5

Starting and control of slip-ring induction motors

Contents

The use of wound motors is on the wane, for reasons of inherent advantages of a squirrel cage motor over a wound motor and the availability of static drives which can make a squirrel cage motor perform the same duties as a wound motor and even better. Nevertheless, the use of wound motors exists and will continue worldwide for years. Where slip-ring motors are employed whose only purpose is limiting the starting current or a limited speed control, the resistance or electrolyte method of starting is most commonly adopted, for reasons of cost. Static drives generate harmonics and distort the supply voltage, and call for larger sizes of cables. It is also cumbersome and cost-inhibiting to provide filter circuits to suppress harmonics, particularly when the installation is small.

But where accurate speed control is the process requirement, static controllers, termed 'slip recovery systems' (Section 6.16.3) are recommended, which in addition to exercising extremely accurate speed control, also conserve slip losses. Static drives are discussed in Chapter 6. Below we describe a procedure to determine the value of resistance, its steps and switching and control schemes for a rotor resistance starter.

An electrolyte starter is almost a standard product like a motor and the manufacturer, depending upon the number of starts and the speed control requirement, can adjust the quantity of electrolyte, size and depth of electrodes etc.

5.1 Important features of a slip-ring motor

These motors are switched through their rotor circuit by inserting suitable resistances and then removing them gradually. In view of their varying characteristics through their rotor circuit, they can provide the following features:

1 The external resistance adds up to the total impedance of the motor windings and limits the starting current. It also improves the starting power factor.
2 Since the performance of an induction motor can be varied by altering the rotor parameters, a slip-ring motor, through its rotor circuit, can be made to suit any specific torque and speed requirement.
3 The speed of a slip-ring motor can be varied through an external resistance. Therefore the torque can be maintained at any value up to the pull-out torque in the entire speed range by suitably varying the external resistance. (See circle diagram in Figure 1.16 and Section 1.10.2). At lower speeds, however, the efficiency of the motor will be poor, as the output is proportional to the speed. The efficiency would be roughly in the ratio of the two speeds, i.e.

$$\frac{\eta_2}{\eta_1} = \frac{N_{r2}}{N_{r1}}$$

In fact, it would be even worse as a result of the equally reduced cooling effect of the fan at lower speeds. Since $kW \propto N_r \cdot T$, kW would vary with speed, the torque remaining almost the same throughout the speed range. The motor would draw the same power from the supply as before, which, proportional to speed variation, would appear as slip loss in the rotor circuit. For instance, at 25% slip, the power output will be 75% minus the cooling effect and this 25% will appear as a slip loss in the rotor circuit.
4 Restriction in starting current and a requirement for high starting torque to accelerate heavy rotating masses sometimes limit the use of a squirrel cage motor. For such applications a slip-ring motor provides a better alternative.
5 As discussed in Section 2.7.1, during start-up, the rotor is more vulnerable to damage due to excessive heat in the rotor compared to the stator. But in slip-ring motors a major portion of this heat is shared by the external resistance, in proportion to its resistive value. Therefore, a slip-ring motor can be switched ON and OFF more frequently, compared to a squirrel cage motor. It can also withstand a prolonged starting time, while accelerating heavy loads. Now the external resistance will have to be suitable for such duty/load requirements.

Slip loss

From Equation (1.9), slip loss = $S \cdot P_s$. If the full-load slip is S and the speed is varied to slip S_1 the additional slip loss due to the increased slip

$$\simeq P_s(S_1 - S)$$

$$\simeq \text{kW } (S_1 - S) \text{ (ignoring rotor losses).}$$

Example 5.1

If the speed of a 125 kW, 1480 r.p.m. motor is varied at constant torque to 750 r.p.m., then the additional slip loss

$$\simeq 125 \times (0.50 - 0.0133)$$

$$\simeq 125 \times 0.4867$$

or 61 kW

where

$$S = \frac{1500 - 1480}{1500} = 0.0133 \text{ and } S_1 = 0.5$$

Disadvantages

A slip-ring motor is expensive, as are its controls, compared to a squirrel cage motor. It also requires meticulous and periodic maintenance of the brushes, brush gear, slip-rings, external rotor resistances etc. A squirrel cage motor is thus preferred to a slip-ring motor. A slip-ring motor also requires a larger space for the motor and its controls.

5.2 Starting of slip-ring motors

These can be started by adopting either a 'current limiting' method or a 'definite time control' method. In a current limiting method the closing of contactors at each step is governed by the current limiting relays which permit the accelerating contactor of each step to close when the motor current has fallen from its first peak value to the second pre-set lower value. The relays determine the closing time by sensing the motor data between each step and close only when the current has fallen to a predetermined value of the current relays. The closing sequence is automatic and adjusts against varying loads.

The starting time may be shorter or longer depending upon the load. The disadvantage is that if for any reason, say, as a result of excessive load due to friction or momentary obstructions the motor takes a longer time to pick up, the second contactor will not close until the motor has picked up to a certain speed, and may thus create a false stalling condition and allow persistence of a higher starting current. In a 'definite time' start the other contactor will close after a pre-set definite time, cutting a piece of external resistance and hence increasing the torque, giving the motor a chance to pick up. Thus, only this method is normally employed for modern slip-ring motor starts and controls. Below we describe only this type of control.

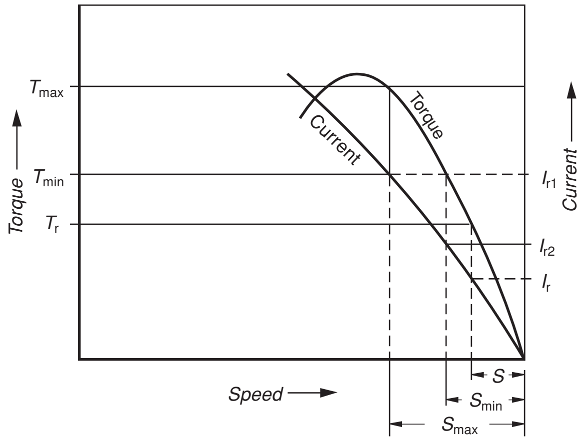


Figure 5.1 Operating region of torque and current curves

5.2.1 Selection of rotor resistance

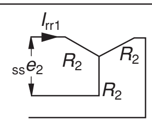
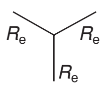
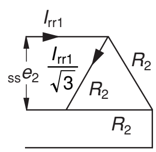
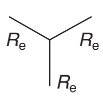
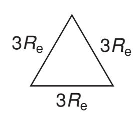
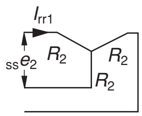
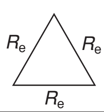
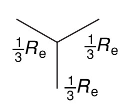
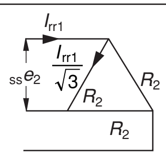
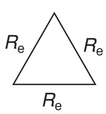
The choice of the external resistance to be introduced in the rotor circuit during start-up will depend upon the torque requirement or limitation in the stator current, without jeopardizing the minimum torque requirement. Since T_{st} and I_{st} are interrelated (Section 2.4) limitation in one will determine the magnitude of the other. Making use of the circle diagram or the torque and current curves available from the motor manufacturer, the value of the stator current corresponding to a particular torque and vice versa can be determined. The slip at which this torque will occur on its operating region can also be found from these curves (Figure 5.1). For this stator current, the corresponding rotor current can be ascertained and the rotor circuit resistance calculated to obtain this current.

