Part I

Electric Motors, Drives and Energy Saving

1

Theory, performance and constructional features of induction motors and energy saving

Contents

1.1 Introduction

The age of electricity began with the work of Hans Christian Oersted (1777–1851), who demonstrated in 1819 that a current-carrying conductor could produce a magnetic field. This was the first time that a relationship between electricity and magnetism had been established. Oersted's work started a chain of experiments across Europe that culminated in the discovery of electromagnetic induction by Michael Faraday (1791–1867) in 1831. Faraday demonstrated that it was possible to produce an electric current by means of a magnetic field and this subsequently led to the development of electric motors, generators and transformers.

In 1888 Nikola Tesla (1856–1943) at Columbus, Ohio, USA, invented the first induction motor which has become the basic prime mover to run the wheels of industry today. Below, for simplicity, we first discuss a polyphase and then a single-phase motor.

1.2 Brief theory of operation of a polyphase motor

When a multiphase winding distributed uniformly in space (360°) is supplied with sinusoidal voltage/current also distributed uniformly in time phase, a rotating field is created in space. In case of three phase winding distributed at 120° in circular space and supplied with sinusoidal voltage/current displaced at $1/3f$ in time (f = frequency and time of 1 Hz = $1/f$) will produce a field rotating at $2f/p$ rev./sec. or $120f/p$ rev./min (p = no. of poles). Further when one of the two-coupled winding (so that the flux produced by one can link the other) is supplied with sinusoidal voltage/current, voltage/current is induced in second winding due to electromagnetic induction. This is the basic principle of an electric motor, appropriately termed an induction motor. Here applies the theory of the 'left-hand rule' to define the relative positions of the current, field and force. The rule states that when the thumb, the forefinger and the middle finger of the left hand are arranged so that they all fall at right angles to each other then the forefinger represents the flux ϕ or the magnetic intensity H, the middle finger the current and the thumb the force or the motion (Figure 1.1). The field thus induced would rotate at a synchronous speed and the magnitude of flux built up by the stator current would be equal to ϕ_m in 2-ϕ windings and $^3/_2\phi_m$ in 3-ϕ windings. For brevity, we are not discussing the basics here. Figures 1.2–1.4 illustrate a current-flux phasor representation, the flux waveform and the magnetic field, respectively, in a 3-ϕ winding.

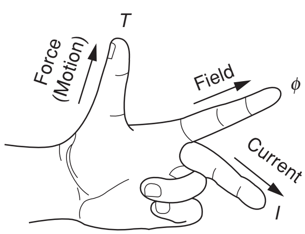


Figure 1.1 Fleming's left-hand rule

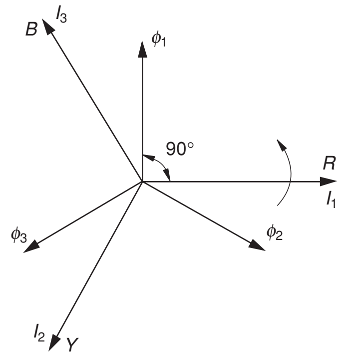
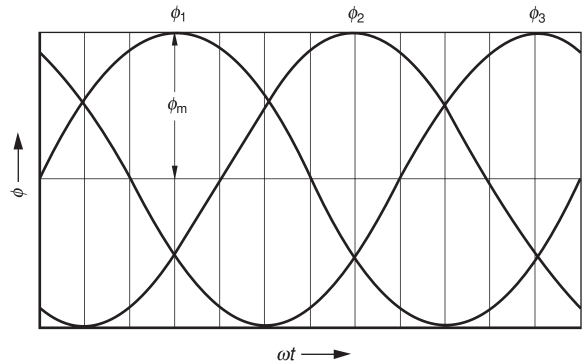
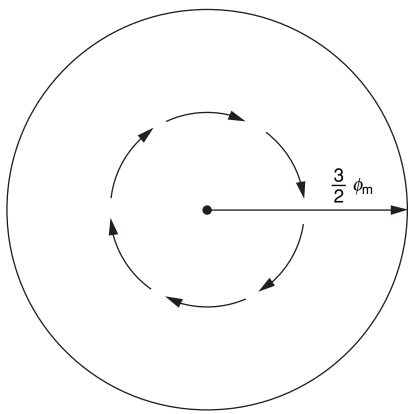


Figure 1.2 Phasor representation of current and flux phase disposition



$\phi_1 = \phi_m \sin \omega t$
$\phi_2 = \phi_m \sin (\omega t - 120)$
$\phi_3 = \phi_m \sin (\omega t - 240)$

Figure 1.3 Magnetic flux waveform



At any instant

$\bar{\phi}_1 + \bar{\phi}_2 + \bar{\phi}_3 = \frac{3}{2}\phi_m$

A constant field rotating at synchronous speed N_s

Figure 1.4 Production of magnetic field in a 3-ϕ winding

The winding that is static is termed a stator and that which rotates is a rotor. If I_{rr} is the rotor current and ϕ the instantaneous flux, then the force in terms of torque, T, produced by these parameters can be expressed by

$$T \propto \phi_m \cdot I_{rr} \tag{1.1}$$

where

$$\phi = \phi_m \sin \omega t$$

and ϕ_m = maximum field strength

In a 3-ϕ winding, therefore, for the same amount of current, the torque developed is 50% more than in a 2-ϕ winding.

The rotor power P developed by torque T at a speed N can be expressed by

$$P = \frac{T \cdot N}{974} \tag{1.2}$$

where

P = rotor power in kW
T = torque in mkg
N = speed in r.p.m.
'P' can also be written as

$$P = \frac{2\pi \cdot N \cdot T}{60} \text{ when '}T\text{' is in kN-m}$$

Since the kW developed by a 3-ϕ winding is 50% more than by a 2-ϕ winding for the same value of stator current I_r, the economics of this principle is employed in an induction motor for general and industrial use. As standard practice, therefore, in a multi-phase system, only 3-ϕ induction motors are manufactured and employed, except for household appliances and applications, where mostly single-phase motors are used.

The magnetic field rotates at a synchronous speed, so it should also rotate the rotor. But this is not so in an induction motor. During start-up, the rate of cutting of flux is the maximum and so is the induced e.m.f. in the rotor circuit. It diminishes with motor speed due to the reduced relative speed between the rotor and the stator flux. At synchronous speed, there is no linkage of flux and thus no induced e.m.f. in the rotor circuit, consequently the torque developed is zero and the rotor stops.

Since,

$$T \propto \frac{S \cdot {}_{ss}e_2^2 \cdot R_2}{R_2^2 + S^2 \cdot {}_{ss}X_2^2} \tag{1.3}$$

the impedance considered represents only the rotor side. For simplicity, the stator impedance has been ignored, being too small with little error.

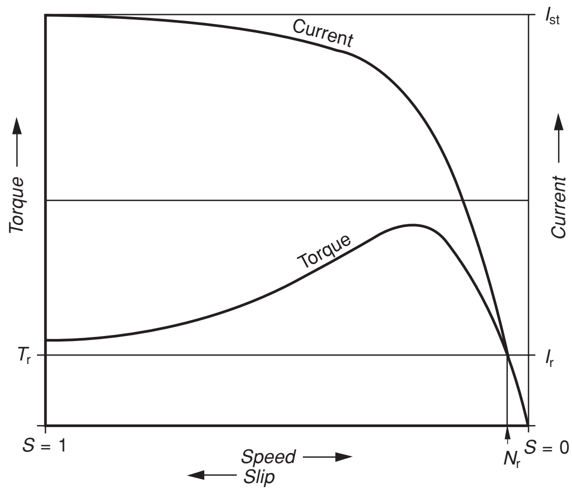
In equation (1.3)

T = torque developed
S = slip
R_2 = rotor resistance per phase
${}_{ss}X_2$ = standstill rotor reactance per phase, and
${}_{ss}e_2$ = standstill rotor induced e.m.f. per phase

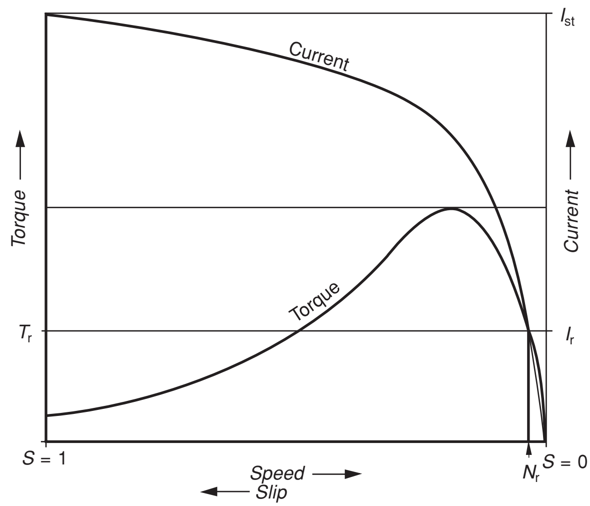
The last two parameters are maximum during start-up, diminish with speed and become zero at the synchronous speed (when $S = 0$). Therefore $T = 0$ when ${}_{ss}e_2 = 0$.

Corollary

The speed–torque characteristics of a motor will largely depend upon its rotor parameters such as R_2 and ${}_{ss}X_2$. The higher the rotor resistance R_2, the higher will be the torque. From Equation (1.3) we can draw a speed–torque curve of a motor as shown in Figures 1.5(a) and (b).



(a) Typical for an LV motor



(b) Typical for an MV motor

Figure 1.5 Speed-torque and speed–current curves at the rated stator voltage

During start-up or at high slips, the value of ${}_{ss}X_2$ will be too high compared to R_2 and Equation (1.3) can be approximated to

$$T_{st} \propto \frac{S \cdot {}_{ss}e_2^2 \cdot R_2}{S^2 \cdot {}_{ss}X_2^2}$$

where

T_{st} is the torque during start-up or

$$T_{st} \propto \frac{{}_{ss}e_2^2 \cdot R_2}{S \cdot {}_{ss}X_2^2} \tag{1.3a}$$

and at lower slips or at near the rated speed, when $S \cdot {}_{ss}X_2 << R_2$, Equation (1.3) will modify to

$$T_r \propto \frac{S \cdot {}_{ss}e_2^2 \cdot R_2}{R_2^2}$$

or

$$T_r \propto \frac{S \cdot {}_{ss}e_2^2}{R_2} \quad (1.3b)$$

T_r is referred to as the rated torque.

R_2 and ${}_{ss}X_2$ are thus the vital parameters that are used at the design stage to accomplish the desired characteristics and performance of an induction motor. The normal starting torque T_{st} for a medium-sized LV squirrel cage motor, say up to 400 kW, can be attained up to 200–250% and even more of the full-load torque T_r, and the pull-out torque T_{po} up to 200–350% of T_r (see also Chapter 2). In slip ring motors, the starting torque (T_{st}) can be varied up to its pull-out torque (T_{po}). (See Chapter 5.) For MV motors (3.3 kV and above) these figures are quite low compared to LV motors, due to the design economics for such machines. One consideration is the rotor slots that are normally not made with a double cage but with tapered or deep bars, to reduce rotor size and hence, the overall size of the machine and thus the cost. The T_{st} is now of the order of 70–130% of T_r and T_{po} 170–250% for motors up to 3000 kW. For yet larger machines these figures may be lower, say T_{st} of the order of 33–70% and T_{po} of the order of 150–225% of T_r. Large motors are normally switched at no-load through hydraulic couplings, (Section 8.3), closed discharge valve or suction throttling on the load side (a static drive is usually not employed just for soft switching being a costly proposition). A low starting torque therefore should not matter in the majority of cases.

These figures are for general reference only. For actual values the reader should refer to the data sheet or the motor manufacturer. Motors can, however, be designed to suit a particular application. Large LV and all MV motors are generally custom built.

If e_2 is the induced e.m.f. in the rotor circuit at any speed then

$$e_2 \propto -Z_r \cdot \frac{d\phi}{dt} \quad (1.4)$$

The negative expression of voltage is according to Lenz's law, which states that 'The direction of the induced e.m.f. is such that it tends to oppose the change in the inducing flux'. In Equation (1.4)

Z_r = number of turns in the rotor circuit per phase and
$d\phi/dt$ = rate of cutting of the rotor flux.

An illustration of this expression will give

$$e_2 = 4.44\ \text{Kw} \cdot \phi_m \cdot z_r \cdot f_r \quad (1.5)$$

where
Kw = winding factor and
f_r = rotor frequency = S.f.

At synchronous speed, $d\phi/dt = 0$ and therefore $e_2 = 0$.

This is why an induction motor ceases to run at synchronous speed. The rotor, however, adjusts its speed, N_r, such that the induced e.m.f. in the rotor conductors is just enough to produce a torque that can counter-balance the mechanical load and the rotor losses, including frictional losses. The difference in the two speeds is known as slip, S, in r.p.m. and is expressed in terms of percentage of synchronous speed, i.e.

$$S = \frac{N_s - N_r}{N_s} \cdot 100\% \quad (1.6)$$

where synchronous speed

$$N_s = \frac{120 \cdot f}{p}\ \text{r.p.m} \quad (1.6a)$$

f = frequency of the supply system in Hz and
p = number of poles in the stator winding.

1.2.1 Stator current

An induction motor draws a high current during start-up which further increases due to magnetic saturation (Section 1.6.2A(iv)). The rapid voltage change from one peak to another ($2V_m$) (Figure 1.5(c)) within one-half of a cycle saturates excessively the iron core of the stator and the rotor. The saturation induces a very low inductance, L, and hence a low switching impedance (R being low already). The inductance of the circuit L varies with the level of saturation. Since $e = -L\ (di/dt)$, a high e and low L cause a very high starting current. This is seen to be of the order of six to seven times the rated current and exists in the system until the rotor picks up to almost its rated speed. We will notice subsequently that the performance of a motor is the reflection of its rotor characteristics. As the rotor picks up speed, it reduces the secondary induced e.m.f. $S \cdot {}_{ss}e_2$, which in turn raises the inductance of the rotor circuit and diminishes the start-up inrush current. The duration of start-up current thus depends upon the time the rotor will take to pick up speed to almost its rated speed.

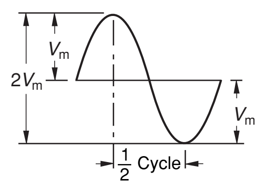


Figure 1.5(c)

Corollary: The case of a transformer

The situation in the case of a transformer is somewhat different. Its primary and secondary circuits form a composite unit and behave as one winding only. Since there is no air gap between the primary and the secondary windings, the combined winding impedance is less than that of a motor on switching (considering secondary open-circuited or connected on load). Consequently the switching current is a little higher, of the order of 8–12 times the rated current. If the secondary is short-circuited, the short-circuit current will be much more than this, as indicated in Table 13.7. As will stabilize the voltage initial spikes, so it will diminish the level of saturation, raising the value of L. It will provide a high damping effect (R/L) initially and slowly thereafter. The current will also decay rapidly initially and then slowly. The same will be true for any inductive circuit other than a motor.

1.2.2 Rotor current

With the same parameters, the rotor current of a motor, I_{rr}, can be expressed by

$$I_{rr} = \frac{S \cdot {}_{ss}e_2}{\sqrt{R_2^2 + S^2 \cdot {}_{ss}X_2^2}} \tag{1.7}$$

at high slips, i.e. during the starting region when $S \cdot {}_{ss}X_2 >> R_2$

$$I_{rr} \simeq \frac{{}_{ss}e_2}{{}_{ss}X_2} \tag{1.7a}$$

This is a vital relationship, which reveals that during start-up and until such speed, the reactance of the motor windings $S \cdot {}_{ss}X_2 >> R_2$, the rotor current will also remain almost the same as the starting current and will fall only at near the rated speed. (Refer to the current curves in Figures 1.5(a) and (b).) The initial inrush current in a squirrel cage induction motor is very high. In a slip-ring motor, however, it can be controlled to a desired level. (Refer to Section 5.2.1.)

Note
For all practical purposes the stator performance data are only a replica of rotor data for torque and current. The performance of a motor is the performance of its rotor circuit and its design.

1.3 Motor output and torque

Motor rating, i.e. power available at the motor shaft, P_r, can be expressed in kW by

$$P_r = \frac{T_r \cdot N_r}{974} \text{ kW} \tag{1.8}$$

where
N_r = rotor speed in r.p.m.

The power transferred by the stator to the rotor, P_s, also known as air gap power at synchronous speed, N_s, can be expressed in kW by:

$$P_s = \frac{T_r \cdot N_s}{974} \text{ kW} \tag{1.8a}$$

where
N_s = synchronous speed in r.p.m.

The difference in the two is the electric power loss in the rotor circuit and is known as slip loss, i.e.

$$\text{Slip loss} = P_s - P_r = S \cdot P_s \tag{1.9}$$

and from Equation (1.8)

$$T_r = \frac{P_r \cdot 974}{N_r} \text{ mkg} \tag{1.10}$$

Example 1.1

For a 150 h.p., 1480 r.p.m. (N_r) motor, the torque

$$T_r = \frac{110 \times 974}{1480} \text{ (150 h.p. = 110 kW)}$$

$$= 72.5 \text{ mkg}$$

Similarly for a 4000 kW, 1493 r.p.m., 6.6. kV, 97.0% efficiency and 0.89 p.f. motor

$$T_r = \frac{4000 \times 60}{2\pi \times 1493} = 25.58 \text{ kN-m}$$

1.4 Motor ratings and frame sizes

The standard kW ratings are internationally adopted and are based on the recommendations made by IEC* 60072-1 and 2. The ratings in kW up to 110 kW and their corresponding h.p. are shown in Table 1.1. Preferred ratings beyond 110 kW are given in Table 1.1(a). For recommended frame sizes, adopted by national and international manufacturers to harmonize and ensure interchangeability between all makes of motors, refer to IEC 60072-1 and 2. For easy reference we have provided these frame sizes in Table 1.2. These standards suggest the vital dimensions of a motor such as the shaft height, extension, its diameter and the mounting dimensions, etc.

Table 1.1 Preferred kW ratings and their nearest horsepower

kW	*HP*	*kW*	*HP*	*kW*	*HP*
0.06	0.08	2.2	3.0	37	50
0.09	0.12	3.7	5.0	45	60
0.12	0.16	5.5	7.5	55	75
0.18	0.25	7.5	10.0	75	100
0.25	0.33	9.3	12.5	90	125
0.37	0.50	11	15	110	150[a]
0.55	0.75	15	20	–	–
0.75	1.0	18.5	25	–	–
1.1	1.5	22	30	–	–
1.5	2.0	30	40	–	–

According to IEC 60072-1

[a]Beyond 110–4000 kW, the preferred ratings can follow the 'Renard Series', R-20 of preferred numbers as in ISO 3. Refer to Table 1.1(a).

Table 1.1(a) Preferred ratings beyond 110 kW according to the Renard Series, 'R-20' of ISO 3

kW	*kW*	*kW*
112	400	1400
125	450	1600
140	500	1800
160	560	2000
180	630	2240
200	710	2500
224	800	2800
250	900	3150
280	1000	3550
315	1120	4000
355	1250	–

Note
Of these, ratings up to 1000 kW with some modifications have now been standardized by IEC 60072-1. For details refer to IEC 60072-1.

IEC*: International Electro-technical Commission, Switzerland.

Table 1.2 Recommended frame sizes

Frame size	*Shaft height for B_3 (Figure 1.17) motors (mm)*	*Frame size*	*Shaft height for B_3 (Figure 1.17) motors (mm)*
56	56	225L	225
63	63	250S	250
71	71	250M	250
80	80	250L	250
90S	90	280S	280
90L	90	280M	280
100S	100	280L	280
100L	100	315S	315
112S	112	315M	315
112M	112	315L	315
112L	112	355S	355
132S	132	355M	355
132M	132	355L	355
132L	132	400S	400
160S	160	400M	400
160M	160	400L	400
160L	160	450	450
180S	180	500	500
180M	180	560	560
180L	180	630	630
200S	200	710	710
200M	200	800	800
200L	200	900	900
225S	225	1000	1000
225M	225	–	–

According to IEC-60072-1 and 60072-2

Note
Designations *S*, *M* and *L* denote the variation of length in the motor housing for the same shaft height.

1.5 Preferred ratings at different voltages

The preferred ratings at different rated voltages according to publication MG-1† are given in Table 1.3.

