Xi'an Jiaotong-Liverpool University

EEE108 Electromagnetism and Electromechanics

Lecture 20

AC Machinery Fundamentals
Synchronous Generators

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Last Lecture

AC Machinery Fundamentals:

1. A simple loop in a uniform magnetic field

- The voltage induced in a simple rotating loop
- The torque induced in a current-carrying loop

2. The rotating magnetic field

- The rotating magnetic field concept
- Reversing the direction of magnetic field rotation
- The relationship between electrical frequency and the speed of magnetic field rotation $f_e = \frac{n_m P}{120}$

Today

AC Machinery Fundamentals:

- Induced voltage in AC machines
- Induced torque in AC machines
- Losses in AC machines
- Voltage regulation and speed regulation

Synchronous Machines

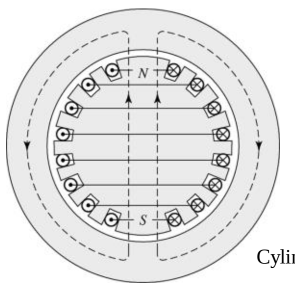
- Synchronous generators

Induced Voltage in AC Machines

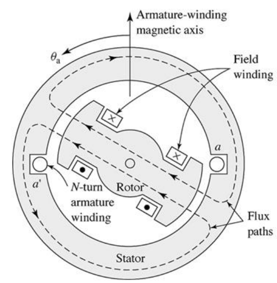
$$e_{ind} = \Phi_{\max}\omega \sin \omega t$$

For N turns:

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



Cylindrical rotor



Salient pole rotor

Induced Voltage in AC Machines

The Induced Voltage in a 3-Phase Set of Coils

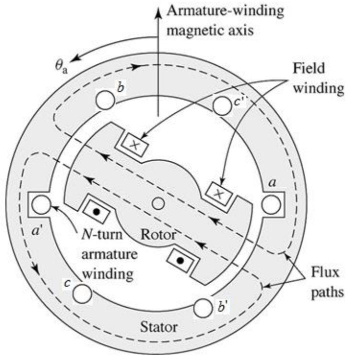
If the stator now has 3 sets of different windings as such that the stator voltage induced due to the rotating magnetic field produced by the rotor will have a phase difference of 120º, the induced voltages at each phase will be as follows:

$$e_{aa'} = N\Phi\omega_e \sin\omega_e t$$
$$e_{bb'} = N\Phi\omega_e \sin(\omega_e t - 120^0)$$
$$e_{cc'} = N\Phi\omega_e \sin(\omega_e t - 240^0)$$

where ω_e is electrical angular frequency

Φ is the short form of Φ_{max}

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



Induced Voltage in AC Machines

The Induced Voltage in a 3-Phase Set of Coils

The RMS voltage in a three-phase stator:

$$\boxed{\begin{aligned} e_{aa'} &= N\Phi\omega_e \sin\omega_e t \\ e_{bb'} &= N\Phi\omega_e \sin(\omega_e t - 120^0) \\ e_{cc'} &= N\Phi\omega_e \sin(\omega_e t - 240^0) \end{aligned}}$$

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:

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

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

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

4.44

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?

Solution

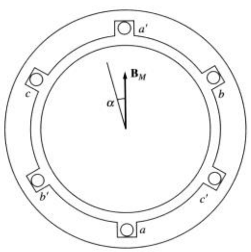
$$\boxed{\begin{aligned} e_{aa'} &= N\Phi\omega_e \sin\omega_e t \\ e_{bb'} &= N\Phi\omega_e \sin(\omega_e t - 120^0) \\ e_{cc'} &= N\Phi\omega_e \sin(\omega_e t - 240^0) \end{aligned}}$$

The flux in this machine is given by

$$\Phi = 2rlB = dlB = 0.5\times0.3\times0.2 = 0.03 \text{ Wb}$$

The rotor speed is

$$\omega = \frac{3600\times2\pi}{60} = 377 \text{ rad/s}$$



Induced Voltage in AC Machines

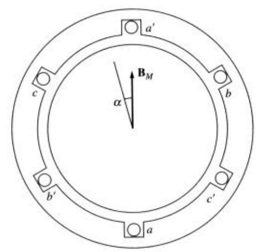
Example

a) The magnitude of the peak phase voltage is

$$E_{max} = N\Phi\omega = 15\times0.03\times377 = 169.7 \text{ V}$$

and the three phase voltages are:

$$e_{aa'}(t) = 169.7\sin(377t)$$
$$e_{bb'}(t) = 169.7\sin(377t - 120^0)$$
$$e_{cc'}(t) = 169.7\sin(377t - 240^0)$$



b) The rms voltage of the generator is

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

Induced Torque in AC Machines

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

In an AC machine under normal operating conditions two magnetic fields are present:

- a field from the rotor and
- a field from the stator circuits.

