2

Motor torque, load torque and selection of motors

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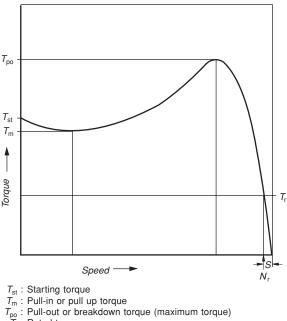
2.1 Motor speed-torque curve

Refer to Figure 2.1 where

- $T_{\rm st}$ = starting torque or breakaway torque.
- $T_{\rm m}$ = minimum, pull-in or pull-up torque.
- $T_{\rm po}$ = pull-out, breakdown or maximum torque, obtainable over the entire speed range. In a good design this should occur as close to the rated slip as possible to ensure that the motor runs safely, even during momentary overloads, load fluctuations exceeding the load torque, or abrupt voltage fluctuations, without harmful slip losses (Equation (1.9)). In some specially designed rotors, however, to achieve a high starting torque sometimes the pull-out torque $T_{\rm po}$ may not be available on the speed-torque curve. It is possible that in such cases the $T_{\rm st}$ may be the highest torque developed by the motor in the entire speed range (Figure 2.2).
- $T_{\rm r}$ = rated or the full-load torque and should occur as near to the synchronous speed as possible to reduce slip losses.
- S = rated slip at which occur the rated torque and current.

2.2 NEMA rotor designs

As a further step towards standardization and to achieve more harmony in motor sizes and designs, for better interchangeability in the motors produced by different manufacturers, in the same country or by other countries,



 T_r : Rated torque

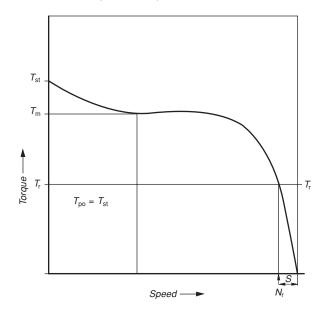


Figure 2.2 T_{st} too high to have T_{po} on the speed-torque curve

NEMA,* in its publication *MG-1 for Induction Motors*, has prescribed four rotor designs, A, B, C, and D, covering almost all sizes of LV motors, to possess a prescribed minimum T_{st} , T_{po} and pull-up torques. These torques are generally as drawn in Figure 2.3 to meet all normal industrial, agricultural or domestic needs. (Refer to the said publication or IEC 60034-12 for values of these torques. IEC 60034-12 has also provided similar stipulations.)

However, motor manufacturers may adopt more flexible designs with more reserve capacity and better speedtorque characteristics to suit the requirements of a particular sector. These are particularly for installations where the distribution system may have wider voltage fluctuations or the load itself may have varying load demands. It is possible that the same motor may have to drive more than one type of loads at different times. An agricultural pump motor may be one such application where it may also have to drive a thrasher or a winnower at different times. A motor with higher flexibility would be more desirable for such applications.

Manufacturers, depending upon market needs, may adopt all or a few such designs or even have their own designs, still conforming to such stipulations. Special applications may, however, call for a custom-built motor as noted later. As a standard practice all MV motors are custom-built for each application and no rotor designs are prescribed for these.

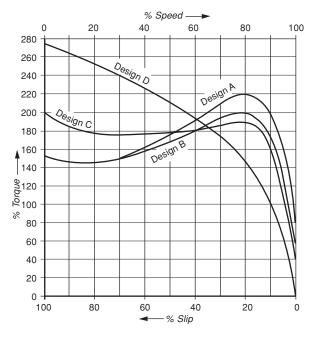


Figure 2.3 Speed-torque characteristics of motors as per NEMA standard

2.3 Special designs of rotors

2.3.1 Double squirrel cage motors

If the torque requirement of a load is high, an ordinary squirrel cage motor, even on a DOL* switching, may not be suitable to meet the stringent starting requirements. If, however, the resistance of the rotor circuit is increased the starting torque can be improved as discussed in Section 1.2 (Equation (1.3)). But high rotor resistance will mean high running slip, causing greater rotor losses and heat in the rotor circuit. The solution to this problem is found in a double squirrel cage motor. In such motors the rotor has two cages, one closer to the periphery of the rotor and the other deeper and nearer to the core.

The one closer to the periphery has a high resistance and the one nearer to the core a low one. To accomplish a high rotor resistance, high-resistivity materials such as brass is generally used. The inner cage has a high leakage reactance due to its depth, while the outer one has a high resistance and a low reactance like an ordinary squirrel cage rotor.

During start-up the inner cage has a very high impedance and thus, the larger portion of the current passes through the outer cage only. Because of high resistance and high I^2R loss in the rotor circuit, it develops a high starting torque and accomplishes an analogue to a slip-ring motor. When the rotor reaches the rated speed, the reactances of both the cages are almost negligible because of low slip and the rotor current is carried into two parallel paths made of these two cages, having a low effective resistance, being in parallel. In such designs, therefore, the speedtorque curve can be achieved to take any desired shape by suitably choosing the resistances of the two cages, the width of the slot opening and the depth of the inner cage. The equivalent circuit diagram of a motor with a single and a double cage rotor is illustrated in Figure 2.4(a) and (b) respectively. To draw the speed-torque curve for such a motor theoretically, consider the two cages developing two different torques separately. The effective torque will be the summation of these two, as shown in Figure 2.5.

Notes

- The inner and outer cages are separated by a narrow slit to facilitate linking of the main flux with the inner bars which are quite deep.
- 2 MV motors are also manufactured with double cage rotors. They are designed especially to match a particular load requirement when the load characteristics are known, or as in NEMA class C, or as the manufacturer's own practice, when the starting torque requirement exceeds 150% of the full-load torque (FLT). The likely applications for a high starting torque may be induced-draught fans, blowers, coal crushers, mill motors and coal conveyor motors.
- 3 Generally, depending upon the type of load, different manufacturers may adopt to different design practices, such as high T_{st} and low thermal withstand time or moderate T_{st} and high thermal withstand time.

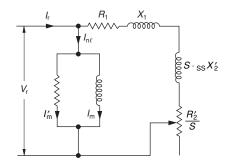


Figure 2.4(a) Equivalent circuit diagram of a single squirrel cage motor

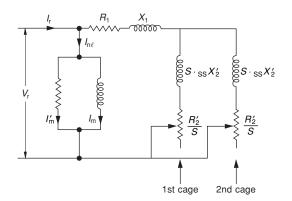


Figure 2.4(b) Equivalent circuit diagram of a double squirrel cage motor

^{*} DOL - Direct On-Line.

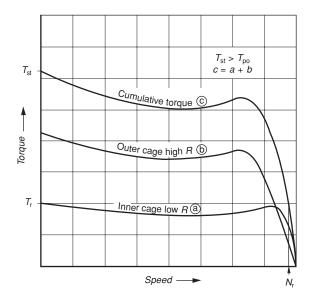


Figure 2.5 Speed-torque characteristics of a double squirrel cage motor

Performance

In such motors the pull-out torque is normally less than the starting torque. This is because the pull-out torques by the two cages occur at different speeds. Such motors would possess a low power factor and efficiency compared to an ordinary squirrel cage motor, because of the high leakage reactance of inner cage and comparatively higher I^2R losses. Such motors would have a slightly higher slip than an ordinary squirrel cage motor due to higher rotor resistance.

Limitations

During start-up since only the outer cage is in the circuit with a very high current, the motor is heated up quickly by every start and may not be suitable for frequent starts and reversals.

There are several other designs available to achieve a considerably high staring torque and yet overcome the above limitation. It is possible by employing a deep cage, tapered cage or special types of rotor materials such as brass and selenium to increase the starting resistance of the rotor circuit, and hence the starting torque. These methods are discussed briefly below.

