3 Phase Induction Motor – Construction and Working

The popularity of 3 phase induction motors onboard ships is because of their simple, robust construction, and high-reliability factor in the sea environment. An induction motor can be used for different applications with various speed and load requirements.

The ship's generator 3 phase AC supply can be connected to the AC induction motor via a starter or any other arrangement like an auto-transformer to improve the torque and current characteristics.

What is an Induction Motor?

An induction motor or asynchronous motor is an AC motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding.

2. 3 Phase Induction Motor:

These 3 phase motor is supplied with 3 three-phase AC supply and is widely used in ships for heavier loads. 3 phase induction motors are of two types, squirrel cage and slip ring motors.

Squirrel cage motors are widely used on ships due to their rugged construction and simple design, few e.g. of their applications are:

- Lifts
- Cranes
- Large capacity exhaust fans
- Engine Auxiliary pumps
- Engine blower fan motor
- Engine room heavy load pumps –

Ballast, Fire, Freshwater, Sea Water etc.

- Winch motor
- Windlass motor

Construction of 3 Phase Induction Motor

The main body of the Induction Motor comprises of two major parts:

Stator

The stator is made up of a number of stampings in which different slots are cut to receive 3 phase winding circuit which is

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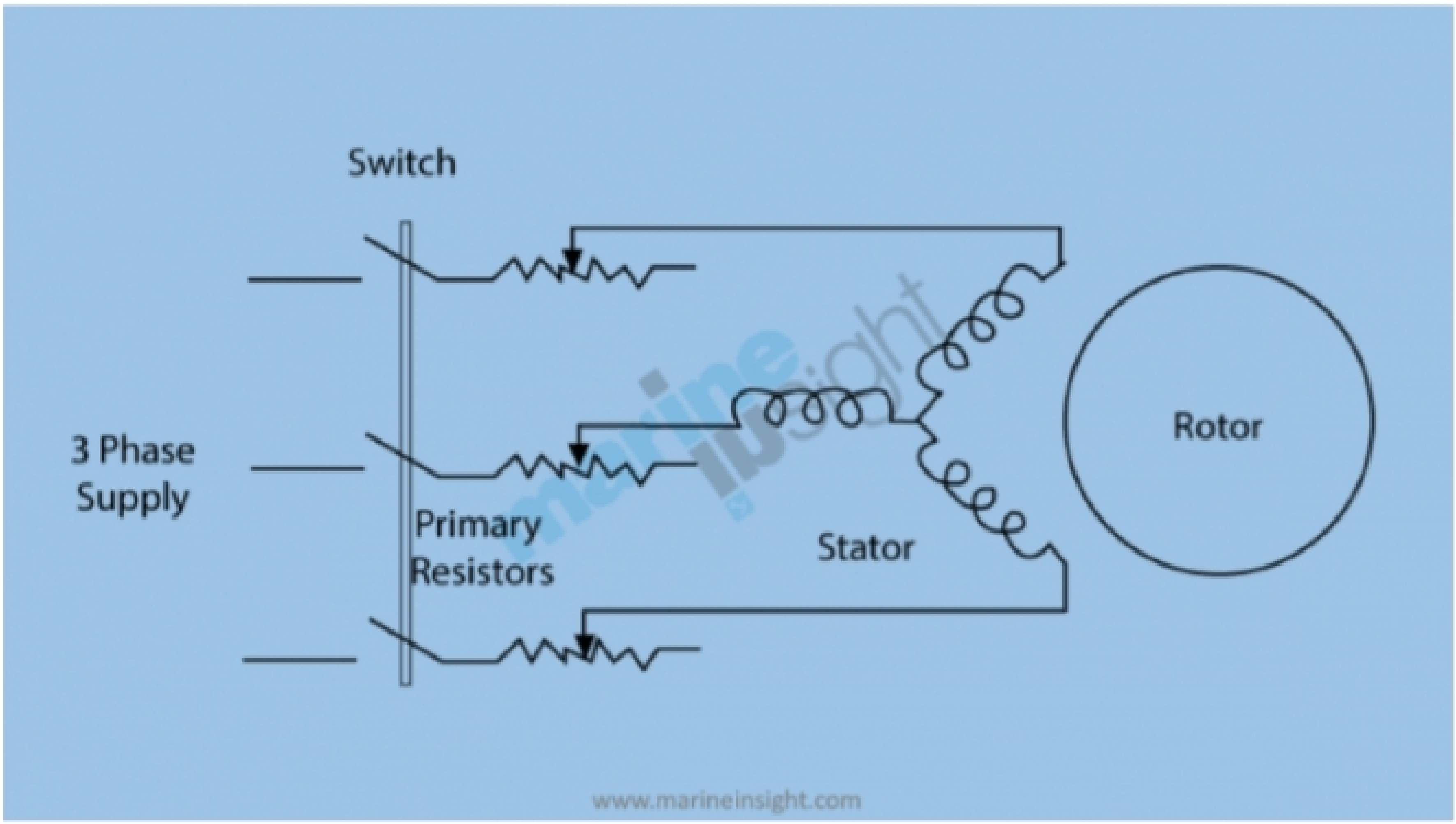
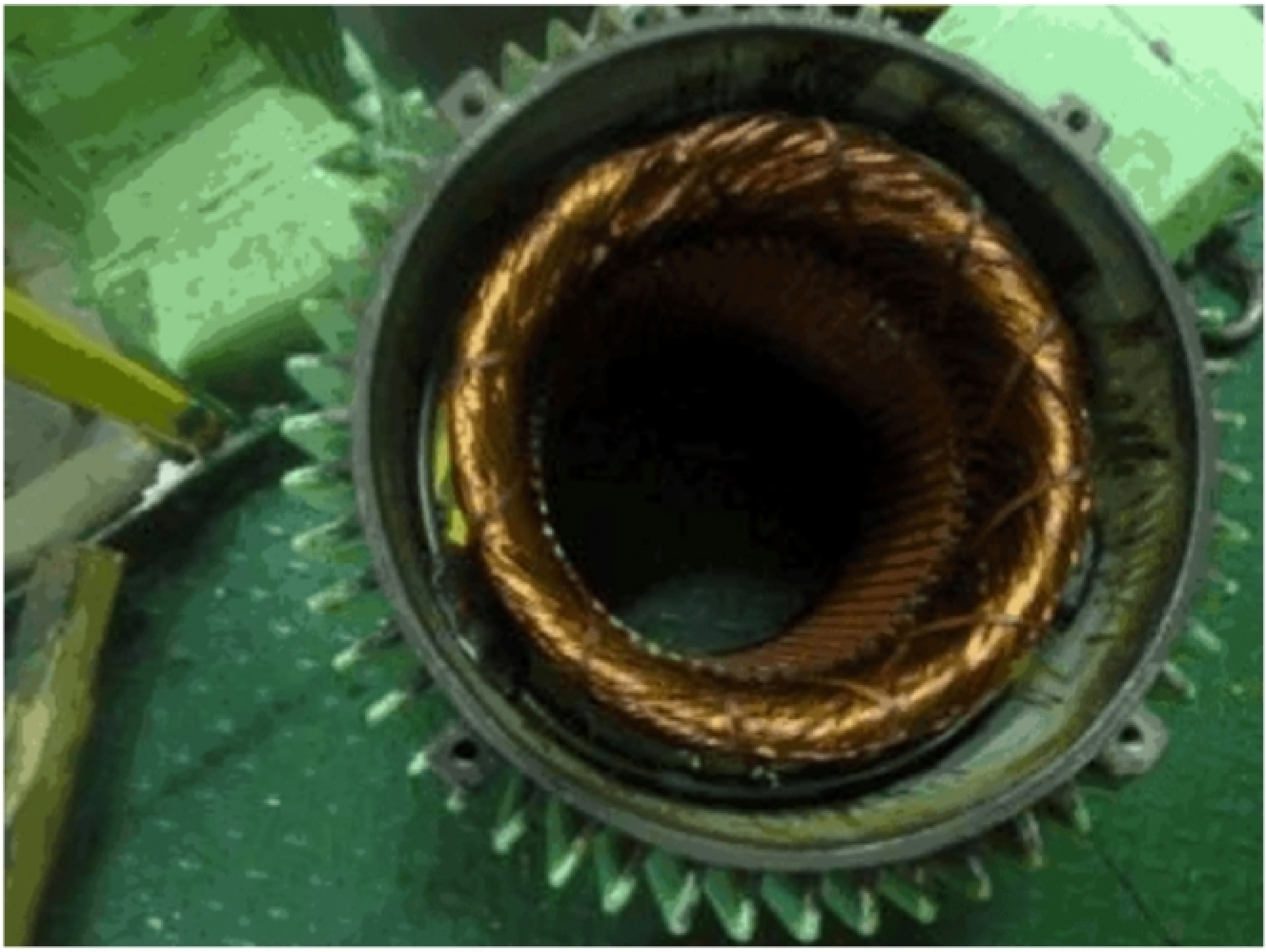


