5

Induction Motors

5.1 PRINCIPLE OF OPERATION OF THE THREE-PHASE MOTOR

In the form used for industrial drives, induction motors have two main components, the stator and the rotor. The stator carries a three-phase winding that receives power from the supply. The rotor carries a winding that is in the form of a set of single-bar conductors placed in slots just below the surface of the rotor. The slots have a narrow opening at the surface of the rotor, which serves to lock the conductor bars in position. Each end of each bar conductor is connected to a short-circuiting ring, one at each end of the rotor. The stator winding is a conventional type as found in three-phase generators and synchronous motors.

The three-phase stator winding produces a rotating field of constant magnitude, which rotates at the speed corresponding to the frequency of the supply and the number of poles in the motor. The higher the number of poles the lower the speed of the rotation. Assume that the rotor is stationary and the motor has just been energised. The magnetic flux produced by the stator passes through the rotor and in so doing cuts the rotor conductors as it rotates. Since the flux has a sinusoidal distribution in space its rotation causes a sinusoidal emf to be induced into the rotor conductors. Hence currents are caused to flow in the rotor conductors due to the emfs that are induced. The emfs are induced in the rotor by transformer action, which is why the machine is called an ‘induction’ motor. Since currents now flow in both the stator and the rotor, the rotor conductors will set up local fluxes which interact with the excitation flux from the stator. This interaction causes a torque to be developed on the rotor. If this torque exceeds the torque required by the mechanical load the shaft will begin to rotate and accelerate until these two torques are equal. The rotation will be in the direction of the stator flux since the rotor conductors are being driven by the stator flux.

Initially the speed is much less than that of the stator field, although it is increasing. Consequently the rate at which the stator flux cuts the rotor conductors reduces as the shaft speed increases. The frequency and magnitude of the induced rotor emfs therefore decrease as the shaft accelerates. The local flux produced by the rotor conductors therefore rotates at a slower speed relative to the rotor surface. However, since the rotor body is rotating at a slow speed, the combined effect of the body speed plus the rotational speed of the local rotor flux causes the resulting rotor flux to rotate at the same speed as the stator field.

The rotor currents are limited by the short-circuit impedance of the rotor circuit. This circuit contains resistance and reactance. The inductive reactance is directly proportional to the frequency of the induced emfs in the rotor. As the rotor accelerates two effects take place:-

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a) The rotor impedance increases.

b) The rotor emf reduces.

These effects result in the supply current is being nearly constant during most of the run-up period.

The rotor speed cannot reach the same speed as that of the stator field, otherwise there would be no induced emfs and currents in the rotor, and no torque would be developed. Consequently when the rotor speed is near to the synchronous speed the torque begins to decrease rapidly until it matches that of the load and rotational friction and windage losses. When this balance is achieved the speed will remain constant.

5.2 ESSENTIAL CHARACTERISTICS

The most significant design characteristics of interest to power system engineers in the oil industry are:-

- Torque versus speed.
- Stator current versus speed.

Characteristics such as efficiency and power factor at running conditions have traditionally been of secondary importance, but nowadays with an emphasis on energy conservation more attention is being paid to efficiency in particular. The main objectives in the choice of a motor are that:-

- It creates plenty of torque during the whole run-up period.
- It can be started easily using simple switching methods.
- It is a ‘standard’ design from a manufacturer.

5.2.1 Motor Torque versus Speed Characteristic

Many of the electrical engineering textbooks that include the subject of motors in their contents describe the equivalent circuit of an induction motor as a series and parallel combination of resistances and reactances, see References 1 to 8. The equivalent circuit usually defines the situation for one of the three phases and so care needs to be taken to ensure that the final results obtained apply to the complete motor. Care is also necessary in using the ohmic data from manufacturers, they may have either star winding values or delta winding values and the choice may not be obvious. The equivalent circuit of most practical use is shown in Figure 5.1 for one star connected winding, where:-

$$
\begin{aligned}
s &= \text{slip} = \frac{\text{stator frequency} - \text{rotor frequency}}{\text{stator frequency}} \quad \text{per unit} \\
&= \frac{(f \text{ or } \omega) - (f_r \text{ or } \omega_r)}{(f \text{ or } \omega)} \quad \text{per unit}
\end{aligned}
$$

V_s = supply voltage per phase.

I_1 = supply and stator current per phase.

I_2 = rotor current per phase.

R_c = resistance representing the iron core eddy current loss. In some situations the manufacturer may add to this a component to represent friction and windage

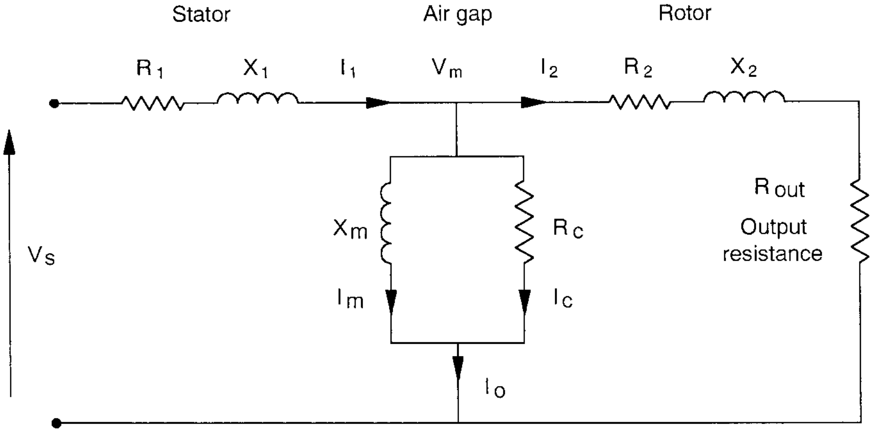


Figure 5.1 Commonly used equivalent circuit of an induction motor.

so that the calculated efficiency and power factor more closely match their measured values when the motor is tested in the factory.
X_m = magnetising reactance of the complete iron core, which represents the flux that passes across the air gap between the stator and the rotor.
R_1 = stator winding resistance.
X_1 = stator winding reactance.
R_2 = rotor winding resistance.
X_2 = rotor winding reactance.
R_{out} = rotor resistance that represents the power delivered to the shaft.
f = supply frequency in Hz.
ω = supply frequency in radians per second.
f_r = rotor frequency in Hz.
ω_r = rotor frequency in radians per second.

This equivalent circuit takes account of the turns ratio between the stator and the rotor if all the rotor resistances and reactance are given in the data as 'referred to the stator' values. The circuit can be used with actual quantities such as ohms, amps and volts, or in their 'per-unit' equivalent values which is often more convenient. This approach is customary since it easily corresponds to measurements that can be made in practice when tests are carried out in the factory.

The resistance R_2 and reactance X_2 are designed by the manufacturer to be functions of slip, so that they take advantage of what is called the 'deep-bar' effect. If the rotor bars are set deep into the surface of the rotor then the rotor resistance R_2 is not so influenced by surface eddy currents, and the rotor leakage reactance X_2 is relatively high due to the depth of the slot which gives a low reluctance path across the slot sides for the flux produced by the bars. Conversely if the conductors are set near to the surface then R_2 becomes high and X_2 becomes low for a given slip. Some special motors actually have two separate cages in their rotors. These are called 'double-cage' motors and are used for driving loads that have high and almost constant torques, such as conveyor belts and cranes. Modern motors utilise the principle of deep bars by designing bars that are shaped rather than simple round bars. The shapes, or cross-sectional areas, are arranged to be narrower at the surface than at their bases. Manufacturers tend to have their own preferences for the shapes and geometries of the rotor bars.

The functions $R_2(s)$ and $X_2(s)$ can be approximated by the following simple linear expressions:-

$$R_2(s) = (R_{21} - R_{20})s + R_{20}$$

and

$$X_2(s) = (X_{21} - X_{20})s + X_{20}$$

Where the suffix 1 refers to the standstill value, and suffix 0 to the full-load value.

The ratio of the standstill values of $R_2(s)$ and $X_2(s)$ to their full-load values are called the 'deep-bar factors' which are:-

$$\text{Deep-bar resistance factor} = u_{r2} = \frac{R_{21}}{R_{20}} > 1.0$$

$$\text{Deep-bar reactance factor} = u_{x2} = \frac{X_{21}}{X_{20}} < 1.0$$

The values of these factors vary with the kW rating and number of poles for the motor, and from one manufacturer to another. Figures 5.2 and 5.3 show the variations in the deep-bar factors for a range of motor ratings from 11 kW to 11 MW, taken from a small sample of typical oil industry two-pole and four-pole motors.

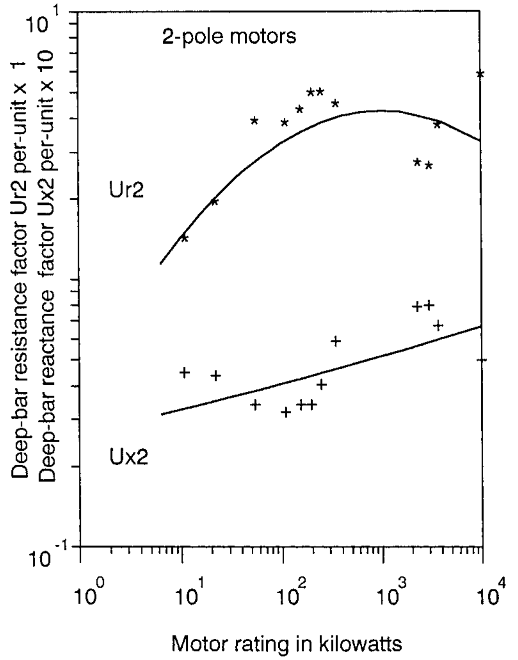


Figure 5.2 Approximate deep-bar resistance and reactance factor curves for two-pole motors rated from 10 kW to 10 MW.

