EEE210:
Energy Conversion and Power Systems

Synchronous Generators

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Review of previous contents

[Electrical Grid 101 : All you need to know !]

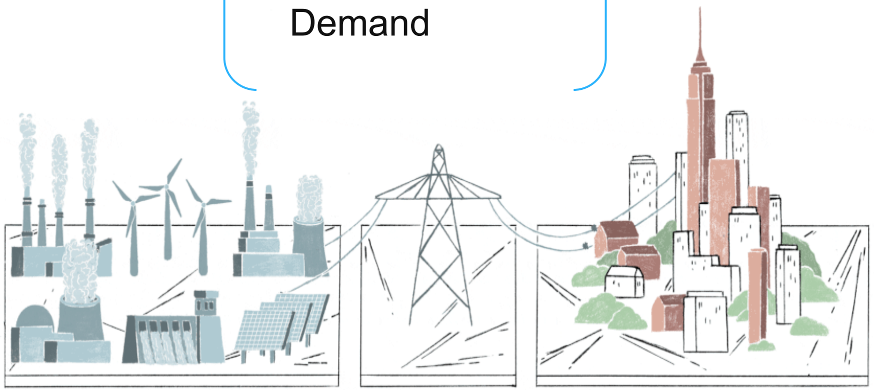
What is power system analysis?

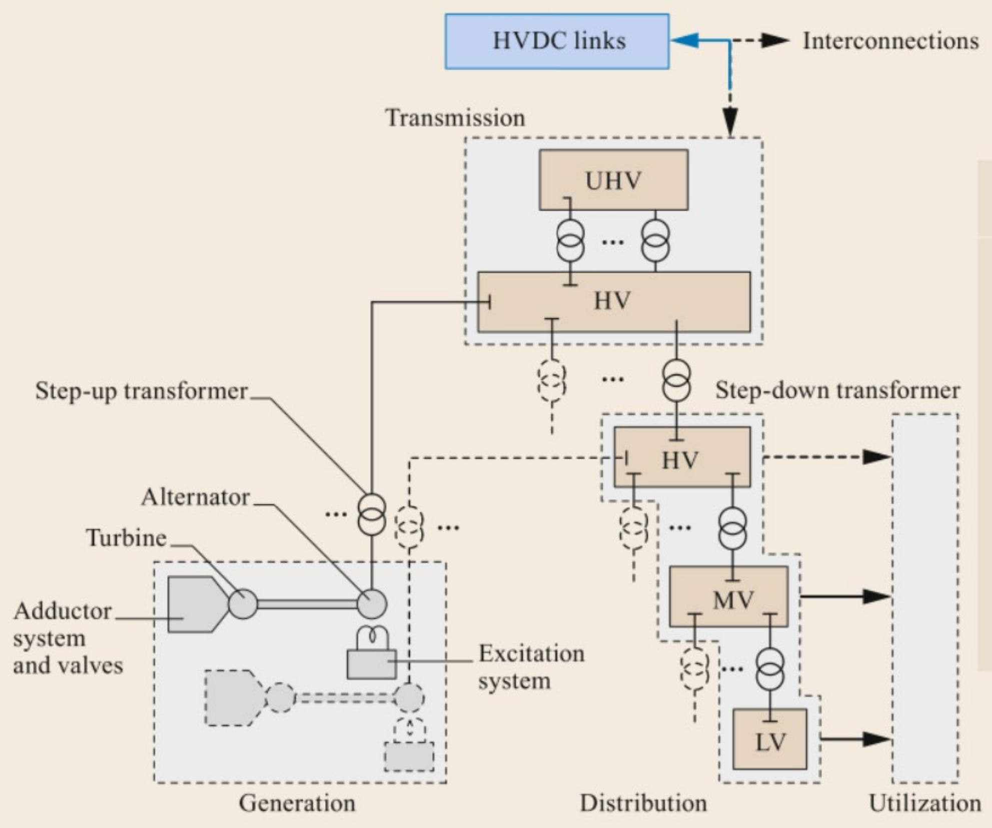
Study

- Generators
- Transformers
- Transmission lines
- Demand

Economical

Reliable





Overview of the last half of EEE210

- Models of generators and transformers for steady-state balanced operations.

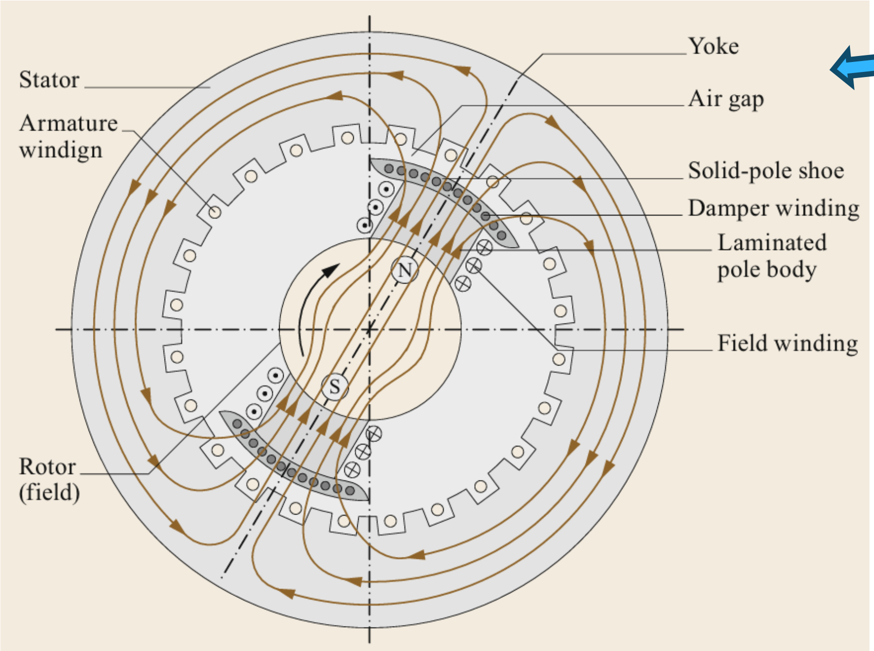
- One-line diagram of a power system showing generators, transformers, transmission lines, capacitors, reactors, and loads.

