, etc. gets adversely effected.

We know that for the induction motor:

The speed of motor $N = N_s(1-S)$.

$$\text{And, the torque } T \propto \frac{SE_2^2R_2}{R_2^{\,2}+(SX_2)^2}. \qquad (8.21)$$

From the above two relations:

The speed of the induction motor can be changed either by changing its synchronous speed (Ns) or by changing the slip and also the parameters R2 and E2 are changed then to keep torque constant for constant load condition, slip will change, then its speed gets effected. Thus, the following methods are used for controlling the speed of the three-phase induction motors.

From stator side

1. Supply frequency control.
2. Supply voltage control.
3. Controlling the number of stator poles.

From rotor side

1. Adding external resistance in the rotor circuit.
2. Cascade control.

Stator side control

Thus, following any one method is used for controlling the speed of the three-phase induction motors on stator side.

Speed control by varying the supply frequency:

This method is impractical for most applications because the frequency of the supply system must remain fixed. The synchronous speed is given by:

$$N_s = \frac{120f}{P}$$ [illegible]

Thus, by controlling the supply frequency, the synchronous speed can be controlled over a wide range that gives the smooth speed control of the induction motor. Hence, in this method, variable voltage and frequency is achieved by using converter and inverter circuit as shown in Fig.

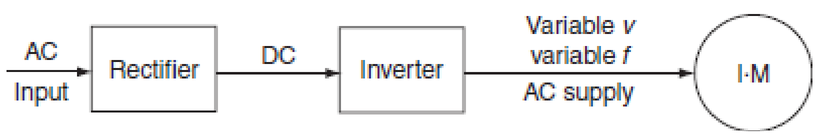


Fig. Electronic circuit for variable frequency

Rectifier converts normal AC supply to constant DC voltage. This DC supply is then given to inverter that converts constant DC to variable AC voltage and frequency.

Supply voltage control:

This is a slip-control method with constant frequency variable supply voltage. In this method, the voltage applied to the stator is varied.

We know that

$$T \propto \frac{SE_2^2 R_2}{R_2^{\,2} + (SX_2)^2}.$$

But, at standstill, rotor-induced emf depends on the supply voltage.

i.e., $E_2 \propto V$.

In the operating region of an induction motor or for low-slip region $(SX_2) << R_2$.

$$\text{So that } T = \frac{SE_2^2}{R_2}.$$

Rotor resistance is constant; therefore:

$$T \propto SE_2^2 \propto SV^2. \qquad (8.23)$$

From the above relation, if the supply voltage '*V* ' is reduced below the rated value torque developed by the induction motor reduce. But, so as to maintain the torque constant for constant load, it is necessary to increase the slip thereby decreasing the speed of induction motor.

This method of speed control is simple, low initial cost, and has low maintenance cost, but it has limited use because, the operation at voltage is restricted by magnetic saturation and also large change in voltage is required for relatively for small change in speed.

Speed control by changing the number of poles:

In this method, it is possible to have one or two speeds, one double of the other which is generally obtained by changing the number of poles. It is also called as pole-changing method. Changing the number of poles is simply affected by changing the connections of stator winding with the help of simple switches. Due to this number of stator poles gets changed, in the ratio 2:1. Hence, either of the two speeds can be selected.

Consider the single phase of a certain three-phase winding when the supply is across the two terminals and the third is kept open, as shown in Fig.

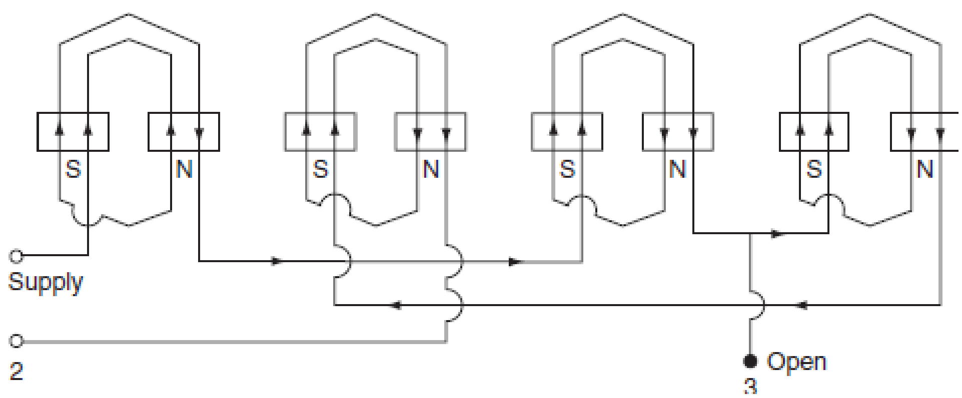


Fig. Eight-pole winding

Let the conductors which are carrying current in upward direction from South Pole, while the conductors which carry current in downward direction from north polarity. The distribution of current is as shown in Fig due to these eight poles get formed.

Now, the two terminals 1 and 2 which the supply was given earlier are joined together and supply is given to the common point of the first two terminals and the third terminal, on observing the direction of current, it will be found that total eight poles are changed to four poles only as shown in Fig; so that, the speed now will be double of the previous value.