If stator full load current = I_r
Corresponding rotor current $RA = I_{rr}$
Rotor standstill voltage = ${}_{ss}e_2$
Rotor voltage at a particular speed $RV = S \cdot {}_{ss}e_2$

Then, for a stator current of I_{r1}, corresponding to a starting torque of T_{max}, the required rotor current will be

$$I_{rr1} = \frac{I_{r1}}{I_r} \cdot I_{rr}$$

To obtain this rotor current, the required rotor circuit resistance can be calculated as below for the various configurations of the rotor windings and the resistance

Sl. no.	Rotor configuration	External resistance			Total rotor circuit resistance
		Configuration	Figure	Equivalent configurations of the rotor	
1			5.2(a)	—	$R_{21} = R_2 + R_e = \frac{{}_{ss}e_2}{\sqrt{3} \cdot I_{rr1}}$ (5.1a)
2			5.2(b)		$R_{21} = R_2 + 3R_e = \frac{\sqrt{3}\, {}_{ss}e_2}{I_{rr1}}$ (5.1b)
3			5.2(c)		$R_{21} = R_2 + \frac{1}{3} R_e = \frac{{}_{ss}e_2}{\sqrt{3} \cdot I_{rr1}}$ (5.1c)
4			5.2(d)	—	$R_{21} = R_2 + R_e = \frac{\sqrt{3} \cdot {}_{ss}e_2}{I_{rr1}}$ (5.1d)

Where, rotor resistance = R_2 Ω/phase; External resistance = R_e Ω/phase; Total rotor circuit resistance = R_{21} Ω/phase

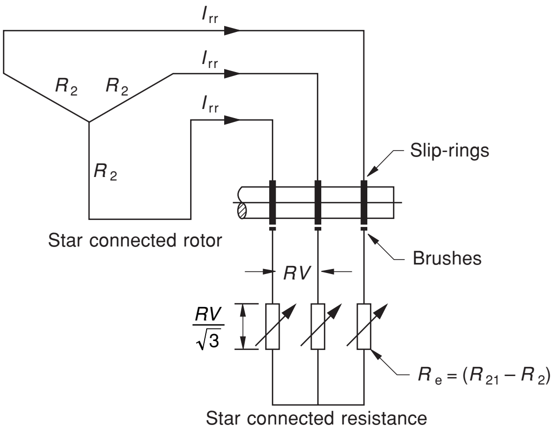


Figure 5.2(a) External rotor resistance

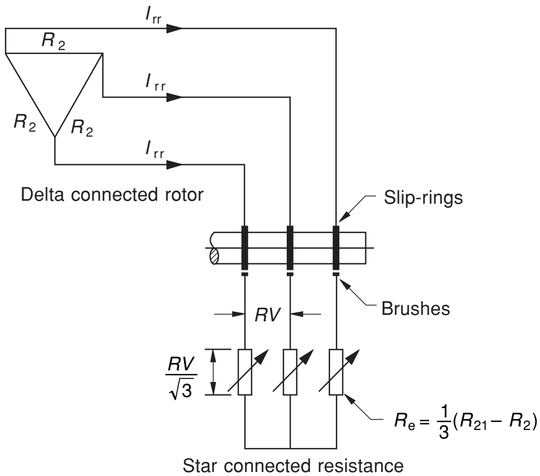


Figure 5.2(b) External rotor resistance

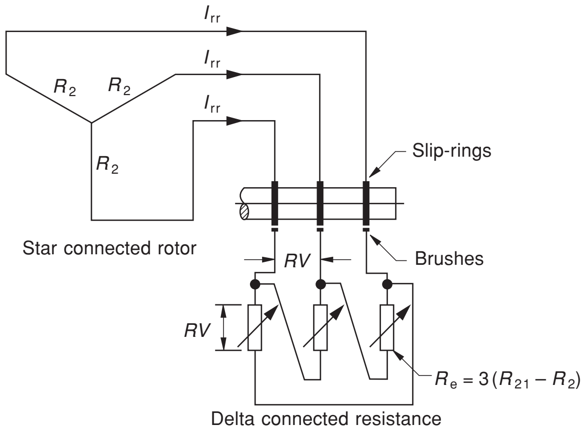


Figure 5.2(c) External rotor resistance

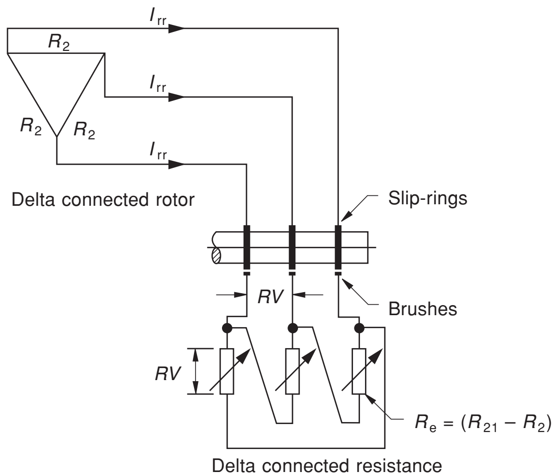


Figure 5.2(d) External rotor resistance

units. It may be noted that, when the resistance configuration is not the same as that of the rotor, it must first be converted to the equivalent configuration of the rotor (see Example 23.4 in Chapter 23 for conversion) to facilitate calculations.

Notes

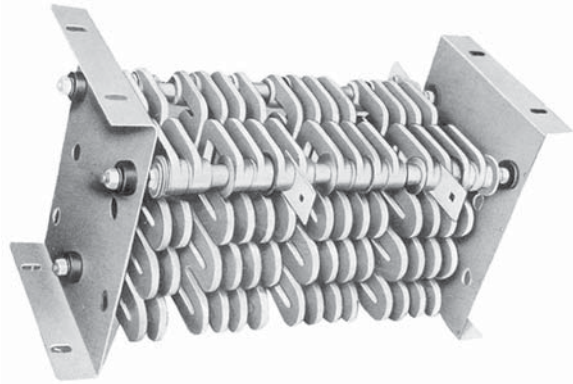
1 Normally the external resistances are connected in star. But for larger motors, calling for high resistance grids, they may also be connected in delta, to reduce their current rating and hence the cost. Insulation is not a limiting factor usually, in case of resistance grids.

2 The rotor voltage, ${}_{ss}e_2$ refers to the standstill secondary induced e.m.f., between the slip-rings. Whereas the rotor current, I_{rr1} refers to the full load rotor current, when the slip-rings are short-circuited.

Refer to Figure 5.3(a) for a typical cast iron and Figure 5.3(b) for a stainless steel resistance grid used for such purposes. Cast iron grids are, however, not preferred due to their resistance change with temperature, which may alter the predefined performance of the motor for which the resistance was designed, particularly when the resistance is used to effect speed variation. Cast iron grids are also brittle and may break during transportation, installation or maintenance. They may also not be able to absorb shocks and vibrations during normal service.

The stainless steel punched grids, generally alloys of aluminium and chromium, are normally preferred. Figure 5.3(c) shows an Al–Cr alloy steel punched grid resistance in a multi-tier arrangement. They are unbreakable, on the one hand, and possess a high specific resistance (about 120 $\mu\Omega$–cm), on the other. A high specific resistance helps in saving the material required to make the grid of a particular resistance value.

More importantly, such alloys also possess a very low temperature coefficient of electrical resistance (of the order of 220 $\mu\Omega/\Omega/°C$, typical), which causes only a marginal change in its resistance value with variation in temperature. They can therefore ensure a near-consistent predefined performance of the motor for which the resistance grid is designed, even after frequent starts and stops. They are also capable of absorbing shocks and vibrations during stringent service conditions and are therefore suitable for heavy-duty drives, such as steel mill applications.