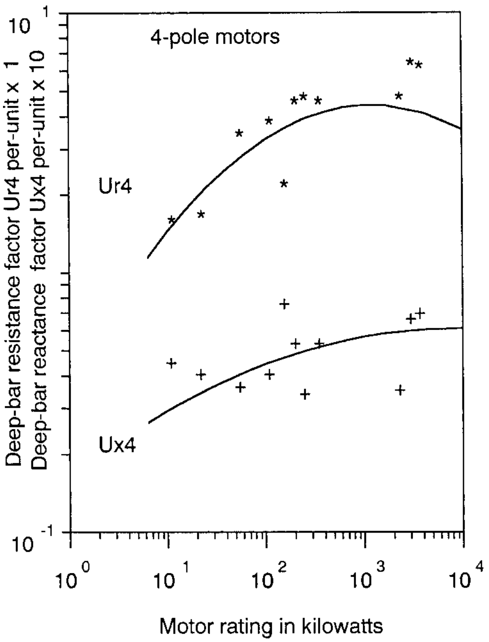


Figure 5.3 Approximate deep-bar resistance reactance curves for four-pole motors rated from 10 kW to 10 MW.

The torque T_e developed in the rotor shaft can be expressed as a function of the air-gap voltage V_m:-

$$T_e = \frac{sR_2{V_m}^2}{{R_2}^2 + (sX_2)^2} \quad \text{Newton metres}$$

Where R_2 and X_2 are both functions of the slip s as explained above. The air-gap voltage can be found from the supply voltage V_s by noting that a voltage divider circuit exists which consists of the series components of the stator and the parallel combination of the magnetising branch and the rotor circuit. Hence V_m becomes:-

$$V_m = \frac{V_s Z_{2m}}{Z_1 + Z_{2m}}$$

where

$$Z_1 = R_1 + jX_1$$

and

$$Z_{2m} = \frac{1}{\dfrac{1}{R_c} + \dfrac{1}{jX_m} + \dfrac{1}{R_2 + R_{\text{out}} + jX_2}}$$

but

$$R_2 + R_{\text{out}} = \frac{R_2}{s}$$

and

$$R_{\text{out}} = \frac{R_2(1-s)}{s}$$

A reasonable and practical approximation can be made for Z_{2m}, which is that the magnitudes of R_c and X_m are each much greater than the magnitude of R_2 and X_2. (For a more precise analysis see Reference 1, Chapter 12.) Hence Z_{2m} reduces to:-

$$Z_{2m} = \frac{R_2}{s} + jX_2$$

And so V_m becomes:-

$$V_m = \frac{V_s(R_2 + jsX_2)}{sR_1 + R_2 + jsX_{12}} \qquad \text{where } X_{12} = X_1 + X_2$$

And so V_m^2 becomes:-

$${V_m}^2 = \frac{{V_s}^2({R_2}^2 + js^2{X_2}^2)}{(sR_1 + R_2)^2 + s^2{X_{12}}^2}$$

Hence the torque becomes:-

$$T_e = \frac{sR_2{V_s}^2}{(sR_1 + R_2)^2 + s^2{X_{12}}^2} \tag{5.1}$$

There are three important conditions to consider from the torque equation:

a) The starting condition in which the slip is unity.
b) The full-load condition in which the slip is small, i.e. 0.005 to 0.05 per-unit.
c) The value and location of the maximum torque $T_{\max}$.

a) The starting condition.

When the slip s equals unity the starting torque T_1 can be found from equation (5.1) as:

$$T_1 = \frac{R_2{V_s}^2}{{R_{12}}^2 + {X_{12}}^2} \tag{5.2}$$

Where,

$$R_{12} = R_1 + R_2$$

The starting torque is very dependent upon R_2 because for typical parameters the total reactance X_{12} is significantly larger than the total resistance R_{12}. During the starting process the denominator remains fairly constant until the slip approaches a value that creates the maximum torque, which is typically a value between 0.05 and 0.2 per-unit, as seen in Figures 5.4 and 5.5 for two ratings of low voltage motors. The higher value of slip generally applies to the lower kW rated motors.

b) The full-load condition

Full-load is obtained when the slip is typically in the range 0.005 to 0.05 per-unit. The higher values apply to the lower kW rated motors. The full-load torque T_0 can be approximated as:-

$$T_0 \approx \frac{s{V_s}^2}{R_2} \tag{5.3}$$

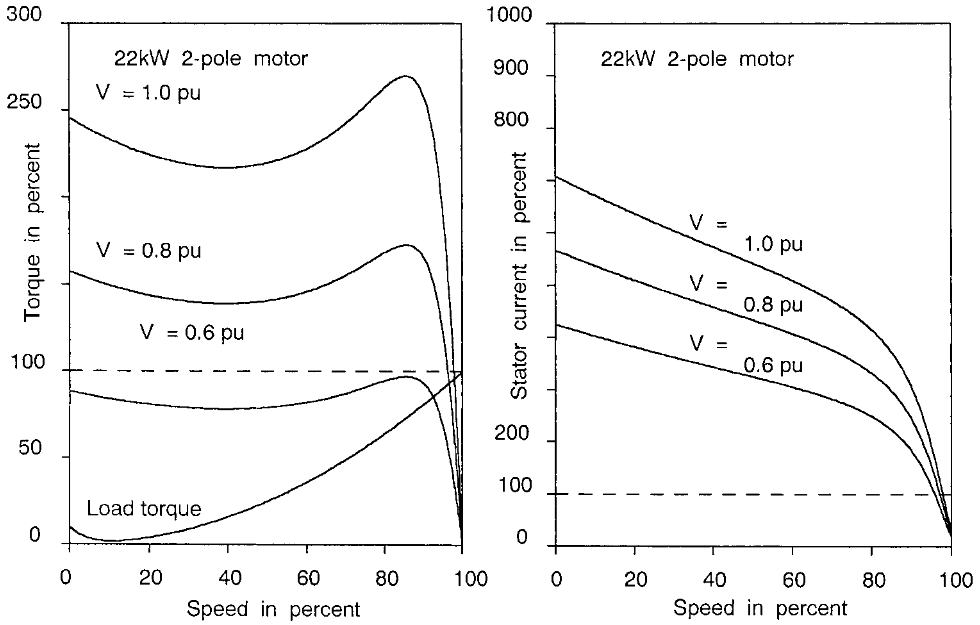


Figure 5.4 Torque and current versus speed curves 22 kW two-pole motor, for different values of applied voltage. Also shown is a typical torque versus speed curve for a centrifugal pump or compressor.

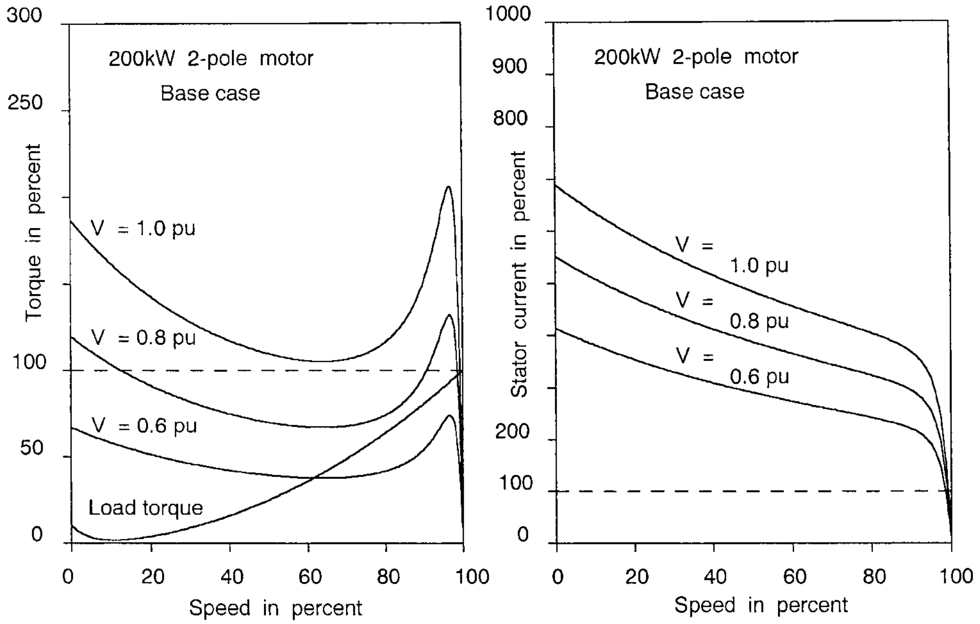


Figure 5.5 Torque and current versus speed curves 200 kW two-pole motor, for different values of applied voltage. Also shown is a typical torque versus speed curve for a centrifugal pump or compressor.

Hence the torque-slip curve has a steep straight-line section near to the region of zero slip. Small changes in slip cause large changes in torque. If the value of R_2 is increased to raise the starting torque then the slope of the full-load straight-line section is reduced, and the speed regulation for changes in load torque becomes poor. The efficiency at and near full-load also falls with increasing values of R_2.

c) The condition for maximum torque.

The maximum torque $T_{\max}$ can be found by differentiating the torque with respect to the slip and equating the derivative to zero. The torque occurs at a particular slip $s_{\max}$, which is found to be:-

$$s_{\max} = \frac{R_2}{\sqrt{{R_1}^2 + {X_{12}}^2}} \tag{5.4}$$

The torque $T_{\max}$ is found by substituting $s_{\max}$ into (5.1):-

$$T_{\max} = \frac{s_{\max} R_2 {V_s}^2}{(s_{\max} R_1 + R_2)^2 + (s_{\max} X_{12})^2} \tag{5.5}$$

For actual motors chosen for oil company applications the value of $s_{\max}$ is very small when compared with unity. Therefore some approximations can be made. In the denominator the resistive term can be simplified as:-

$$(s_{\max} R_1 + R_2)^2 \simeq {R_2}^2$$

The reactive component approaches zero in value for small values of slip. Therefore the maximum torque can be expressed as:-

$$T_{\max} \approx \frac{{V_s}^2}{\sqrt{{R_1}^2 + {X_{12}}^2}} \quad \text{or} \quad \frac{s_{\max} {V_s}^2}{R_2} \tag{5.6}$$

In practice R_1 is much smaller than X_{12} and so the maximum torque is very dependent upon the value of the leakage reactances, especially the rotor leakage reactance X_2. The maximum torque is also called the ‘breakdown’ torque.