1.6 Influence of service conditions on motor performance

The performance of an induction motor is influenced by the service conditions, when these differ from the design assumptions. The parameters that may affect the performance of a motor are

1 Voltage unbalance
2 System harmonics
3 Voltage variation
4 Frequency variation
5 Ambient temperature and
6 Altitude.

They may influence the performance of the motor by its

1 Output and
2 Torque. IEC 60034-1 stipulates for a minimum in-built capacity of a machine (all ratings and voltages) to sustain an excessive torque of 60% for a minimum of 15 seconds, without stalling or an abrupt change in its speed. This stipulation is to meet the need for an excessive torque of a transitory nature due to the above parameters or for a momentary excessive load torque itself during operation. This stipulation, however, would not apply to motors designed and manufactured to specific requirements.
3 Efficiency
4 Power factor
5 Speed
6 Slip and
7 Current

Note
According to the stipulations of IEC 60034-1, any factor noted above which may influence the performance and cause an excessive current than rated, or because of an excessive load itself, motors rated up to 315 kW and rated voltage up to 1.0 kV should be capable of withstanding a current equal to 150% of the rated current for a minimum of two minutes. No such tolerance is, however, recommended for motors beyond 315 kW and all MV motors. This stipulation would not apply to motors that are designed and manufactured to specific requirements.

The extent to which these performance data may be influenced, by the non-standard operating conditions is discussed briefly below.

Table 1.3 Preferred horsepower rating for different voltages

Nominal voltage (kV)	*Preferred rating (h.p.)*
0.415*	Up to 600
3.3	200–6000
6.6	1000–12 000
11	3500–25 000

*This voltage is now revised to 0.4 kV as in IEC 60038 (see Introduction).

†MG-1: Reference to a publication on Motors and Generators by NEMA (National Electrical Manufacturers Association, USA) which is adopted universally.

1.6.1 Voltage unbalance and system harmonics

As standard practice, all motors are designed for a balanced and virtually sinusoidal supply system, but it may not be feasible to obtain the designed supply conditions in practice. Hence, a motor is designed with a certain in-built capacity to sustain small amounts of voltage unbalances and some degree of harmonic quantities, such that the voltage waveform may still be regarded as sinusoidal.

Voltage unbalance

The performance of a motor is greatly influenced by a voltage unbalance in the supply system. It reduces its output and torque and results in a higher slip and rotor loss. This subject is covered in more detail in Section 12.2(v). For likely deratings, refer to Figure 12.1. A system with an unbalance of up to 1% or so calls for no derating, whereas one having an unbalance of more than 5% is not recommended for an industrial application, because of a very high derating and the highly unstable performance of the motor.

The system may be regarded as balanced when the negative sequence component does not exceed 1% of the positive sequence component over a long period, or 1.5% for short durations of a few minutes and the zero sequence component does not exceed 1% of the positive sequence component. Refer to Section 12.2(v) for more details on positive, negative and zero sequence components.

System harmonics

A supply system would normally contain certain harmonic quantities, as discussed in Section 23.5.2. The influence of such quantities on an induction motor is to add to its no-load iron losses (Equations (1.12) and (1.13)). To maintain a near-sinusoidal voltage waveform, it is essential that the harmonic voltage factor (HVF) of the supply voltage be contained within 0.02 for all 1-ϕ and 3-ϕ motors, other than design N* motors and within 0.03 for design N motors, where

$$\mathrm{HVF} = \sqrt{\Sigma \frac{\upsilon_h^2}{n}} \tag{1.11}$$

Here

υ_h = per unit summated value of all the harmonic voltages in terms of the rated voltage V_r

n = harmonic order not divisible by 3 (presuming that the star-connected motors (normally MV motors) have only isolated neutrals) in 3-ϕ motors, i.e. 5, 7, 11 and 13, etc. Beyond 13, the content of harmonic quantity may be too insignificant to be considered.

For example, for a system having $\upsilon_{h5} = 5\%$, $\upsilon_{h7} = 3\%$, $\upsilon_{h11} = 2\%$ and $\upsilon_{h13} = 1\%$

Then

$$\mathrm{HVF} = \left(\frac{0.05^2}{5} + \frac{0.03^2}{7} + \frac{0.02^2}{11} + \frac{0.01^2}{13} \right)^{1/2}$$

$$\simeq 0.026$$

1.6.2 Voltage and frequency variations

These have a great influence on the performance of a motor and the driven equipment, as analysed later. The motors are, however, designed for a combined variation in voltage and frequency according to zone A of Figure 1.6. The maximum variation during service must fall within this zone. It will permit a variation in these parameters as indicated in Table 1.4.

Where, however, a higher variation in voltage and frequency is envisaged, motors suitable to fall within zone B in Figure 1.6 can also be manufactured. See also Chapter 7 for special design considerations for certain types of load requirements.

*IEC 60034-12 has recommended four rotor designs, i.e. *N*, *H* and *NY*, *HY*, to define starting performance for *DOL* and *Y/Δ* startings respectively. They are along similar lines, ones to those in NEMA MG-1. They define minimum torques, though the manufacturer can produce better ones.

Table 1.4 Combined permissible voltage and frequency variations

	← *Zone A* →		← *Zone B* →	
Voltage variation	+5% to –3%	–5% to +3%	+10% to –7%	–10% to +5%
Frequency variation	0 to 2%	0 to –2%	0 to 3%	0 to –5%

According to IEC 60034-1

Note
IS 325 specifies voltage variation ± 6% and frequency variation ± 3% or any combination of these.

A *Effect of voltage variation*

Voltage variation may influence the motor's performance as shown below.

(i) Torque
From Equation (1.3), $T \propto {}_{ss}e_2^2$, and since the standstill rotor voltage is a function of supply voltage V_ℓ

$$\therefore T \propto V_\ell^2$$

During start-up, at lower voltages, the starting torque is

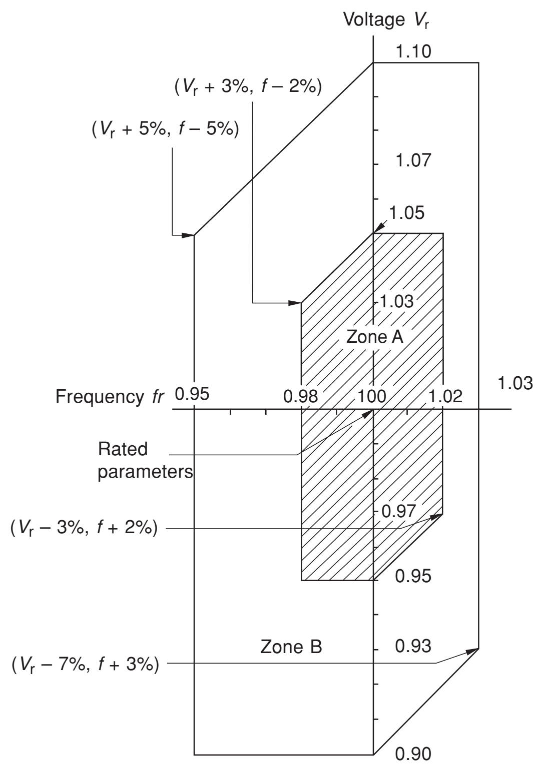


Figure 1.6 Voltage and frequency limits for motors

reduced squarely and one should ensure that this is sufficient to accelerate the load within a reasonable time, without injurious heat or causing a stalled condition. This aspect is discussed at length in Chapter 2. The torque, however, improves in the same proportion at higher voltages.

Example 1.2

During a run, if the supply voltage to a motor terminal drops to 85% of its rated value, then the full load torque of the motor will decrease to 72.25%. Since the load and its torque requirement will remain the same, the motor will start dropping speed until the torque available on its speed–torque curve has a value as high as 100/0.7225 or 138.4% of T_r, to sustain this situation. The motor will now operate at a higher slip, increasing the rotor slip losses also in the same proportion. See Equation (1.9) and Figure 1.7.

Solution

1 To ensure that the motor does not stall or lock-up during pick-up under such a condition, it should have an adequately high pull-out torque (T_{po}).
2 Since the motor now operates at a higher slip, the slip losses as well as the stator losses will increase. Circle diagram (Figure 1.16) illustrates this.
3 Judicious electrical design will ensure a pull-out torque slip as close to the full-load slip as possible and minimize the additional slip losses in such a condition. See Figure 1.8. A motor with a pull-out torque as close to full load slip as possible would also be able to meet a momentarily enhanced load torque during a contingency without any injurious heat or a stalling condition.

An increased voltage should improve the performance of the machine in the same way by reducing slip and the associated slip losses and also stator losses as a result of lower stator currents, but this would hold good only up to a certain increase in voltage, say up to 5%. Beyond this, not only will the no-load losses, as discussed above, assume a much higher proportion than the corresponding reduction in the stator current and the associated losses, the winding insulation will also be subject to higher dielectric stresses and may deteriorate, influencing its operating life. At over-voltages of about 10% and higher the insulation may even fail. Moreover, the stator current may start rising much more than the corresponding increase in the output to account for higher no-load losses and a poorer power factor. Figure 1.9 illustrates the approximate effect of voltage variation on the motor output. Higher voltages beyond 5% may thus be more harmful, even if the insulation level is suitable for such voltages. The circle diagram of Figure 1.16 explains this by shifting the semicircle to the right, because of higher $I_{n\ell}$ and $\phi_{n\ell}$ and a larger circle diameter, due to higher I_{st} thereby increasing I_r proportion of which will depend upon the magnitude of voltage.

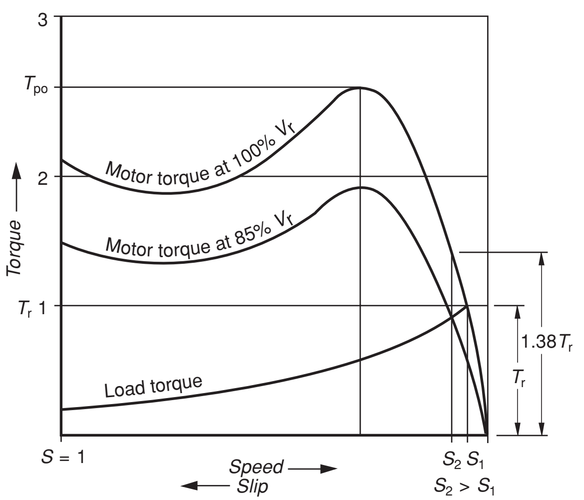


Figure 1.7 Higher full-load slip at lower voltages

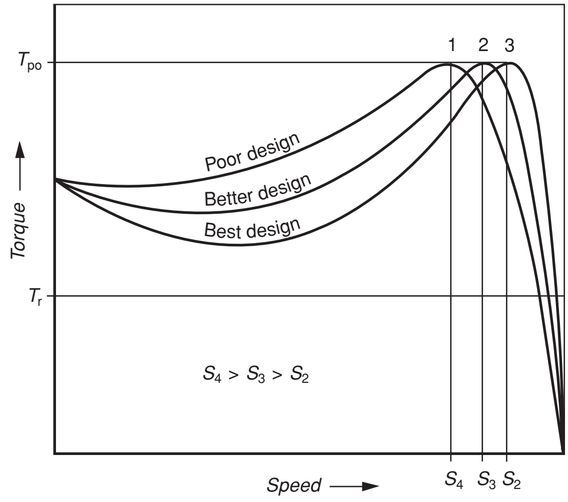
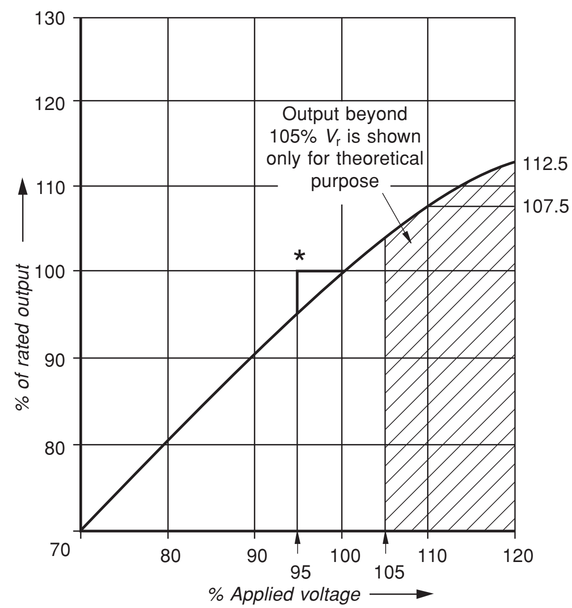


Figure 1.8 Significance of lower T_{po} slip



* Motors are designed to develop rated output at 95% voltage

Figure 1.9 Effect of voltage variation on the motor output

Important note on starting torque, T_{st}

It is important to note that at voltages lower than rated the degree of saturation of the magnetic field is affected as in Equations (1.1) and (1.5). There will also be a further drop in the supply voltage at the time of start-up. The net effect of such factors is to further influence the starting performance of the motor. See also IEC 60034-12. For risk-free duties and large motors, MV motors particularly, which have a comparatively lower starting torque, it would be appropriate to allow margins for such factors during start-up. Table 1.5, based on the data provided by a leading manufacturer, shows such likely factors at various voltages. The square of these must be applied to derive the more realistic operating starting torques at lower voltages than rated, rather than applying only the square of the applied voltage. Such a precaution, however, may not be necessary for normal-duty and smaller motors.

Example 1.3

Consider a 750 kW, 4-pole motor, having a rated starting torque T_{st} as 125% of the rated and starting current I_{st} as 600% of the rated. At 80% of the rated voltage the starting torque T_{st} will reduce to

T_{st} at 80% V_r $= 125 \times 0.745^2$

$\simeq$ 69% of rated (and not 125×0.8^2 or 80% of rated)

(ii) Starting current

In the same context, the starting current will also decrease linearly according to this factor and not according to the supply voltage. In the above example, the starting current I_{st} at 80% of the rated voltage will therefore reduce to

$I_{st} = 600 \times 0.745$

$=$ 447% of the rated current (and not 600×0.8 or 480%).

(iii) Load current

In addition to the increased stator current necessitated by the lower voltage, the stator must draw a higher current from the supply to compensate for the higher losses at lower voltages. Since

$$\text{kW} \propto \frac{\sqrt{3} \cdot V \cdot I \cdot \cos\phi \cdot \eta}{1000}$$

if the supply voltage falls to 85%, the stator current for the same load should increase by $I_r' = I_r/0.85$, i.e. by roughly 18% and if the voltage increases by 15%, the stator current should decrease to $I_r/1.15$ or 87% of I_r, i.e. a reduction of 13%. These would be the values when the core losses are ignored. But the core losses will also vary with the voltage as discussed below. Moreover, at a higher voltage, the p.f. will also become poorer and the motor will draw a higher current to account for this. All such factors, therefore, must be considered when making a selection of the rating of a motor, particularly for critical applications.

Table 1.5 Multiplying factor for starting torque at lower voltages for risk free duties and all MV motors

System voltage as % of rated	*Approx. multiplying factor (apply square of this)*	
	For 2- and 4-pole motors	*For 6- and 8-pole motors*
100	1.0	1.0
95	0.93	0.925
90	0.87	0.86
85	0.805	0.79
80	0.745	0.73
75	0.68	0.665
70	0.625	0.605
60	0.51	0.49
50	0.40	0.38

Source: Siemens Catalogue M20-1980

Note

These factors are applicable only during start as there is no saturation effect when the voltage drops during run.

(iv) Core and load losses

A current-carrying conductor produces two types of losses, i.e.

1 Resistive losses $\propto I^2R$ and
2 Core losses or magnetizing losses, which comprise
   - Eddy current losses and
   - Hysteresis losses

Magnetizing losses, however, as the name implies, are a phenomenon in electromagnetic circuits only. They are absent in a non-magnetic circuit. A motor is made of steel laminates and the housing is also of steel, hence these losses. Some manufacturers, however, use aluminium die-cast stator frames in smaller sizes, where such losses will be less (the bulk of the losses being in the laminations).

Since the resistive loss would vary in a square proportion of the current, the motor will over-heat on lower voltages (drawing higher currents). At higher voltages, while the stator current may decrease, the core losses will be higher.

To understand magnetizing losses, we must first identify the difference between the two types of losses. Both represent losses as a function of the electric field, generated by the current-carrying conductors. A current-carrying conductor generates an electric field in the space around it such that $I \propto \phi$. The higher the current through the conductor, the stronger will be the field in the space. Some of the field will penetrate through the conductor itself, because of the skin effect and the rest will occupy the space. In an electric motor it will penetrate through the stator and the rotor core laminations and the housing of the motor and cause losses in the following way:

1 Resistive losses within the current-carrying conductors, i.e. within the electrical circuit itself, caused by the leakage flux (Figure 2.6), as a result of the deep conductor skin effect. This effect increases conductor resistance and hence the losses. For more details refer to Section 28.7.
2 Losses as caused by its penetration through the magnetic structures (core) and components existing in the vicinity. These losses can be expressed by:

(a) *Eddy current loss,* L_e:

Because of the skin effect

$$L_e \propto \frac{t_\ell^2 \cdot f^2 \cdot B^2}{\rho} \qquad (1.12)$$

i.e. $\propto B^2$, other parameters remaining same.

where

f = supply frequency

t_ℓ = thickness of steel laminations. To reduce such losses, particularly in large motors, it is imperative to use thinner laminations. To economize on the size and bulk of windings, because of the skin effect, motor manufacturers adopt the method of transposition when manufacturing stator windings. See also Section 28.8.4.

B = flux density

ρ = resistivity of the steel laminations.

(b) *Hysteresis loss,* L_h

To understand this, consider the rotor as magnetized up to a certain level *a*, as illustrated in Figure 1.10. When the current (i.e. flux ϕ or flux density B since $I \propto \phi \propto B \propto H$ etc.) is reduced to zero, the magnetic circuit would still have a quantum of residual magnetism, ϕ or B. For instance, at no current, i.e. when $H = 0$, there would still be a residual magnetic field in the circuit as indicated by *ob* and this would account for the hysteresis loss.

See the curve *abcda* in the shape of a loop, which is drawn at different values of H after the magnetic core was magnetized up to its saturation level *oa*. This is known as a hysteresis loop and the magnetic area represented by *daebd* as the energy stored. This energy is not released in full but by only a part of it (*bae*) back to the magnetizing circuit when the magnetic field H (or current) is reduced to zero. The loss of this energy (*dab*) is termed hysteresis loss and appears as heat in the magnetizing circuit, i.e. the stator and the rotor of an induction motor. This loss may be attributed to molecular magnetic friction (magnetostriction) and is represented by

$$L_h \propto f \cdot (B_m)^{1.5 \text{ to } 2} \qquad (1.13)$$

i.e. $\propto f \cdot (B_m)^{1.5 \text{ to } 2}$

Eddy current and hysteresis losses are complex quantities and can be estimated in a laboratory, on no-load, in the form of power input, less $I_{n\ell}^2 \cdot R$ and friction and windage losses etc. as shown in Section 11.5. Based on this,

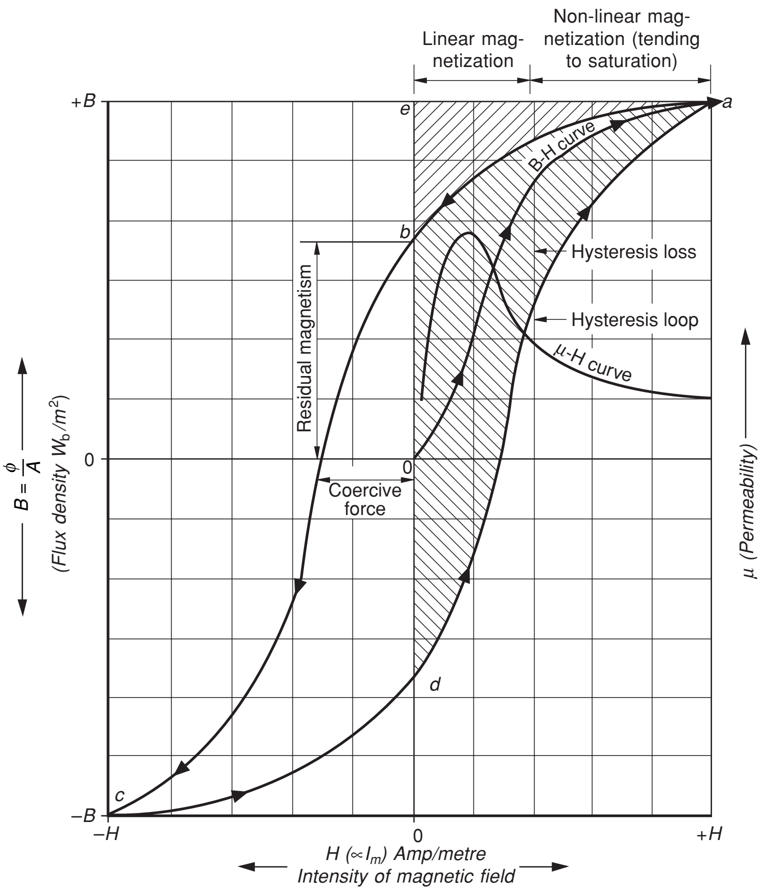


Figure 1.10 Hysteresis loop and magnetizing curve illustrating hysteresis loss

a designer can take corrective action to minimize these losses.

