CAN102

Electromagnetism and Electromechanics

2023/24-S2

Lecture 20 Synchronous Generator

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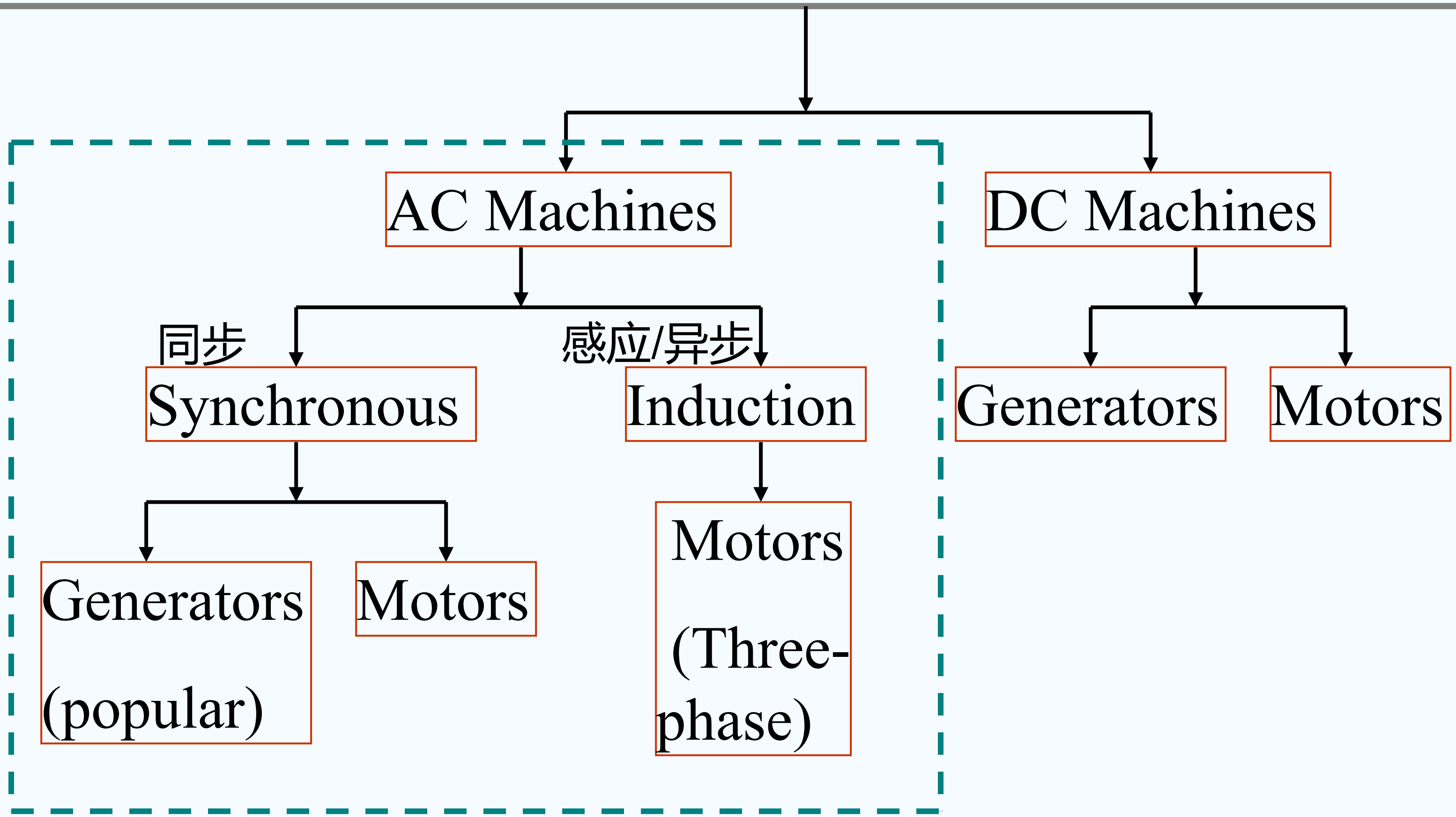
Electrical Machines



AC Machine Efficiency and Losses

The efficiency of an AC machine is defined :

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{P_{in} - P_{loss}}{P_{in}} \times 100\%$$

Four basic losses in AC machines:

1. **Electrical or copper losses** (I^2R losses):

The resistive heating losses in the stator (armature) windings:

$$P_{SCL} = 3I^2{}_A R_A \quad \text{(in a three-phase AC machine)}$$

The resistive heating losses in the rotor (field) windings:

$$P_{RCL} = I^2{}_F R_F$$

Where I_A and I_F are currents flowing in each armature phase and in the field winding respectively. R_A and R_F are resistances of each armature phase and of the field winding respectively.

AC Machine Losses

Four basic losses in AC machines:

2. **Core losses**: The hysteresis losses and eddy current losses occurring in the metal of the machine. They vary as B^2 (flux density) and as $n^{1.5}$ (speed of rotation of the magnetic field).

3. **Mechanical Losses**: There are two types of mechanical losses: friction (friction of the bearings) and windage (friction between the moving parts of the machine and the air inside the casing). These losses are often lumped together and called the no-load rotational loss of the machine. They vary as the cube of rotation speed n^3.

4. **Stray losses**: All other losses not covered by above.

   These are the losses that cannot be classified in any of the above categories. They are usually due to inaccuracies in modeling. For many machines, stray losses are assumed as 1% of full load.