- The per-unit system and the impedance diagram on a common MVA base.

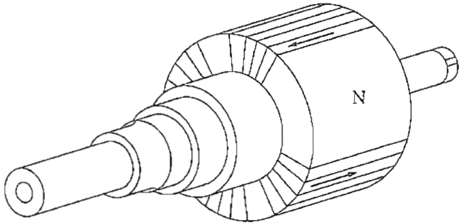
Synchronous Generators

1. Structure

[How alternating current motors work?]

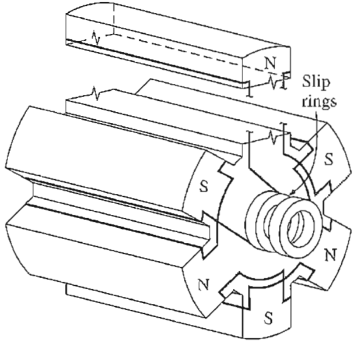


Nonsalient or Cylindrical rotor



The windings of the electromagnet are embedded in notches on the surface of the rotor.

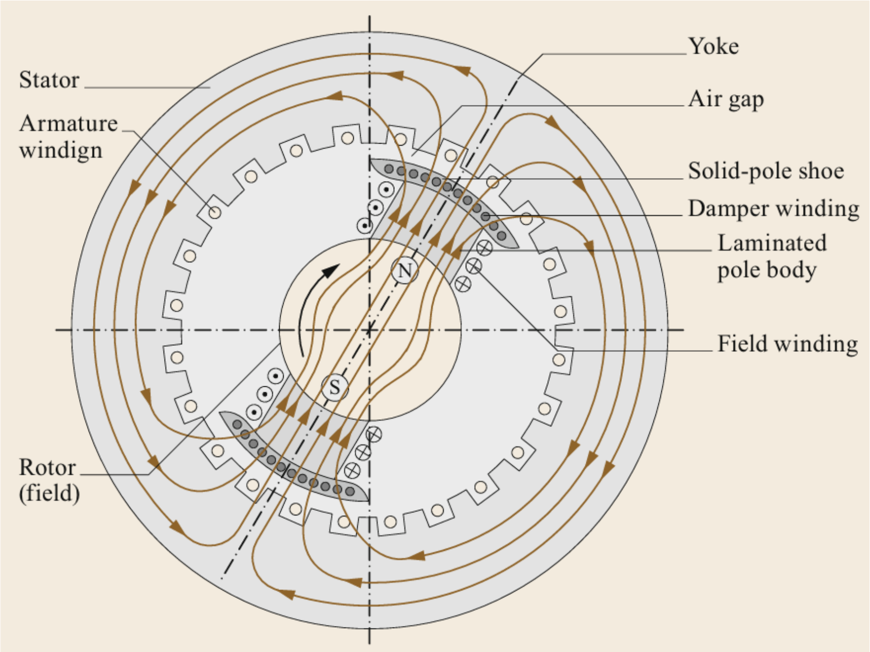
Salient rotor



The windings of the electromagnet are wrapped around the pole itself.

Synchronous Generators

1. Structure



Characteristics:

1. **Rotor** is normally selected to generate the magnetic field as a **permanent magnet** or by applying a **dc current** to a rotor winding to **create an electromagnet.**
2. This **rotating magnetic field induces a three-phase set of voltages** within the stator windings of the generator.

Specific terms:

1. **Field windings** applies to the windings that **produce the main magnetic** field in a machine. (Rotor windings)
2. **Armature windings** applies to the windings where **the main voltage is induced.** (Stator windings)

Synchronous Generators

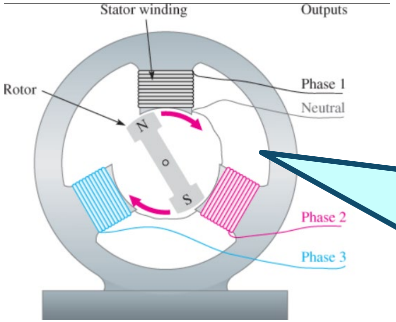
2. Speed

Why is the generator defined as synchronous?

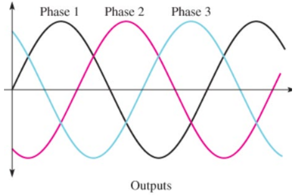
Generation

Demand

three-legged race



2 poles
50 Hz
Speed?



Rotating speed = Terminal voltage frequency = System voltage frequency

The electrical frequency produced is locked in or synchronized with the mechanical rate of rotation of the generator.

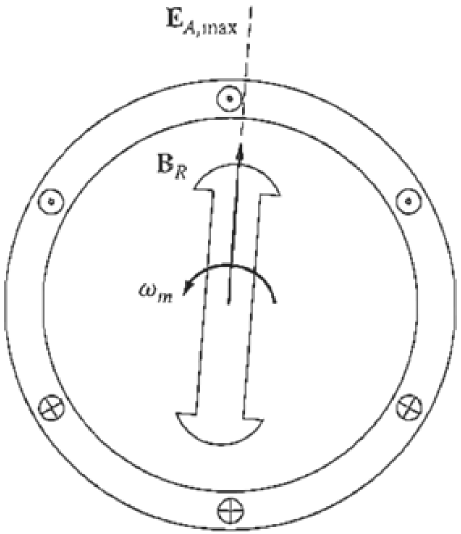
$$f = \frac{n_s P}{120}$$

f is the electrical frequency; n_s is the rotating speed of the generator (r/min); P is the number of poles