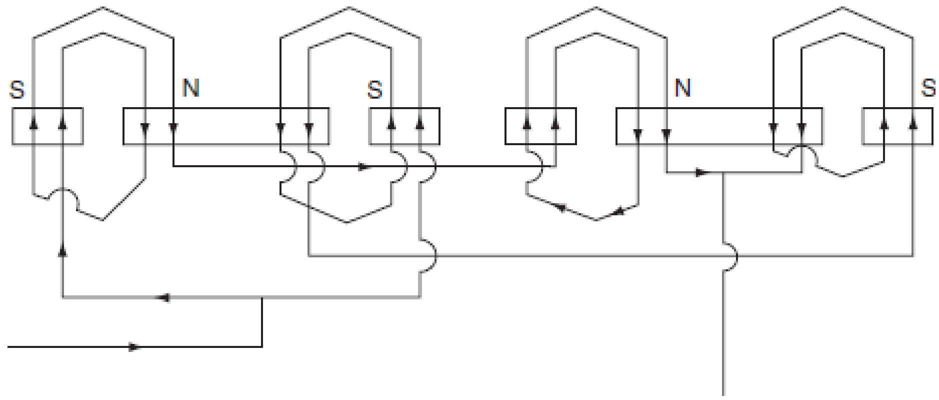


Fig. Four-pole winding

Control on rotor side:

The following method is used for controlling the speed of three-phase induction motors on rotor side.

Cascade control:

Multiple speeds are derived and motors are sometimes operated in tandem or cascade. If two motors are to be mechanically coupled together, one of the machines must be phase-wound motor while the other can be a squirrel-cage motor. The first is connected to the mains in the usual way, while that of the second stator is fed from the rotor winding of the first, as shown in Fig.

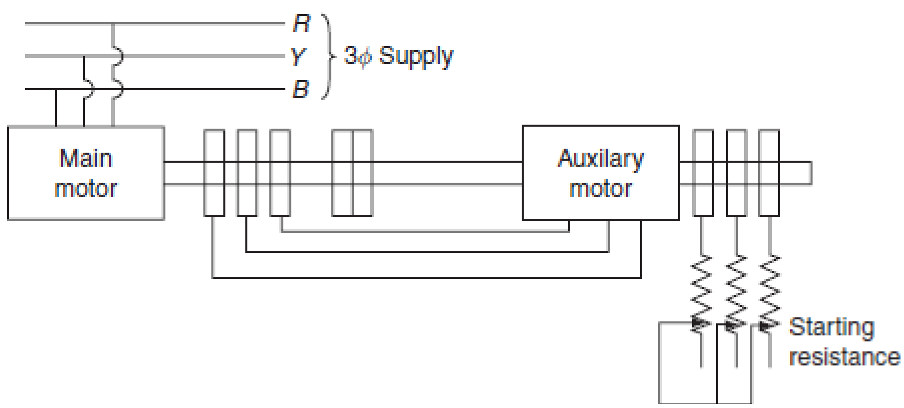


Fig. Cascade control of induction motor

When two motors are operated in tandem, they may be running in the same direction, or the phase rotation of one motor may be reversed, thus tending to make it in reverse direction. In both the cases, the set will run after it is started, but in the later case, no starting torque is developed so that this connection is rarely used.

If P_1 and P_2 be the number poles of both the machines, then the synchronous speed of the set is depending on total number of poles $P_1 + P_2$ in the first case and $P_1 - P_2$ in the second. If the number of poles of the two motors is not equal; four speeds possible: two for tandem operation and one for each motor separately.

Let 'P_1' be the poles of main motor and 'P_2' be the poles of the auxiliary motor.

If 'S' is the slip, the actual rotating speed of the motor is:

$$\begin{aligned} N_1 &= (1-S)N_s \\ &= (1-S)\left(\frac{120f}{P_1}\right) = \frac{120}{P_1}(f - S \times f). \end{aligned} \tag{8.24}$$

But, for the induction motor, the frequency of the rotor current is 'S' times of supply frequency.

Frequency $f_r = Sf$.

Let, f_{r1} be the frequency of the rotor current of the main motor and the frequency of the rotor current of the auxiliary motor is f_{r2} then:

The speed of the main motor

$$N_1 = N_1 = \frac{120}{P_1}(f - f_{r1}). \tag{8.26}$$

The speed of the auxiliary motor

$$N_2 = N_2 = \frac{120}{P_2}(f_{r1} - f_{r2})$$

As f_{r1} is so small, so f_{r2} will be very small; so that, it can be neglected.

$$\therefore N_2 = \frac{120}{P_2}(f_{r1}). \tag{8.27}$$

Since, the two motors are coupled together:

$$N_1 = N_2$$

$$\frac{120}{P_1}(f - f_{r1}) = \frac{120}{P_2} f_{r1}$$

$$(f - f_{r1})P_2 = P_1 f_{r1}$$

$$f P_2 = f_{r1}(P_1 + P_2)$$

$$\therefore f_{r1} = \frac{fP_2}{P_1 + P_2}.$$

Substituting f_{r1} from above equation in Equation, we get:

$$N_2 = \frac{120}{P_2} \times \frac{fP_2}{P_1 + P_2}$$

$$= \frac{120f}{P_1 + P_2}, \qquad (8.28)$$

Above Equation shows that the speed of the set is that of a single machine having the number of poles equal to the sum of the numbers of poles of the two machines. Hence, the set can give four different speeds. If it is required to have the speeds above the normal, the torque of the second motor is reversed by simply changing two of the leads of the second. This is known as differential cascading.