The three-phase windings are arranged in such a manner in the slots, that they produce a rotating magnetic field after AC supply is given to them.

Usually, windings are kept at different pitch circle with 30 % overlap to each other.



The windings are wound for a definite number of poles depending upon the speed requirement, as speed is inversely proportional to the number of poles, given by the formula:

$N_S = 120f/p$

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Where N_S= synchronous speed

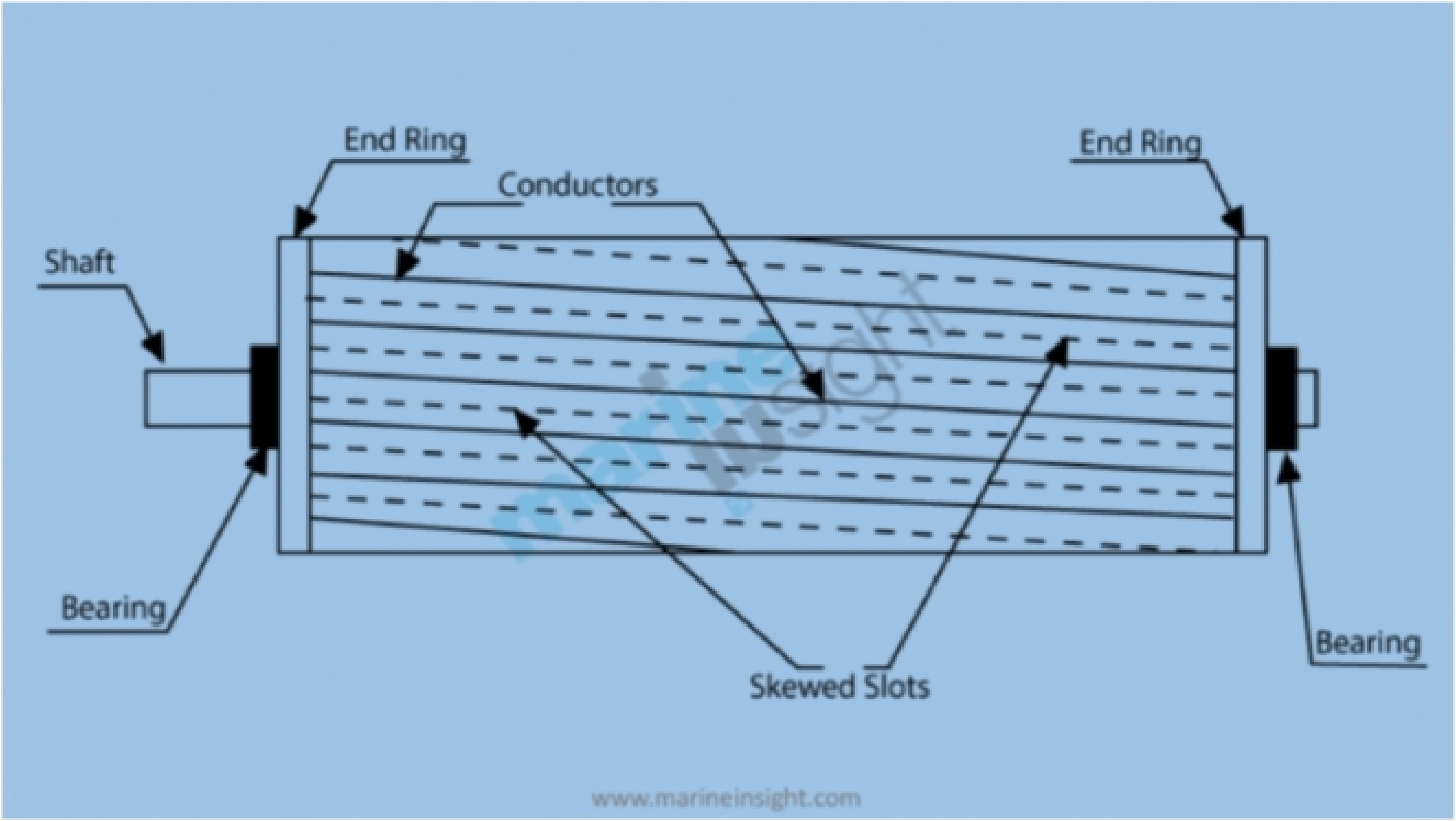
f = Frequency

p = no. of poles

Rotor

The rotor consists of a cylindrical laminated core with parallel slots that carry conductor bars.

