CAN102

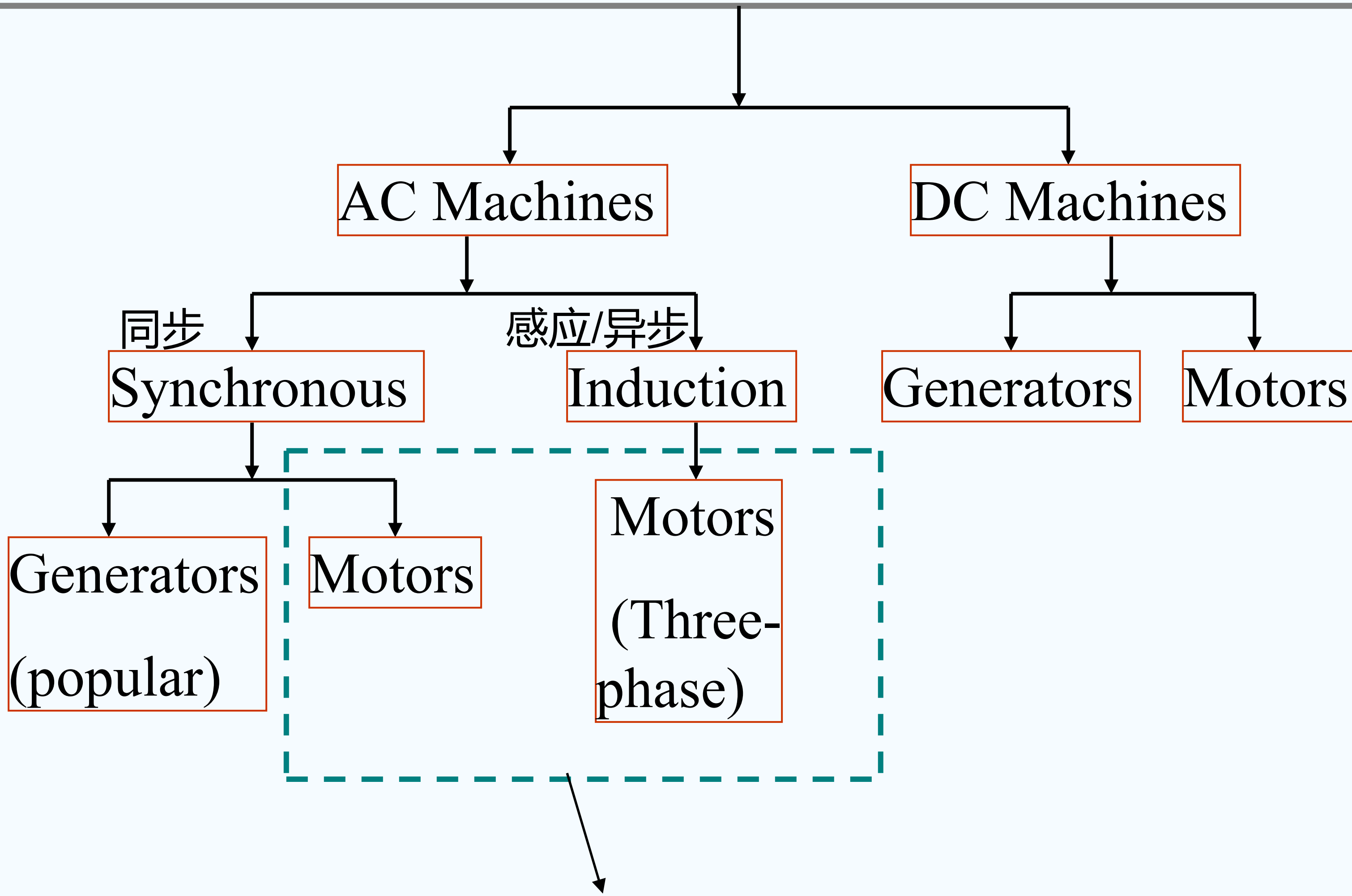
Electromagnetism and Electromechanics

2023/24-S2

Lecture 21 Synchronous/Induction Motors

Jingchen Wang
SAT
jingchen.wang@xjtlu.edu.cn

Electrical Machines



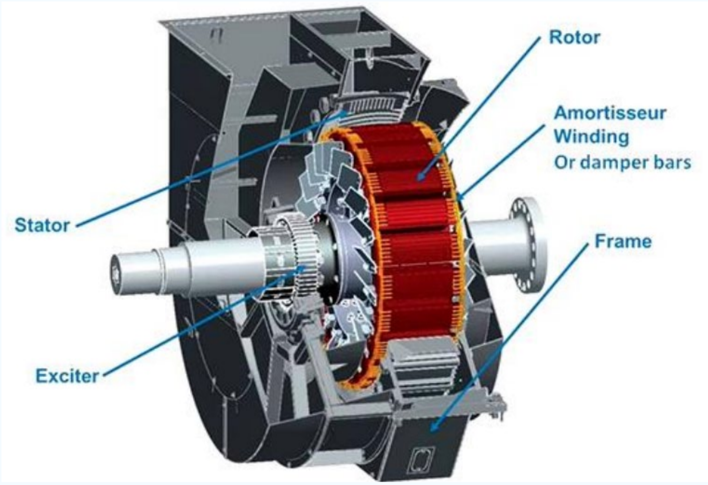
convert electrical power to mechanical power.

Synchronous Motors

A synchronous motor is the same physical machine as a synchronous generator, all of the basic speed, power and torque equations in Lecture 19 and 20 apply to synchronous motor, except that the direction of power flow and current is reversed.

A synchronous motor is composed of two parts:

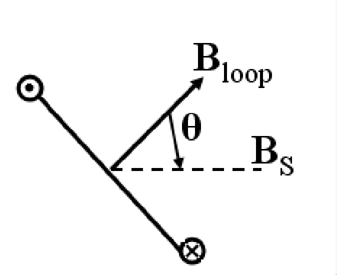
The **stator** is the outer shell of the motor, which carries the **armature winding**. This winding is spatially distributed for poly-phase AC current.