Made of
1. tough iron casting free from brittleness or
2. stainless steel or
3. aluminium chromium corrosion and vibration resistant

Possesses high specific resistance $\simeq$ 120 $\mu\Omega$–cm and low temperature coefficient of 0.00022 $\Omega/\Omega/°C$. Causes negligible change from start to run and therefore provides a fairly accurate speed control

Figure 5.3(a) Cast iron grid resistance (Courtesy: BCH)

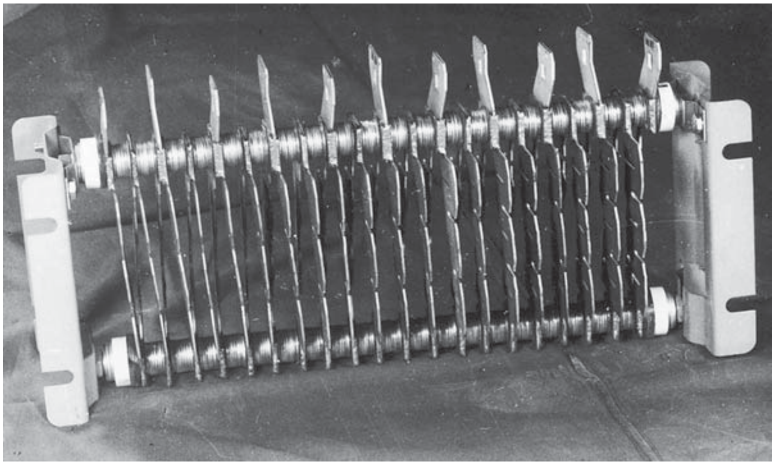


Figure 5.3(b) Stainless steel punched grid resistance (Courtesy: BCH)

Figure 5.3(c) Al–Cr alloy steel punched grid resistor in multitier arrangement (Courtesy: BCH)

Example 5.2
A 125 kW, 415 V, 3ϕ wound rotor has the following parameters:

$$I_r = 230\ \text{A}$$
$$_{ss}e_2 = 500\ \text{V}$$
$$I_{rr} = 180\ \text{A}$$
$$T_{po} = 250\%$$
$$R_2 = 0.09\ \text{ohm (star connected)}$$

The torque and current curves are as shown in Figure 5.4. Determine the external resistance required to achieve a starting torque of 200%.

Solution
From these curves, for a torque of 200% the stator current should be 250%, i.e. 230 × 2.5 A.

∴ Corresponding rotor current,

$$I_{rr1} = \frac{180}{230} \times 230 \times 2.5\ \text{A}$$
$$= 180 \times 2.5\ \text{A}$$

and rotor circuit resistance, with a star-connected resistance unit,

$$R_{21} = \frac{500}{\sqrt{3} \times 180 \times 2.5}$$
$$= 0.641\ \Omega$$

∴ External resistance required, $R_e = 0.641 - 0.09$
$= 0.551\ \Omega$ per phase

Method of cutting off the external resistance

The simplest method is performing it manually. Once the total external resistance is known, the resistance unit can be built with a hand-operated mechanism to manually cut-off the external resistance. However, this method is suitable only for applications where the magnitude of torque during the pick-up period (torque at different speeds) is of little consequence. In such starters, there is no control over the time of start or resistance in the circuit (torque at different speeds) during the start-up period. Liquid rotor starters are one type and are suitable only for light duties. For heavy loads, requiring specific torque values during pick-up, specific resistances must be introduced into the rotor circuit at specific speeds. The specific resistances so required can be determined as discussed below and manufactured in the form of a grid. These resistance grids are then controlled through contactors and timers. The duration between each step of the resistance grid is pre-determined, the torque demand is already ascertained and the resistance required at each step is pre-calculated. The starter can then be made pushbutton-operated fully automatic. With the help of pre-set timers at each step, the entire resistance is cut off gradually and automatically, maintaining the predetermined torque profile.

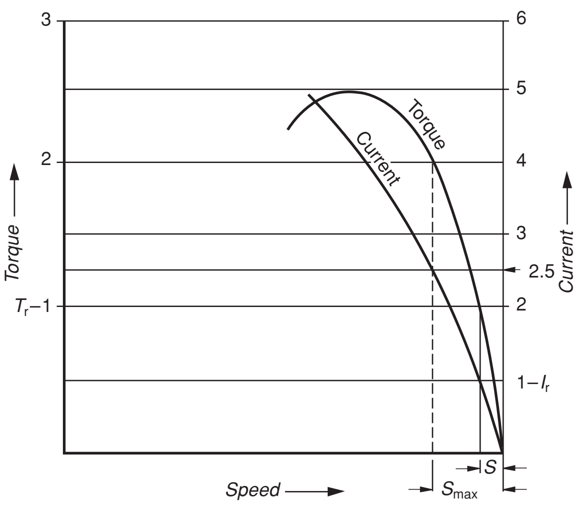


Figure 5.4 Speed–torque and speed–current curves of a 125 kW motor

5.2.2 Determining external resistance and time of start

Consider Figure 5.5 with six steps (rotor resistance unit with five steps) and assume the maximum and minimum torques as T_{max} and T_{min} between each step, to suit a particular load demand (Figure 5.6(a)). Let the corresponding rotor currents be I_{max} and I_{min}. Then by a simple hypothesis using Equation (1.7),

