Three Phase Induction Motor

Three-phase induction motors are the motors most frequently used in industry. They are simple, low-cost, rugged and easy to maintain. However, their speed is frequency dependent and as a result these motors are not easily adapted to speed control. In this section we investigate the principles of the three-phase induction motor.

Induction Motor Components

An induction motor has two main parts:

• A stator – consisting of a steel frame that supports a hollow, cylindrical core of stacked laminations. Slots on the internal circumference of the stator house the stator winding.

• A rotor – also composed of punched laminations, with rotor slots for the rotor winding.

The rotor is separated from the stator by a small air-gap which ranges from 0.4 mm to 4 mm, depending on the power and the size of the motor.

Rotor and **Stator** are **two magnets**, which generate magnetic flux using coil windings or a permanent magnet. The rotor is mounted on a bearing-supported shaft, which can be connected to *mechanical loads (if machine is a motor)* or to a *prime mover (if machine is a generator)*. Figure 1 depicts a three-phase rotation machine with the main terminalolgy.

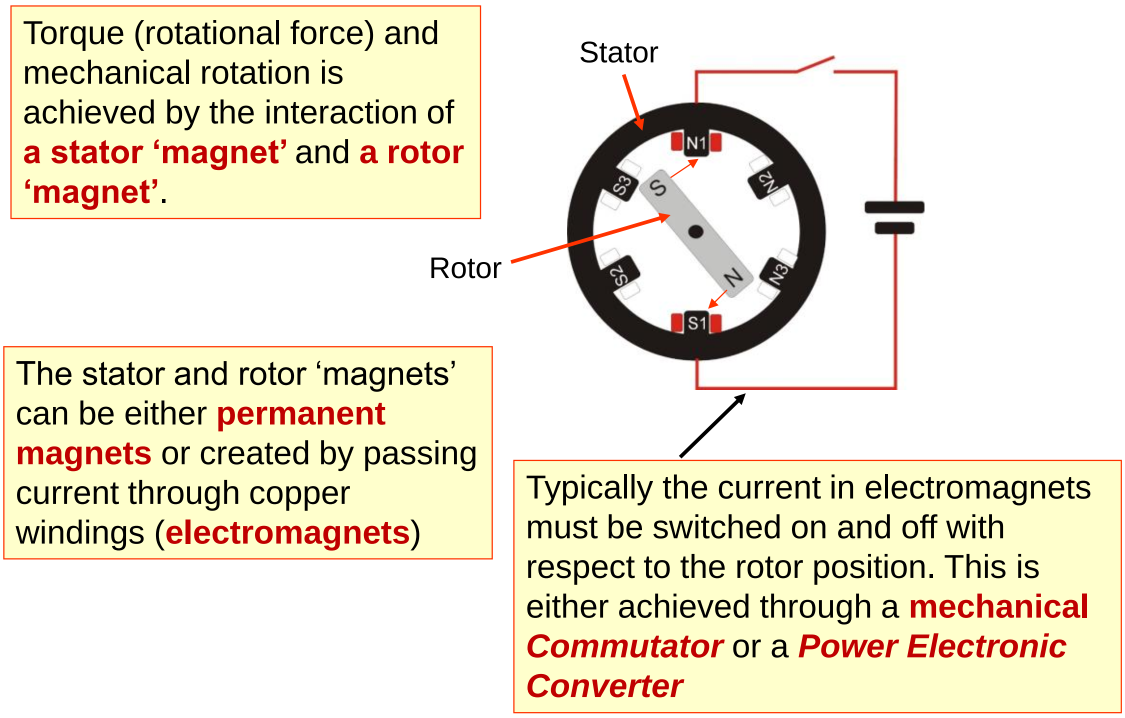

Figure 1. Depiction of a rotating machine

Types of ac induction motor rotors

There are two-types of rotor windings, squirrel-cage and wound rotor. Almost 90% of the three-phase AC Induction motors are squirrel-cage so we will focus on this. A squirrel-cage rotor is composed of bare copper bars, slightly longer than the rotor that are inserted into the slots. The opposite ends of the copper bars are welded to two copper endrings so that all the bars are short-circuited together.