Motors are usually started ‘direct-on-line’ with no series impedance added or starting transformers inserted between the supply and the stator terminals of the motor. The starting current is therefore high and an associated volt-drop occurs in the feeder cable to the motor. It is normally a requirement in motor specifications that the motor should start and run up to speed whilst the terminal voltage is reduced to 80% of its rated value. This is an allowance for the volt-drop in the feeder cable. The torque produced by the motor varies with the square of the terminal voltage. Consequently at 80% voltage the torque is reduced to 64% of its value at any slip in the range of zero to unity. This is shown in Figure 5.4 for a 22 kW motor and in Figure 5.5 for a 200 kW low voltage motor. For most designs of motors the ability to start at a voltage of 80% is assured if the motor drives a centrifugal machine. If the voltage falls much lower e.g. 70% or less, then the motor may not develop enough torque to accelerate the load to its full speed. In practice the motor would accelerate the load up to some intermediate speed and then remain at that speed. It would draw a high current and eventually fail from overheating, or be shut down by the protective devices in the switchgear. It is also important that the motor develops a sufficient minimum torque during the run-up period. This torque is often called the ‘pull-up’ torque and it must not fall below the load torque at the associated slip. This is shown in Figure 5.5 for a voltage of 75%, where the rotor would settle at a speed of about 85% and a current of about 230%.

5.2.2 Motor Starting Current versus Speed Characteristic

Once it is established that the motor will produce sufficient torque throughout the speed range then the next considerations are the starting and run-up currents. By examining typical motor impedance values or data from manufacturers, it can be seen that the starting current for typical motors varies between 3.5 times full-load current for large high voltage motors and about 7 times for small low voltage motors. For oil industry applications it is often required that the starting current of the motor should be kept to a low value for direct-on-line starting. The oil industry standard EEMUA132, 1988, gives recommended reduced ratios of starting current to full-load current (I_s/I_n) for ratings above 40 kW, see clauses 5.2 and 5.3 therein. These clauses refer to 'Design N' and 'Design D' motors, which are described in BS4999 part 112 and IEC60034 part 12. Both designs are for direct-on-line starting. Design N provides for general purpose motors, whereas Design D requires the motor to have reduced starting current. These standards have several tables which state the limiting values of 'locked rotor apparent power', which is synonymous with starting current and takes account of the power factor at starting. There are also tables that give limiting values for the starting torque, pull-up torque and breakdown torque for these two types of designs. American practice is covered by NEMA publication MG1 which gives comprehensive tables and data for many different 'designs' and 'codes' for induction motors.

The starting current can be calculated from the equivalent circuit with the value of slip set equal to zero. Once the starting current has been calculated then the starting kVA and power factor can easily be found. The variation of starting current over the full range of slip values is shown in Figure 5.4 for a 22 kW motor and in Figure 5.5 for a 200 kW low voltage motor. The engineer is usually given the following data by a manufacturer for full-load operation of the motor:-

- Rated line-to-line voltage V in volts.
- Rated line current I in amps.
- Rated output power P_0 in kilowatts.
- Rated power factor $\cos\phi$ in per-unit.
- Rated efficiency η in per-unit or percent
- Rated slip in per-unit or percent

These variables are related by the following expressions:-

$$\text{Rated kVA} \qquad S_0 = \frac{\sqrt{3}VI}{1000}$$

$$\text{Rated input power} \qquad P_i = \frac{P_0}{\eta} = S_0 \cos\phi$$

$$\text{Rated input current} \qquad I = \frac{S}{\sqrt{3}V} = \frac{P_0}{\sqrt{3}V\eta\cos\phi}$$

5.2.3 Load Torque versus Speed Characteristic

Most mechanical loads in the oil industry may be classified into two groups:-

- Quadratic torque versus speed.
- Constant torque versus speed.

A quadratic characteristic is typical of centrifugal pumps, centrifugal compressors, screw and axial compressors, fans and turbo-machinery. The characteristic generally consists of two parts, a static part and a dynamic part. The static part accounts for the initial torque that is required at zero and very low speeds. When the driven shaft is stationary, or is rotating slowly, the lubrication between the shaft surface or journal and its bearing is poor. About 5% to 15% of the full-load torque is required to move the shaft. This initial torque is occasionally called 'stiction'. As the shaft begins to rotate this torque declines as the lubrication improves. Once the speed is above about 10% the static torque can be ignored, since the shaft is well supported in its bearings by the lubricant. The dynamic part of the torque is associated with the energy required to compress the fluid in the machine and deliver it from its discharge port. The dynamic characteristic can be expressed in the form:-

$$T_{\text{dynamic}} = KN^2 \quad \text{where } N \text{ is the shaft speed}$$

Most large centrifugal pumps and compressors are started in a 'no-load' state. This means that the suction valve is open and the discharge valve is closed. The machine is filled with fluid but there is little or no throughput of the fluid. The machine therefore requires the minimum energy and torque from the motor. The full-speed torque for 'no-load' operation is between 40% and 60% of the full-load operating torque. When the driven machine reaches full speed the discharge valve is opened and the machine becomes fully loaded. The driven machine should not be allowed to operate continuously in its start-up mode because the energy transmitted to the fluid will be rapidly converted into heat. The machine could be thereby damaged. Small centrifugal pumps and compressors may be started in a partly or fully loaded state. Starting the machine in a no-load state gives the advantage of allowing the motor to create significantly more torque than the machine requires. The surplus torque is able to accelerate the machine in the shortest possible time. The conventional induction motor has only one rotor winding and has the torque characteristic already outlined. Such a motor is usually adequate for driving centrifugal machinery. Figures 5.4, 5.5 and 5.6 show the complete curve for the load torque of a centrifugal machine.

A constant torque versus speed characteristic is typical of reciprocating pumps, reciprocating compressors, conveyors, lifting and cranage equipment and crushers. From zero to full speed the torque is usually almost constant. In addition to high frictional and load torque, these systems may also require a substantial accelerating torque due a high inertia being present. This type of machinery may therefore be difficult to start and run up to full speed. The motor has to be carefully selected and what is called a 'double-cage' motor may prove necessary. A double-cage motor has a rotor which has two rotor windings, one on the outer surface as normal and one set deeper in the same or a separate set of slots. The deeper winding is called the 'inner winding'. By choosing different X-to-R ratios for these two windings or cages it is possible for the motor to develop two torque characteristics simultaneously for a particular slip. The combined torque can be almost constant during the run-up period. However, it is still necessary to ensure that the motor develops adequate surplus torque to accelerate the load when the terminal voltage is depressed.

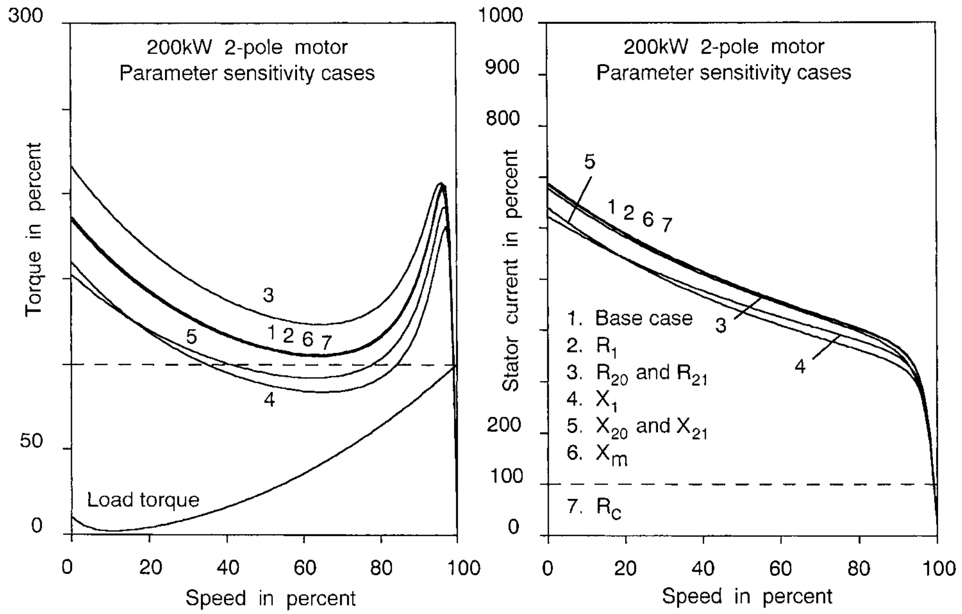


Figure 5.6 Sensitivity of the torque and current versus speed curves to a 20% increase in the nominal value of the resistance or reactance for a 200 kW two-pole motor.

5.2.4 Sensitivity of Characteristics to Changes in Resistances and Reactances

The international standards set recommended limits on the variations of the parameters given by manufacturers. These limits are given as percentage tolerances, and their recommended values are generally not too difficult to achieve. IEC60034 part 1 describes the requirements for duty (as S1 to S9), ratings, operating conditions, temperature rise, tolerances and the like for rotating electrical machines. Regarding tolerances its section 9, Table VIII, gives values for the performance parameters such as losses, running power factor, slip, locked rotor current, locked rotor torque, breakdown torque, pull-up torque and moment of inertia. The standard does not set tolerances on the particular resistances and reactances of the equivalent circuit. In order to show how sensitive the torque–speed and stator current–speed curves are to changes in impedance values, Figure 5.6 was prepared for a typical 200 kW two-pole motor of the Design D type. The six components R_1, X_1, R_2, X_2, R_c and X_m were individually increased by 20% from their nominal values and the appropriate slip recalculated so that the nominal shaft output power was re-established. The following can be seen:-

- Changes in R_1, R_c and X_m have little effect.
- Changes in R_{20} and R_{21} increase the starting and run-up torque, but only change the current by a small amount.
- Changes in X_1, X_{20} and X_{21} reduce both the torque and the current.