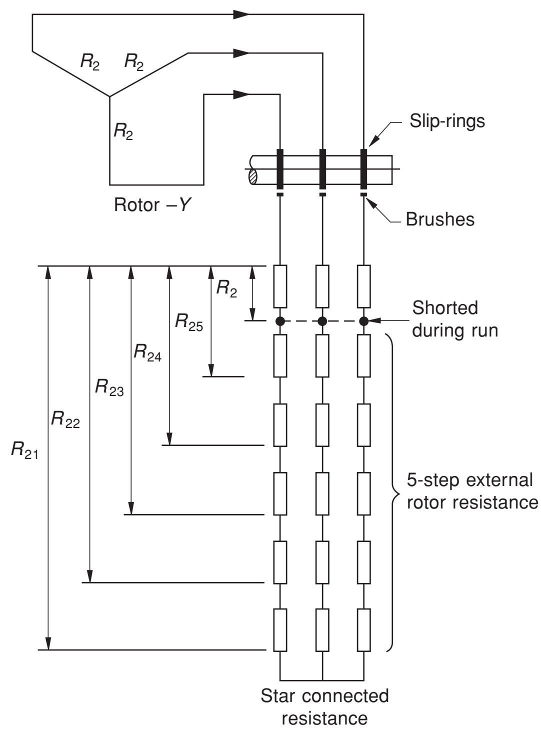


Figure 5.5 Five-step rotor resistance

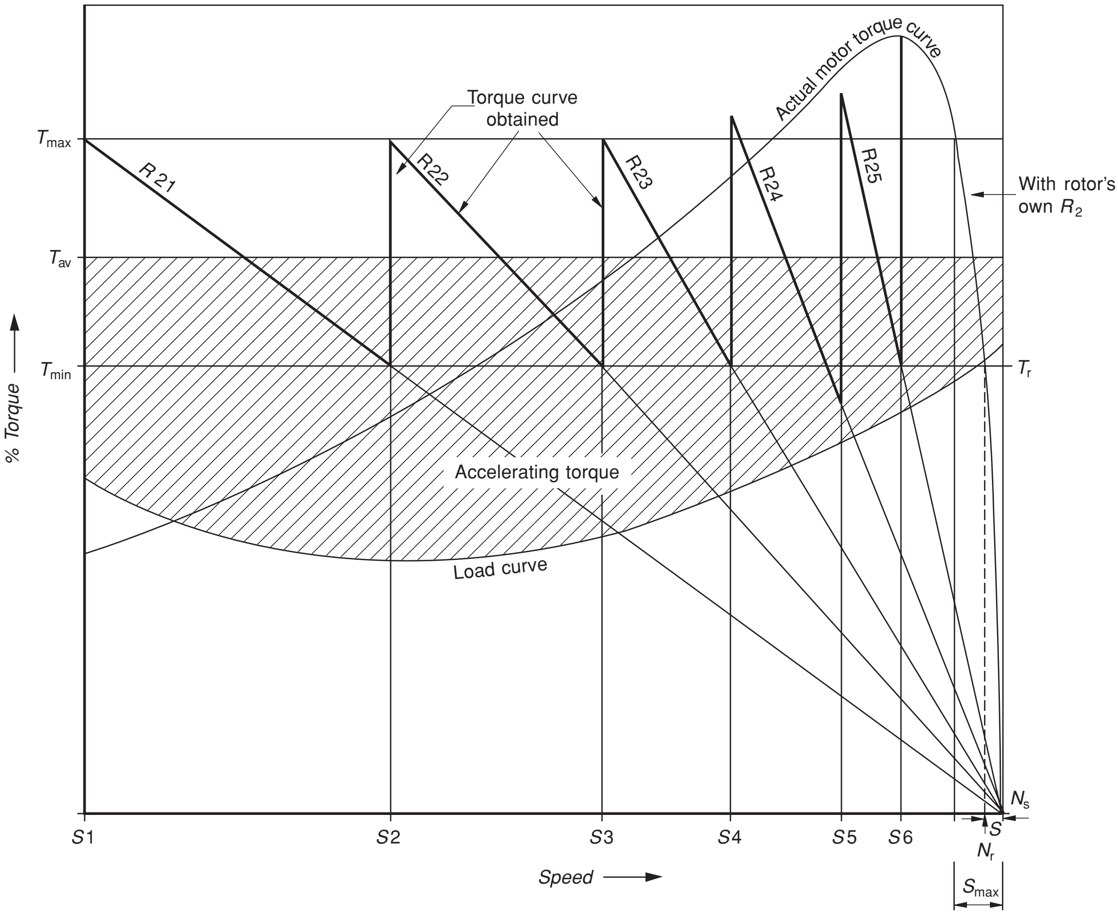


Figure 5.6(a) Torque curve with a five-step external resistance

$$I_{max} = \frac{_{ss}e_2}{\sqrt{(R_{21}/S_1)^2 + {_{ss}X_2^2}}} = \frac{_{ss}e_2}{\sqrt{(R_{22}/S_2)^2 + {_{ss}X_2^2}}} \text{ etc.}$$

$$\text{or } \frac{R_{21}}{S_1} = \frac{R_{22}}{S_2} \text{ etc.} = \frac{R_2}{S_{max}} \qquad \text{(a)}$$

where R_{21}, R_{22}, … R_{25} etc. are total rotor resistances per phase after introducing the external resistances, or

$$R_{21} = S_1 \cdot \frac{R_2}{S_{max}} \qquad (5.2)$$

At the start, when $S_1 = 1$

$$R_{21} = \frac{R_2}{S_{max}}$$

Similarly

$$I_{min} = \frac{_{ss}e_2}{\sqrt{\left(\frac{R_{21}}{S_2}\right)^2 + {_{ss}X_2^2}}} = \frac{_{ss}e_2}{\sqrt{\left(\frac{R_{22}}{S_3}\right)^2 + {_{ss}X_2^2}}} \text{ etc.}$$

$$\text{or } \frac{R_{21}}{S_2} = \frac{R_{22}}{S_3} \text{ etc.} = \frac{R_{25}}{S_{max}} \qquad \text{(b)}$$

From (a) and (b)

$$\frac{I_{min}}{I_{max}} = \frac{S_2}{S_1} = \frac{S_3}{S_2} = \ldots = \frac{R_{22}}{R_{21}} = \frac{R_{23}}{R_{22}} \ldots = \frac{R_2}{R_{25}} = \beta \qquad \text{(c)}$$

$$\therefore \quad R_{22} = \beta \cdot R_{21}$$

$$R_{23} = \beta \cdot R_{22} = \beta^2 \cdot R_{21} \text{ etc.}$$

$$\text{and} \quad R_2 = \beta \cdot R_{25}$$

$$= \beta \cdot \beta^4 \cdot R_{21}$$

$$= \beta^5 \cdot R_{21}$$

$$\text{or} \quad R_2 = \beta^5 \cdot \frac{R_2}{S_{max}} \text{ or } \beta^5 = S_{max}$$

$$\therefore \quad \beta = \sqrt[5]{S_{max}}$$

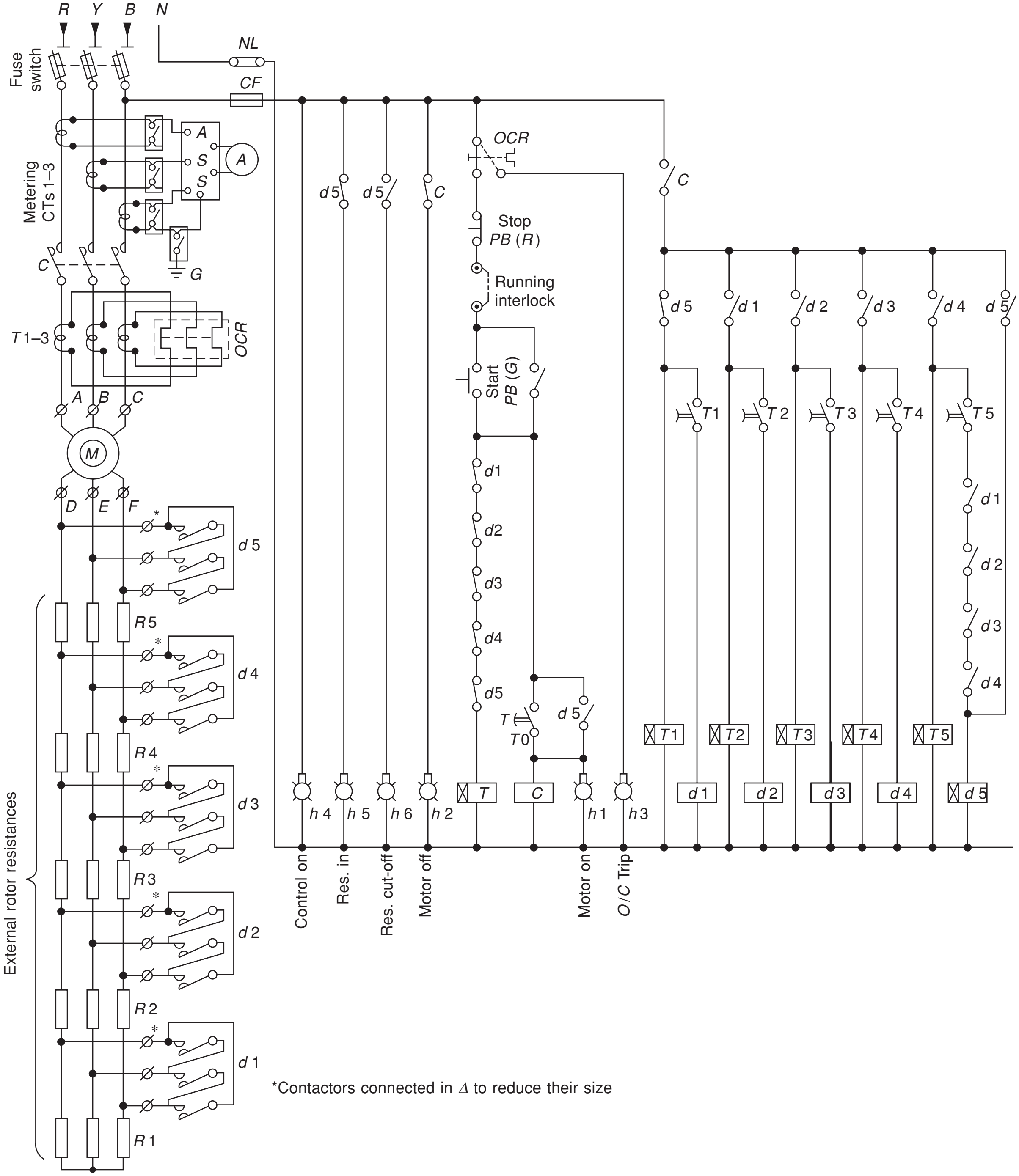


Figure 5.6(b) Power and schematic diagram for a five-step stator-rotor starter

Generalizing this for a number of resistance steps α,

$$\beta = \sqrt[\alpha]{S_{\max}} \tag{5.3}$$

Once β is known, the resistance value for each step can be determined. In the above case, the slip $S_{\max}$ corresponds to the slip at the operating point of the torque or current curve, where the desired torque $T_{\max}$ or current $I_{\max}$ occurs. This can be obtained from the torque and current curves available from the motor manufacturer (Figure 5.4).