For all practical purposes, the core losses may be regarded as proportional to the square of the flux density. With a reduction in voltage, the flux ϕ and so the flux density B will decrease in the same proportion as the voltage and so will the core losses.

As a rough estimate, except for a rise or fall in the current drawn by the stator, at lower and higher voltages respectively, the variation in the I^2R loss will be more or less counterbalanced by the fall or rise in the core loss. The core loss is proportional to B^2, provided that no-load iron loss and full-load resistive loss are roughly equal, which is so for most designs. A comparatively higher resistive loss to core loss will result in a higher I^2R loss at lower voltages compared to a corresponding reduction in the no-load loss and vice versa. While on no-load, the no-load current will be more or less according to the square of the voltage.

(v) Effect on power factor, efficiency and speed

At lower voltages the rotor will adjust its speed at a higher slip. The extent of slip will depend upon the speed–torque characteristics of the motor and the supply voltage. The efficiency is now low but the power factor better, due to the lower inductive core loss. These figures are reversed when the voltage is high. Table 1.6 shows the variation in the various parameters with the voltage.

(vi) Performance of the driven equipment

The speed of the motor is affected slightly as is the speed of the driven load. Since the output of the load is a function of speed, it is also affected although only marginally, unless the variation in the voltage is substantial, which may also cause a substantial reduction in speed. The poorer the speed–torque characteristic of the motor, the higher will be the speed variation, as illustrated in Figure 1.8.

B *Effect of frequency variation*

On a 3-ϕ system the frequency variation is normally within limits, which according to IEC 60034-1 is ±2% (Figure 1.6). The reason for keeping the frequency variation low is that it is not influenced by any condition outside the generating point, and at the generating point, it is maintained constant through automatic speed regulation of the prime mover (frequency is directly proportional to the speed, Equation (1.6a)). The effect of frequency variation, however small, is discussed below:

(i) **Speed** Since the speed is proportional to frequency, it is affected the most and in turn influences the performance of the driven equipment in the same proportion as its relation to the speed.

(ii) **Slip** The motor adjusts its speed according to the frequency and therefore there is no change in the slip.

Table 1.6 Approximate effects of voltage and frequency variations on motor performance

Parameters	*Voltage (as percentage of the rated voltage)*			*Frequency (as percentage of the rated frequency)*	
	120	*110*	*90*	*105*	*95*
Torque[a]					
Starting and max. running	Increase 44%	Increase 21%	Decrease 19%	Decrease 10%	Increase 11%
Speed					
Synchronous	No change	No change	No change	Increase 5%	Decrease 5%
Full load	Increase 1.5%	Increase 1%	Increase 1.5%	Increase 5%	Decrease 5%
Percentage slip	Decrease 30%	Decrease 17%	Decrease 23%	Little change	Little change
Efficiency					
Full load	Small increase	Increase 0.5 to 1%	Decrease 2%	Slight increase	Slight decrease
Three-quarter load	Decrease 0.5–2%	Little change	Little change	Slight increase	Slight increase
Half load	Decrease 7–20%	Decrease 1–2%	Increase 1–2%	Slight increase	Slight increase
Power factor					
Full load	Decrease 5–15%	Decrease 3%	Increase 1%	Slight increase	Slight increase
Three-quarter load	Decrease 10–30%	Decrease 4%	Increase 2–3%	Slight increase	Slight increase
Half load	Decrease 15–40%	Decrease 5–6%	Increase 4–5%	Slight increase	Slight increase
Current[b]					
Starting	Increase 25%	Increase 10–12%	Decrease 10–12%	Decrease 5–6%	Increase 5–6%
Full load	Decrease 11%	Decrease 7%	Increase 11%	Slight decrease	Slight increase
Temp. rise	Decrease 5–6°C	Decrease 3–4°C	Increase 6–7°C	Slight decrease	Slight decrease
Max. overload capacity	Increase 44%	Increase 21%	Decrease 19%	Slight decrease	Slight decrease
Magnetic noise	More significant increase	Slight increase	Slight decrease	Slight decrease	Slight decrease

[a]See also the important note in Section 1.6.2A(i).
[b]See also Section 1.6.2A(ii).

(iii) Motor output and torque From Equation (1.5) $V_\ell \propto \phi_m \cdot f$, i.e. for the same applied voltage, V_ℓ, an increase or decrease in the system frequency will decrease or increase the flux in the same proportion. Consider the variation in the rotor current I_{rr} with frequency from Equation (1.7):

$$I_{rr} = \frac{S \cdot {}_{ss}e_2}{\sqrt{R_2^2 + S^2 \cdot {}_{ss}X_2^2}}$$

since ${}_{ss}X_2 = 2\pi \cdot f \cdot L$

where
L = inductance of the rotor circuit

$$\therefore I_{rr} \simeq \frac{{}_{ss}e_2}{2\pi fL}$$

$$\text{or} \propto \frac{1}{f}$$

Torque
From Equation (1.1)

$$T \propto \phi_m \cdot I_{rr}$$

$$\text{i.e} \quad \propto \frac{1}{f} \cdot \frac{1}{f}$$

$$\text{or} \quad \propto \frac{1}{f^2}$$

The torque of the motor would approximately vary inversely as the square of the frequency.

Power
This will also be affected, being a multiple of $T \cdot N$, i.e. by roughly $1/f$.

(iv) Effect on power factor The no-load losses will slightly decrease or increase with an increase or decrease in the supply frequency since

$$L_e \propto B^2 \cdot f^2 \text{ and} \qquad \text{(from Equation (1.12))}$$

$$L_h \propto B_m^2 \cdot f \qquad \text{(from Equation (1.13))}$$

where the cumulative effect of flux density is in the square proportion and that of frequency $f^{1.1}$ (approx.). With an increase in frequency, therefore, the core losses decrease slightly and vice versa. The efficiency improves slightly and so does the power factor at higher frequencies and vice versa. Table 1.6 shows approximate variations in these parameters with frequency.

C *Effect of ambient temperature*

The motors are universally designed for an ambient temperature of 40°C according to IEC 60034-1, unless specified otherwise. For temperatures below 40°C, the motor will run cooler by the amount the ambient temperature is lower. To utilize a higher output because of lower ambient temperature may, however, not be worthwhile, one may, however, consult the manufacturer.

For a higher ambient temperature, the end temperature of the winding will exceed the permissible limit by the amount the ambient temperature is higher. For example, for a class E motor, an ambient temperature of 50°C will cause the end temperature to reach 125°C as against 115°C permissible by the resistance method. For details refer to Sections 9.1 and 11.3.2.

To restrict the end temperature to less than the permissible limits, it is essential that the motor output be reduced, or for a required output, a higher-capacity motor be chosen. Table 1.7 gives the approximate derating factors for different ambient temperatures. Figure 1.11 is based on these figures from which the derating factor even for intermediate temperatures can be quickly determined.

To consider a higher ambient temperature, we must assess the temperature rise so affected. For instance, an ambient temperature of 50°C will require the temperature rise to be restricted by 10°C or 65/75, i.e. 86.67% in class E insulation and 70/80, i.e. 87.5% in class B insulation. The derating for insulation B will be less than E for the same ambient temperature. But for simplicity, a derating graph has been drawn in Figure 1.12, based on the temperature rise restrictions for class E insulation. For all practical purposes, this curve will also hold good for class B insulation. These values are only for guidance and may vary from one manufacturer to another depending on the design and the reserve capacity available in a particular frame.

Example 1.4
A 100 h.p. motor is required to operate at 50°C and limit the temperature rise to 60°C. The derating and h.p. to be chosen for class B insulation can be determined as follows:

Table 1.7 Derating for temperature rise restriction

Ambient temperature °C	*Class E*		*Class B*		*Permissible output %*
	Permissible temp. rise °C	*Percentage rise*	*Permissible temp. rise °C*	*Percentage rise*	
40	75	100.00	80	100.00	100
45	70	93.33	75	93.75	96
50	65	86.67	70	87.50	92
55	60	80.00	65	81.25	87
60	55	73.33	60	75.00	84
65	50	66.67	55	68.75	78
70	45	60.00	50	62.50	71

Note
Unless specified otherwise, all temperature measurements of motor are referred to by the resistance method.

Total permissible temperature for class B,	40 + 80 = 120°C
End temperature required	50 + 60 = 110°C

Note
If the manufacturer can ascertain that a 100 h.p. frame has a reserve capacity such that at full load the temperature rise will not go beyond 60°C, the derating as calculated below will not be necessary.

If the machine is derated for a 60°C temperature rise above 40°C, then the total temperature the motor would attain will be 100°C. In this case, even if the ambient temperature rises to 50°C (the temperature rise remaining the same) the total temperature the motor will attain will be:

= 50° + 60° = 110°C as desired

Therefore, derating the machine only for limiting the temperature rise to 60°C will be adequate.

Derating from Table 1.7 for restricting the temperature rise to 60°C is 84%.

$\therefore$ h.p. required = $\frac{100}{0.84}$, i.e. 119 h.p.

The next nearest size to this is a 125 h.p. motor.

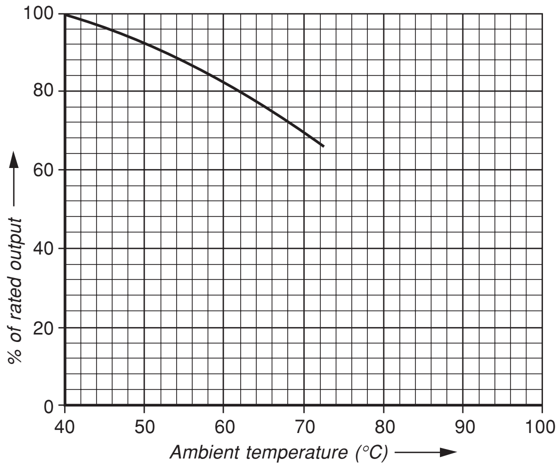


Figure 1.11 Derating curve for higher ambient temperatures for insulation class E or B

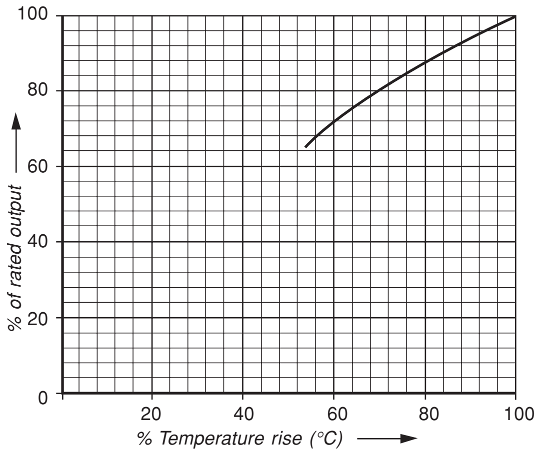


Figure 1.12 Derating curve for temperature rise restriction (drawn for class E insulation)

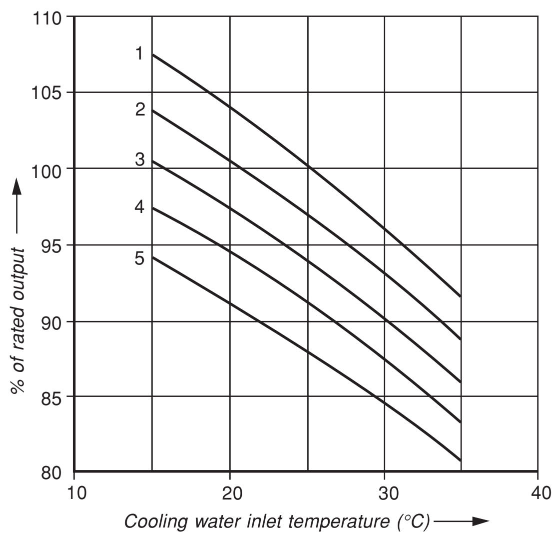
Effect of cooling water inlet temperature

For large motors, which use water as the secondary coolant in a closed circuit, the temperature of the cooling air, i.e. of the primary coolant, varies with the temperature of the cooling water inlet temperature and its rate of flow. For the performance of the motor output, this primary coolant, temperature has the same significance as the ambient temperature for an air-cooled motor. The motor output is unaffected by the ambient temperature. For such motors the output graph is shown in Figure 1.13 at different coolant temperatures and altitudes. The rating at 25°C inlet water temperature for water-cooled machines is the same as for air-cooled machines at an ambient temperature of 40°C.

D *Effect of altitude*

Motors are designed for an altitude up to 1000 m from mean sea level, according to IEC 60034-1. At higher altitudes, cooling reduces due to lower atmospheric pressure and should be compensated as for higher ambient temperature. It is estimated, that for every 1000 m above 100 m, the cooling is affected to the extent of 1% and the required output must be enhanced accordingly. Table 1.8 shows temperature rise restrictions for different altitudes above 1000 m and the corresponding deratings based on Table 1.7. With these values, a graph is also drawn in Figure 1.14, from which the derating for intermediate values can also be ascertained.

Note
A slightly higher derating for higher-speed motors, 1500 r.p.m. and above, is required in view of the cooling which in higher-speed motors will be affected more than in lower-speed motors.



(1) Altitude up to –1000 m
(2) Altitude above 1000–1500 m
(3) Altitude above 1500–2000 m
(4) Altitude above 2000–2500 m
(5) Altitude above 2500–3000 m

Figure 1.13 Effect of the cooling water inlet temperature on output, at different altitudes

Table 1.8 Derating for higher altitudes

Altitude (m)	Class E			Class B		
	Permissible temp. rise above 40°C		*Permissible output from the curves*	*Permissible temp. rise above 40°C*		*Permissible output from the curves*
	(°C)	*(%)*	*(%)*	*(°C)*	*(%)*	*(%)*
Up to 1000	75[a]	100	100	80[a]	100	100
Reduction in temperature rise for every 100 m above 1000 m	0.75	1.0	–	0.8	1.0	–
2000	67.5	90	94	72	90	94
3000	60.0	80	87	64	80	87
4000	52.5	70	79	56	70	79

[a]IEC 60034-1 has now substituted this by reduction in the ambient temperature. For insulation classes F and H see IEC 60034-1.

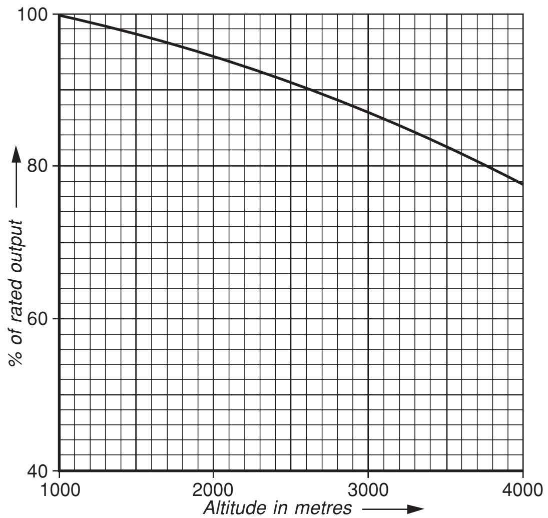


Figure 1.14 Derating curve for higher altitudes

Example 1.5

In the previous example, if altitude be taken as 2000 m, then a further derating by 94% will be essential.

$$\therefore \text{h.p. required} = \frac{100}{0.84 \times 0.94} = 126.8 \text{ h.p.}$$

A 125 h.p. motor may still suffice, which the manufacturer alone can confirm, knowing the maximum capacity of a 125 h.p. frame.

1.7 No-load performance

A study of no-load performance suggests that no-load current, power factor and losses may vary in the following proportions, depending upon the type, size and design of the motor:

1 No-load current

This may be 25–50% of the full-load current and sometimes even up to 60%. The higher the rating, the lower will be this current and it will depend upon the magnitude of magnetic induction (type and depth of slots) and air gap, etc.

2 No-load losses

- **Windage losses:** A result of friction between the moving parts of the motor and the movement of air, caused by the cooling fan, rotation of the rotor, etc.
- **Core losses** (Section 1.6.2A(iv)):
  - Eddy current losses, caused by leakage flux
  - Hysteresis losses, caused by cyclic magnetization of steel.

These may be considered up to 3–8% of the rated output.

3 No-load power factor

An induction motor is a highly inductive circuit and the no-load p.f. is therefore quite low. It may be of the order of 0.06–0.10 and sometimes up to 0.15.

The above values give only a preliminary idea of the no-load data of a motor. The exact values for a particular motor may be obtained from the manufacturer.

1.8 Effect of loading on motor performance

The declared efficiency and power factor of a motor are affected by its loading. Irrespective of the load, no-load losses as well as the reactive component of the motor remain constant. The useful stator current, i.e. the phase current minus the no-load current of a normal induction motor, has a power factor as high as 0.9–0.95. But because of the magnetizing current, the p.f. of the motor does not generally exceed 0.8–0.85 at full load. Thus, at loads lower than rated, the magnetizing current remaining the same, the power factor of the motor decreases sharply. The efficiency, however, remains practically constant for up to nearly 70% of load in view of the fact that maximum efficiency occurs at a load when copper losses (I^2R) are equal to the no-load losses. Table 1.9 shows an approximate variation in the power factor and efficiency with the load. From the various tests conducted on different types and sizes of motors, it has been established that the extent of variation in efficiency and power factor with load is universal for all makes of motors.

Table 1.9 Approximate values of efficiency and power factor at three-quarter and half loads corresponding to values at full load

% Efficiency			*Power factor*		
Full load	*Three-quarter load*	*Half load*	*Full load*	*Three-quarter load*	*Half load*
94	93.5	92	0.91	0.89	0.83
93	92.5	91	0.90	0.88	0.81
92	92	91	0.89	0.86	0.78
91	91	90	0.88	0.85	0.76
90	91	90	0.87	0.84	0.75
89	90	89	0.86	0.82	0.72
88	89	88	0.85	0.81	0.70
87	88	87	0.84	0.80	0.69
86	87	86	0.83	0.79	0.67
85	86	85	0.82	0.77	0.66
84	85	84	0.81	0.76	0.65
83	84	83	0.80	0.75	0.64
82	82	81	0.79	0.74	0.62
81	81	79	0.78	0.72	0.61
80	80	77	0.77	0.70	0.59
79	79	76	0.76	0.69	0.57
78	77	74	0.75	0.68	0.56
77	76	73	0.74	0.67	0.54
76	75	72	0.73	0.65	0.52
75	74	71	0.72	0.63	0.50
72	70	64	0.70	0.63	0.50
70	67	60	0.68	0.58	0.48
65	62	57	0.65	0.56	0.46
60	57	46	0.63	0.55	0.45
55	51	45	0.60	0.51	0.42
50	47	35	0.55	0.45	0.35

Note
In energy efficient (EE) motors (Section 1.19) the efficiency and pf remain almost constant from full load down to about 50% load or so (Figure 1.28).

1.9 Effect of steel laminations on core losses

The steel laminations play a very significant role in determining the heating and the power factor of a motor. See Section 1.6.2A(iv). A better design with a judicious choice of flux density, steel of laminations and its thickness are essential design parameters for a motor to limit the core losses to a low level.

For a lower range of motors, say up to a frame size of 355, the silicon steel normally used for stator and rotor core laminations is universally 0.5–0.65 mm thick and possesses a high content of silicon for achieving better electromagnetic properties. The average content of silicon in such sheets is of the order of 1.3–0.8% and a core loss of roughly 2.3–3.6 W/kg, determined at a flux density of 1 Wb/m^2 and a frequency of 50 Hz. Standard IEC 60404-8-4 for cold rolled non-grain oriented (CRNGO) steel for motors, however, expresses it at a flux density of 1.5 Wb/m^2 when the core losses are in the range of 3.5–5.3 W/kg. For medium-sized motors, in frames 400–710, silicon steel with a still better content of silicon, of the order of 1.3–1.8% having lower losses of the order of 2.3–1.8 W/kg is preferred, with a thickness of lamination of 0.5–0.35 mm.

