## 3f AC induction motors

Motors transform electromagnetic energy into mechanical energy. Before developing equations and models, let's first discuss their principles of operation.

The basic mechanism of almost all rotating motors is very similar, no matter what particular type they happen to be. Rotating machines can be viewed as two magnets. One magnet is hooked to the motor's shaft, and the second magnet surrounds the first magnet. An induction machines works by causing the outside magnet to rotate which, in turn, pulls the magnet hooked to the shaft along with it. This induced rotation is what is seen when the motor is turned on—the shaft begins to rotate.

How are these two magnets are produced in the AC induction machine?

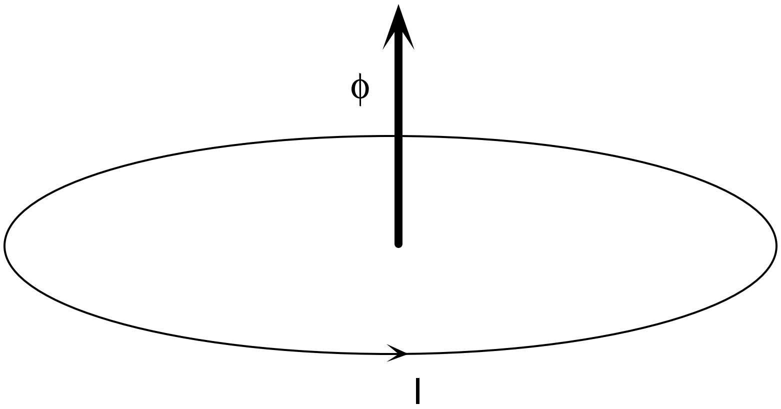
## 1st magnet—the stator

Stator operation is based on two ideas.

i. A magnetic field can be produced by a current loop.

ii. A magnetic field produced from a three-phase source can produce a rotating magnetic field.

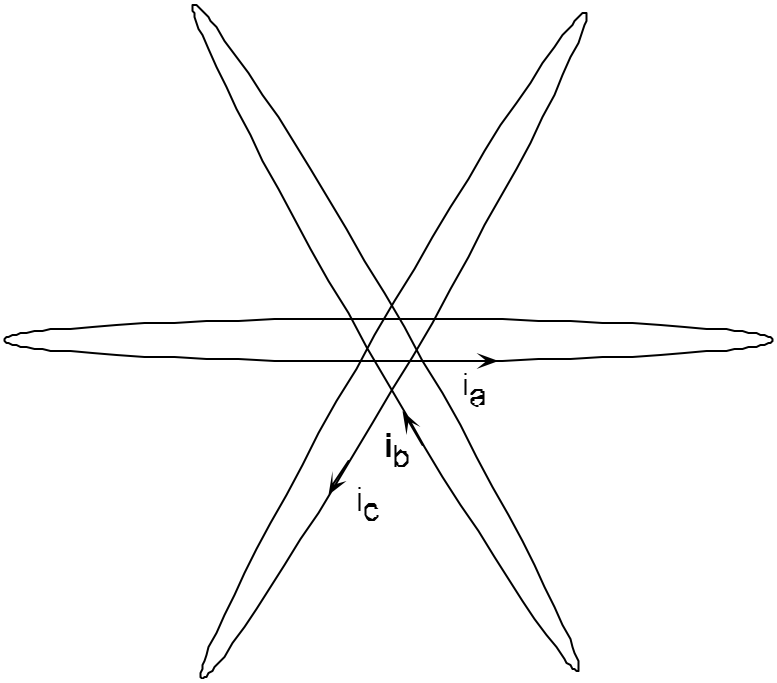
i) Suppose the current, I, is sinusoidal. It would grow large (and positive), achieve its maximum value, grow smaller, become zero, then begin to grow large again (this time negative), achieve its maximum value, grow smaller, become zero again, grow large (again positive) etc.



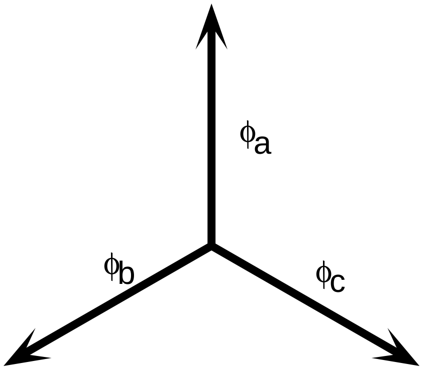
This would, in turn, cause the magnetic flux, $\phi$, to grow large (pointing upward), achieve its maximum value, grow smaller, become zero, then become larger (this time pointing downward), achieve its maximum value, grow smaller, become zero, grow large (again upward) etc.

This magnetic field is not rotating.

A 3$\phi$ source can produce a rotating magnetic field. The three currents differ in phase by 120° and are also spatially displaced from one another by 120°.



When $i_a$, $i_b$, and $i_c$ are positive, the resulting magnetic fields are as shown below.



