Lecture Notes
ELE-B7

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Synchronous Machine

Classification of AC Rotating Machines

- **Synchronous Machines:**
- **Synchronous Generators:** A primary source of electrical energy.

- **Synchronous Motors:** Used as motors as well as power factor compensators (synchronous condensers).

- **Asynchronous (Induction) Machines:**
- **Induction Motors:** Most widely used electrical motors in both domestic and industrial applications.
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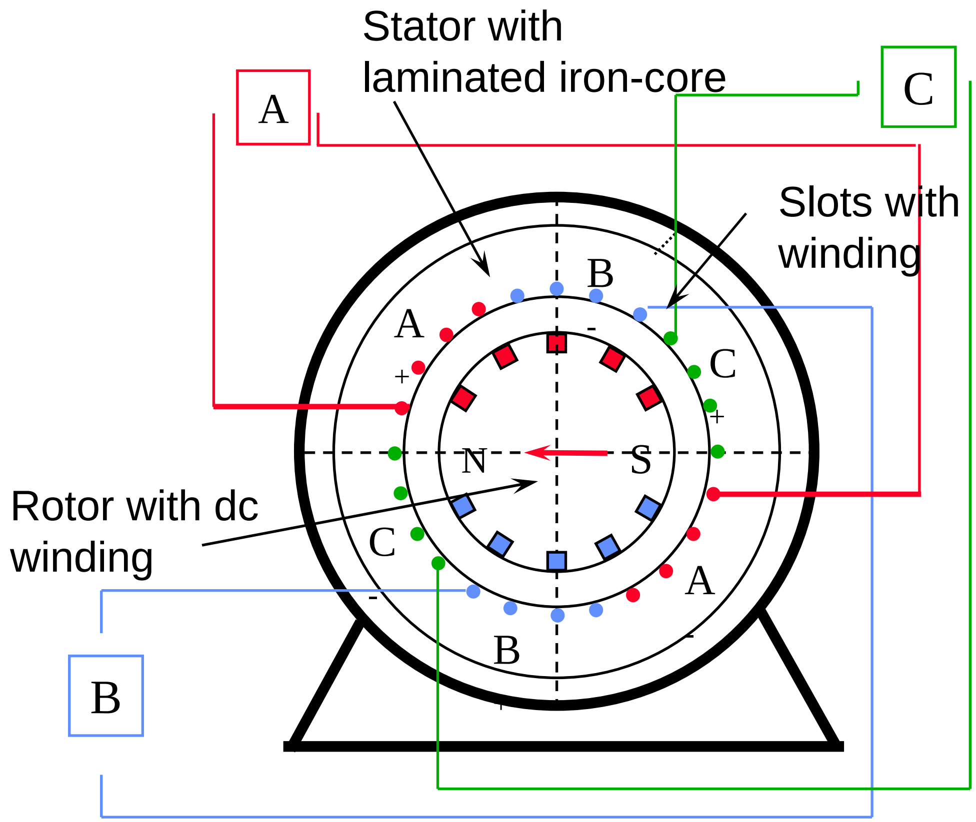
- **Induction Generators:** Due to lack of a separate field excitation, these machines are rarely used as generators.

SYNCHRONOUS MACHINES

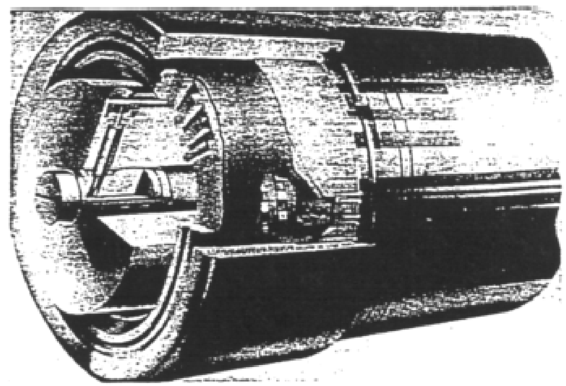
Round Rotor Machine

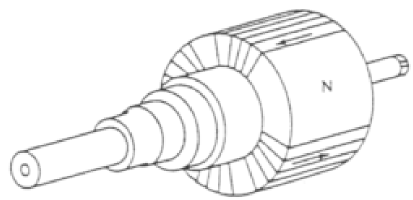
- **The stator is a ring shaped laminated iron-core with slots.**
- **Three phase windings are placed in the slots.**
- **Round solid iron rotor with slots.**
- **A single winding is placed in the slots. Dc current is supplied through slip rings.**