5.2.5 Worked Example

A 22 kW two-pole motor drives a water pump and is supplied from a 415 V, 50 Hz power system. Assume that there is no voltage dropped between the supply and the motor. The full-load slip is

0.02208 per-unit. The following ohmic values apply at 415 V for an equivalent star-wound stator:-

$$\begin{array}{llll} R_1 & = 0.179 & X_1 & = 0.438 \\ R_{20} & = 0.0145 & X_{20} & = 0.8230 \\ R_{21} & = 0.253 & X_{21} & = 0.333 \\ R_c & = 115.0 & X_m & = 17.0 \end{array}$$

Calculate the following:-

- Full-load current from the supply.
- Full-load power factor.
- Full-load efficiency.
- Full-load torque.

- Starting current from the supply.
- Starting power factor.
- Starting torque.

Figure 5.1 is the appropriate equivalent circuit for the calculations.

a) Solution for full-load.

The applied voltage per phase V_p is:-

$$V_p = \frac{415.0}{\sqrt{3}} = 239.6 \text{ volts}$$

The rotor resistance R_2 and reactance X_2 are:-

$$R_2 = (0.253 - 0.145) \times 0.02208 + 0.145 = 0.1474 \text{ ohms}$$

$$X_2 = (0.333 - 0.823) \times 0.02208 + 0.823 = 0.8122 \text{ ohms}$$

The rotor 'output power' resistance R_{out} at the given slip is:-

$$R_{\text{out}} = R_2 \left(\frac{1 - s}{s} \right) = 0.1474 \left(\frac{1 - 0.02208}{0.02208} \right) = 6.5273 \text{ ohms}$$

The total rotor impedance Z_{22} is:-

$$\begin{aligned} Z_{22} &= R_2 + jX_2 + R_{\text{out}} = 0.1474 + j0.8122 + 6.5273 \\ &= 6.6747 + j0.8122 \end{aligned}$$

The shunt components at the air gap are combined in parallel as:-

$$Z_{mc} = \frac{R_c\, jX_m}{R_c + jX_m} = \frac{115.0 \times j17.0}{115.0 + j17.0}$$
$$= 2.4593 + j16.6365 \text{ ohms}$$

The total air-gap impedance Z_{m22} is:-

$$Z_{m22} = \frac{Z_{mc} Z_{22}}{Z_{mc} + Z_{22}} = \frac{(2.4593 + j16.6365) \times (6.6747 + j0.8122)}{2.4593 + j16.6365 + 6.6747 + j0.8122}$$
$$= 5.1534 + j2.5313 \text{ ohms}$$

The total motor impedance Z_{mot} is:-

$$Z_{\text{mot}} = R_1 + jX_1 + Z_{m22} = 0.179 + j0.438 + 5.1534 + j2.5313$$
$$= 5.3324 + j2.9693 \text{ ohms, which has a magnitude of } 6.1033 \text{ ohms.}$$

The stator current per phase I_1 is:-

$$I_1 = \frac{V_p}{Z_{\text{mot}}} = \frac{239.6 + j0.0}{5.3324 + j2.9693} = 34.2982 - j19.0987 \text{ amps,}$$

which has a magnitude of 39.257 amps.

The air-gap voltage V_m is:-

$$V_m = V_p - I_1 Z_1 = (239.6 + j0.0) - (34.2982 - j19.0987)(0.179 + j0.438)$$
$$= 225.096 - j11.604 \text{ volts, which has a magnitude of } 225.395 \text{ volts.}$$

The rotor current per phase I_2 is:-

$$I_2 = \frac{V_m}{Z_{22}} = \frac{225.06 - j11.604}{6.6747 + j0.8122} = 33.0235 - j5.7569 \text{ amps,}$$
$$R_c + jX_m = 115.0 + j17.0$$

which has a magnitude of 33.5215 amps.

The output power P_{out} is:-

$$P_{\text{out}} = 3 \times {I_2}^2 \times R_{\text{out}} = 3 \times 1123.691 \times 6.5273 = 22.004 \text{ kW}$$

The magnetising current per phase I_m is:-

$$I_m = \frac{V_m}{jX_m} = \frac{225.06 - j11.604}{j17.0} = 0.6826 - j13.241 \text{ amps}$$

The core loss current per phase I_c is:-

$$I_c = \frac{V_m}{R_c} = \frac{225.06 - j11.604}{115.0} = 1.9574 - j0.1009 \text{ amps}$$

Therefore the total shunt current I_o at the air gap is:-

$$I_o = I_m + I_c = 2.6400 - j13.342 \text{ amps}$$

The input kVA S_{in} is:-

$$S_{\text{in}} = \frac{3 \times I_1{}^* \times V_p}{1000} = \frac{3}{1000}(34.2982 + j19.0987)(239.6 + j0.0)$$
$$= 24.653 + j13.728 \text{ kVA, which has a magnitude of 28.218 kVA.}$$

Hence the input active power P_{in} in kW and input reactive power Q_{in} in kVAr are:-

$$P_{\text{in}} = 24.653 \text{ kW and } Q_{\text{in}} = 13.728 \text{ kVAr}$$

The input power factor PF_{in} of the stator current is:-

$$PF_{\text{in}} = \frac{P_{\text{in}}}{S_{\text{in}}} = \frac{24.653}{28.218} = 0.8737 \text{ pu lagging}$$

The efficiency η of the motor at full-load is:-

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{22.004}{24.653} = 0.8925 \text{ pu}$$

The full-load torque T_e is:-

$$T_e = \frac{3sR_2V_m{}^2}{R_2{}^2 + s^2X_2{}^2} = \frac{3 \times 0.02208 \times (0.1474 \times 225.395)^2}{0.1474^2 + (0.02208 \times 0.8122)^2} = 22524.2 \text{ nm}$$

b) Solution for starting.

The same sequence of calculations can be followed for the starting condition as was used for the full-load condition, but with the slip set to unity. The results of each step are summarised below:-

$$R_2 = R_{21} = 0.253 \text{ ohms and } X_2 = X_{21} = 0.333 \text{ ohms}$$

The rotor 'output power' resistance R_{out} is zero.

The total rotor impedance Z_{22} is:-

$$Z_{22} = R_2 + jX_2 + 0.0 = 0.253 + j0.333 \text{ ohms}$$

The shunt components at the air gap are combined in parallel as:-

$$Z_{mc} = \frac{R_c jX_m}{R_c + jX_m} = \frac{115.0 \times j17.0}{115.0 + j17.0} = 2.4593 + j16.6365 \text{ ohms}$$

The total air-gap impedance Z_{m22} is:-

$$Z_{m22} = \frac{Z_{mc} Z_{22}}{Z_{mc} + Z_{22}} = 0.2437 + j0.3288 \text{ ohms}$$

The total motor impedance Z_{mot} is:-

$$Z_{\text{mot}} = R_1 + jX_1 + Z_{m22} = 0.4227 + j0.7668 \text{ ohms}$$

The stator current per phase I_1 is:-

$$I_1 = \frac{V_p}{Z_{\text{mot}}} = 132.124 - j239.64 \text{ amps},$$

which has a magnitude of 273.65 amps, which is 6.97 times the full-load value.

The air-gap voltage V_m is:-

$$\begin{aligned} V_m &= V_p - I_1 Z_1 \\ &= 110.988 - j14.9748 \text{ volts, which has a magnitude of } 111.994 \text{ volts.} \end{aligned}$$

The rotor current per phase I_2 is:-

$$I_2 = \frac{V_m}{Z_{22}} = \frac{110.988 - j14.9748}{0.253 + j0.333} = 132.039 - j232.98 \text{ amps},$$

which has a magnitude of 267.795 amps.

The output power P_{out} is zero.

The total shunt current I_o at the air gap is:-

$$I_m = \frac{V_m}{\dfrac{R_c j\ X_m}{R_c + j\ X_m}} = 0.0842 - j\ 6.6589 \text{ amps}$$

The input kVA S_{in} is:-

$$\begin{aligned} S_{\text{in}} &= \frac{3 \times I_1{}^* \times V_p}{1000} \\ &= 94.971 + j\ 172.253 \text{ kVA, which has a magnitude of } 196.699 \text{ kVA.} \end{aligned}$$

Hence the input active power P_{in} in kW and input reactive power Q_{in} in kVAr are:-

$$P_{\text{in1}} = 94.971 \text{ kW and } Q_{in1} = 172.253 \text{ kVAr}$$

The input power factor PF_{in} of the stator current is:-

$$PF_{\text{in}} = \frac{P_{\text{in1}}}{S_{\text{in1}}} = \frac{94.971}{196.699} = 0.4828 \text{ pu lagging}$$

The efficiency η of the motor at starting is zero.

The starting torque T_{e1} is:-

$$T_{e1} = \frac{3\ R_2\ {V_m}^2}{{R_2}^2 + {X_2}^2} = \frac{3 \times 0.253 \times 111.994^2}{0.253^2 + 0.333^2} = 54431.0 \text{ nm}$$

which is 2.417 times the full-load value.

5.2.6 Typical Impedance Data for two-Pole and four-Pole Induction Motors

Tables 5.1–5.4 show the approximate resistance and reactance values in per-unit for two-pole and four-pole low voltage induction motors that are generally of the Design D type. Tables 5.5–5.8 show the approximate resistance and reactance values in per-unit for two-pole and four-pole high voltage induction motors that are of the reduced starting current type. In the absence of exact data from a manufacturer these data can be used for system studies such as starting motors, transient stability and fault current contribution. The data from a manufacturer should be used for calculations and system studies that are to be carried out during the detailed design phase of a project.

