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

- **Stator**
- **Round rotor**
- **Salient-pole rotor**
- **Field winding**
- **Armature winding**

\[ n = n_s = 120f/p \]
**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)

(Source: [http://emadrle.blogspot.com](http://emadrle.blogspot.com))
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)

Sources: Wikipedia & PatrickSchneiderPhoto.com

Stator winding of a hydor-unit

An employee of Siemens Charlotte Turbine-Generator Center in the Stator winding area inspects the coils
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

![Diagram of brushless excitation system]

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

- \( E_o \) is the electromotive force 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: \( E_o + E_{ar} = jX_lI + RI + E \)
- Let \( E_{ar} = -jX_{ar}I \): \( E_o = j(X_l + X_{ar})I + RI + E \)
- Define \( X_s = X_{ar} + X_l \) (called synchronous reactance)

\[
E_o = jX_sI + R_dI + E
\]
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 $E_n$, which is equal to the internal electromotive force $E_{on}=E_o(I_{Xn})$

• **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 $I_{Xn}$ in order to induce the same $E_{on}=E_n$.
  - Record current $I_{SC}$ in the stator windings
    If armature resistance $R$ is ignorable:
    \[
    X_S = \frac{E_n}{I_{SC}}
    \]

• **Per-unit $X_S$:** $X_S \text{ (pu)} = \frac{X_S}{Z_B}$ (usually in 0.8-2 pu)
  \[
  Z_B = \frac{E_B^2}{S_B} \quad \text{base impedance (line-to-neutral) of the generator} \quad \Omega
  \]
  \[
  E_B = \text{base voltage (line-to-neutral)} \quad \text{[V]}
  \]
  \[
  S_B = \text{base power per phase} \quad \text{[VA]}
  \]
Synchronous generator connected to an isolated load

\[ E_o = E_x + E = jX_s I + Z I \]
\[ Z = |Z| \angle \theta \quad PF = \cos \theta \]

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

\[ |E_o| = 6928 / 1.73 = 4000 \text{V} \]
\[ X_S = |E_o| / |I| = 4000 / 800 = 5 \Omega \]

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

\[ Z = 12 + j5 \Omega \]
\[ E = R \times E_o / Z = 4000 \times 12 / (12 + j5) = 3692 \angle -22.6^\circ \text{ V} \]
\[ E_L = 1.73 |E| = 6387 \text{ V} \]
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

$$E_B = E_L / 1.73 = 15000 / 1.73 = 8660 \text{ V}$$
$$S_B = 30 / 3 = 10 \text{ MVA}$$
$$Z_B = E_B^2 / S_B = 8600^2 / 10^7 = 7.5 \text{ } \Omega$$

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

$$X_S = X_S(\text{pu}) \times Z_B = 1.2 \times 7.5 = 9 \text{ } \Omega$$
$$R = R(\text{pu}) \times Z_B = 0.02 \times 7.5 = 0.15 \text{ } \Omega$$

c. The total full-load copper losses

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