Synchronous Generators

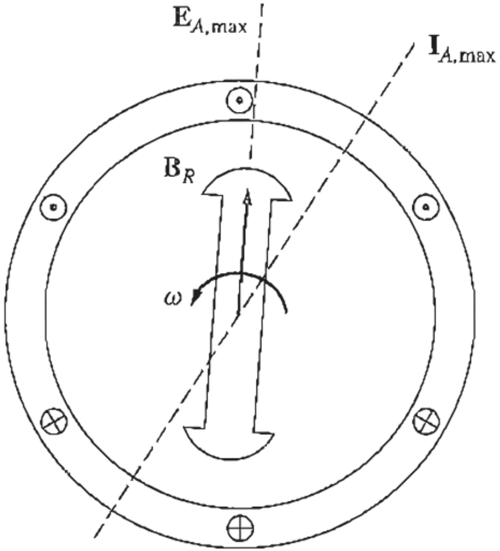
3. Working flows

a No load



- **No load** to the stator.
- The **rotor magnetic field** $\boldsymbol{B_R}$ produces an **internal generated voltage** $\boldsymbol{E_A}$ with a peak in the same direction of B_R
- The voltage **positive out** of the conductors at the **top** and **negative into** the conductors at the **bottom**. With no load, there is no armature current, and $\boldsymbol{E_A} = \boldsymbol{V_A}$ (phase voltage) .

b Lagging load

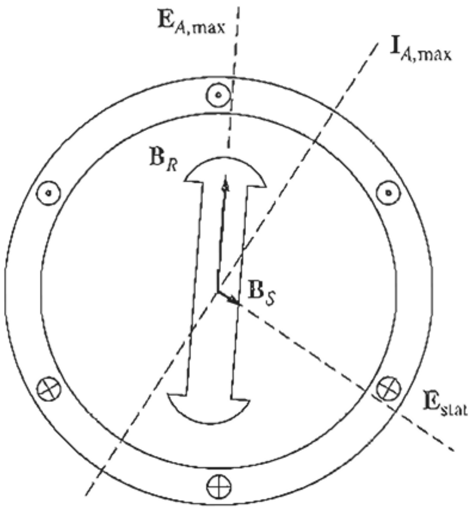


Because the load is lagging, the peak current $\boldsymbol{I_{A.max}}$ will occur at an angle behind the peak voltage.

Synchronous Generators

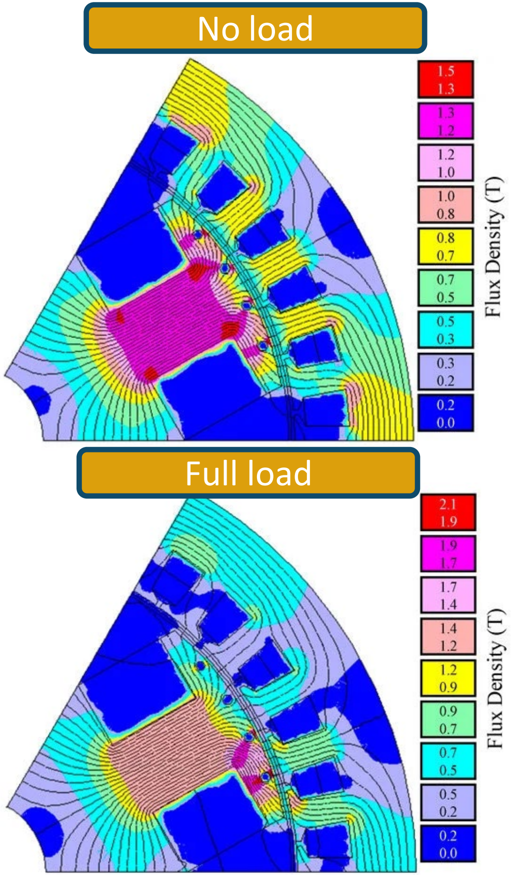
3. Working flows

c Armature reaction



- The current flowing in the stator windings produces a magnetic field of its own.
- This stator magnetic field is called $\boldsymbol{B_S}$ and its direction is given by the right hand rule.
- The stator magnetic field $\boldsymbol{B_S}$ produces a voltage of its own in the stator, and this voltage is called $\boldsymbol{E_{Stat}}$.

The simulated armature reaction by FEA

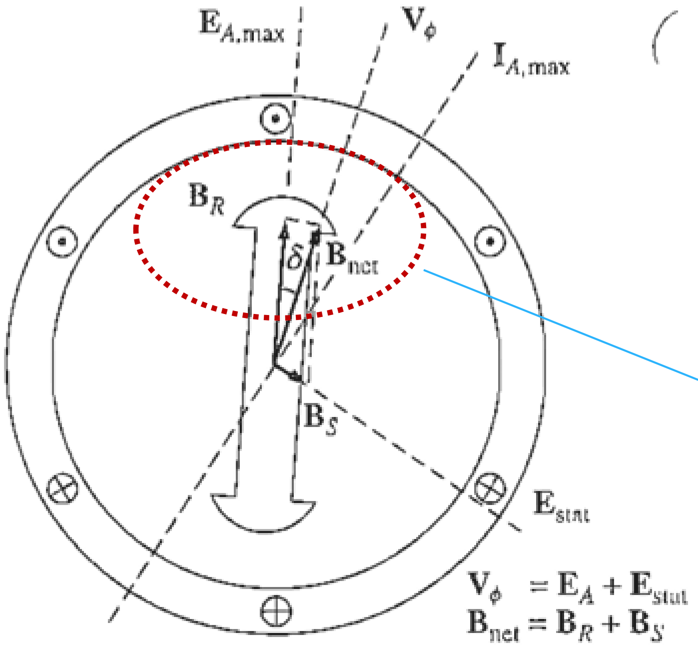


Bazzo, T.d.P.M.; Moura, V.d.O.; Carlson, R. A Step-by-Step Procedure to Perform Preliminary Designs of Salient-Pole Synchronous Generators. Energies 2021, 14, 4989.

