EEP 225 : Electric Machines

Lecture 9

AC Machines V

Taha Ahmed

1 Power Flow and Torque Calculations

Remember from last lecture : the power flow of the synchronous motors.

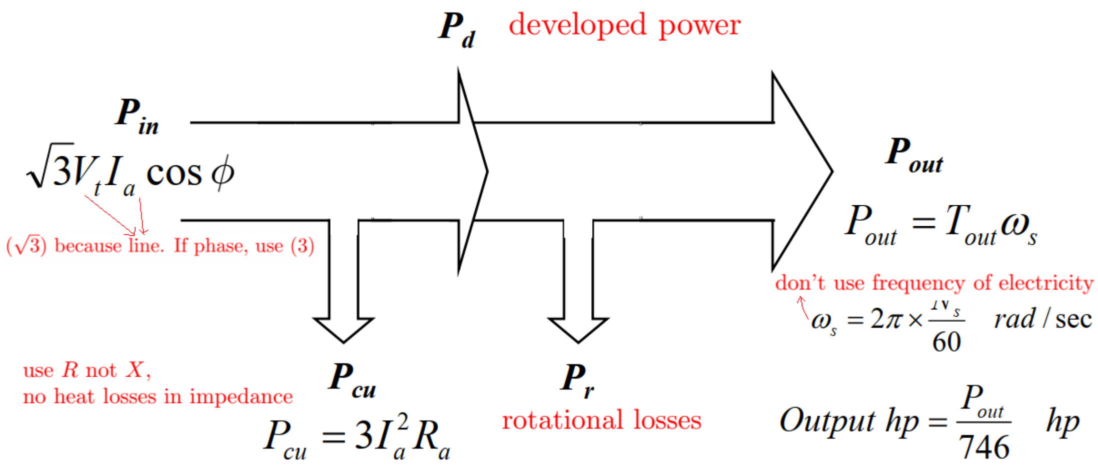

Figure 1: Power Flow of the synchronous motors.

If we neglected the armature resistance, the copper loss becomes zeros, therefore the motor developed power becomes equal to the input power $P_{\text{in}} = P_d$ and the power-angle relationship obtained for synchronous generator will be valid as well for synchronous motor

The complete power-angle curve for both synchronous generator and motor:

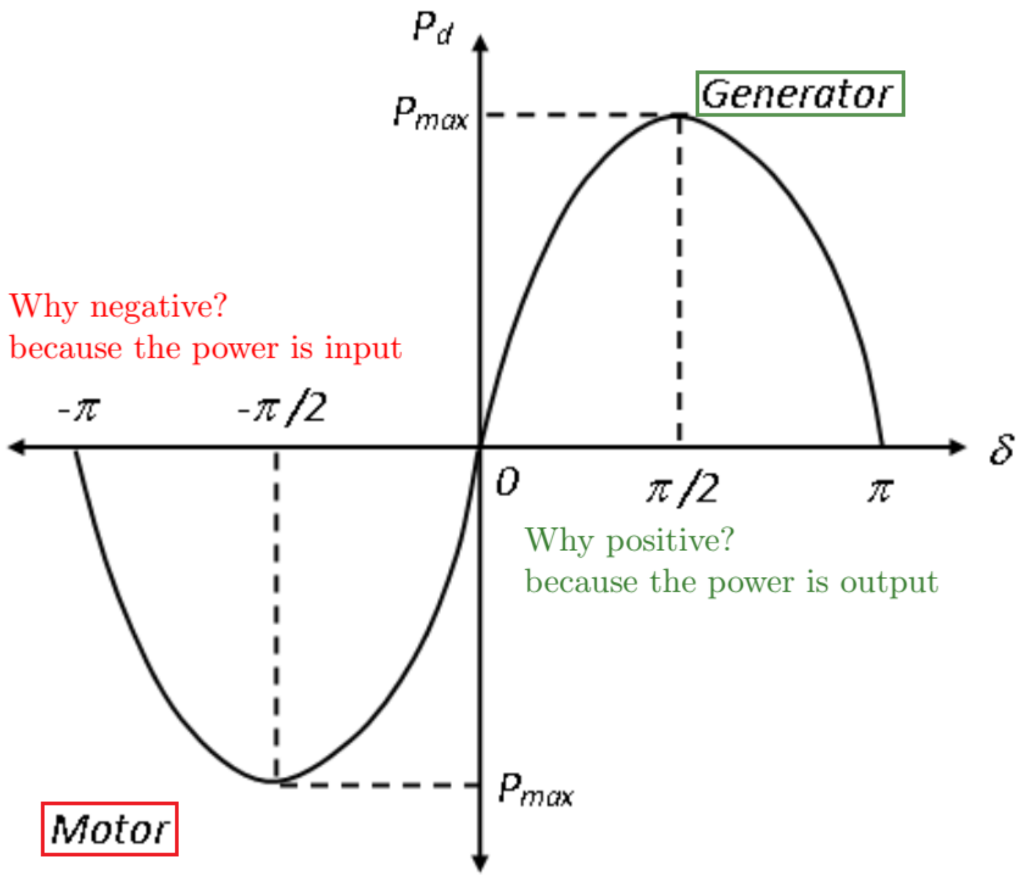

Figure 2

Note that for both generator and motor, the range $0 < \delta < \frac{\pi}{2}$ and $-\frac{\pi}{2} < \delta < 0$ is the stable range, while $\frac{\pi}{2} < \delta < \pi$ and $-\pi < \delta < -\frac{\pi}{2}$ in unstable range.

The **maximum (developed = input) power** occurs at $\delta = \dfrac{\pi}{2}$ and is given by :

$$\boxed{P_{\text{d max}} = 3\frac{|E||V_t|}{X_s}}$$

To get the **maximum developed torque** occurs at $\delta = \dfrac{\pi}{2}$ and is given by:

$$\boxed{T_{\text{d max}} = \frac{P_{\text{d max}}}{\omega_s} = 3\frac{|E||V_t|}{\omega_s X_s}}$$

2 The Synchronous Motor Torque-Speed Characteristic Curve

The synchronous motor torque-speed characteristic curve, is pretty simple. Why? because the speed of the synchronous motor is constant regardless the load why? because the motor is **synchronized** (remember why it is called synchronous motor) with the input frequency, the speed is constant at constant frequency

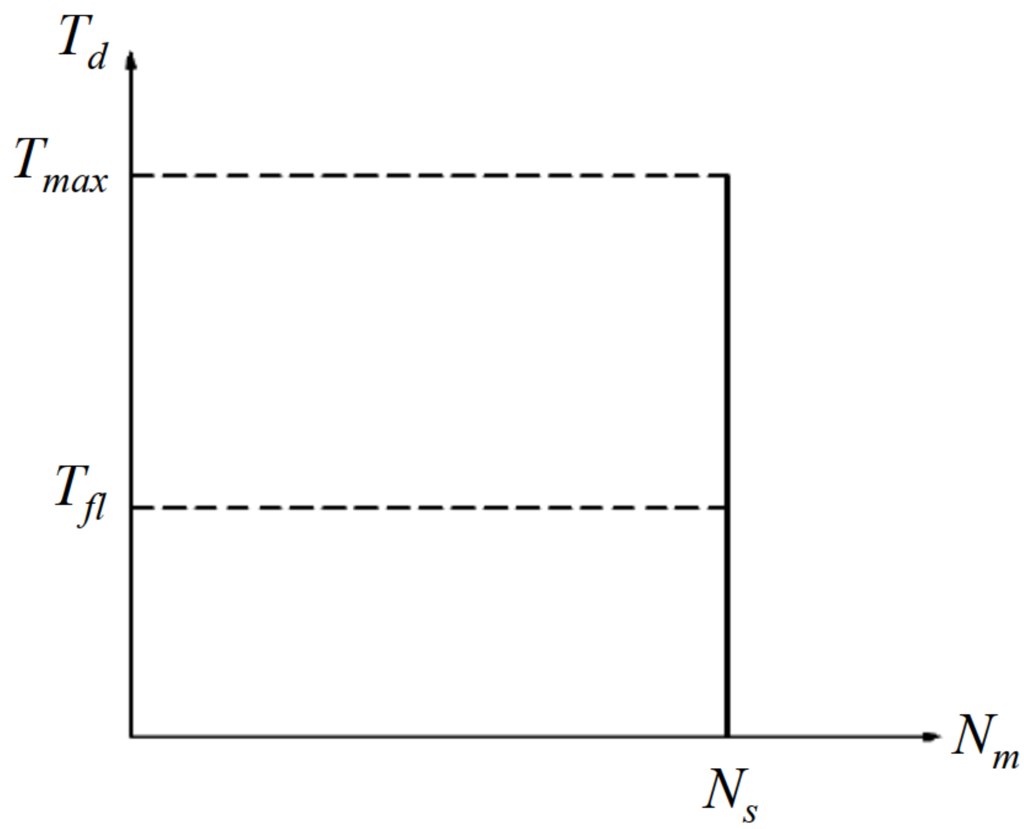

Figure 3

The steady-state speed of the motor is constant from no load all the way up to the maximum torque.