2.3.2 Other designs of rotor cage

Use of skin effect

The basic concept used in the design and selection of other types of rotors to provide better starting characteristics is the high rotor resistance during startup. Other than the double cage rotors, this can also be achieved by making deep or taper rotor bars as shown in Figure 2.6. (See also Figure 2.7.) At different frequencies, the rotor has different effective resistances, due to a change

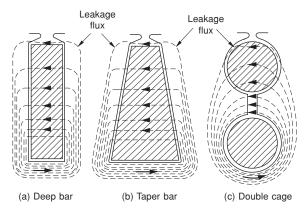


Figure 2.6 Different types of rotor slots, making use of skin effect

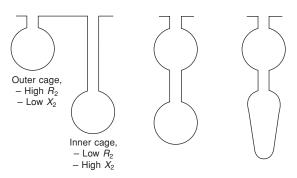


Figure 2.7 Other designs of a few double cage slots

in inductive reactance $(S \cdot ssX_2)$, which in an induction motor varies with rotor frequency (i.e. speed). This effect of change of resistance is termed the 'skin effect'. For more details, see Section 28.7. To make use of this effect, the slot, irrespective of its configuration, may be made deep to create higher eddy currents and correspondingly higher eddy current losses, to add to the effective resistance of the rotor during start-up and to diminish this with speed. (See also Section 2.4.) In this way the depth, in deep bars, and depth and taper, in tapered bars, can be varied to achieve the desired performance. For the same torque characteristics either of these types of cages can be employed which, for one characteristic, will require the same area of cross-section but the depth will vary depending upon the type. The deep bars will be deeper than a taper bar. Moreover, the taper slot will have a better grip for rotor conductors during a run than a deep parallel bar and also better cooling properties.

Angle of skew in squirrel cage rotors

The movement of rotor teeth around the stator produces a clogging effect, resulting into vibrations and noise. To reduce this effect, the common practice is not to provide the rotor slots parallel to the shaft axis but at an angle. This practice is known as 'rotor bar skew'. A proper skewing can also improve the starting torque and reduce the starting current, in addition to the effects of space harmonics and slot losses. The angle of twist (skew) is a matter of experience, by results obtained over the years. The most common skew angles, for various combinations of stator and rotor slots in practice, are given in Table 2.1.

Table 2.1	Typical	analos	of	ckow	for	anco	rotore
Table 2.1	Ivpical	anules	UI.	Skew	101	caue	TOLOIS

Number of poles	Number of stator slots	Number of rotor slots	Skew angle (degrees)
	(18	14	26
2	24 36	16 28	20 16
4	<u>24</u>	18	20
+	36	28	13 to 14
6	36	33	11 to 14

$I_{st3} \xrightarrow{F_{or}} T_{st2}$ $I_{st1} \xrightarrow{F_{or}} T_{st2} \xrightarrow{F_{or}} T_{st2} \xrightarrow{F_{or}} T_{st2} \xrightarrow{F_{or}} T_{st3} \xrightarrow{F_{or}} T_{st3} \xrightarrow{F_{or}} T_{st2} \xrightarrow{F_{or}} T_{st3} \xrightarrow{F_{or}} T_{st2} \xrightarrow{F_{or}} T_{st3} \xrightarrow{F_{or}}$

2.4 Effect of starting current on torque

Ignoring the friction and core losses, the torque developed in synchronous watts,

 $T_{\rm r} = 3 \cdot I_{\rm rr}^2 \cdot R_2 \cdot \frac{1-S}{S}$ or $\simeq 3 \cdot \frac{I_{\rm rr}^2 \cdot R_2}{S}$ $I_{\rm rr}^2 \cdot R$

i.e.
$$T_{\rm r} \propto \frac{I_{\rm rr}^2 \cdot R_2}{S}$$
 (2.1)

Since the stator current is a function of the rotor current, the motor torque is proportional to the square of the stator current. Generalizing,

$$\frac{T_{\rm st}}{T_{\rm r}} = \left(\frac{I_{\rm st}}{I_{\rm r}}\right)^2 \cdot S \text{ (slip at start = 1)}$$
(2.2)

$$\frac{T_{\text{st1}}}{T_{\text{st2}}} = \left(\frac{I_{\text{st1}}}{I_{\text{st2}}}\right)^2 \text{ (for the same rotor resistance } R_2\text{)}$$
(2.3)

or
$$\frac{T_{\text{st1}}}{T_{\text{st2}}} = \left(\frac{I_{\text{st1}}}{I_{\text{st2}}}\right)^2 \cdot \frac{R_2}{R_2'}$$
 (for different rotor resistances)
(2.4)

Analyzing Equation (2.2), the higher the starting torque, the higher will be the starting current for the same motor parameters (Figure 2.8). An attempt to keep the starting current low and yet achieve a higher starting torque may be feasible, but only up to a certain extent, by suitably redesigning the rotor with a higher resistance (Equation (2.1)). However, the results of such an attempt may adversely affect the other performance of the motor. For example, the T_{po} will be reduced due to a higher rotor resistance and may occur at a higher slip, even if the full-load slip is the same. The increased slot leakage, due to the skin effect, will also diminish the full-load power factor. (See the circle diagram, Figure 1.16,

Figure 2.8 Starting (locked rotor) currents corresponding to different starting torques

corroborating this statement.) The T_{st} and I_{st} are, therefore, a matter of compromise to achieve a good T_{po} , a better power factor and a lower slip. Figure 2.9 shows for different starting torques the corresponding pull-out torques and their occurrence of slip, maintaining the same full-load slip.

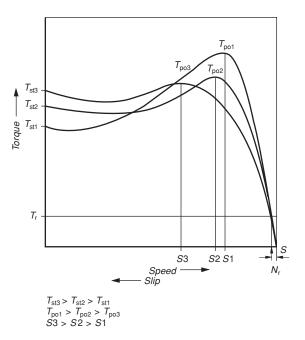


Figure 2.9 Effect of starting torque on $T_{\rm no}$ and slip

2.4.1 NEMA recommendations on starting currents

With a view to achieve yet more standardization in motor design, NEMA Standard MG-1 has also recommended the maximum locked rotor current of single-speed three-phase motors for the various rotor designs A, B, C, and D, for various recommended torque values. These have been derived for a 415 V a.c. system and are shown in Table 2.2.

 Table 2.2
 Recommended maximum locked rotor currents for various rotor designs

HP	Approx. maximum locked rotor current	Rotor design
1	18	B.D.
1.5	25	B.D.
2	31	B.D.
2 3 5	39	B.C.D.
5	56	B.C.D.
7.5	77	B.C.D.
10	98	B.C.D.
15	141	B.C.D.
20	178	B.C.D.
25	222	B.C.D.
30	265	B.C.D.
40	354	B.C.D.
50	441	B.C.D.
60	529	B.C.D.
75	661	B.C.D.
100	884	B.C.D.
125	1105	B.C.D.
150	1319	B.C.D.
200	1764	B.C.

Note

For motors beyond 200 h.p., NEMA has not covered these data. It is, however, recommended that larger motors may be designed to have even lower locked rotor currents than the above to reduce the starting transient effects on the distribution system as well as on the motor windings.

Table 2.3 Types of loads and their characteristics

2.5 Load torque or opposing torque

For smaller loads, say up to 20/30 kW, it may not be essential to pre-check the load curve with that of the motor. But one should ensure that working conditions or the load demand are not so stringent that they may cause a lock-up of rotor during pick-up due to a very low applied voltage or accelerating torque, or a prolonged starting time as a consequence or due to a very large inertia of rotating masses etc. For critical applications and for larger motors it is essential to check the speed-torque requirement of the load with that of the motor. Loads can generally be classified into four groups. Table 2.3 indicates the more common of these and their normal torque requirements, during start-up and variation with speed. The corresponding curves are also drawn in Figures 2.10-2.13. To ascertain the output requirement of a motor, for different applications a few useful formulae are given in Appendix I at the end of Part I of this book.

2.6 Selection of motors

The recommended practice would require that at each point on the motor speed-torque curve there should be a minimum 15–20% surplus torque available, over and above the load torque, for a safe start (Figure 2.14). The torque thus available is known as the accelerating torque.