For yet larger motors of frame sizes 710 and above, core losses play a more significant role, and require very effective cooling to dissipate the heat generated. Cooling of larger machines, complicated as it is in view of their size and bulk, necessitates core losses to be restricted as low as possible.

To meet this requirement, the use of steel with a still better silicon content and lower losses is imperative. A cold-rolled non-grain oriented (CRNGO) type of sheet steel is generally used for such applications, in the thickness range of 0.35–0.5 mm, with a higher silicon content of the order of 2.0–1.8% and losses as low as 1.0–1.5 W/kg.

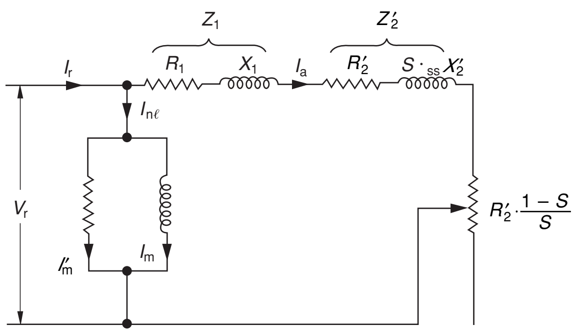
When the correct grade of steel is not available the core losses may assume a higher proportion and require a reduction in output or a larger frame than necessary. The data provided above are only for general guidance, and may vary slightly from one manufacturer to another and according to the availability of the silicon-grade steel at the time of manufacture.

1.10 Circle diagram

This is an approximate nomogram to understand the performance of a motor with the help of only no-load and short-circuit test results. In slip-ring motors, it also helps to determine the external resistance required in the rotor circuit to control the speed of the motor and achieve the desired operating performance. Slip-ring motors are discussed in Chapter 5. The concept behind this nomogram is that the locus of the rotor and the stator currents is a circle. Consider the equivalent circuit of an induction motor as shown in Figure 1.15, where

R_1 = stator resistance
X_1 = stator reactance
R'_2 = rotor resistance referred to stator
$S \cdot {}_{ss}X_2 = X'_2$ = rotor reactance referred to stator
$I_{n\ell}$ = no-load current
$R'_e = R'_2 \cdot \dfrac{I - S}{S}$ is the external rotor resistance referred to the stator.

All these values are considered on per phase basis.



$\bar{I}_{n\ell} = \bar{I}'_m + \bar{I}_m$
I'_m = Loss or active component supplying the hysteresis and eddy current losses to the stator core.
I_m = Magnetizing or reactive component producing the field (flux).
I_a = Active or torque producing component.

Figure 1.15 Simple equivalent circuit diagram of a motor

1.10.1 Drawing the circle diagram (Figure 1.16)

1 Take V_ℓ on the vertical axis and draw $I_{n\ell}$ at an angle $\phi_{n\ell}$ obtained from the no-load test.
2 From a short-circuit test draw the start-up current I_{st} at an angle ϕ_{st}.
3 Join *AB* and determine the centre *C* and draw the circle. The diameter of the circle can also be determined by:

$$AD = \frac{V_\ell}{X_1 + X_2'}$$

4 *BB′* will determine the locked rotor torque and power loss while the rotor is locked.
Divide *BB′* at *M* in the ratio of $R_2' : R_1$ and join *AM*

where

$$R_2' = R_2\left(\frac{Z_s}{Z_r}\right)^2$$

R_2 = rotor resistance per phase
Z_s = number of turns in the stator circuit per phase
Z_r = number of turns in the rotor circuit per phase

5 At load current I_r, i.e. *OP*, the rotor current I_{rr} is *AP*. PP_1 will determine the power input per phase and the performance of the motor as follows:

(i) Power input = $3 \cdot V_\ell \cdot PP_1$ watts
(ii) Core and friction loss = $3 \cdot V_\ell \cdot D_1 D_2$ watts
(iii) Stator copper loss = $3 \cdot V_\ell \cdot M_1 P_0$ watts
(iv) Rotor copper loss = $3 \cdot V_\ell \cdot bM_1$ watts
(v) Motor output = $3 \cdot V_\ell \cdot Pb$ watts
AB is known as the output line, since the output is measured above this.
(vi) Running torque,

$$T = 3 \cdot V_\ell \cdot PM_1 \text{ synchronous watts}$$

and since $3 \cdot V_\ell \cdot PM_1 = \dfrac{T \cdot N_r}{0.974}$

$$\therefore T = \frac{3 \cdot V_\ell \cdot 0.974 \cdot PM_1}{N_r} \text{ mkg.}$$

This is the maximum torque that can be developed by the rotor during a run, but the useful torque will be in accordance to output, i.e.

$$\frac{3 \cdot V_\ell \cdot Pb}{N_r} \cdot 0.974 \text{ mkg}$$

Since the maximum torque is measured by line *AM*, it is known as the torque line.
(vii) Starting torque or short-circuit torque

$$T_{st} = 3 \cdot V_\ell \cdot \frac{BM}{N_r} \cdot 0.974$$

(viii) Full-load slip, $S = \dfrac{bM_1}{PM_1}$

1.10.2 Inference from the circle diagram

The maximum value of the output and torque of the motor can be obtained by dropping perpendiculars CC_1 and CC_3 on the output and torque lines respectively from the centre *C*. C_1C_2 and C_3C_4 indicate the magnitude of the maximum output and torque, respectively, that the motor can develop. This torque is the pull-out torque T_{po}. In slip-ring motors it can be obtained at any speed on the normal speed–torque curve by inserting a suitable resistance into the rotor circuit to vary the slip.

Under normal conditions, the starting current is too high, whereas the corresponding starting torque is not so high. If we can shift the I_{st} point to the left, or in other words increase the slip, the torque will increase and I_{st} will decrease. This is used, in a slip-ring motor to control both T_{st} and I_{st} with suitable external resistances. For instance, if the starting torque is required to be equal to T_{po}, i.e. C_3C_4, then the start-up current should be controlled to OC_3. The starting resistance, R_{st}, therefore should be such as to achieve this current during start-up:

i.e. $R_{st} = \dfrac{{}_{ss}e_2}{AC_3}$

and external resistance $R_e = R_{st} - R_2$

Corollary

The higher the full load slip, the higher will be the rotor losses and rotor heat. This is clear from the circle diagram and also from Equation (1.9). An attempt to limit the start-up current by increasing the slip and the rotor resistance in a squirrel cage motor may thus jeopardize the motor's performance. The selection of starting current and rotor

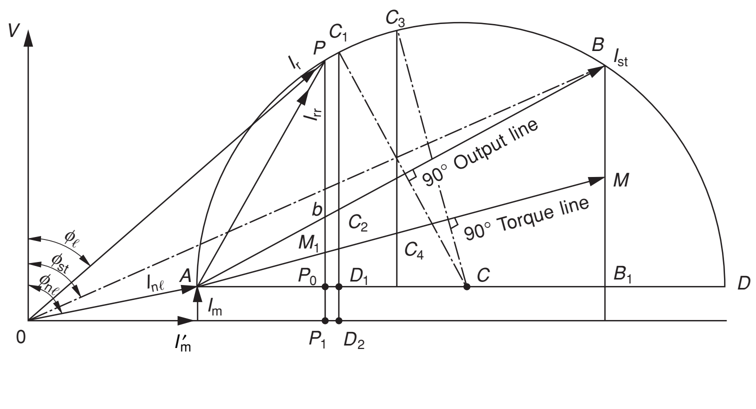


Figure 1.16 Circle diagram

resistance is thus a compromise to achieve optimum performance.

1.11 Types of induction motors

These are of two types:

1 Squirrel cage rotor
2 Slip-ring or wound rotor

In a squirrel cage motor the rotor winding is made of solid metallic rods short-circuited at both ends of the rotor. Short-circuiting of rotor bars leads to fixed rotor parameters. In slip-ring motors the rotor is also wound like the stator and the six winding terminals are connected to a slip-ring assembly. This gives an opportunity to vary the rotor circuit impedance by adding external resistance and thus vary the rotor circuit parameters to achieve the required performance.

Although it may seem easy to alter the speed–torque and speed–current characteristics of such a motor through its rotor circuit, the use of such motors is recommended only for specific applications where the use of a squirrel cage motor may not be suitable. The reason is its slip-rings and the brushes which are a source of constant maintenance due to arcing between the rings and the brushes, besides a much higher initial cost and equally expensive control gears.

Specific applications for such motors are rolling mills, rice mills, paper mills and cranes etc. for one or more of the following reasons:

1 To contain the start-up inrush current, as a result of low start-up impedance and to control the same as needed through external resistance in the rotor circuit.
2 To provide a smoother start.
3 To meet the requirement of a high start-up torque and yet contain the start-up inrush current.
4 To meet the load demand for more frequent starts and reversals, as for cranes and other hoisting applications.
5 To achieve the required speed variation through variation in rotor circuit impedance.

Note
The latest trend, however, is to select only squirrel cage motors as far as practicable and yet fulfil most of the above load requirements. Fluid couplings and static (IGBT, IGCT, SGCT or thyristor) drives can meet the above requirements by starting at no-load or light load and controlling the speed as desired, besides undertaking energy conservation. See also Chapters 6 and 8.

1.11.1 Choice of voltage

Because of heavy start-up inrush currents, the use of LV motors should be preferred up to a medium sized ratings, say, up to 160 kW, in squirrel cage motors and up to 750 kW in slip-ring motors. For still higher ratings, MV motors should be used.

1.12 Mounting of motors

The common types of mountings are illustrated in IEC 60034-7, and the most frequently used are shown in Figure 1.17. The legends to represent these mountings are

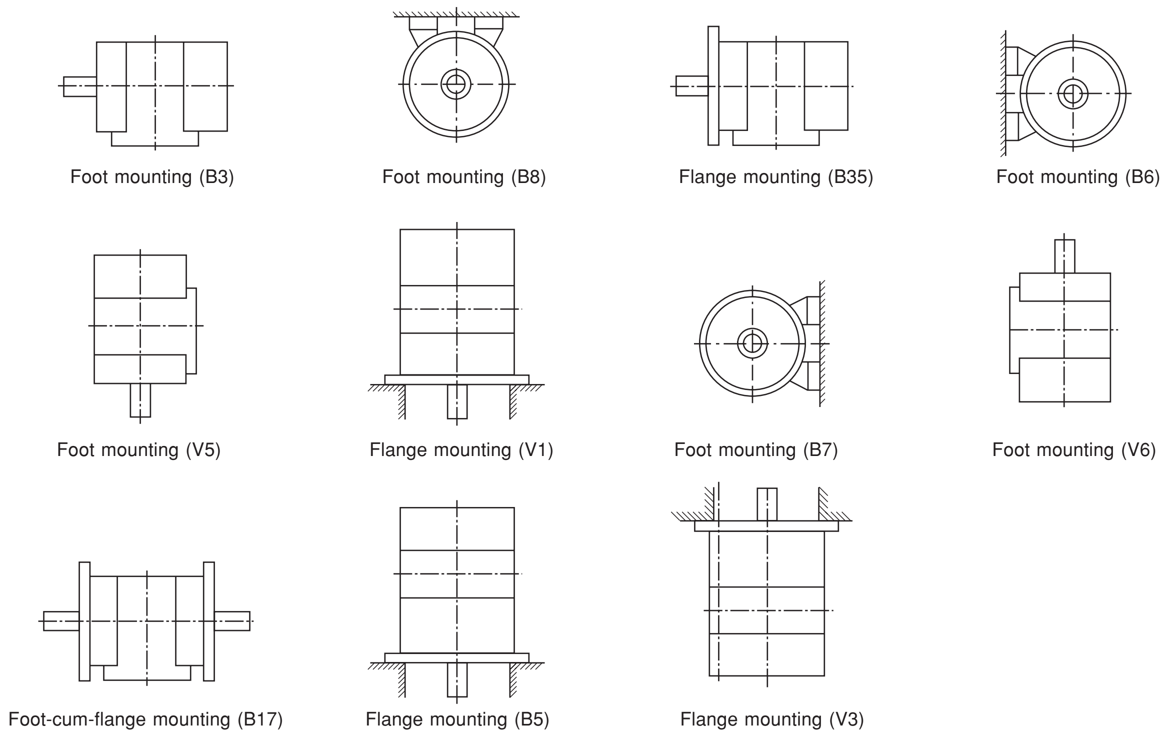


Figure 1.17 Types of mounting arrangements

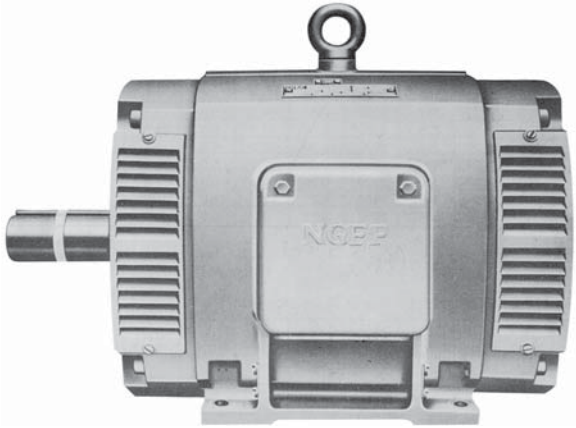


Figure 1.18(a) Screen protected dripproof (SPDP) squirrel cage motor (Cooling system ICOA1)

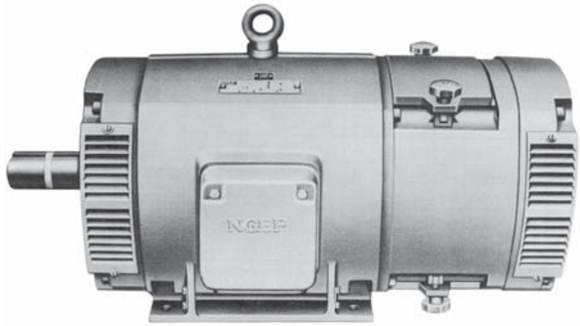


Figure 1.18(b) Screen protected dripproof slip ring motor (Cooling system ICOA1)

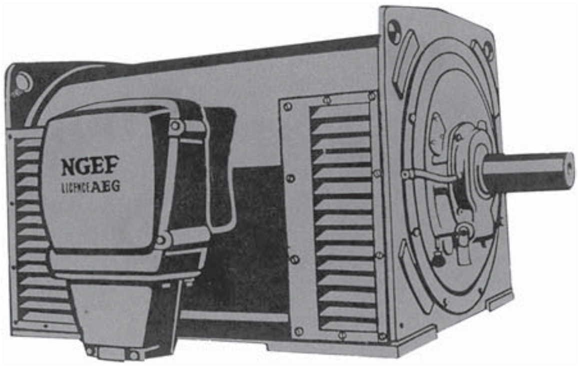


Figure 1.18(c) Large SPDP squirrel cage motor (enclosure IP 12) (Cooling system ICOA1)

given below:

1	Floor mounting	*B*3
2	Wall mounting	*B*6/*B*7
3	Ceiling mounting	*B*8
4	Wall mounting	*V*5
5	Wall mounting	*V*6
6	Flange mounting	*B*5
7	Flange mounting	*V*1
8	Flange mounting	*V*3
9	Foot-cum-flange mounting	*B*3/*B*5
10	Foot-cum-flanges on both sides	*B*17

Note
For brevity, the prefix *IM*, representing 'International Mounting', has been omitted from these legends. In common practice the different types of mountings are represented as noted above. While designation *B* represents a horizontal mounting, designation *V* represents a vertical mounting. For more details and numerical designation of motors refer to IEC 60034-7.

Care should be taken in selecting the mounting for applications where the motor weight would apparently fall on its flange or the foot, as in mountings *B*5, *B*6, *B*8, *V*3, *V*5 and *V*6. In such mountings, the foot or the flange is subject to a shearing force due to a cantilever effect and is vulnerable to breakage. For small sizes, where the weight of the motor may not matter so much, these types of mountings can be employed, otherwise reinforcement may be necessary either to the foot or to the flange, if possible. For larger motors it is advisable to select an alternative mounting.

1.13 Enclosures

A motor can be constructed in different enclosures to suit a particular location as follows.

1.13.1 **Protected motors** (degree of protection IP 12, 21 or 23)

1 Screen protected (SP): Not a common enclosure. For locations clear of dust and water.
2 Screen protected, dripproof (SPDP): As above, but with additional protection against dripping of water Figures 1.18(a)–(d).
3 Splashproof: As in (2) but, unless the degree of protection according to IEC 60034-5 is specified, this remains a vague term and is not in frequent use.

1.13.2 **Totally enclosed fan-cooled (TEFC) motors** (degree of protection IP 44, 54 or 55)

These motors are suitable for locations prone to dust, coal dust and metal particles etc. and occasional water spray and rain (Figures 1.19(a) and (b)).

Note
SPDP motors also have a cooling fan but their surface is plain, whereas TEFC motors have fins on their housings that add to their cooling surface. Refer to Figures 1.18(a)–(c) and 1.19(a) and (b).

1.14 Weatherproof (WP) motors (degree of protection IP 55)

These are an improvised version of a totally enclosed motor to protect its live parts from ingress of water, rain, snow or airborne particles etc. This is achieved by providing them with additional protection such as labyrinths at joints such as bearing end covers, centrifugal discs, end shields

1 Access for checking air gap
2 Air-deflecting baffle
3 Coil bracing ring
4 Fan
5 Rotor end ring
6 Rotor bars
7 Rotor core
8 Fully-formed coils of the two layer stator winding
9 Air guide shell
10 Core duct separator
11 Preformed coil in section
12 End winding connections
13 Bearing endshield
14 Terminal box with bolt on cable sealing end
15 Shaft
16 Grease ejector handle
17 Grease collector
18 Anti-friction bearing with grease regulator
19 Grease impeller

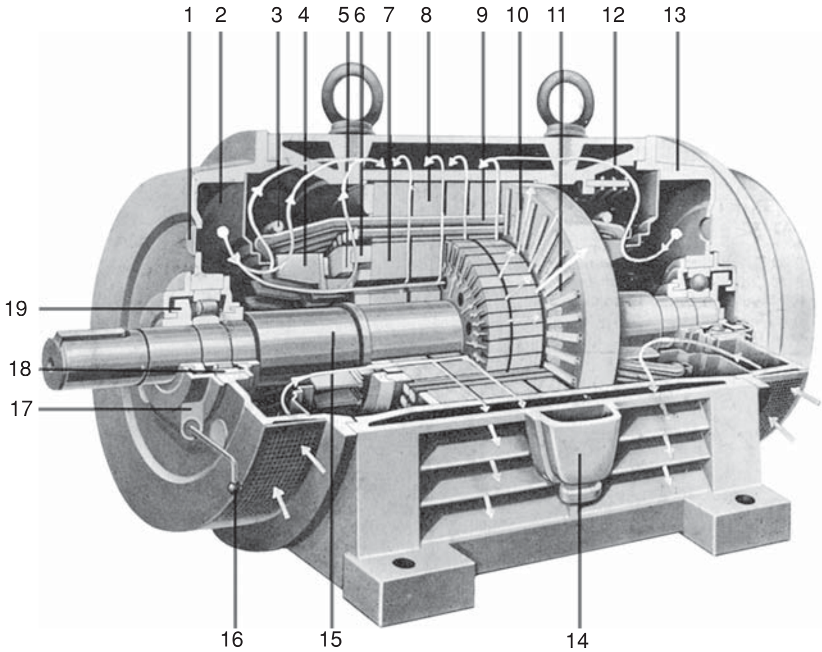
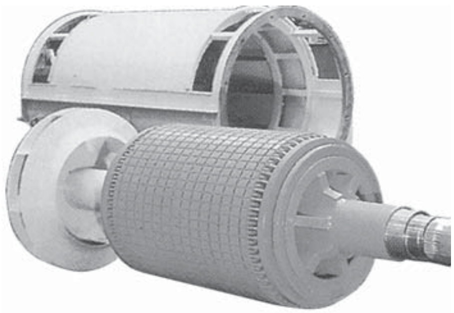
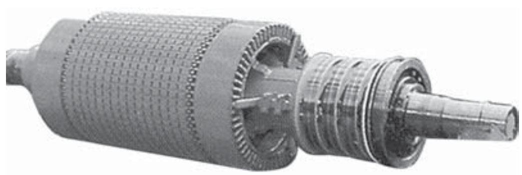


Figure 1.18(d) Cross-sectional view of a large screen protected motor showing the cooling circuit (Cooling System ICOA1) (Courtesy: NGEF Ltd)



Squirrel cage rotor



Slip ring rotor

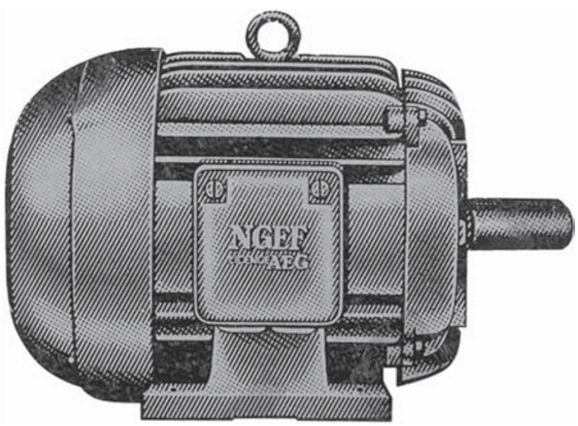


Figure 1.19(a) TEFC squirrel cage motor (Cooling system ICOA1) (Courtesy: NGEF Ltd)

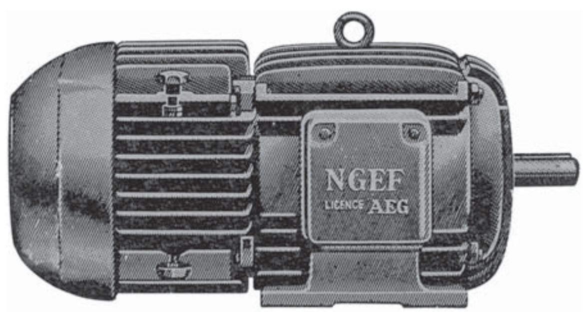


Figure 1.19(b) TEFC slip ring motor (Cooling system ICOA1) (Courtesy: NGEF Ltd)

and terminal box and giving the outer surface a special coat of paint to protect against unfavourable weather conditions.