The interaction of these magnetic fields produces the torque in the machine.

The torque in an AC machine is dependent upon:

•Strength of rotor magnetic field
•Strength of stator magnetic field
•Angle between the 2 fields
•Machine constants – represent the construction of the machine

$$\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times \mathbf{B}_S \quad \text{with} \quad \mathbf{B}_{net} = \mathbf{B}_R + \mathbf{B}_S \quad \Rightarrow \quad \mathbf{B}_S = \mathbf{B}_{net} - \mathbf{B}_R$$

so the torque can be written as: $\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times (\mathbf{B}_{net} - \mathbf{B}_R) = k\mathbf{B}_R \times \mathbf{B}_{net}$

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

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

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:

$P_{SCL} = 3I^2{}_A R_A$ (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 Efficiency and Losses

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).

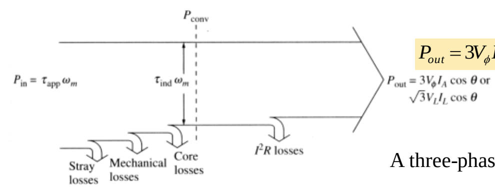
3. **Mechanical Losses**: There are two types of mechanical losses: friction (friction of the bearings) and windage (friction between the moving parts of the machine and the air inside the casing). These losses are often lumped together and called the no-load rotational loss of the machine. They vary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

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: $P_{conv} = \tau_{ind}\omega_m$

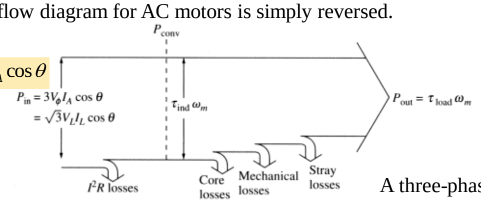


$P_{out} = 3V_\phi I_A \cos\theta$

A three-phase AC **generator**

Power-flow diagram for AC motors is simply reversed.

$P_{out} = 3V_\phi I_A \cos\theta$



A three-phase AC **motor**

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

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:

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

or

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

The magnitude of the speed regulation tells approximately how steep the slope of the torque-speed curve is.

Summary of AC Machinery Fundamentals

AC Machinery Fundamentals:

A simple loop in a uniform magnetic field

The rotating magnetic field

Induced voltage in AC machines

Induced torque in AC machines

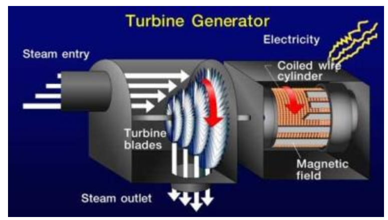
Losses in AC machines

Voltage regulation and speed regulation

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.

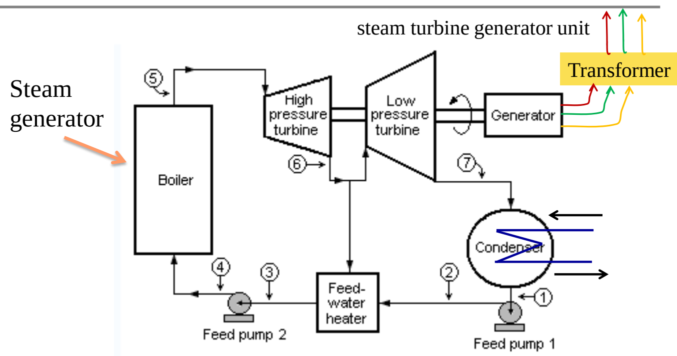


The commercial birth of the synchronous generator can be dated back to more than one hundred years ago.

Synchronous generators remained the universal machines of choice for the generation of electric power.

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.

Thermal-Power Plants



- Geothermic-sources
- Fuel of boilers: coal, oil, gas
- Nuclear reactors
- ….

Synchronous Generators Construction

The synchronous generator has two parts: Stator and Rotor

- 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.
- This rotating magnetic field induces a 3-phase set of voltages within the stator windings of the generator.
- The electrical frequency of the 3-phase output depends upon the mechanical speed and the number of poles.

