ECE 325 – Electric Energy System Components
7- Synchronous Machines

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Content

(Materials are from Chapters 16-17)

• Synchronous Generators

• Synchronous Motors
Synchronous Generators

\[ f = \frac{pn}{120} \]
Types of Rotors

• Salient pole rotors
  – Have concentrated windings on poles and non-uniform air gap
  – Short axial length and large diameter to extract the maximum power from a waterfall
  – On hydraulic turbines operated at low speeds at 50-300 r/min (having a large number of poles)
  – Have a squirrel-cage windings (damper windings) embedded in the pole-faces to help damp out speed oscillations

• Cylindrical/round rotors
  – Distributed winding and uniform air gap
  – Large axial length and small diameter to limit the centrifugal forces
  – Steam and gas turbines, operated at high speeds, typically 1800-3600r/min (4 or 2-pole)
  – Eddy in the solid steal rotor gives damping effects
  – 70% of large synchronous generators (150~1500MVA)
Main features of the stator

• Same as the stator of a 3-phase inductor motor

• The winding is always in Y connection with the neutral grounded (the voltage per phase only 1/1.73 or 58% of that in Δ connection)

• Factors affecting the size of synchronous generators: usually, a larger generator has
  – a larger capacity
  – a higher efficiency
  – a larger power output per kilogram (cheaper)
  – more serious cooling problems (higher power losses per unit surface area)
Field excitation and exciters

Using a main exciter and a pilot exciter, the DC field excitation not only ensures a stable AC terminal voltage of the synchronous generator, but must also quickly respond to sudden load changes in order to maintain system stability.

**DC Exciter (DC generator)**

**AC generator**

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**Figure 16.1**

Schematic diagram and cross-section view of a typical 500 MW synchronous generator and its 2400 kW dc exciter. The dc exciting current $I_x$ (6000 A) flows through the commutator and two slip-rings. The dc control current $I_c$ from the pilot exciter permits variable field control of the main exciter, which, in turn, controls $I_x$. 
**Brushless excitation**

- Electronic rectifiers replace the commutator, slip-rings and brushes

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**Figure 16.8**
Typical brushless exciter system.
Equivalent circuit of a 3-phase AC generator

- $E_o$ is induced by rotor flux $\phi$ (field current $I_x$)
- $E_{ar}$ is induced by armature flux $\phi_{ar}$ (armature current $I$)
- $X_l$ is leakage reactance
- $R$ is armature resistance
- KVL: $E_o + E_{ar} = jX_l I + R_a I + E$
- Let $E_{ar} = -jX_{ar} I$ : $E_o = j(X_l+X_{ar}) I + R_a I + E$
- Define $X_s = X_{ar} + X_l$ (called synchronous reactance)

$$E_o = jX_s I + R_a I + E$$
Determining the value of $X_s$

- **Open-circuit test:**
  - Open stator terminals ($I=0$) and drive the generator at the rated speed
  - Raise exciting current $I_X$ until the rated line-to-line voltage is attained.
  - Measure the corresponding $I_X = I_{Xn}$ and line-to-neutral voltage $E_n$

- **Short-circuit test:**
  - Reduce the excitation to 0 and short-circuit three stator terminals.
  - With the generator running at rated speed, gradually raise $I_X$ to $I_{Xn}$.
  - Record current $I_{SC}$ in the stator windings

If armature resistance $R$ is ignorable:

$$X_s = E_n / I_{SC}$$

- **Per-unit $X_s$:** $X_s \text{ (pu)} = X_s / Z_B$ (usually in 0.8-2 pu)

$Z_B = E_B^2 / S_B$  base impedance (line-to-neutral) of the generator [Ω]

$E_B$ = base voltage (line-to-neutral) [V]

$S_B$ = base power per phase [VA]
Synchronous generator connected to an isolated load

\[ E_o = E_X + E = jX_s I + Z I \]

\[ Z = |Z| \angle \theta \quad \text{PF} = \cos \theta \]

Voltage Regulation = \[ \frac{|E_{NL}| - |E_B|}{|E_B|} \times 100 \]

*\( E_{NL} \): no-load voltage \((E_o)\)  
\*\( E_B \): rated voltage \((E_n)\)
Example 16-2

A 3-phase synchronous generator produces an open-circuit line voltage of 6928V when the DC exciting current is 50A. The AC terminals are then short-circuited, and the three line currents are found to be 800A

a. Calculate the synchronous reactance per phase

\[ |E_o| = \frac{E_{oL}}{1.73} = \frac{6928}{1.73} = 4000 \text{V} \]

\[ X_S = \frac{|E_o|}{|I|} = \frac{4000}{800} = 5 \ \Omega \]

b. Calculate the terminal voltage if three 12 Ω resistors are connected in Y across the terminals

\[ |Z| = \sqrt{R^2 + X_S^2} = 13 \ \Omega \]

\[ |E| = |I| R = \frac{|E_o| R}{|Z|} = \frac{4000 \times 12}{13} = 3696 \ \text{V} \]

\[ E_L = 1.73 |E| = 6402 \ \text{V} \]
Example 16-3

A 30MVA, 15kV, 60Hz AC generator has a synchronous reactance $X_S=1.2$ pu and a winding resistance $R=0.02$ pu. Calculate

a. Its base voltage, base power and base impedance

$$E_B = E_L / 1.73 = 15000 / 1.73 = 8660 \, \text{V}$$

$$S_B = 30 / 3 = 10 \, \text{MVA}$$

$$Z_B = E_B^2 / S_B = 8600^2 / 10^7 = 7.5 \, \Omega$$

b. The actual values of $X_S$ and $R$ per phase

$$X_S = X_S(\text{pu}) \times Z_B = 1.2 \times 7.5 = 9 \, \Omega$$

$$R = R(\text{pu}) \times Z_B = 0.02 \times 7.5 = 0.15 \, \Omega$$

c. The total full-load copper losses

$$I(\text{pu}) = E(\text{pu}) / Z(\text{pu}) = 1 / 1 = 1 \, \text{pu}$$

$$P_{\text{loss}} = 3I^2R \times S_B = 3 \times 1 \times 0.02 \times 10 = 0.6 \, \text{MW}$$