Conductors are heavy copper or aluminium bars which fit in each slot. These conductors are brazed to the short-circuiting end rings.



Rotor of 3-phase Induction motor

The slots are not exactly made parallel to the axis of the shaft but are slotted a little skewed for the following reasons:

- They reduce magnetic hum or noise
- They avoid stalling of the motor

Principle and Working

When 3 phase supply is given to the motor, the resulting current generates a magnetic flux “Ø”.

Due to the switching sequence of 3 phase current in R, Y, and B, the generated flux rotates around the rotor conductor.

According to Faraday’s law, which states that –“an emf induced in any closed circuit is due to the rate of change of magnetic flux through the circuit”, Emf is induced in the Copper bar and due to this, current flows in the rotor.

The direction of the rotor can be given by Lenz law which states that – “the direction of induced current will be in the opposite of the motion causing it.”

Advantages of Induction Motor

The motor construction and the way electric power is supplied give the induction motor several benefits such as:

– They are robust and simple in construction with very few moving parts

– They can efficiently operate in a rugged and harsh environment such as in seagoing vessels

– The maintenance cost of 3 phase induction motor is less and unlike that of DC or synchro motor, they do not have parts like brushes, commuters or slip rings etc.

Disadvantages of 3 phase Induction motor:

– During starting, it draws high initial starting current when attached to a heavy load. This causes a dip in voltage during the starting period of the machine. Soft starting methods are connected to the 3 phase electric motor to avoid this problem.

Squirrel Cage Rotor

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Squirrel Cage Rotor
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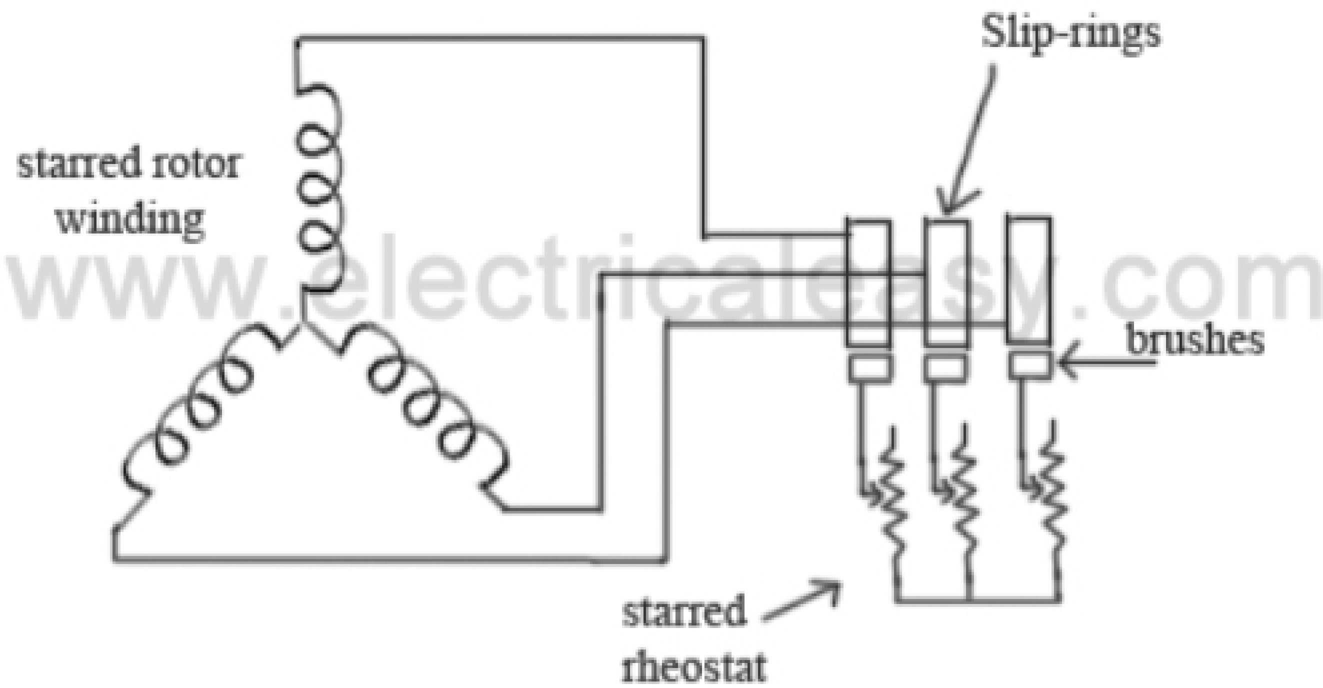
ction motors (upto 90%) are of squirrel cage type. **Squirrel cage type rotor** has very simple and almost indestructible construction. This type of rotor consist of a cylindrical laminated core, having parallel slots on it. These parallel slots carry rotor conductors. In this type of rotor, heavy bars of copper, aluminum or alloys are used as rotor conductors instead of wires.

Rotor slots are slightly skewed to achieve following advantages -

1. it reduces locking tendency of the rotor, i.e. the tendency of rotor teeth to remain under stator teeth due to magnetic attraction.
2. increases the effective transformation ratio between stator and rotor
3. increases rotor resistance due to increased length of the rotor conductor

Phase Wound Rotor



Phase wound rotor connections

Phase wound rotor is wound with 3 phase, double layer, distributed winding. The number of poles of rotor are kept same to the number of poles of the stator. The rotor is always wound 3 phase even if the stator is wound two phase.

The three phase rotor winding is internally star connected. The other three terminals of the winding are taken out via three insulated sleep rings mounted on the shaft and the brushes resting on them. These three brushes are connected to an external star connected rheostat. This arrangement is done to introduce an external resistance in rotor circuit for starting purposes and for changing the speed / torque characteristics.

Various **starting methods of induction motors** are described below.