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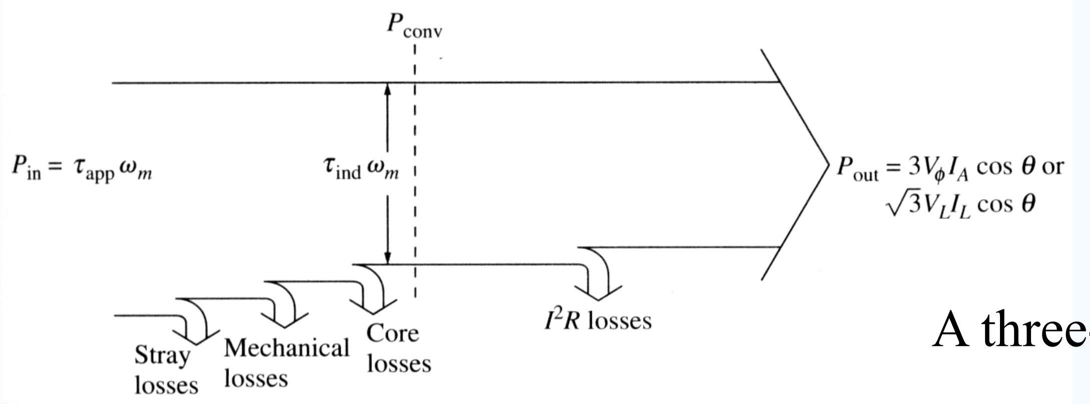
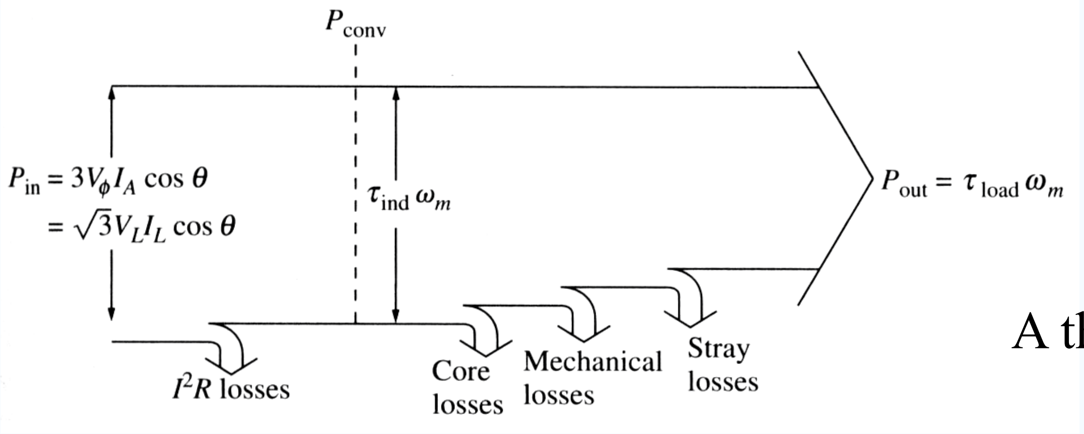
AC Machine Power Flow Chart

The mechanical power is input, and then all losses but cupper are subtracted. The remaining power P_{conv} is ideally converted to electricity: $P_{conv} = \tau_{ind}\omega_m$



A three-phase AC **generator**

Power-flow diagram for AC motors is simply reversed.



A three-phase AC **motor**

The Ability of AC machine

◆ Voltage Regulation

Voltage regulation (*VR*) is a measure of the ability of **a generator** to keep a constant voltage at its terminals as load varies. It is defined by:

$$VR = \frac{\boxed{V_{nl}} - V_{fl}}{V_{fl}} \times 100\%$$

The smaller, the better

No-**l**oad terminal voltage

Full-**l**oad terminal voltage

The Ability of AC machine

◆ Speed Regulation

Speed regulation (*SR*) is a measure of the ability of **a motor** to keep a constant shaft speed as load varies. It is defined by:

$$SR = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\%$$

No-load constant speed

Or

$$SR = \frac{\omega_{nl} - \omega_{fl}}{\omega_{fl}} \times 100\%$$

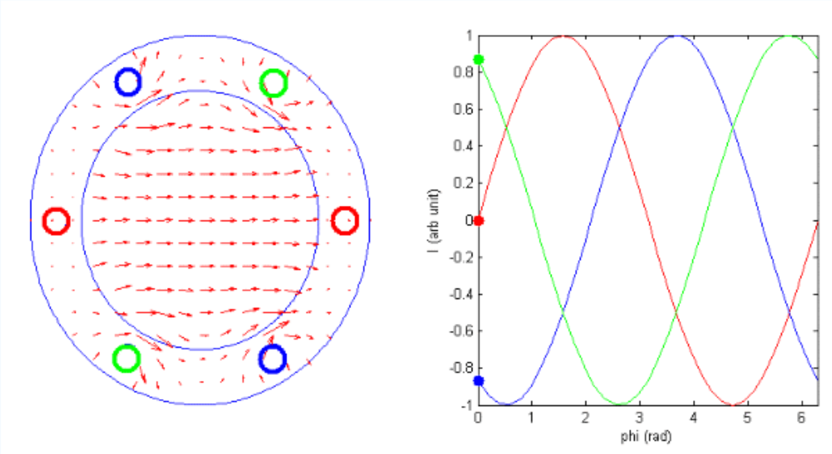
Full-load constant speed

Positive: a motor's speed drops with increasing load

Negative: a motor's speed increases with increasing load

The Rotating Magnetic Field

The rotating magnetic field concept is illustrated below – empty stator containing 3 coils 120º apart. It is a 2-pole winding (one north and one south).