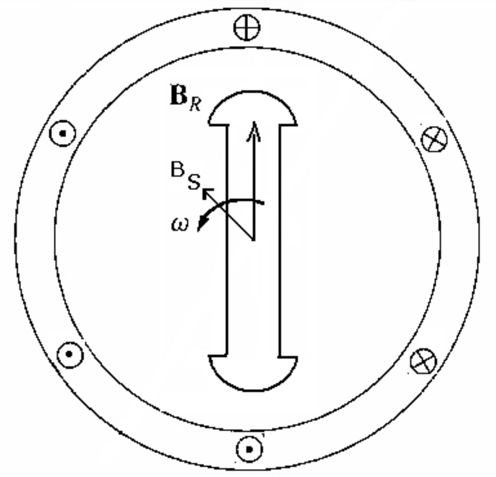
The **rotor** is the rotating portion of the motor. It carries **field winding**, which may be supplied by a DC source.

Synchronous Motors-Operation principle

$$\boldsymbol{\tau}_{ind} = k\mathbf{B}_{loop} \times \mathbf{B}_S$$



- **Rotor magnetic field:** The field current I_F (generated by an external DC source) of a synchronous motor produces a steady-state magnetic field $\mathbf{B}_R$
- **Stator magnetic field:** A three-phase set of voltages is applied to the stator windings of the motor, which produces a three-phase current I_A flow in the windings. This three-phase set of currents I_A in the armature winding produces a rotating magnetic field of $\mathbf{B}_s$



Synchronous Motors-Operation principle

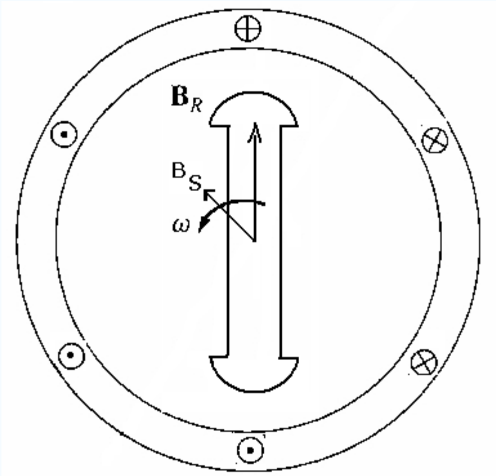
Therefore, there are two magnetic fields present in the machine, and ***the rotor field will tend to line up with the stator field***, just as two bar magnets will tend to line up if placed near each other.

Since the stator magnetic field is rotating, the rotor magnetic field (and the rotor itself) will try to catch up.

As long as the two magnetic fields are "locked in" and rotate in synchronism, a torque is developed.

The larger the angle between the two magnetic fields (up to certain maximum), **the greater the torque** on the rotor of the machine

$$\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times \mathbf{B}_S \text{ counterclockwise}$$



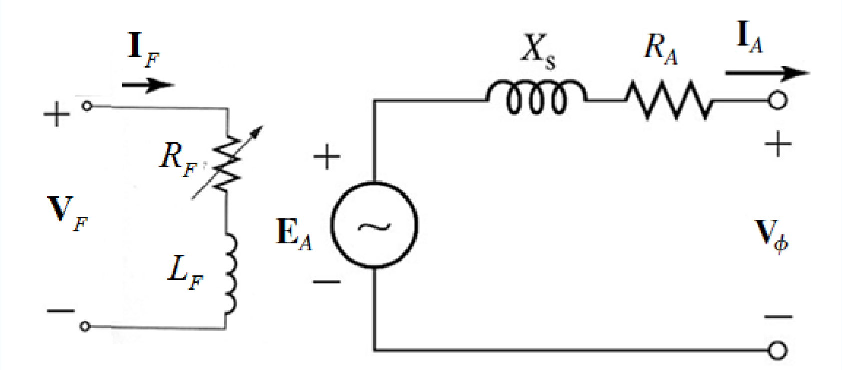
The basic principle is that the rotor "chases" the rotating stator magnetic field around in a circle, never quite catching up with it.

Synchronous Motors-Equivalent circuit

A synchronous motor is the same physical machine as a synchronous generator, all of the basic speed, power and torque equations in Lecture 19 and 20 apply to synchronous motor, except that **the direction of power flow and current is reversed**.

Single-phase circuit is shown:

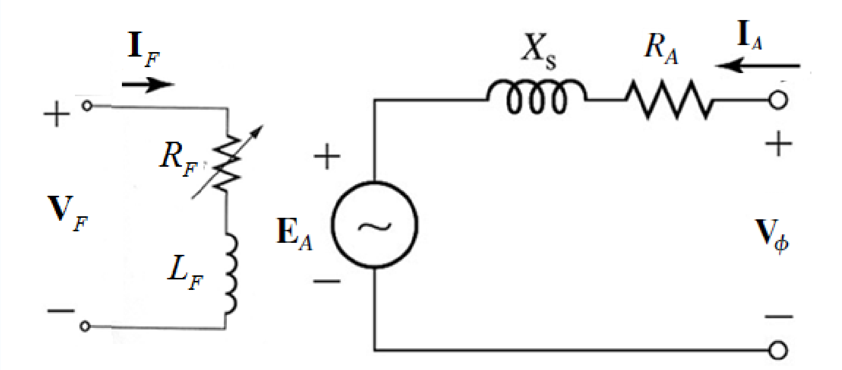
Generators



$$\mathbf{E}_A = \mathbf{V}_\phi + jX_s\mathbf{I}_A + R_A\mathbf{I}_A$$

$$\mathbf{V}_\phi = \mathbf{E}_A - jX_s\mathbf{I}_A - R_A\mathbf{I}_A$$

Motors

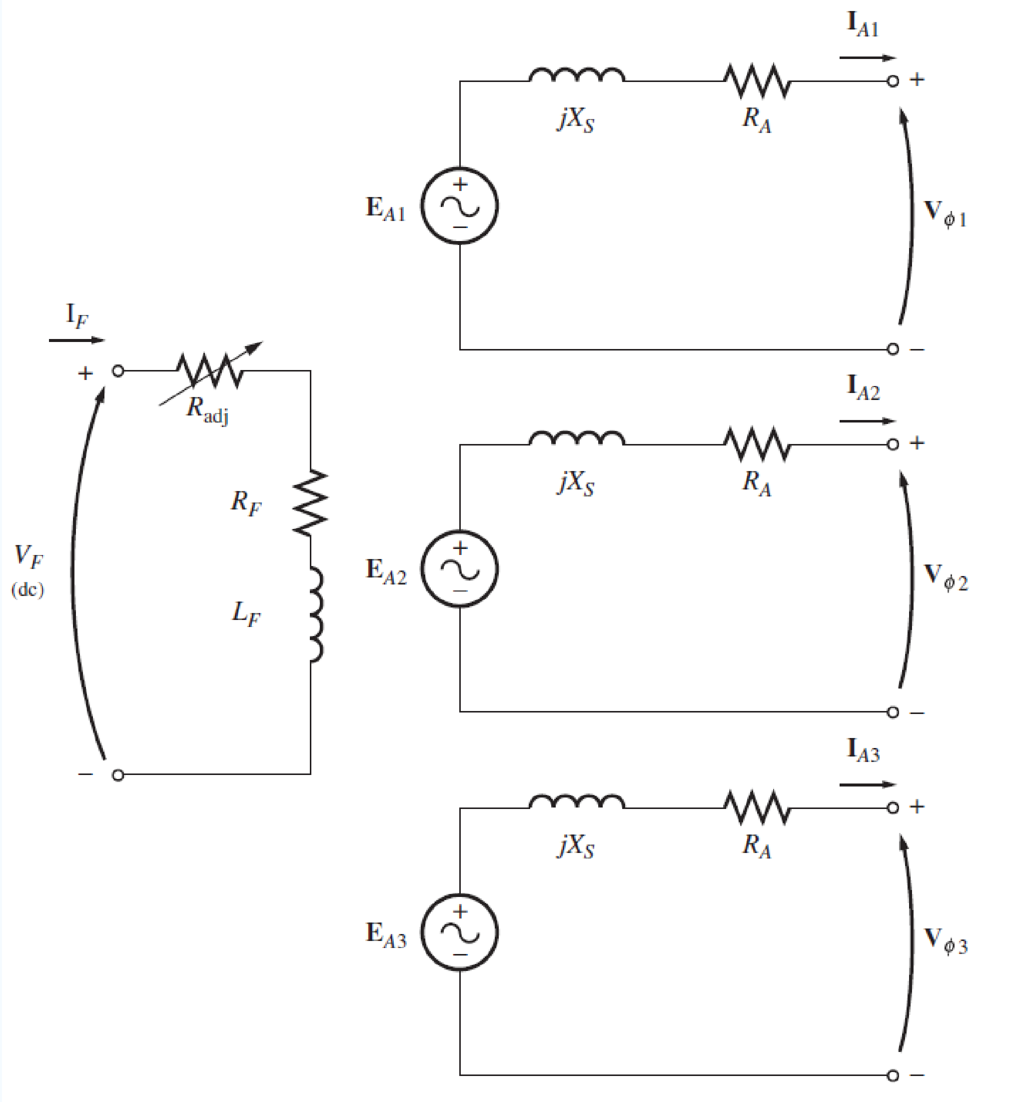


$$\mathbf{E}_A = \mathbf{V}_\phi - jX_s\mathbf{I}_A - R_A\mathbf{I}_A$$

$$\mathbf{V}_\phi = \mathbf{E}_A + jX_s\mathbf{I}_A + R_A\mathbf{I}_A$$

Synchronous Motors-Equivalent circuit

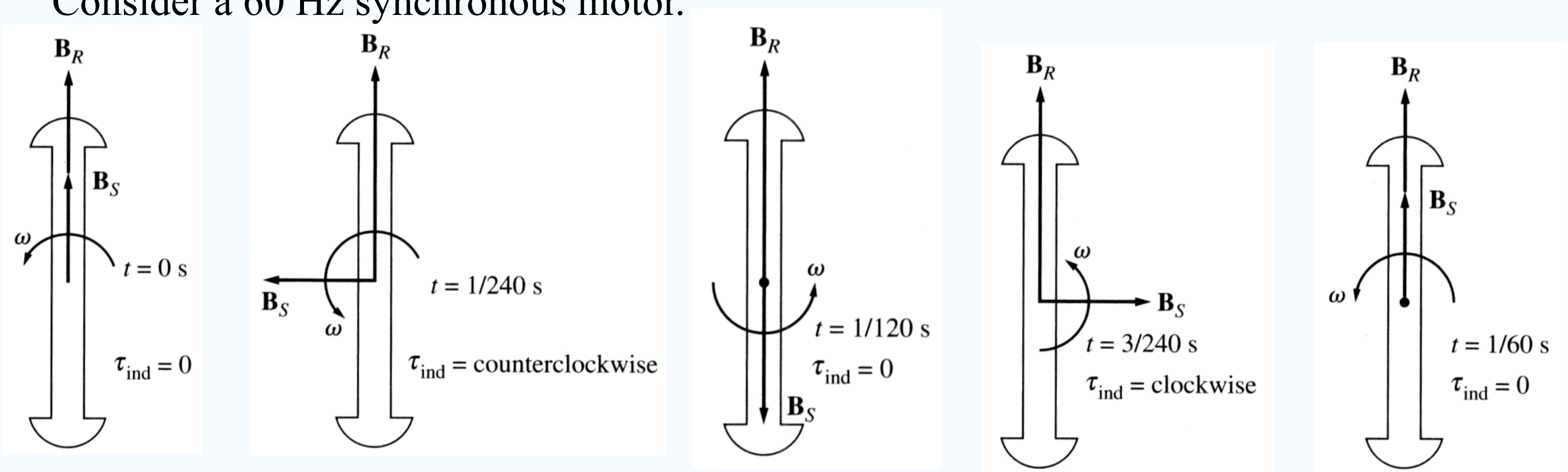
Three-phase circuit



Synchronous Motors-Starting

During one electrical cycle, the torque was counter-clockwise and then clockwise, and the average torque is zero. The motor will vibrate heavily and finally overheats!