"Field windings" applies to the windings that produce the main magnetic field in a machine. The field windings are on the rotor, so the terms "rotor windings" and "field windings" are used interchangeably.

"Armature windings" applies to the windings where the main voltage is induced. The armature windings are on the stator, so the terms "stator windings" and "armature windings" are used interchangeably.

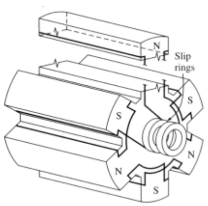
Advantage: having a single, low-power (low voltage and current) field winding on the rotor and the multiple-phase, high-power armature winding on the stator.

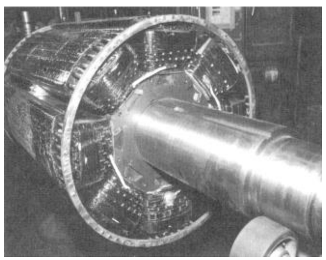
Synchronous Generator Construction

Salient Pole

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.

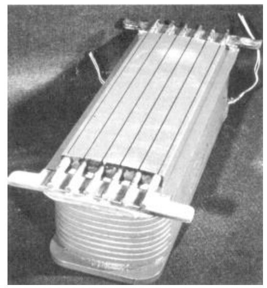
Salient Poles: are used for 4 or more poles rotor. All hydro-machines use salient pole construction as salient pole construction is less expensive.

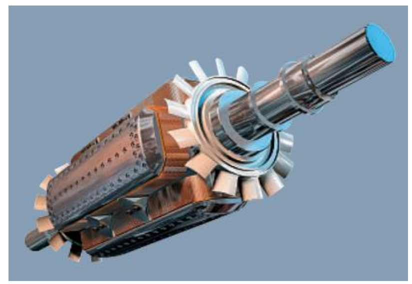




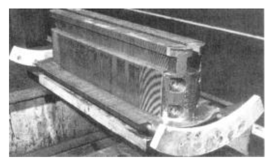
Synchronous Generator Construction

Salient Pole





Salient pole with field windings

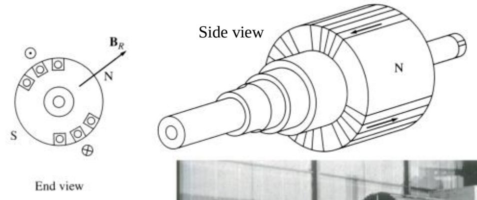


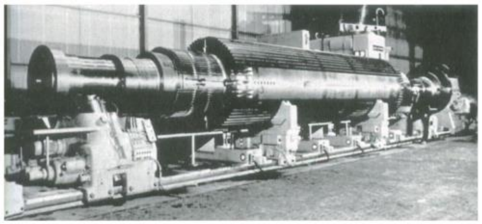
Salient pole without field windings

Synchronous Generator Construction

Non Salient Pole

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

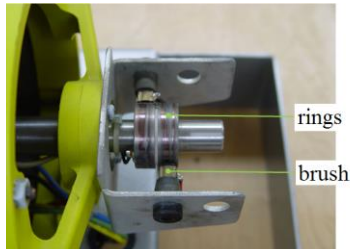
Synchronous Generator Construction

Field Winding

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.

The common ways are:

- Use slip rings and brushes to pass DC current to the rotor from a stationary circuit
  * 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.

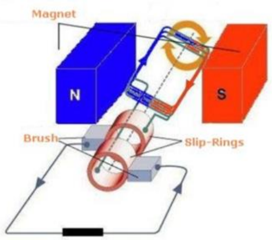


Synchronous Generator Construction

Slip Rings and Brush

Slip rings are metal rings completely encircling the shaft of a machine but insulated from it. One end of the DC rotor winding is tied to each of the 2 slip rings on the shaft of the synchronous machine, and a stationary brush rides on each slip ring.

A "**brush**" is a block of graphite like carbon compound that conducts electricity freely but has very low friction, hence it doesn't wear down the slip ring. If the positive end of a DC voltage source is connected to one brush and the negative end is connected to the other, then the same DC voltage will be applied to the field winding at all times regardless of the angular position or speed of the rotor.



Simplified diagram illustrating the slip-ring connection to the field winding

Synchronous Generator Construction

Slip Rings and Brush

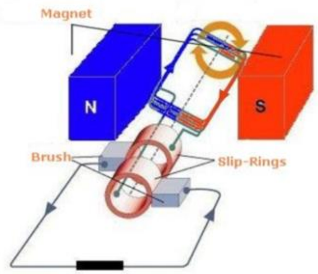
Some problems with slip rings and brushes:

-They increase the amount of maintenance required on the machine, since the brushes must be checked for wear regularly.

