ELECTRICAL MOTORS

Three Phase Induction Motor Control

Need for a Starter in a 3-Phase Induction Motor

Starting a **3-phase induction motor** directly from the supply line can lead to various issues such as:

- ⚡ **High inrush current** (often 5-7 times the full-load current)
- 🛠️ **Mechanical stress** on motor components (rotor, shaft, bearings)
- 🔻 **Voltage dips** in the power network, affecting other connected equipment

Key Purposes of Using a Starter

A **starter** is designed to address these issues and ensure **safe and efficient operation** of the motor. The main functions are:

1. **To reduce the heavy starting current drawn by the motor**
    - **Inrush current** at startup can be significantly higher than the normal running current. A starter limits this current to prevent damage to the motor windings and the power supply system.
2. **To provide overload and under-voltage protection for the motor**
    - **Overload protection** prevents the motor from drawing excessive current when running at high loads.
    - **Under-voltage protection** automatically disconnects the motor if the supply voltage drops below a safe level, preventing stalling or damage to the motor.
3. **To ensure smooth and safe startup of the motor**
    - Starters allow for **controlled acceleration**, avoiding mechanical shock or sudden jerks, which can damage the motor components.

The following four methods are extensively used for starting the three-phase induction motors −

1. **Direct-On-Line Starter**
2. **Auto-Transformer Starter**
3. **Star-Delta Starter**
4. **Rotor Resistance Starter**

1. **Direct-On-Line (D.O.L.) Starter**

The **Direct-On-Line (D.O.L.) starter** is one of the simplest and most commonly used methods for starting **3-phase induction motors**. As the name suggests, it involves connecting the motor **directly to the 3-phase AC supply** without any intermediate components to limit the starting current.

Working Principle

- **Connection:** The motor is directly connected to the **supply line** using **a contactor**, **overload relay**, and **fuses** for protection.
- **High Starting Current:** When the motor starts, it draws a very high **inrush current** — typically 4 to 10 times the full-load current. This is because the impedance of the motor at standstill is low (close to a short circuit).

Features of D.O.L. Starting

- **High Starting Current:** The main drawback is the high **starting current**, which can cause voltage dips in the supply and potential damage to the motor windings and electrical components.
- **Simple & Low Cost:** The D.O.L. method is simple to implement and does not require complex circuitry, making it cost-effective.
- **Suitable for Low-Power Motors:** It is commonly used for small to medium-sized motors that do not have very high starting current demands.

Limitations of D.O.L. Starting

1. **High Inrush Current:**
    - The motor draws up to **10 times** the rated current during startup, which can cause voltage dips in the network.
    - This can lead to issues in other equipment connected to the same supply.
2. **Mechanical Stress:**
    - The **sharp startup** can subject the motor components (rotor, bearings, etc.) to **high mechanical stress**.
3. **Not Suitable for Large Motors:**
    - D.O.L. starting is not suitable for motors with a higher power rating (>7.5 kW) because the high starting current may cause damage to both the motor and the power supply system.

Applications of D.O.L. Starter:

- Small pumps, Fans, Compressors, Conveyors.

Conclusion:

- The **Direct-On-Line (D.O.L.) starter** is an easy and cost-effective solution for **low-power motors** but should be avoided for **high-power motors** due to its high starting current and mechanical stresses.