Example 5.3

Consider a rotor resistance unit with five sections (total number

Step no.	*Total rotor circuit resistance R* Ω	*External resistance R_e* Ω	*Resistance between steps* Ω
1	R_{21} = 0.643	0.643 – 0.09 = 0.553	0.643 – 0.435 = 0.208
2	$R_{22} = \beta \cdot R_{21}$ = 0.676 × 0.643 = 0.435	0.435 – 0.09 = 0.345	0.435 – 0.294 = 0.141
3	$R_{23} = \beta \cdot R_{22}$ = 0.676 × 0.435 = 0.294	0.294 – 0.09 = 0.204	0.294 – 0.199 = 0.095
4	$R_{24} = \beta \cdot R_{23}$ = 0.676 × 0.294 = 0.199	0.199 – 0.09 = 0.109	0.199 – 0.135 = 0.064
5	$R_{25} = \beta \cdot R_{24}$ = 0.676 × 0.199 = 0.135	0.135 – 0.09 = 0.045	0.135 – 0.09 = 0.045
6	R_2 = 0.09 = 0.09	0.09 – 0.09 = 0	0.09 – 0 = 0.090

Total rotor resistance R_{21} = 0.643 Ω per phase. See Figure 5.5.

of steps is six). Then in the previous example (Figure 5.4), considering T_{st} as 200% and the corresponding slip S_{max} as roughly 14% then

$$R_{21} = \frac{0.09}{0.14}$$

$$= 0.643\ \Omega$$

and $\frac{I_{min}}{I_{max}}$, i.e. $\beta = \sqrt[5]{0.14}$

$$\simeq 0.676$$

Based on this value of β the resistance for each step is worked out in the above table. The power and schematic diagram for this configuration of resistance unit is given in Figure 5.6(b).

5.2.3 Number of steps

Generally, the number of steps is decided by the limits required in the maximum and minimum torque values. It is therefore not an arbitrary figure as assumed in the above example. We will, however, conclude in the next article, that the lower the limits of T_{max} and T_{min} the higher will be the required number of steps and vice versa.

The recommended number of steps, i.e. the number of accelerating contactors for general-purpose (light-duty) application, may be chosen as indicated in Table 5.1.

However, for specific load demands and accurate minimum and maximum torque requirements, the number of steps can be calculated on the basis of actual requirement as discussed in Section 5.2.2. Sometimes, for an economical design of the resistance unit, the number of steps can be reduced without jeopardizing the basic requirement of torque except for slightly higher or lower limits in its values as shown in Figure 5.6(a). Also, as we approach the rated speed, the closer become the steps and the greater the tendency to become infinite. In such a situation it becomes essential to liberalize the torque limits to achieve a quicker objective. Moreover, by now the motor will have almost run to its full speed and will pose no problem of a current or torque kick. Sometimes, however, when the motor possesses a substantially high pull-out torque than is required by the connected load, a quick removal of external resistance may cause an abrupt jump in the torque and may exert a jerk on the load, which may not be desirable. To overcome such a situation and to economize on the resistance design, a small resistance is sometimes left permanently connected in the rotor circuit, even when the motor is running at full load. Such a practice will apparently add to the rotor resistance and increase the full-load operating slip. The higher slip losses will, however, be shared by the rotor's own resistance and the external resistance, which is now permanently connected in the rotor circuit. The external resistance has to be continuously rated. One should, however, make sure that this slightly increased slip does not influence the performance of the driven machine or cause over-heating of the rotor windings.

5.2.4 Duty cycle and duty rating of resistance units

The resistance units, when used only for starting purpose, are in the circuit for only a short time and are thus short-time rated. However, when they are employed for speed control, braking or plugging operations, in addition to the starting duty, they may be rated for continuous duty. The resistance units are thus classified according to their duty demand, i.e. number of operations per hour (c/h). See Chapter 3 on the duty cycle.

The following information is essential to decide the duty class of the resistance units:

1 The duty cycle of the motor

i.e. which one out of *S*-1 to *S*-10 (Chapter 3)
Say, for a duty cycle of
S_4 – 40% – 90 c/h and *FI* as 2.5

i.e. each cycle of $\frac{60 \times 60}{90}$ = 40 seconds

Table 5.1 Recommended number of starting steps of a resistance unit to switch a slip-ring motor

	Motor output in kW for different starting torques			*Standard no. of starting steps*
Torque	50% T_r	100% T_r	> 100% T_r	
	kW ≤ 20	kW ≤ 10	kW ≤ 7	3
	20 < kW ≤ 200	10 < kW ≤ 100	7 < kW ≤ 70	4
	kW > 200	kW > 100	kW > 70	6

2 The starting current and the peak current during each cycle

By referring to NEMA publication ICS 2–213: with the above details, the resistance class can be found. The resistance units are designated by class number, current and resistance. NEMA tables ICS 2-213 to ICS 2-213-5 can be referred to for this purpose.

5.2.5 Temperature rise limits

As in NEMA/ICS-2-213, the exposed conductor resistance units can attain a temperature rise up to 375°C, whereas when they are enclosed in a housing, the temperature rise must be restricted to 350°C. Accordingly, the temperature rise of the air in the vicinity of the housing, when measured at a gap of 1 inch from the enclosure, should not exceed 175°C.

Corollary

Very high temperature-rise permissible limits of resistance units render them unsuitable for installations that are fire-prone such as pulp and paper industries, chemical industries, refineries, textile mills, etc. For specific applications and surroundings, however, resistance design can be altered (derated) to restrict the temperature rise to within desirable limits.

Moreover, high-temperature variation may result in large variations in the resistance of the grid and may vary the performance of a variable-speed drive if care is not exercised in selecting a proper alloy of the resistance. An alloy such as aluminium–chrome steel should be preferred when it is required to perform a speed control or a speed variation, as discussed above.

5.3 Hypothetical procedure to calculate the rotor resistance

The following is a more appropriate method to determine the number of steps and resistance of each step of the resistance grid, making use of only rotor data and desired limits of T_{max} and T_{min} as ascertained from the available load curve. The concept used in arriving at the number of steps is based on the fact that the rotor current varies in direct proportion of torque (Equation (1.1)). For more clarity we will discuss this method using a practical example. The procedure is generally the same as that adopted in Example 5.3.

Example 5.4

Consider a conveyor system, requiring an average torque of 100% during pick-up. The motor data are as follows:

kW = 450
N_r = 980 r.p.m.
V_ℓ = 6.6 kV
I_r = 50 A
$_{ss}e_2$ = 750 V
I_{rr} = 435 A
T_{po} = 250%
R_2 = 0.02 Ω (star connected)

Solution

For conveyors, the torque should not be very high, to economize on belt size and cost. Otherwise a higher safety factor must be considered for the belts, resulting in a wider or thicker belt at an extra cost. Therefore considering a torque demand of T_{max} as 180% and T_{min} as 120%, for a conveyor torque of 100%, providing an average starting torque of 150% and an accelerating torque of 50% (Figure 5.7(a)):

$$\text{For } T_{max}\ (180\%) \quad R_{21} = \frac{750}{\sqrt{3} \times 435 \times 1.8}\ \Omega$$

$$= 0.553\ \Omega$$

$$\text{and for } T_{min}\ (120\%) \quad R_{21} = \frac{750 \cdot S_2}{\sqrt{3} \times 435 \times 1.2}\ \Omega \text{ etc.}$$

Determine slip S_2 to give the same value of R_{21} as above. Then for this slip, determine one step on the torque curve. Calculate for this slip S_2, R_{22}, etc. as shown in Table 5.2. Since the torque at synchronous speed is zero and the end portion of a torque curve is almost a straight line, the same results are obtained if a straight line is drawn from starting point '*a*' to zero torque '*A*'. Where it meets the T_{min} line determines one step. Here again, the torque goes up to T_{max} by another resistance value and this can also be joined to *A*. Continuation of such a procedure gives a point where it meets the motor curve. To reduce the number of steps, slight variations in T_{max} and T_{min} can be made as shown. Note that complete resistance cannot be removed at step '*f*' otherwise the torque will jump to about 212%, which may not be desirable. Thus, the total number of steps amounts to seven (resistance segments six), which is reasonable.