1.14.1 NEMA enclosures

These have only a historical significance, in the light of better defined enclosures now available. They are briefly defined here:

- **Type I** A weather-protected Type I machine is an open machine with its ventilating passages so constructed as to minimize the entrance of rain, snow and air-borne particles to the electrical parts and having its ventilated openings so constructed as to prevent the passage of a cylindrical rod 3/4-inch in diameter.
- **Type II** A weather-protected Type II machine will have, in addition to the enclosure defined for a weather-protected Type I machine, ventilating passages at both intake and discharge ends so that high-velocity air and air-borne particles blown into the machine by storms or high winds can be discharged without entering the internal ventilating passages leading directly to the electrical parts of the machine. The normal path of the ventilating air which enters the electrical parts of the machine is so arranged by baffling or separate housings that it provides at least three abrupt changes in its direction, none of them being less than 90°. In addition, an area of low velocity not exceeding 600 feet per minute is also provided in the intake air path to minimize the possibility of moisture or dirt being carried into the electrical parts of the machine.

Table 1.10 Types of protection against contact with live or moving parts

First characteristic number as in IEC 60034-5	*Type of protection*
0	No special protection of persons against accidental or inadvertent contact with live or moving parts inside the enclosure.
	No protection of equipment against ingress of solid foreign bodies.
1	Protection against accidental or inadvertent contact with live and moving parts inside the enclosure by a larger surface of the human body, for example a hand, but not against deliberate access to such parts.
	Protection against ingress of large solid foreign bodies (diameter greater than 50 mm).
2	Protection against contact with live or moving parts inside the enclosure by fingers.
	Protection against ingress of small solid foreign bodies (diameter greater than 12 mm).
3	Protection against contact with live or moving parts inside the enclosure by tools, wires or objects having a thickness greater than 2.5 mm.
	Protection against ingress of small solid foreign bodies (diameter greater than 2.5 mm).
4	Protection against contact with live or moving parts inside the enclosure by tools, wires, or such objects of thicknesses greater than 1 mm.
	Protection against ingress of small solid foreign bodies (diameter greater than 1 mm) excluding the ventilation openings (intake and discharge) and the drain hole of the enclosed machine which may have degree 2 protection.
5	Complete protection against contact with live or moving parts inside the enclosure.
	Protection against harmful deposit of dust. The ingress of dust is not totally prevented, but dust will not be able to enter in an amount sufficient to harm the machine.
6	Totally dust-tight. No ingress of dust.

1.15 Degree of protection

The nomenclatures used above to define an enclosure were earlier interpreted in different ways by different manufacturers. To achieve harmonization, IEC 60034-1 has eliminated the use of these codes. Instead, designation IP, followed by two characteristic numerals according to IEC 60034-5, is now introduced to define an enclosure. The first characteristic numeral defines the protection of personnel from contact with live or moving parts inside the enclosure and of machines against the ingress of solid foreign bodies. The second numeral defines the type of protection against ingress of water. Tables 1.10 and 1.11 show these requirements.

Table 1.11 Types of Protection against ingress of water

Second characteristic number	*Type of protection*
0	No special protection
1	Dripping water (vertically falling droplets) will have no harmful effect.
2	Droplets of water falling at any angle up to 15° from the vertical will have no harmful effect.
3	Water falling as a spray at an angle equal to or smaller than 60° from the vertical will have no harmful effect.
4	Water splashed under stated conditions against the machine from any direction will have no harmful effect.
5	Water injected under stated conditions through a nozzle against the machine from any direction will have no harmful effect.
6	Water from heavy seas will not enter the machine in a harmful quantity.
7	Ingress of water in the machine immersed in water under stated conditions of pressure and time will not be possible in a harmful quantity.
8	Ingress of water into the machine immersed in water under specified pressure and for an indefinite time will not be possible in a harmful quantity.

1.16 Cooling systems in large motors

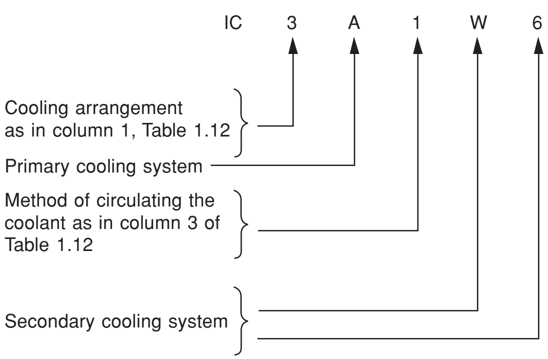
The cooling system in large motors becomes vital, as one fan cannot cover the entire length of the motor body or cool the inside bulk of the motor windings. Now a more judicious design is required for adequate cooling to eliminate any hot spots in the rotor, stator or the overhangs of the stator windings and bearings etc. There are many cooling systems adopted by various manufacturers, depending upon the size of the machine and the heat generated in various parts during full-load continuous running. The cooling system may be self-ventilated, closed circuit, not requiring any external source to augment the cooling system, or a forced cooling system, employing an external source, to basically work as heat exchangers to dissipate the heat. Thus, there may be a variety of cooling systems to cool a large machine.

IEC 60034-6 has specified a number of probable cooling systems, as adopted by various manufacturers. The more commonly used practices are shown in Table 1.12. According to this specification any cooling system may be expressed by the letters IC (international cooling) followed by

1 A number to indicate the arrangement of the cooling circuit as in column 1 of Table 1.12.
2 Each cooling circuit is then identified for the primary cooling medium by a letter A, H or W etc. which specifies the coolant as noted below:
   For gases
   - Air – A
   - Freon – F
   - Hydrogen – H
   - Nitrogen – N
   - Carbon dioxide – C

   For liquids
   - Water – W
   - Oil – U
3 The letter is then followed by a number, describing the method to circulate the coolant as in column 3 of Table 1.12.
4 Another letter and a number are added after the above to describe the secondary cooling system.

Example



Depending upon its size, a machine may adopt more than one cooling system, with separate systems for the stator and the rotor and sometimes even for bearings. To define the cooling system of such a machine, each system must be separately described. For more details refer to IEC 60034-6.

The following are some of the more prevalent systems for totally enclosed large machines:

Tube Ventilated Self Cooled (TV)
Closed Air Circuit Water Cooled (CACW)
Closed Air Circuit Air Cooled (CACA)

The above cooling systems will generally comprise the following:

1 *Tube ventilation* In this system cooling tubes which work as heat exchangers are welded between the core packet and the outer frame and are open only to the atmosphere. See to Figures 1.20 (a)–(c). One fan inside the stator, mounted on the rotor shaft, transfers the internal hot air through the tube walls which form the internal closed cooling circuit. A second fan mounted outside at the NDE blows out the internal hot air of the tubes to the atmosphere and replaces it with fresh cool air from the other side. This forms a separate external cooling circuit.
2 *Closed Air Circuit Water Cooled (CACW)* The motor's interior hot air forms one part of the closed air circuit that is circulated by the motor's internal fans. A separate heat exchanger is mounted on top of the motor as the cooling water circuit. This forms the second cooling circuit.

   The heat exchanger consists of a large number of cooling tubes connected to the stator through headers/ducts. The tubes may have coils of copper wire wound around them to enhance their cooling capacity. Filtered water (soft water), to avoid scaling of tubes, is circulated through these tubes. The hot air circulating through the motor stator and rotor ducts passes through these heat exchangers and becomes cooled. See Figure 1.21.
3 *Closed Air Circuit Air Cooled (CACA)* This cooling system is the same as for CACW except that, instead of water, air flows through the top-mounted heat exchangers. See Figures 1.21 and 1.22.

1.17 Single-phase motors

Applications – Domestic appliances
– Small machine tools
– Industrial and domestic fans, pumps, polishers, grinders, compressors and blowers etc.

1.18 Theory of operation

A single-phase winding cannot develop a rotating field, unlike a multi-phase winding. But once it is rotated, it will continue rotating even when the rotating force is removed so long as the winding is connected to a supply source. To

Table 1.12 Normal systems of cooling for totally enclosed large machines

First characteristic number to indicate the cooling system	*Description*	*Second characteristic number for means of supplying power to circulate the coolant*	*Description*
1	2	3	4
0	**Free circulation of the coolant** from the machine to the surrounding medium	0	**Free convection:** No external power source is essential. Heat dissipation is achieved through natural convection like a surface cooled motor
1	**Inlet pipe-circulation:** The coolant flows to the machine through inlet pipes from a source other than the surrounding medium and then freely discharges to the surrounding medium (as in the use of separately driven blowers)	1	**Self-circulation:** Movement of the coolant is normally through a fan mounted on the rotor shaft, like a normal fan cooled motor (Figures 1.18(a)–(d) and 1.19(a) and (b))
2	**Outlet pipe circulation:** The coolant is drawn from the surrounding medium but is discharged remotely through the pipes	2	–
3	**Inlet and outlet pipe circulation:** The coolant flows from a source other than the surrounding medium through the inlet pipes and is discharged remotely through the outlet pipes	3	–
4	**Frame surface cooled** (using the surrounding medium): The primary coolant is circulated in a closed circuit and dissipates heat to the secondary coolant, which is the surrounding medium in contact with the outside surface of the machine. The surface may be smooth or ribbed, to improve on heat transfer efficiency (as, in a TEFC or tube ventilated motor) (Figures 1.19 and 1.20)	4	–
5	**Integral heat exchanger** (using surrounding medium): As at No. 4 above, except that the medium surrounding the machine is a heat exchanger, which is built-in as an integral part of the machine like a totally enclosed, tube-ventilated motor (Figure 1.20)	5	**Circulation by integral independent component:** Like a fan, driven by an electric motor, and the power is drawn from a separate source, rather than the main machine itself
6	**Machine-mounted heat exchanger** (using the surrounding medium): As at No. 5 above, except that the heat exchanger is neither externally mounted nor forms an integral part of the machine. Rather it is mounted as an independent unit, directly on the machine (Figures 1.21 and 1.22)	6	**Circulation by independent component mounted on the machine**: As at No. 5 above, but the movement of the coolant is through an intermediate component and mounted on the machine and not an integral part of the machine
7	**Integral heat exchanger** (not using the surrounding medium): As at No. 5 above, except that the cooling medium is different from the surrounding medium. It can be liquid or gas	7	**Circulation by an entirely separate system**: As at No. 6 above, but the circulation of the coolant is by an entirely independent system, not forming a part of the main machine in any way and mounted separately like a water-distribution system or a gas-circulation system
8	**Machine-mounted heat exchanger** (not using the surrounding medium): As at No. '6' above except that the cooling medium is different from the surrounding medium. It can be liquid or gas (Figures 1.21 and 1.22)	8	**Circulation by relative displacement**: As at No. 0 above, except that instead of surface cooling the cooling is achieved through the relative movement of the coolant over the machine
9	**Separately mounted heat exchanger**: The primary coolant is circulated in a closed circuit and dissipates heat to the secondary coolant. It can be a heat exchanger as an independent unit separately mounted	9	This numeral is used for circulation by any means other than stated above

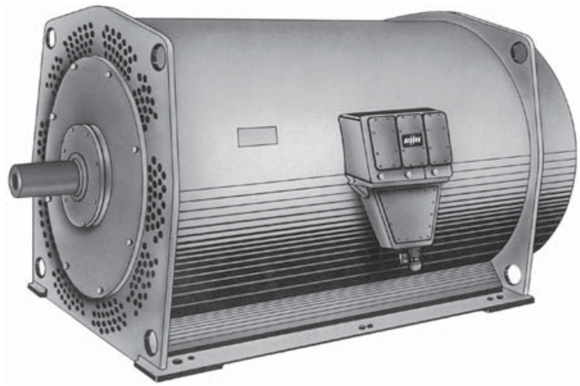


Figure 1.20(a) Totally enclosed tube ventilated (TETV) squirrel cage motor (Cooling system IC5A1A1) (Courtesy: BHEL)

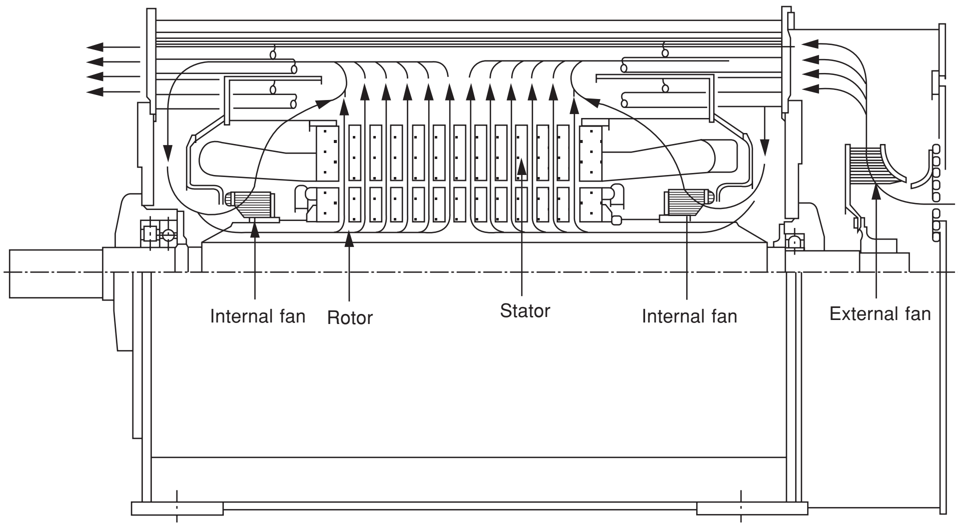


Figure 1.20(b) A typical cooling circuit type IC5A1A1

1. Lifting lug
2. Air baffle
3. Coil bracing ring
4. Cooling tubes
5. Short-circuiting ring
6. Stator core packet
7. Two-layer fully formed coils of stator winding
8. Air guide shell
9. Bearing endshield
10. Fan for outer air circuit
11. Fan hood with protective grid for cooling air intake
12. Handle for emptying grease collecting box
13. Welded frame
14. Terminal box with cable sealing box
15. Rotor core packet
16. Section bars of the squirrel cage
17. Rotor end plate
18. Grease collecting box
19. Grease thrower of labyrinth seal
20. Opening for checking air gap
21. Fan for inner air circuit

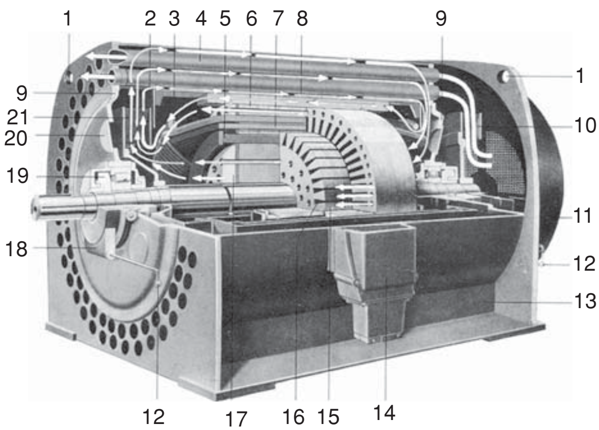


Figure 1.20(c) Cross-sectional view of a large tube-ventilated squirrel cage motor showing the cooling circuit (Cooling system IC5A1A1) (Courtesy: NGEF Ltd)

provide a rotating magnetic field, an auxiliary winding or start winding is therefore necessary across the main winding. It is placed at 90° from the main winding and connected in parallel to it, as shown in Figures 1.23 and 1.24. The impedances of the two windings are kept so that they are able to provide a phase shift between their own magnetic fields. This phase shift provides a rotating magnetic field as already discussed. The auxiliary windings may be one of the following types:

1 Split phase winding

When another inductive winding is placed across the main winding (Figures 1.23(a) and (b)) so that R/X_{L1} of the auxiliary winding is high, a phase shift will

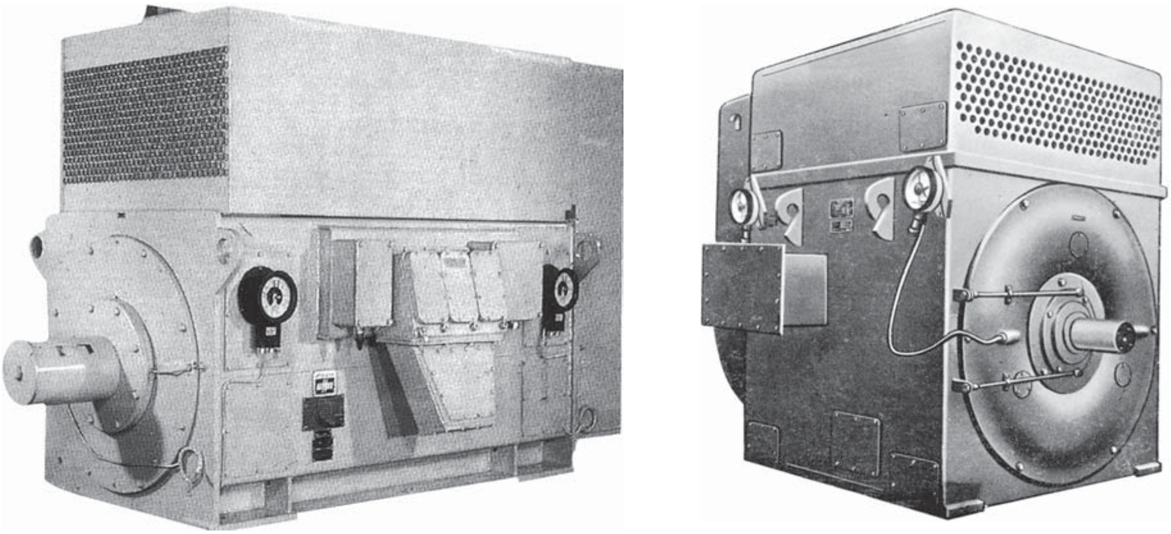


Figure 1.21 Closed air circuit, air cooled (CACA) squirrel cage motors (likely cooling systems IC6A1A1 or IC6A1A6) (Courtesy: BHEL)