2.7 Time of start-up and its effect on motor performance

This depends upon the applied voltage, i.e. type of switching, starting torque of the motor, counter-torque of the load and the inertia of the rotating masses etc. It is expressed by

Serial no.	Load	Characteristics of load	Starting torque	Opposing torque with speed	Figure no.
1	Presses, punches, latches and drilling machines	-	Light duty 20-30%	Torque remains constant and at a very low value, since the load is applied when the motor has run to speed	2.10
2	Fans, blowers, centrifugal pumps and compressors	The power is proportional to the third power of the speed $(P \propto N^3)$	Medium duty 10-40%	Torque rises with square of the speed $(T \propto N^2)$	2.11
3	Rolling mills, ball mills, hammer mills, calendar drives and sugar centrifuges	The power is proportional to the square of the speed $(P \propto N^2)$	Heavy duty 30–40%. May be more and have to accelerate large masses of heavy moment of inertia, requiring a prolonged time of start-up	Near full-load torque	2.12
4	Conveyors and hoists	The power is proportional to the speed $(P \propto N)$	Heavy duty 100-110%	Torque remains constant throughout the speed range and at almost the full-load torque	2.13

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$$t_{\rm s} = \frac{GD_{\rm T}^2 \cdot N_{\rm r}}{375 \cdot T_{\rm a}} \tag{2.5}$$

where

 $t_{\rm s}$ = time of start-up in seconds

- $GD_{\rm T}^2$ = total weight moment of inertia of all the rotating masses, referred to the motor speed in kg.m²
 - $= GD_{\rm M}^2 + GD_{\rm L}^2$

 $(GD_{\rm M}^2$ is motor and $GD_{\rm L}^2$ is load weight moment of inertia referred to the motor speed)

where

20

0

1. Torque \propto (speed)²

2. Power \propto (speed)³

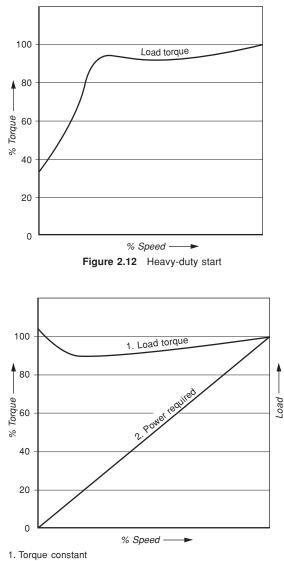
- $GD^2 = 4 \cdot g \cdot M \cdot K^2$ $g = 9.81 \text{ m/s}^2$
- 100 80 % Torque – 60 40 Load torque 20 0 % Speed Figure 2.10 Light duty 100 80 l 60 Torque -Load 40 %

- M = mass and
- $g \cdot M = W$ (weight in kg)
 - K = radius of gyration in m
 - $T_a = \text{average accelerating torque in mkg (Figure 2.14),}$ i.e. average ($T_{\text{st}} T_{\text{L}}$) in mkg $T_{\text{L}} = \text{opposing torque (load torque)}$

GD_L^2 at motor speed

If the load is driven through belts or gears at a speed different from that of the motor, the effective value of GD^2 of the load, as referred to the motor speed, will be different. Equating the work done at the two speeds:

$$GD_{\rm L}^2 \cdot N_{\rm r}^2 = GD_1^2 \cdot N_{\rm L}^2$$



2. Power ∝ speed

% Speed _

2. Power

,e⁰¹

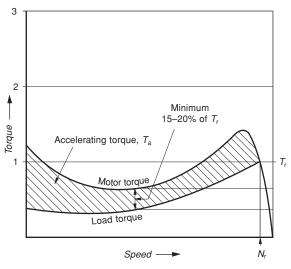


Figure 2.14 Accelerating torque (T_a)

or
$$GD_{\rm L}^2 = GD_{\rm I}^2 \cdot \left(\frac{N_{\rm L}}{N_{\rm r}}\right)^2$$
 (2.6)

where

 GD_1^2 = weight moment of inertia of load at a speed N_L .

Example 2.1

A 100 kW, 750 r.p.m. motor drives a coal mill, having GD_1^2 as 600 kg.m² through belts, at a speed of 500 r.p.m. Then its effective GD_1^2 at motor speed will be

$$GD_{L}^{2} = 600 \times \left(\frac{500}{750}\right)^{2}$$
$$= 600 \times 0.445$$
$$\approx 267 \text{ kg m}^{2}$$

Note

For simplicity, the synchronous speed of the motor is considered, which will make only a marginal difference in calculations.

2.7.1 Motor heating during start-up

Irrespective of the type of switching adopted or the load driven by the motor, each time it is switched it generates heat, in both the rotor and the stator components. The magnitude of the start-up heat will depend upon the inertia of the rotating masses, the type of switching, the torque developed by the motor and the opposing (load) torque etc., as can be inferred from Equation (2.5). The higher the time of start-up, the higher will be the heat generated. The corresponding temperature rise of the stator or the rotor windings can be measured as below: Heat generated:

$$H = I_{st}^2 \cdot R \cdot t_s \quad \text{watt} \cdot s \cdot (W \cdot s.) \tag{2.7}$$

also
$$H = W \cdot \delta \cdot \theta$$
 (2.8)

or
$$\theta = \frac{H}{W \cdot \delta} \circ \theta$$

where

W = weight of heated portion in kg

 δ = specific heat of the material of windings, in watt \cdot s/kg/°C

 θ = temperature rise in °C (Table 11.1)

A possible way to restrict the temperature rise is the use of a material having a high specific heat. An increase in the weight would require more material and prove to be a costly proposition. A motor's constructional features should be such as to provide good heat dissipation through its body. Motors for high inertia will be longer.

Sharing of heat

The rotor and stator heats, during start-up and run, are interrelated and vary in the same proportion as their respective resistances. (See circle diagram Figure 1.16 in Section 1.10.)

If H_r = the heat of rotor in W \cdot s.

and H_s = the heat of stator in W · s.

Then
$$\frac{H_s}{H_r} = \frac{R_1}{R_2'}$$
 (2.9)

While the total heat generated in the rotor is comparatively higher than the stator, there is a significant difference in the temperature rise of the respective parts as a result of the bulk of their active parts and area of heat dissipation. For the same material, the rotor will have a much higher temperature rise compared to the stator, in view of its weight, which may be several times less than the stator. During start-up, therefore, the rotor will become heated quickly and much more than the stator. Repeated start-ups may even be disastrous. During a run, however, when the temperature has stabilized, an overload will render the stator more vulnerable to damage than the rotor. The rotors, as standard can withstand much higher temperature rises (200–300°C) and may be suitable to withstand such marginal overloads.

Corollary

During start-up the rotor, due to its lighter weight compared to the stator, and during a run, the stator, due to overload are more vulnerable to damage through excessive heat.

Example 2.2

A rotor fails during start-up, possibly due to a lower supply voltage than desired or a smaller accelerating torque than required or reasons leading to similar conditions. In such cases the rotor fails first, due to higher rotor currents and a prolonged acceleration time or a locked rotor. At this instant, unless the motor controlgear trips, the stator may also fail due to excessive heat. Instances can be cited where even the short-circuit end rings of a squirrel cage rotor melted, and the molten metal, through its centrifugal force, hit the stator overhangs and damaged that also through its insulation, causing an inter-turn fault.

2.7.2 Heating during a no-load start-up

During a no-load start-up, i.e. when the motor shaft is free, half the energy drawn from the supply appears as heat in the rotor and the stator windings. In slip-ring motors the bulk of the rotor heat is shared by the external resistance, a feature which makes it a better choice for frequent starts and stops, and for driving loads that possess large inertia. It has been seen that most of the stringent load requirements can also be met with high torque squirrel cage motors, manufactured with a judicious design of stator and rotor resistances, an efficient means of heat dissipation and a proper choice of active material. The heat generated during a no-load start-up can be expressed by:

$$H_{n\ell} = \frac{GD_{\rm M}^2 \cdot N_{\rm r}^2}{730} \,\,\mathrm{W} \cdot \mathrm{s} \tag{2.10}$$

This expression, except for the mechanical design, is totally independent of the type of start and the electrical design of the motor. Electrically also, this is demonstrated in the subsequent example. The expression, however, does not hold good for an ON-LOAD start. On load, the accelerating torque diminishes substantially with the type of load and the method of start, as can be seen from Figure 2.14, and so diminishes the denominator of Equation (2.5), raising the time of start.