Concept (two poles)

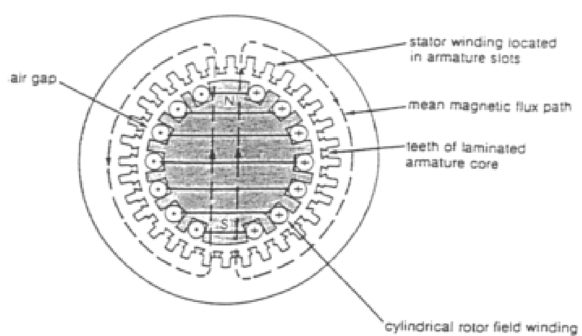


Round Rotor Machine





Side view

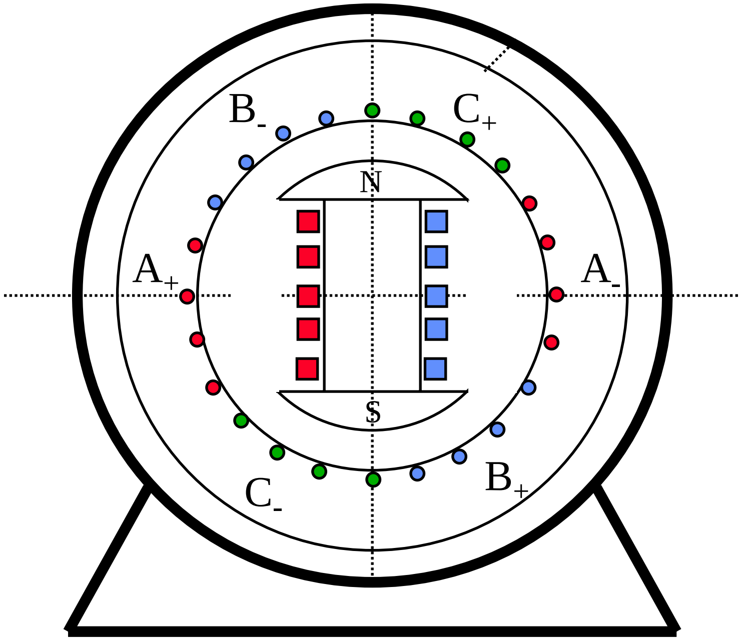


SYNCHRONOUS MACHINES

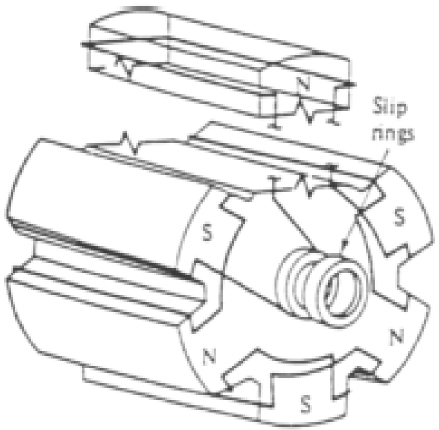
Salient Rotor Machine

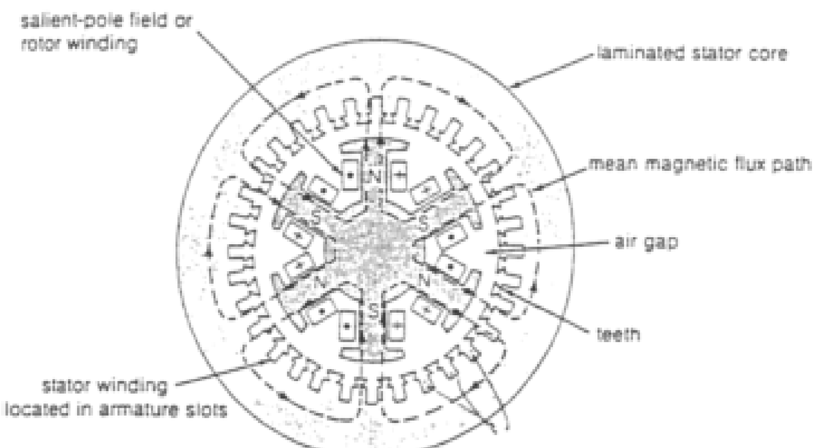
- **The stator has a laminated iron-core with slots and three phase windings placed in the slots.**
- **The rotor has salient poles excited by dc current.**
- **DC current is supplied to the rotor through slip-rings and brushes.**