We must also check whether the starting time of the motor with this profile of starting torque would be safe for the motor to pick-up to the rated speed. Considering the same data as for Example 7.1, GD_T^2 = 1866 kgm^2

$$\text{and } T_a = \frac{450 \times 974}{980} \times 0.5$$

$$= 223.62 \text{ mkg}$$

$$\therefore \text{ Accelerating time } t_s = \frac{1866 \times 980}{375 \times 223.62}$$

$$= 21.8 \text{ seconds}$$

This seems to be high and must be checked with the thermal withstand time of the motor (Section 3.5).

The upper limit of the starting torque chosen at 180% appears to be too low and can be raised to, say, 210%. This will also help in reducing the number of steps. Number of steps at 4–6 are preferable to economize on the cost of switchgears, and yet provide a reasonably smooth (free from overshoots) starting torque.

Considering T_{max} = 210%

$$\therefore \quad T_a = \frac{210 + 120}{2} - 100$$

$$= 65\%$$

$$\text{and} \quad t_s = 16.77 \text{ sec.}$$

which is quite reasonable. A modified accelerating torque diagram is drawn in Figure 5.7(b), providing a smooth acceleration. Now we can cut off the last resistance at *e*, giving a jump in T_{max} of even less than 210%.

To obtain the starting characteristics according to Figure 5.7(b), it is essential to calculate the total rotor resistance, R_{21} and resistances between each step along the lines of Table 5.2.

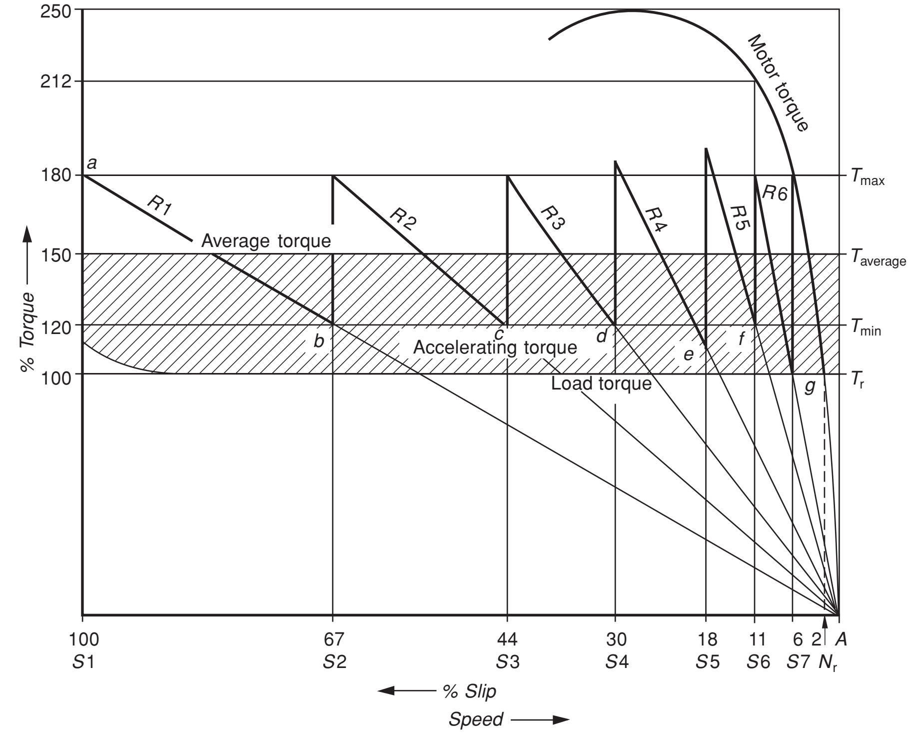


Figure 5.7(a) Determining the number of steps and accelerating torque between each step

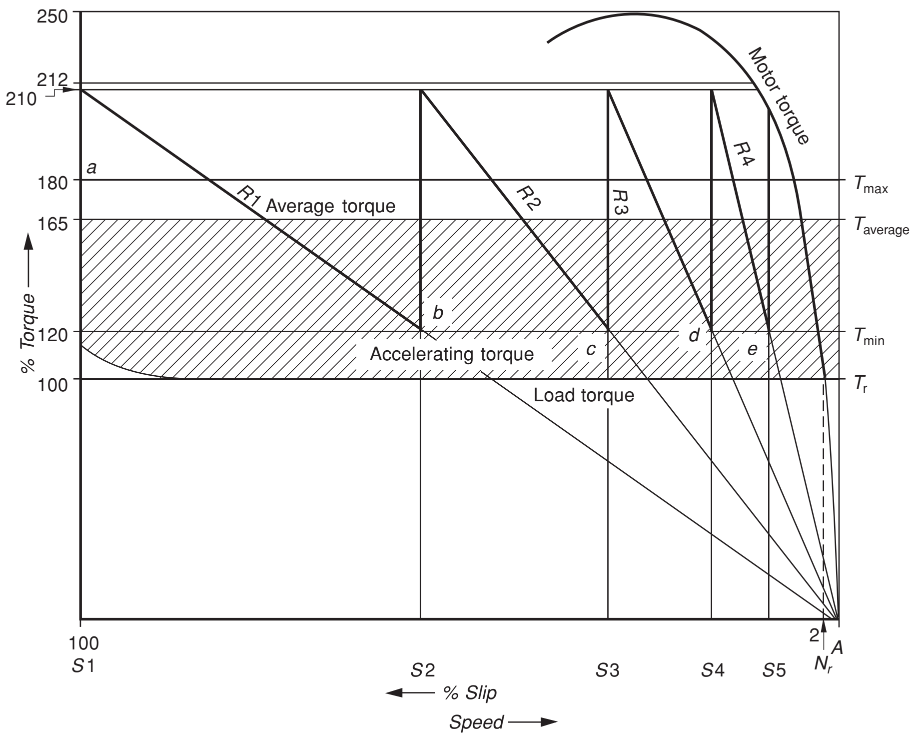


Figure 5.7(b) Determining the number of steps and accelerating torque between each step

Table 5.2 Determining the resistance between each step

Step no.	Total resistance (R) for T_{max}			Evaluation of slip for T_{min}		Resistance between each step Ω
	Symbol	Value Ω	At slip	For the same resistance	Chosen value of slips	
1	R_{21}	$\frac{750}{\sqrt{3} \times 435 \times 1.8} = 0.553$	$S_1 = 100\%$	R_{21}	$S_2 = \frac{1.2}{1.8} \cdot S_1 \simeq 67\%$	$R_{21} - R_{22} = 0.182$
2	R_{22}	$R_1 . S_2 = 0.371$	$S_2 = 67\%$	R_{22}	$S_3 = \frac{1.2}{1.8} \cdot S_2 \simeq 44\%$	$R_{22} - R_{23} = 0.127$
3	R_{23}	$R_1 \cdot S_3 = 0.244$	$S_3 = 44\%$	R_{23}	$S_4 = \frac{1.2}{1.8} \cdot S_3 \simeq 30\%$	$R_{23} - R_{24} = 0.078$
4	R_{24}	$R_1 \cdot S_4 = 0.166$	$S_4 = 30\%$	R_{24}	$S_5 = \frac{1.2}{1.8} \cdot S_4 \simeq 18\%$	$R_{24} - R_{25} = 0.070$
5	R_{25}	$R_1 \cdot S_5 = 0.096$	$S_5 = 18\%$	R_{25}	$S_6 = \frac{1.2}{1.8} \cdot S_5 \simeq 11\%$	$R_{25} - R_{26} = 0.035$
6	R_{26}	$R_1 \cdot S_6 = 0.061$	$S_6 = 11\%$	R_{26}	$S_7 = \frac{1.2}{1.8} \cdot S_6 \simeq 6\%$	$R_{26} - R_2 = 0.041$
7	R_2	$R_2 = 0.020$	$S_7 = 6\%$	R_2	(at rated speed) = 2%	$R_2 = 0.020$

Note
Total resistance, $R = 0.553\Omega$

5.3.1 Calculation of time between each step

To make the whole starting sequence automatic in a contactor type automatic starter unit it is essential to know the time the motor will take to accelerate from one slip to another between each step. It is required to select and set the timer relay to automatically remove, one by one, each resistance step and provide a smooth acceleration. The procedure for calculating the acceleration time between each step is dealt with in Chapter 2 and a schematic diagram is given in Figure 5.6(b).