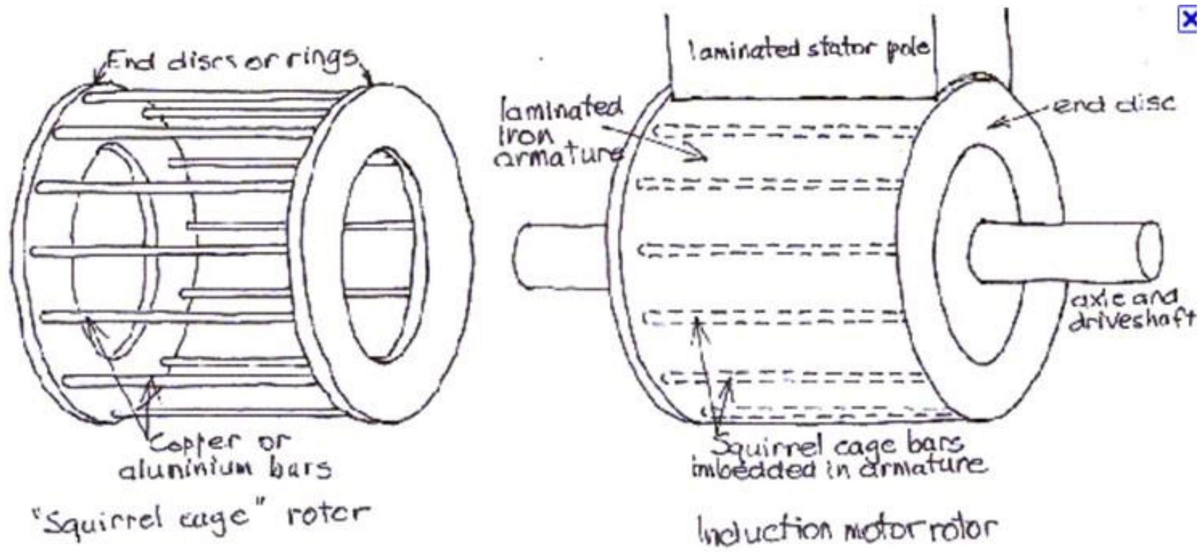

Figure 2. Construction of squirrel-cage induction motor rotor

Operational Principle

Before discussing the theory of operation for the induction motor the concept of rotating field, must be understood. A rotating and constant resultant magnetic field rotating at a constant speed may be produced by any three-phase group of windings displaced in space if the currents flowing through the windings are also displaced in time.

The three fluxes generated by the phase windings are separated by 120° in space and in time for a two-pole motor. The total flux in the machine is the sum of the three fluxes. The summation of the three ac fluxes results in a rotating flux, which turns with constant speed and has constant amplitude. The rotating flux induces a voltage in the short-circuited bars of the rotor. This voltage drives current through the bars. The interaction of the rotating flux and the rotor current generates a force that drives the motor.The force is proportional with the flux density and the rotor bar current.

The voltage and current generation in the rotor bar require a speed difference between the rotating field and the rotor. Consequently, the rotor speed is always less than the magnetic field speed.

Number of Poles and Synchronous Speed

The synchronous speed is the speed of revolution of the magnetic field in the stator winding of the motor. It is the speed at which the electromotive force is produced by the alternating machine and is given by:

$$N_s = \frac{60 \times f_s}{(P/2)} = \frac{120 \times f_s}{P} \text{ rpm} \qquad (1)$$

Where f_s is the supply frequency and P is the machine pole number. Figure 3 shows a 2 pole and 4 pole machine. The key thing to note is that if the number of poles change so does the synchronous speed.