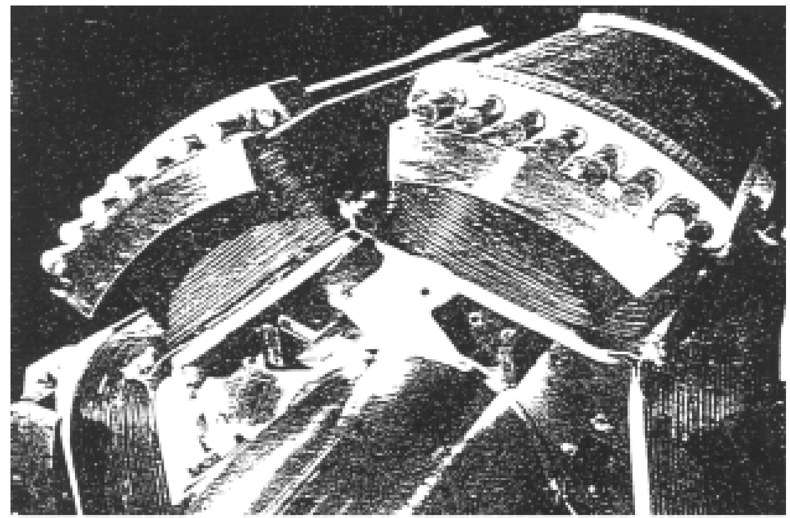
- **Concept (two poles)**

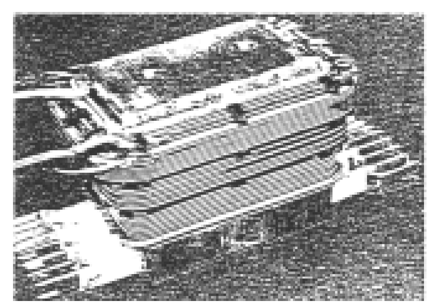


Salient Rotor Machine





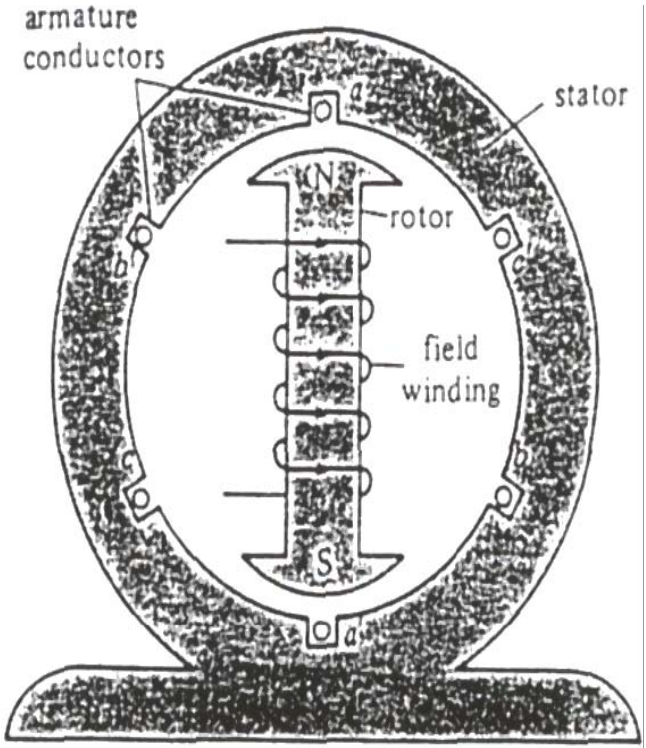




SYNCHRONOUS GENERATOR

•**Principle of Operation**

1) From an external source, the field winding is supplied with a DC current -> excitation.
2) Rotor (field) winding is mechanically turned (rotated) at synchronous speed.
3) The rotating magnetic field produced by the field current induces voltages in the outer stator (armature) winding. The frequency of these voltages is in synchronism with the rotor speed.