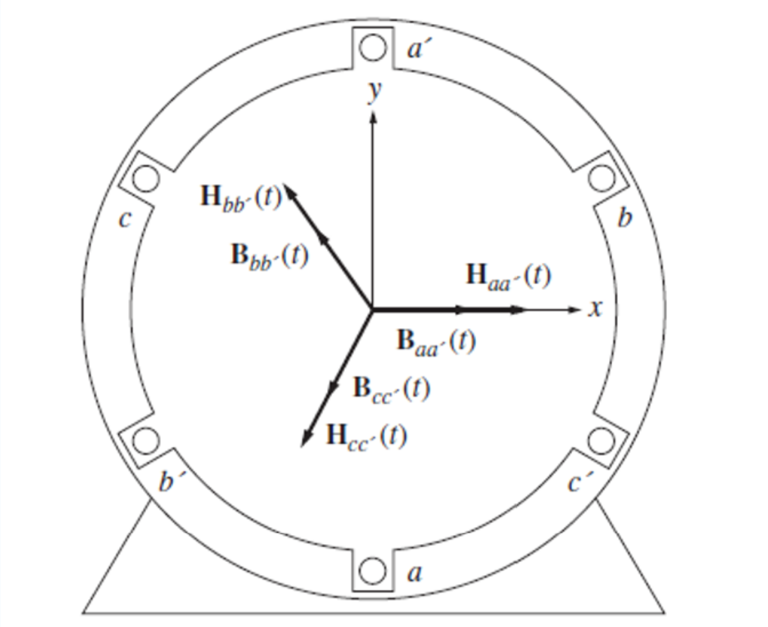


Assume currents in the 3 coils are:

$$i_{aa'}(t) = I_M \sin \omega t \ A$$

$$i_{bb'}(t) = I_M \sin(\omega t - 120°) A$$

$$i_{cc'}(t) = I_M \sin(\omega t - 240°) A$$



(a)

(a) A simple three phase stator. Currents in this stator are assumed positive if they flow into the unprimed end and out the primed end of the coils.

Induced Voltage in AC Machines

The induced voltage in a 3-Phase set of coils

$$e_{ind} = \Phi_{\max}\omega \sin \omega t$$

For N turns:

$$e_{ind} = N\Phi_{\max}\omega \sin \omega t$$

Suppose a rotating magnetic field is produced by the rotor the system, if 3 sets of different windings, each of N turns, the stator voltage induced due to the rotating magnetic field produced by the rotor will have a phase difference of 120°, the induced voltages at each phase will be as follows:

$$e_{aa'} = N\Phi\omega_e \sin \omega_e t$$

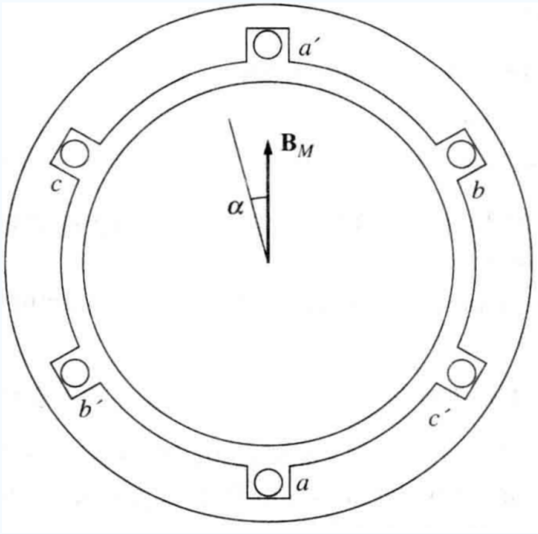
$$e_{bb'} = N\Phi\omega_e \sin(\omega_e t - 120°)$$

$$e_{cc'} = N\Phi\omega_e \sin(\omega_e t - 240°)$$

where ω_e is electrical angular frequency

Φ is the short form of $\Phi_{\max}$

When SI units are used, the unit of the induced voltage is volts.



Induced Voltage in AC Machines

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$$e_{bb'} = N\Phi\omega_e \sin(\omega_e t - 120°)$$

$$e_{cc'} = N\Phi\omega_e \sin(\omega_e t - 240°)$$

The peak voltage in any phase:

$$E_{max} = KN\Phi\omega_e = N_C\Phi\omega_e$$

With $\omega_e = 2\pi f_e$, we have:

$$E_{max} = 2\pi N_C \Phi f_e$$

A three-phase set of currents can generate a uniform rotating magnetic field in a machine stator

A uniform rotating magnetic field can generate a three-phase set of voltage in such a stator

Rotating magnetic field $\Leftrightarrow$ Three-phase voltage

The RMS (Root Mean Square) voltage of any phase, say A-phase:

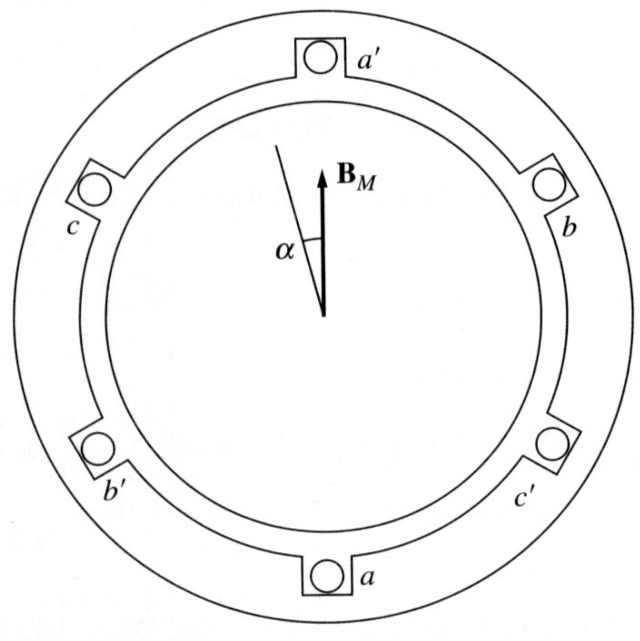
$$E_A = \sqrt{2}\pi \underline{N_C} \Phi f_e$$

Depends on the number of turns, construction, material…

Induced Voltage in AC Machines-Example

The peak flux density of the rotor magnetic field in a simple 2-pole 3-phase generator is 0.2 T; the mechanical speed of rotation is 3600 rpm; the stator diameter is 0.5 m; the length of its coil is 0.3 m and each coil consists of 15 turns of wire.

a) What are the 3-phase voltages of the generator as a function of time?
b) What is the rms phase voltage of the generator?



Induced Voltage in AC Machines-Example

a) What are the 3-phase voltages of the generator as a function of time?

