Starting of squirrel cage induction motors

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An induction motor can be regarded as a transformer with a small air gap in the magnetic circuit. When at rest, having no induced back e.m.f., it can be regarded as a transformer with a short-circuited secondary. A squirrel cage induction motor therefore draws a very high starting current, as noted in Section 1.2.1. However, it reduces substantially in a slip-ring motor due to the high impedance of the rotor circuit.

The starting of an induction motor does not relate to simple switching alone. It also involves its switchgears to control its starting inrush current, starting torque, or both, and its over-load and short-circuit protection.

The following are common methods to start a squirrel cage motor, depending upon the limitation, if any, on the magnitude of switching current, $I_{st}$.

### 4.1 Direct on-line starting (DOL)

This is an ideal type of starting, simple and economical. In this type the full voltage is applied across the stator windings. The torque developed by the motor is maximum. The acceleration is fast and the heat of starting is low (Figure 4.1(a)). For heavy rotating masses, with large moments of inertia, this is an ideal switching method. The only limitation is the initial heavy inrush current, which may cause severe voltage disturbances to nearby feeders (due to a large $I_{st} \cdot Z$ drop). With this in mind, even local electricity authorities sometimes restrict the use of DOL starting beyond a certain rating, say, 10 h.p., for small installations. For large installations, this condition may be of little significance as, in most cases, the power from the electricity authorities may be available on MV 3.3–33 kV. When it is so, a transformer is provided at the receiving end for the distribution of power on the LV side thus eliminating the cause of a line disturbance due to a voltage dip. On the MV side, the effect of a voltage dip, caused by small motors, is of little significance. However, the method of DOL switching for larger motors is recommended only where the supply source has enough capacity to feed the starting kVA of the motor, with a voltage dip of not more than 5% on the LV side.

For a large LV motor, say, 300 h.p. and above, there is no economical alternative other than DOL starting. One can, however, employ delayed action coupling (Section 8.3) with DOL starting to start the motor lightly and quickly. (See also Example 7.1, in Chapter 7 for more clarity.) Soft starting through a solid-state device (Section 6.16.1) or a liquid electrolyte (Section 4.2.3) are costly propositions. Autotransformer starting is also expensive due to the cost of its incoming and outgoing control gears and the cost of the autotransformer itself. This is not the case with $Y/\Delta$ starting. But, $A/T$ and $Y/\Delta$ startings are reduced voltage startings and influence the starting torque of the motor. It is possible that the reduced starting torque may not be adequate to drive the load successfully and within the thermal withstand time of the motor. Unlike in smaller ratings, where it is easy and economical to obtain a high $T_{st}$ characteristic, in large motors, achieving a high $T_{st}$, say, 200% and above, may be difficult and uneconomical. (See Section 2.2.)

With the availability of large contactors up to 1000 A and breakers up to 6400 A, DOL starting can be used for LV motors of any size, say, up to 600 $^3$ h.p. The use of such large LV motors is, however, very rare, and is generally not recommended. Since large electrical installations are normally fed from an MV or HV network, whether it is an industry, residential housing, an office or a commercial complex, DOL switching, even when large LV motors are used, may not pose a problem or cause any significant disturbance in the MV or HV distribution network. It is, however, advisable to employ only MV motors, in large ratings.
MV motors have little alternative to be switched other than a DOL or a soft starting. \(Y/\Delta\) switching in an MV motor is neither advisable nor possible for its windings are normally wound in a star formation to reduce the windings’ design voltage and economize on the cost of insulation. Autotransformer switching is possible, but not used, to avoid a condition of open transient during a changeover from one step to another, as discussed in Section 4.2.2(a) and for economic reasons as noted above. Moreover, on a DOL in MV, the starting inrush current is not very high as a result of low full-load current. For example, a 300 h.p. LV motor having a rated full-load current (FLC) of 415 A on a DOL will have a starting inrush of approximately 2500 A, whereas a 3.3 kV motor will have an FLC of only 45 A and starting inrush on a DOL of only 275 A or so. An MV motor of 3.3, 6.6 or 11 kV will thus create no disturbance to the MV or HV distribution network on DOL starting.