SYNCHRONOUS MACHINES

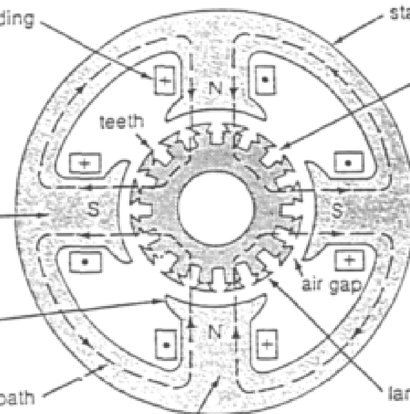
<u>Operation concept</u>

- The frequency - speed relation is **$f = (p / 120)\ n = p\ n / 120$**
  p is the number of poles.
- Typical rotor speeds are 3600 rpm for 2-pole, 1800 rpm for 4 pole and 450 rpm for 16 poles.
- The rms. value of the induced voltages is:

$$E_A = 4.44\ N\ BA\ f\ ,\ (BA = \phi)$$

- where:
  N = number of turns, B= flux density, A = cross sectional area of the magnetic circuit, f = frequency, and ϕ = flux per pole

Comparisons Between DC and Synchronous Machines



Synchronous Generators Equivalent Circuit (round rotor)

1) DC current in the field winding produces the main flux, ϕ_f.

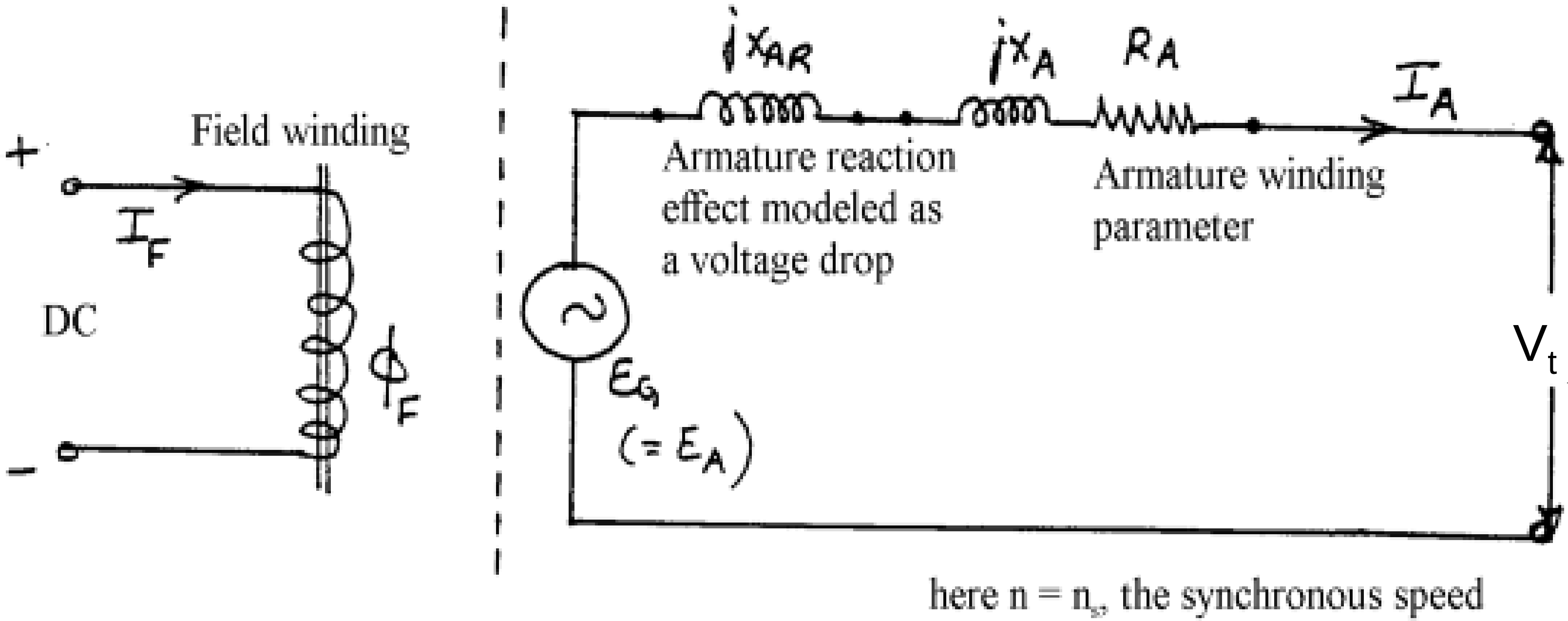
2) ϕ_f induces an emf, E_G, in the armature winding.