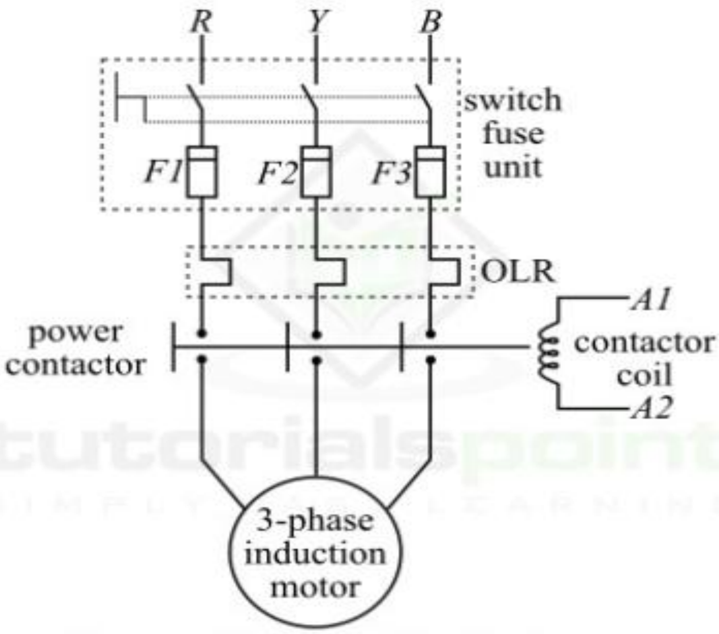

Figure 1 - Direct-On Line Starter

2. Autotransformer Starter

The **Autotransformer Starter** is another method for starting a **3-phase induction motor**. It uses an **autotransformer** to reduce the voltage supplied to the motor at startup, thereby reducing the high inrush current associated with Direct-On-Line (D.O.L.) starting.

Working Principle of Autotransformer Starter

1. **Reduced Voltage at Start:**
   During startup, the **autotransformer** provides a reduced voltage (typically 60% to 80% of the full supply voltage) to the motor. This reduces the **starting current** and the mechanical stress on the motor components.
2. **Transition to Full Voltage:**
   Once the motor reaches a sufficient speed (typically about 70-80% of the full speed), the motor is then switched to the **full supply voltage**. This method helps in providing a smoother start while still maintaining sufficient torque for the motor to run efficiently.

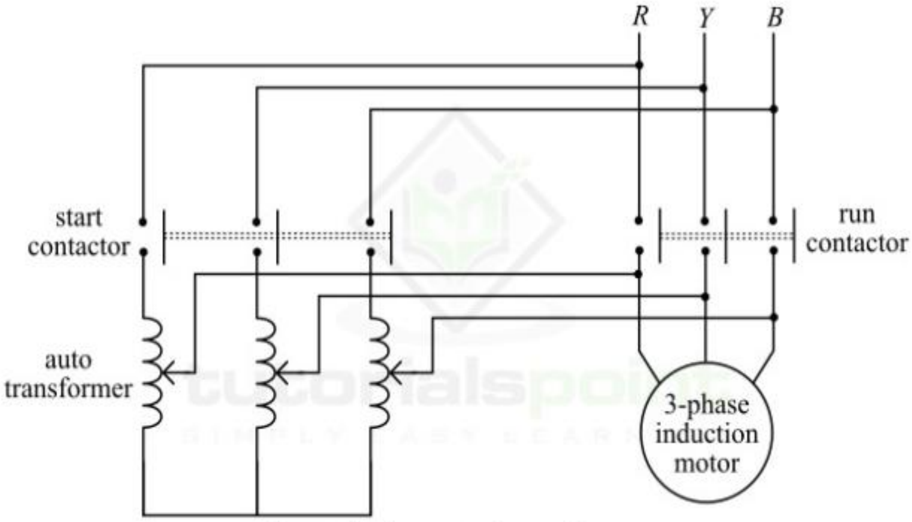

Figure 2 - Autotransformer Starter

Advantages of Autotransformer Starter

- **Reduced Starting Current:** The autotransformer limits the starting current, typically reducing it to about **2 to 3 times** the full-load current, compared to 4 to 10 times in D.O.L. starting.
- **Lower Mechanical Stress:** Since the starting current is lower, it reduces the **mechanical shock** and stress on the motor's rotor, bearings, and other components.
- **Higher Starting Torque:** The reduced starting current still allows for a higher starting torque compared to D.O.L. starters (about **1.5 to 2 times** the full-load torque).

Limitations of Autotransformer Starter

1. **Cost and Complexity:** The autotransformer starter is more expensive than the **Direct-On-Line (D.O.L.) starter** because it requires an additional component — the autotransformer.
2. **Still Requires High Starting Torque:** While the current is reduced, the **starting torque** is still higher than the **D.O.L. method** and might not be sufficient for some high-torque applications.
3. **Not Suitable for High-Power Motors:** Though it reduces starting current, this method is still not ideal for very large motors, as the system might still experience voltage dips.

Applications of Autotransformer Starter:

- Medium-power motors (above 7.5 kW, but not too large), Pumps, Fans, Compressors.

🛑 **Conclusion:**

The **Autotransformer Starter** offers a balance between the simplicity of **D.O.L. starters** and the need for **controlled acceleration** and **lower starting current**. It's most suitable for motors where reduced inrush current is important but still requires adequate starting torque.