2.1 Speed regulation

Analogous to voltage regulation in generators, in motors, speed regulation is the change in speed when the load changes

$$\text{Speed regulation} = \frac{\text{speed at no load - speed at full load}}{\text{speed at full load}} = \frac{N_{\text{nl}} - N_{\text{fl}}}{N_{\text{fl}}}$$

In synchronous motor, speed at no load = speed at full load, so speed regulation is **zero**.

In other motors, speed at no load > speed at full load, so speed regulation is positive.

In differential motor (unstable DC motor), speed at no load < speed at full, so speed regulation is negative.

Normal full load torques are much less than maximum or pullout full load torque, In fact, the pullout torque may typically be 3 times the full-load torque of the machine.

3 Effect of Field Current Changes on a Synchronous Motor

Consider a synchronous motor operating at lagging power factor, We change (increase) the field current I_f to see what correspondingly changes.

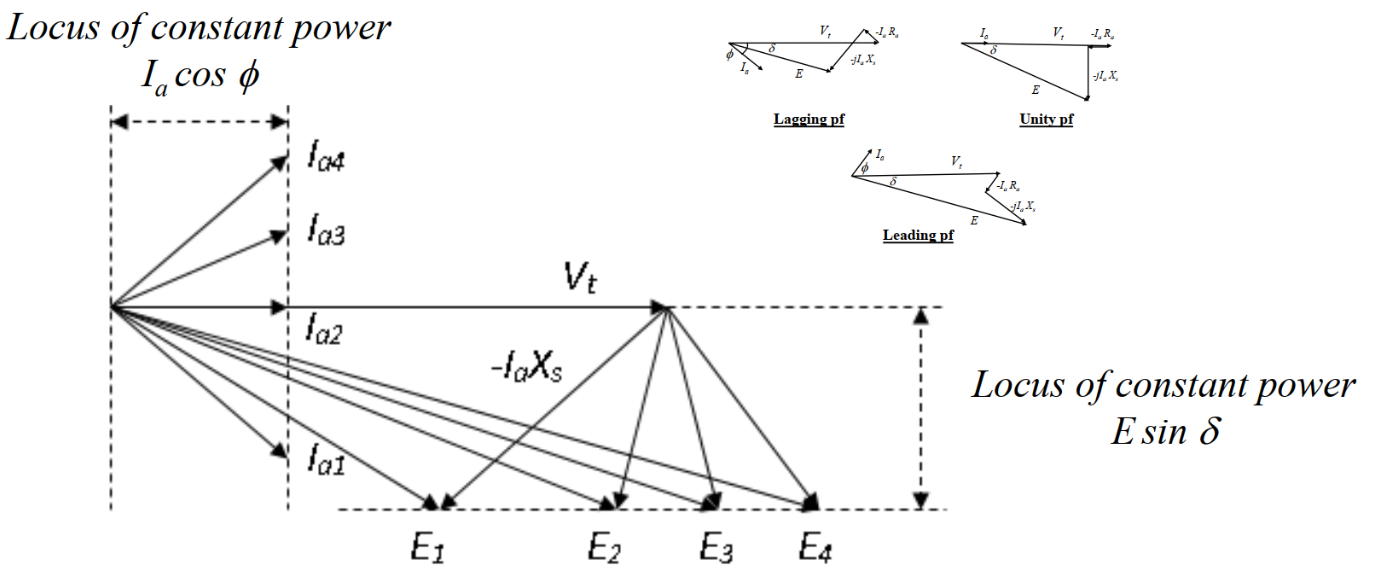

Figure 4: Phasor diagrams of many values of E

Since :

$$P = T\omega_s$$

Power changes only if shaft load torque or shaft speed changes.

Changing I_f changes E, but not torque or speed, so power doesn't change.

Where is the locus of constant power? Remember from last lecture :

$$P_{\text{out}} = 3\underbrace{\frac{V_t}{X_s}}_{\text{scale}}\underbrace{I_a X_s \cos(\phi)}_{\text{length}}$$

Locus of constant power is a horizontal line with height $= I_a X_s \cos(\phi)$

We know that

$$P_{\text{out}} = 3\frac{EV_t}{X_s}\sin(\delta)$$

{power, V_t, X_s} are constants(we only changed (increased) I_f, which will increase E), which means that when E increases $\uparrow$, $\sin(\delta)$ decreases $\downarrow$ so δ decreases $\downarrow$.