For power and control circuit diagrams refer to Figure 4.1(b).

\(a\) Note
With the availability of soft starters size of LV motors too is no bar as the starting inrush current \(I_{\text{in}}\) can be controlled to any level without jeopardizing the torque requirements of the motor. Similarly with the use of fluid couplings the motor can be switched light and duration of \(I_{\text{in}}\) achieved very low. It is a different matter that LV distributions of such large capacity may be rare. Nevertheless due to cost consideration LV motors 1000–1500 h.p. and related switchgears are still in use.

### 4.2 Reduced voltage starting

When the power distribution network is available on LV, and the motors are connected on such a system, it becomes desirable to reduce the starting inrush currents, for motors beyond a certain rating, say, 10 h.p., to avoid a large dip in the system voltage and an adverse influence on other loads connected on the same system. Sometimes it may also be a statutory requirement of the local electricity authorities for a consumer to limit the starting inrush of motor currents beyond a certain h.p. to protect the system from disturbances. This requirement can be fulfilled by adopting to a reduced voltage starting.

Sometimes the load itself may call for a soft start and a smoother acceleration and a reduced voltage switching may become essential. A few common methods to achieve a reduced voltage start are described below.

#### 4.2.1 Star/delta (\(Y/\Delta\)) starting

The use of this starting aims at limiting the starting inrush current, which is now only one third that of DOL starting. This is explained in Figure 4.2. This type of starting is, however, suitable for only light loads, in view of a lower torque, now developed by the motor, which is also one third that of a DOL. If load conditions are severe, it is likely that at certain points on the speed–torque curve of the motor the torque available may fall short of the load torque and the motor may stall. See the curves in Figure 4.3(a), showing the variation in current and torque in the star and delta positions and the severe reduction in the accelerating torque.

When employing such a switching method precautions should be taken or provision made in the starter to ensure that the windings are switched ON to delta only when the motor has run to almost its full speed. Otherwise it may again give almost a full kick as on a DOL and defeat the purpose of employing a star/delta switching. Figure 4.3(a) explains this.

**Limitations**

1. Due to the greatly reduced starting torque of the motor, the accelerating torque also reduces even more sharply and severely (Figure 4.3(a)). Even if this reduced accelerating torque is adequate to accelerate the load, it may take far too long to attain the rated speed. It may even exceed the thermal withstand capacity of the motor and be detrimental to the life of the motor. One should consider this aspect when selecting this type of switching.

To achieve the required performance, it is essential that at every point on the motor speed–torque curve the minimum available accelerating torque is 15–20% of its rated torque. In addition, the starting time must also be less than the thermal withstand time of the motor. For more details see Section 2.8.

2. This type of switching is limited to only LV system as MV motors are normally wound in star. However, in special cases, MV motors can also be designed for
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delta at a higher cost to the insulation system which may also call for a larger frame size. Also a provision can be made in the switching device to avoid the condition of an open transient during the changeover from $Y$ to $\Delta$ as discussed in Section 4.2.2(b).

3 This type of switching requires six cable leads to the motor as against three for other types of switchings to accomplish the changeover of motor windings from $Y$ to $\Delta$.

**Ratings of contactors**

Since all the contactors now fall in phase, they may be rated for the phase current only, i.e. $\frac{I_r}{\sqrt{3}} = 58\%$ of $I_r$.

The star contactor is in the circuit only for a short period and is generally chosen a size lower than the main and $\Delta$ contactors.

For power and control circuit diagrams see Figure 4.3(b).