Example 2.3

A squirrel cage motor is started through an auto-transformer starter with a tapping of 40%. Compare the starting heat with a DOL starting when the motor shaft is free. With DOL $T_a = 100\%$

With an auto-transformer $T_a = (0.4)^2$ or 16%

... Starting time with DOL, $t_s = \frac{GD_M^2}{375} \times \frac{N_r}{T_a}$

and with auto-transformer,
$$t_{s1} = \frac{GD_{M}^{2}}{375} \times \frac{N_{r}}{0.16T_{a}}$$

i.e. 6.25 times of DOL

Since the heat during start-up $\propto (I_{st})^2 \cdot t$

: Heat during start on a DOL
$$\propto (I_{st})^2 \cdot t$$

and on an auto-transformer $\propto (0.4I_{st})^2 \cdot t_{s1}$

or

$$\propto 0.16(I_{\rm st})^2 \times 6.25t_{\rm s}$$

i.e. $\propto (I_{st})^2 \cdot t_s$

Thus at no-load, irrespective of the motor torque and the type of switching, the starting heat would remain the same.

2.7.3 Heating during an on-load start-up

Against an opposing torque, the accelerating torque of the motor, which hitherto had varied in proportion to the type of switching, will now diminish disproportionately with a switching other than DOL (Figure 2.15). The starting time rises disproportionately and so does the

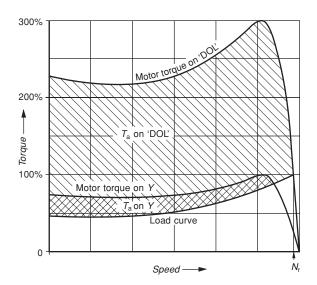


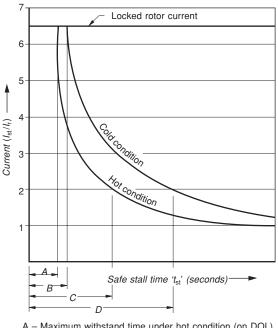
Figure 2.15 Variation in T_a with Y/Δ switching

starting heat. Care should therefore be taken when selecting a motor for a particular type of switching and magnitude of the opposing torque. This is to avert possible damage to the motor due to prolonged starting time, as a consequence of an inadequate accelerating torque.

Maintaining a minimum accelerating torque at each point, during the pick-up may also not be adequate sometimes. In which case the starting time may exceed the locked rotor or thermal withstand time of the motor, as discussed below.

2.8 Thermal withstand time

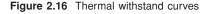
This is also known as safe stall time or the locked rotor withstand capacity of the motor. This is the time during which the motor can safely withstand electromagnetic effects and consequent heating in a locked condition. These are drawn for the cold and hot conditions of the motor in Figure 2.16. Evidently, the motor must come to speed within this time, irrespective of type of load or method of switching. In a reduced voltage start-up or slip-ring motors the starting current would be low and these curves would signify that for any reason if the rotor becomes locked during start or run, or takes a prolonged time to come up to speed, the protective device must operate within the safe stall time. Generally, these curves are drawn for the stator to monitor the actual running condition and not the condition during start-up. The rotor can withstand much higher temperatures during a run. With the help of these curves, knowing the starting time and the starting current of the motor, one can ascertain the number of starts and stops the motor would be capable of undertaking. These curves also help in the selection of the protective relays and their setting as discussed in Chapter 12.



A - Maximum withstand time under hot condition (on DOL)

B - Maximum withstand time under cold condition (on DOL)

C – Maximum withstand time under hot condition during Y D – Maximum withstand time under cold condition during Y



2.8.1 Heating phenomenon in a motor during a stalled condition

(a) For the stator

Stalling is a condition in which the rotor becomes locked due to excessive load torque or opposing torque. Stalling is thus a replica of a locked rotor condition and can occur at any speed below the T_{po} region, as illustrated in Figure 2.17. The figure also shows that the stator current during stalling will generally correspond to I_{st} only, due to the characteristic of the motor speed-current curve. Whenever the rotor becomes locked in a region that almost corresponds to the I_{st} region of the motor (Figure 2.17) it will mean a stalling condition.

In such a condition, if the heat generated in the windings raises the temperature of the windings by θ above the temperature, the motor was operating just before stalling. Then by a differential form of the heat equation:

$$H_{\rm st\ell} \cdot t_{\rm st\ell} = \theta \cdot C \tag{2.11}$$

 $H_{\rm st\ell}$ = heat generated during stalled condition per second in watts

= power loss

$$= I_{\mathrm{st}\,\ell}^2 \cdot R_\ell$$

 $I_{\text{st}\ell}$ = current at the point of stalling in Amps

 R_{ℓ} = resistance of the stator windings per phase in Ω $t_{\rm st\ell}$ = time for which the stalling condition exists in seconds

- C = heat capacity of the motor
 - = heat required to raise the temperature of the windings by 1 °C in Joules

 $= \dot{W} \cdot \delta$

where

- W = weight of the stator windings in kg
 - = volume of stator windings \times specific gravity of the metal of the windings

$$= L_{\rm mt} \cdot Z_{\rm s} \cdot A_{\rm cu} \cdot a$$

 $L_{\rm mt}$ = length of a mean turn of the winding in metres

- $Z_{\rm s}$ = number of stator turns per phase
- $A_{\rm cu}$ = area of the whole windings in m²
 - d = specific gravity of the winding material in kg/m³
 - δ = specific heat of winding metal in watt · s/kg/°C

Note 1

In Equation (2.11) it is presumed that the heating of the windings is adiabatic, i.e. whatever heat is generated during a stalled condition is totally consumed in raising the temperature of the stator windings by θ . An adiabatic process means that there is no heat transfer from the system to the surroundings. This is also known as the heat sink process. The presumption is logical, because the duration of heating is too short to be able to dissipate a part of it to other parts of the machine or the surroundings.

$$t \cdot t_{\text{st}\,\ell} = \frac{\theta \cdot C}{H_{\text{st}\,\ell}} = \frac{\theta \cdot W \cdot \delta}{I_{\text{st}\,\ell}^2 \cdot R_{\ell}}$$
$$= \frac{\theta \cdot (L_{\text{mt}} \cdot Z_{\text{s}} \cdot A_{\text{cu}} \cdot d) \cdot \delta}{I_{\text{st}\,\ell}^2 \cdot R_{\ell}}$$
where $R_{\ell} = \frac{\rho \cdot L_{\text{mt}} \cdot Z_{\text{s}}}{A_{\text{cu}}}$

and
$$\rho = \rho_{40}(1 + \infty h)$$

where ∞ = temperature coefficient of resistivity

$$=\frac{1}{234.5}$$
 °C

 ρ_{40} = resistivity of copper at 40°C

h is known as the middle temperature during the entire temperature variation in the locked rotor condition.

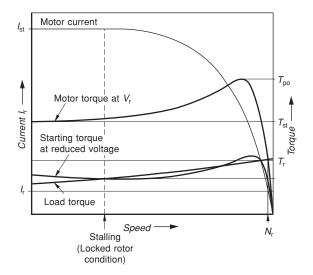


Figure 2.17 Stalled or locked rotor condition

$$\therefore t_{\mathrm{st}\,\ell} = \frac{\theta \cdot L_{\mathrm{mt}} \cdot Z_{\mathrm{s}} \cdot A_{\mathrm{cu}} \cdot d \cdot \delta}{I_{\mathrm{st}\,\ell}^2 \cdot \rho_{40} \left(1 + \infty h\right) \cdot \frac{L_{\mathrm{mt}} \cdot Z_{\mathrm{s}}}{A_{\mathrm{cu}}}}$$
$$= \left(\frac{A_{\mathrm{cu}}}{I_{\mathrm{st}\,\ell}}\right)^2 \cdot \theta \cdot \frac{d \cdot \delta}{\rho_{40} \left(1 + \infty h\right)}$$

and $\frac{I_{st\ell}}{A_{cu}} = J_{ss} \simeq$ current density during start in A/cm² and

$$\frac{\rho_{40}\left(1+\infty h\right)}{d\cdot\delta}=k$$

where

k = material constant for the metal;

(i) for aluminium = 0.016

- (ii) for copper = 0.0065
- (iii) for brass = 0.0276

$$\therefore \quad t_{\text{st}\ell} = \frac{1}{J_{\text{ss}}^2} \cdot \theta \cdot \frac{1}{0.0065} \quad \text{(for copper windings)}$$

Note 2

Since no system can be heat adiabatic in practice there is a certain amount of heat dissipation from the impregnated windings to the stator core and housing. This heat dissipation is considered as 15% of the total heat generated as in IEC 60079-7.