5.4 Speed control of slip-ring motors

The speed of a slip-ring motor can be varied by up to 25% of the rated speed. A further reduction may greatly diminish the cooling effect and reduce the output in a much larger proportion and will not be worthwhile. Moreover, it will now operate in a region which is unstable and may thus stall (see any speed–torque curve). As discussed in Section 5.1, during speed reduction, with the torque remaining almost constant, the motor will draw the same power from the supply lines while the output will be proportional to the speed minus the cooling effect. On the subject of cooling, Table 5.3 shows the approximate values of h.p. and torque a motor will be able to develop at various speed reductions. Figure 5.8 gives the curves for output and torque. From these curves it is evident that the losses increase in a much larger proportion than the speed variation. The speed in such motors can be varied in the following four ways:

1 Torque and output varying as in the curves, in which case no derating is necessary.
2 Keeping torque constant throughout the speed range. At reduced speed the torque is low and therefore the motor rating should be derated accordingly, e.g. at 50% speed, the torque is 73%. To obtain 100% torque, the motor should be rated for 100/0.73, i.e. 137%.
   Table 5.3 shows the derating values and Figure 5.9 the derating curve. The variation in the rotor current is also in the same proportion as the torque.
3 Torque varying with the square of the speed as for fans and centrifugal pumps etc. as discussed in Chapter 2.
4 Keeping the output constant throughout the speed

Table 5.3 Variation in torque and output with speed in slip-ring motors

Serial no.	% of rated speed	Output		Torque or current rating	
		%	Rating required for constant output (%)	%	Rating required for constant torque (%)
1	2		3		4
1	100	100.0	100	100	100
2	90	86.8	115	96	104
3	80	73.6	136	92	109
4	70	61.0	164	87	115
5	60	48.0	208	80	125
6	50	36.5	274	73	137
7	40	26.0	384	65	154
8	30	16.5	605	55	182

Notes
1 These value are only indicative and may vary from one manufacturer to another, depending upon their design and cooling efficiency and also the normal speed of the motor. The higher the motor rated speed, the lower will be the cooling at lower speeds, compared to a slow-speed motor, and will require yet higher deratings.
2 The rotor current also varies in the same proportion as the torque.

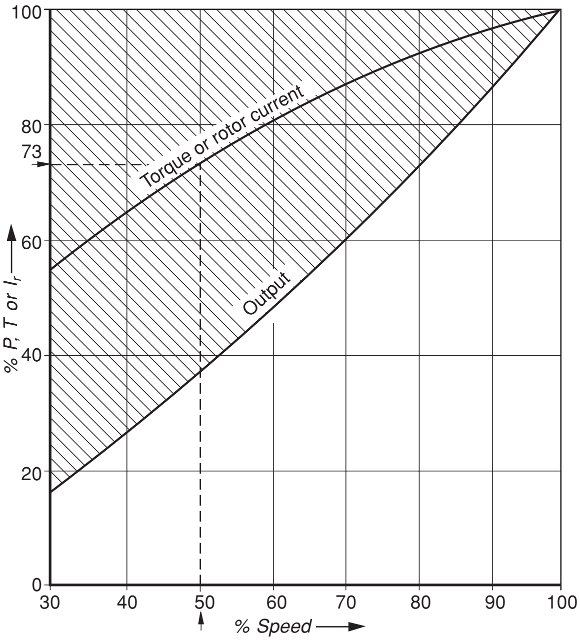
range. As a result of still higher derating, the torque of the selected higher size motor (column 3 of Table 5.3) will become very high and is generally not preferred. See also Figure 6.51.

5.4.1 Resistance for speed control

In this case the regulating resistance grids are normally continuous duty, unlike those for start-up, which are short-time duty. Equations (5.1a–d) can be used, for determining the total rotor circuit resistance for a particular speed variation, i.e.

$$R_{21} = \frac{{}_{\text{ss}}e_2}{\sqrt{3} \cdot I_{\text{rr}}} \cdot \frac{\%\text{Speed reduction}}{\%\text{Current at the reduced speed}} \qquad (5.4)$$

To achieve a better torque, the slip-ring rotors are normally wound in star, in which case the rotor current is $\sqrt{3}$ time more than in delta for the same output. Also since the torque is proportional to the rotor current Equation (1.1), the torque developed will be greater in this case.



Shaded portion indicates power loss in the rotor circuit

Figure 5.8 Variation in torque and output with speed

Example 5.5

For the 125 kW motor of Example 5.2, if a speed reduction is required by 50% at constant torque (see also Figure 6.51) and the rotor current is now 73% of its rated value (Table 5.3), then the total rotor circuit resistance

$$R_{21} = \frac{500 \times 0.5}{\sqrt{3} \times 180 \times 0.73}$$

$$\simeq 1.098\ \Omega$$

and external resistance

$$R_e = 1.098 - 0.09$$

or $\quad 1.008\ \Omega$

5.5 Moving electrode electrolyte starters and controllers

5.5.1 As a rotor resistance for slip-ring motors

These are similar to stator resistance starters, as discussed in Section 4.2.3 and can be used in the rotor circuit to control the rotor side resistance. Figure 5.10 shows the

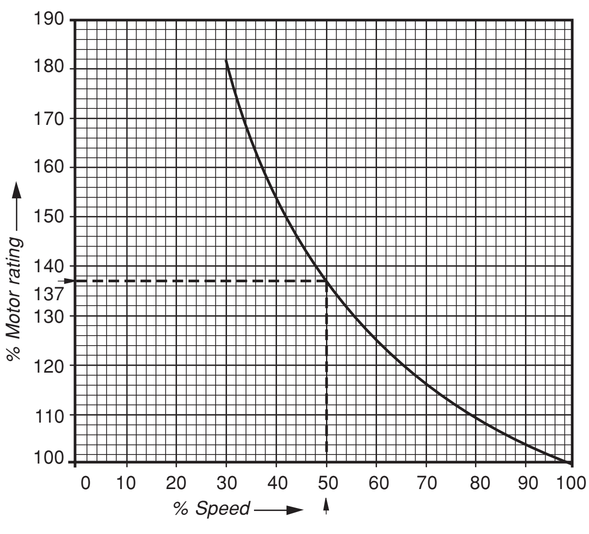
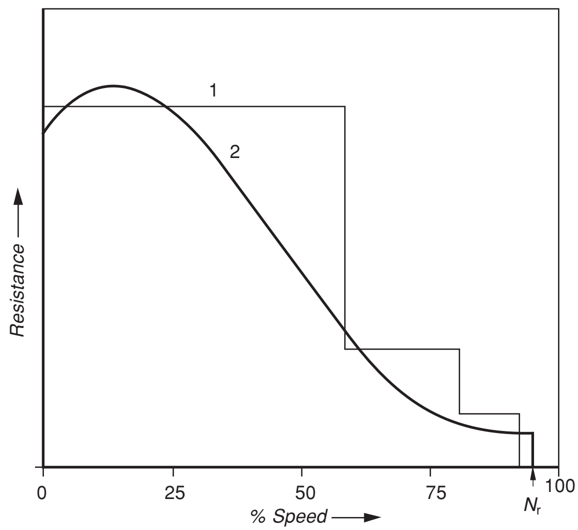


Figure 5.9 Multiplying factor for motor rating for speed variation at constant torque



Variation in resistance during starting
1. 3–Step metallic resistance
2. Liquid electrolyte

Figure 5.10 Variation of electrolyte resistance with speed smooth variation of resistance by electrolytic vaporization compared to a conventional metallic resistance variation. The self-variable resistance of electrolyte is equivalent to almost three or four steps of a metallic resistance and makes such starters economical. Normally one step is sufficient for motors up to 160 h.p. (For speed–torque characteristics see Figure 5.11). Starting requirements such as electrolyte quality and electrode depth, the active area of the electrode and the positioning of the flanges etc., are determined by the requirement of the drive.