Synchronous Generators

3. Working flows

d Terminal voltage



With two voltages present in the stator windings, the terminal voltage in a phase is just the sum of the internal generated voltage $\boldsymbol{E_A}$ and the armature reaction voltage $\boldsymbol{E_{Stat}}$.

$$\boldsymbol{V_A = E_A + E_{Stat}}$$

The net magnetic field $\boldsymbol{B_{net}}$ is given by:

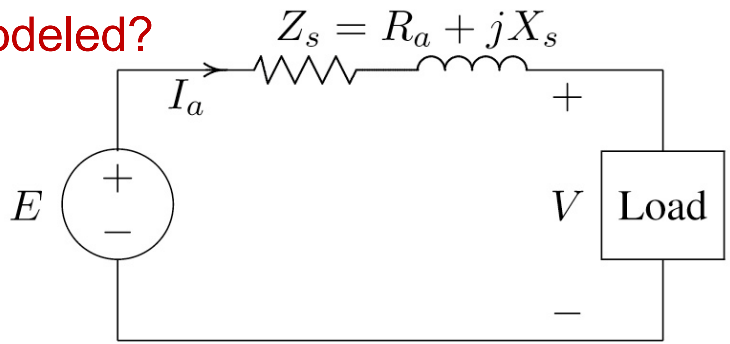
$$\boldsymbol{B_{net} = B_R + B_S}$$

The angle $\boldsymbol{\delta}$ between $\boldsymbol{B_R}$ and $\boldsymbol{B_{net}}$ is known as the **internal angle** or **torque angle** or **power angle** for the machine. The large of this angle, the greater of the generated power (before losing synchronous).

Synchronous Generators

4. Equivalent circuit

How can the effects of armature reaction on the phase voltage be modeled?



- The voltage $\boldsymbol{E_{Stat}}$ lies at an angle of 90° behind the plane of maximum current $\boldsymbol{I_A}$

  Same effect as reactance

- The voltage $\boldsymbol{E_{Stat}}$ is directly proportional to the current $\boldsymbol{I_A}$

$$\boldsymbol{E_{Stat} = -jX_A * I_A}$$

$\boldsymbol{X_A}$ is the equivalent armature reactance

- The terminal voltage:

$$\boldsymbol{V_A = E_A - jX_A * I_A}$$

In addition to the effects of armature reaction, the stator coils have a self inductance $\boldsymbol{X_{si}}$ and an armature resistance $\boldsymbol{R_s}$

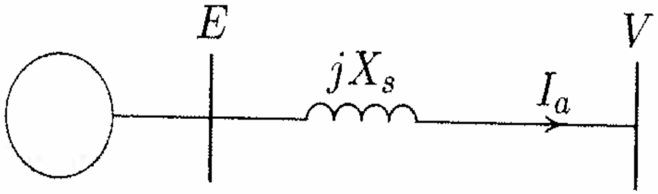
$$\boldsymbol{V_A = E_A - jX_A * I_A - jX_{si} * I_A - R_s * I_A}$$

Voltage Drops

$$\boldsymbol{V_A = E_A - jX_s * I_A - R_s * I_A}$$

where $\boldsymbol{X_s = X_A + X_{si}}$ is the synchronous reactance.

In reality, the armature resistance is much smaller than the synchronous reactance and is often neglected.



Synchronous Generators

5. Generation control: principle

Max power before losing synchronous:

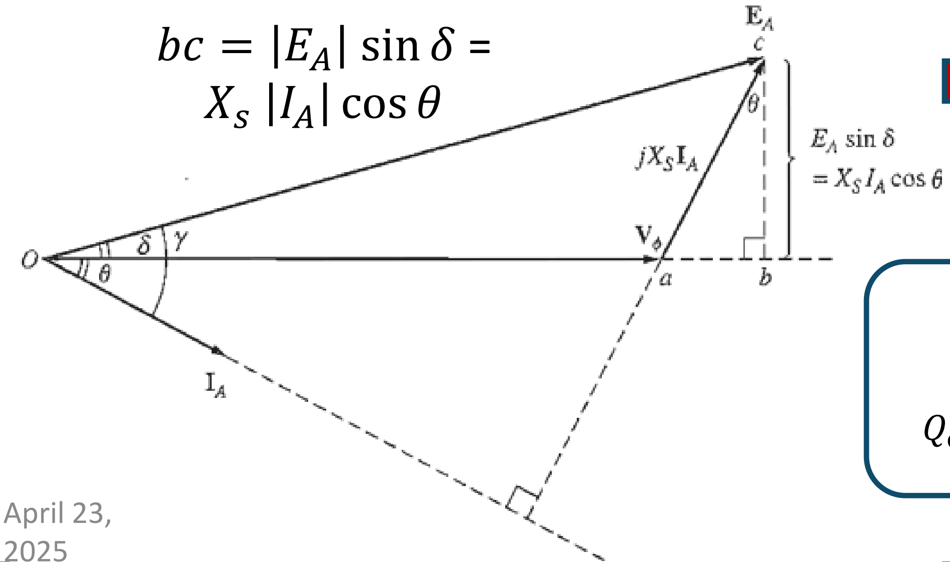
$$P_{\text{out.}max} = \frac{3|V_A||E_A|}{X_s}$$

What could be generated? What could be controlled?