Temperature Rise:

The various losses takes place in any motor will be converted into heat. The heat thus produced will increase the temperature of various parts of the motor. The increase in temperature is mainly dependent on the following two factors:

1. Amount of heat developed internally at uniform rate.
2. The amount of heat dissipated from the surface of the motor.

In fact, the continuous rating of a machine is that rating for which the final temperature raise is equal to or just below the permissible value of the temperature raise for the insulating material used in protection of motor windings. When the machine is overloaded for such a long time that its final temperature raise exceeds the permissible limit, it is likely to be damaged. Sometimes, it will results immediate breakdown of insulating material which will cause a sudden short circuit in the motor, which may also lead to a fire. Since temperature raise is one of the chief features in fixing the size of motor. The temperature raise will be high in the beginning and will decrease gradually with the passage of time and finally the temperature of the motor attains a steady-state value. At this point, the heat produced and dissipated will be equal.

The above circumstances make the heating calculations very complex and practically impossible unless certain assumptions are made as:

1. Heat developed, i.e., losses remains constant during temperature raise.

2. The heat dissipation is directly proportional to the difference in the temperature of motor and cooling medium, i.e., Newton's law of cooling hold's good.

3. The temperature of cooling medium remains unchanged.

4. The motor is assumed to be a homogeneous mass having the same and uniform temperature in all parts. It implies high thermal conductivity.

Temperature Rise Calculations:

For finding the expression for temperature rise of an electrical machine after time t seconds from the instant of switching on. Let,

Power converted in to heat = W Joules/sec. or Watts
Mass of the Active parts of the machine = M kg
Specific heat of material = S Joules/Kg/°C
Surface Area of cooling =A $meters^2$
Co-efficient of cooling = α in watts per $meters^2$ of surface per °C of difference between surface and ambient cooling temperature.

(i) Heating Curve: Suppose a machine attains a temperature rise of θ °C above ambient temperature in °C after t seconds of switching on the machine and further rise of temperature by $d\theta$ in very small time dt.

Energy converted into heat = W. dt Joules

Heat absorbed = $MSd\theta$ Joules

Heat dissipated = $A\theta\alpha\, dt$ Joules.

Since energy converted into heat = Heat absorbed + Heat dissipated

$$W\,dt = M.S.d\theta + A.\theta.\alpha\,dt \qquad \ldots\ldots\ldots\ldots\ (1)$$

Or

$$(W - A.\alpha.\theta)\,dt = MSd\theta$$

Or

$$\frac{dt}{MS} = \frac{d\theta}{W - A\alpha\theta}$$

Or

$$\frac{dt}{MS/A\alpha} = \frac{d\theta}{W/A\alpha - \theta} \ldots\ldots (2)$$

When final temperature is reached, there is no absorption of heat. Whatever heat is generated, has to be dissipated.

$$W\,dt = A\theta_m \alpha\,dt$$

Or steady state temperature, $\theta_m = \frac{W}{A\,\alpha}$ ………(3)

Substituting Eq. (3) in Eq. (2), we get

$$\frac{A\,\alpha}{MS}.t = \int \frac{d\theta}{(\theta_m - \theta)}$$

Integrating both sides, we get,

$$\frac{A\,\alpha}{MS}.t = -\log_e(\theta_m - \theta) = K_1 \qquad \text{…… (4)}$$

Where K_1 is a constant of integration.

Substituting, $t=0, \theta=\theta_1$, ambient temperature from initial conditions, we get,

$$0 = -\log_e(\theta_m - \theta_1) + K_1$$

$$K_1 = \log_e(\theta_m - \theta_1)$$

Substituting, $K_1 = \log_e(\theta_m - \theta_1)r$ in Eq. (4), we get,

$$\frac{A\,\alpha}{MS}.t = \log_e(\theta_m - \theta) + \log_e(\theta_m - \theta_1)$$

$$¿\log_e\left[\frac{(\theta_m - \theta_1)}{(\theta_m - \theta)}\right]$$

$$e^{\frac{A\alpha}{MS}t} = \frac{(\theta_m - \theta_1)}{(\theta_m - \theta)}$$

Or

$$\theta_m - \theta = (\theta_m - \theta_1)e^{\frac{-A\alpha}{MS}t}$$

$$\theta = \theta_m - (\theta_m + \theta_1)e^{\frac{-A\alpha}{MS}t}$$

$$¿\,\theta_m - (\theta_m - \theta_1)e^{-t/\lambda} \qquad \text{……… (5)}$$

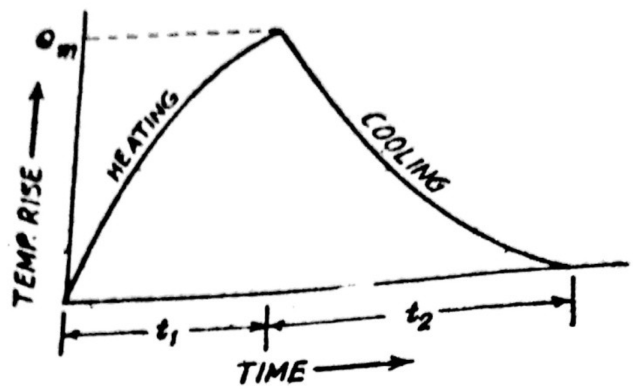
Where $\lambda = \frac{MS}{A\alpha}$ and is known as heating time constant.