### 4.2.2 Autotransformer ($A/T$) starting

For smoother acceleration and to achieve a still lower starting current than above, this type of switching, although more expensive, may be employed. In this case also the starting current and the torque are reduced in a square proportion of the tapping of the autotransformer. The normal tappings of an autotransformer are 40%, 60% and 80%. At 40% tapping the starting current and the starting torque will be only 16% that of DOL values. At 40% tapping, therefore, the switching becomes highly vulnerable as a result of greatly reduced torque and necessitates a proper selection of motor.

**To determine the tapping of the autotransformer**

Consider an autotransformer with a tapping at 40%. Then by equating the powers of the primary and the secondary sides of the autotransformer (Figure 4.4)

$$\sqrt{3} \cdot V_t \cdot I_{AT} \cdot \cos \phi = \sqrt{3} \cdot (0.4V_t) \cdot \sqrt{3} \cdot \frac{(0.4V_t)}{Z} \cdot \cos \phi$$

or

$$I_{AT} = (0.4)^2 \cdot \frac{V_t}{Z}$$

while the starting current on DOL:

$$I_{DOL} = \frac{\sqrt{3} \cdot V_t}{Z}$$

$$\therefore I_{AT} = (0.4)^2 \cdot I_{DOL}$$

i.e. proportional to the square of the tapping, where $I_{AT}$ = starting current on an autotransformer switching $I_{DOL}$ = starting current on a DOL switching $Z$ = impedance of the motor windings referred to the stator side per phase.

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**Note** Current jumps to almost DOL current even at around 60% speed, if switched to $\Delta$ position.

(a) Torque-current characteristics on a $Y/\Delta$ starting

(b) Power and control circuit diagram

Figure 4.3 Star-delta starting
Generalizing the above equation, autotransformer tapping for a particular starting current, $I_{AT}$ is

$$\text{Tapping} = \frac{I_{AT}}{I_{DOL}} \cdot 100\%$$  \hspace{1cm} (4.1)

From this equation, the desired tapping of the autotransformer, to limit the starting current to a desired value can be determined.

**Example 4.1**
A squirrel cage motor has its $I_{st}$ on DOL as six times its rated current. Find the required tapping on an autotransformer to limit the starting current to 1.5 times.

$$\text{Tapping} = \frac{1.5}{6} \times 100\%$$

or 50%

**Rating of autotransformer**
Since an autotransformer is in the circuit for only a short period (during the start only), it can be short-time rated. The rating of the autotransformer can be calculated from

$$\text{kVA}_{(\text{CMR})} = \sqrt{3} \cdot kV \cdot I_{AT}$$  \hspace{1cm} (4.2)

where

- $kV$ = applied voltage, and
- $\text{kVA}_{(\text{CMR})}$ = continuous rating of the autotransformer.

Since the transformer will be in the circuit for only 15 to 20 seconds, the approximate short-time rating of the transformer can be considered to be 10–15% of its continuous rating. The manufacturer of the auto transformer would be a better guide to suggest the most appropriate rating of the transformer, based on the tapping and starting period of the motor.

**Ratings of contactors**
Star contactor $C_1$ and $A/T$ contactor $C_2$ may be rated for the square of the percentage tapping. For a tapping of 80%, for instance, the rating of the contactors $C_1$ and $C_2$ will be $(0.8)^2$ or 64% of the full-load current of the motor. The main contactor $C_3$, however, will be rated for the full-load current. For power and control circuit diagrams see Figure 4.4.

**Example 4.2**
For a 3.3 kV 450 kW motor, with a full-load current of 100 A and starting current on DOL as six times the rated current,
the kVA rating of the transformer for 50% tapping will be
\[
I_{AT} = 0.5^2 \times 100 \times 6 = 150 \text{ A from Equation (4.1)}
\]
\[
\therefore \quad \text{kVA (CMR)} = \sqrt{3} \times 3.3 \times 150 = 860 \text{ kVA}
\]
An autotransformer of nearly 100 kVA continuously-rated should be sufficient for this application.

**Note**
The above example is only for a general reference. The CDF of the transformer, for the short-time rating, should be increased with the starting time and the number of starts per hour. Refer to the transformer manufacturer for a more appropriate selection.