3. Star-Delta Starter

The **Star-Delta Starter** is a commonly used method for starting **squirrel cage 3-phase induction motors**. It provides a way to **reduce the starting current** and is suitable for motors designed to run in **delta configuration** during normal operation.

Working Principle

- **Start in Star Configuration:**
  At the moment of starting, the motor windings are connected in a **star (Y)** configuration. In this configuration, each phase winding receives only **V/√3** of the line voltage (where **V** is the line voltage), reducing the **starting current and torque**.
- **Run in Delta Configuration:**
  After the motor attains about **70–80% of its rated speed**, a **changeover switch** (typically operated by a timer or relay) reconnects the motor windings into a **delta (Δ)** configuration. Now, each phase gets the **full line voltage**, and the motor runs at

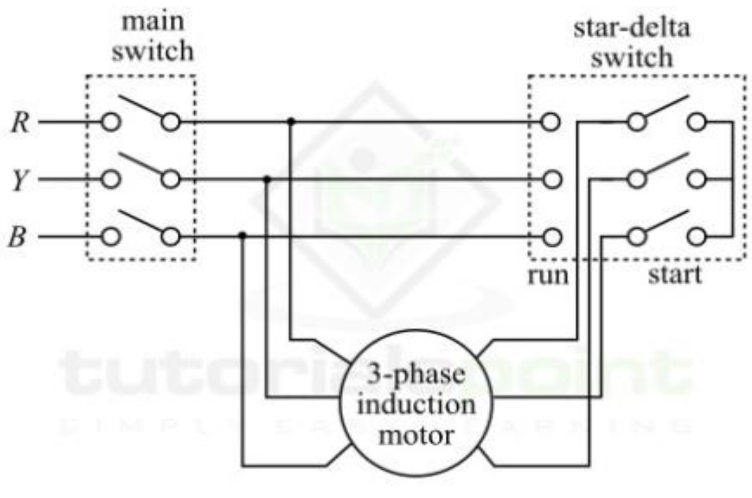

Figure 3 - Star-Delta Starter

Advantages of Star-Delta Starter

- **Reduced starting current** (about 33% of D.O.L. starter).
- **Simple and economical** for motors rated up to 25–50 HP.
- **No additional voltage drop** in the system compared to autotransformer method.

Limitations of Star-Delta Starter

- **Reduced starting torque** (only 33% of full-load torque), which may not be sufficient for high-load or heavy inertia applications.
- **Mechanical stress** when switching from star to delta if not properly timed.
- **Requires six terminals** on the motor to allow external reconnection from star to delta.

🛠️ **Applications**

- Suitable for **low to medium voltage motors** that are lightly loaded at startup: Blowers, Fans, Pumps, Compressors

🛑 **Conclusion**

The **Star-Delta Starter** is a **cost-effective and widely used** method to reduce starting current in 3-phase induction motors, provided the application does **not require high starting torque**.

4. Rotor Resistance Starter for Slip-Ring Induction Motors

The **Rotor Resistance Starter** is a special method used **only with slip-ring (wound-rotor) induction motors**. This method takes advantage of the fact that the rotor circuit of a slip-ring motor is **externally accessible via slip rings**, allowing insertion of resistors to control the startup behavior.

🧠 **Working Principle**

1. **Maximum Resistance at Start:**
   At startup, a **star-connected rheostat** (variable resistor) is inserted into the **rotor circuit**. This introduces **maximum resistance**, which:
   - **Limits the starting current**
   - **Increases the starting torque**
2. **Gradual Removal of Resistance:**
   As the motor accelerates, the external resistance is **gradually decreased** by adjusting the rheostat.