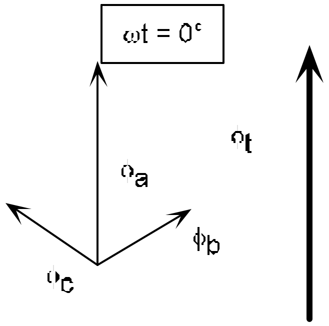
Let’s see how the resultant field acts as a function of time.

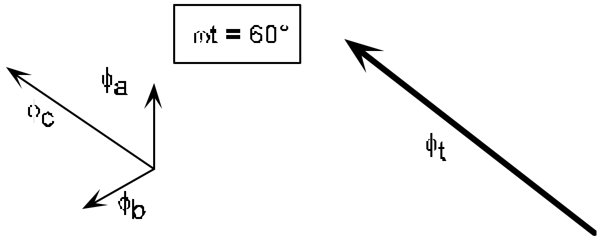
$$i_a(t) = I \cos \omega t \text{ A}$$
$$i_b(t) = I \cos (\omega t - 120°) \text{ A}$$
$$i_c(t) = I \cos (\omega t + 120°) \text{ A}$$

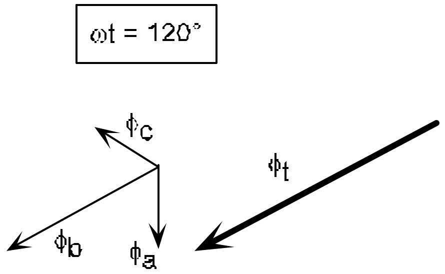
Let's look at the resultant magnetic fields for

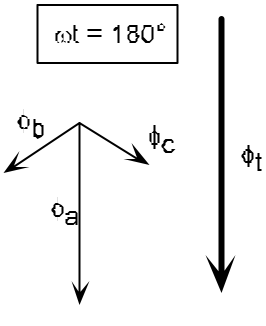
$$\omega t = 0$$
$$\omega t = 60°$$
$$\omega t = 120°$$
$$\omega t = 180°$$
$$\omega t = 240°$$
$$\omega t = 300°$$
$$\omega t = 360°$$

We'll look at the first four to get the idea.









This is how the rotating magnetic field is produced in a 3ϕ induction machine. The stator windings are spatially diplaced by 120° from one another.

More precisely, this is the way if the machine is to have a synchronous speed of 3600 rpm. For slower speed motors, we adjust a bit—more on this later.

## 2nd magnet—the rotor

The 2nd magnet is mounted on the shaft and can rotate. It's called the rotor magnet.

The rotor is wound by wrapping wire around magnetic material. How does this wire and magnetic material ever cause the current that is necessary for a 2nd magnetic field to exist?

Recall Faraday's law of electromagnetic induction—the same one giving rise to transformer action.

$$\oint_{loop} \mathbf{E} \cdot d\mathbf{l} = -\frac{df}{dt}$$

$$V_{loop} = \frac{df}{dt}$$

The rotor does not rotate at "synchronous speed," the speed of the stator's rotating magnetic field. It rotates a bit more slowly.

How much more slowly? Well, that depends on the torque required by the load. The more slowly it rotates the greater $d\phi/dt$, and the greater its current and magnetic field strength.

The rotor comes to a speed that just balances the load and output torque. Slip is a measure of the difference between the rotor speed and the synchronous speed.

In general, the synchronous speed, $n_s$, and slip, s, of an induction motor is given by the formulas below. ($n_s$ in rpm)

$$n_s = \frac{60\,f}{p/2}$$

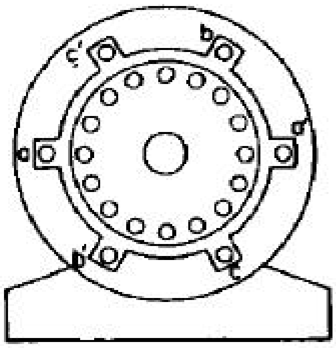
f ~ supply freqency in Hz
p ~ number of poles

$$\text{slip} = s = \frac{n_s - n_m}{n_s}$$

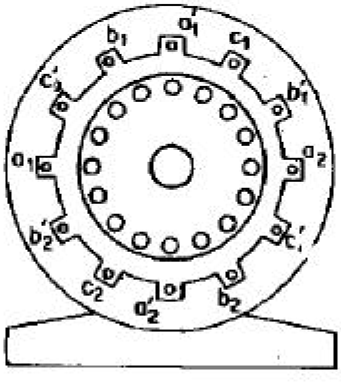
## Working with AC induction motors

Induction machines are the most common of all electrical machines. They are simple in construction, rugged, reliable, inexpensive and compact. They come in single-phase and three-phase constructions. We will only be concerned with three-phase induction motors.

A 2-pole motor ($n_s$ = 3600 rpm for f = 60Hz) compared with a 4-pole motor ($n_s$ = 1800 rpm for f = 60Hz).



two-pole induction motor



four-pole induction motor

For 60 Hz systems, $n_s$ can be 3600, 1800, 1200, 900 rpm etc.

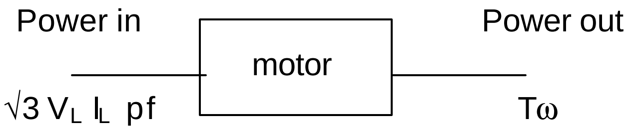
**Example**

For a 60 Hz, 8 pole motor, find the slip at i) standstill ($n_m = 0$), ii) 855 rpm.