-Brush voltage drop can be the cause of significant power losses on machines with larger field currents.

-Small synchronous machines: use slip rings and brushes.

Larger machines: brushless exciters are used to supply the DC field current.



The Speed of Rotation of a Synchronous Generator

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.

$$f_e = \frac{n_m P}{120}$$

f_e: electrical frequency, in Hz

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

P: number of poles

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

50 Hz: UK, China

Non Salient Poles: are normally used for rotors with 2 or 4 poles rotor. All steam-turbine generator units use smooth rotor construction.

The Speed of Rotation of a Synchronous Generator

$$f_e = \frac{n_m P}{120} \qquad n_m = \frac{120 f_e}{P}$$

The surface speed of a 1 meter diameter rotor:
operating at 3600 RPM: about 210 m/s.
3000 RPM: about 167 m/s.

Salient poles incur very high mechanical stress and windage losses at this speed and therefore cannot be used.

All steam-turbine generator units use smooth rotor construction.

Nuclear plant: half RPM, due to big size of the rotor of the turbine.

Generally, high speeds is more efficient, most steam turbine generator units are 2 poles.

	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 Speed of Rotation of a Synchronous Generator

$$n_m = \frac{120 f_e}{P}$$

Hydro-turbines cannot achieve high speeds, they must use a higher number of poles, e.g., 24 and 32 pole hydro-machines are common. But because salient pole construction is less expensive, all hydro-machines use salient pole construction.

The Internal Generated Voltage

Voltage induced is dependent upon flux and speed of rotation, hence from what we have learnt so far, the induced voltage can be found as follows:

$$E_A = \underbrace{\sqrt{2}\pi}_{4.44} N_C \phi f$$

$$E_A = K\phi\omega$$

$$\theta_e = \frac{P}{2}\theta_m$$
$$f_e = \frac{P}{2} f_m$$
$$\omega_e = \frac{P}{2}\omega_m$$

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

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

The Equivalent Circuit of a Synchronous Generator
Armature Reaction

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

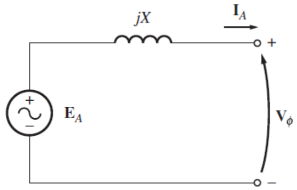
The armature reaction voltage is directly proportional to the current I_A. If X is a constant of proportionality, then the armature reaction voltage can be expressed as:

$$jX\mathbf{I}_A$$

Therefore:

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

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



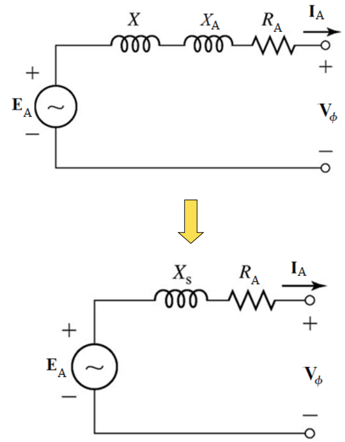
The Equivalent Circuit of a Synchronous Generator
Self inductance and Resistance

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:

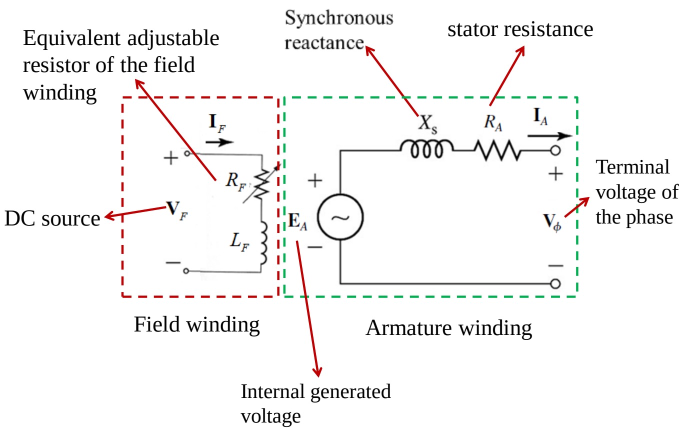
$$\mathbf{V}_\phi = \mathbf{E}_A - jX\mathbf{I}_A - jX_A\mathbf{I}_A - R_A\mathbf{I}_A$$
$$= \mathbf{E}_A - jX_s\mathbf{I}_A - R_A\mathbf{I}_A$$