Similarly :

Let's get another locus of constant power Remember from a previous lecture :

$$P_{\text{out}} = \underbrace{3V_t}_{\text{scale}} \underbrace{I_a \cos(\phi)}_{\text{length}}$$

Locus of constant power is a vertical line with offset $= I_a \cos(\phi)$

We know that

$$P_{\text{out}} = 3V_t I_a \cos(\phi)$$

{power, V_t } are constants, we only changed (increased) I_f, which will increase E, which will change the angle ϕ correspondingly How? moves towards leading power factor, which is described by V-curves of synchronous motors.

3.1 V-Curves of Synchronous Motors

The relationship between the field current I_f and armature current I_a for different values of load power

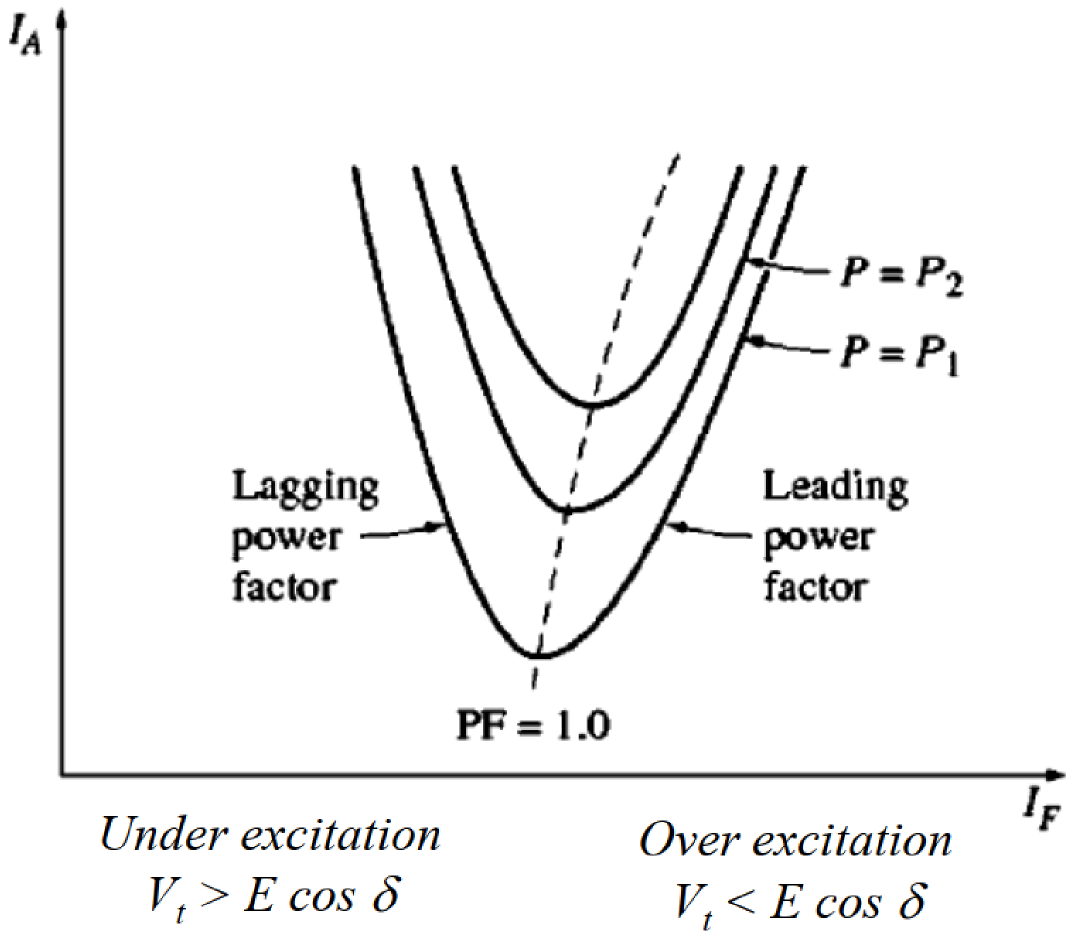

Figure 5: V-Curves of Synchronous Motors

From any phasor diagram, how to determine if it is leading, lagging or unity power factor?

if $E\cos(\delta) < V_t \rightarrow$ lagging power factor

if $E\cos(\delta) = V_t \rightarrow$ unity power factor

if $E\cos(\delta) > V_t \rightarrow$ leading power factor

which means that in synchronous motor, power factor can be controlled by controlling E, which is controlled by controlling I_f.