Direct-On-Line (DOL) Starters

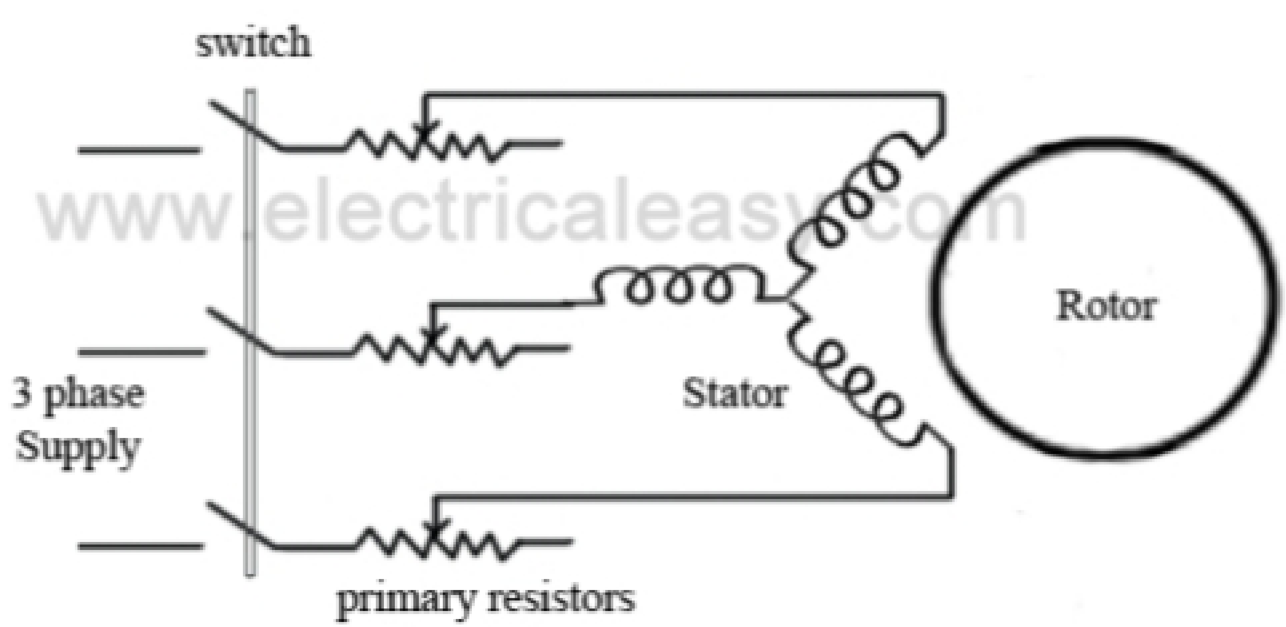
Small three phase induction motors can be started direct-on-line, which means that the rated supply is directly applied to the motor. But, as mentioned above, here, the starting current would be very large, usually 5 to 7 times the rated current. The starting torque is likely to be 1.5 to 2.5 times the full load torque. Induction motors can be started directly on-line using a DOL starter which generally consists of a contactor and a motor protection equipment such as a circuit breaker. A DOL starter consists of a coil operated contactor which can be controlled by start and stop push buttons. When the start push button is pressed, the contactor gets energized and it closes all the three phases of the motor to the supply phases at a time. The stop push button de-energizes the contactor and disconnects all the three phases to stop the motor.
In order to avoid excessive voltage drop in the supply line due to large starting current, a DOL starter is generally used for motors that are rated below 5kW.

Starting Of Squirrel Cage Motors

Starting in-rush current in squirrel cage motors is controlled by applying reduced voltage to the stator. These methods are sometimes called as **reduced voltage methods for starting of squirrel cage induction motors**. For this purpose, following methods are used:

1. By using primary resistors
2. Autotransformer
3. Star-delta switches

1. Using Primary Resistors:



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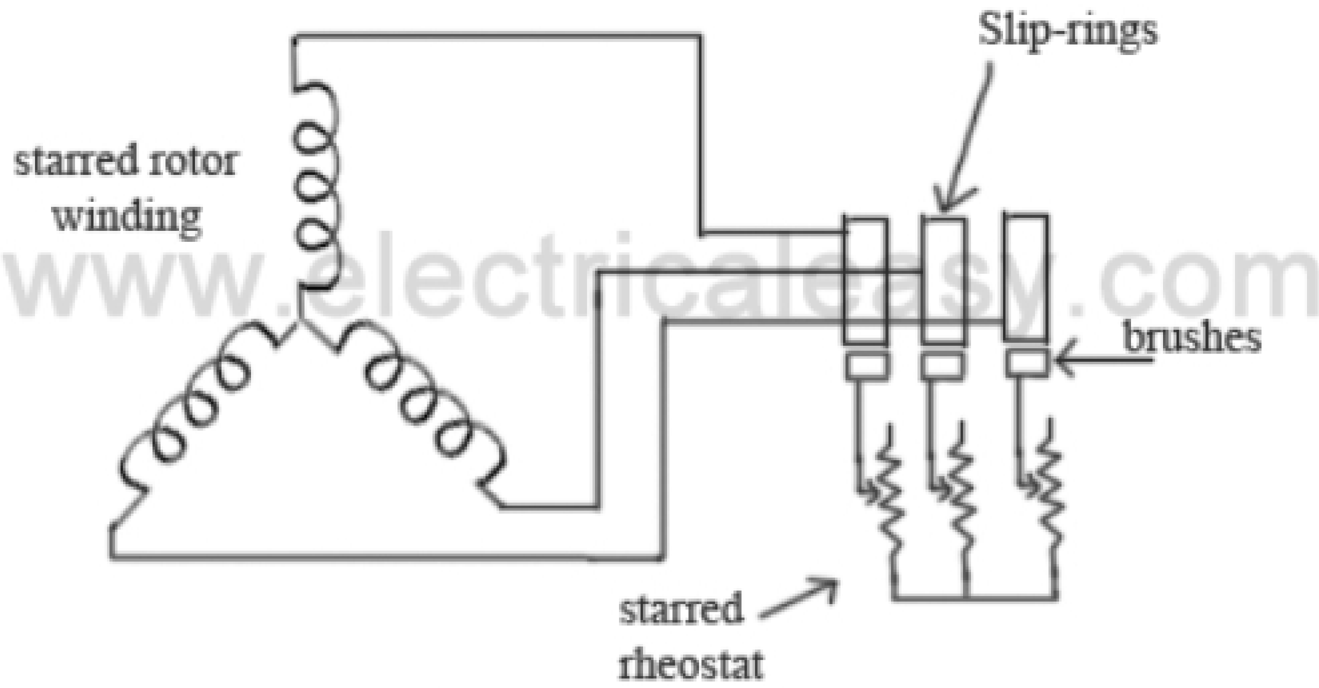
Starting Of Slip-Ring Motors

Slip-ring motors



Phase wound rotor connections

are started with full line voltage, as external resistance can be easily added in the rotor circuit with the help of slip-rings. A star connected rheostat is connected in series with the rotor via slip-rings as shown in the fig. Introducing resistance in rotor current will decrease the starting current in rotor (and, hence, in stator). Also, it improves power factor and the torque is increased. The connected rheostat may be hand-operated or automatic.