If motor is started from ambient temperature, $\theta_1 = 0$, we get,

$$\theta = \theta_m - \theta_m e^{\frac{-t}{\lambda}} = \theta_m \left(1 - e^{\frac{-t}{\lambda}}\right) \quad \cdots\cdots\cdots (6)$$

Substituting $t = \lambda$ in above expression, we get,

$\theta = \theta_m \left(1 - e^{-1}\right) = 0.632\theta_m$



Heating time constant:

It is defined as the time taken in attaining the final steady temperature if the initial rate of increases of temperature were maintained. It is also depend as the time required to heat it, up to 0.632 times its final temperature rise.

The usual value of heating time constant is upon to 90 minutes for motors of output up to 15 KW and up to 5 hours for large rating motors.

Cooling curves: let the machine be switched off after reaching steady state temperature rise of θ_m. when the machine is switched off, no heat is produced, therefore,

$O = Heat\ absorbed + Heat\ dissipated$

$O = MSd\theta - A\theta\alpha' dt$

Where α' is the rate of heat dissipation during cooling.

Or $$dt = \frac{-MSd\theta}{A\alpha'\theta}$$

Integrating both sides, we get,

$$t=\frac{-MS}{A\alpha^{'}}-\log_e\theta+K_2 \qquad \text{........ (7)}$$

Where K_2 is a constant of integration.

To get the value of K_2 substitute, $t=0,\theta=\theta_m$ from initial conditions in the above expression,

$$O=\frac{-MS}{A\alpha^{'}}\log_e\theta_m+K_2$$

$$K_2=\frac{-MS}{A\alpha^{'}}\log_e\theta_m$$

Substituting the value of K_2 in above expression Eq. (7), we get,

$$t=\frac{-MS}{A\alpha^{'}}\log_e\theta+\frac{MS}{A\alpha^{'}}\log_e\theta_m$$

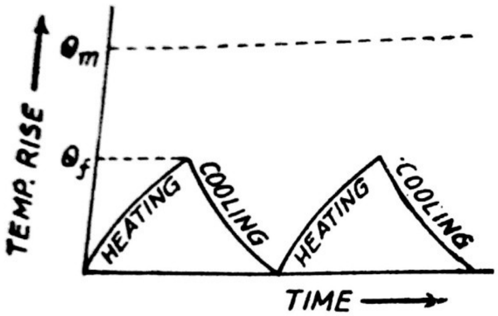
$$t=\frac{-MS}{A\alpha^{'}}\log_e\frac{\theta}{\Phi_m}$$

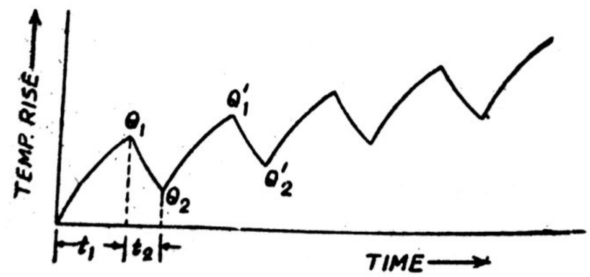
$$\theta=\theta_m e^{-A^{'}/MS} \qquad \text{......... (8)}$$

$$\theta=\theta_m e^{\frac{-t}{\lambda}}$$

$$\lambda^{'}=\frac{MS}{A\alpha^{'}}$$

The heating and cooling curves follow an exponential law. The heating and cooling curves for a motor which attains final temperature, the maximum permissible value and then cools down to ambient temperature.





Particular Applications of Electric Drives:

Industrial applications are far too numerous and it is not practical to decide the suitability of a particular electric motor except by way of broad guidelines for the purpose, but the broad fields of applications here under

1 Domestic Applications: Small universal motor, usually series type is used for various domestic appliances such as for domestic refrigerators shavers, vacuum cleaners, mixi, and cloth washing etc.

2 Cranes: D.C series motor or D.C compound motors are preferred on account of their high starting torque. Easy speed control for lifts.

3 Lifts: D.C compound wound or A.C slip ring induction motors are used. To get speed control, shunt flied regular method or ward Leonard method is used.

4 Lathes, Millings and Grinding Machines: lathes are usually driven by constant speed. Squirrel cage induction motor for milling and grinding machines.

5 Planer: D.C shunt or compound motor is used, if D.C supply is available otherwise slip ring induction motor is used.

6 Shapers and Cranes: Constant speed squirrel cage induction motors are used.

7 Punches and Shears: Punches and shears are usually equipped with flywheel to supply momentary demand power.

8 Sugar Mills: In sugar mills, a centrifugal is used to separate out sugar crystals from the syrup by the action of centrifugal forces.

9 Machine Tool Applications: squirrel cage induction motors are the most widely used ones for most machine tools drives due to its simplicity, reliability, low cost and minimum maintenance requirement.

10 Petro Chemical Industry: Pumps have been driven by induction motors with control of flow, when desired, accomplished by throttling valves.