4 Synchronous Motors As Capacitor

Synchronous motors can act as capacitors if it operates at leading power factor region, motor then is called **synchronous condenser** or **synchronous capacitor**

One of its application is power factor correction.

5 Starting of Synchronous Motors

Unlike DC motors, synchronous motors are not self starting motors, they have to be started using special arrangements.

All synchronous motors are now manufactured with Damper bars, which are copper bars fitted on the poles and short circuited from both sides.

By this arrangement, with the field winding de-energized, applying the three phase supply makes the synchronous motor starts as squirrel cage induction motor[1], when its speed reaches near the synchronous speed. Then the field winding is energized and the motor speed reaches the synchronous speed.

For example : rated speed of a synchronous motor is 1500 rpm, connecting it to a AC source it will start a squirrel cage induction motor because of the damper bars, after which, field winding is energized and the motor speed reaches the synchronous speed (1500 rpm).

[1] Will be discussed after a couple of pages

Figure 6: Synchronous motors with damper bars

What if the synchronous motor has no damper bars?

To be able to start, synchronous motor needs another motor to start it, called auxiliary motor.

$\boxed{\text{1. Q}}$ — A 230 V, 60 Hz, 4-pole, Y-connected synchronous motor has an armature resistance and synchronous reactance of 0.5Ω and 5Ω per phase respectively. If the motor takes an input power of 7 kW at 0.707 pf leading and the rotational loss is 100 W. Determine:

1. The generated emf and the power angle.
2. The output hp (horse power), and the output torque.
3. The efficiency.

A —

Given line value, we want to get the phase value

$$V_t = \frac{230}{\sqrt{3}} = 132.8V$$

$$P_{\text{out}} = 3V_tI_a\cos(\phi) = 3V_tI_a \times \text{power factor}$$

$$\therefore I_a = \frac{7000}{\sqrt{3} \times 230 \times 0.707} = 24.85A$$

$$E\angle\delta = V_t\angle 0 - I_a\angle\phi \times (R_a + jX_s)$$

$$\therefore \overline{E} = 132.8\underline{/0} - (24.85\underline{/45^\circ})(0.5 + j5) = \underbrace{232.8}_{E}\ \underbrace{\underline{/-24.5^\circ}}_{\text{power angle}}$$

output power = input power - rotational losses - copper losses

$$P_{cu} = 3I_a^2R_a = 3 \times 24.85^2 \times 0.5 = 926.2W$$

$$\therefore P_{\text{out}} = 7000 - 926.2 - 100 = 5973.8W$$

$$\text{hp} = \frac{5973.8}{746} \approx 8\text{hp}$$

$$N_s = 120 \times \frac{\text{frequency}}{\text{Number of poles}} = 120 \times \frac{60}{4} = 1800\text{rpm}$$

$$\omega_s = 2\pi \times \frac{N_s}{60} = 2\pi \times \frac{1800}{60} = 188.4\text{rad / sec}$$

$$T_{\text{out}} = \frac{P_{\text{out}}}{\omega_s} = \frac{5973.8}{188.4} = 31.7\text{N.m.}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{5973.8}{7000} = 85.3\%$$

6 Three Phase Induction Motor

Nikola Tesla conceived the basic principles of the polyphase induction motor in 1883, and had a half horsepower (400 Watt) model by 1888. Though he received a million dollars from George Westinghouse for the rights to manufacture this invention, he died penniless.

Induction motor requires no electrical connection to the rotor, the transfer of energy from stator to rotor is achieved by electromagnetic induction (like transformer action).

About 90% of industrial motors are induction motors.

Induction motors can range in size from fractional hp to over 100,000 hp.

The rating of three phase induction motors are the highest among all other motors

6.1 Advantages of Three Phase Induction Motor

1. It has very simple and extremely rugged (strong) construction.
2. Its cost is low and it is very reliable.
3. It has very high efficiency (85% - 90%).
4. It has a good lagging power factor (0.8 - 0.85).
5. It requires minimum maintenance.

7 Construction of Three Phase Induction Motor

7.1 Stator

Similar to synchronous machine.