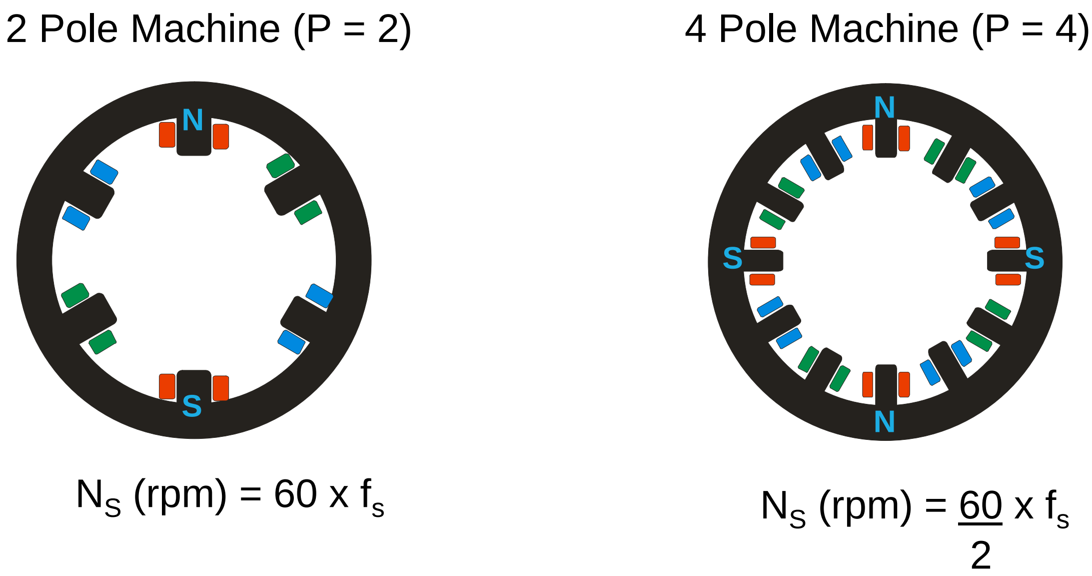

Figure 3. Synchronous speed and number of poles

The key points are that:

1. The three phase voltages input to the three phase windings in the stator producing rotating stator flux in the motor airgap.
2. The stator flux rotates at a synchronous speed set by the supply frequency and the number of poles.

Asynchronous Operation and Slip

If we consider a single point on the rotor and initially the rotor is stationary. The sinusoidal flux (Φ) will induce a sinusoidal voltage across the rotor bars. This will cause sinusoidal currents to flow along the rotor bars, Figure 4.

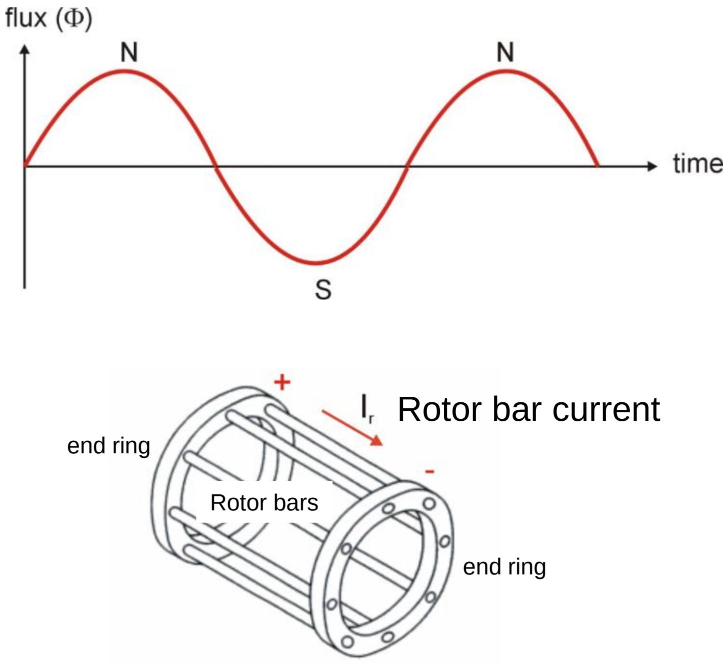

Figure 4. Sinusoidal flux induces a sinusoidal current in the rotor bars

The current in the rotor bars will enhance the flux on one side of the bar and reduce it on the other side causing a force on the rotor, as depicted in Figure 5.