The flux in this machine is given by

$$\Phi = 2rlB = dlB = 0.5 \times 0.3 \times 0.2 = 0.03 \quad \text{Wb}$$

The rotor speed is

$$\omega = \frac{3600 \times 2\pi}{60} = 377 \quad \text{rad/s}$$

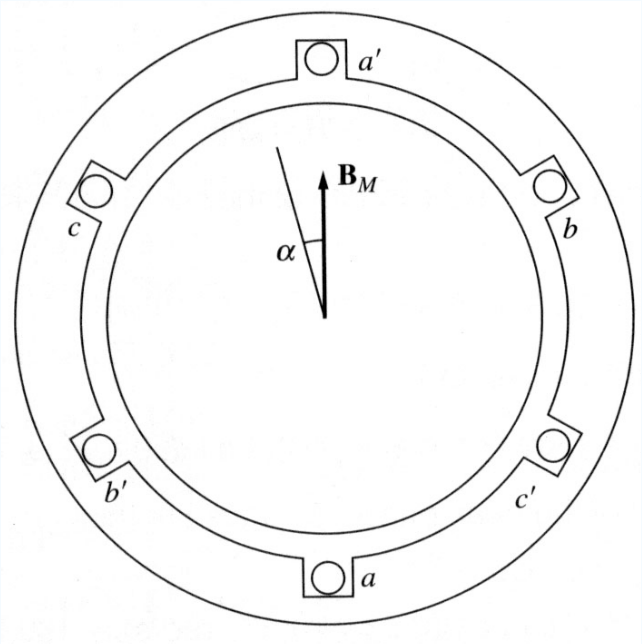
$$e_{aa'} = N\Phi\omega_e \sin \omega_e t$$
$$e_{bb'} = N\Phi\omega_e \sin(\omega_e t - 120°)$$
$$e_{cc'} = N\Phi\omega_e \sin(\omega_e t - 240°)$$

The magnitude of the peak phase voltage is

$$E_{\max} = N\Phi\omega = 15 \times 0.03 \times 377 = 169.7 \quad \text{V}$$

and the three phase voltages are:

$$e_{aa'}(t) = 169.7 \sin(377t)$$
$$e_{bb'}(t) = 169.7 \sin(377t - 120°)$$
$$e_{cc'}(t) = 169.7 \sin(377t - 240°)$$



b) What is the rms phase voltage of the generator?

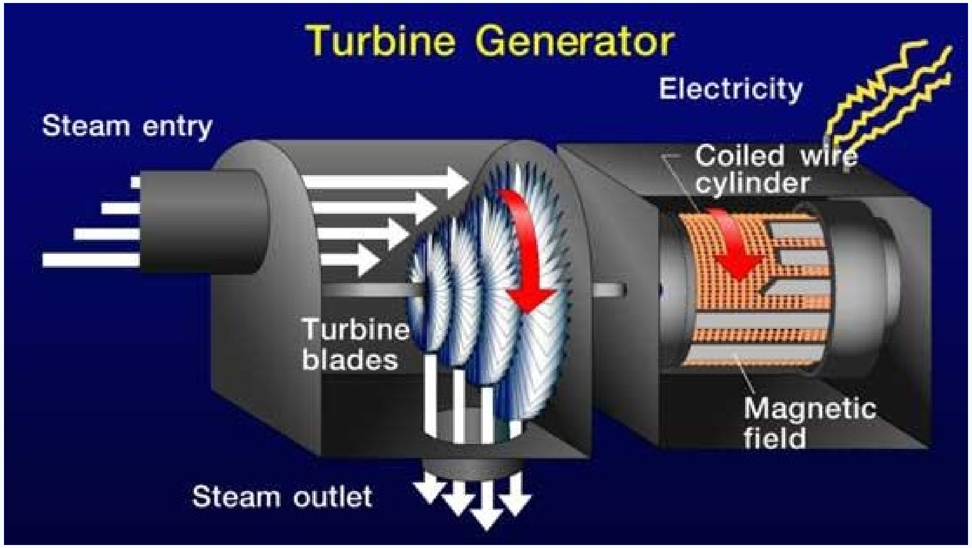
$$E_A = \frac{E_{\max}}{\sqrt{2}} = \frac{169.7}{\sqrt{2}} = 120 \quad \text{V}$$

Synchronous Generators

Synchronous generators are used to convert mechanical power from the turbine to AC electric power.

The turbine converts some kind of energy (heat, water, wind) into mechanical energy.

Although tremendous development in machine ratings, insulation components, and design procedures has occurred now for over one hundred years, the basic constituents of the machine have remained practically unchanged.



Synchronous Generators-Construction

The synchronous generator has two parts: **Stator** and **Rotor**

The Stator has **a three-phase winding**.
This rotating magnetic field induces a **3-phase set of voltages** within the stator windings of the generator.

" **Armature windings**" applies to the windings where the main voltage is induced. The armature windings are on the stator

the terms "**stator windings**" and "armature windings" are used interchangeably.

A DC current is applied to the rotor winding, which then produces a rotor magnetic field.

The rotor is turned by a prime mover, producing **a rotating magnetic field**.

" **Field windings**" applies to the windings that produce the main magnetic field in a machine. The field windings are on the rotor

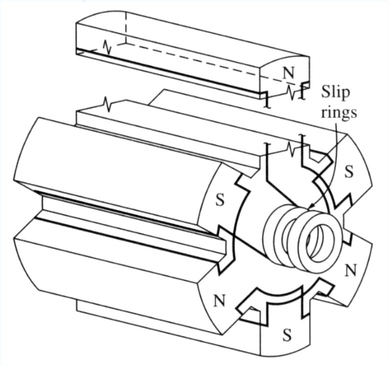
the terms "**rotor windings**" and "field windings" are used interchangeably.