3) Depending on the load condition, the armature current I_A is established. In the following discussions, it is assumed to be a lagging power factor.

4) I_A produces its own flux due to armature reaction, E_{AR} is the induced emf by ϕ_{AR}.

5) The resulting phasor, $E_{resultant} = E_G + E_{AR}$ is the “true” induced emf that is available.

Synchronous Generators Equivalent Circuit (round rotor)



Synchronous Generators Equivalent Circuit (round rotor)

Phasor Diagrams:

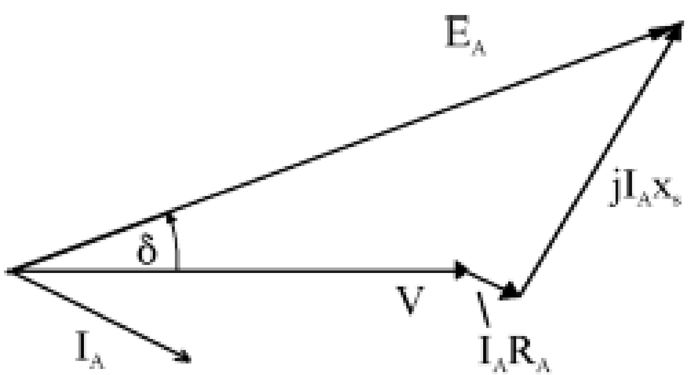
$$V_t = E_A - I_A jX_A - I_A jX_{AR} - I_A R_A = E_A - jX_s I_A - I_A R_A$$

$$V_t = E_A - I_A\left(R_A + jX_s\right)$$

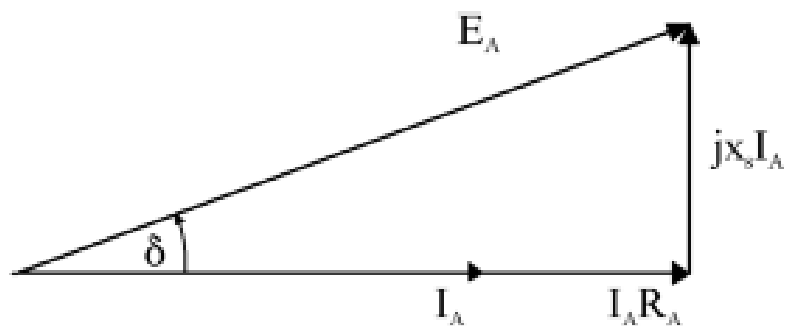
where, (X_{AR} + X_A) = synchronous reactance, X_s.

Synchronous Generators Equivalent Circuit (round rotor)

Inductive Load



Resistive Load



δ = power angle

Power Supplied by a Synchronous Generator

$$S = P + jQ = 3V_t I_A^*$$

$$S = 3V_t\angle 0\left(\frac{E_a\angle(-\delta) - V_t\angle 0}{-jX_s}\right)$$

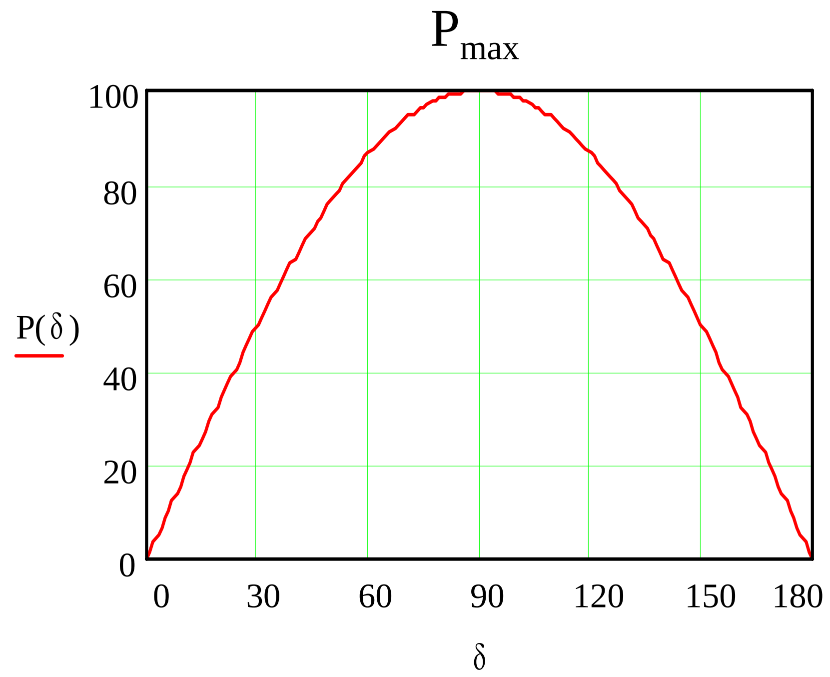
$$P = 3\frac{E_a V_t}{X_s}\sin(\delta)$$