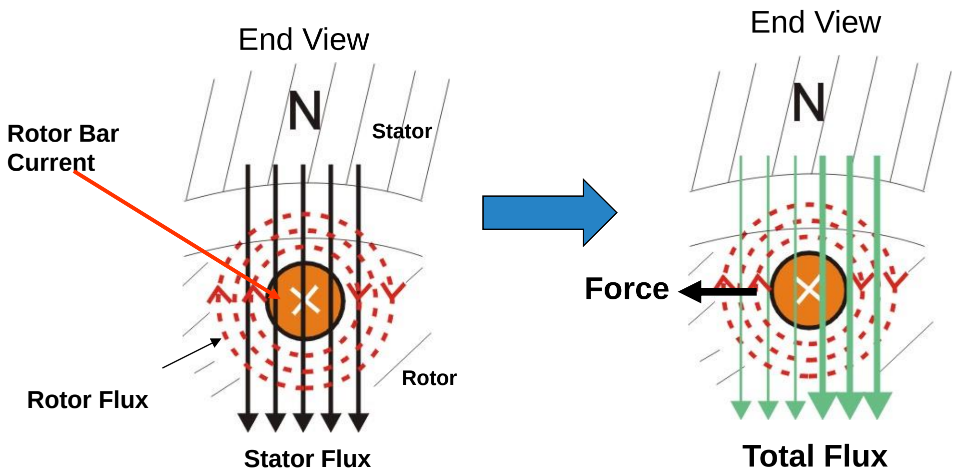

Figure 5. Rotor flux and force

The force is given by:

$$Force = B.I_r.L \tag{2}$$

Where **B** is the stator flux density, I_r is the rotor current and L is the length of the rotor bar.

We can now determine the rotor torque at start up, or standstill since:

$$\text{Torque (Nm)} = \text{Force} \times \text{d} \tag{3}$$

Where d is shown in Figure 6.

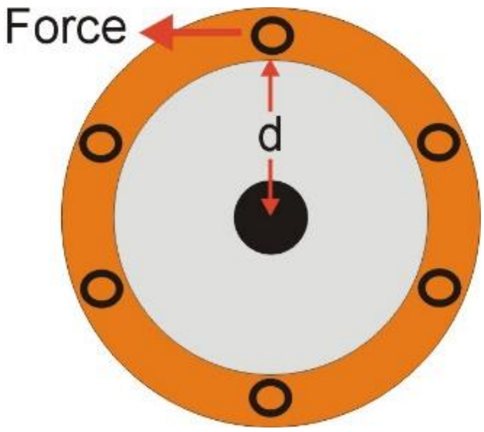

Figure 6. Force exerted on a rotor bar

We now want to determine the rotor torque at synchronous speed (N_s). If the rotor was rotating at Synchronous Speed then the rotor would be travelling at the same speed as the Stator Magnetic Field and therefore the Flux at any point on the rotor would be constant value. Since the rate of change of flux would be zero there would be no induced current in the rotor bars and no torque would be produced. Therefore, a difference in speed between the rotor and the stator magnetic field is required to produce torque. That is the rotor can never rotate at the synchronous speed. We can now define something called slip:

$$\text{Slip (s)} = \frac{N_s - N_r}{N_s} \tag{4}$$

Where N_r is the rotor speed.

The frequency of the rotor voltage and current (f_R) is now given by:

$$f_R = s \times f$$

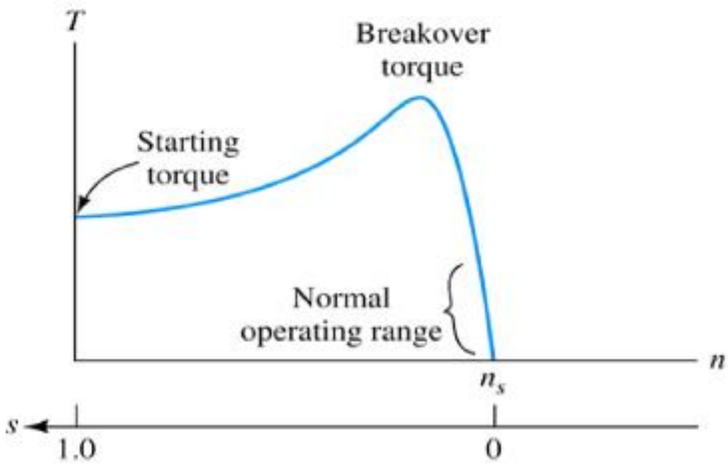

Figure 7. Torque versus slip.