### 4.2.2(a) Open transient condition during a reduced-voltage switching sequence

Whenever a changeover of a switching device (contactors generally) from one condition to another takes place, as discussed above, in changing over from one tapping to another, as in an autotransformer switching, or from star to delta as in a \(Y/\Delta\) switching, there appears a small time gap of, say, 20–80 ms before the next contactor closes, after the first has dropped. During this period, while the machine will drop its speed only very marginally, and which may not influence the load, the power from across the motor terminals will cease for this duration (except its own induced e.m.f.). This time gap, when switching MV motors particularly, may cause switching transients (Section 17.7.2). This is termed an open transient condition. The situation is aggravated further because of the motor’s own induced e.m.f. This time gap, when switching may become necessary when the capacity of the feeding transformer is not adequate to withstand the start-up inrush of DOL switching, or when the drive calls for a frequent switching, such as in a large compressor or pump house, and the feeding transformer is not adequate for such a duty, apart with the applied voltage and magnify the voltage transients, in addition to causing current transients. The current transients may far exceed even 14–20 times the rated current of the motor, as illustrated in Figure 4.5, depending upon the transient recovery voltage (TRV) (Section 17.6.2). We will describe the effect of an open transient condition on an LV and MV machine separately.

1. **LV motors** In LV motors, such a situation may not be a matter of concern as no switching surges would generally occur. The voltage would be too low to cause a re-strike between the interrupting contacts of the contactors (Section 17.7.6) and cause surges. The motor’s own induced e.m.f. may, however, fall phase apart with the applied voltage and the voltage across the motor windings may double. In all likelihood the windings of a motor would be suitable to withstand effect of the same (Table 11.4). In locations, however, that are humid or chemically contaminated, or where the motor is likely to be switched on after long gaps, it is possible that the windings may have attained a low dielectric strength to withstand a voltage up to twice the rated one. Open transient conditions must be avoided in all such cases. An SPD, however, is recommended at each pole of the main switching device similar to shown in Figure 17.23 and discussed in Section 17.13.

2. **HV Motors** \(Y/\Delta\) switching in MV motors is rare, while an \(A/T\) switching may become necessary when the capacity of the feeding transformer is not adequate to withstand the start-up inrush of DOL switching, or when the drive calls for a frequent switching, such as in a large compressor or pump house, and the feeding transformer is not adequate for such a duty,

![Figure 4.5 Open and closed transient conditions in \(Y/\Delta\) switching](image)
or when a number of large drives are to be switched in quick succession and the feeding transformer may not be adequate to sustain such heavy inrush currents. However, unlike an LV distribution system, which may impose a limitation while switching large motors on DOL, the MV or HV feeding lines in all probability may not pose any such limitation, as it may be feeding many more loads and may already be of sufficient capacity. In MV or HV systems an open transient condition may lead to severe voltage transients, which may prove disastrous for the motor windings. All motors that are switched A/T are therefore recommended to have a surge suppressor on each interrupting pole as noted in Section 17.10.3 which will take care of these surges. Precautions such as adopting a closed transient switching method noted below will be essential where surge suppressors are not provided.

### 4.2.2(b) Closed transient switching

1. **In a Y/Δ starter** When desired, the above situation can be averted by inserting a bridging resistor in the motor windings through an additional contactor, which can be called a transition contactor, $C$. A typical power and control scheme is shown in Figure 4.6 for a $Y/Δ$ switching. This contactor is energized through a timer, $T_1$, just before the desired time of changeover (before the $Y$ contactor opens) and energizes the auxiliary contactor, $d$, which de-energizes the $Y$ contactor $S$ through its NC contact and energizes the $Δ$ timer, $T_2$. Timer $T_2$ energizes the $Δ$ contactor $D$, thus bridging the time of the second contactor and eliminating the condition of an open transient. In fact, the use of timer $T_2$ becomes redundant with the introduction of the auxiliary contactor, $d$, which introduces the required delay (by its closing time) to close the $Δ$ contactor $D$. It is, however, provided to allow only for an additional delay. The time of this timer, when provided, may be set low to account only for the transient time. As soon as the changeover is complete, the resistor contactor, $C$, drops through the NC contact of $D$.