3. **Full-Speed Running:**
   Once the motor reaches about **80% of rated speed**, the external resistance is **completely shorted out** (i.e., the rotor windings are directly short-circuited

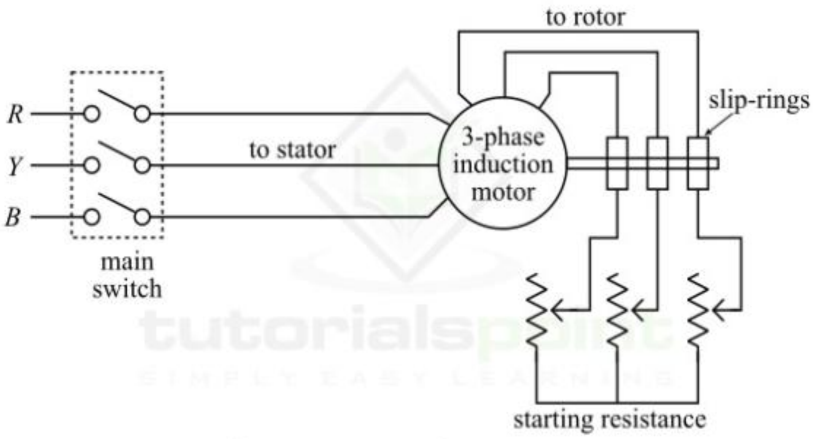

Figure 4 - Rotor Resistance Starter

   internally), and the motor runs normally.

✅ Advantages

- **High starting torque** (ideal for heavy-duty applications)
- **Smooth acceleration**
- **Reduced mechanical and electrical stress**

⚠️ Disadvantages

- **Applicable only to slip-ring induction motors**
- **More complex and expensive** due to additional hardware (slip rings, resistors)
- **Maintenance required** for slip rings and brushes

🛑 Conclusion

The **Rotor Resistance Starter** is ideal where **high starting torque and low starting current** are essential, and it's specifically suited to **slip-ring induction motors**. It provides a flexible and effective way to control motor startup, although it's limited to special motor types and requires regular maintenance.

⚙️ Speed Control of 3-Phase Induction Motor

Three-phase induction motors generally operate at **constant speed**, close to but slightly less than **synchronous speed**. However, for various industrial applications, **controlling motor speed** becomes necessary — though it's technically challenging and can affect efficiency and power factor.

🧮 Key Formulae

🔹 **Synchronous Speed**

The synchronous speed (Ns) is the theoretical speed of the rotating magnetic field:

$$Ns = \frac{120 \times f}{p}$$

Where:

- Ns = Synchronous speed in RPM
- f = Supply frequency in Hz
- P = Number of poles in the stator

🔹 **Actual Rotor Speed (Nr)**

The rotor always rotates slightly less than the synchronous speed:

$$Nr = Ns(1 - s)$$

Where:

- Nr = Rotor speed in RPM
- s = Slip (typically 2–6% for normal loads)

🔹 **Slip**

$$s = \frac{Ns - Nr}{Ns}$$

Slip is a measure of how much slower the rotor moves compared to the magnetic field.

Torque Equation of a 3-Phase Induction Motor

The torque developed in a 3-phase induction motor depends on slip, rotor resistance, rotor reactance, and supply voltage. The general torque equation is derived from the **power transferred to the rotor** and is given by:

$$T = \frac{3}{2\pi Ns} * \frac{s.E2^2.R2}{R2^2 + (sX2)^2}$$

Where:

- T: Torque (in N·m)
- s: Slip
- E2: Rotor induced EMF per phase at standstill
- R2: Rotor resistance per phase
- X2: Rotor reactance per phase
- Ns: Synchronous speed in RPM

The **speed of a 3-phase induction motor** can be controlled from both the **stator side** and the **rotor side**. Here's a clearer breakdown of **speed control methods from the stator side**:

⚙️ Speed Control from Stator Side

1. V/f Control or Frequency Control

- Most effective and widely used method (especially with VFDs - Variable Frequency Drives).
- Supply voltage and frequency are varied **proportionally** to keep magnetic flux constant.
- Provides **smooth speed control** over a wide range without affecting torque.
- Common in fans, conveyors, elevators, etc.

2. Pole Changing (Changing Number of Stator Poles)

- Based on the synchronous speed formula:

$$Ns = 120 \cdot \frac{f}{p}$$

- By changing number of poles P, speed can be changed in discrete steps.
- Achieved using **consequent pole method** or **multiple windings**.
- Used in two-speed motors for machine tools, pumps, etc.

3. Stator Voltage Control

- Reduces the stator voltage while keeping frequency constant.
- Reduces torque along with speed.
- Suitable for **low-load applications** like fans or blowers.

4. Adding Rheostat in Stator Circuit

- Rare and inefficient method due to high power losses.
- Rheostat drops voltage, affecting torque and speed.
- Not commonly used in practice.