Active power
Reactive power

Excitation system
Speed

$bc = |E_A| \sin\delta = X_s\,|I_A| \cos\theta$



$$P_{\text{out}} = 3|V_A||I_A| \cos\theta$$
$$Q_{\text{out}} = 3|V_A||I_A| \sin\theta$$

Change θ and power factor of the generator

$$P_{\text{out}} = \frac{3|V_A||E_A|}{X_s} \sin\delta$$

$$Q_{\text{out}} = \frac{3|V_A|}{X_s}(|E_A|\cos\delta - |V_A|)$$

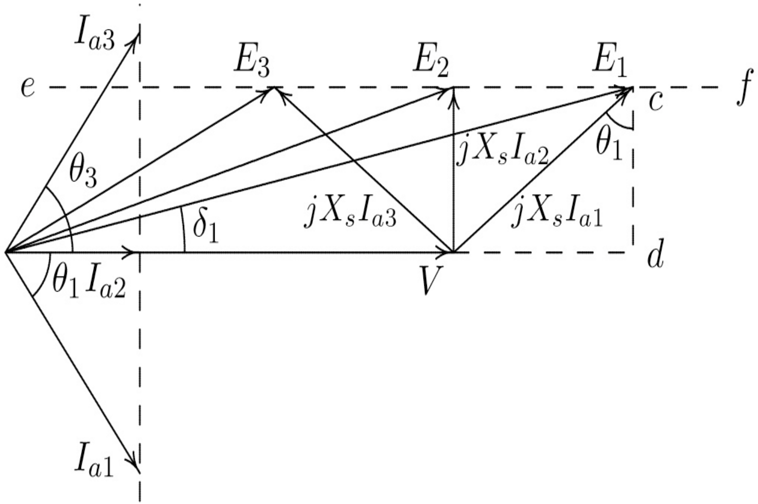
If terminal voltage is constant

E_A is the control variable

Synchronous Generators

5. Generation control: case analysis

Reactive power control with **constant Active Power**



$$V_A = E_A - jX_s * I_A$$

If the active power is constant:

$$P_{\text{out}} = \frac{3|V_\phi||E_A|}{X_s}\sin\delta$$

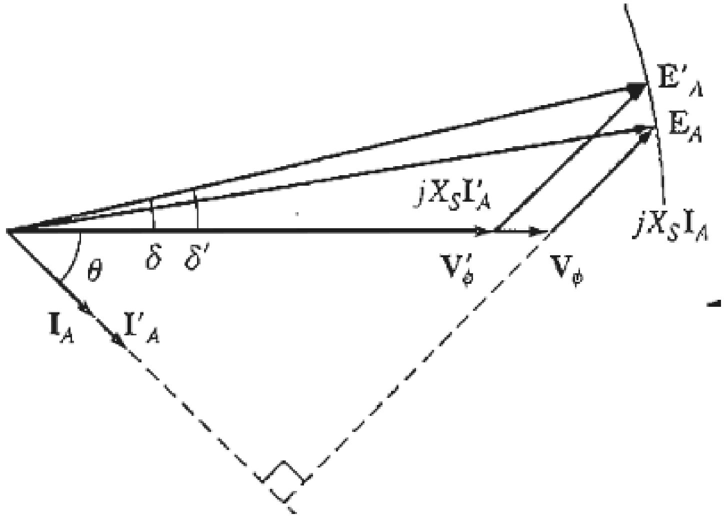
- I_{a1} ~~ $\theta < 0$ lagging power factor;
- I_{a2} ~~$\theta = 0$; pf = 1;
- I_{a3} ~~$\theta > 0$ leading power factor;

E_A could be specifically controlled to locus on the line *ef* to generate different reactive power, while active power is constant.

Synchronous Generators

5. Generation control: case analysis

Demand increase with **constant speed and internal generated voltage**



Demand is lagging;
Demand increases from I_a to I'_a at the same power factor angle θ;
$|E_A|$ is constant;

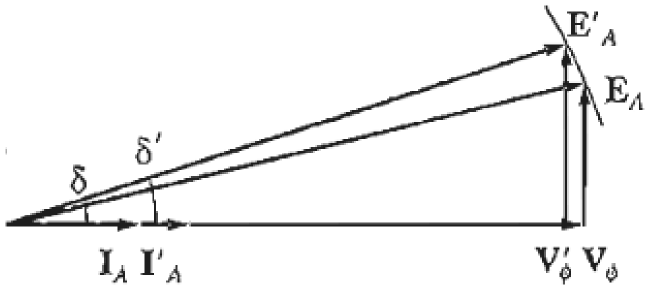
Lead to:

Power angle $\boldsymbol{\delta}$ increases to $\boldsymbol{\delta}'$;
Terminal voltage reduces from $V_\emptyset$ to $V'_\emptyset$

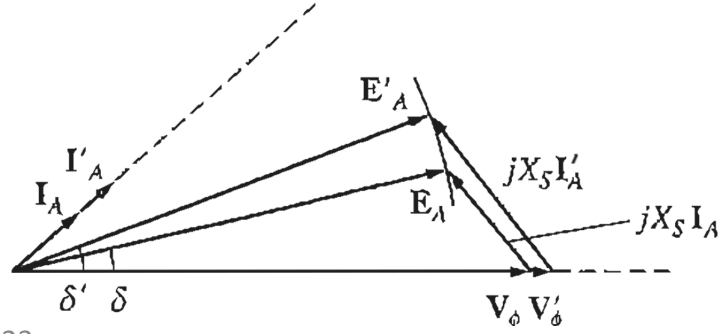
Synchronous Generators

5. Generation control: case analysis

Demand increase with **constant speed and internal generated voltage**



Unity-power factor;
Demand increases from I_a to I_a';
$|E_A|$ is constant;
Lead to:
Power angle $\boldsymbol{\delta}$ increases to $\boldsymbol{\delta}'$;
Terminal voltage reduces from $V_\emptyset$ to $V_\emptyset'$