 \therefore actual $H_{\rm s}$ = 85% of what has been calculated above

and
$$t_{\text{st}\,\ell} = \frac{\theta}{J_{\text{ss}}^2 \times 0.0065 \times 0.85}$$

or
$$t_{\mathrm{st}\,\ell} = \frac{\theta}{J_{\mathrm{ss}}^2 \times 0.00552}$$
 seconds (s) (2.12)

Application

For safe stall conditions $t_{st\ell}$ should be less than the thermal withstand time of the motor under locked or short-circuit condition.

- (i) θ is called the permissible rise in temperature in the stalled condition.
- (ii) For class *B* insulation, the maximum limiting temperature is 185°C and for class F 210°C (short-time permissible temperature). The permissible rise in temperature in class *B* is 80°C above an ambient of 40°C.

$$\therefore \theta = 185 - (40 + 80)$$

 $= 65^{\circ}C$ for hot conditions

and
$$\theta = 185 - 40$$

= 145° C for cold conditions

(b) For the rotor

To ascertain whether the stator or the rotor would fail first during a stalled condition, the thermal withstand time of the rotor should also be determined separately for the rotor bars and the end rings. The lowest values for the stator or the rotor will be the safe stall time for the entire motor. The limiting temperatures in rotor components may be considered as follows:

Limiting temperature for bars

450°C

Limiting temperature for rings100°COperating temperature for bars150°COperating temperature for rings70°CTherefore the permissible rise in temperature in a stalledcondition will be as follows:

 θ for bars in cold conditions = 450 - 40 = 410°C θ for bars in hot conditions = 450 - 150 = 300°C θ for rings in cold conditions = 100 - 40 = 60°C θ for rings in hot conditions = 100 - 70 = 30°C

2.8.2 Plotting thermal withstand characteristics of the motor

Calculate the thermal withstand times $t_{st\ell}$'s under cold and hot conditions and also at different I_{st} , say 200%, 300% and 400% etc. of I_r as shown below. After determining the corresponding safe thermal withstand times, according to the above formula, draw the graph (Figure 2.16), I_{st} vs t_{st} :

Stalled current $I_{st\ell}$ There as % of I_r	nal withstand time, $t_{st\ell}$ in seconds
200	<i>t</i> ₅
300	t_4
400	t_3
500	t_2
600	t_1
and for J_{ss} (for Δ windings) =	$\frac{I_{\text{st}\ell}}{\sqrt{3} \cdot (\text{Area of windings/turn}) \cdot Z_{\text{s}}}$

Note

 J_{ss} is a design parameter and more details may be obtained from the motor manufacturer.

Example 2.4

A 250 kW motor has a cold thermal withstand time of 30 seconds and a hot thermal withstand time of 25 seconds. If the starting time is 7 seconds, determine the consecutive cold or hot starts that the motor will be able to sustain safely.

Number of consecutive cold starts = $\frac{30}{7}$ = 4.3

i.e. 4 starts

and number of hot starts
$$=\frac{25}{7}=3.6$$
 i.e. 3 starts

The period after which this can be repeated will depend upon the heating curve and the thermal time constant of the motor, i.e. the time the motor will take to reach thermal equilibrium after repeated starts (see Chapter 3).

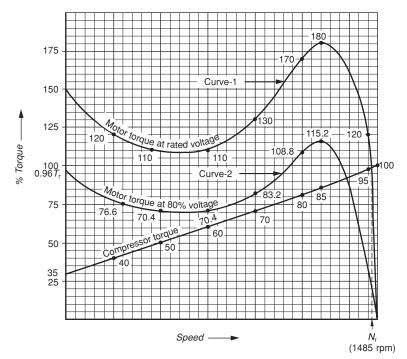
Example 2.5

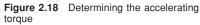
A centrifugal compressor driven through V belts at a speed of 4500 r.p.m. having the torque curve as shown in Figure 2.18 and a moment of inertia MK^2 of 2.50 kgm² employs a squirrel cage motor with the following parameters:

 $N_{\rm r} = 1485 \text{ r.p.m.}$

speed-torque characteristic as in Figure 2.18

Safe stall time
$$\begin{cases} hot - 30 \text{ s.} \\ cold - 40 \text{ s.} \end{cases}$$





Calculate the starting time and consecutive cold and hot starts for which the motor will be suitable with a DOL starting.

Solution

To determine the exact accelerating torque, measure the ordinates of torque as shown at different speeds and calculate the average torque as follows:

(a) Average load torque

$$T_{L} = \frac{35 + 40 + 50 + 60 + 70 + 80 + 85 + 95 + 100}{9}$$
$$= \frac{615}{9}$$
$$= 68.33\%$$

(b) Average motor torque

$$T = \frac{150 + 120 + 110 + 110 + 130 + 170 + 180 + 120 + 100}{9}$$

$$=\frac{1190}{9}$$
$$\simeq 132.2\%$$

(c) .: Average accelerating torque

= 63.87%

(d) Motor rated torque

$$T_{\rm r} = \frac{350 \times 974}{1485}$$

$$\simeq$$
 230 mkg

 $\therefore T_a = 230 \times 0.6387$

= 146.9 mkg

(e) Total GD_{T}^{2} at motor speed = 30 + (4 × 9.81 × 2.5) $\left(\frac{4500}{1485}\right)^{2}$

where $[GD_{L}^{2} = 4 \cdot g \cdot MK^{2}]$ (at the compressor speed)

i.e.
$$GD_T^2 = 30 + 901$$

= 931 kgm²

(f) Stating time
$$t_s = \frac{931 \times 1485}{375 \times 146.9}$$

= 25.1 seconds

Take roughly 10% more to account for any tolerance and variations,

$$\therefore t_{\rm s} = 25.1 \times 1.1$$

 \simeq 27.6 seconds

This motor is therefore suitable for only one cold or one hot start at a time until the temperature rise stabilizes again.

If this motor is started with an auto-transformer with a tapping of 80%, the motor average torque will be

or T = 84.6%

and

and accelerating torque $T_a = 84.6 - 68.33$

i.e.
$$230 \times 0.1627 = 37.42$$
 mkg

$$t_{\rm s} = \frac{931 \times 1485}{375 \times 37.42}$$

which is much more than the safe stall-withstand time.

Inference

On an ON-LOAD start, the starting time increases disproportionately, depending upon the type of switching. This load therefore cannot be accelerated within a safe stall time through an auto-transformer, even with a tapping as high as 80% although the motor possesses some accelerating torque at each point during pick-up (curve 2 of Figure 2.18).

2.9 Braking

Braking results in heating, irrespective of the method used. When the braking is external, the heat will appear in the external circuit and the motor windings will remain unaffected. But when it is internal, the entire braking heat will be generated within the motor windings. Due consideration of this must be made when selecting the motor rating, particularly when the loads are heavy and the braking frequent. An analogue to the starting time gives the braking time t_b as

$$t_{\rm b} = \frac{GD_{\rm T}^2 \cdot N}{375 \cdot T_{\rm b}} \text{ seconds (s)}$$
(2.13)

where $N = N_r - N_{r1}$, i.e. speed reduction in r.p.m. T_b = braking torque in mkg

An analogue to starting heat (Equation (2.10)) gives the braking heat $H_{\rm b}$ as

$$H_{\rm b} = \frac{GD_{\rm T}^2}{730} \cdot (N_{\rm r}^2 - N_{\rm rl}^2) \text{ watt-seconds (W \cdot s)} \quad (2.14)$$

The wider the speed range of braking, the greater will be the heat generated.

2.9.1 Types of braking

There are several methods of braking, external or internal, and they are briefly discussed below. Any of them can be employed, depending upon the torque requirement, i.e. size of motor, its speed, the type of load, etc.