SYNCHRONOUS MACHINES

Power angle Characteristics

- The P(δ) curve shows that the increase of power increases the angle between the induced voltage and the terminal voltage.
- The power is maximum when δ =90º
- The further increase of input power forces the generator out of synchronism. This generates large current and mechanical forces.
- The maximum power is the static stability limit of the system.
- Safe operation requires a 15-20% power reserve.

Round Rotor Machine



Example 1

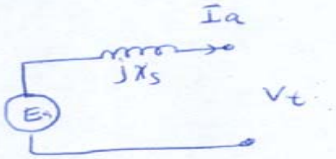
- A 25 kVA, 230 V three phase, four pole, 60 Hz, Y-connected synchronous generator has a synchronous reactance of 1.5 Ω/phase and a negligible resistance. The generator is connected to an open circuit of constant voltage (230 V) and frequency (60 Hz), find:

a) The generated EMF (E_G) when the machine is delivering rated kVA at 0.8 power factor lagging.

b) If the field current If is increased by 20 % without changing the power input find the stator current I_a.

(a) $V_t = \frac{230}{\sqrt{3}}\angle 0 = 132.8\angle 0$

$I_a = \frac{25,000}{230\sqrt{3}}\angle -\cos^{-1}(0.8) = 62.8\angle -36.9$ A.



$E_a = V_t + I_a(\cancel{R_a} + jX_s)$

$= 132.8\angle 0 + 62.8\angle -36.9\,(j1.5)$

$= 203.8\angle 21.7 \Rightarrow \delta = 21.7$

$E_a(L-L) = 353$ V

(b) Since I_f increased by 20% $\Rightarrow E_a$ will increase by same % $\Rightarrow E_a' = 1.2E_a = (1.2)(203.8) = 244.6$ V

Since the input power from prime mover remains unchanged $\Rightarrow P' = P$

$\Rightarrow 3\left(\frac{E_a' V_t}{X_s}\right)\sin\delta' = 3\left(\frac{E_a V_t}{X_s}\right)\sin\delta$

$\Rightarrow \delta' = 17.9$

$I_a = \frac{E_a - V_t}{jX_s} = \frac{244.6\angle 17.9 - 132\angle 0}{j1.5}$

$= 83.4\angle -53$

$\Rightarrow pf = \cos(53) = 0.6$ lagging.

$$\Rightarrow Q = 3 V_t I_a \sin\theta = 3(132.8)(83.4)\sin 53$$ (8)

$$= 26.5 \text{ KVAR}.$$

Voltage Regulation

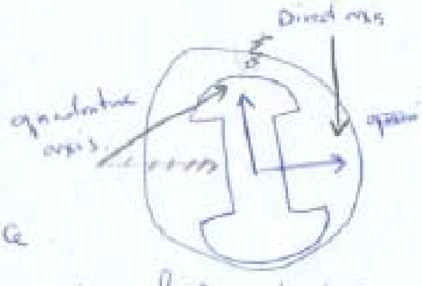
- As the load on the generator increases, the terminal voltage drops. *But,* the terminal voltage, must be maintained constant, and hence the excitation on the machine is varied, or input power to the generator is varied. That means, E_G has to be adjusted to keep the terminal voltage V_t constant.
- Voltage Regulation, V. R. = $\frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$

Example 2

Calculate the percent voltage regulation for a three phase, Y-connected, 20 MVA ,13.8 kV synchronous generator operating at full load and 0.8 power factor lagging. The synchronous reactance is 8 ohm per phase and the armature resistance can be neglected.