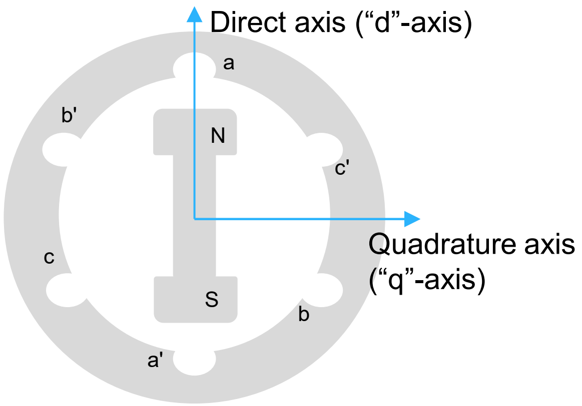


Demand is leading;
Demand increases from I_a to I_a' at the same power factor angle θ;
$|E_A|$ is constant;
Lead to:
Power angle $\boldsymbol{\delta}$ increases to $\boldsymbol{\delta}'$;
Terminal voltage increases from $V_\emptyset$ to $V_\emptyset'$

Synchronous Generators

6. Salient Pole Synchronous Generator

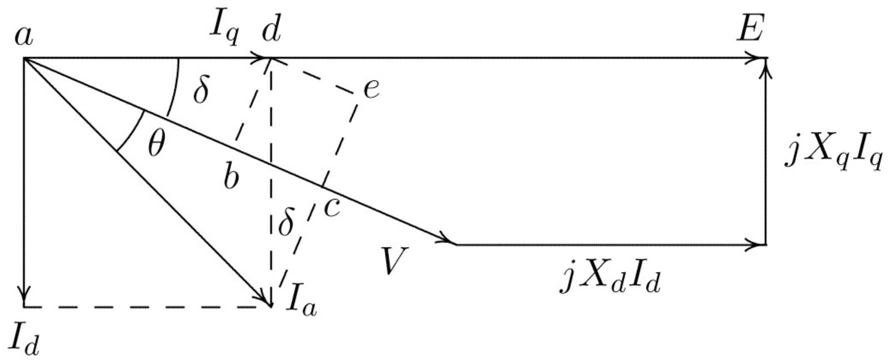
Compared to non-salient pole generator, the airgap is non-uniform for the salient pole generators.



Airgap	Reluctance	Reactance
$A_d < A_q$	$R_{m,d} < R_{m,q}$	$X_d > X_q$

To derive **the armature reaction** induced voltage drop:

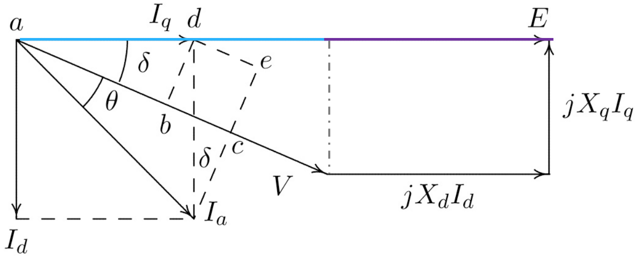
- Normally, the armature current per phase is decomposed into two components
  - ✓ I_d, along the direct axis,
  - ✓ I_q, along the quadrature axis
- I_d will induce higher voltage than I_q in the quadrature direction, since $X_d > X_q$



Synchronous Generators

6. Salient Pole Synchronous Generator

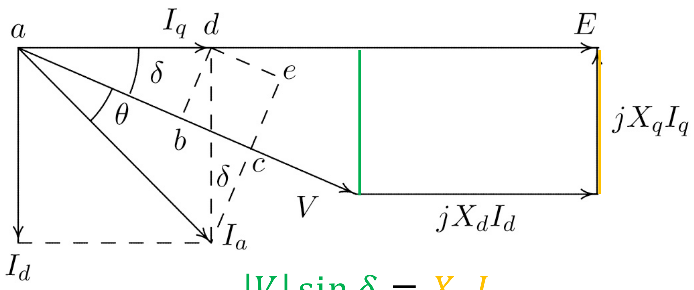
How to derive the output power?



The excitation voltage E is given by

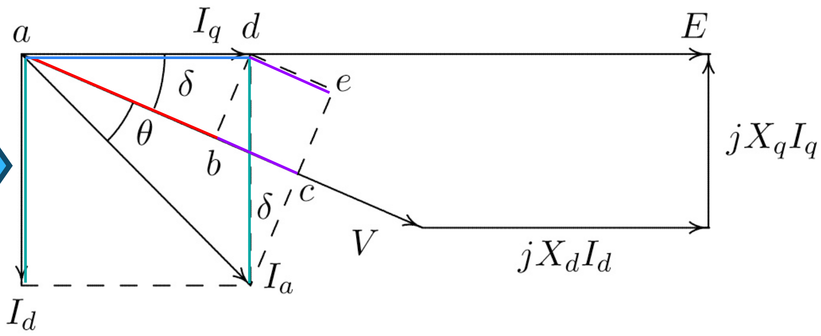
$$|E| = |V|\cos\delta + X_d I_d$$

Or $$I_d = \frac{|E| - |V|\cos\delta}{X_d}$$



$$|V|\sin\delta = X_q I_q$$

Or $$I_q = \frac{|V|\sin\delta}{X_q}$$



The three-phase real power at the generator terminal is

$$P_{3\emptyset} = 3|V||I_a|\cos\theta$$

The armature current I_a can be decomposed into I_d and I_q as follows.

$$|I_a|\cos\theta = ab + de$$
$$= I_q\cos\delta + I_d\sin\delta$$

Synchronous Generators

6. Salient Pole Synchronous Generator

How to derive the output power?