Consider a 60 Hz synchronous motor.



Synchronous motors are **not self-starting** motors. This property is due to the inertia of the rotor.

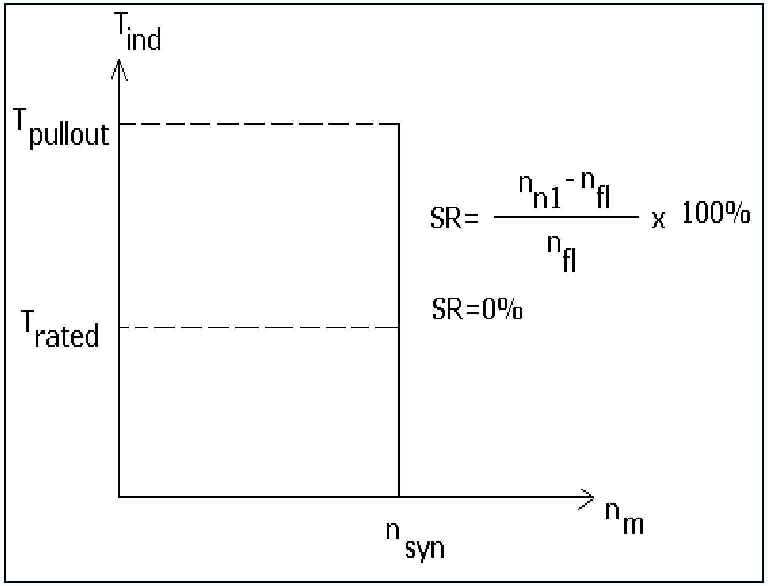
A very straightforward method is to use exciters (**external prime mover**) as starting motors to accelerate the synchronous motor up to synchronous speed.

Synchronous Motors-Steady-state

Once the motor is in operation, the terminal voltage and the system frequency will be constant regardless of the amount of power drawn by the motor. The speed of rotation of the applied mechanical fields is locked to the applied electrical frequency , so *the speed of the synchronous motor will be constant regardless of the load*.

$$n_m = \frac{120 f_{se}}{P}$$

The steady-state speed of the motor is constant from no load all the way up to the maximum torque that the motor can supply (called the pullout torque), Hence, $S_R = 0\%$.



Torque-speed characteristic

$$\tau_{ind} = kB_R B_{net} \sin\delta$$

where δ is the angle between $\mathbf{B}_R$ and $\mathbf{B}_{net}$.

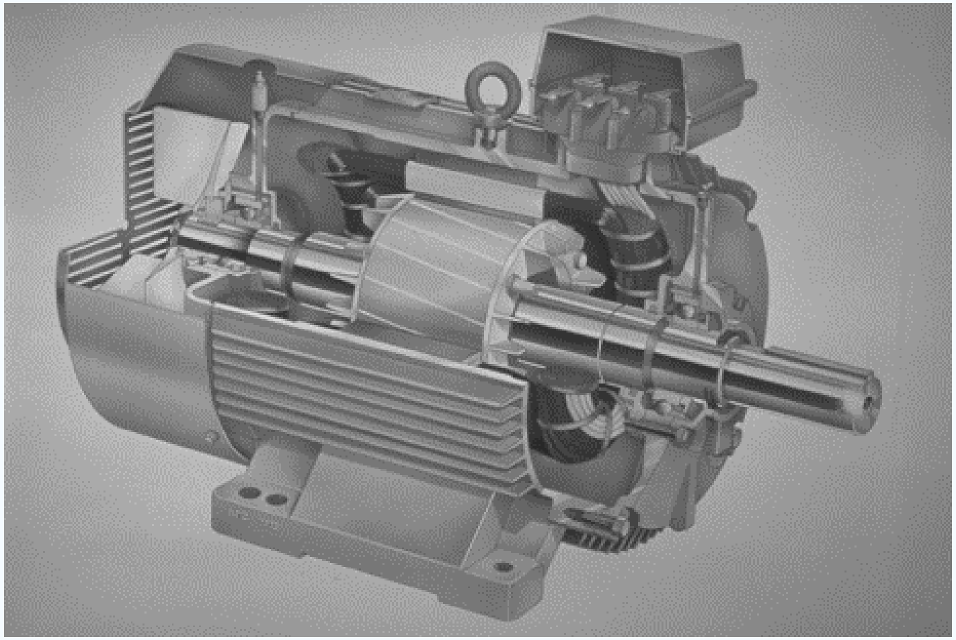
Maximum torque (pullout torque) is achieved when $\sin\delta = 1$.

Full load torque is much less than that, may typically be 1/3 of pullout torque.

If load exceeds the pullout torque, the rotor will slow down and can not remain locked to stator magnetic field.

Induction Motors

Induction machine – the rotor voltage that produces the rotor current and the rotor magnetic field is **induced in the rotor windings** rather than being physically connected by wires. **No DC field current is required to run the machine.**



Its characteristic features are:

- ✓ Simple and rugged construction
- ✓ Low cost and minimum maintenance
- ✓ High reliability and sufficiently high efficiency
- ✓ Need no extra starting motors and need not be synchronized

Induction Motors-Construction

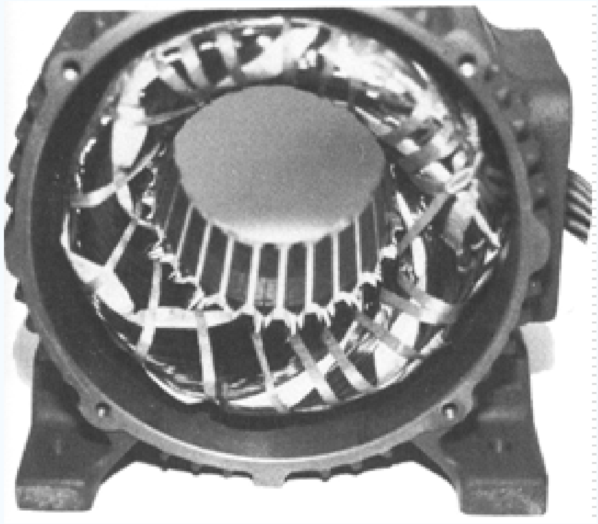
An induction motor has basically two parts – **Stator** and **Rotor**