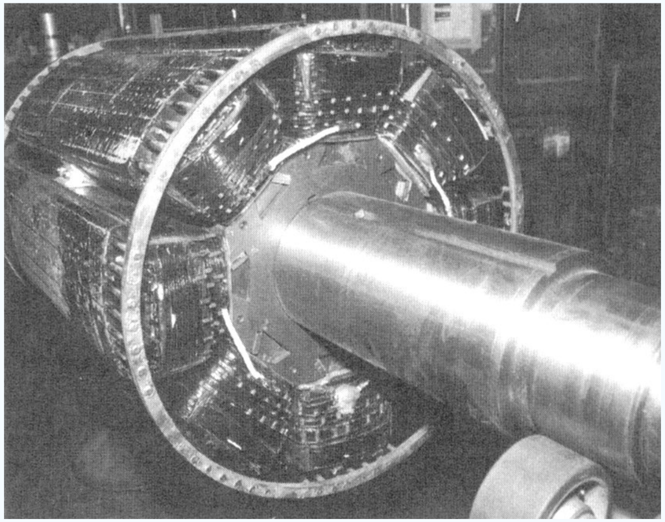
Advantages: having a single, low-power (low voltage and current) field winding on the rotor and the multiple-phase, high-power armature winding on the stator.

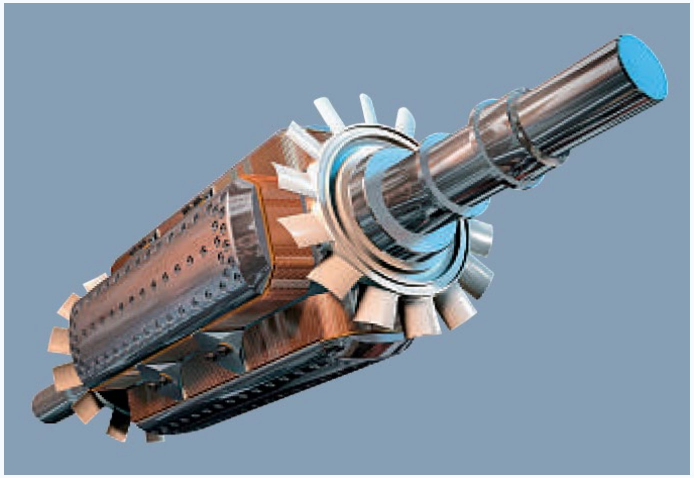
Synchronous Generators-Construction

The rotor of a synchronous machine is a large electromagnet. The magnetic poles can be either salient (sticking out of rotor surface) or non-salient construction.

Salient Poles: are used for 4 or more poles rotor. All hydro-machines use salient pole construction as salient pole construction is less expensive.



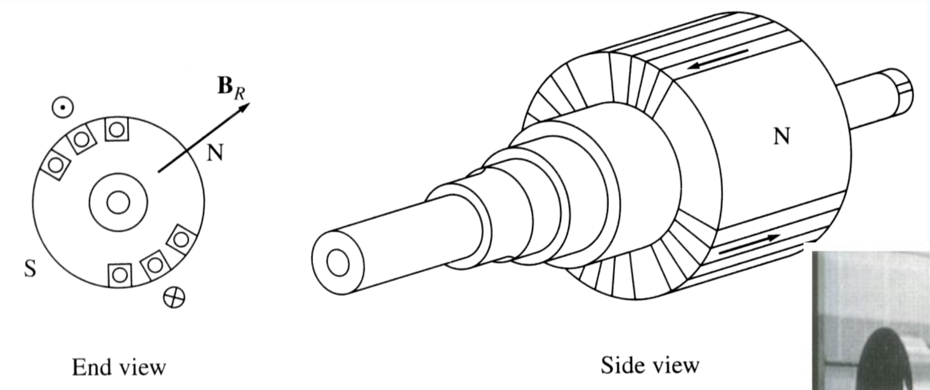


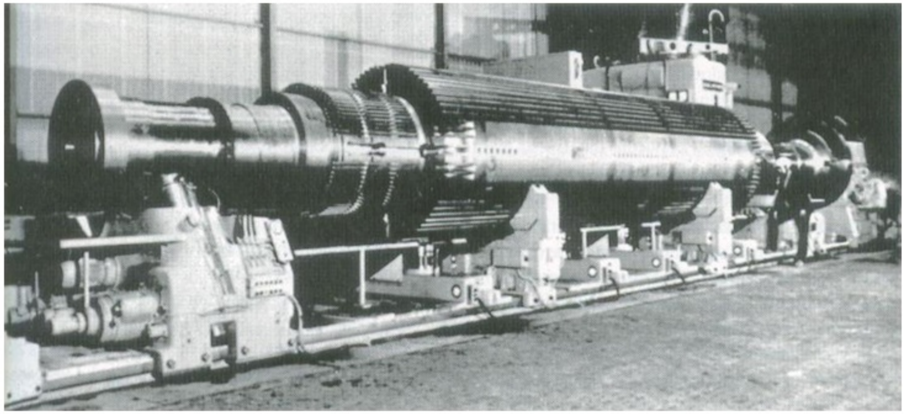


Synchronous Generators-Construction

The rotor of a synchronous machine is a large electromagnet. The magnetic poles can be either salient (sticking out of rotor surface) or non-salient construction.

Non Salient/Cylindrical/Round Poles: are normally used for rotors with 2 or 4 poles rotor. All steam-turbines use smooth rotor construction.





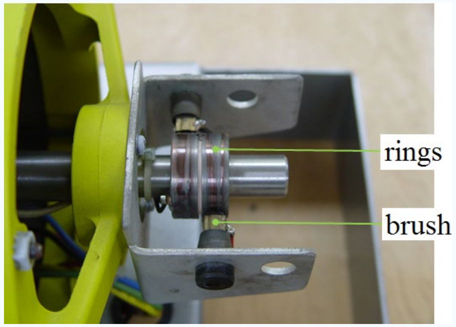
Cylindrical rotor

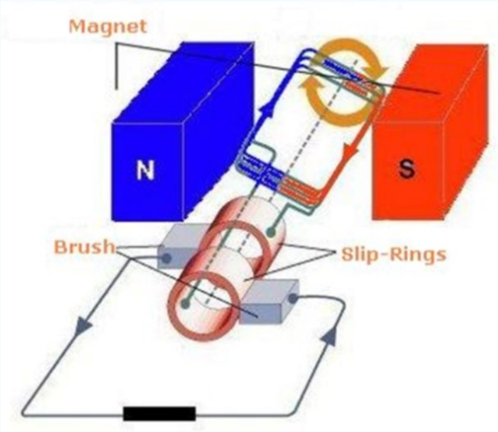
Supplying DC Power to Rotor

A **DC current** must be supplied to the field circuit on the rotor. Since the rotor is rotating, a special arrangement is required to get the DC power to its field windings.