A. External: mechanical or friction braking

This type of braking is suitable for small motors and can be achieved through

- 1 Solenoid-operated brakes,
- 2 Electro-magnetically operated brakes, or
- 3 Magnetic particle brakes.

In the first two types a brake shoe, operated by an external auxiliary supply, is mounted on the extended shaft at the NDE (non-driving end) of the motor. These brakes are normally operated after the motor is switched OFF. The heat of braking appears in the external circuit and the motor windings are not affected. For motors with this braking, only the starting heat need be considered, depending upon the frequency of starts and not the heat of braking.

Note

Friction braking may be employed for all sizes of drives, either as the only braking means as noted below, or as a supplementary safety means to keep the drive locked stationary when required.

- 1 AC solenoid brakes These are employed for small motors, say, up to 15–20 h.p. They are suitable for applications such as conveyors, hoists, cranes, machine tools, lock gates and dumb waiters (Figure 2.19). The brakes are spring loaded and mounted on two mechanically opposing brake shoes. They grip a brake drum or disc, coupled rigidly at the NDE of the motor shaft. The brakes are applied mechanically and released electrically. The braking action takes place by deenergizing the spring. The brakes are normally applied in the OFF position for reasons of safety in the event of a power failure. They are released only when the solenoid is energized.
- 2 Electromagnetic shoe-brakes These are similar to the above, but are used for still higher motor ratings, say, 5–800 h.p. (Figure 2.20.) In this case instead of a solenoid coil, an electromagnetic coil is employed. This releases the brakes and develops a torque at least equal to the motor torque, to brake or hold the full load. In this case also, the brakes are applied on the motor shaft when the holding coil (electromagnet) is de-energized and is released only when the electromagnet is energized to make it safe against failure. Possible applications include cranes, hoists, elevators, conveyors, machine tools, rolling mills and ball mills, etc. and also holding of loads in conveyors, hoists and elevators, etc.

Notes

(i) In both the above types of braking systems, a hand-operated device is also provided, to release the mechanical brakes in applications such as lifts, elevators, cranes, and winders. This lowers the load to the ground loading station or the desired

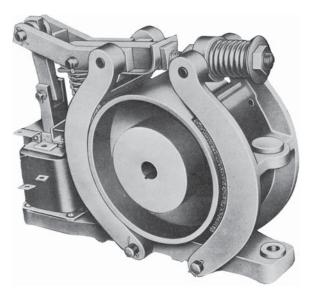


Figure 2.19 AC solenoid brake (Courtesy: BCH)

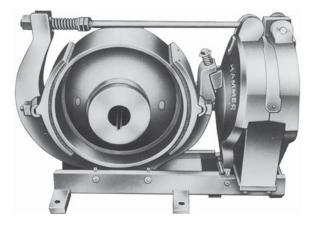


Figure 2.20 Electro-magnetic shoe brake (Courtesy: BCH)

platform, as the situation may require in the event of a power failure.

- (ii) The ratings of the brakes noted above are only indicative.
- (iii) The braking torque of the shoe brakes may diminish with the number of operations. The heat of braking wears out the brake linings. The extent of fading will depend upon the braking torque to decelerate the heavy loads and frequency of its operations. They may also need replacement of the brake linings, similar to an automotive vehicle.
- 3 *Magnetic particle brakes* One type of these brakes is illustrated in Figures 2.21(a) and (b). They are also known as powder brakes and have a main body (stator) that houses a drive cylinder, forming the main rotating part of the brake. Through its extended shaft is coupled the main drive that requires the braking facilities. Within and concentric to the drive cylinder is a rotor rigidly fixed with the housing. There is a space between the drive cylinder and the rotor, which is filled with small granules of steel in the form of powder, with excellent magnetic properties. This powder, when magnetized, condenses into a solid mass between the drive cylinder and the rotor and provides the required braking effect. This is possible with the help of a magnetic field which is provided through a stationary magnetic coil placed in the main housing outside the periphery of the drive cylinder as shown. The field strength of this coil can be varied with the help of a variable current source to obtain a variable braking torque and thus achieve more precise braking control, even remotely. Depending upon the type of application and accuracy of the speed control desired, extremely precise and accurate electronic controls are available. These can infinitely vary the torque and hence the speed of the motor. Such braking devices are available in the range 0.1 kW-60 kW.

Strength of brakes

The brakes should be suitable to counter at least the torque developed by the motor. They must therefore develop at least this amount of torque. To find the least braking torque, the brake drums must be able to develop, in either of the above types of mechanical brakes, the torque shown in Equation (1.10) may be used, i.e.

$$T_{\rm r} = \frac{P_{\rm r} \cdot 974}{N_{\rm r}} \,\mathrm{mkg}$$

The brakes must develop at least this amount of torque or slightly more, i.e.

$$T_{\rm b} \ge \frac{P_{\rm r} \cdot 974}{N_{\rm r}} \,\mathrm{mkg} \tag{2.15}$$

where $T_{\rm b}$ is the torque of braking

B. Internal type

1 Electrodynamic or d.c. electrical braking When a d.c. voltage is applied to the motor windings, a steady flux is produced since f = 0. The theoretical synchronous speed of the motor, N_s , now reduces to zero. When this steady flux is cut by the rotor conductors, as the rotor is rotating, it induces a steady (d.c.) e.m.f. in the rotor circuit, which produces the required braking effect. In slip-ring motors, the



Figure 2.21(a) A magnetic particle brake (Courtesy: Dynaspede)

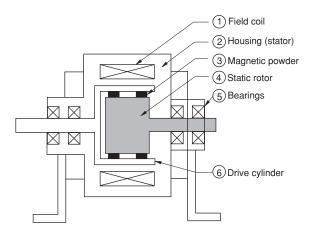


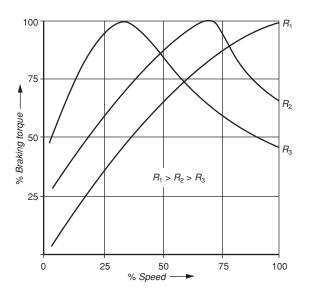
Figure 2.21(b) Cross-section of a typical magnetic particle brake

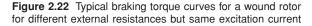
braking torque can be controlled by inserting suitable resistance in the rotor circuit and varying the excitation voltage (Figure 2.23), keeping the excitation current the same. Braking in slip-ring motors by this method is more accurate and simple. Some typical braking curves are shown in Figure 2.22 for a slip-ring motor.

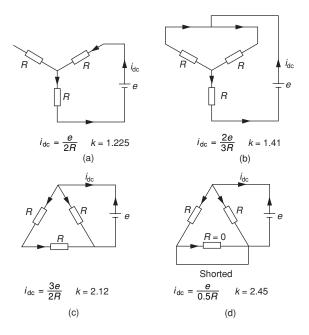
In squirrel cage motors, in the absence of external resistance, the stator windings can be arranged in different configurations such as series, parallel, star or delta, as shown in Figure 2.23, to achieve the varying effects of excitation voltage. This type of braking is useful for both squirrel cage and slip-ring motors, but is rarely used.

For applying the brakes, the stator is disconnected from the supply and a d.c. excitation voltage is applied to the windings as shown in Figure 2.23. The windings can be arranged in any configuration, as illustrated, to obtain the required braking torque. If the ampere turns during braking are maintained as during normal running, the braking torque curve will almost take the shape of the motor's normal speed–torque curve.