As, introduction of additional resistance in rotor improves the starting torque, slip-ring motors can be started on load.

The external resistance introduced is only for starting purposes, and is gradually cut out as the motor gathers the speed.

Torque of a three phase induction motor is proportional to flux per stator pole, rotor current and the power factor of the rotor.

$T \propto \phi I_2 \cos\phi_2$ OR $T = k \phi I_2 \cos\phi_2$.

where, ϕ = flux per stator pole,

I_2 = rotor current at standstill,

ϕ_2 = angle between rotor emf and rotor current,

k = a constant.

Now, let E_2 = rotor emf at standstill

we know, rotor emf is directly proportional to flux per stator pole, i.e. $E_2 \propto \phi$.

therefore, $T \propto E_2 I_2 \cos\phi_2$ OR $T = k_1 E_2 I_2 \cos\phi_2$.

Starting Torque

The torque developed at the instant of starting of a motor is called as starting torque. Starting torque may be greater than running torque in some cases, or it may be lesser.

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Starting Torque

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We know, $T = k_1 E_2 I_2 \cos\phi_2$.

let, R2 = rotor resistance per phase

X2 = standstill rotor reactance

$$Z_2 = \sqrt{(R_2^2 + X_2^2)} \quad = \text{rotor impedence per phase at standstill}$$

then,

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \quad \text{and} \quad \cos\phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}}$$

Therefore, starting torque can be given as,

$$Tst = k_1 E_2 \frac{E_2}{\sqrt{(R_2^2 + X_2^2)}} \times \frac{R_2}{\sqrt{(R_2^2 + X_2^2)}} = \frac{k_1 E_2^2 R_2}{R_2^2 + X_2^2}$$

The constant k1 = 3 / 2πNs

$$Tst = \frac{3}{2\pi Ns} \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Condition For Maximum Starting Torque

If supply voltage V is kept constant, then flux ϕ and E_2 both remains constant. Hence,

$$Tst = k_2 \frac{R_2}{R_2^2 + X_2^2}$$

Hence, it can be proved that **maximum starting torque** is obtained when rotor resistance is equal to standstill rotor reactance. i.e. $R_2^2 + X_2^2 = 2R_2^2$.

Torque Under Running Condition

$T \propto \phi I_r \cos\phi_2$.

where, E_r = rotor emf per phase under running condition = sE_2. (s=slip)

I_r = rotor current per phase under running condition

reactance per phase under running condition will be $= sX_2$

therefore,

$$I_r = \frac{E_r}{Z_r} = \frac{sE_2}{\sqrt{(R_2^2 + (sX_2)^2)}} \quad \text{and} \quad \cos\phi_2 = \frac{R_2}{Z_r} = \frac{R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

$$T = \frac{k\,\phi\, sE_2\, R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

Induction Motor Speed Control From Stator Side

1. By Changing The Applied Voltage:

From the torque equation of induction motor,

$$T = \frac{k_1 s E_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}} = \frac{3}{2\pi N_S} \frac{s E_2^2 R_2}{\sqrt{(R_2^2 + (sX_2)^2)}}$$

Rotor resistance R_2 is constant and if slip s is small then $(sX_2)^2$ is so small that it can be neglected. Therefore, $T \propto sE_2^2$ where E_2 is rotor induced emf and $E_2 \propto V$

Thus, $T \propto sV^2$, which means, if supplied voltage is decreased, the developed torque decreases. Hence, for providing the same load torque, the slip increases with decrease in voltage, and consequently, the speed decreases. This method is the easiest and cheapest, still rarely used, because

1. large change in supply voltage is required for relatively small change in speed.
2. large change in supply voltage will result in a large change in flux density, hence, this will disturb the magnetic conditions of the motor.

2. By Changing The Applied Frequency

Synchronous speed of the rotating magnetic field of an induction motor is given by,

$$Ns = \frac{120\ f}{P} \quad \text{(RPM)}$$

where, f = frequency of the supply and P = number of stator poles.
Hence, the synchronous speed changes with change in supply frequency. Actual speed of an induction motor is given as **N = Ns (1 - s).** However, this method is not widely used. It may be used where, the induction motor is supplied by a dedicated generator (so that frequency can be easily varied by changing the speed of prime mover). Also, at lower frequency, the motor current may become too high due to decreased reactance. And if the frequency is increased beyond the rated value, the maximum torque developed falls while the speed rises.

3. Constant V/F Control Of Induction Motor

4. Changing The Number Of Stator Poles

From the above equation of synchronous speed, it can be seen that synchronous speed (and hence, running speed) can be changed by changing the number of stator poles. This method is generally used for squirrel cage induction motors, as squirrel cage rotor adapts itself for any number of stator poles. Change in stator poles is achieved by two or more independent stator windings wound for different number of poles in same slots.
For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles.
for supply frequency of 50 Hz
i) synchronous speed when 4 pole winding is connected, Ns = 120*50/4 = 1500 RPM
ii) synchronous speed when 6 pole winding is connected, Ns = 120*50/6 = 1000 RPM