The remaining details are the same as for stator resistance starters. Here also, by adding individual electrolyte stacks, starters of any rating up to 25 000 h.p. can be produced from a smaller unit of 10 h.p. or so (Figures 5.12(a), (b) and (c)). These starters are almost 20–25% more economical than a conventional contactor and timer-operated metallic rheostatic starters discussed earlier.

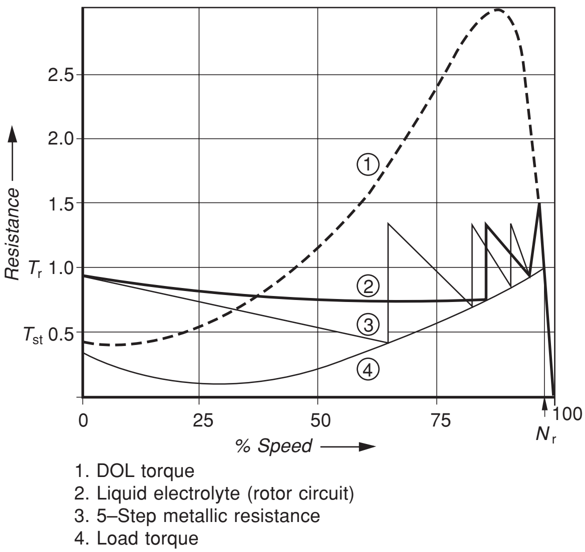


Figure 5.11 Smooth variation of torque with smaller number of steps in liquid electrolyte starters

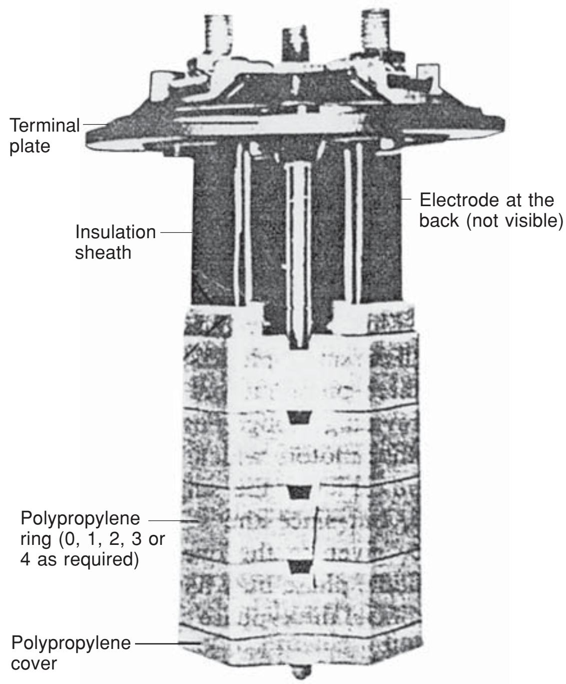
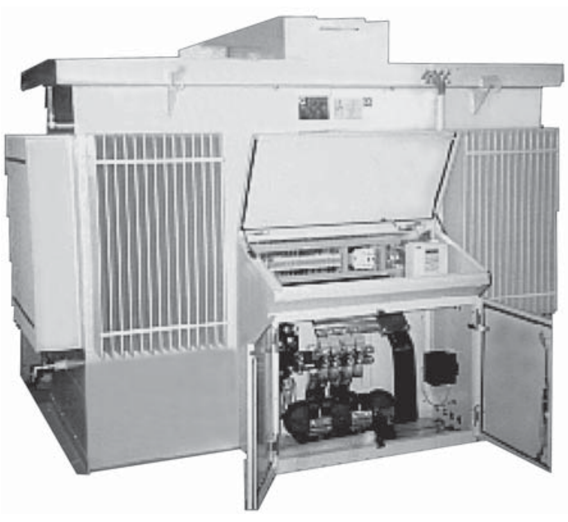
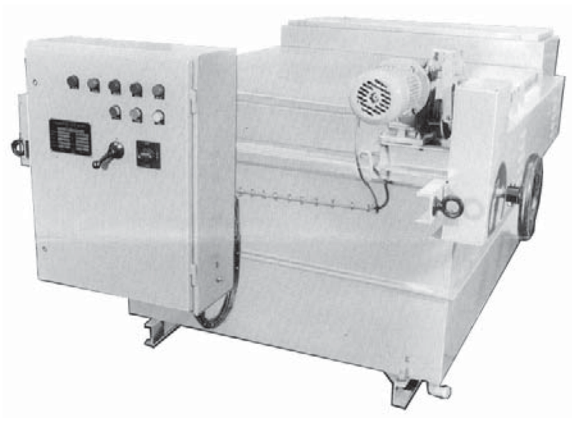


Figure 5.12 (a) (Source: AOYP Engineering)



(b) (Source: Elektroschaltgeräte Meerane GmbH)



(c) (Courtesy: Pioneer electro switchgear)

Figure 5.12 Liquid rotor starters

5.5.2 Automatic speed control of slip-ring motors

By making the electrodes move through a geared motor, it is possible to achieve even automatic speed control of slip-ring motors through such starters.

Relevant Standards

IEC	*Title*	*IS*	*BS*
60947-1/2004	Specification for low voltage switchgear and control gear. General rules.	13947-1/1998	BS EN 60947-1/2004
60947-4-1/2001	Low voltage switchgear and controlgear. Electromechanical contactors and motor starters including rheostatic rotor starters.	13947-4-1/1998	BS EN 60947-4-1/2001
–	Motor starters for voltages not exceeding 1000 V. Rheostatic motor starters.	8544-3/1979 (Section 1&2)	

Related US Standards ANSI/NEMA and IEEE

NEMA/ICS-2-213/2000	*Resistors and rheostats.*

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

Selection of rotor resistance

$$R_{21} = R_2 + R_e = \frac{{}_{ss}e_2}{\sqrt{3} \cdot I_{rr1}} \tag{5.1a}$$

(Rotor ⅄, external resistance ⅄)

$$R_{21} = R_2 + 3R_e = \frac{\sqrt{3} \cdot {}_{ss}e_2}{I_{rr1}} \tag{5.1b}$$

(Rotor Δ, external resistance ⅄)

$$R_{21} = R_2 + \frac{1}{3} R_e = \frac{{}_{ss}e_2}{\sqrt{3} \cdot I_{rr1}} \tag{5.1c}$$

(Rotor ⅄, external resistance Δ)

$$R_{21} = R_2 + R_e = \frac{\sqrt{3} \cdot {}_{ss}e_2}{I_{rr1}} \tag{5.1d}$$

(Rotor Δ, external resistance Δ)

R_2 = Rotor resistance Ω/phase
R_e = External resistance Ω/phase
R_{21} = Total rotor resistance Ω/phase
R = required rotor circuit resistance
${}_{ss}e_2$ = rotor standstill voltage
I_{rr1} = required rotor current

To determine external resistance and time of start

$$R_{21} = S_1 \cdot \frac{R_2}{S_{max}} \tag{5.2}$$

R_{21}, R_{22}, are total rotor resistances per phase after introducing the external resistances
S_1 = slip at the beginning of a step
S_{max} = slip at the end of a step

$$\beta = \sqrt[\alpha]{S_{max}} \tag{5.3}$$

$$\beta = \frac{I_{min}}{I_{max}} = \frac{S_2}{S_1} = \frac{S_3}{S_2} = \ldots = \frac{R_{22}}{R_{21}} = \frac{R_{23}}{R_{22}} = \ldots$$

α = no. of resistance steps

Resistance for speed control

$$R_{21} = \frac{{}_{ss}e_2}{\sqrt{3} \cdot I_{rr}} \cdot \frac{\text{\% Speed reduction}}{\text{\% Current at the reduced speed}} \tag{5.4}$$