11 Paper Mills: In paper mills grinders are operated at almost constant speed and can be started under light load conditions. Hence synchronous motors are considered as most suitable for grinder's drives.

12 Machine Tools Shears: To drive small portable tools such as drill etc. high speed motors with gear arrangements are often used. D.C series motor and slip ring induction motor is used.

13 Electric Traction: D.C series motor which is simple and robust is used for sub urban services where high rate acceleration in essential for main line works.

14 Cement Works: 3 phase 11 kV slip ring induction motor are used as the size of motors used for rotating the current kilns is very large.

Different Types of Industrial loads:

There are three different types of loads under which the motor is required to work, these are:

1. Continuous Loads
2. Intermittent Loads
3. Variable or Fluctuating Loads.

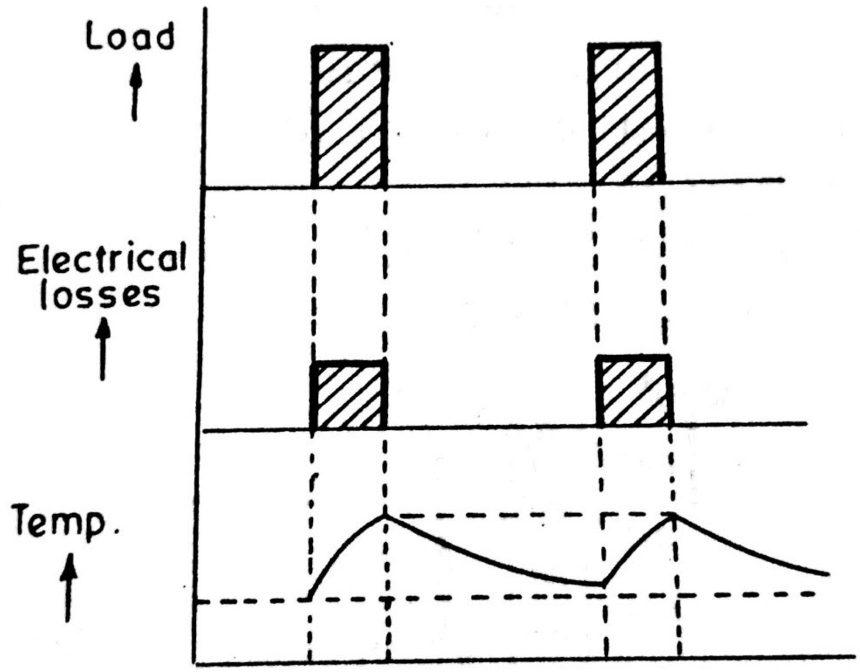
The size of the motor depends upon, firstly the temperature rise, which in turn depends whether the motor is to operate a continuous, intermittent or variable load and secondly, the maximum torque required of the motor.

Thus keeping in the mind the torque requirements of the load, the rating of a motor will be decided by the load condition as under:

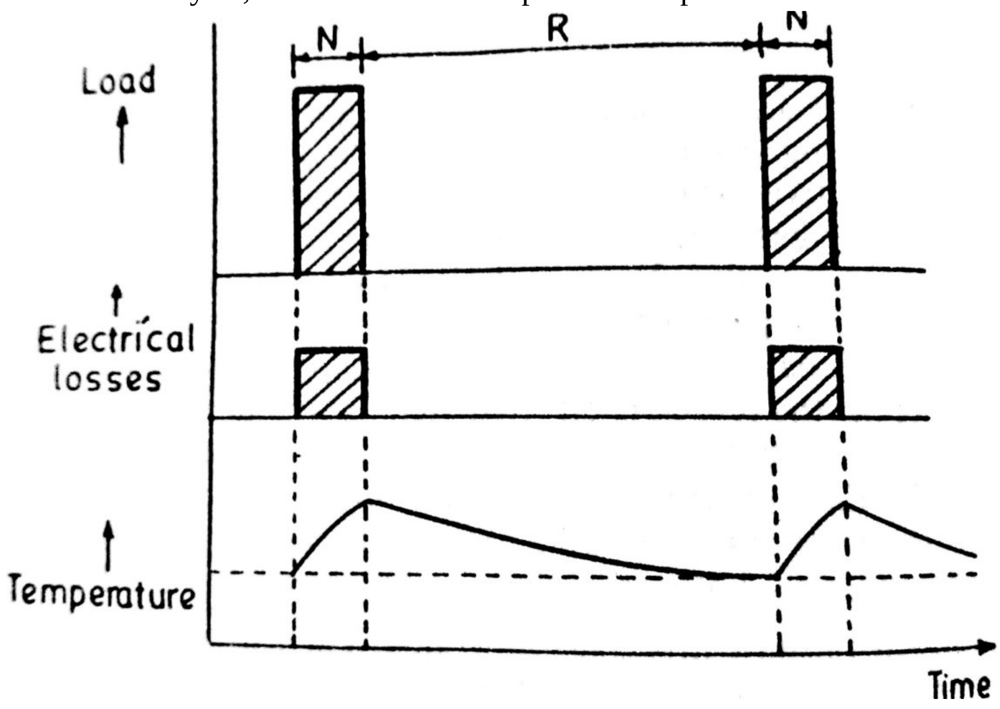
1. Continuous Loads: Drives likes pumps and fans etc. require a constant power as these keep on operating continuously and the choice of a suitable rating of motor is a simple affair.