Stator:

•consisting of a steel frame that supports a hollow, cylindrical core

•core, having a number of evenly spaced slots, providing the space for the stator winding

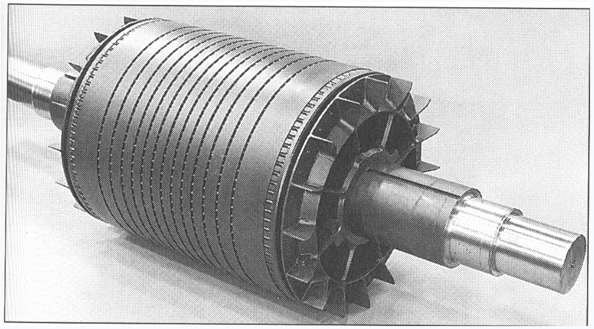
•the windings geometrically spaced 120 degrees apart

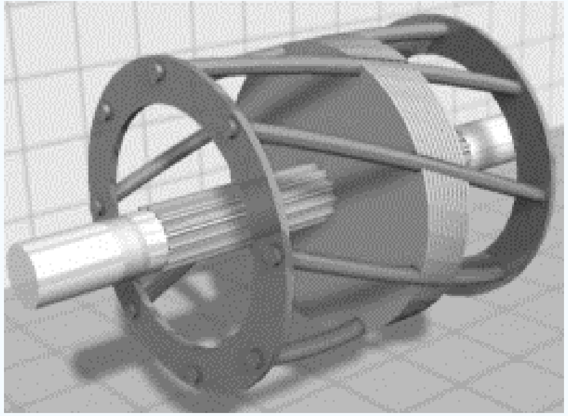


Induction Motors-Construction

Two types of rotors are used in induction motors:

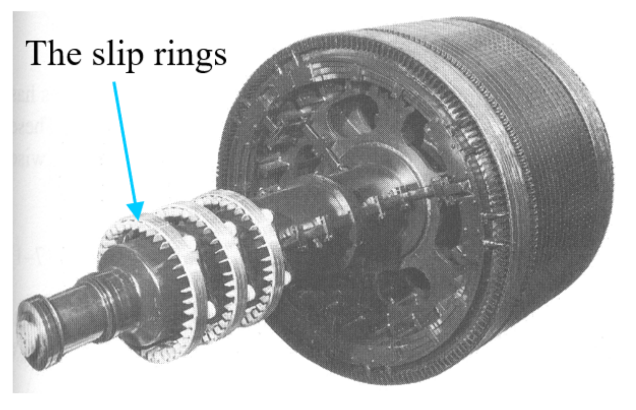
a) Squirrel cage rotor (commonly used)
----no windings and no slip rings





b) Wound rotor (rarely used)
---It has 3 phase windings, usually Y-connected, and the winding ends are connected via slip rings.

Wound rotor are known to be more expensive due to its maintenance cost to upkeep the slip rings, carbon brushes and also rotor windings.

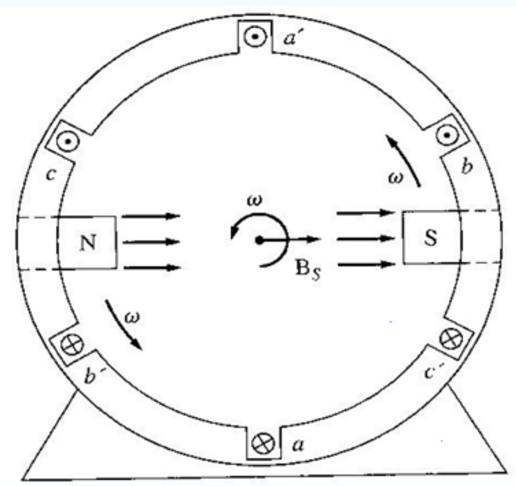


Induction Motors-Basic concepts

When a current produced by a balanced three-phase source flows in the stator, it will produce a magnetic field in stator as such that $\mathbf{B}_s$ (stator magnetic field) rotating at **synchronous speed** as determined by the number of stator poles and the applied stator frequency f_{se}:

$$n_{sync} = \frac{120 f_{se}}{P}$$

where f_{se} is the system electric frequency in hertz, P is the number of poles in the machine.



This rotating magnetic field $\mathbf{B}_s$ passes over the rotor bars and induces a voltage in them. Hence there will be rotor current flow. And this rotor current will produce a magnetic field, $\mathbf{B}_R$. Hence the interaction between both magnetic field would give torque:

$$\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$$

The induced torque would generate acceleration to the rotor, then the rotor will spin.

Induction Motors-Basic concepts

If the induction motor's rotor were turning at synchronous speed → the rotor bars would be stationary relative to the magnetic field → no induced voltage → no rotor current → no rotor magnetic field → Induced torque = 0 → Rotor will slow down due to friction

$$\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$$

An induction motor can thus speed up to near synchronous speed, but it can never reach synchronous speed. ***The rotor turns at a lower speed.***

Induction Motors-Slip speed

The induced voltage in a rotor bar depends on the speed of the rotor relative to the magnetic fields.

Two terms are commonly used to define the relative motion of the rotor and the magnetic fields: **slip speed** and **slip**

Slip speed: $\boxed{n_{slip} = n_{sync} - n_m}$

Where n_{slip} = slip speed of the machine
n_{sync} = speed of the magnetic field.
n_m = mechanical shaft speed of the motor.

Induction Motors-Slip speed

Slip -- the difference percentage of the speed :

$$\boxed{s = \frac{n_{slip}}{n_{sync}} \times 100\% = \frac{n_{sync} - n_m}{n_{sync}} \times 100\%}$$

Slip may also be described in terms of angular velocity, ω

$$s = \frac{\omega_{sync} - \omega_m}{\omega_{sync}} \times 100\%$$

under normal operating conditions, $s = 0.01 \sim 0.05$, which is very small and the actual speed is very close to synchronous speed.