The scheme is termed a closed transient switching. A comparison of the two methods in terms of voltage transients and current overshoots is given in Table 4.1.

2. **In an A/T starter** The same logic can be applied as discussed above. The star point of the A/T is opened and connected through the main contactor $C_3$ to provide a near replica to a $Y/Δ$ switching. Figure 4.7 illustrates the revised scheme.

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**Figure 4.6** Circuit diagram for a closed transient $Y/Δ$ switching

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$M$ = Main contactor  
$D$ = Delta contactor  
$S$ = Star contactor  
$C$ = Resistor contactor  
$T_1$ = Resistor (‘ON’ delay timer)  
$T_2$ = Delta (‘OFF’ delay timer)  
$d$ = Auxiliary contactor
Pressing the start P.B. will energize the auxiliary contactor \(d\) and timer \(T\). The star contactor \(C_1\) is switched on and energizes the \(A/T\) contactor \(C_2\) at the desired tapping. The motor starts at the required reduced voltage. After the preset time of timer \(T\) the star contactor \(C_1\) falls out. The motor is still energized through the transformer winding without any interruption during the changeover. The main contactor \(C_3\) now energizes and the motor runs at full voltage. The \(A/T\) contactor \(C_2\) also falls out thus achieving a closed transient switching sequence.

### 4.2.3 Soft starting

Soft starting minimizes the starting mechanical and thermal stresses/shocks on the machine and the motor. It
results in reduced maintenance cost, fewer breakdowns and hence longer operating life for both. Reduced starting current is an added advantage.

**Through semiconductor devices (static drives)**

In a solid-state static switching device the voltage can be varied smoothly to any required value from high to low or low to high without creating a condition of open transient. For MV motors particularly and large LV motors generally, it provides a more recommended alternative over an autotransformer or a \(Y/\Delta\) starting. For details see Section 6.16.1.

**Through static electrodes liquid electrolyte or chemical resistance starting**

This is a primary resistance starting and has a well-proven French technology for soft starting of all types of induction motors. The device works on the principle of a decrease in resistance of an electrolyte (chemical) having a negative temperature coefficient. The passing of the starting current through the electrolyte raises its temperature inside a static electrode chamber. The rise in temperature of the electrolyte decreases its own resistance progressively. This device thus provides a natural variable resistance during the start-up period and hence the desired variable resistance control. The resistance of the electrolyte varies smoothly, and helps to start up the motor smoothly.

The electrolyte normally consists of sodium-based salts such as sodium carbonate (\(\text{Na}_2\text{CO}_3\)) mixed with distilled, de-mineralized (DM) or soft drinking water. These salts are neutral and non-corrosive and remain stable throughout the life of the electrodes, which can be many years. Evaporation and outside contamination are minimized by providing anti-evaporation/sealant oil. The electrolyte is filled in separate tanks for each phase, each with two electrodes (Figure 4.11). These electrolytic resistances are used in series with the motor’s stator windings. During the start-up period, the current passes through them and causes a voltage drop, which allows a reduced voltage to the motor’s stator windings. The current through the electrolyte causes its temperature to rise and resistance to drop, and thus reduces the voltage drop. Gradually the voltage applied to the stator windings builds up until it almost reaches the rated voltage. At this stage the residual electrolyte can be totally cut off from the circuit with the help of a shorting contactor. A timer can also be introduced in the electrolyte circuit to automatically cut off the electrolyte circuit after a preset starting time.