**Example**

A 60 Hz induction motor runs at 1164 RPM and develops 0.03 slip. Determine the number of poles.

The power rating given for a motor is the mechanical power available from the motor, usually given in hp. A motor rated 10 hp provides 10 hp of output (mechanical) power at full load.



## Efficiency

The quantity of mechanical power available from the motor is less than the electrical energy supplied to it. Losses are due to heating and friction.

The efficiency of large machines is usually well above 90%, but can drop significantly when the motor is operated far from its rated load.

$$\%h = \frac{P_{out}}{P_{in}} 100\%$$

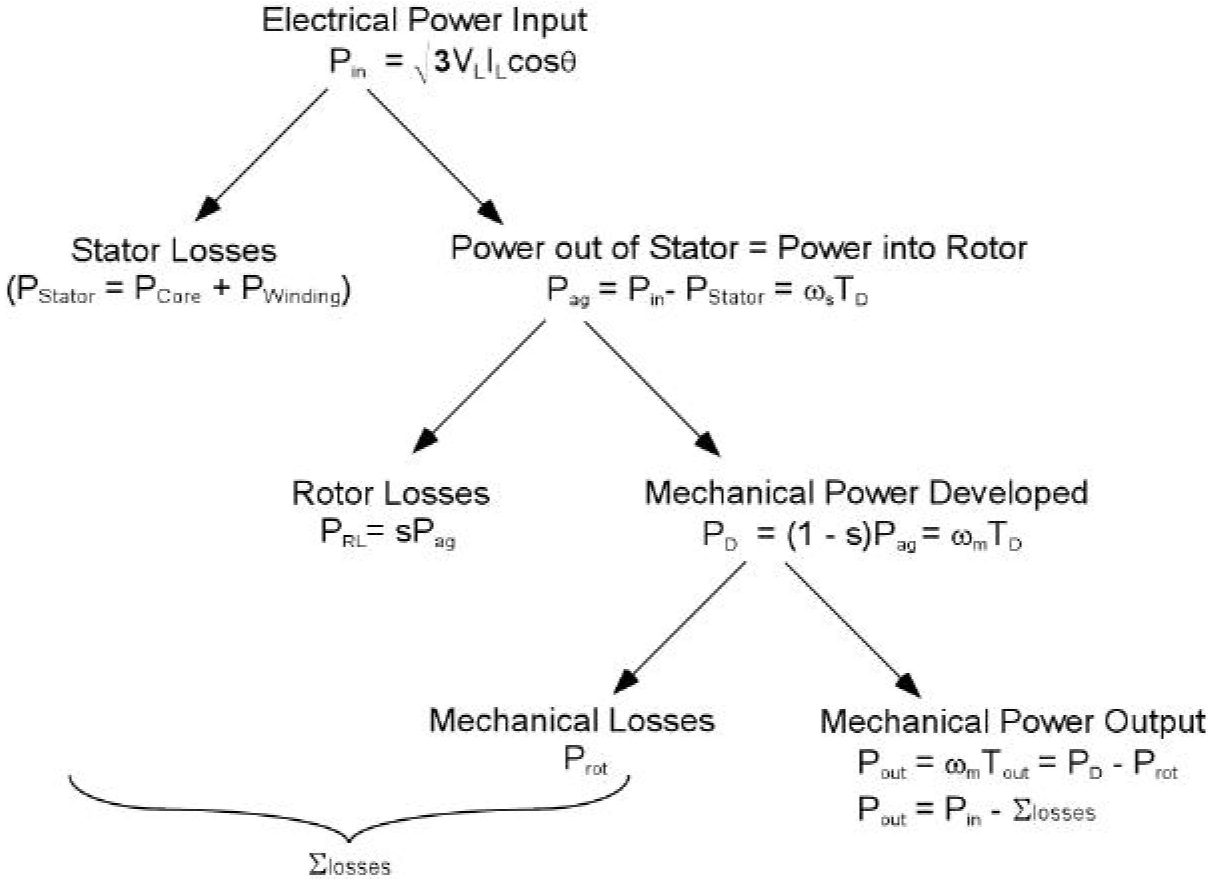
Electrical power is input to the stator. Losses associated with the stator are winding $I^2R$ losses and hysteresis losses in the core.

The remaining power is transferred across the air-gap of the machine and becomes the input power to the rotor—called the air-gap power.

Some of the air-gap power is dissipated by the rotor $I^2R$ losses and the remainder is converted into mechanical power.

Some of the mechanical power is dissipated by the rotational losses—friction, viscous damping.

The remainder is the mechanical output power.



**Example**

A three-phase, 10 hp, 480 V, 60 Hz induction motor has a rated speed of 1152 rpm. Determine:

i) # of poles and rated slip
ii) output torque and efficiency if it draws a line current of 13.3 A, @ 0.75 lag.
iii) air-gap power if the stator losses are 90 W
iv) mechanical power developed and rotor loss
v) developed (electromagnetic) torque
vi) rotational losses