5.2.7 Representing the Deep-Bar Effect by Two Parallel Branches

Consider a series connection of resistance and inductive reactance, denoted as $R_n + jX_n$. Any number, n, of these branches can be connected in parallel. The sum of these parallel branches can also be

Table 5.1. Per-unit resistances and starting-to-full-load current ratio for LV two-pole motors

Rated power (kW)	Slip (pu)	R_1	R_{20}	R_{21}	R_c	I_s/I_n
11	0.0433	0.0437	0.0323	0.0398	15.44	6.29
15	0.0355	0.0377	0.0270	0.0411	16.69	6.42
22	0.0282	0.0312	0.0218	0.0421	18.35	6.55
30	0.0237	0.0268	0.0186	0.0425	19.81	6.65
37	0.0216	0.0241	0.0167	0.0425	20.85	6.70
45	0.0191	0.0219	0.0152	0.0423	21.86	6.74
55	0.0173	0.0197	0.0138	0.0419	22.95	6.78
75	0.0150	0.0168	0.0120	0.0410	24.73	6.83
90	0.0138	0.0153	0.0111	0.0403	25.83	6.85
110	0.0126	0.0138	0.0103	0.0393	27.09	6.86
132	0.0117	0.0125	0.00955	0.0384	28.28	6.87
160	0.0108	0.0113	0.00888	0.0372	29.59	6.87
200	0.00995	0.0100	0.00820	0.0357	31.17	6.85
250	0.00917	0.00887	0.00759	0.0341	32.83	6.83
315	0.00846	0.00782	0.00705	0.0323	34.63	6.79

Table 5.2. Per-unit reactances and starting-to-full-load torque ratio for LV two-pole motors

Rated power (kW)	Slip (pu)	X_1	X_{20}	X_{21}	X_M	T_s/T_n
11	0.0433	0.0840	0.114	0.0531	2.317	1.50
15	0.0355	0.0833	0.124	0.0528	2.503	1.61
22	0.0282	0.0825	0.137	0.0527	2.752	1.73
30	0.0237	0.0819	0.147	0.0529	2.970	1.80
37	0.0216	0.0815	0.153	0.0532	3.126	1.84
45	0.0191	0.0812	0.159	0.0536	3.278	1.86
55	0.0173	0.0809	0.165	0.0541	3.442	1.86
75	0.0150	0.0804	0.173	0.0551	3.708	1.85
90	0.0138	0.0802	0.178	0.0558	3.874	1.83
110	0.0126	0.0799	0.182	0.0567	4.064	1.80
132	0.0117	0.0797	0.186	0.0576	4.244	1.76
160	0.0108	0.0795	0.189	0.0587	4.442	1.70
200	0.00995	0.0793	0.193	0.0601	4.682	1.63
250	0.00917	0.0791	0.196	0.0617	4.934	1.55
315	0.00846	0.0790	0.198	0.0635	5.207	1.45

Table 5.3. Per-unit resistances and starting-to-full-load current ratio for LV four-pole motors

Rated power (kW)	Slip (pu)	R_1	R_{20}	R_{21}	R_c	I_s/I_n
11	0.0527	0.0405	0.0379	0.0497	14.92	6.01
15	0.0436	0.0361	0.0319	0.0488	16.06	6.03
22	0.0352	0.0311	0.0261	0.0478	17.41	6.06
30	0.0299	0.0275	0.0225	0.0471	18.43	6.08
37	0.0270	0.0252	0.0204	0.0468	19.07	6.10
45	0.0246	0.0232	0.0187	0.0464	19.63	6.13
55	0.0225	0.0213	0.0172	0.0462	20.16	6.16
75	0.0197	0.0186	0.0152	0.0458	20.86	6.22
90	0.0183	0.0171	0.0142	0.0456	21.22	6.26
110	0.0170	0.0156	0.0132	0.0455	21.55	6.31
132	0.0159	0.0144	0.0124	0.0454	21.79	6.37
160	0.0148	0.0131	0.0117	0.0453	21.99	6.43
200	0.0138	0.0118	0.0109	0.0453	22.14	6.52
250	0.0129	0.0106	0.0102	0.0453	22.21	6.62
315	0.0121	0.00942	0.00965	0.0454	22.19	6.74

represented by a series circuit of the $R + jX$ type. This approach can be used to represent the deep-bar effect in the rotor of an induction motor. It has the effect of splitting the rotor bars into a set of outer bars and a set of inner bars, both sets then being independent of each other. In addition the resistances become simple reciprocal functions of slip, whilst the inductive reactances remain constant as the slip varies.

Let the outer bars be represented by the series branch $R_{22}/s + jX_{22}$ and the inner bars by the branch $R_{33}/s + jX_{33}$, where s is the slip. Let the sum of the two branches be $R_{23}/s + jX_{23}$. It is

Table 5.4. Per-unit reactances and starting-to-full-load torque ratio for LV four-pole motors

Rated power (kW)	Slip (pu)	X_1	X_{20}	X_{21}	X_M	T_s/T_n
11	0.0527	0.0813	0.149	0.0610	2.245	1.69
15	0.0436	0.0810	0.160	0.0638	2.416	1.67
22	0.0352	0.0806	0.173	0.0668	2.617	1.66
30	0.0299	0.0801	0.183	0.0687	2.768	1.65
37	0.0270	0.0797	0.188	0.0697	2.863	1.65
45	0.0246	0.0793	0.193	0.0705	2.946	1.65
55	0.0225	0.0788	0.197	0.0710	3.023	1.66
75	0.0197	0.0780	0.203	0.0715	3.127	1.68
90	0.0183	0.0775	0.205	0.0715	3.178	1.70
110	0.0170	0.0769	0.207	0.0712	3.226	1.73
132	0.0159	0.0763	0.208	0.0708	3.262	1.76
160	0.0148	0.0756	0.209	0.0702	3.290	1.79
200	0.0138	0.0748	0.208	0.0693	3.311	1.84
250	0.0129	0.0739	0.207	0.0681	3.319	1.90
315	0.0121	0.0730	0.205	0.0666	3.313	1.97

Table 5.5. Per-unit resistances and starting-to-full-load current ratio for HV two-pole motors

Rated power (kW)	Slip (pu)	R_1	R_{20}	R_{21}	R_M	I_s/I_n
630	0.00887	0.00627	0.00771	0.0183	44.16	6.24
800	0.00896	0.00648	0.00776	0.0175	45.20	6.02
1100	0.00901	0.00667	0.00777	0.0172	46.17	5.71
2500	0.00883	0.00662	0.00740	0.0205	46.24	4.85
5000	0.00842	0.00600	0.00672	0.0303	43.63	4.11

Table 5.6. Per-unit reactances and starting-to-full-load torque ratio for HV two-pole motors

Rated power (kW)	Slip (pu)	X_1	X_{20}	X_{21}	X_M	T_s/T_n
630	0.00887	0.112	0.0961	0.0471	4.134	0.694
800	0.00896	0.118	0.0935	0.0470	4.313	0.620
1100	0.00901	0.126	0.0912	0.0477	4.518	0.550
2500	0.00883	0.151	0.0917	0.0537	4.817	0.472
5000	0.00842	0.176	0.0991	0.0651	4.781	0.497

required to find unique values for R_{22}, X_{22}, R_{33} and X_{33} that give the required values of R_{23} and X_{23}. (The double suffices are chosen so as not to cause confusion with the single suffices used for example in sub-section 5.2.1.) This can only be achieved if two values of slip are used, which for convenience are the standstill and full-load values. This choice yields four equations in four unknown variables. Hence a unique solution should be achievable. The equations are not linear and so transposing them into a simple algebraic form is not possible, therefore an iterative method needs to be used to find the solution. The four equations are found as follows.

Table 5.7. Per-unit resistances and starting-to-full-load current ratio for HV four-pole motors

Rated power (kW)	Slip (pu)	R_1	R_{20}	R_{21}	R_c	I_s/I_n
630	0.00828	0.00809	0.00688	0.0285	39.01	5.84
800	0.00932	0.00804	0.00764	0.0288	45.16	5.45
1,100	0.01050	0.00780	0.00844	0.0287	52.88	5.00
1,500	0.01120	0.00742	0.00889	0.0280	59.20	4.66
2,500	0.01120	0.00650	0.00878	0.0256	65.29	4.35
5,000	0.00895	0.00495	0.00713	0.0207	62.59	4.40
6,300	0.00785	0.00441	0.00633	0.0189	59.01	4.53
8,000	0.00667	0.00386	0.00545	0.0169	54.24	4.71
11,000	0.00515	0.00308	0.00450	0.0143	53.06	5.02

Table 5.8. Per-unit reactances and starting-to-full-load torque ratio for HV four-pole motors

Rated power (kW)	Slip (pu)	X_1	X_{20}	X_{21}	X_M	T_s/T_n
630	0.00828	0.109	0.120	0.0594	3.213	0.934
800	0.00932	0.126	0.112	0.0546	3.403	0.828
1,100	0.01050	0.147	0.104	0.0501	3.635	0.697
1,500	0.01120	0.165	0.0996	0.0474	3.834	0.593
2,500	0.01120	0.182	0.0976	0.0460	4.085	0.473
5,000	0.00895	0.177	0.106	0.0498	4.242	0.391
6,300	0.00785	0.173	0.111	0.0528	4.243	0.377
8,000	0.00667	0.155	0.119	0.0570	4.217	0.365
11,000	0.00515	0.135	0.134	0.0647	4.145	0.350

At standstill the slip is 1, therefore the equivalent impedance is,

$$Z_{231} = R_{231} + jX_{231} = \frac{(R_{22} + jX_{22})(R_{33} + jX_{33})}{R_{22} + jX_{22} + R_{33} + jX_{33}} \tag{5.7}$$

At full-load the slip is s, therefore the equivalent impedance is,

$$Z_{230} = R_{230}/s + jX_{230} = \frac{(R_{22}/s + jX_{22})(R_{33}/s + jX_{33})}{R_{22}/s + jX_{22} + R_{33}/s + jX_{33}} \tag{5.8}$$

Taking the real and imaginary parts of each equation separately yields the four equations required for the solution. The given values are R_{230}, X_{230}, R_{231}, X_{231} and the full-load slip s. The solution is the set of values R_{22}, X_{22}, R_{33}, and X_{33}.