It is essential to calculate the exact amount of power needed by the drive so as to make the correct choice of the motor H.P. If the H.P of the motor is less than what is needed, the motor will overheat and subsequently burn out.
On the other hand, if the H.P of the motor is more than what is demanded by the load, more will be operating at less than full load value, and hence lower efficiency and power factor.

2. Intermittent Loads: Intermittent Loads may be of two types:
   ii) The motor may be loaded for a short time and then shut-off for a sufficiency long time allowing the motor to cool down. In such a case a motor with a suitable short time rating is adopted such as in mixies etc.



iii) The motor may be loaded for some time and then shut-off for some times. Before the motor can cool down completely the load cycle repeats. In such a case a suitable continuous or short time rated motor is chosen which when operating on the particular load cycle, will not exceed the specified temperature limits.



3. Variable or Fluctuating Loads: In case of Variable or Fluctuating Loads the most accurate method of selection of a suitable rating of motor is to draw the heating and cooling curves for a number of motors. The smallest motor, which does not exceed the permitted

temperature rise when operating on the particular load cycle, is then chosen for the purpose.

However, an approximate and a simple method of selection of a suitable rating of motor is to assume that heating is proportional to square of the current and hence square of the load. The suitable continuous rating of the motor would be the r.m.s. value of the load curve. The procedure will be clear by the following examples.

LOAD EQUALIZATION:

The load fluctuations take place in many of the industrial drives such as rolling mills, planning machines presses, and reciprocating pumps, where the load on the motor varies widely within a span of few seconds. The sudden and peak load requires very large current from the supply results high voltage drop in the system or alternately would require very large size of cables. It is very essential to smooth out fluctuating load is known as '*load equalization*'. The load equalization involves the storage of energy during the off-peak period and gives out during the peak load period.

Load equalization process is commonly achieved by means of a flywheel. A flywheel is nothing but a big wheel that is mounted on the same shaft of motor, if the speed of the motor is not to be reversed or a heavy rotating body that acts as a reservoir for absorbing and redistributing stored energy is also known as flywheel.

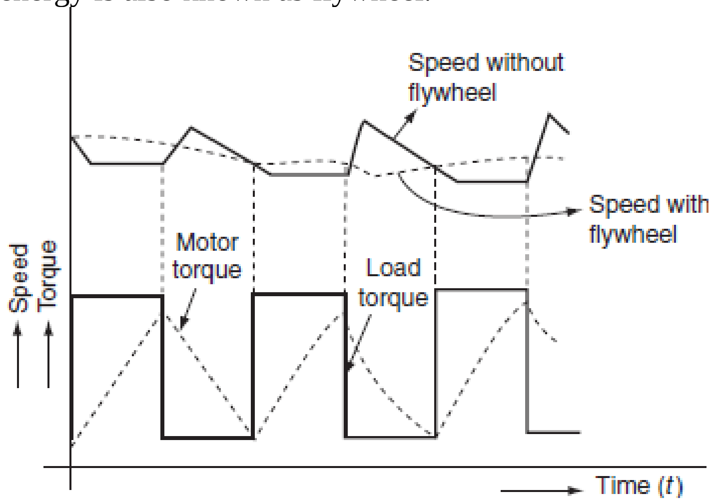


Fig. Motor torque, load torque, and speed variations against time

Fly Wheel Calculations:

Let $T_L = Load\ Torque$

$T_m = Torque\ exerted\ by\ the\ motor$

$T_0 = No\ Load\ Torque$

$T_F = Torque\ supplied\ by\ the\ flywheel$

$\omega = Angular\ speed\ of\ the\ motor\ at\ time, t \in radians/sec$

$\omega_0 = Angular\ speed\ at\ no\ load \in radians/sec.$

$J = Moment\ of\ inertia\ of\ flywheel\ Kg/m^2$

$t = Time \in seconds$

$g = Acceleration\ due ¿ gravity \in meter/sec^2$

The slip of the motor, $S = \frac{\omega_0 - \omega}{\omega_0}$ …… (1)

Case I: Load Increasing

Now consider that the load on the motor is increasing. As explained earlier during this period the flywheel will decelerate and impart its stored kinetic energy to the load. Therefore, the torque on the motor will be,

$$T_m = T_L - T_F \qquad \text{……….. (2)}$$

The kinetic energy given out by the flywheel will also be,

$$¿\frac{1}{2}\frac{J}{g}\left(\omega_0^2 - \omega^2\right) \qquad \text{……….. (3)}$$

$$¿\frac{1}{2}\frac{J}{g}\left(\omega_0 + \omega\right)\left(\omega_0 - \omega\right)$$

Put Eq. (1) in Eq. (3)

$$\text{K.E}¿\frac{J}{g} x \frac{\omega_0 + \omega}{2} x S \qquad \text{…….. (4)}$$

The mean speed ω_m of the motor is nearly equal to ω if the drop in speed is limited to 10%, therefore,

$$\omega_m = \frac{\omega_0 + \omega}{2} = \omega\,(say) \qquad \text{……… (5)}$$

In view of Eq. (4) and (5)

Energy given out by flywheel = $\frac{J}{g}\omega S$ ………… (6)