Figure 7 shows the relationship between torque and slip.

Equivalent circuit for induction motor (per phase)

Hopefully you will recognise that the equivalent circuit is quite similar to the equivalent circuit for a transformer. However, there are a couple of significant differences brought about by the fact that the secondary (rotor) circuit is rotating at a different speed to the stator magnetic field. The starting point is the realisation that AT STANDSTILL each phase of the induction motor is equivalent to a single phase transformer with its secondary winding short circuited (Figure 8).

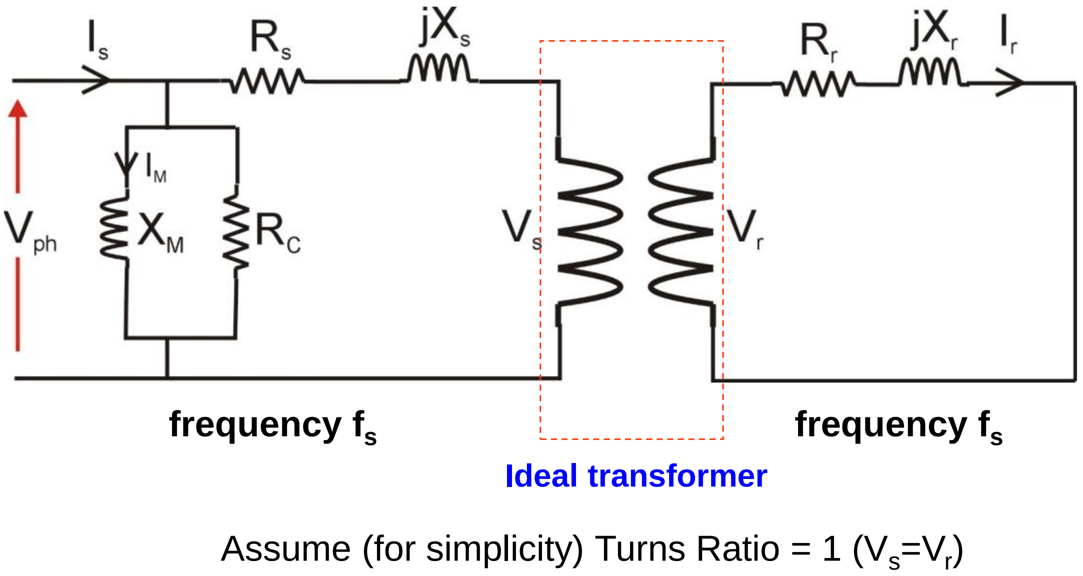

Figure 8. Equivalent circuit at standstill

Once the rotor is no longer at standstill there will be slip and the equivalent circuit needs to be modified accordingly. If we transfer the rotor side to the primary we can modify Figure 8 as shown in Figure 9.