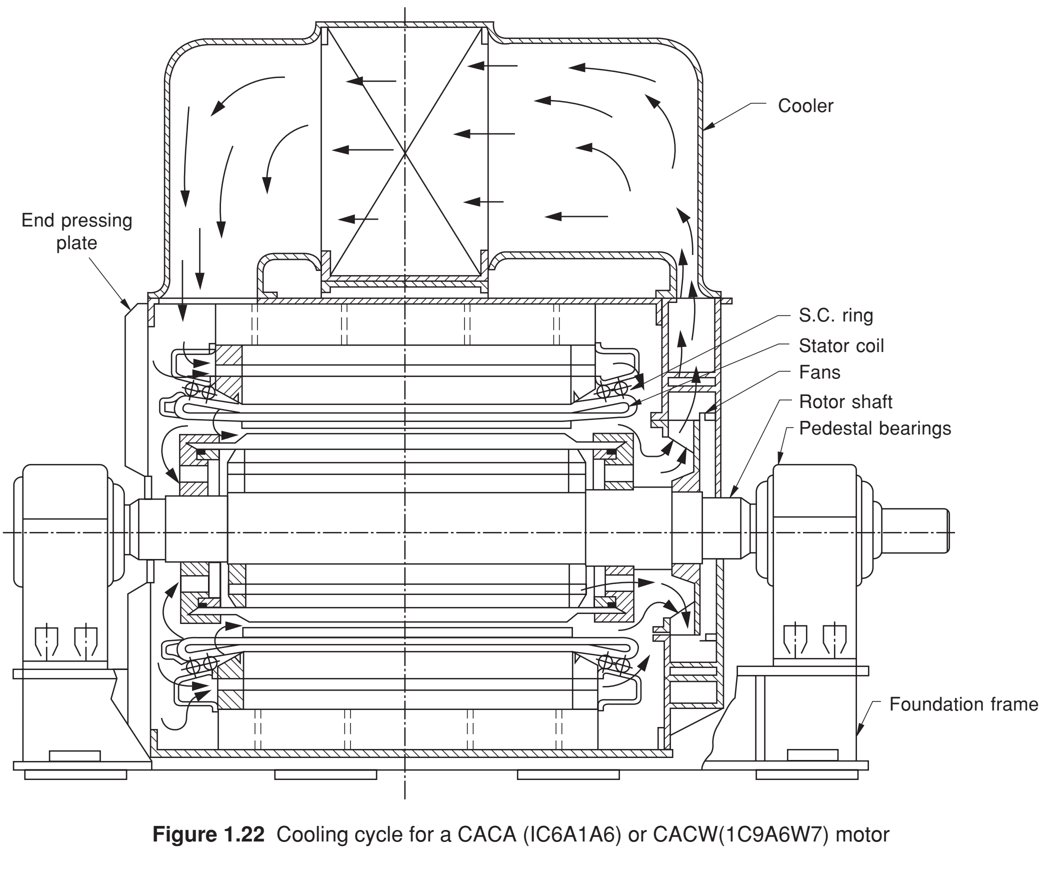


Figure 1.22 Cooling cycle for a CACA (IC6A1A6) or CACW(1C9A6W7) motor

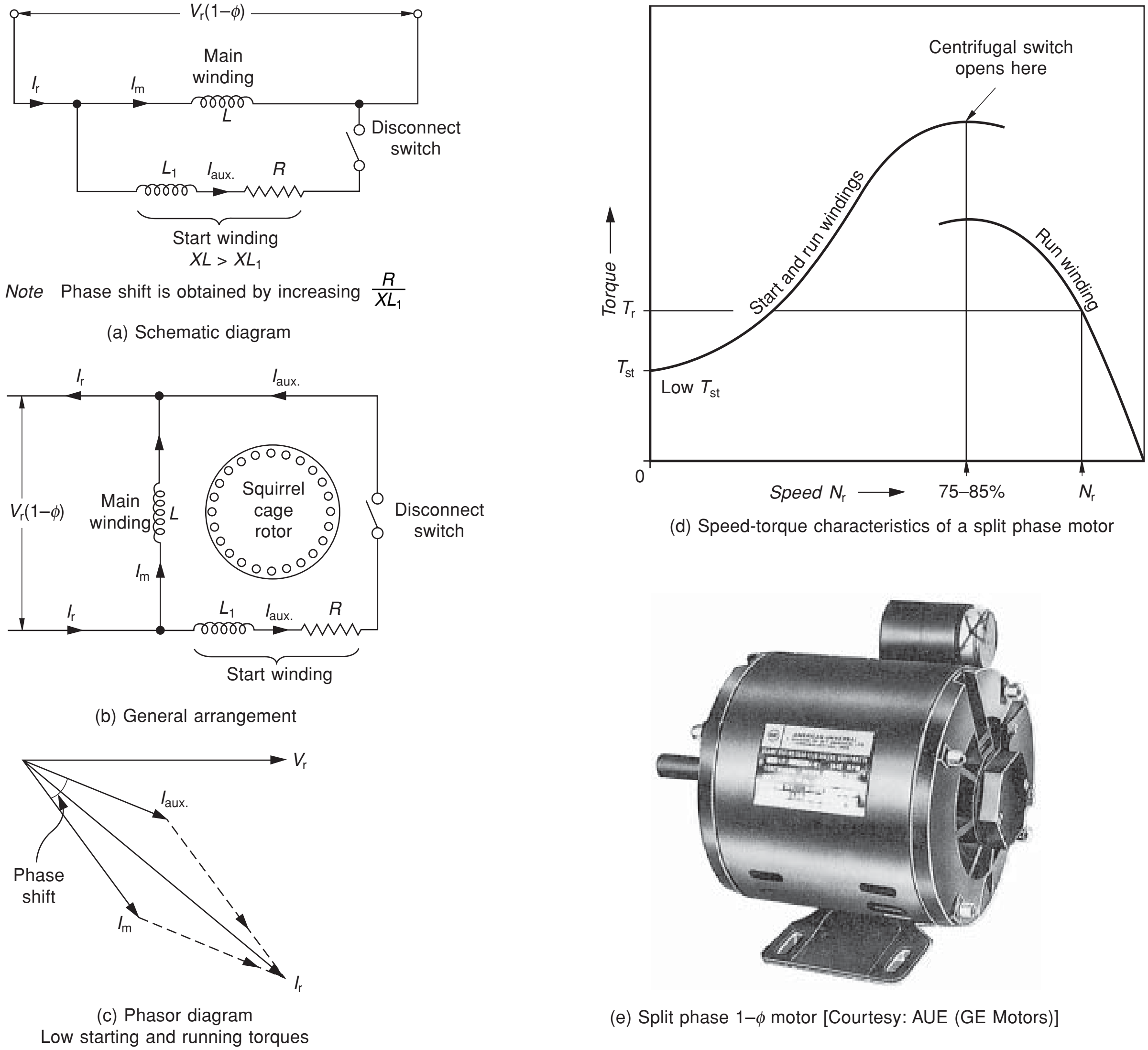


Figure 1.23 Split-phase winding

occur between the two windings. This shift will be low and much less than 90°, as explained in the phasor diagram (Figure 1.23(c)). But it can be made adequate by increasing the R, so that a rotating field may develop sufficiently to rotate the rotor. The higher the ratio R/X_{L1}, the higher will be the starting torque, as R/X_{L1} will move closer to the applied voltage V_ℓ and help to increase the phase shift. In such motors the starting torque, T_{st}, is low and running speed–torque characteristics poor as illustrated in Figure 1.23(d). Figure 1.23(e) shows a general view.

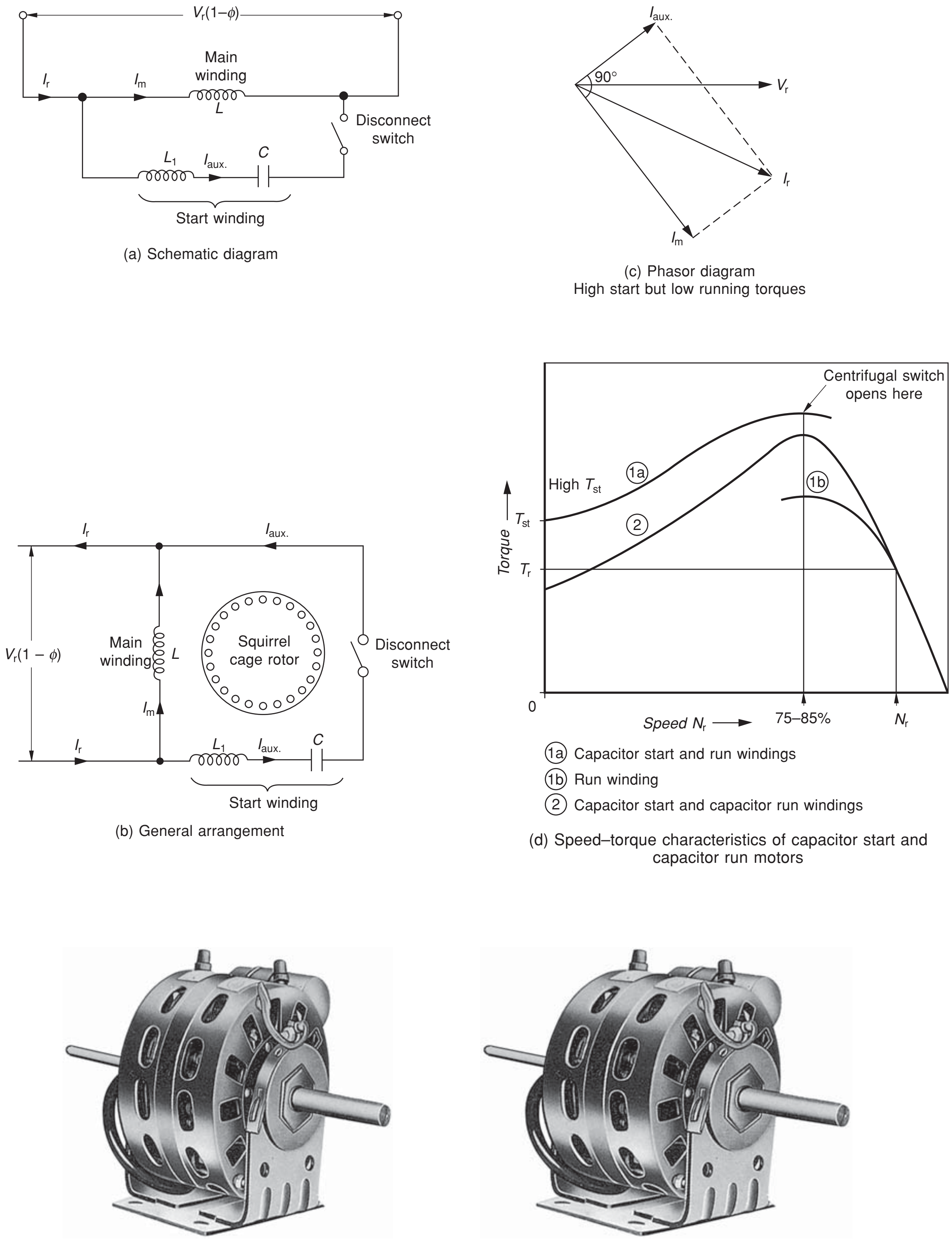
2 Capacitor start winding

If the inductive auxiliary winding is replaced by a capacitive winding by introducing a capacitor unit in series with it (Figure 1.24(a) and (b)) the phase shift will approach 90° (Figure 1.24(c)) and develop a high starting torque. When this capacitor is removed on a run, the running torque characteristics become the same as for a split-phase motor. Figure 1.24(d) illustrates a rough speed–torque characteristics of such a motor.

In both the above methods a speed-operated centrifugal switch is provided with auxiliary winding to disconnect the winding when the motor has reached about 75–85% of its rated speed. Figure 1.24(e) shows a general view.

3 Capacitor start and capacitor run windings

- When the running torque requirement is high but the starting torque requirement not as high then a capacitor of a low value, so that the capacitor current may remain less than the magnetizing components of the two windings, may be provided and the disconnecting switch removed. Figures 1.25(a_1) and



(a) Schematic diagram

(b) General arrangement

(c) Phasor diagram
High start but low running torques

(d) Speed–torque characteristics of capacitor start and capacitor run motors

(e) Capacitor start or capacitor start-capacitor run 1–ϕ motor

Figure 1.24 Capacitor start winding

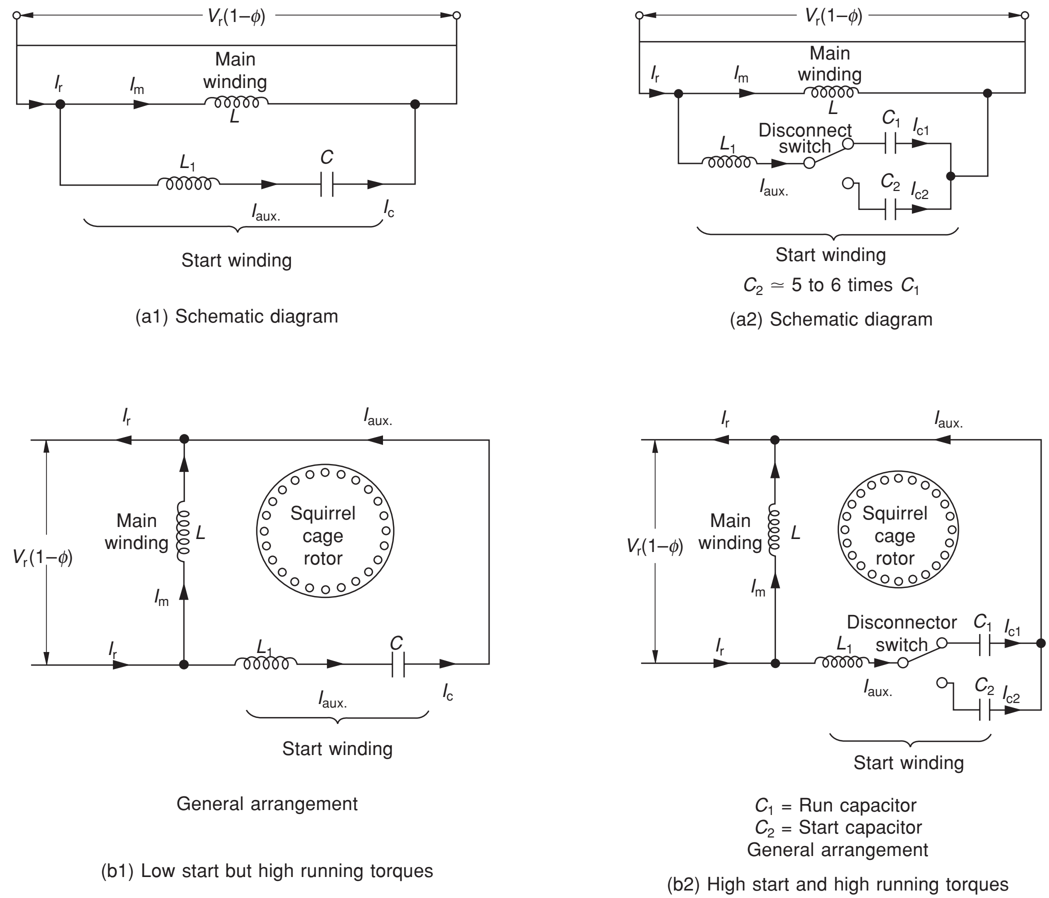


Figure 1.25 Capacitor start and capacitor run windings

(b_1) are drawn with the switch removed. The starting torque in this case may not be very high but the running torque would be higher as required. The value of capacitor C_1 would depend upon the value of L_1 and the running torque requirement.

- We can improve the starting performance of the above method by providing C in two parts, one for start C_2, of a much higher value, depending upon the requirement of T_{st}, through a disconnect switch (Figures 1.25(a_2) and (b_2)), and the other C_1, for a run of a much lower value (so that $I_{C1} < I_m$).

Notes

1 The size of capacitors C, C_1 or C_2 will depend upon the horsepower of the motor and the torque requirement of the load. For starting duty capacitors generally in the range of 30–100 μF and for a run of 2–20 μF will be adequate.

2 Whenever frequent switchings are likely, high transient voltages may develop and harm the motor windings and the capacitors. Fast discharge facilities must be provided across the capacitor terminals to damp such transients quickly. See Section 25.7, for more details on discharge devices.

4 Shaded pole motors

Applications requiring extremely small motors, in both size and horsepower, may be designed for shaded pole construction. Electronic drives, cassette players, recorders and similar applications need an extremely small size of motor, as small as 1 W ($^1/_{746}$ h.p.). Such motors can be designed in shaded pole.

The stator is of a salient pole type that protrudes outwards within the stator housing similar to a d.c. machine but is made of steel laminations. A small side end portion of each pole is split and fitted with a heavy copper ring as shown in Figure 1.26(a). This ring is called a shading coil, as it shades the normal flux distribution through that portion of the pole and substitutes for a split phase and provides the required second winding. The stator poles are wound as usual and the end terminals are brought out to receive the a.c. supply. Figure 1.26(b) illustrates a simple two-pole machine. When the voltage is applied across the stator windings, a magnetic flux is developed in the entire pole, which cuts the copper ring arranged at the tip of the pole. The main flux, thus cutting the copper coil (ring), induces a current in the ring.

The current in the copper ring opposes the main flux in that area of the pole and behaves like an artificial second winding, and develops a rotating field. Although

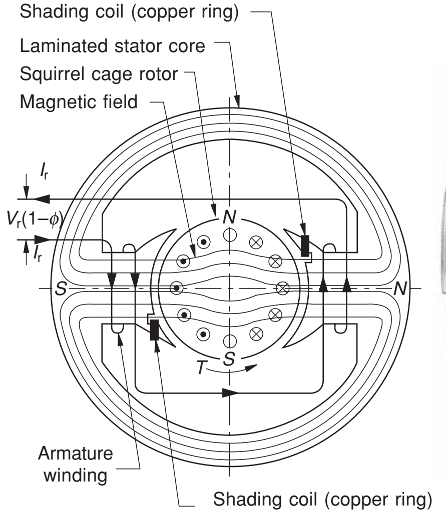


Figure 1.26(a) General arrangement of a shaded pole motor

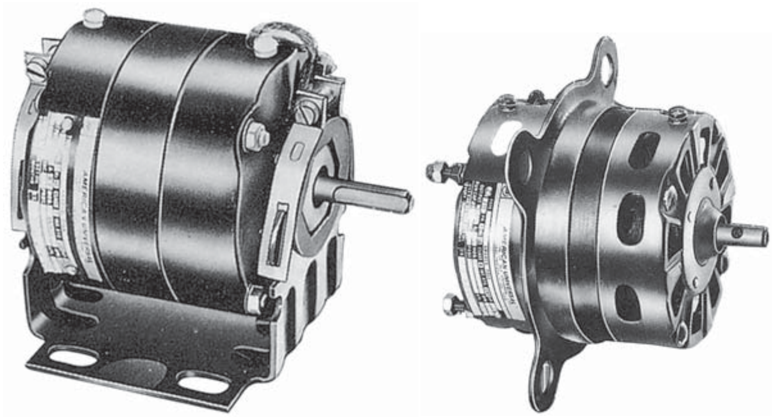


Figure 1.26(b) Shaded pole 1–ϕ motor [Courtesy: AUE (GE Motors)]

the torque so developed is extremely low, it is enough to rotate such small drives, requiring an extremely low starting torque, of the order of 40–50% of the full load torque.

Since there is only one winding and the poles are already shaded at one particular end, the direction of the rotating flux is fixed and so is the direction of rotation of the rotor. The direction of rotation cannot be altered as in the earlier cases. Since there is only one winding and no need of a speed-operated centrifugal switch, these motors require almost no operational maintenance.

5 Universal motors

These are basically series motors, somewhat similar to d.c. motors and designed conventionally with a laminated stator. They can operate on a.c. or d.c. source of supply with equally good performance. To obtain the same direction of field and armature currents the stator (field) and the rotor (armature) windings are connected in series through two brushes fitted on the rotor to connect the field with the armature as shown in Figures 1.27(a) and (b).

When the direction of the line current reverses, the field and armature currents also reverse. This feature is obtained by changing the direction of the field current by interchanging the terminals at the brushes through an external switch. These motors are relatively compact and lightweight compared to an a.c. motor. The use of such motors is, therefore, common for hand tools and home appliances and also for such applications which require a high speed (above 3200 r.p.m.) which is not possible in a conventionally wound a.c. machine. Likely applications are polishers, grinders and mixers.

When operated on a.c., the torque produced is in pulses, one pulse in each half cycle as illustrated in Figure 1.27(c). The normal characteristics for such motors are also illustrated in Figure 1.27(d). The no-load speed may be designed very high, to the order of 2000–20 000 r.p.m. but the speed on load is only around 50–80% of the no-load speed due to windage and friction losses, which constitute a higher percentage for such small to very small motors (1/10 to 1 h.p.). In view of dangerously high speeds of universal motors at no-load, they are usually built into the devices they drive, to provide an immediate counter load on switching to contain the speed. It is easy to vary speed in these motors by introducing a variable resistance in its field circuit. More accurate output speeds depending upon the type of application can be obtained through the use of gears.