Salient Pole mathematical modelling

- Since Salient type machines has non-uniform air gap, ⇒ the equivalent circuit is different than the round rotor.

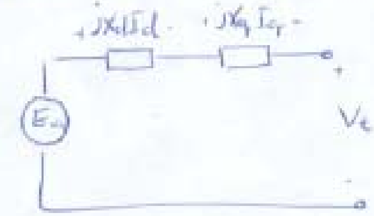


- Because the air gap @ the quadrature axis is small ⇒ flux along quadrature axis encounter lower reluctance.
- The flux on the Direct axis encounter high reluctance.
- The stator current I_a is resolved into two mutually perpendicular components: the direct axis I_d & the quadrature axis component I_q.

$$\Rightarrow I_a = I_d + I_q$$

- Also we have direct axis reactance X_d & quadrature-axis reactance X_q

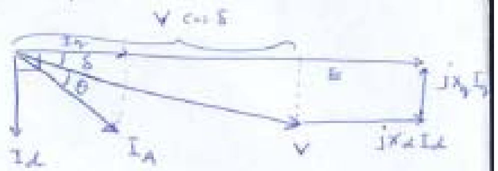
⇒ The equivalent Circuit:



$$E_q = jX_d I_d + jX_q I_q + V_t$$

Prove that $\tan\delta = \dfrac{X_q P}{V^2 + X_q Q}$

$$\tan\delta = \frac{X_q I_q}{V\cos\delta}$$



$$I_q = I_A \cos(\theta + \delta)$$

but $\cos(x+y) = \cos(x)\cos(y) - \sin(x)\sin(y)$

$$\Rightarrow I_q = I_A \left\{ \cos\theta\cos\delta - \sin\theta\sin\delta \right\}$$

$$\Rightarrow \tan\delta = \frac{X_q I_A [\cos\theta\cos\delta - \sin\theta\sin\delta]}{V\cos\delta}$$

$$= \frac{X_q I_A \cos\theta \cos\delta}{V\cos\delta} - \frac{X_q I_A \sin\theta\sin\delta}{V\cos\delta}$$

$$\tan\delta = \frac{X_q I_A\cos\theta}{V} - \frac{X_q I_A \sin\theta\tan\delta}{V}$$

$$\Rightarrow \tan\delta\left[1 + \frac{X_q I_A \sin\theta}{V}\right] = \frac{X_q I_A\cos\theta}{V}$$

$$\tan\delta\left[\frac{V + X_q I_A\sin\theta}{V}\right] = \frac{X_q I_A\cos\theta}{V}$$

$$\Rightarrow \tan\delta = \frac{X_q I_A\cos\theta}{V + X_q I_A\sin\theta} \cdot \frac{V}{V}$$

$$\boxed{\tan\delta = \frac{X_q P}{V^2 + X_q Q}}$$

Parallel Operation of Synchronous Generators

- Generators are rarely used in isolated situations. More commonly, generators are used in parallel, often massively in parallel, such as in the power grid. The following steps must be adhered to:
- when adding a generator to an existing power grid:

1) RMS line voltages of the two generators must be the same.

2) Phase sequence must be the same.

3) Phase angles of the corresponding phases must be the same.

4) Frequency must be the same.

Q1

b- A round rotor synchronous machine is connected to an infinite bus whose voltage is kept constant at 1.05 pu. The synchronous reactance of the machine is 0.4. The table given below relates to two operating conditions of the machine. Complete the table neglecting armature reaction. [15 points]

	P	Q	E	δ
Condition A	?	?	1.3	40°
Condition B	2.0	0	?	?
Condition C	?	0	1.2	?

Q2

A 25-MVA 13.8-kV 0.85-PF-lagging Y-connected round-rotor synchronous generator has a negligible armature resistance and a synchronous reactance of 5 Ω. The generator is connected to a 13.8-kV infinite bus.

b- Find the armature current, the torque angle and the internal generated voltage under rated conditions. [5 points]

c- Assume that the internal generated voltage is decreased by 10 percent, while the active power output is maintained at rated value; find the corresponding torque angle, armature current, and power factor. [10 points]