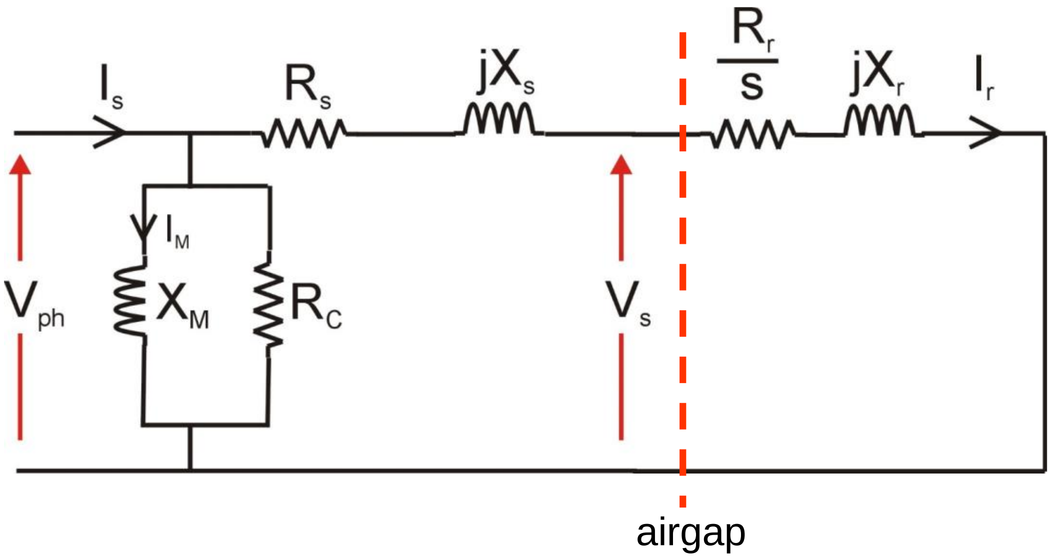

Figure 9. Rotor side referred to primary with slip considered

In Figure 9, the total power that crosses from the stator to the rotor is represented by the R_r/s component. The electrical input power (per phase) is given by:

$$P_{ph} = V_{ph} I_s \cos\phi \tag{5}$$

Where ϕ is the angle between V_{ph} and I_s.

We can now consider the mechanical output power. The total power per phase across the air gap is:

$$P_{gap\_ph} = I_r{}^2 R_r / s \tag{6}$$

Therefore, the total 3 phase power across the airgap is:

$$P_{gap} = 3I_r^2 R_r / s \tag{7}$$

The three phase rotor copper losses are:

$$P_{Rcu} = 3I_r^2 R_r = P_{gap} \cdot s \tag{8}$$

This enables us to calculate the mechanical power:

$$P_{mech} = P_{gap} - P_{Rcu} = I_r{}^2 \frac{R_r}{s}(1-s) = P_{gap} \cdot (1-s) \tag{9}$$

We can now draw a final equivalent circuit (per phase), Figure 10. If we have values for the equivalent circuit parameters then we can calculate Mechanical Output Power (and Torque) and Efficiency at any given speed (slip) and supply voltage. We will look at some examples in the lecture time.

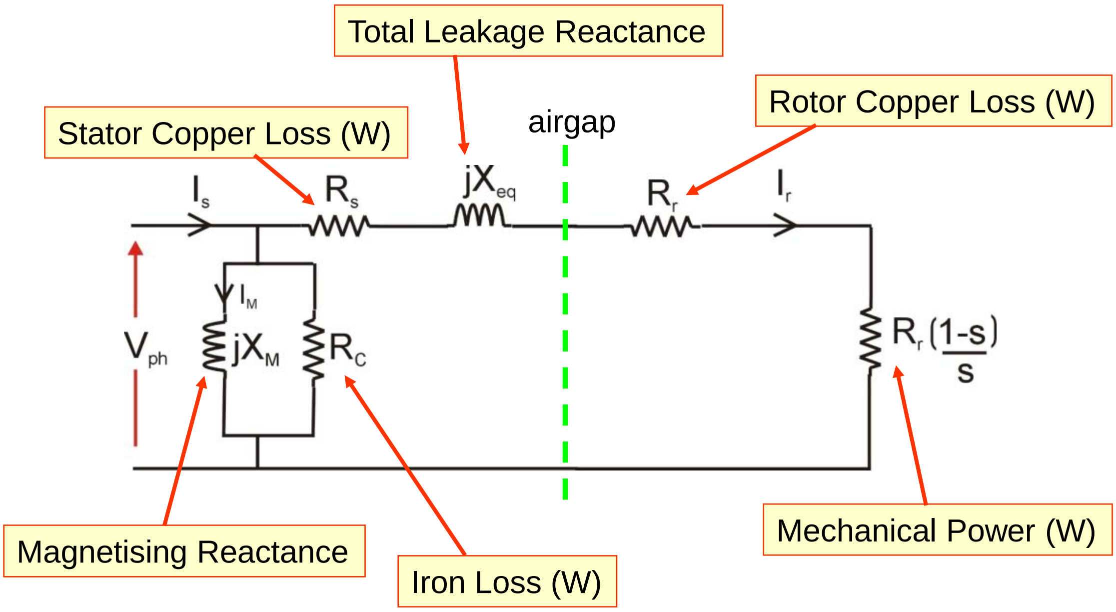

Figure 10. Final Equivalent circuit (per phase) for an induction motor

Bibliography

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