There are two approaches to achieve it:

- ➢ Supply the dc power from an external dc source to the rotor by means of slip rings and brushes
  - * Older machines: directly from a DC machine
  - * Modern system: AC exciters and solid-state rectifiers





- ➢ Supply the DC power from a special DC power source mounted directly on the shaft of the synchronous generator.
  - * This is complex in mechanical structure

The Speed of Rotation

Synchronous generators are by definition synchronous, meaning that **the electrical frequency produced is locked in or synchronized with the mechanical rate of rotation of the generator**. The rate of rotation of the magnetic fields in the machine is related to the stator electrical frequency

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

(Lecture 19 Page 32)

f_{se}: electrical frequency, in Hz

n_m: mechanical speed of magnetic field, in r/min (equals speed of rotor for synchronous machine)

P: number of poles

The Speed of Rotation

Since the rotor turns at the same speed as the magnetic field, the relation relates the speed of rotor rotation n_m to the resulting electrical frequency f_{se}

The grad frequency, f_e: 60 Hz: American , Japan

50 Hz: UK, China

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

The required rate of rotation of a synchronous machine for a given frequency can be calculated

	Rotor speed n_m (r/min)	
No. of poles (P)	60 Hz	50 Hz
2	**3600**	**3000**
4	**1800**	**1500**
6	1200	1000
8	900	750
10	720	600
12	600	500
16	450	375
18	400	333
20	360	300
24	300	250
32	225	188
40	180	150

The Internal Generated Voltage

The induced voltage in a given stator phase is:

$$E_A = \sqrt{2}\pi N_C \Phi f$$

$$\Downarrow$$

$$E_A = K\Phi\omega$$

$$\theta_e = \frac{P}{2}\theta_m$$

$$f_e = \frac{P}{2} f_m$$

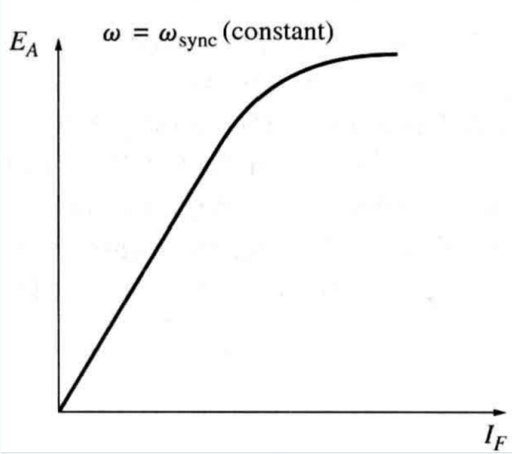
$$\omega_e = \frac{P}{2}\omega_m$$

Where K is a constant representing the construction of the machine

$$K = \frac{N_C}{\sqrt{2}} (\text{if } \omega \text{ in electrical rads/s})$$

$$K = \frac{N_C P}{2\sqrt{2}} (\text{if } \omega \text{ in mechanical rads/s})$$

The internal generated voltage E_A is directly proportional to the flux and to the speed, but the flux itself depends on the current flowing in the rotor field circuit. So the relationship between E_A and I_F is nonlinear.



The Equivalent Circuit

Distortion of the air gap magnetic field by the current flowing in the stator called **armature reaction**.

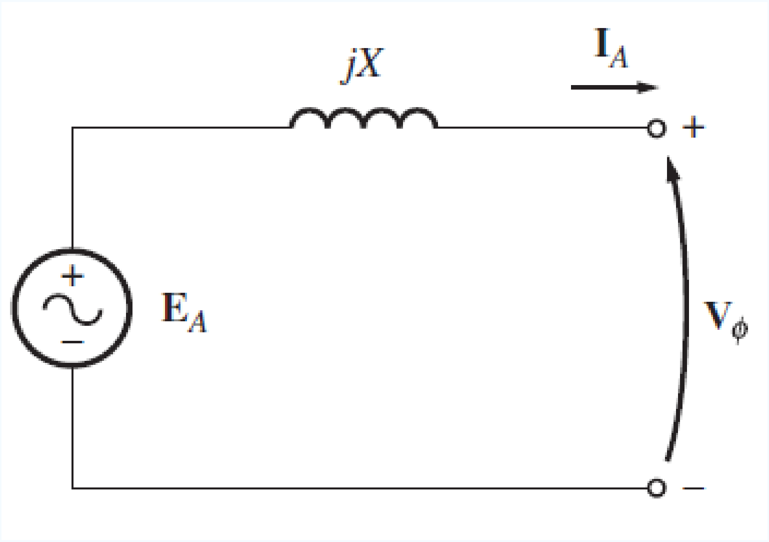
The armature reaction voltage is directly proportional to the current I_A. If X is a constant of proportionality, then the armature reaction voltage can be expressed as:

$$j X \mathbf{I}_A$$

Therefore:

$$\mathbf{V}_\phi = \mathbf{E}_A - j X \mathbf{I}_A$$

Thus, the armature reaction voltage can be modeled as an inductor in series with the internal generated voltage.