Where $X_S = X + X_A$

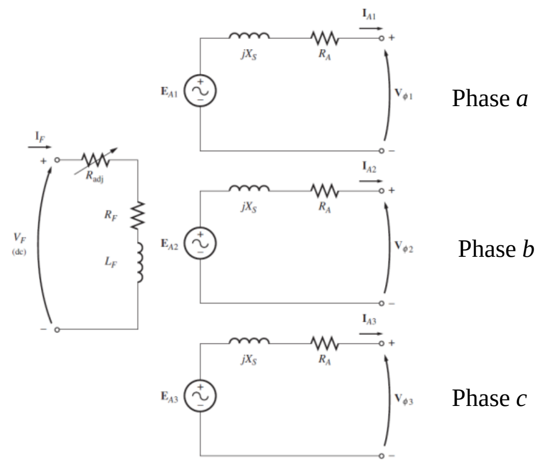
Synchronous reactance



The Equivalent Circuit of a Synchronous Generator
Single Phase

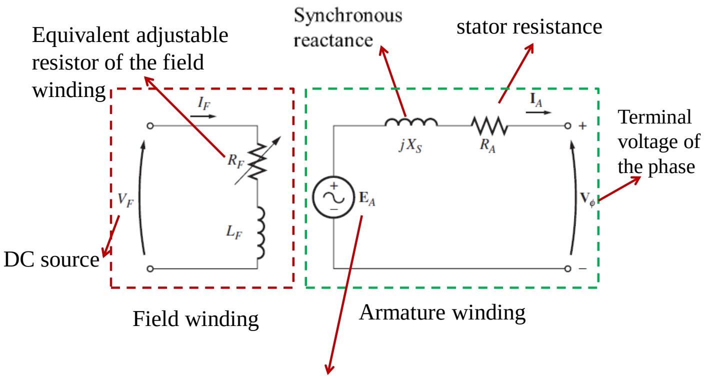


The Equivalent Circuit of a Synchronous Generator
Three-phase



The Equivalent Circuit of a Synchronous Generator

Per-phase



Per-phase equivalent circuit is used when the three-phase are balanced.

Power and Torque in Synchronous Generators

A generator converts mechanical energy into electrical energy, the input power will be a mechanical prime mover, e.g. diesel engine, steam turbine, water turbine or anything similar.

Not all the mechanical power going into a synchronous generator becomes electrical power out of the machine.

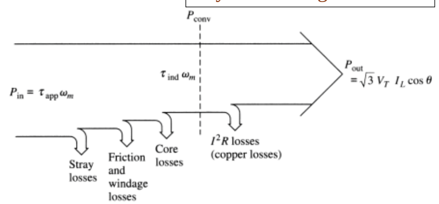
The applied mechanical power: $P_{in} = \tau_{app}\omega_m$

is partially converted to electricity:

$$P_{conv} = \tau_{ind}\omega_m = 3E_A I_A \cos\gamma$$

where γ is the angle between $\mathbf{E}_A$ and $\mathbf{I}_A$.

The power-flow diagram of a synchronous generator.



Power and Torque in Synchronous Generators

Power Factor

Input: $P_{in} = \tau_{app}\omega_m$

Losses: Stray losses, friction and windage losses, core loss

Converted power: $P_{conv} = \tau_{ind}\omega_m = 3E_A I_A \cos\gamma$

where γ is the angle between $\mathbf{E}_A$ and $\mathbf{I}_A$

Losses: Copper losses

The **real electrical output power**:

$P_{out} = \sqrt{3}V_L I_L \cos\theta$

or $P_{out} = 3V_A I_A \cos\theta$

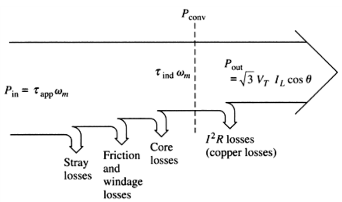
where θ is the angle between $\mathbf{V}_A$ and $\mathbf{I}_A$

The **reactive power output**:

$Q_{out} = \sqrt{3}V_L I_L \sin\theta$

or $Q_{out} = 3V_A I_A \sin\theta$

Power factor: $\cos\theta$



Synchronous Generator Summary

1. Synchronous Generator Construction
2. The Speed of Rotation of a Synchronous Generator
3. The Internal Generated Voltage of a Synchronous Generator
4. The Equivalent Circuit of a Synchronous Generator
5. Power and Torque in Synchronous Generator
6. Power factor

Next

- Synchronous Motors
- Induction Machines

Thanks for your attendance