***s* is not zero, not negligible.**

Using the slip, the mechanical speed of the rotor shaft can be expressed in terms of synchronous speed and slip:

$$\boxed{n_m = (1 - s)\, n_{sync} \qquad or \qquad \omega_m = (1 - s)\, \omega_{sync}}$$

Induction Motors-Electrical frequency

If the rotor is locked (cannot move), like a transformer, the rotor would have the same frequency as the stator. Another way to look at it is to see that when the rotor is locked, rotor speed drops to zero, then slip is 1. We have:

$$f_{re} = f_{se}$$

f_{re} called the slip/rotor frequency,
f_{se} called the electrical frequency on rotor

For any speed in between, the rotor frequency is directly proportional to the difference (n_{sync} - n_m) between the speed of the magnetic filed n_{sync} and the speed of the rotor n_m. The rotor frequency can be written as:

$$f_{re} = sf_{se}$$

With $n_{sync} = \dfrac{120 f_{se}}{P}$ $\quad \therefore f_{se} = \dfrac{n_{sync} P}{120}$

$$s = \frac{n_{sync} - n_m}{n_{sync}} \qquad \therefore f_{re} = \frac{(n_{sync} - n_m)P}{120}$$

Induction Motors-Speed characteristics

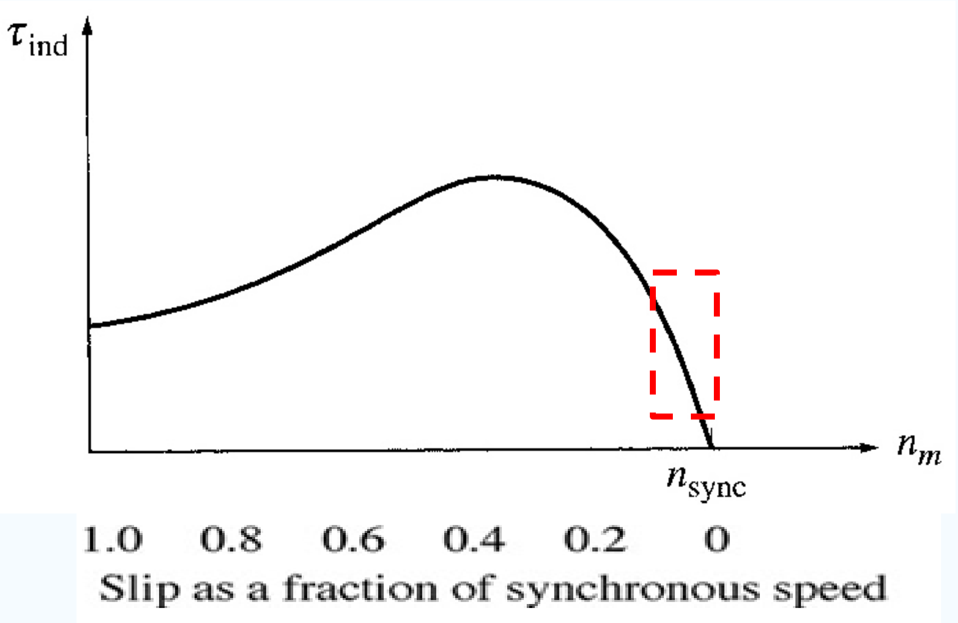
A typical induction motor torque-speed characteristic curve:

a) Induced torque is zero at synchronous speed.

b) The graph is nearly linear between no load and full load (at near synchronous speeds).

c) The torque increases with increasing slip up to a maximum value and then decreases. Max torque is known as *pull out torque* or *breakdown torque,* typically a factor of 2 larger than the rated torque, limits the short-time overload capability of the motor.

d) Starting torque is very large.