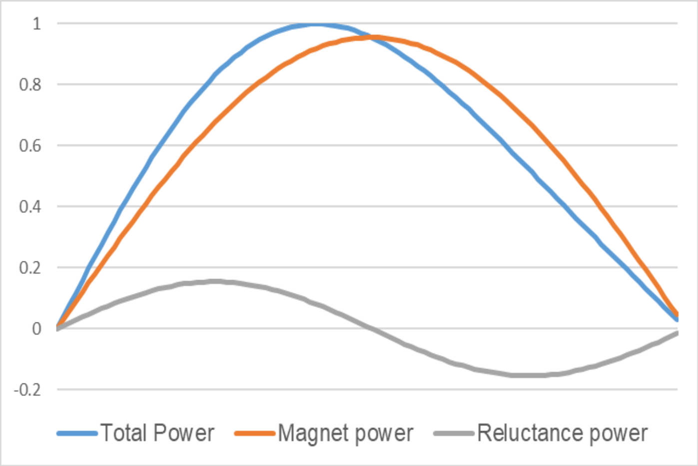
By taking $|\mathrm{I_a}|\cos\theta$ into $\mathrm{P}_{3\emptyset} = 3|\mathrm{V}||\mathrm{I_a}|\cos\theta$:

$$\mathrm{P}_{3\emptyset} = 3|\mathrm{V}|\left(I_d \sin\delta + I_q \cos\delta\right)$$

Substituting the equation of $\mathrm{I_d}, \mathrm{I_q}$ into $\mathrm{P}_{3\emptyset}$

$$\mathrm{P}_{3\emptyset} = 3\frac{|V||E|}{X_d}\sin\delta + \boxed{3\,|V|^2\frac{X_d - X_q}{2X_d X_q}\sin 2\delta}$$

Reluctance Power



- Reluctance power is at frequency twice that of the Magnet power
- The total power-angle relationship is changed from a perfect sinusoid

Synchronous Generators

7. Example question

A 50-MVA, 30-kV, three-phase, 60-Hz synchronous generator has a synchronous reactance of 9 Ω per phase and a negligible resistance. The generator is delivering rated power at a 0.8 power factor lagging at the rated terminal voltage to an infinite bus.

1. Determine the excitation voltage per phase E and the power angle δ
2. With the excitation held constant at the value found in (a), the driving torque is reduced until the generator is delivering 25 MW. Determine the armature current and the power factor.
3. If the generator is operating at the excitation voltage of part (a), what is the steady-state maximum power the machine can deliver before losing synchronism?

Synchronous Generators

7. Example question

A 50-MVA, 30-kV, three-phase, 60-Hz synchronous generator has a synchronous reactance of 9 Ω per phase and a negligible resistance. The generator is delivering rated power at a 0.8 power factor lagging at the rated terminal voltage to an infinite bus.

Known parameters from the description:

- The magnitude of the apparent power: S = 50 MVA;
- The magnitude of the rated voltage: V = 30 kV;
- Synchronous reactance: $X_s = 9\ \Omega$
- Armature reactance: R_a = 0
- The frequency: f = 60Hz
- Power factor: pf = 0.8 lagging

Synchronous Generators

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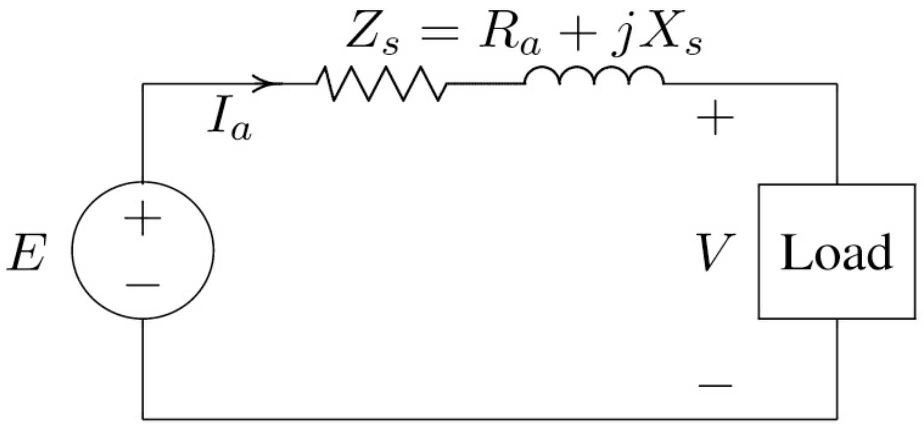
A 50-MVA, 30-kV, three-phase, 60-Hz synchronous generator has a synchronous reactance of 9 Ω per phase and a negligible resistance. The generator is delivering rated power at a 0.8 power factor lagging at the rated terminal voltage to an infinite bus.

1. Determine the excitation voltage per phase E and the power angle δ
   - Given the **per phase equivalent circuit** and the relationship between the excitation voltage E and terminal voltage V:

- $E_a = V_a + (R_a + jX_s)I_a$
- $V_a = V/\sqrt{3}$
- $S = 3V_a I_a^*$



Synchronous Generators

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A 50-MVA, 30-kV, three-phase, 60-Hz synchronous generator has a synchronous reactance of 9 Ω per phase and a negligible resistance. The generator is delivering rated power at a 0.8 power factor lagging at the rated terminal voltage to an infinite bus.

1. Determine the excitation voltage per phase E and the power angle δ

- $E_a = V_a + jX_s I_a = j9 * I_a$
- $V_a = \frac{V}{\sqrt{3}} = 17.32 + j0$
- $I_a = \frac{S^*}{3V_a} = \frac{S^*}{3*\frac{V}{\sqrt{3}}} = \frac{S\cos(\theta)-jS\sin(\theta)}{3*(17.32+j0)} = \frac{40-j30}{51.96} = 0.771 - j0.575$ kA

* $\theta = \arccos(pf)$

$\therefore E_a = V_a + jX_s I_a = 17.32 + j9 * (0.771 - j0.575)$

$= 22.49 + j6.95 = 23.5\angle 17.1°$ kV

Synchronous Generators

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A 50-MVA, 30-kV, three-phase, 60-Hz synchronous generator has a synchronous reactance of 9 Ω per phase and a negligible resistance. The generator is delivering rated power at a 0.8 power factor lagging at the rated terminal voltage to an infinite bus.