If an independent d.c. source is not available a single phase transformer and a rectifier bridge as shown in Figure 2.24 can also be used to obtain the required d.c. voltage. Although the requirement of d.c. excitation voltage is not high, the rating of the rectifier transformer and the bridge should be commensurate with the braking force required. This braking force would depend upon the size of the motor and the time of braking. If the braking current, i_{dc} , is known, which is a measure of the braking torque necessary to fulfil a particular load duty requirement, the excitation voltage *e* can be determined for different winding configurations, as indicated in Figure 2.23. The i_{dc} can be determined







e = Excitation voltage

i_{dc} = Excitation or braking current

R = Stator resistance per phase. For slip-ring motors, external resistance can be added and R varied

Figure	<i>k</i> i	Required dc voltage <i>e</i>
а	1.225	i _{dc} · 2 <i>R</i>
b	1.41	$i_{dc} \cdot 2R$ $i_{dc} \cdot \frac{3R}{2}$
С	2.12	i _{dc} · <u>2R</u>
d	2.45	i _{dc} · <u>R</u>

Figure 2.23 Stator or rotor connections for d.c. electric braking

from the following equation, considering the same ampere turns as for a standard motor:

$$i_{\rm dc} = k_1 \cdot I_{\rm st(ph)} \cdot \sqrt{\frac{T_1 + T_{\rm b} - T_{\rm ex}}{k_2 \cdot T_{\rm st}}}$$
 (2.16)

where

 i_{dc} = braking current

 $I_{\rm st(ph)}$ = phase value of the starting current

- $=\frac{I_{\rm st}}{\sqrt{3}}$ (for a delta-connected stator or rotor)
- k_1 = factor to determine the equivalent ampere turns for a particular configuration, as indicated in Figure 2.23. To avoid overheating and excessive electromagnetic forces, i_{de} is normally not allowed to exceed $L_{u(eb)}$
- $i_{\rm dc}$ is normally not allowed to exceed $I_{\rm st(ph)}$ T_{ℓ} = average load torque between the running speed and the final speed (Figure 2.25)

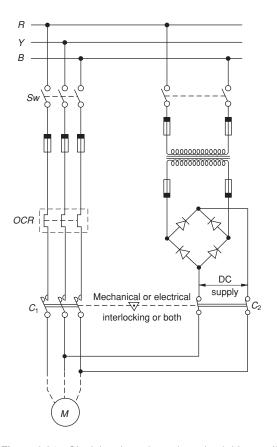
- $T_{\rm b}$ = average braking torque between the running speed and the final speed (Figure 2.25). This will depend upon the braking duty the motor is required to perform such as the final speed, $N_{\rm rl}$ (which we have considered as zero in Figure 2.25), and the duration within which the motor must brake to this speed from $N_{\rm r}$. This can be determined from Equation (2.13)
- T_{ex} = braking torque of the external brakes, if provided otherwise it may be considered to be zero
- $T_{\rm st}$ = locked rotor (starting) torque of the motor
- k_2 = a factor to account for the average braking torque. This may be considered to be 1.3–1.7 (consult the manufacturer for a more accurate value)

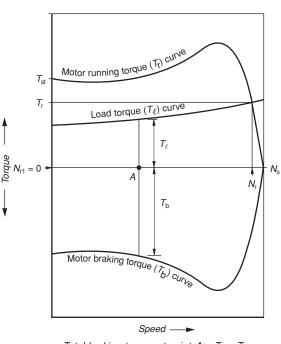
In addition to electrical braking, a mechanical brake, as discussed in Section 2.9.1(A) may also be essential if the motor is required to be stopped completely because, at any value of excitation current, the motor will never reach a standstill condition. The heat of braking up to the standstill condition (N_{r1} =0) is roughly equal to one start and is expressed by Equation (2.14).

2 *Plugging* By changing any two of the phases the motor will develop a torque in the reverse direction and provide the necessary braking. The voltage across the windings at the instant of plugging becomes twice the rated voltage, and slip as 2S, for the changed magnetic field. With these changed parameters, the current and torque curves can be approximately determined from Equations (1.7a) and (1.3a) respectively, for high slip conditions.

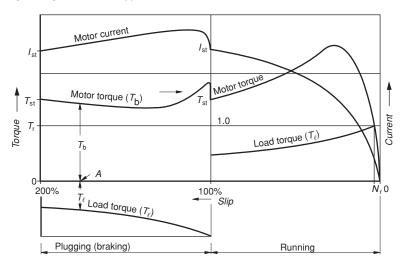
Current and voltage will both give a transitory kick at the instant of plugging, depending upon the effective voltage across the windings, under the influence of the motor's self-induced e.m.f. and the applied voltage. The transitory state will last only a few cycles and then the curves will generally take the shape as in the equations noted above and illustrated in Figure 2.26. Generally, except for the initial kick, there will be no significant variation in the current and torque values compared to their starting values at S = 1. These values can be varied in slip-ring motors by altering the rotor's circuit resistance. During plugging, if the supply is not switched OFF at the instant of reaching the standstill position, the motor will start rotating in the reverse direction, tracing the same speed-torque and speed-current curves as in the forward direction. But a reverse direction may damage the driven load. Precautions are essential to prevent such a situation by providing an electrical interlocking and/or a reverse ratchet arrangement in the load coupling.

The windings may, however, be subject up to twice the rated voltage and must be suitable to withstand this voltage repeatedly when necessary. The heat generated during braking will be roughly three times the heat generated during start-up as determined below:





Total braking torque at point $A = T_{\ell} + T_{b}$



Total braking torque at point $A = T_{\ell} + T_{b}$

Figure 2.26 Approximate motor torque and current characteristic curves during plugging

Rotor losses per phase $W = I_{rr}^2 \cdot R_2$ Rotor torque per phase $T = \frac{I_{rr}^2 \cdot R_2}{S}$

 \therefore Rotor loss per unit torque $\frac{W}{T} = S$

Average loss between slip S_1 and $S_2 = \frac{(S_1 + S_2)}{2} \cdot T$

- (i) During a normal running,
 - when $S_1 = 1$ and $S_2 = 0$

starting heat \propto starting loss $\propto \frac{T}{2}$

- (ii) During plugging,
 - when, $S_1 = 2$ and $S_2 = 1$

Heat generated during plugging

$$\propto \frac{(1+2)}{2}T$$
 or $\propto \frac{3}{2}T$

Therefore the heat of the motor during plugging is three times that of during a normal start. Stator heat and thus the total motor heat is a function of the rotor heat (see also Section 2.7.1). Such a method is therefore not suitable for larger motors or for frequent brakings.

Note

This is an approximate derivation for a simple illustration of the ratio of heats. The time of start and braking is not considered in the above derivation, whereas both would be different and so will be the heat generated. The time of start would be much higher than the time of braking, as the latter is much higher than the former. Figure 2.26 illustrates this. But in view of the high current during plugging the ratio of heat as noted above is a near approximation.

3 Regenerative braking If the motor be run beyond synchronous speed by some external means it will work as a generator and feed back useful energy to the supply system. It will draw only the necessary excitation current, $I_{\rm m}$, for the generator action from the source of supply. In such a condition, the motor will exert a counter torque, the magnitude of which will depend upon the motor speed above synchronous. Such braking conditions may occur automatically in downhill conveyors, lifts and hoists etc. while descending with the load, i.e. operating as an induction motor while ascending and as an induction generator while descending. The generator and the braking action ceases at synchronous speed. For speed control below synchronous speed, therefore, it will be essential to employ a multi-speed motor which, at a higher speed, can be switched to the lower speed winding to make the motor work as a generator between the high and the low speeds. Such a braking method, however, has only limited commercial applications, as in a sugar centrifuge motor (Section 7.4).

With the application of solid-state technology, however, as discussed in Chapter 6, the potential energy of the loads in hoists, lifts and conveyors during descents can be saved and fed back to the source.

2.10 Inching or jogging

This means repeated short-duration application of power to the motor to cause small movements of the shaft from rest to perform certain load requirements. The motor may normally not reach its full speed, nor at times complete even one full revolution, and can be rotated in either direction. Likely applications may relate to lifting or hoisting which may call for delicate handling and a rather slow, smooth and more accurate final movement for exact positioning, lifting or unloading etc. Similarly in torque motors or actuator motors (Section 7.8) for throttle and vane controls.

This is a severe duty for the switching contactors as they have to endure repeated arcing of the interrupting contacts every time they make or break. (Select only AC-4 duty contactors: see Section 12.10.)