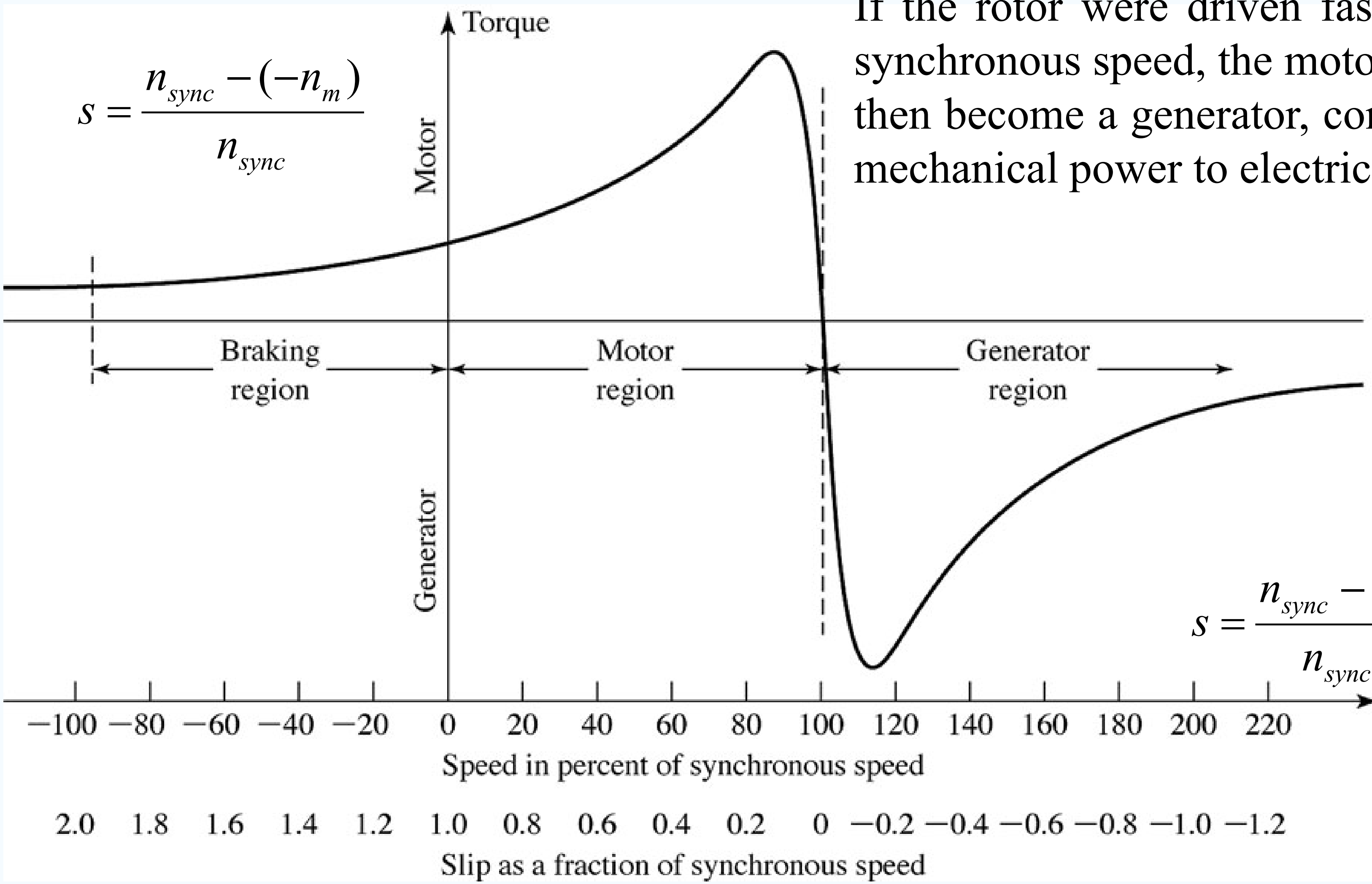


$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

Typical induction-motor torque-speed curve for constant-voltage, constant-frequency operation

Induction Motors-Speed characteristics

If the rotor were driven faster than synchronous speed, the motor would then become a generator, converting mechanical power to electric power.



$$s = \frac{n_{sync} - (-n_m)}{n_{sync}}$$

$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

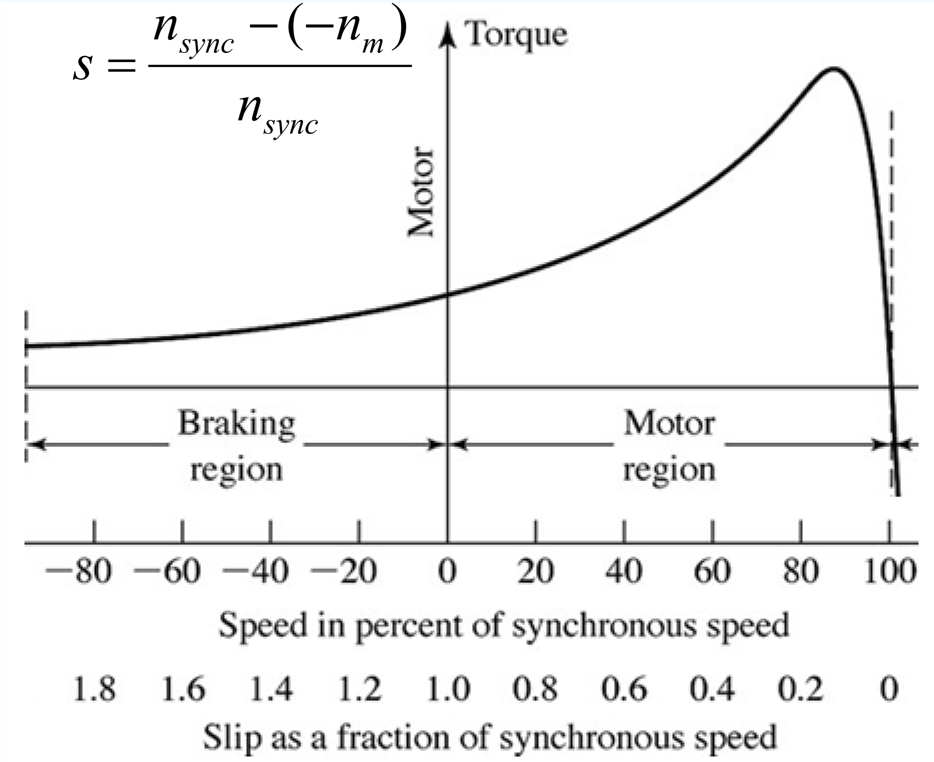
Induction Motors-Speed characteristics

In normal motor region: the rotor rotates in the direction of rotation of the magnetic field produced by the stator currents

Braking region: the motor is driven backward: the motor rotates against the direction of rotation of the magnetic field – by a source of mechanical power capable of counteracting the electromechanical torque.

Usefulness: quick stop the motor

How: interchanging two stator leads in a three-phase motor



Induction Motors-Speed control

Induction motors are not good machines for applications requiring considerable speed control. The normal operating range of a typical induction motor is confined to less than 5% slip, and the speed variation is more or less proportional to the load.

$$\boxed{n_m = (1-s)n_{sync}}$$

There are basically 2 general methods to control induction motor's speed:
a) Varying stator magnetic field speed
b) Varying slip