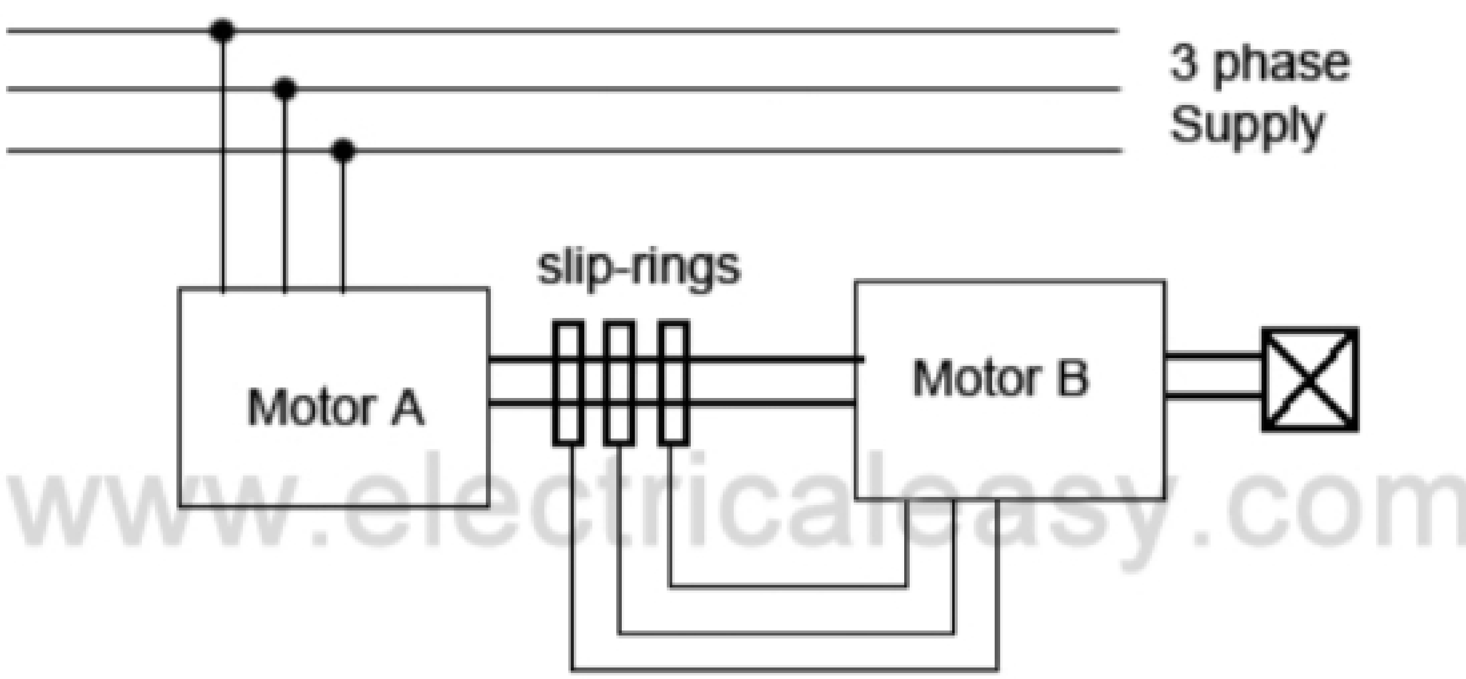
Speed Control From Rotor Side:

1. Rotor Rheostat Control

This method is similar to that of armature rheostat control of DC shunt motor. But this method is only applicable to slip ring motors, as addition of external resistance in the rotor of squirrel cage motors is not possible.

2. Cascade Operation

In this method of speed control, two motors are used. Both are mounted on a same shaft so that both run at same speed. One motor is fed from a 3phase supply and the other motor is fed from the induced emf in first motor via slip-rings. The arrangement is as shown in following figure.



Motor A is called the main motor and motor B is called the auxiliary motor.

Let, N_{s1} = frequency of motor A

N_{s2} = frequency of motor B

P_1 = number of poles stator of motor A

P_2 = number of stator poles of motor B

N = speed of the set and same for both motors

f = frequency of the supply

Crawling

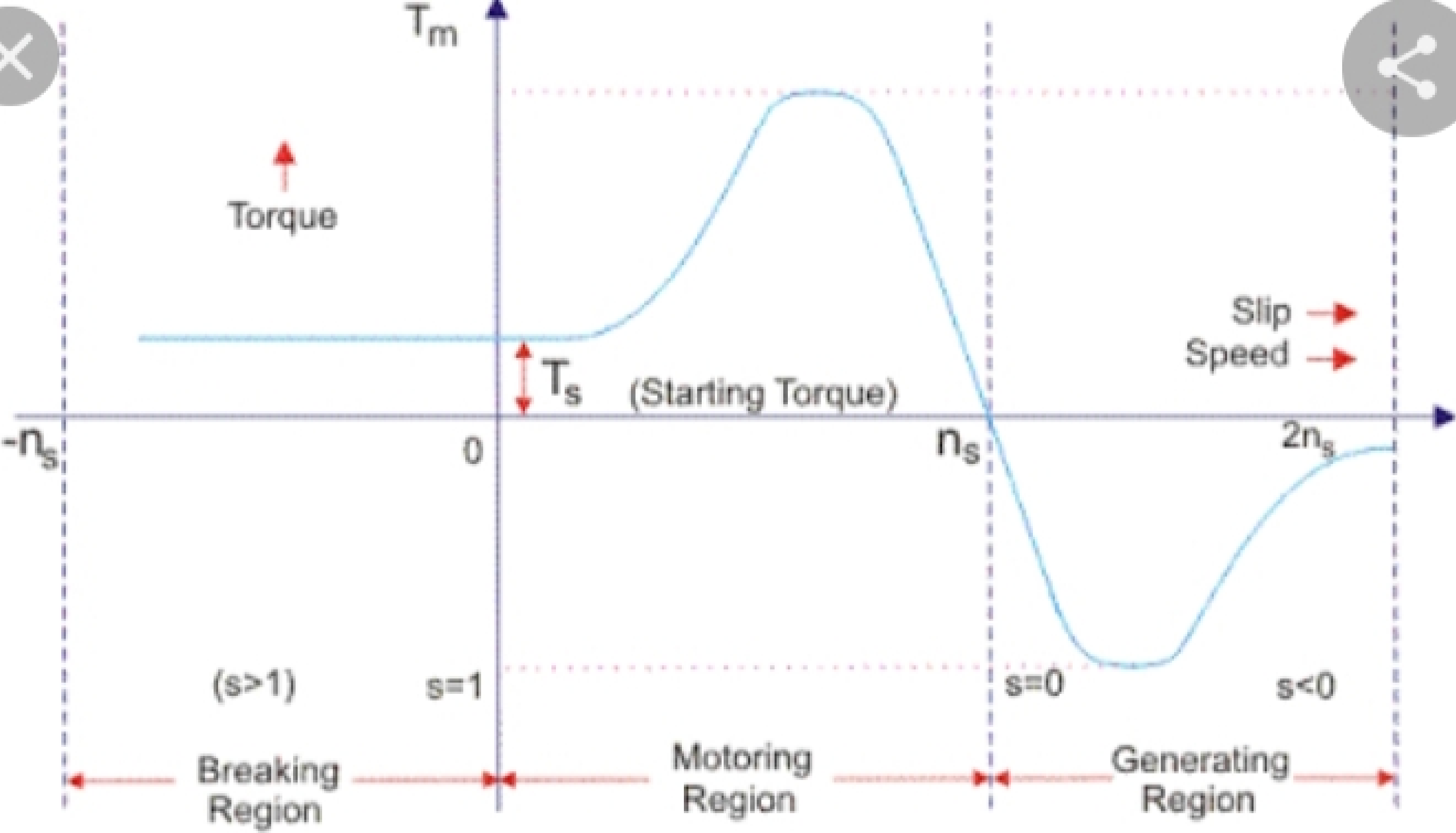
Sometimes, squirrel cage induction motors exhibits a tendency to run at very slow speeds (as low as one-seventh of their synchronous speed). This phenomenon is called as **crawling of an induction motor**.