There can be numerous types of single phase motors which can be specially developed for specific applications, but for brevity's sake we have discussed only the more common ones.

1.19 Energy conservation

The fast changing global ecology, green house effect, global warming, melting of polar ice and glaciers and rising levels of seas are all frightening phenomena and a matter of grave concern for those who care. Human endeavour around the world in the changed scenario is to minimize these effects as far as possible by observing certain niceties and disciplines in our daily lives, for instance by minimizing effluent discharges and toxic gases at the first instance and then treating them at source before discharging them into drains or releasing them into the atmosphere (see Appendix Chapter 13 for effluent treatment). Restrictions on the use of certain hazardous substances (RoHS) in the manufacture of electrical and electronic equipment (EEE) and their waste management (WEEE) is yet another effort to minimizing the hazardous wastes (see Section 14.1.1)

Energy consumption is yet another major source contributing to this effect by excessive electrical and

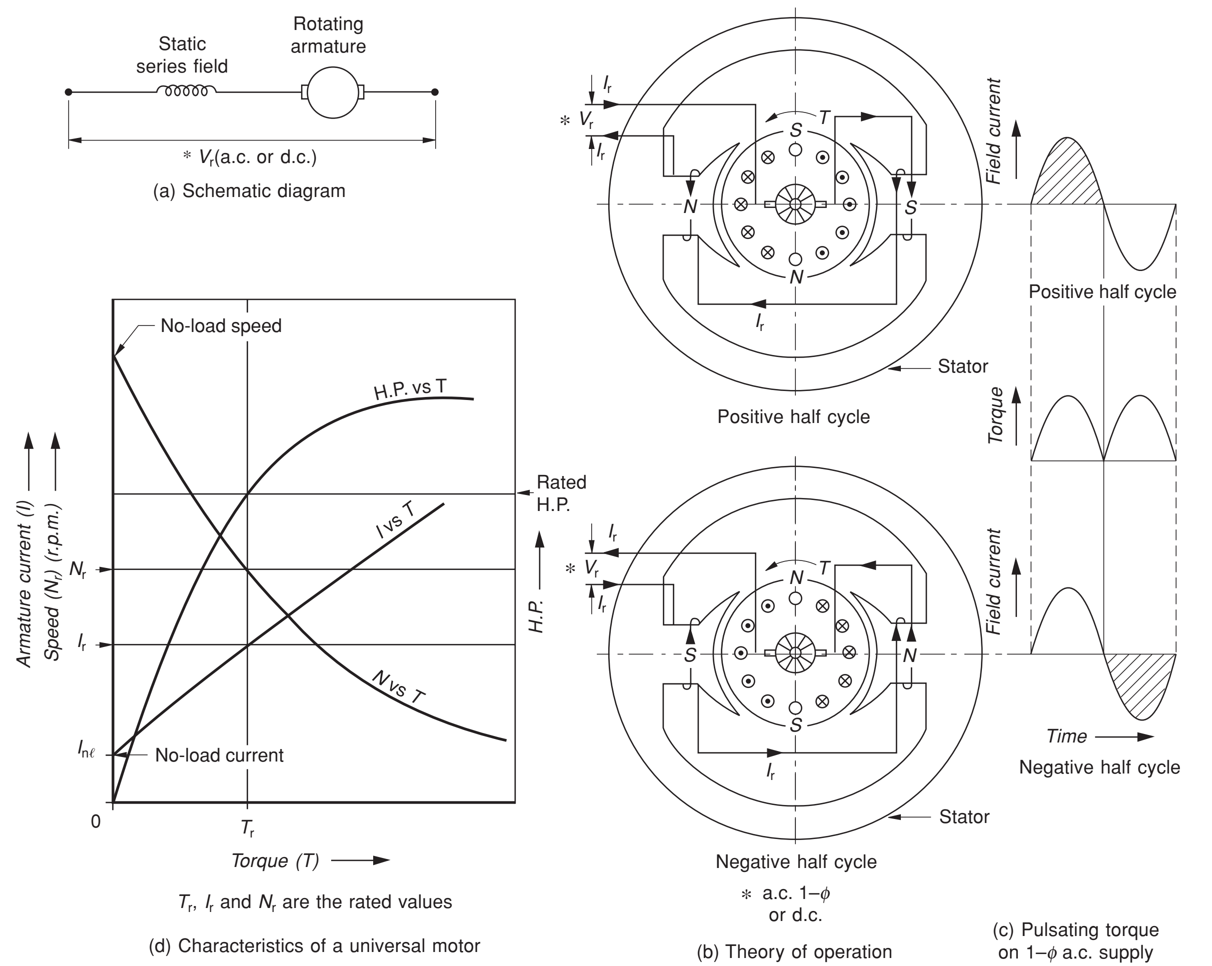


Figure 1.27 Theory of operation of a universal motor

mechanical (frictional) losses both appearing as heat. Energy conservation can help mitigate, if not stop, further erosion of environment by containing excessive heat dissipation worldwide as caused by electrical and mechanical losses besides saving scarce electrical power for industries, agriculture and human needs.

Constantly rising industrial, agricultural, commercial and domestic power demands are also making it increasingly difficult for most countries to cope up with the energy situation, irrespective of additional generating capacity being regularly created by them to the already complex power transmission and distribution networks. It is, therefore, imperative that energy is conserved in all possible manner. Improving p.f. is just one such means, as discussed in Chapter 23.

United States taking lead on energy conservation through US Department of Energy (DoE) has estimated that in 1994 electric motor driven systems alone consumed 679b kWh and that was 23% of the total energy sold during the year. It also estimated that about 11–18% of this energy could be saved if energy efficient technologies and practices were adapted. This energy saving would mean about 75–122b kWh energy, equivalent to about 26 million MT of reduced carbon emission (contributing to global warming). In terms of money it could save about $3.6b–$5.8b in 1997, while cost of implementation to such energy efficient technologies and practices could cost about $11b–$18b, representing roughly just 3 years of payback period in terms of energy saved. Most of this saving would be contributed through electric motors and hence this topic in this chapter. Today energy saving is a buzzword worldwide.

To emphasize the urgency of practising energy saving disciplines, US in 1992 promulgated an Energy Policy Act (EPACT) in association with NEMA (National Electrical Manufacturers' Association) underlying mandatory efficiency standards and testing methods for electric motors. Motors conforming to these norms are also provided DoE certification. Many other countries following suit have framed National Energy Policies and established similar agencies to promulgate and monitor implementation of energy saving measures in their countries also. Such as Copper Development Association (CDA) and European Union (EU). EU may even ban the use of standard motors by 2006.

There are a number of regulatory and energy conservation organizations throughout the world to promulgate awareness amongst the large consumers and manufacturers and to find out ways and means to address this problem more forcefully and effectively. The buzzword is 'conserve energy'. Many countries even offer incentives to their consumers for using high or extra high efficiency equipment to conserve energy.

With the rising awareness in energy conservation, efforts are being made by industries and individuals to optimize the use of their equipment by employing such equipment which are low loss and energy efficient, even replace the old ones not meeting the norms with energy efficient ones. It means:

– Using only energy efficient (EE) motors at all new installations.
– Retrofitting old installations with EE motors.
– Replacing failed motors with EE motors rather than getting them rewound.
– Using only the right size of motor: the normal trend in industries, agriculture and domestic applications has been to choose a higher size motor as a safety measure. But at most times these motors operate at much below their capacities. It is possible that the load itself was much less than was contemplated by adding a number of margins and safety factors rendering the motor unduly oversized, and operating at much below its capacity. Consequently at poor p.f. and efficiency and this is not desirable.
– Improvising electrical and mechanical designs of machines and reducing their electrical and mechanical losses.
– Improvising process lines by employing better bearings, hydraulic couplings and energy efficient belt drives etc.
– Employing static drives for cyclic and varying speed duties and discarding conventional throttle (valve) or vane controls to make flow of liquid, gas or heating more efficient.
– Employing low loss (higher size) cables (Section A16.9)
– Using low loss (higher bus-section) bus systems (Section 28.8.5)

It is estimated that minimum 25–30% of energy saving is possible by observing the energy efficient practices resulting in cost cutting to industries and agro-sector and in turn to the consumer. One can visualize the enormous economic benefits in the long term by saving on energy. In USA it has been estimated that all extra investments in carrying out these changes may be recovered in just two to three years, and thereafter it will be only recurring savings for all times to come. Energy conservation is, therefore, an essential tool to save environment, save electricity and save money, even improve the economy of a country in the long term. It is prudent to adapt to such practices immediately than be left behind in contributing towards a human cause.

Energy saving is a global buzzword today and many countries are working rigorously to optimise their energy consumption and save it to the utmost. There are agencies dedicated to pursue this cause through R&D, Energy Auditing and imparting education to the manufacturers and users. To the manufacturers to produce only energy efficient machines and systems; and, to the consumers to adapt to only such machines and systems. To propagate these initiatives many countries are even offering incentives to those practising these (such as by improving p.f. and using high efficiency motors, static drives and energy efficient belt drives) and imposing penalties on those not abiding by these directives. The purpose is to educate all and inculcate in them a sense of urgency and discipline to practise all such measures which can save energy and environment.

One may notice that any kind of energy loss results in heating. Some prominent areas in power engineering and mechanical installations where most energy is lost, emanating heat, are noted below along with remedial measures that can minimize the same

– Transformers, switchgears, capacitors and all rotating machines by making them energy efficient. Electric motors are discussed in the subsequent sections
– Power cables can be chosen a size or so higher to reduce I^2R losses
– Transmission and distribution losses through reactive power control (Chapter 24)
– Transmitting power on d.c. rather than a.c. (passing reference is provided in Section 6.7.4)
– Using GIS switchgears for HV systems (Section 19.10)
– Using compact bus systems wherever possible (Section 28.2)
– Making household appliances and white metal goods (fridges, air-conditioners, washing machines) as energy efficient with least possible mechanical and electrical losses
– All equipment, devices and components consuming electricity to be energy efficient
– Losses in mechanical systems like friction in the rotating masses or frictional losses caused by throttling, damping or vane control in the flow of air, gas, and fluid (Section 6.15) and also leakages in feeding lines connected to pumps, fans, blowers and compressors. In all such cases losses can be controlled by improving the rotating and mechanical systems such as by employing energy efficient belt drives (Section 8.5.2), plugging the leakages and reducing the frictional losses in pipes by choosing a slightly bigger inner diameter of pipes and using frictionless pipes and fittings as far as possible (like using rigid PVC pipes and fittings and where PVC is not suitable using copper, stainless steel or good quality MS pipes). For control of flow by employing energy saving devices like variable speed static drives (Section 6.9.5) or fluid coupling drives (Section 8.4) and using only right sizes of motors as far as possible.

The above are some areas where one can save energy and consequent generation of heat to a great extent. Presently we limit our discussions only to energy efficient (EE) motors.

Present trend

To promote energy conservation practices and save money in the process the usual practice of many users is to compare the cost of a product or a complete project on its running cost basis (including cost of energy consumption) rather than the basic cost of the product or the project only. One may thus calculate the repayment period for using energy efficient products and encouraged by its benefits adapt to energy conservation practices. It is suggestive that manufacturers and equipment suppliers, who deal with energy efficient products or technologies, provide repayment schedule as customary, to their users to encourage them use energy efficient products and technologies and enable them take a more pragmatic decision while making the purchases.

Energy auditing

Energy conservation is relatively a new global buzzword and has become popular in the last about ten years or so. There is greater awareness now amongst users of electric energy and this is increasing. As noted above many countries have formed energy saving regulatory bodies to spread awareness, implement and monitor energy saving programmes by all consumers, extend incentives to those pursuing energy saving programmes. The higher the saving the more the incentives. To promote energy saving even soft loans are made available by the state governments to those willing to implement energy conservation programmes and are short of funds. Those who are aware and more concerned can indeed save a lot of scarce energy for others and large savings in terms of money for themselves, besides smoother operation and longevity of their plant and machinery. It is expected that gradually we will accomplish greater successes in conserving scarce energy and improving economy of a country for the benefit of all.

To understand 'Energy Audit' and promulgate general awareness amongst engineers, architects, consultants and general consumers, industries, commercial houses, public utilities, power utility companies, 'Energy Efficiency Manuals' are available. It is advisable that all in the field may refer to the same for implementing energy efficient schemes in their areas of operations. There are individuals, consultants and 'Energy Auditing Organizations' in most countries to guide and assist consumers on effective energy saving. They suggest means to conserve energy and also help assist a user identify potential areas and opportunities where energy can be saved.

Basic objectives of energy audit

An energy audit programme is a systematic approach to making a power utilizing system more efficient and containing energy waste to the bare minimum. Accordingly, the basic objectives of an energy audit organization can be summarized as

- Study areas and plants utilizing energy
- Study the types of loads, their operating characteristics, loading conditions
- Study supply power quality and all factors responsible for plant operation
- Identify areas where energy can be saved
- Group them in various sections like,
    - Plant and machinery
    - Lighting
    - Heating, cooling, flow of material
    - Utilities
    - Any other
- Study each area for energy consumption, scope of energy saving and its likely magnitude
- Cost estimate in implementing energy saving programme for each area and likely payback period
- Prioritise areas for gradual upgradation as convenient to the consumer
- Draw action plan – like plugging leakages, improving power quality, retrofitting important energy efficient machines and accessories, improvising/upgrading mechanical and power transmission system.
- Implementing, evaluating and monitoring actual conservation through log-books and management information system (MIS).

A meticulous energy audit will suggest numerous areas where energy is being inconspicuously wasted and where it can effectively be saved. In an industry for instance, there can be thousands of such areas where one can save energy.

To identify potential areas is an onerous task. While in-house energy auditing is always the best, it is advisable to avail services of independent consultants or energy auditors to independently study the system without disturbing the routine activities. They with their meticulous study and analysis can identify areas that can be systematically planned for effective energy saving such as, plugging leakages of heating, cooling, pressure and flow of material-fluid, water, gas through their insulation system, pipes or ducts, unwanted or obscure openings in doors, windows and ventilators and all other electrical and mechanical areas discussed earlier.

Management approach

For the energy conservation programme to be successful, management awareness to energy efficient systems is first and foremost for others in the system to follow energy disciplines. It is similar to adapting to quality systems by one and all in an organization to implement ISO requirements and sustain the same in the long term (Section 11.1).

1.19.1 Energy efficient motors (EEM)

Electric motor is the basic prime-mover for all industrial drives or commercial, municipal and domestic utilities and constitutes a large share of total power utilized. At least 70% of total industrial loads are electric drives. Most of them are usually oversized, operate under-loaded and cause low to very low p.f. and efficiency and are a considerable and continuous drain on useful electrical energy. This drain is a matter of grave concern and calls for concerted and continuous efforts by the consumers to contain the same as much and as fast as possible.

Under these compulsions it called for extensive R&D to identify areas of energy saving and means of making the changes cost effective, even provide incentives and financial assistance where needed to pursue research programmes. European Commission and forum of motor manufacturers 'The European Committee of Manufacturers of Electric Machines and Power Electronics' (CEMEP) have been working to convince the manufacturers and the users to adapt to energy efficient (EE) motors. So far, only a small range of motors (1.1–90 kW, 2–4 pole and 400–415 V, 50 Hz) is covered under this agreement, applicable to all manufacturers. But the emphasis is to gradually change-over the whole range of motors that are not energy efficient to only EE motors. This may be considered up to frame sizes 315–355 only, as all motors in LV or MV above these frames as standard, are manufactured as EE motors only as discussed later. Because of special features (as noted below), costlier inputs and closer tolerances that are to be maintained during manufacture of these motors, EE motors are costlier than normal motors. But lower losses in terms of energy saving recover the initial high cost within a short period depending upon the loading and running hours of a motor. In a process industry the payback period can be as short as a few months to a year and guarantee large recurring savings in the long term by way of reduced electricity bills and longevity of the machine. These motors are classified in three groups Eff 1 (highest efficiency motors), Eff 2 improved efficiency and Eff 3 low efficiency or standard motors as per IEC 60034-1 and 2. IEC 60034-2 also mentions the efficiency levels of these categories as shown in Table 1.13 for a few ratings and speeds of motors. Gradually, motors with Eff 3 shall be withdrawn and only high efficiency motors Eff 1 shall be used say, by 2006. Similar provisions are incorporated for high efficiency motors in NEMA motors (MG-1 (Rev.1)) and IEEE-112. Table 1.14 covers almost the whole range of motors for minimum efficiency as per IEEE-112. IS 12615 and IEEMA Standard-19 have also covered the high efficiency motors and a few ratings are shown in Table 1.13. Most manufacturers by now have already changed over to EE motors up to frames 355.

Note

Presently different standards stipulate for different efficiency levels presumably because of different testing methods adapted in determining the efficiency particularly the stray load losses as noted in Section 11.4. Many manufacturers have already achieved better efficiencies than stipulated. Gradually most standards may define same methodology to determine efficiency and same levels of efficiency with a view to achieve better harmony and interchangeability of this machine in the global market.

Since these are basically low loss motors they can deliver higher outputs at the same operating conditions and in the same frame size. It also facilitates easy retrofitting at the old installations. They can also sustain higher voltage and frequency variations. These standards mention these variations in voltage as ±10% and frequency ±5% as against normal ±5% and ±2% for zone A and ±10% and +5% –3% for zone B motors respectively (Table 1.4). Most of these standards stipulate the motor name plate to display the category of motor in terms of its efficiency class.

Improvising design parameters

We have discussed in the previous sections various design and constructional features which can influence the performance of a machine. If we are able to improve upon these parameters we can reduce the losses to a great extent and optimize the machine performance. Below we discuss the areas that generate losses (for details see Section 11.4.1) and consequent heat and the means how the same can be minimized and efficiently dissipated. The approximate percentage losses of various parts of a motor as established

Table 1.13 Recommended efficiency for 3-phase motors

	IEC 60034-2			*IS 12615*		*IEC 60034-2*			*IS 12615*	
	2-pole motors Efficiency %					*4-pole motors Efficiency %*				
kW	eff_3	eff_2	eff_1	eff_2	eff_1	eff_3	eff_2	eff_1	eff_2	eff_1
1.1	<76.2	≥76.2	>82.8	76.2	82.8	<76.2	≥76.2	>83.8	76.2	83.8
1.5	<78.5	≥78.5	>84.1	78.5	84.1	<78.5	≥78.5	>85.0	78.5	85.0
2.2	<81.0	≥81.0	>85.6	81.0	85.6	<81.0	≥81.0	>86.4	81.0	86.4
3	<82.6	≥82.6	>86.7	–	–	<82.6	≥82.6	>87.4	–	–
4	<84.2	≥84.2	>87.6	–	–	<84.2	≥84.2	>88.3	–	–
5.5	<85.7	≥85.7	>88.6	85.7	88.6	<85.7	≥85.7	>89.2	85.7	89.2
7.5	<87.0	≥87.0	>89.5	87.0	89.5	<87.0	≥87.0	>90.1	87.0	90.1
11	<88.4	≥88.4	>90.5	88.4	90.5	<88.4	≥88.4	>91.0	88.4	91.0
15	<89.4	≥89.4	>91.3	89.4	91.3	<89.4	≥89.4	>91.8	89.4	91.8
18.5	<90.0	≥90.0	>91.8	90.0	91.8	<90.0	≥90.0	>92.2	90.0	92.2
22	<90.5	≥90.5	>92.2	90.5	92.2	<90.5	≥90.5	>92.6	90.5	92.6
30	<91.4	≥91.4	>92.9	91.4	92.9	<91.4	≥91.4	>93.2	91.4	93.2
37	<92.0	≥92.0	>93.3	92.0	93.3	<92.0	≥92.0	>93.6	92.0	93.6
45	<92.5	≥92.5	>93.7	92.5	93.7	<92.5	≥92.5	>93.9	92.5	93.9
55	<93.0	≥93.0	>94.0	93.0	94.0	<93.0	≥93.0	>94.2	93.0	94.2
75	<93.6	≥93.6	>94.6	93.6	94.6	<93.6	≥93.6	>94.7	93.6	94.7
90	<93.9	≥93.9	>95.0	93.9	95.0	<93.9	≥93.9	>95.0	93.9	95.0

Source: Copper Development Centre, S.E.A. Handbook

Table 1.14 Minimum efficiency base line for high efficiency motors as per IEEE 112 method B at 60 Hz

HP	*2 Poles*	*4 Poles*	*6 Poles*	*8 Poles*
7.5	88.5	89.5	89.5	85.5
10	89.5	89.5	89.5	88.5
15	90.2	91.0	90.2	88.5
20	90.2	91.0	90.2	89.5
25	91.0	92.4	91.7	89.5
30	91.0	92.4	91.7	91.0
40	91.7	93.0	93.0	91.0
50	92.4	93.0	93.0	91.7
60	93.0	93.6	93.6	91.7
75	93.0	94.1	93.6	93.0
100	93.6	94.5	94.1	93.0
125	94.5	94.5	94.1	93.6
150	94.5	95.0	95.0	93.6
200	95.0	95.0	95.0	94.1
250	95.4	95.0	95.0	94.5
300	95.4	95.4	95.4	94.5
400	95.4	95.4	95.4	94.5
500	95.4	95.8	95.4	94.5

Source: Copper Development Centre, S.E.A Handbook

Note
NEMA energy efficient motors shall possess minimum efficiencies as noted above.

by actual experiments that can be minimized are shown in Table 1.15.