The iterative solution can be carried out by one of various algorithms, for example Newton's approximation to find roots, steepest descent to find a minimum quadratic error, rough search, successive substitution. Newton's method in four dimensions works reasonably well, although instability can set in if the incremental changes are allowed to be too large. Hence some 'deceleration' is required to stabilise the algorithm. The method of successive substitution is more efficient, but also requires stabilising with a ‘deceleration’ factor. Equation (5.7) for slip = 1 can be expanded to yield the following equation,

$$Z_{231} = R_{231} + jX_{231} = \frac{C_1E_1 + D_1F_1}{G_1} + \frac{j(D_1E_1 - C_1F_1)}{G_1} \tag{5.9}$$

Similarly (5.8) for slip $= s$ can be expanded to yield the following equation,

$$Z_{230} = R_{230} + jX_{230} = \frac{C_0E_0 + D_0F_0}{G_0} + \frac{j(D_0E_0 - C_0F_0)}{G_0} \tag{5.10}$$

From (5.9) a new value of R_{22} can be found as R_{22N},

$$R_{22N} = \frac{G_1R_{231} - D_1F_1}{E_1R_{33}} + \frac{X_{22}X_{33}}{R_{33}} \tag{5.11}$$

Also from (5.9) a new value of X_{22} can found be as X_{22N},

$$X_{22N} = \frac{G_1X_{231} + C_1F_1}{E_1R_{33}} - \frac{R_{22}\ X_{33}}{R_{33}} \tag{5.12}$$

From (5.10) a new value of R_{33} can be found as R_{33N},

$$R_{33N} = \frac{G_0R_{230} - D_0F_0}{U^2E_0R_{22}} + \frac{X_{22}\ X_{33}}{U^2R_{22}} \tag{5.11}$$

Also from (5.10) a new value of X_{33} can be found as X_{33N},

$$X_{33N} = \frac{G_0X_{230} + C_0F_0}{UE_0R_{22}} - \frac{X_{22}\ R_{33}}{R_{22}} \tag{5.12}$$

Where $U = 1/\text{slip} = 1/s$
$C_1 = R_{22}R_{33} - X_{22}X_{33}$
$D_1 = R_{22}X_{33} + X_{22}R_{33}$
$E_1 = R_{22} + R_{33}$
$F_1 = X_{22} + X_{33}$
$G_1 = E_1{}^2 + F_1{}^2$

and $C_0 = U^2R_{22}R_{33} - X_{22}X_{33}$
$D_0 = UR_{22}X_{33} + X_{22}R_{33}$
$E_0 = U(R_{22} + R_{33})$
$F_0 = X_{22} + X_{33}$
$G_0 = U^2E_0{}^2 + F_0{}^2$

The calculation process is simple and convergent provided some deceleration ‘k’ is applied. An initial guess is required for R_{22}, X_{22}, R_{33} and X_{33}, which may require a little trial and error experimentation to find suitable values. These values are used in the equations to yield a new set of

$R_{22\mathrm{N}}$, $X_{22\mathrm{N}}$, $R_{33\mathrm{N}}$ and $X_{33\mathrm{N}}$. The cycle is repeated using the 'old' values (call these $R_{22\mathrm{O}}$, $X_{22\mathrm{O}}$, $R_{33\mathrm{O}}$ and $X_{33\mathrm{O}}$) plus a small amount of the error between the 'new' and 'old' values, i.e.,

$$R_{22} = R_{22\mathrm{O}} + k(R_{22\mathrm{N}} - R_{22\mathrm{O}})$$

$$X_{22} = X_{22\mathrm{O}} + k(X_{22\mathrm{N}} - X_{22\mathrm{O}})$$

$$R_{33} = R_{33\mathrm{O}} + k(R_{33\mathrm{N}} - R_{33\mathrm{O}})$$

$$X_{33} = X_{33\mathrm{O}} + k(X_{33\mathrm{N}} - X_{33\mathrm{O}})$$

The value of 'k' should be chosen to be between +0.001 and +0.01 to ensure stability. The process is stopped once the absolute error in each of the parameters has fallen below a suitably small value, e.g. 0.001 per-unit of its absolute value. Tables 5.9 and 5.10 for two-pole induction motors were complied from Tables 5.1, 5.2, 5.5 and 5.6, to show the results of the method.

5.3 CONSTRUCTION OF INDUCTION MOTORS

The physical construction of an induction motor is greatly influenced by the environment and ambient conditions. The environmental conditions include considerations for explosion, corrosion, dampness, ingress of dust and solid particles, proximity to human operators, cost and economics. Ambient conditions relate to surface temperature, methods of cooling, fan design and appropriate derating factors.

Table 5.9. Per-unit resistances for equivalent double-cage two-pole motors

Rated power (kW)	Slip (pu)	R_{20}	R_{21}	R_{22}	R_{33}
LV	—	—	—	—	—
11	0.0433	0.0323	0.0398	0.0434	0.11308
15	0.0355	0.0270	0.0411	0.05127	0.05491
22	0.0282	0.0218	0.0421	0.05865	0.03391
30	0.0237	0.0186	0.0425	0.06165	0.02619
37	0.0216	0.0167	0.0425	0.06342	0.02232
45	0.0191	0.0152	0.0423	0.06389	0.01967
55	0.0173	0.0138	0.0419	0.06402	0.01737
75	0.0150	0.0120	0.0410	0.06378	0.01461
90	0.0138	0.0111	0.0403	0.06312	0.01332
110	0.0126	0.0103	0.0393	0.06210	0.01222
132	0.0117	0.00955	0.0384	0.06119	0.01120
160	0.0108	0.00888	0.0372	0.06007	0.01032
200	0.00995	0.00820	0.0357	0.05840	0.00945
250	0.00917	0.00759	0.0341	0.05685	0.00868
315	0.00846	0.00705	0.0323	0.05485	0.00802
HV	—	—	—	—	—
630	0.00887	0.00771	0.0183	0.03660	0.00920
800	0.00896	0.00776	0.0175	0.03491	0.00995
1100	0.00901	0.00777	0.0172	0.03587	0.00989
2500	0.00883	0.00740	0.0205	0.06099	0.00841
5000	0.00842	0.00672	0.0303	0.12957	0.00709

Table 5.10. Per-unit reactances for equivalent double-cage two-pole motors

Rated power (kW)	Slip (pu)	X_{20}	X_{21}	X_{22}	X_{33}
LV	—	—	—	—	—
11	0.0433	0.114	0.0531	0.05442	1.1944
15	0.0355	0.124	0.0528	0.05573	0.4755
22	0.0282	0.137	0.0527	0.05619	0.3236
30	0.0237	0.147	0.0529	0.05571	0.2899
37	0.0216	0.153	0.0532	0.05596	0.2741
45	0.0191	0.159	0.0536	0.05640	0.2678
55	0.0173	0.165	0.0541	0.05716	0.2635
75	0.0150	0.173	0.0551	0.05882	0.2591
90	0.0138	0.178	0.0558	0.06012	0.2591
110	0.0126	0.182	0.0567	0.06195	0.2590
132	0.0117	0.186	0.0576	0.06357	0.2590
160	0.0108	0.189	0.0587	0.06601	0.2582
200	0.00995	0.193	0.0601	0.06892	0.2594
250	0.00917	0.196	0.0617	0.07223	0.2593
315	0.00846	0.198	0.0635	0.07597	0.2586
HV	—	—	—	—	—
630	0.00887	0.0961	0.0471	0.07070	0.1413
800	0.00896	0.0935	0.0470	0.06432	0.1493
1100	0.00901	0.0912	0.0477	0.06695	0.1433
2500	0.00883	0.0917	0.0537	0.08472	0.1173
5000	0.00842	0.0991	0.0651	0.08768	0.1101

The stator design is more affected by these factors than that of the rotor but the rotor needs to be designed so that efficient fan cooling can be achieved. The stator winding and magnetic iron circuit are part of the enclosure. The enclosure is the frame and casing which anchors the windings and provides the fixing structure of the motor, e.g. bed-plate, flange mounting. The enclosure may be of an ‘open’ or ‘closed’ type. The simplest and cheapest motors use an open enclosure. All the windings are exposed to the surrounding air by virtue of deliberately placed windows or openings at the ‘drive’ and ‘non-drive’ ends of the enclosure. The surrounding air is drawn through these windows by a simple shaft-mounted fan which is used to cool the rotor and the stator materials. The air is drawn along the air gap and discharged at the outlet end. An example of such a simple construction is a modern domestic washing machine or vacuum cleaner, but in an industrial situation this design would be deemed unsafe to human operators and would be exposed to any kind of pollution present in the cooling air, e.g. moisture, dust, chemicals, flammable gas. There are several forms of open-type motors as defined in American documentation. For example NEMA standard MG1 classifies those appropriate for general non-hazardous use. Not all open-type motors can be used in oil industry plants.

The oil industry normally specifies closed or enclosed type motors. Industrial motors are designed so that their windings and bearings are given the least exposure to poor quality air and, to this end, a ‘totally enclosed’ (TE) construction is used. In a TE design the bearings, rotor and stator windings are surrounded by an enclosed air atmosphere. The enclosed air is circulated by one or two shaft-mounted fans. The NEMA MG1 standard also classifies those that are appropriate for both hazardous and non-hazardous area installations. IEC60034 part 5, IEC60079 and NEC articles

500 to 516 give recommendations for the use of motors in hazardous areas and different types of environment, see also Chapter 10. Air is arranged to pass along the air gap to absorb the rotor heat and along and between the stator windings to absorb the stator heat. The heat is radiated from the outer surface of the stator frame. The design of the fans and the air paths is a complicated subject and has to be optimised for each type of motor and its rated speed.

As the motors become larger the removal of heat becomes more difficult to achieve and hence more elaborate means need to be employed. To rely solely on simple surface radiation from the stator would not be a sufficient means for motors above about 50 kW. A second air circuit is created by mounting an external fan on the non-drive end of the rotor. This fan draws in cool air from the non-drive end face, under a cowling, and blows it over the stator surface. The stator surface may be ribbed to increase the surface area or be fitted with longitudinal air tubes. These methods are satisfactory for motors up to about 500 kW. Beyond 500 kW the methods of fan cooling can become very elaborate, involving large air-to-air heat exchangers or even air-to-water exchangers.