2. With the excitation held constant at the value found in (a), the driving torque is reduced until the generator is delivering 25 MW. Determine the armature current and the power factor.

- $P_G = 3\frac{|V_a||E_a|}{X_s}\sin\delta$
- $E_a = |E_a|\angle\delta = V_a + (R_a + jX_s)I_a$

$$\therefore\ I_a = \frac{|E_a|\angle\delta - V_a}{jX_s} = \frac{|E_a|\angle\arcsin\left(\frac{P_G X_s}{3|V_a||E_a|}\right) - V_a}{jX_s} = \frac{23.5\angle 10.59° - 17.32}{j9}$$

$$= 0.481 - j0.647 = 0.807\angle -54.43°\ \text{kA}$$

$$\theta = 0 - (-54.43) = 54.43$$

$$pf = \cos(54.43°) = 0.594$$

Synchronous Generators

7. Example question

A 50-MVA, 30-kV, three-phase, 60-Hz synchronous generator has a synchronous reactance of 9 Ω per phase and a negligible resistance. The generator is delivering rated power at a 0.8 power factor lagging at the rated terminal voltage to an infinite bus.

3. If the generator is operating at the excitation voltage of part (a), what is the steady-state maximum power the machine can deliver before losing synchronism?

- $P_G = 3\frac{|V_a||E_a|}{X_s}\sin\delta$
- Theoretically when $\sin\delta = 1$, P_G is at the maximal.
-

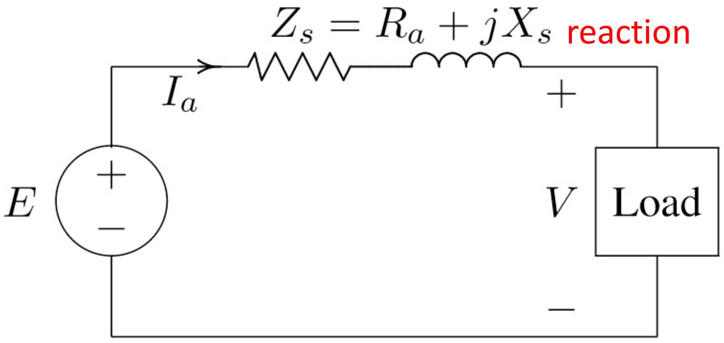
$$\therefore P_G = 3\frac{|V_a||E_a|}{X_s} = 3\frac{17.32\times 23.5}{9} = 136\ \text{MW}$$

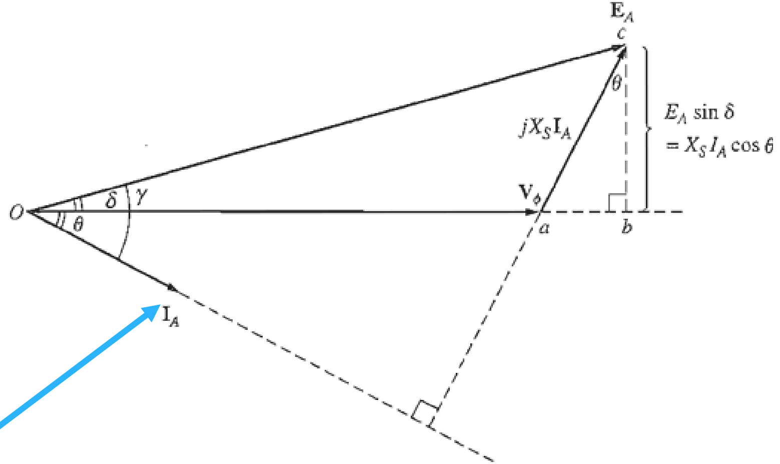
Synchronous Generators

8. Keys

Nonsalient or Cylindrical rotor

Armature reaction





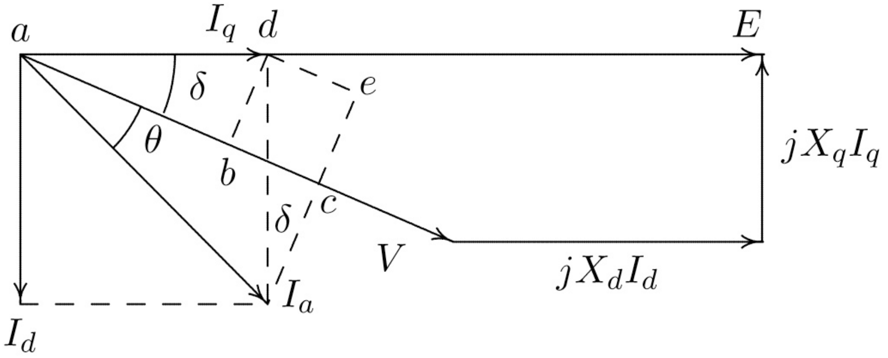
$$P_{\text{out}} = \frac{3|V_A||E_A|}{X_s} \sin\delta$$

$$Q_{\text{out}} = \frac{3|V_A|}{X_s}(|E_A|\cos\delta - |V_A|)$$

Max power before losing synchronous:

$$P_{out.max} = \frac{3|V_A||E_A|}{X_s}$$

Salient rotor



$$P_{3\emptyset} = 3\frac{|V||E|}{X_d}\sin\delta + 3\,|V|^2\frac{X_d - X_q}{2X_d X_q}\sin 2\delta$$