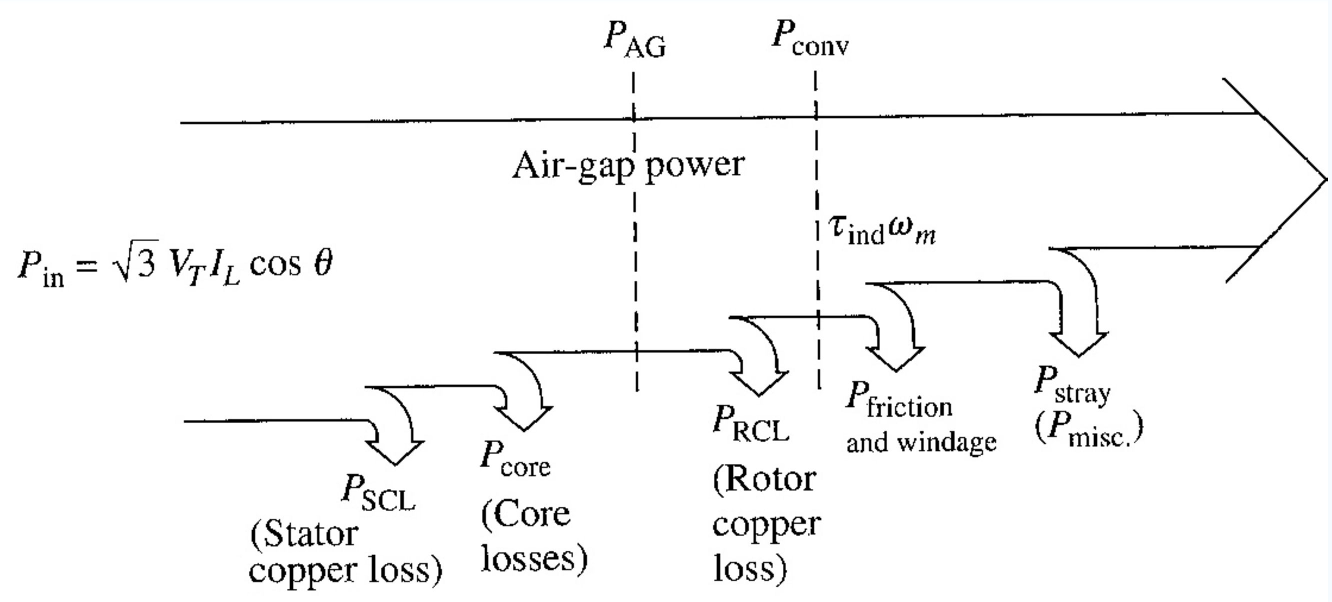
Varying the magnetic field speed may be achieved by varying the electrical frequency or by changing the number of poles.

$$n_{sync} = \frac{120 f_e}{P}$$

Varying slip may be achieved by varying rotor resistance or varying the terminal voltage.

Induction Motors-Power flow

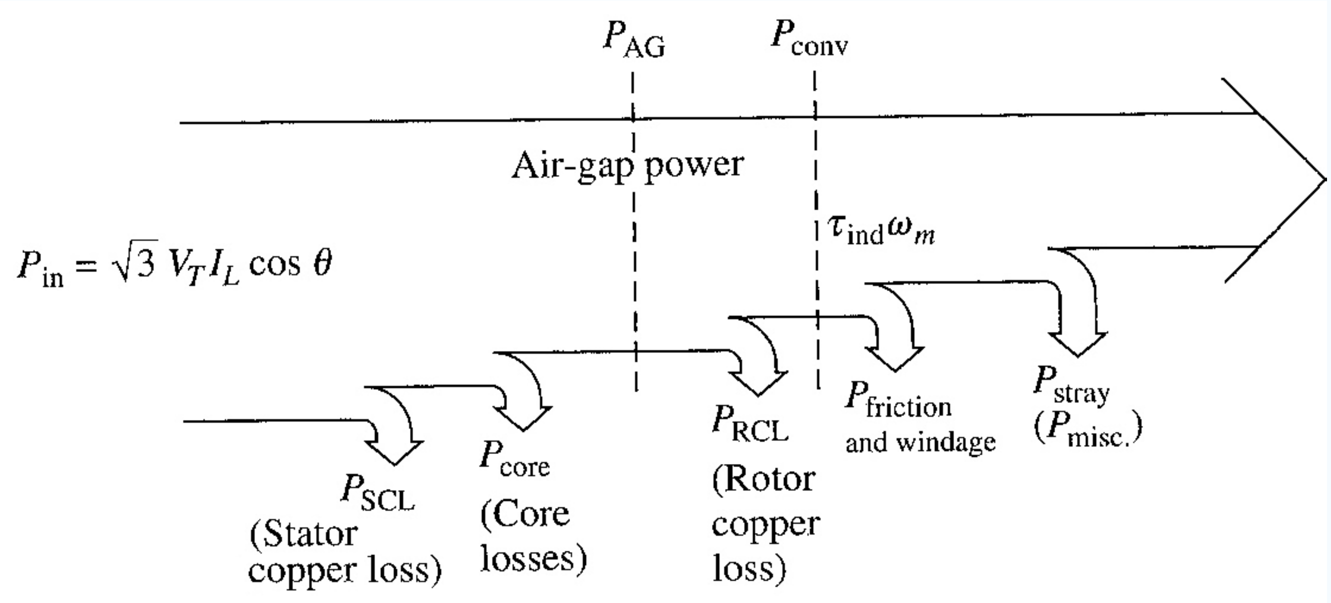
The relationship between the input electric power and the output mechanical power of this motor is shown below:



The core losses of an induction motor come partially from the stator circuit and partially from the rotor circuit.

The rotor core losses are very tiny compared to the stator core losses, all the core losses are lumped together at that point on the diagram.

Induction Motors-Power flow



The higher the speed of an induction motor, the higher the friction, windage, and stray losses. The higher the speed of the motor, the lower its core losses.

Therefore, these three categories of losses are sometimes lumped together and called *rotational losses*.

The total rotational losses of a motor are often considered to be constant with changing speed, since the component losses change in opposite directions with a change in speed.

Example

A 208V, 4 pole, 60Hz, induction motor has a full-load slip of 5%.

(a) What is the synchronous speed of this motor?
(b) What is the rotor speed of this motor at the full-load?

Solution

(a) The synchronous speed :

$$n_{sync} = \frac{120 f_e}{P} = \frac{120 \times 60}{4} = 1800 \text{ r/min}$$

(b) The rotor speed :

$$n_m = (1-s)n_{sync} = (1-0.05)(1800) = 1710 \text{ r/min}$$

Summary

Synchronous Motors:

- Construction
- Operation principle
- Equivalent circuit
- Starting
- Torque-speed characteristics

Induction Motors:

- Construction
- Basic concepts
- Slip speed and slip
- Electrical frequency on the rotor
- Torque-Speed characteristics
- Speed Control
- Power flow

Next

Review of Electromechanics

Thanks for your attention