Ingress of water and particles is defined in various international standards as outlined in Chapters 3 and 10.

5.4 DERATING FACTORS

In common with other power system equipment, motors need to be derated to suit a high ambient temperature. Equipment that is manufactured in America, UK and Europe is usually based on a maximum design temperature of 40°C. For higher ambient temperatures, e.g. 50°C as found in the Middle East and Far East, the continuous duty output power and supply current would need to be reduced. The continuous duty is that as defined as type S1 in IEC60034 part 1. International standards recommend performance and design criteria suitable for 40°C. Although most of these standard requirements will apply to ambient temperatures above 40°C there may be some addition restrictions to apply. In particular aspects of full-load current, duty, radiation of heat loss and outer surface temperature will need to be considered, see for example IEC60034 part 1 clauses 11 and 16.3. Some countries that experience high ambient temperatures and who enjoy a substantial 'home market' for their own products, such as India, use national standards that set the ambient temperature to a higher value such as 45°C, which is more practical in their circumstances. When a purchase specification is being prepared it is recommended that this aspect of operating a motor continuously at or near its full-load rating in a high ambient temperature is highlighted.

IEC60085 and IEC60034 part 1 describe the limitations placed on materials used inside motors (and other electrical equipment). Most electrical machines with air or gas as the cooling medium use Class B or F solid insulation material. Where the environment is harsh, and high ambient temperatures occur, then it is advisable to specify Class F insulation materials but with a restriction of Class B temperature rise. Such a specification will inherently increase the mean time to failure of the materials since they will be less stressed.

5.5 MATCHING THE MOTOR RATING TO THE DRIVEN MACHINE RATING

The importance of having sufficient motor torque for all speeds has been described earlier. For general guidance it is possible to choose the kW rating of the motor on a 'rule-of-thumb' basis by using Table 5.11 below.

Table 5.11. Margin of motor rating above the machine rating

Driven machine power rating (kW)	Margin multiplier (per-unit)
Up to 15	1.25
16 to 55	1.15
56 and above	1.10

When considering centrifugal machines it is important to base the motor rating on the 'end of curve' condition of the driven machine, because in practice the machine may need to run at this extreme condition for a reasonably long period of time. This condition is generally defined as 125% of the capacity of the machine at the maximum working efficiency point on the 'head-flow' curve for the designed shaft speed.

For belt-driven loads the margin factor should be a little larger than for direct in-line driven machines due to the lower transmission efficiency of belt drives. Let an additional multiplying factor be used to that given in Table 5.11. This factor should be approximately 1.2 for the smaller motors to 1.4 for the larger motors. It is also advisable to obtain advice from the manufacturers of both the driven machine and the motor.

In addition to overcoming the static torque of the load at all speeds the motor must be capable of accelerating the inertia of the load. If the inertia is too high the motor will take an excessive length of time to reach the desired speed. In the worst case it may not be able to accelerate at all. In both cases the motor will overheat and possibly suffer damage. The international standards recommend a maximum polar moment of inertia (J) in $\mathrm{kg\,m^2}$ units of the load. This information is given for a wide range of kW ratings and numbers of poles in the motor. For example Table III of IEC60034 part 12 gives inertia values for 2, 4, 6 and 8 pole motors rated up to 630 kW. Table 5 also gives formulae that can be used for higher ratings. This subject is also addressed in IEC60034 part 1 clause 6 in connection with the nine different 'duty types, S1 to S9'. If a load has an inertia higher than the limit for a motor matched by other criteria, then the rating of the motor will need to be increased until the inertia criterion is met. This will result in a motor that will run continuously at a continuous power appreciably less than its rated power. Some attention may need to be given to the choice of the protective overload relay and its settings in such a circumstance.

5.6 EFFECT OF THE SUPPLY VOLTAGE ON RATINGS

Since the torque at any speed is a function of the supply voltage squared it is important that the voltage at the terminals of the motor does not fall too far during the starting period or during predictable system disturbances. As a general guide or 'rule-of-thumb' the motor should operate satisfactorily and accelerate the load quickly even when the terminal voltage remains as low as 80% of its rated value for a long period of time. Hence the torque will be 64% of its value during this situation. This amount of torque should be at least 15% above the load torque at the worst-case slip.

As the motor kW ratings increase the supply voltage becomes limited and a higher voltage will be needed. This is because large currents cannot be carried in the stator windings. The design and fabrication of the slots, windings and end connections become physically very difficult when the

Table 5.12. Limits to motor ratings due to system voltage

Motor power rating (kW)	Appropriate system line voltage (volts)
Up to 250	LV e.g. 380 to 440
150 to 3000	HV e.g. 2400 to 4160
200 to 3000	HV e.g. 3300 to 7200
1000 to 15,000	HV e.g. 6600 to 13,800

cross-sectional area of the conductors becomes large. The typical kW limits for various voltages are given in Table 5.12, see also IEC60034 part 1 clause 29.

5.7 EFFECT OF THE SYSTEM FAULT LEVEL

Motors are controlled by circuit breakers or contactors. With high voltage motors it is necessary to ensure that the main terminal box and the terminals inside can withstand the effects of a major three-phase fault inside the box. This applies especially to motors that are to be used in a hazardous area. As a guide to the level of safeguard, Table 5.13 may be used.

When contactors are backed up by fuses it is possible to reduce the fault levels considerations. The current versus let-through-time characteristics of the fuses need to be studied if the above fault levels are to be reduced.

5.8 CABLE VOLT-DROP CONSIDERATIONS

The conductor size and length of the motor feeder cable need to be chosen carefully and the following points should be considered:-

- Normal running current.
- Starting current.
- Ambient temperature.
- Laying cables in air or buried in the ground.
- Laying cables vertically or horizontally.
- Derating factors for grouping cables.

Table 5.13. Correspondence between system voltage and fault level at the motor terminals

System line voltage (volts)	System peak fault current (kA_{pk})	System fault level (MVA)
3300 to 4160	85 to 110	150 to 250
6600 to 7200	70 to 110	350 to 500
11,000 to 13,800	65 to 80	500 to 750

- Motor power rating relative to the power supply capacity.
- Fault withstand capacity of the cable for a major fault at the motor.

Assuming 100% voltage at the switchboard or motor control centre, the volt-drop at the motor terminals should not exceed the following guidelines:-

- LV cable volt-drop at starting 20%.
- LV cable volt-drop when running at full-load 2.5% to 5.0%.
- HV cable volt-drop at starting 15%.
- HV cable volt-drop when running at full-load 1.5% to 3.0%.

The cable conductor area will need to be increased if the ambient temperature is greater than 20°C (or the standard temperature given by the cable manufacturer). The derating that will be necessary depends upon the construction and the design offered by the manufacturers, see Chapter 9. If the cables are grouped together on racks, in concrete trenches or directly buried then various derating factors must be applied. When cables are to be buried in the ground the soil conditions need to be known since the heat dissipated from the cable outer surface must be absorbed by the soil in a stable manner. The efficiency of the heat absorption varies greatly with the type of soil. For example the soil may be sandy, predominantly composed of clay or rocks, or it may be dry or wet. References 8 and 9 give recommended derating factors for grouping and burying cables. See also Chapter 10.

Where the power system has self-contained generation, the maximum size of the motor that can be started direct-on-line becomes limited, as is discussed later in this chapter. For example if a 15% volt-drop is permitted at the motor during starting then the motor kW rating should not exceed about 1/6, as a 'rule-of-thumb' guide, of the kW rating of the minimum generation that will be available. If a power system has, say three 20 MW generators then the largest direct-on-line starting of a motor will be about 3.5 MW, since it may need to be started when only one generator is operating. Detailed studies and calculations will be needed to determine exactly the maximum motor rating. In such a case full details of parameters from the chosen manufacturers will be required, together with the tolerances for each parameter. The worst-case situation should be used.

When high voltage motors are being considered, it is usually found that the minimum conductor size of the cable is determined by the let-through fault withstand capability rather than the full-load or starting current. Cable manufacturers provide graphical data for fault withstand capabilities of their cables, which are based on practical tests. These aspects are also associated with the protection system used for the motor, e.g. a contactor-fuse combination, a circuit breaker, the protective relay characteristics (thermal, inverse time with or without instantaneous or earth fault elements).

Appendix G gives detailed calculations of cable volt-drops for the starting and full-load running conditions of a 500 kW induction motor that is to be started direct-on-line in a power system that is fed by three 3125 kVA generators. This appendix demonstrates the following aspects of starting large motors:-

- Errors between rigorous and simplified solutions.
- The use of simple formulae methods based on comparing the kVA rating of the motor with that of the generation capacity.

- The use of graphical methods that consist of a family of curves for different scenarios.
- The use of nomographs to easily find the volt-drops.

5.9 CRITICAL TIMES FOR MOTORS

There are two important time periods that are critical in the application of induction motors. One is the allowable run-up or starting time and the other is the maximum stalling time.

The run-up time is determined by the static torque versus speed characteristic, and the moment of inertia of the load. High inertia loads can cause very long run-up times. However, a long run-up time in itself is not usually a problem for the driven machine. Most induction motors in the oil industry are started direct-on-line and the starting and run-up currents drawn by the motor can be in the range between about 4 and 7 times the rated current. When these currents exist for, say, 20 seconds, the amount of heat created in the stator windings and the rotor bar conductors is considerable. The surface temperature of these conductors can reach values high enough to cause damage to the winding insulation and slot wedges. With hazardous area applications this temperature rise can be very significant for some types of enclosures, especially Ex(e) motors. Attention should be given to the temperature classification, e.g. T1 to T6 as defined for example in IEC60079 part 8.

When considering the run-up time it is also necessary to know how many times the motor needs to be started in, say, one hour because successive starting would not permit the conductors or the insulation time to cool down before the next start takes place. (In that event the insulation temperature would creep up and the material would eventually fail. This process could also cause the windings to become loose in their slots and such damage would be followed by vibrational wear of the insulation.)