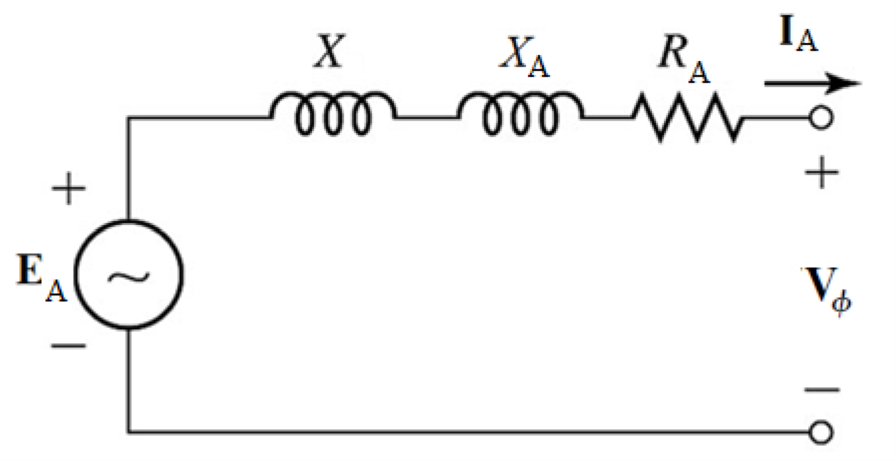
The Equivalent Circuit

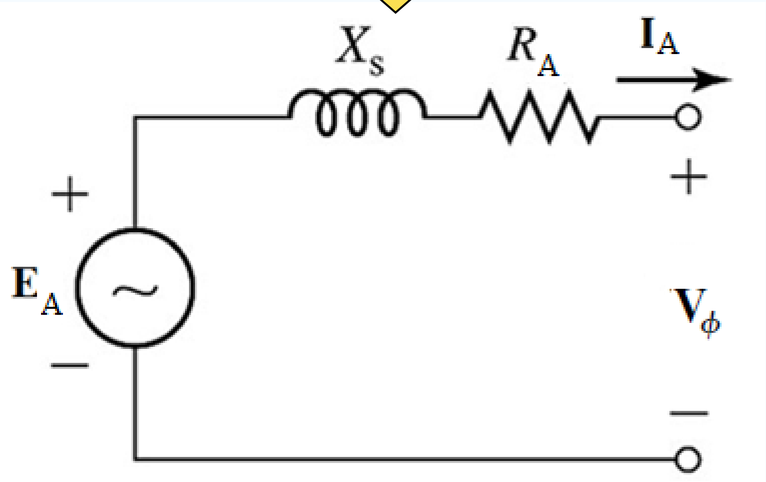
If the stator self-inductance is called L_A (reactance is X_A) while the stator resistance is called R_A, then the total difference between E_A and V_A is:

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

Where $X_S = X + X_A$

Synchronous reactance





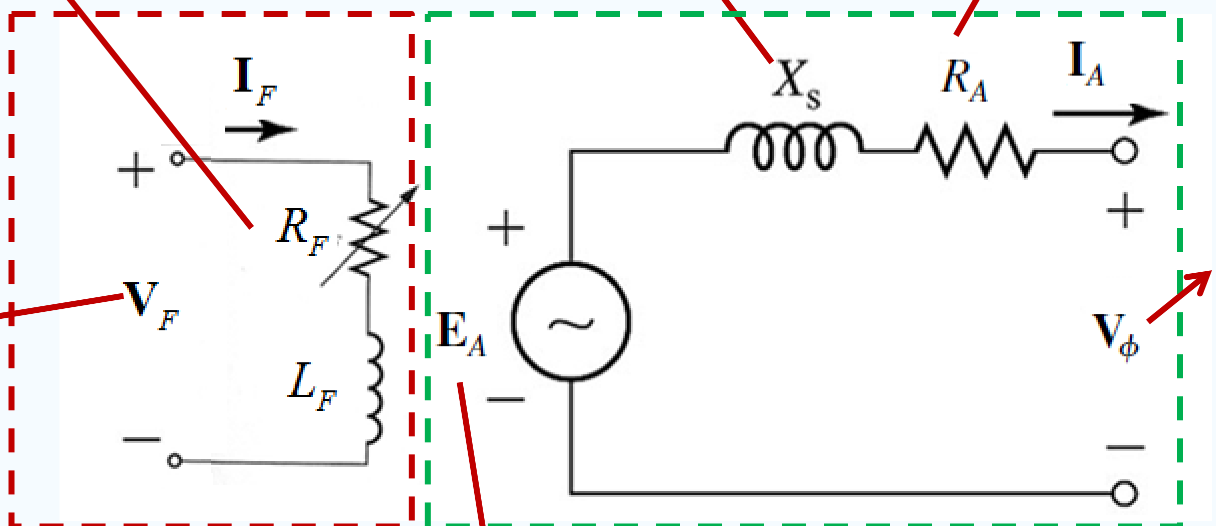
The Equivalent Circuit-Single Phase

Equivalent adjustable resistor of the field winding

Synchronous reactance

stator resistance

DC source



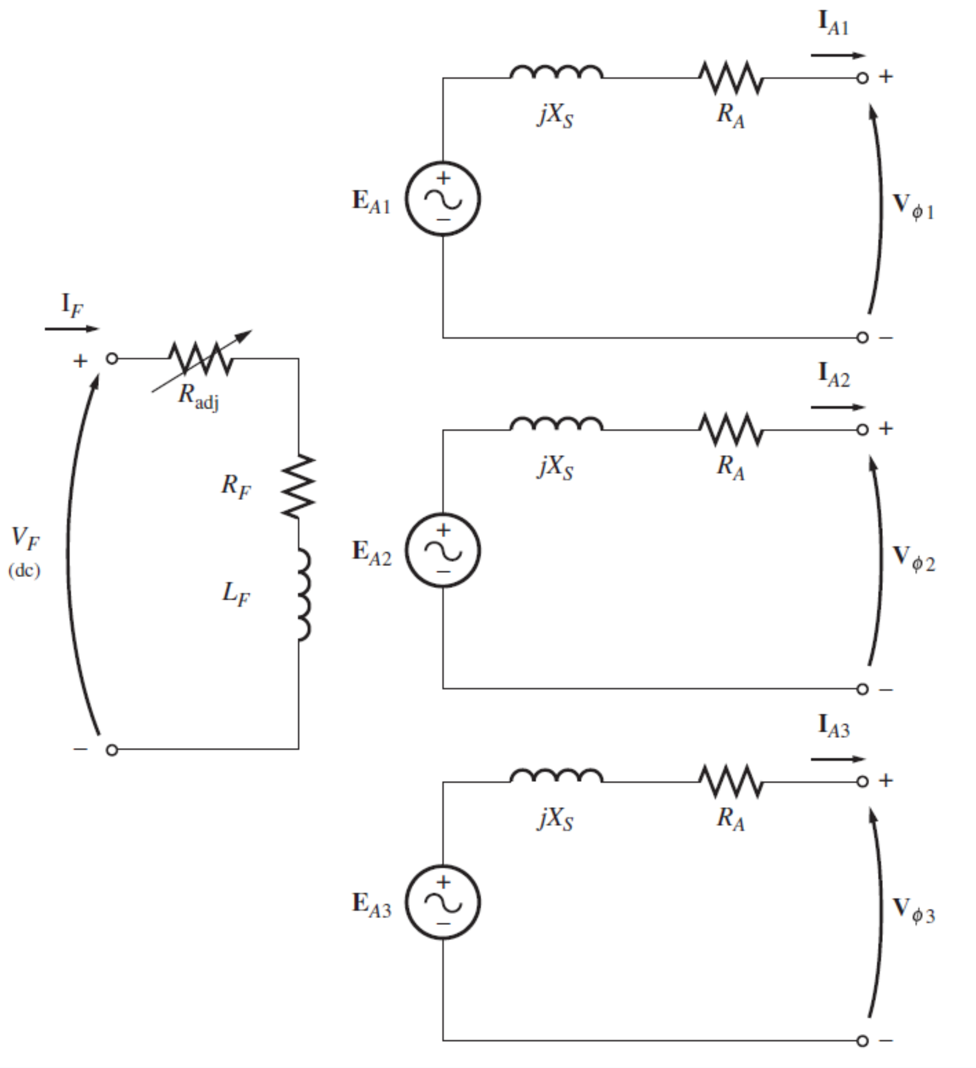
Terminal voltage of the phase

Field winding

Armature winding

Internal generated voltage

The Equivalent Circuit-Three Phase



Phase *a*

Phase *b*

Phase *c*

Example

The rotor of a six-pole synchronous generator is rotating at a mechanical speed of 1200 r/min.

(a)Express this mechanical speed in radians per second.

(b)What is the frequency of the generated voltage in hertz and in radians per second?

(c)What mechanical speed in revolutions per minute would be required to generate voltage at a frequency of 50 Hz?

Example

(a) Mechanical speed in radians per second.

$$\omega_m = \frac{n_m \times 2\pi}{60} = \frac{1200 \times 2\pi}{60} = 125.6 \ \text{rad/sec}$$

(b) The frequency of the generated voltage in hertz and in radians per second:

$$f_e = \frac{n_m P}{120} = \frac{1200 \times 6}{120} = 60 \quad \text{Hz}$$

$$\omega_{\mathrm{e}} = 2\pi f_e = 2\pi \times 60 = 376.8 \ \text{rad/sec}$$

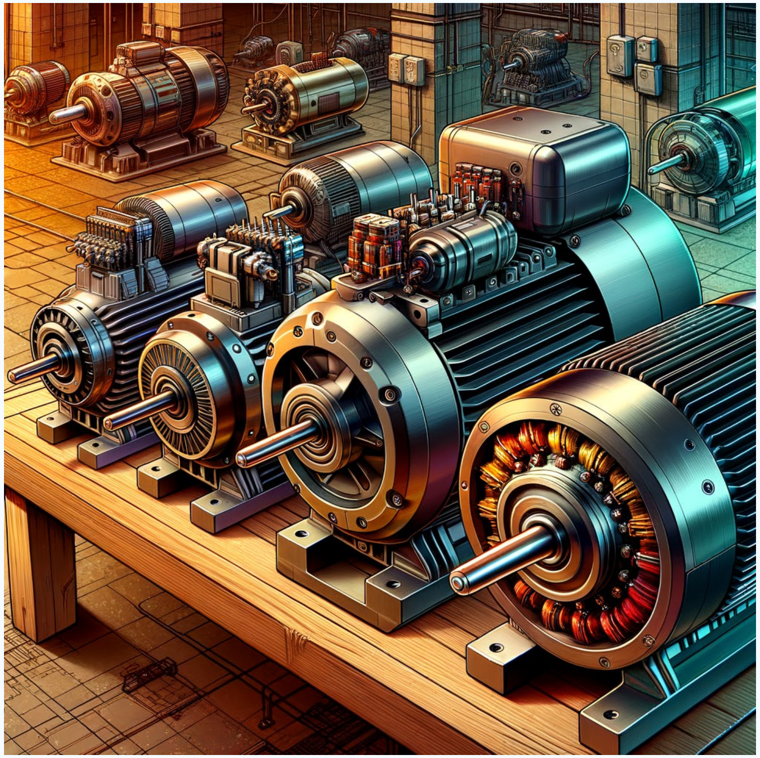
(c) Mechanical speed in revolutions per minute would be required to generate voltage at a frequency of 50 Hz:

$$n_m = \frac{120 f_e}{P} = \frac{120 \times 50}{6} = 1000 \ \text{r/min}$$

Summary

1. Efficiency and losses of AC machines
2. Power flow chart of AC machines
3. Voltage regulation and speed regulation
4. Induced voltage in a 3-phase set of coils
5. Synchronous Generator Construction
6. The Speed of Rotation of a Synchronous Generator
7. The Internal Generated Voltage of a Synchronous Generator
8. The Equivalent Circuit of a Synchronous Generator

Next



Synchronous/Induction Motors

Thanks for your attention