2.11 Number of starts and stops

Due to excessive starting and braking heat losses it is not advisable to switch an induction motor ON and OFF frequently. The number of starts and stops a motor is capable of performing will depend upon its working conditions such as type of switching, braking and load demand etc. and can be determined from

$$Z_{\rm L} = Z_{\rm NL} \cdot \frac{K_{\rm b}}{FI} \cdot K_{\rm L} \tag{2.17}$$

where

- $Z_{\rm L}$ = number of starts and equivalent stops per hour on load. For example, in plugging one start and one stop will mean four starts and if reversal is also involved then five starts.
- $Z_{\rm NL}$ = permissible number of starts per hour for a motor with a free shaft, using mechanical braking, thus

placing no strain on the motor. This factor will depend upon the electrical and mechanical design of a motor and will vary from one manufacturer to another. The cooling capacity, its effectiveness, i.e. heating and cooling characteristics and starting torque of a motor, are the parameters that would determine this factor. The smaller the motor, the greater number of starts it will be capable of performing. For a lower-speed motor, the average starting torque will be normally less and the inertia more. Therefore the permissible number of switching operations will be comparatively less for a low-speed motor than for a high-speed motor of similar rating. As a rough guide, small motors, say, up to 20 h.p., may have a factor as high as 1000-2000.

 $K_{\rm b}$ = factor of braking, which depends upon the type of braking used, such as

(a) Mechanical braking	$K_{\rm b} = 1$
(b) D.C. braking	$K_{\rm b} = 0.6 - 0.5$
(c) Plugging	$K_{\rm b} = 0.3 - 0.4$
(d) Regenerative braking	$K_{\rm b} = 0.4 - 0.5$

 $K_{\rm L}$ = mean load factor, i.e. the ratio of the average load torque to the motor torque which depends upon the loading on the motor during start-up. For most applications (e.g. cranes, lifts or machine tools) this factor is based on a loading of 0.5 or 0.75. This factor is also determined by the manufacturer and may have a shape as shown in Figure 2.27

$$FI = \frac{GD_{\rm M}^2 + GD_{\rm L}^2}{GD_{\rm M}^2} \tag{3.1}$$

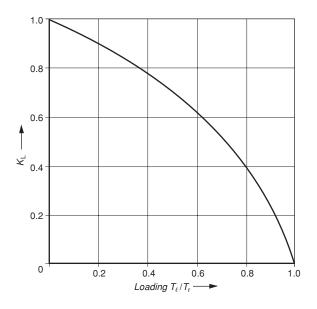


Figure 2.27 Average load factor $K_{\rm L}$ when started against load

Relevant Sta	ndards
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IEC	Title	IS	BS	
60034-12/2002	Rotating electrical machines. Starting performance of single-speed three-phase cage induction motors for voltages up to and including 660 V.	8789/2002	BS EN 60034-12/2002	_
60079-7/2004	Electrical apparatus for explosive gas atmospheres. Increased safety motors type 'e'.	6381/2001	BS EN 50019/1977	_
	Related US Standards ANSI/NEMA a	and IEEE		
NEMA/MG-1/2003 NEMA/MG-2/2001	Motor and generators ratings, construction, testir Safety standards (enclosures) for construction machines.	0 1		rotating

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

Effect of starting current on torque

$$T_{\rm r} \propto \frac{I_{\rm rr}^2 \times R_2}{S} \tag{2.1}$$

$$\frac{T_{\rm st}}{T_{\rm r}} = \left(\frac{I_{\rm st}}{I_{\rm r}}\right)^2 \times S \tag{2.2}$$

$$\frac{T_{\text{st1}}}{T_{\text{st2}}} = \left(\frac{I_{\text{st1}}}{I_{\text{st2}}}\right)^2 \text{ (for the same rotor resistance } R_2)$$
(2.3)

or
$$\frac{T_{\text{st1}}}{T_{\text{st2}}} = \left(\frac{I_{\text{st1}}}{I_{\text{st2}}}\right)^2 \times \frac{R_2}{R_2'}$$
 (for different rotor resistances)
(2.4)

Time of start-up

$$t_{\rm s} = \frac{GD_{\rm T}^2 \cdot N_{\rm r}}{375 \cdot T_{\rm a}} \tag{2.5}$$

 $t_{\rm s}$ = time of start in seconds

$$GD_{\rm T}^2 = GD_{\rm M}^2 + GD_{\rm L}^2$$

 $GD_{\rm M}^2$ = motor and

 $GD_{\rm L}^2$ = load weight moment of inertia referred to the motor speed

or
$$GD_{\rm L}^2 = GD_{\rm l}^2 \cdot \left(\frac{N_{\rm L}}{N_{\rm r}}\right)^2$$
 (2.6)

 GD_1^2 = weight moment of inertia of load at a speed N_L

Motor heating during start-up

$$H = I_{\rm st}^2 \cdot R \cdot t_{\rm s} \text{ watt} \cdot \text{s. (W} \cdot \text{s.)}$$
(2.7)

also,
$$H = W \cdot \delta \cdot \theta$$
 (2.8)

W = weight of heated portion in kgm

- δ = specific heat of the material of windings, in watt \cdot s/kg/°C.
- θ = temperature rise in °C

Sharing of heat

$$\frac{H_{\rm s}}{H_{\rm r}} = \frac{R_{\rm l}}{R_{\rm 2}'}$$

$$H_{\rm r} = \text{rotor heat in W} \cdot \text{s.}$$

$$H_{\rm s} = \text{stator heat in W} \cdot \text{s.}$$
(2.9)

Heating during a no-load start

$$H_{n\ell} = \frac{GD_{\rm M}^2 \cdot N_{\rm r}^2}{730} \,\,{\rm W} \cdot {\rm s}. \tag{2.10}$$

Heating in a motor during a stalled condition:

for the stator

$$H_{\mathrm{st}\ell} \cdot t_{\mathrm{st}\ell} = \theta \cdot C \tag{2.11}$$

- $H_{\rm st\ell}$ = heat generated during stalled condition per second in watts
- $t_{\mathrm{st}\ell}$ = time for which the stalling condition prevails in seconds
- C = heat capacity of the motor

or
$$t_{\text{st}\,\ell} = \frac{\theta}{J_{\text{ss}}^2 \times 0.00552}$$
 seconds (2.12)

 $J_{\rm ss} \simeq$ current density during start in A/cm²

Braking time

$$t_{\rm b} = \frac{GD_{\rm T}^2 \cdot N}{375 \cdot T_{\rm b}} \text{ seconds(s)}$$
(2.13)

 $N = N_r - N_{r1}$ (i.e. speed reduction in r.p.m.) $T_{\rm b}$ = braking torque in mkg

Braking heat

$$H_{\rm b} = \frac{GD_{\rm T}^2}{730} \cdot (N_{\rm r}^2 - N_{\rm rl}^2) \,\,{\rm W} \,\,.\,\,{\rm s} \tag{2.14}$$

Minimum braking torque

$$T_{\rm b} \ge \frac{P_{\rm r} \cdot 974}{N_{\rm r}} \,\mathrm{mkg} \tag{2.15}$$

Electrodynamic or d.c. electric braking

$$i_{\rm dc} = k_1 \cdot I_{\rm st(ph)} \cdot \sqrt{\frac{T_1 + T_{\rm b} - T_{\rm ex}}{k_2 \cdot T_{\rm st}}}$$
 (2.16)

 $i_{\rm dc}$ = braking current

 $I_{\rm st(ph)}$ = phase value of the starting current

$$= I_{\rm st}/\sqrt{3}$$

- k_1 = factor to determine the equivalent ampere turns for a particular configuration
- T_1 = average load torque between running speed and the final speed

- $T_{\rm b}$ = average braking torque between running speed and the final speed
- $T_{\rm ex}$ = braking torque of the external brakes, if provided; otherwise this may be considered as zero
- $T_{\rm st}$ = starting torque of the motor

 $k_2 =$ a factor to account for the average braking torque

Number of starts and stops

$$Z_{\rm L} = Z_{\rm NL} \cdot \frac{K_{\rm b}}{FI} \cdot K_{\rm L} \tag{2.17}$$

- $Z_{\rm L}$ = Number of starts and equivalent stops per hour on load.
- $Z_{\rm NL}$ = Permissible number of starts per hour with a free shaft

 $K_{\rm b}$ = Factor of braking $K_{\rm L}$ = Mean load factor FI = Factor of inertia

Further Reading

Machinery Hand Book, Industrial Press Inc., 200 Madison Avenue, New York, USA.