The stalling time that can be tolerated needs to be known. This will enable the relay protection for stalling to be correctly set. A motor can withstand a stall condition for a limited period of time, during which the starting (or stalling) current will be much higher than the normal current. The same kind of damage that can occur during prolonged run-up times will be caused by a stalling condition, but the time taken will be less because the rotor remains stationary and so no air can be circulated to remove the heat. Therefore the rate of rise of surface temperature is bound to be faster in a stalling situation. Stalling can be caused by the drive shaft being seized, for example due to a loss of lubricating oil, corrosion of bearing surfaces, fluid in the driven machine becoming very thick or even solidifying. It can also be caused by an open circuit of one of the supply phases. Modern protective relays are available for detecting a stalling condition and a loss of one phase of the supply. See also Chapter 12.

5.10 METHODS OF STARTING INDUCTION MOTORS

When the maximum kW rating of an induction motor is reached for direct-on-line starting, it becomes necessary to introduce an alternative method of starting the motor. There are several methods used in the oil industry. The object is to reduce the starting current drawn from the supply during all or part of the run-up period. There are two basic approaches that can be used:-

- Select special-purpose designs for the motor in which the winding arrangements are modified by external switching devices that are matched to the motor, e.g. star-delta motor and starter.

- Select conventional motors but use special external starting devices, e.g. Korndorfer starter, auto-transformer starter, 'soft-starter' using a controlled rectifier-inverter system.

In all cases of reduced voltage starting, care must be taken to check that the motor will create sufficient torque at the reduced voltage to accelerate the load to the desired speed in as short a time as possible. Excessive run-up times must be avoided as explained in sub-section 5.9. When the run-up time is expected to be high the manufacturer of the motor should be consulted regarding the possibility of damage and infringement of its guarantees. The following methods are the most commonly used, typically in the order shown:-

- Star-delta method.
- Korndorfer auto-transformer method.
- Soft-start power electronics method.
- Series reactor method.
- Part winding method.

5.10.1 Star-Delta Method

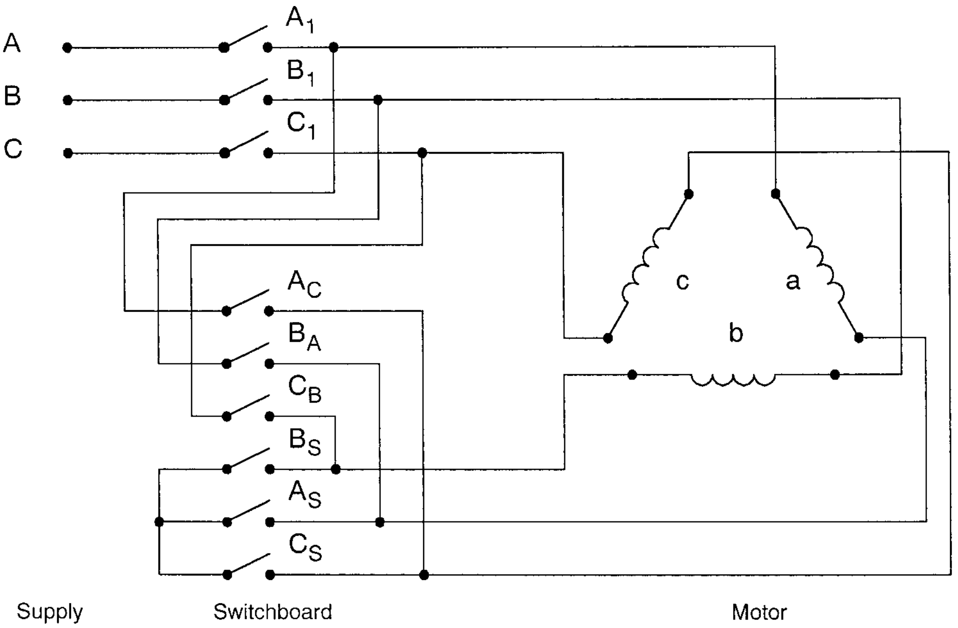
A specially designed motor is used. The stator windings are arranged so that the start and finish of each phase winding in the stator is brought out to the main terminal box so that six terminals are available for connection to cables. Usually two three-core or four-core cables are used unless their conductor size becomes too large, in which case single-core cables would be used. The windings are connected externally in star for starting and delta for running. The external connections are made by using a special starter in the motor control centre which also provides control relays and current transformers that determine when the transfer from star to delta should take place. This method has several disadvantages:-

- The windings are open-circuited during the transfer and this is not considered good practice, a delay should be incorporated to allow the flux in the motor to decay during the transfer.
- The starting current and torque are reduced to 33% of their value during the run-up period. This reduction may be too much for some applications.
- The running condition requires a delta winding connection and this has the disadvantage that harmonic currents can circulate in the windings.

Figure 5.7 shows the basic circuit for a star-delta starter.

5.10.2 Korndorfer Auto-Transformer Method

A standard design of motor is used. An external auto-transformer is connected between the main circuit breaker, or contactor, and the motor during the starting and run-up period. Figure 5.8 shows the connections that are commonly used in a balanced three-phase arrangement. The voltage ratio of the auto-transformer needs to be carefully selected. If it is too high then the full benefit is not achieved. If too low then insufficient torque will be created. The most effective ratio is usually found



Start Close As, Bs, Cs then Close A1, B1, C1
Run Open As, Bs, Cs then Close AC, BA, CB

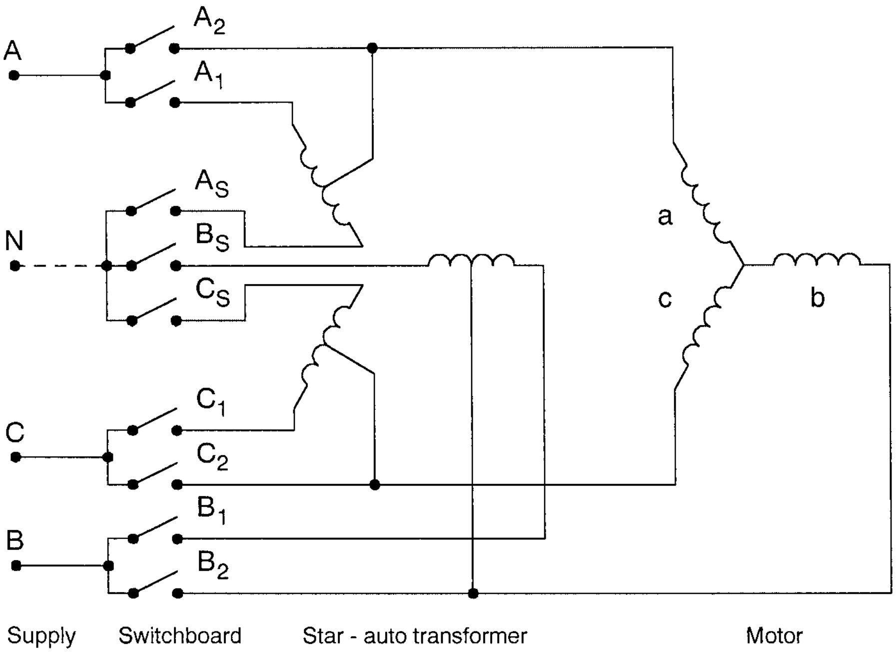
Figure 5.7 Circuit diagram for an induction motor using a star-delta starter.

between 65% and 80%. Table 5.14 illustrates the effect of reduced voltage on the starting current, line current and torque for various ratios. A disadvantage of the method is that two extra three-phase circuit breakers or contactors are necessary, thus making three in total for the motor circuit, which require space to be allocated. Retro-fitting a Korndorfer starter may therefore be difficult if space is scarce.

5.10.3 Soft-Start Power Electronics Method

A standard design of motor is used. An external rectifier-inverter is connected between the main circuit breaker, or contactor, and the motor during the starting and run-up period. The starter varies the frequency and voltage magnitude of the applied three-phase supply to the motor. Upon starting the frequency and voltage are set to their lowest values, and thereafter they are slowly raised as the shaft speed increases. The intent is to operate the motor in its near-synchronous speed state for each frequency that the motor receives. The process is explained in more detail in Chapter 14. The rectifier-inverter equipment is expensive when compared with other switching and transformer methods, but it has several advantages:-

- The starting current can be limited to a value that is equal to or a little higher than the full-load current of the motor.
- The torque created in the motor during the whole run-up period can be in the order of the full-load value, and so the shape of the inherent torque-speed curve of the motor is not a critical issue for most standard designs of motors.



Start Open A2, B2, C2 Close As, Bs, Cs then Close A1, B1, C1
Run Open A1, B1, C1 Close A2, B2, C2 then Open As, Bs, Cs

Figure 5.8 Circuit diagram for an induction motor using a Korndorfer auto-transformer starter.

Table 5.14. Auto-transformer starting of an induction motor

Voltage applied to motor in per cent of rated voltage	Line current in per cent of locked rotor current	Motor current in per cent of locked rotor current	Locked rotor torque in per cent of full voltage value
100	100	100	100
90	81	90	81
80	64	80	64
70	49	70	49
60	36	60	36
50	25	50	25

5.10.4 Series Reactor Method

A standard design of motor is used. This is a simple method that requires the insertion of a series reactor during starting. The reactor is bypassed once the motor reaches its normal working speed. Only one extra circuit breaker or contactor is required. The amount of reactance is calculated on the basis of the desired reduction of line current during starting, but the limiting factor is the reduced starting torque. The torque is reduced for two reasons, firstly because the total circuit impedance is increased and secondly the reactance-to-resistance ratio is increased.

5.10.5 Part Winding Method

A special design of motor is used. The stator has two three-phase windings that are arranged in parallel and wound in the same slots. If the two windings are the same then on starting and during run-up one winding would provide half of the total torque at any speed. Hence one winding is used for starting and both for running. The method is not suited to small or high speed motors. With two equal windings the starting current and torque are half of their totals. This method is seldom used in the oil industry because of the preference for standard motors, and the availability of satisfactory alternative methods.

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