Power given out by the fly wheel = Rate of Change of energy

$$¿\frac{d}{dt}\left(\frac{J}{g}\omega S\right) = \frac{J}{g}.\omega.\frac{ds}{dt} \qquad \text{……. (7)}$$

Flywheel Torque, $T_F = \frac{Power\ given\ out\ by\ the\ flywheel}{\omega}$

$$\text{¿}\frac{\frac{J}{g}.\omega.\frac{ds}{dt}}{\omega}=\frac{J}{g}.\frac{ds}{dt} \qquad \text{.... (8)}$$

In view of Eq. (2) and (8), the motor torque,

$$T_m=T_L-\frac{J}{g}.\frac{ds}{dt} \qquad \text{.......... (9)}$$

If the drop of speed, i.e. slip is limited to 10%, then,

$$S\alpha T_m \qquad \text{........... (10)}$$

$$\frac{ds}{dt}=K.\frac{dT_m}{dt} \qquad \text{............ (11)}$$

Where K is a constant.
Set Eq. (11) in Eq. (9),

$$T_m=T_L-\frac{JK}{g}\frac{dT_m}{dt} \qquad \text{....... (12)}$$

Or

$$T_L-T_m=\frac{JK}{g}x\frac{dT_m}{dt} \qquad \text{........ (13)}$$

Or

$$\frac{dT_m}{T_L-T_m}=\frac{g.dt}{JK} \qquad \text{......... (14)}$$

Integrating Eq. (14)

$$-\log_e(T\text{¿¿}L-T\text{¿¿}m)=\frac{g}{KJ}t+C_1\text{¿¿} \qquad \text{...... (15)}$$

Where C_1 is the constant of proportionality and can be determined from the initial condition, when

$$\begin{Bmatrix} t=0 \\ T_m=T_0 \end{Bmatrix} \qquad \text{........... (16)}$$

From Eq. (15) and (16), $-\log_e(T\text{¿¿}L-T\text{¿¿}0)=C_1\text{¿¿}$ .... (17)
Sub Eq. (17) in Eq. (15)

$$-\log_e(T\text{¿¿}L-T\text{¿¿}m)=\frac{g}{KJ}.t-\log_e(T\text{¿¿}L-T\text{¿¿}0)\text{¿¿¿¿} \qquad \text{...... (18)}$$

Or

$$e^{\frac{-g}{KJ}t}=\frac{(T\text{¿¿}L-T\text{¿¿}m)}{(T\text{¿¿}L-T\text{¿¿}0)\text{¿¿}}\text{¿¿} \qquad \text{...... (20)}$$

$$T_L-T_m=(T\text{¿¿}L-T\text{¿¿}0)e^{\frac{-g}{KJ}t}\text{¿¿} \qquad \text{..... (21)}$$

$$T_m=T_L-(T\text{¿¿}L-T\text{¿¿}0)e^{\frac{-g}{KJ}t}\text{¿¿} \qquad \text{..... (22)}$$

Case II. Load Decreasing

While load decreases or is totally removed, the motor starts accelerating and so the kinetic energy is stored by the flywheel. The speed of the flywheel will increase to normal and thereby decreasing the slip.

Under these conditions, $\frac{ds}{dt}$ is –ve.

Now motor torque will be, $T_m=T_0+T_F$ ...... (23)

But

$$T_F=\frac{-J}{g}.\frac{ds}{dt} \qquad \text{........ (24)}$$

The minus sign is used as $\frac{ds}{dt}$ is negative in view of Eq. (23) and (24)

$$T_m=T_0-\frac{J}{g}.\frac{ds}{dt}$$

If the above Eq. (25) is solved in the similar way as Eq. (9) was solved then the expression, we get,

$$T_m=T_0+(T'_m-T_0)e^{\frac{-g}{KJ}t}$$

T'_m is the torque of the motor when the load is decreased or removed.

Assignment-Cum-Tutorial Questions

Unit – 1

A. Questions testing the remembering / understanding level of students

I) Objective Questions

1. What type electric drive is used in cranes?

(a) Group Drive (b) Individual Drive

(c) Multi motor Drive (d) None of these

2. Electric drive is becoming more and more popular because

(a) it provide smooth and easy control (b) it is cheaper in cost

(c) it is simple and reliable **(d) all of Above**

3. The basic elements of a electric drive are

(a) Electric Motor (b) Control System

(c) Electric motor & Control system (d) None of these

4. The Speed control by variation of field flux results in

(a) Constant power drive (b) constant torque drive

(c) Variable power drive (d) None of these

5. Which speed control method preferred for constant torque drive?

(a) Field control **(b) Armature voltage control**

(c) Mechanical loading system (d) None of these

6. When smooth and precise speed control over a wide range is desired, the motor preferred...

(a) synchronous motor (b) Squirrel cage induction motor

(c) wound rotor induction motor **(d) dc motor.**

7. The drive motor for large rice mill would be

(a) Dc Series motor **(b) Squirrel cage induction motor**

(c) wound rotor induction motor (d) None of these

8. The motor having wider range of speed control is

(a) Dc Series motor **(b) Dc Shunt motor**

(c) Induction Motor (d) None of these

II) Descriptive Questions

1. Define Electric drive and give its classification and explain the each category of Electric drive
2. Discuss the advantages and disadvantages of electric drive over other drives.
3. Compare Group drive and Individual drive.
4. For selecting a drive, what are factors to be taken into account?
5. Explain the staring and running characteristics of motor used for Industrial loads.
6. Explain the effect of temperature rise in Electrical machines and how can it be overcome.
7. Derive the relation between the temperature of a motor at a particular time during operation and final temperature.
8. Compare the characteristics of DC series motor and 3-phase induction motor.
9. Explain the characteristics of D.C. compound motors and explain its advantage over the series motor.
10. Give with reasons the type of application for which the following motors are best