This action is due to the fact that, flux wave produced by a stator winding is not purely sine wave. Instead, it is a complex wave consisting a fundamental wave and odd harmonics like 3rd, 5th, 7th etc. The fundamental wave revolves synchronously at synchronous speed Ns whereas 3rd, 5th, 7th harmonics may rotate in forward or backward direction at Ns/3, Ns/5, Ns/7 speeds respectively. Hence, harmonic torques are also developed in addition with fundamental torque.

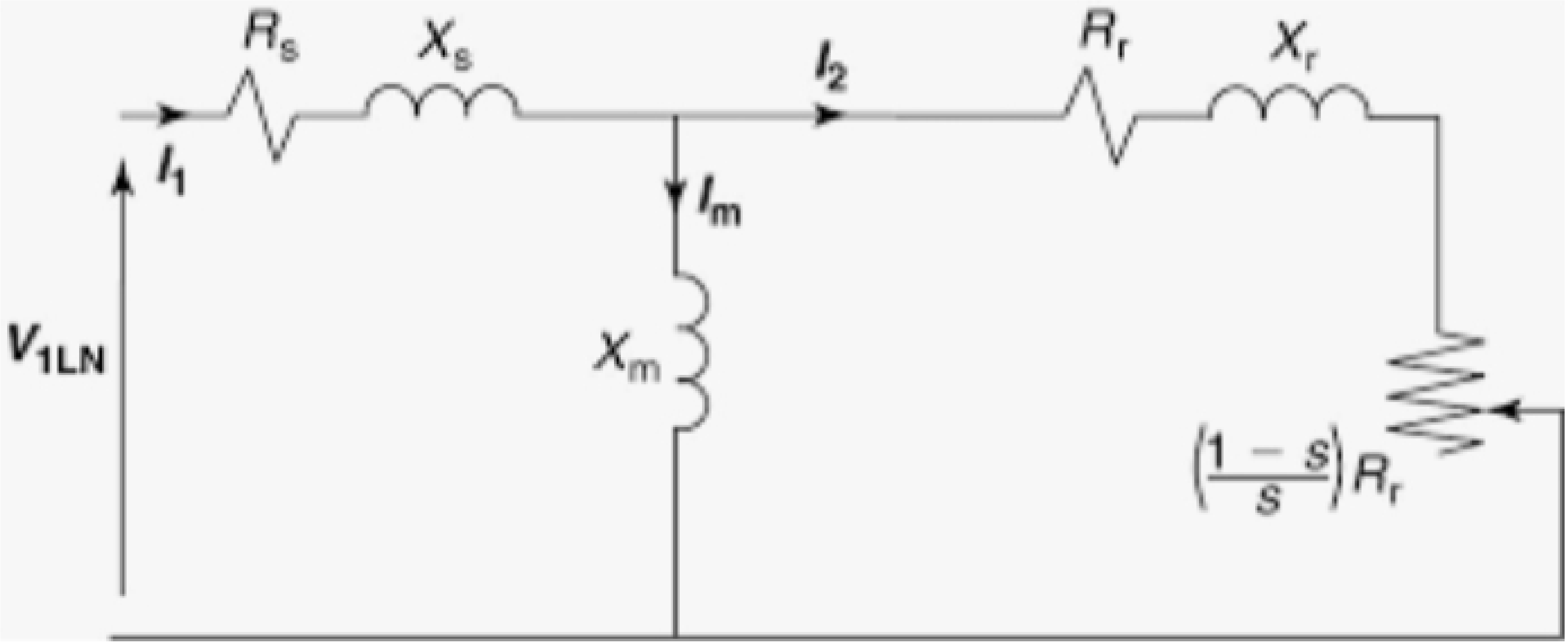
3rd harmonics are absent in a balanced 3-phase system. Hence 3rdd harmonics do not produce rotating field and torque. The total motor torque now consist three components as: (i) the fundamental torque with synchronous speed Ns, (ii) 5th harmonic torque with synchronous speed Ns/5, (iv) 7th harmonic torque with synchronous speed Ns/7 (provided that higher harmonics are neglected).

Cogging (Magnetic Locking Or Teeth Locking)

Sometimes, the rotor of a squirrel cage induction motor refuses to start at all, particularly if the supply voltage is low. This happens especially when number of rotor teeth is equal to number of stator teeth, because of magnetic locking between the stator teeth and the rotor teeth. When the rotor teeth and stator teeth face each other, the reluctance of the magnetic path is minimum, that is why the rotor tends to remain fixed. This phenomenon is called cogging or **magnetic locking of induction motor**.