Made of laminated core, where it is slotted on its inner cylinder surface to accommodate the stator winding which will be fed from a three-phase supply

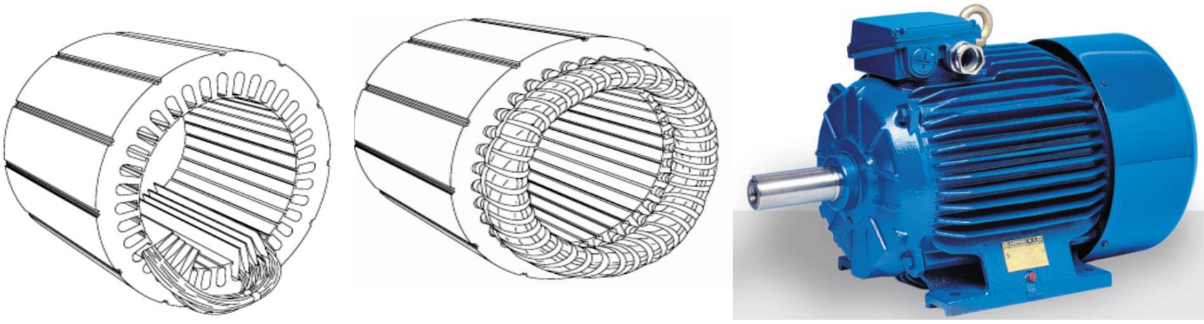

Figure 7: Stator of induction motor

7.2 Rotor

There are two different types of induction motor rotors:

7.2.1 Wound motor (more expensive and low usage)

A wound rotor has a complete set of three-phase windings that are mirror images of the windings on the stator.

The three phases of the rotor windings are usually Y-connected, and the ends of the three rotor wires are tied to slip rings on the rotor's shaft.

The rotor windings are shorted through brushes riding on the slip rings.

Due to brushes and skip rings, this machines requires periodic maintenance, has limitation on its speed and not safe to use in all applications due to sparks.

7.2.2 Squirrel cage rotor (cheaper and more usage)

No coils, The windings in this case are made of copper or aluminum bars laid into rotor slots and short circuited from both sides (remember damper bars). These bars are brazed to end rings.

This design is referred to as squirrel cage rotor because the conductors would look like one of the exercise wheels that squirrels or hamsters run on.

Property	Squirrel-cage rotor	Wound rotor
Maintenance	Almost no maintenance required	Requires periodic maintenance
Efficiency	High (no coils, just bars)	Low (because of winding)
Advantages	1. Cheaper and more robust. 2. Higher power factor. 3. The risk of sparks is eliminated by the absence of slip rings and brushes.	1. Higher starting torque. 2. Lower starting current. 3. Means of varying speed by use of external rotor resistance.

8 Theory of Operation

Induction motor is a self starting motor.

When the three-phase stator windings are excited by the three-phase supply, a rotating magnetic[2] field is produced in the stator and rotates by speed equals N_s , where

$$N_s = 120 \times \frac{f_s}{P}$$

This magnetic field is generated in the stator and cuts rotor winding, hence an emf is induced in the rotor. (Faraday's law of electromagnetic induction).

Since rotor is short-circuited (and there are emf produced by Faraday), a current is produced in the rotor.

Remember Lenz's law :

Direction of electric current induced by changing magnetic field is such that the magnetic field created by the induced current **opposes** changes in the initial magnetic field

What induced the current ? the relative speed between stator field (with speed =

[2]There are two types of magnetic field: Rotating magnetic field produced by 3 phase (self starting motors) and pulsating or stationary magnetic field produced by single phase (not self starting motors)

N_S) and rotor (with speed $= 0$ till now) $(N_s - 0)$

How to oppose the action of stator field on rotor? Make relative speed equal zero.

how? rotor start to rotate by speed called N_r in the **same direction**[3] with N_s, and the relative speed between stator field and rotor becomes $(N_s - N_r)$

Note that rotor can't rotate by N_s, if it did, the relative speed would be $N_s - N_r = 0$ so rotor current will equal zero so the torques becomes zero, so it can't rotate by N_s but the speed of rotation of rotor is close to the speed of rotation of stator field.

8.1 Slip

Slip(s) is defined as per unit relative speed:

$$s = \frac{N_s - N_r}{N_s} \qquad N_r = N_s(1 - s)$$

At starting

$$N_r = 0 \qquad \therefore s = 1$$

At:

$$N_r = N_s \qquad \therefore s = 0$$

$$\boxed{\therefore 0 < s \leq 1}$$

Practical value of s is near to zero $(0.05 \sim 0.1)$

[3] A common mistake is to say the that rotor will rotate in the opposite direction with stator field, we are not blindly oppose every thing! due to Lenz's law, we want to reduce(oppose) the relative speed, which means that rotor rotates in the same direction with stator field