    suited: (i) Dc Shunt Motor (ii) Dc Series motor (iii) 3- Phase Induction Motor
11. Write about various types of industrial loads with their examples and load characteristics.
12. Explain in detail about load Equalization.

B. Question testing the ability of students in applying the concepts

I) Multiple choice questions

1. Belt Conveyors offer ___________ starting torque?

   (a) Small **(b) Medium**

   (c) High (d) None of the above

2. Which of the following motor is best suited for rolling mills?

   (a) **Dc Motor** (b) Stepper motor

   (c) Universal motor (d) None of the above

3. An Existing workshop is to be changed over from an engine drive to electric drive………..type of drive is to be employed.

   (a) Group (b) Individual (c) Multi motor (d) None

4. In which of the following motor is best suited for Centrifugal pumps & washing machines?

   (a) Dc Series motor **(b) Dc Shunt motor**

   (c) Squirrel cage Induction Motor (d) None of these

II) Problems

1. A 25 H.P motor has a heating time constant of 90 minutes. When run continuously on full load, it attains a final steady temperature of 45^0 C. Calculate the temperature of the motor after 30 minutes, the initial temperature being 10^0 C.
2. A 15 H.P motor has a heating time constant of 2 Hours. Determine the time in which it attains a temperature of 40^0 C from its value of 10^0 C while working continuously on full load, if its final steady temperature is 45^0 C.
3. Calculate the maximum over load that can be carried by a 25 KW motor, if the temperature rise is not exceed 50^0 C after one hour on over load. The temperature rise on the full load after one hour is 30^0 C and after 2 hours is 40^0 C. The losses vary as square of the load.
4. A 220 V dc series motor runs at a 1000 rpm and takes 20 A. Combined resistance of armature and series field is 0.4 ohms. Calculate the resistance to be inserted in series so as to reduce the speed to 800 rpm assuming torque to vary as square of the speed and linear magnetization curve.
5. A 250V dc Shunt motor with constant field excitation drives a load whose torque varies as the square of the speed. The armature current is 20A. when the motor is running at 500 rpm. Find the speed of the motor when running with a 25 ohm resistor connected in series with the armature. Neglect motor losses.

C. Questions testing the analyzing/evaluating/Creative ability of students

1. A 25 hp, 3 phase, 10 pole, 50 Hz induction motor provided with a flywheel has to supply

a load torque of 800 N-m for 10 second followed by a no load period during which flywheel regains the full speed. The full load slip of the motor is 4% and the torque-speed curve may be assumed linear over working range. Find the moment of inertia of the flywheel. If the motor is not to exceed twice the full load torque.

2. A 10 pole 50Hz induction motor has to supply a load torque of 1000 N-m for 10 seconds followed by a non-load period during which it regains its original speed. The motor has a full load slip of 4% and can exert a maximum torque of 300 N-m. The flywheel connected to the motor has an inertia of 1400 kg-m^2 while the motor has a moment of inertia of 100 kg-m^2 only. Determine the torque exerted by the motor, at the end of the decelerating period and the time taken for the motor torque to fall a 300 N-m after the peak is over.
3. A 4 pole, 50 Hz induction motor has a flywheel on its shaft. Total inertia at the motor shaft is 1000 kg-m^2. Load torque is 100 kg-m for 10 seconds followed by a no load period long enough for the flywheel by regains its full speed. Motor has a slip of 6% at a torque of 50 kg-m. Calculate the speed at the end of the decelerating period. Assume motor speed – torque characteristic to be a straight line in the region of interest and neglect friction and windage.
4. An 8 pole, 50 Hz, 3- phase cage induction motor equipped with a flywheel is driving a mill, which requires a load torque of 1400 kg-m during the rolling operation lasting 10 seconds. The torque then drops to 200 kg-m for 30 sec, the cycle being repeated. The motor is capable delivering a maximum torque of 1050 kg-m running at a slip of 10%. The moment of inertia of a moving parts 50,000 kg-m^2. Determine the speed of the motor after 5 seconds during rolling operation.
5. A motor is fitted with a flywheel supplies a load torque of 1000 kg-m for 10 seconds, after which it is at no load and regions, its original speed of 500 rpm. The motor can exert a maximum torque of 600 kg-m only. Determine the moment of inertia of flywheel, assuming the full load slip of motor to be 10%
6. A motor is fitted with a flywheel supplies a load torque of 200 kg-m for 10 seconds, followed by a no- load period. During the no load period, the motor regain its speed. if it is desired to limit the motor torque to 100 kg-m, what should be the moment of inertia of

the flywheel? The no load speed of the motor is 500 rpm and has a slip of 10% at a torque of 100 kg-m.