Torque Slip Curve for Three Phase Induction Motor



Three Phase Induction Motor Equivalent Circuit | Electrical Academia

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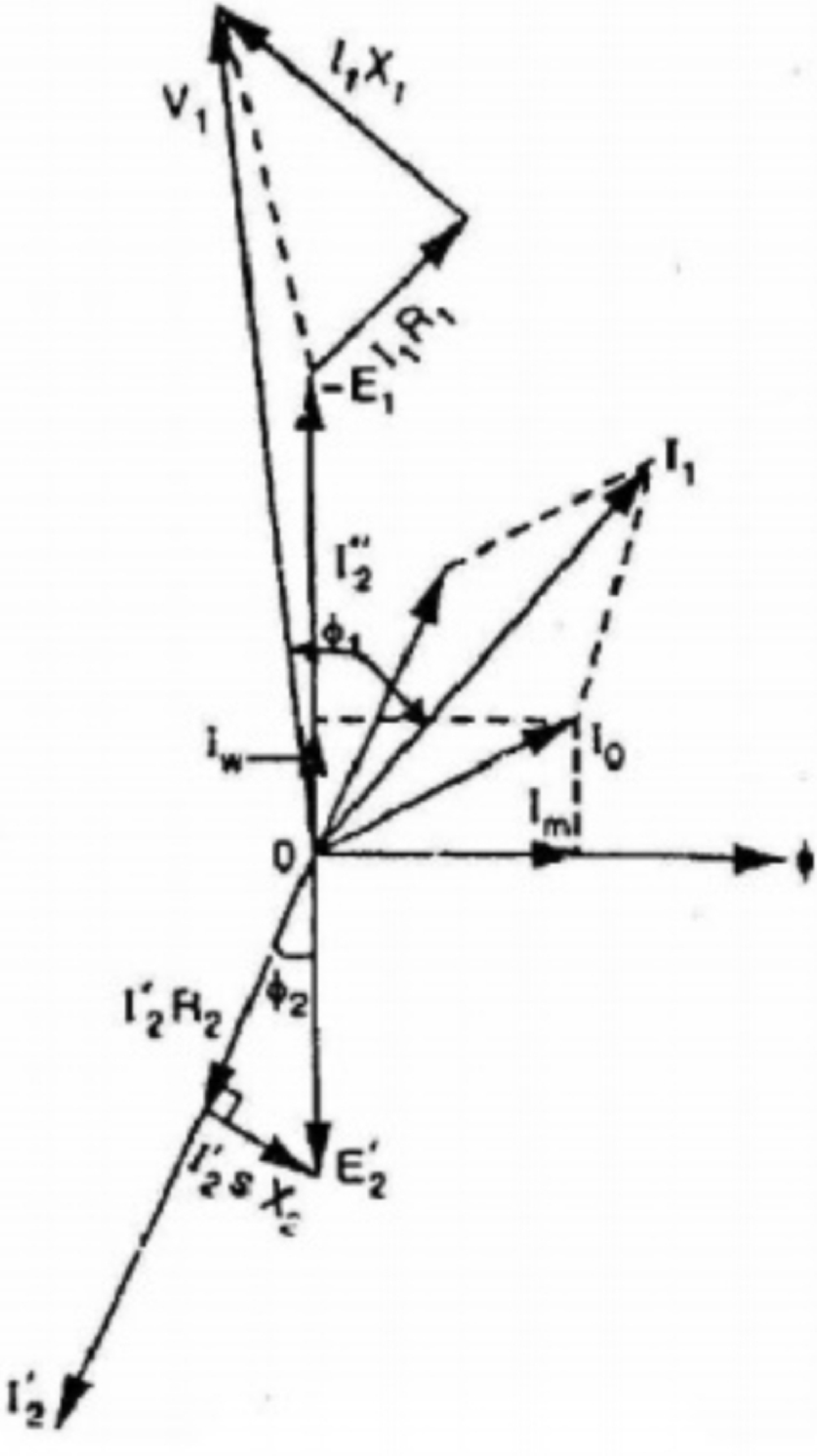

V_1
I_1X_1
I_1R_1
$-E_1$
I_1
I_2''
ϕ_1
I_w
I_0
I_m
0
ϕ
ϕ_2
$I_2'R_2$
E_2'
$I_2' s X_2$
I_2'

Efficiency is defined for an induction motor the same way as it is for any device:

$$\eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{P_{out}}{P_{in}} \qquad (1)$$

Defining the losses in the machines as P_{loss}, equation 1 can be written in other forms:

$$\eta = \frac{Pout}{Pout+P_{loss}} = \frac{P_{in}-P_{loss}}{P_{in}} = 1 - \frac{P_{loss}}{P_{in}} \qquad (2)$$

Losses in the motor directly affect the cost of operation it and, indirectly, the motor rating. The efficiency is frequently determined by measuring the losses. Measurement standards are precisely defined by ANSI, IEEE, NEMA, and the Canadian Standards Association.

Types of Losses in the Induction Motor

Resistive or I^2R losses are frequently referred to as copper losses and are found in the stator and rotor windings of the induction machine. Typically, in the induction motor, the stator copper loss is about 33% and the rotor copper loss is about 15% of the total loss of the machine.

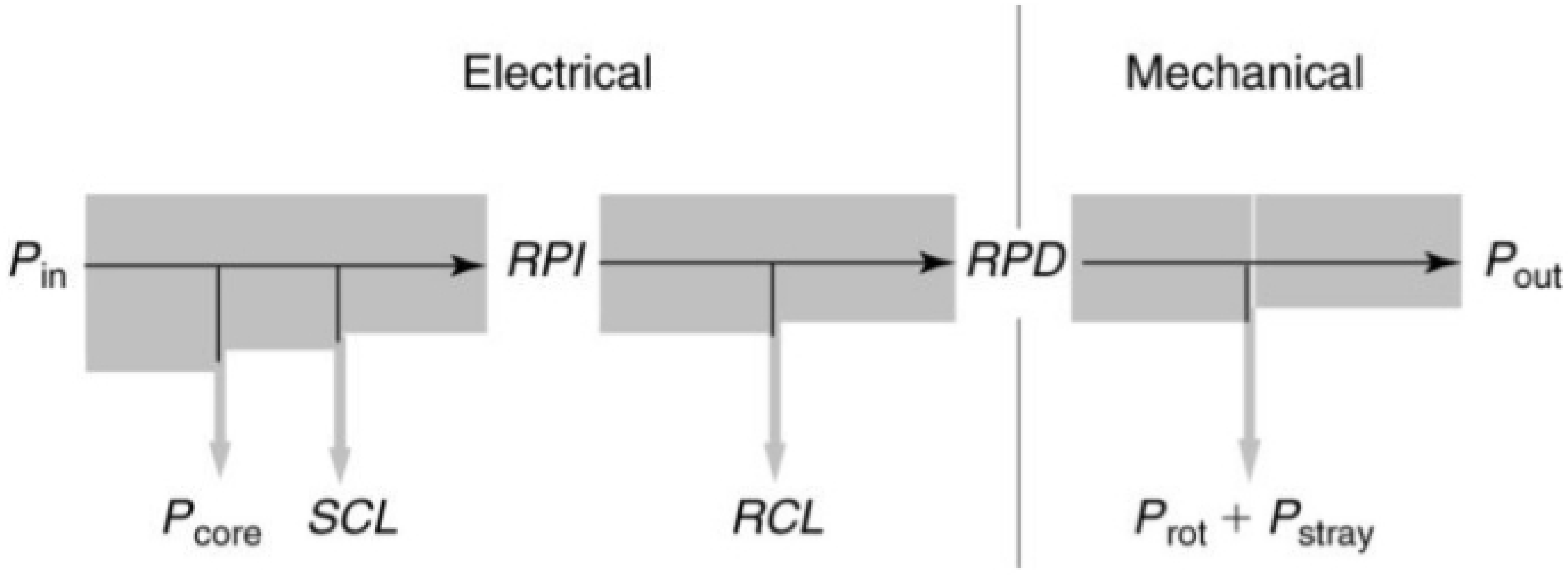

FIGURE 1 Power flow diagram for an induction motor.