Note
The losses shown in Table 1.15 are approximate and generally up to frames 355. In larger frames they may vary with motor synchronous speed, ventilating fans efficiency, quality of laminations and electrical and mechanical design parameters etc.

I. **Electrical design considerations**

(i) *Friction and windage loss:*
It is because of friction in bearings and air flow of cooling air as noted in Section 7.9. The measures noted in this section to reduce noise level shall reduce friction and windage losses also to a great extent and provide a sound electrical and mechanical design.

(ii) *Stator copper loss (I^2R loss)*
It can be reduced by reducing resistance of the motor windings. The practice to achieve this is by increasing the cross-sectional area of the conductor ($R \propto 1/A$) and accommodating the larger volume of windings by increasing the slot area (by deepening and widening of the slots) and using a more compact insulating material such as F/H.

(iii) *Rotor I^2R loss*
Rotor reduced resistance also results in a lower slip (Equation 1.3b) and lesser slip losses and greatly improves the efficiency of the machine. A reduced rotor resistance however, will also reduce the starting torque T_{st} but in most cases it may be immaterial as it will still meet NEMA torque requirements and remain within acceptable range.

(iv) *Optimizing (narrowing) air gap* between the stator and the rotor to reduce magnetizing current, slip losses and improving pf.

(v) *Core losses* eddy current and hysteresis losses (Equations (1.12) and (1.13))
- By using thinner and better grade of high silicon steel laminations as discussed in Section 1.9.
- Inter lamination insulation
  As discussed in Section 9.3, it is advisable to insulate the laminations on both sides and stack them in one direction only to avoid contact between the punching burrs and ensure adequate insulation between each laminate. Nevertheless it may not exactly be true in actual practice, as wherever laminations' edges would make contacts with the adjacent laminations, it will increase their effective thickness t and add to eddy current loss. It is also possible that the rotor conductors may make conducting paths between the adjacent laminations and enhance iron loss. Since this conductivity (in the rotor body) may not be uniform it may also cause current pulsations and influence the motor performance. Special insulation and treatment to edges is, therefore, essential to eliminate such rise in losses and pulsations in current.
- Use of high permeable steel
  High permeability (μ) steel can reduce the mmf (amp.turns) requirement for the same amount of flux (ϕ) and reduce magnetization current, $I_{n\ell}$ (Figures 1.15 and 1.16) and reduce the no-load losses.

(vi) *Stray losses*
As the reactance of the machine varies with speed, a variable speed motor becomes a non-linear load and generates harmonics causing circulating currents. This effect can be minimized by choosing a proper angle of skew (Section 2.3.2) which can reduce harmonics and the circulating currents to a great extent and hence the slot losses.

Table 1.15 Losses in different parts of a motor

	Motor parts	*Approx. losses %*
1	Stator I^2R loss	37
2	Rotor I^2R loss	18
3	Iron loss	20
4	Friction and windage loss	09
5	Stray loss caused by harmonics and circulating currents	16
	Total	100

II. **Constructional and design considerations**
- An efficient heat dissipation would mean better cooling and more capacity of the machine. This also can make the machine energy efficient. Motor housing with thinner wall and thinner and more number of fins on its periphery, extending end to end can also contribute a lot in efficient heat dissipation.
- Similarly, using better quality inputs, maintaining close tolerances and monitoring strict quality control

checks can also improve the efficiency and performance of the machine.

III. **Some more ways to save on losses**

As noted above electric motors constitute a large share of total power consumption worldwide. By one estimate even 1% further improvement in motor efficiency can save about 20b kWh/year electrical energy or $1.4b in terms of money for USA (source CDA*).

Through concerted R&D to discover additional means to further save on motor losses it is found by actual laboratory motor efficiency tests (based on IEEE-112 method B and shown in Table 1.16) that if the rotor is also made of copper bars and end rings also of copper than conventional aluminium die-cast (up to frames 315–355) then the motor efficiency can be further improved by 1.2–1.6% (see Hasuike under 'Further Reading'). The universal practice so far has been to use aluminium die cast rotors that are easy to produce, cost effective and above all capable to provide excellent rotor characteristics as desired.

There are four types of rotors in practice. To understand them briefly,

1. *Aluminium die-cast* – It is used universally for all small and medium range motors say up to frame size 355. The rotor laminations (punching) are stacked on a stacking mandrel in end connector mould, aluminium is injected (die cast) into the rotor slots and rotor shaft is inserted into the hot rotor core. The whole rotor assembly is then turned on a lathe to make it balanced and concentric to the shaft. Technological advances have made it possible to die cast rotors up to 750 mm ϕ and 1250 mm core length which is adequate for motors up to 10 000 HP. But because of tooling cost at higher sizes this practice is adapted only up to 1500 HP or so. Beyond this the rotor is fabricated, as noted below.
2. *Aluminium fabricated rotor* – After stacking the rotor laminates (punchings) rotor shaft is inserted into the hot core and aluminium bars are inserted into the slots and machined at the end. The short-circuit rings are welded to the bars. The rotor is turned as above to make it concentric to the shaft. All motors using aluminium rotors above 1500HP adopt to this practice. But it is a usual practice to use copper rotors in such high ratings, as cost of copper rotors in this range is not much higher than aluminium fabrication.
3. *Copper or copper alloy die-cast rotors* – It has not been possible as yet to adapt to this practice because of many constraints such as,
   – Very high melting point of copper (1083°C). It is difficult to fabricate mould and plates for such a high temperature and consequently the mould life is also short
   – For die and plates molybdenum based or ceramic material is required and that is a costly affair
   – It also calls for very high temperature and pressure for moulding. The technology is in nascent state of development.

   All this meant a high cost of rotor. This however, narrows down with the rise in size. Nevertheless efforts are on to produce low-cost copper die-cast rotors. Until then aluminium die-cast rotors shall continue which pose no limitation or deficiency in achieving the desired performance. Their resistance can also be reduced by increasing the rotor conductor size as for the stator to achieve a rotor resistance as desired. When copper rotor becomes essential it can also be fabricated like the large size rotors noted below. Fabricated copper rotors in small and medium ranges are not practised because of their very high cost (>25% for 200HP which rises in lower ratings).
4. *Fabricated copper rotors* – Same procedure is adopted as for aluminium fabricated rotors but instead of welding, now short-circuit rings are brazed to the rotor bars. Constructing copper rotors in this fashion is the oldest practice but it is costly and time consuming for smaller ratings. Fabricated rotors are easy to repair, in die-cast rotors access to the failed area within the slot is not possible.

Table 1.16 Saving in rotor losses using copper bars and end rings compared to conventional aluminium die-cast rotors (based on IEEE-112 method B for motor efficiency tests)

S. No	*Parameters*	*Aluminium die-cast rotor*	*Copper rotor*	*Remarks*
1	Stator Copper and Iron losses	100%	100%	There being no change in stator windings and laminates.
2	Rotor I^2R loss	100%	86%	Saving 14%*
3	Stray losses	100%	77%	Saving 23%*
Other parameters				
4	Operating temperature	100%	– 4.5°C	Motor running cooler will mean more reserve capacity or better life expectancy (≃45% more) similar to thermal ageing at higher operating temperatures (Section 9.2)
5	Starting torque	100%	64%	– 36%. But in most cases it will still meet NEMA torque requirements
6	Break-down torque	100%	83%	– 17%. This may also not matter

Source: CDA, USA
* Overall reduction can be up to 15–20%

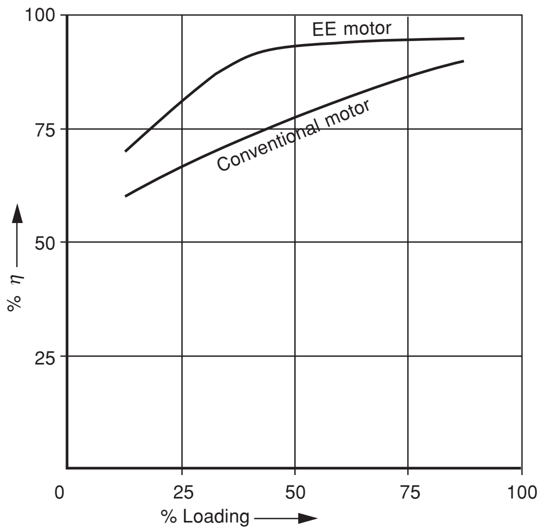
*CDA Copper Development Association, USA.

Corollary
Emphasis for EE motors is therefore largely for small and medium range motors only say up to 370 kW (up to 355 frame size)(as per IEEE-112). In larger ranges energy efficient measures are usually practised as they are usually tailored to specific driven equipment.

Variation in efficiency with loading in EE motors

An EE motor designed with above parameters has an efficiency that remains almost constant from full loading down to 50% loading or so. This feature saves its droop when the motor operates under-loaded unlike a conventional motor that has a sharply drooping efficiency at lower loads (Table 1.9). Figure 1.28 shows this feature.

Corollary
Power factor and efficiency are two different parameters. Improving p.f. with means of power capacitors is no substitute to high efficiency. One cannot achieve the defined energy saving in this way. For energy saving use of high efficiency EE motors is imperative.



Note: Losses are nearly constant above 50% loading

Figure 1.28 Variation of η with loading

Matching of EE motors with existing installations

- For retrofitting of EE motors for variable speed drives at old installations – see Section 6.20.
- For co-ordination of EE motors and drives for retrofitting at hazardous locations – see Section 7.17.1.

Calculation for energy saving

If the rating of a motor = kW
Efficiency of standard motor = η_1%
Efficiency of an EE motor = η_2%
Operating hours/day = x
Working days/year = y
Local tariff per kWh = z

Then power consumed by standard motor $= \frac{\text{kW}}{\eta_1} \times 100$

and power consumed by EE motor $= \frac{\text{kW}}{\eta_2} \times 100$

$\therefore$ energy saving per year

$$= \text{kW} \cdot 100 \left(\frac{1}{\eta_1} - \frac{1}{\eta_2}\right) x \cdot y$$

and in local currency $= \text{kW} \cdot 100 \left(\frac{1}{\eta_1} - \frac{1}{\eta_2}\right) x \cdot y \cdot z$ (1.14)

For example if $\eta_1 = 86\%$
$\eta_2 = 91\%$
$x = 8$ hrs/day
and $y = 300$ days/year

Then energy saving per kW rating of motor per year

$$= 1 \times 100 \left(\frac{1}{86} - \frac{1}{91}\right) \times 8 \times 300$$

$$= \frac{100 \times 5}{86 \times 91} \times 8 \times 300$$

$$= 1533.3 \text{ kWh per kW}$$

this multiplied by actual kW rating of the motor and local rate of tariff will show the saving in terms of money. One can easily calculate the payback period if the excess cost of the EEM is known for a new installation, or the cost of retrofitting of a whole installation or cost of replacement of a damaged standard motor with an EE motor is known. Usually the payback period may not exceed about a year if the machine operates around 2000–2400 hrs a year.

Relevant Standards

IEC	*Title*	*IS*	*BS*	*ISO*
60034-1/2004	Rotating electrical machines. Rating and performance.	4722/2001, 325/2002	BS EN 60034-1/1998	–
60034-2/1996	Method for determining losses and efficiency of rotating electrical machines.	4029/1991	BS EN 60034-2/1999	–
60034-5/2001	Rotating electrical machines. Classification of degrees of protection provided by enclosures for rotating machinery.	4691/1999	BS EN 60034-5/2001	–
60034-6/1991	Designation of methods of cooling of rotating electrical machines (IC code).	6362/2002	BS EN 60034-6/1994	–

IEC	Title	IS	BS	ISO
60034-7/2000	Rotating electrical machines. Classification of types of constructions and mounting arrangements (IM code).	2253/2002	BS EN 60034-7/1993	–
60034-12/2002	Values of performance characteristics for induction motors.	8789/2002	BS EN 60034-12/2002	–
60038/1994	IEC standard voltages.	–	–	–
60059/1999	Standard current ratings (Based on Renald Series R-10 of ISO-3)	1076-1 to 3/2000	BS 2045/1982	3/1973, 17/1973, 497/1973
60072-1/1991	Dimensions and output series for rotating electrical machines. Frame number 56 to 400 and Flange number 55 to 1080.	1231/1997	BS 4999-141/2004	–
60072-2/1990	Dimensions and output series for rotating electrical machines. Frame number 355 to 1000 and flange number 1180 to 2360.	1231/1997, 2223/2002	BS 4999-103/2004	–
60072-3/1994	Dimensions and output series for rotating electrical machines. Small built-in motos – Flange numbers BF 10 to BF 50.	996/2002	BS 5000-11/1989	–
60404-8-4/1998	Magnetic materials – specifications for individual materials – Cold-rolled non-oriented electrical steel sheets and strips.	–	–	–
60529/2001	Specification for degrees of protection provided by enclosures (IP Code).	4691/1999	BS EN 60529/1993	–
–	Induction motors energy efficient, three phase Squirrel case – specification	12615/1999	–	–
–	Dimensions for vertical shaft motors for pumps	2254/2002	–	–
–	Dimensions of motors and output series for rotating electrical machines.	8223/1999	BS 2048-1/1989	–

Related US Standards ANSI/NEMA and IEEE

ANSI-C84.1/1995	Electric power systems and equipment – voltage ratings (60 Hz).
ANSI/IEEE-112/1996	Test procedures for poly-phase induction motors and generators.
IEEMA Standard 19/2000	For energy efficient induction motors.
NEMA/MG-1/2003	Motors and generators ratings, construction, testing and performance.
NEMA/MG-2/2001	Safety standards (enclosures) for construction and guide for selection, installation and use of rotating machines.
NEMA/MG-10/2001	Energy management guide for selection and use of three-phase motors.
NEMA/MG-11/2001	Energy management guide for selection and use of single phase motors.
NEMA/MG-13/1990	Frame assignments for a.c. integral horsepower induction motors.

Notes

1 In the table of relevant Standards while the latest editions of the Standards are provided, it is possible that revised editions have become available or some of them are even withdrawn. With the advances in technology and/or its application, the upgrading of Standards is a continuous process by different Standards organizations. It is therefore advisable that for more authentic references, one may consult the relevant organizations for the latest version of a Standard.

2 Some of the BS or IS Standards mentioned against IEC may not be identical.

3 The year noted against each Standard may also refer to the year it was last reaffirmed and not necessarily the year of publication.

List of formulae used

Theory of operation

$$T \propto \phi_m \cdot I_{rr} \tag{1.1}$$

$$\phi = \phi_m \sin \omega t$$

T = torque developed
ϕ_m = maximum field strength
I_{rr} = rotor current

$$P = \frac{T \cdot N}{974} \tag{1.2}$$

P = rotor power in kW
T = torque in mkg
N = speed in r.p.m

$$T \propto \frac{S \cdot {}_{ss}e_2^2 \cdot R_2}{R_2^2 + S^2 \cdot {}_{ss}X_2^2} \tag{1.3}$$

S = slip

R_2 = rotor resistance per phase
${}_{ss}X_2$ = standstill rotor reactance per phase and
${}_{ss}e_2$ = standstill rotor induced e.m.f. per phase.

$$\text{or } T_{st} \propto \frac{{}_{ss}e_2^2 \cdot R_2}{S \cdot {}_{ss}X_2^2} \qquad (1.3a)$$

T_{st} = starting torque and

$$\text{or } T_r \propto \frac{S \cdot {}_{ss}e_2^2}{R_2} \qquad (1.3b)$$

T_r = rated torque

$$e_2 \propto -z_r \cdot \frac{d\phi}{dt} \qquad (1.4)$$

z_r = number of turns in the rotor circuit per phase and $d\phi/dt$ = rate of cutting of rotor flux

$$e_2 = 4.44\ Kw \cdot \phi_m \cdot z_r \cdot f_r \qquad (1.5)$$

Kw = winding factor
f_r = rotor frequency = $S \cdot f$

$$S = \frac{N_s - N_r}{N_s} \cdot 100\% \qquad (1.6)$$

N_s = synchronous speed
N_r = rated speed

$$N_s = \frac{120 \cdot f}{p} \text{ r.p.m.} \qquad (1.6a)$$

f = frequency of the supply system in Hz
p = number of poles in the stator winding

Rotor current

$$I_{rr} = \frac{S \cdot {}_{ss}e_2}{\sqrt{R_2^2 + S^2 \cdot {}_{ss}X_2^2}} \qquad (1.7)$$

$$\text{for } S \text{ high, } I_{rr} \simeq \frac{{}_{ss}e_2}{{}_{ss}X_2} \qquad (1.7a)$$

Motor output and torque

$$P_r = \frac{T_r \cdot N_r}{974} \text{ kW} \qquad (1.8)$$

P_r = rotor power

$$P_s = \frac{T_r \cdot N_s}{974} \text{ kW} \qquad (1.8a)$$

P_s = synchronous power

$$P_s - P_r = S \cdot P_s \qquad (1.9)$$

$P_s - P_r$ = slip loss

$$T_r = \frac{P_r \cdot 974}{N_r} \text{ mkg} \qquad (1.10)$$

System harmonics

$$\text{HVF} = \sqrt{\Sigma \frac{v_h^2}{n}} \qquad (1.11)$$

HVF = harmonic voltage factor
v_h = per unit harmonic voltages
n = harmonic order not divisible by 3

(a) Eddy current loss

$$L_e \propto \frac{t_1^2 \cdot f^2 \cdot B^2}{\rho} \qquad (1.12)$$

t_1 = thickness of steel laminations
B = flux density
ρ = resistivity of the steel laminations

(b) Hysteresis loss

$$L_h \propto f \cdot (B_m)^{1.5 \text{ to } 2} \qquad (1.13)$$

Energy saving in local currency,

$$= \text{kW} \cdot 100 \left(\frac{1}{\eta_1} - \frac{1}{\eta_2} \right) x \cdot y \cdot z \qquad (1.14)$$

kW = rating of the motor
η_1 = % efficiency of the standard motor
η_2 = % efficiency of an EE motor
x = operating hours/day
y = working days/year
z = local tariff per kWh

Further Reading

1 Golding, E.W., *Electrical Measurements and Measuring Instruments,* The English Language Book Society and Sir Isaac Pitman & Sons Ltd, London.
2 Humphries, J.T., *Motor and Controls for 1–ϕ motors.* Merrill, Columbus, OH.
3 Puchstein, A.F., Lloyd, T.C. and Conard, A.G., *Alternating Current Machines,* Asia Publishing House, Bombay (1959).
4 Say, M.G., *The Performance and Design of Alternating Current Machines,* Pitman & Sons Ltd, London (1958).
5 Smeaton, R.W., *Motor Application and Maintenance Hand Book,* McGraw-Hill, New York (1969).
6 Cowie, John G., *Copper Motor Rotors – Application of High Temperature Mould Materials to Die-cast the Copper Motor Rotor,* Copper Development Association, New York.
7 *Copper Motor Rotor,* **I**, Issue I, Copper Development Association, New York, October (2001).
8 Finley, William R., Hodowanec, Mark. M., Siemens Energy & Automation Inc., Norwood, OH 45212, *Selection of Copper vs. Aluminium Rotors for Induction Motors,* IEEE paper no. PCIC-2000–19.
9 Hasuike, K., *Efficiency Improvement Studies of Low Voltage Three Phase Squirrel Cage Induction Motors for General Purpose,* IEEE Trans. Power Apparatus and Systems, 102, 12, pp. 3803–3809 (1983).