**Starting characteristics**

With this type of switching we can also obtain similar speed–torque or speed–current characteristics as with reduced-voltage starting, in a star-delta or an autotransformer starting. Since the variation in the resistance of the electrolyte with the starting heat, is very smooth, as shown in Figure 4.8, the speed–torque and speed–current characteristics are also very smooth. The characteristics are now without any torque, current or voltage spikes, unlike in \(Y/\Delta\) or autotransformer startings as noted in Table 4.1. It also eliminates the changeover open transient condition. Figure 4.9 illustrates transient-free switching through such electrolyte starters. This is a definite advantage of electrolytic switching over conventional \(Y/\Delta\) or autotransformer switching.

**Important features of electrolyte switchings**

1. They have in-built safety features to prevent excessive frequent starting, by means of thermostats and low level electrolyte monitors

![Figure 4.8 Variation in electrolyte resistance with speed](image)

![Figure 4.9 Smooth acceleration through liquid electrolyte starters](image)
2 It is important to maintain the level of the electrolyte to retain the desired characteristics on a repeat start. However, this may be necessary only once a year as a result of very little evaporation. In the event of a lower level the electrolyte can be filled up with drinking water, as in a car battery.

3 This type of switching provides very smooth acceleration. This is an advantage of electrolyte switchings over other conventional types of switchings. It exerts no kicks and calls for no special coupling arrangement to transmit the power smoothly to the load if the requirement of the load is to be precise and to have a smoother acceleration.

4 Since the starting characteristics will depend upon the initial resistance of the electrolyte, the concentration of electrolyte and the active area of the electrode must be determined beforehand for a particular type of load, and the requirements of starting torque and current. Small adjustments at site are, however, possible by varying the depth of electrodes, adjusting the active area of the electrode, repositioning the flanges and changing the concentration of the electrolyte etc.

5 Electrode assembly – a general arrangement of an electrode assembly is shown in Figure 4.10. The value of the resistance is preset at the works, according to load requirements, starting current, torque limitation, starting time etc. Small adjustments are possible at site as noted above.

6 The electrolytes are non-corrosive and the electrodes do not corrode with time. This feature is of special significance when compared with an ordinary liquid resistance starter used commonly for slip-ring motors.

7 Electrolytes do not deteriorate and therefore do not require replacement. The evaporated liquid can be replenished with drinking water when the level of the electrolyte falls as a result of evaporation. In Europe such starters have been in use for over 20–25 years.

8 Electrolyte switching is a costlier proposition compared to direct on-line or star/delta switching due to additional shorting contactor and timer, and the cost of electrolyte, its tank and thermostatic control etc. The cost may, however, be comparable with autotransformer switching. With the easy availability of static drives (Chapter 6) the application of these starters has been on the wane.

Applications, ratings and sizes

Electrolyte switchings are simple in construction and possess high thermal capacity. They are ideally suited for difficult starting duties and remotely located plants, where expert services, such as are required for static drives, are not easily available. These starters are not bulky and rating is no bar. The common range is from 1 h.p. to 1000 h.p. for LV as well as MV squirrel cage motors (Figure 4.11).

![Figure 4.10](image1)

**Figure 4.10** A typical liquid electrolyte electrode assembly
(Source: AOYP Engineering)

![Figure 4.11](image2)

**Figure 4.11** Electrolyte starter

Note One single unit is normally designed for 10 to 40 H.P.

(a) Typical arrangement of two electrolyte units being used in parallel one above the other

(b) Overview of the starter
List of formulae used

**Tapping of autotransformer**
\[ \frac{I_{\text{AT}}}{I_{\text{DOL}}} \cdot 100\% \]  \hspace{1cm} (4.1)

\( I_{\text{AT}} \) = starting current on an autotransformer switching

\( I_{\text{DOL}} \) = starting current on a DOL switching

**Rating of autotransformer**
\[ \text{kVA}_{(\text{CMR})} = \sqrt{3} \cdot \text{kV} \cdot I_{\text{AT}} \]  \hspace{1cm} (4.2)

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.

Further Reading

Relevant Standards

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