Chapter 16: Synchronous Generators
Synchronous Generators

- Three-phase synchronous generators are the primary source of all electrical energy
  - power ratings up to 1500 MW
  - stator construction is the same as and induction machine
    - three-phase windings distributed on the stator
    - arranged in pairs of poles
  - rotor construction forms a dc magnet
    - permanent magnet or electro-magnet with a dc current
    - number of poles equals the number of winding sets on the stator
  - the ac frequency depends on the rotor’s speed of rotation and the number of poles
    - the rotor speed is the synchronous speed \( f = \frac{n_s \cdot P}{120} \)
Synchronous Generators

pilot exciter
25 kW

main exciter
2400 kW, 400 V

3-phase alternator
500 MW, 12 kV, 60 Hz

3-phase stator winding

exciting coil

rotor

pole

air gap

brush

slip ring

commutator

I_c

I_x

6000 A

A

B

C

alternator terminals
Synchronous Generators

• Example
  – a hydraulic turbine turning at 200 rpm is connected to a synchronous generator
  – if the induced voltage has a frequency of 60 Hz, how many poles does the rotor have?
Stator Construction

- From an electrical standpoint the stator of a synchronous machine and an induction machine are identical
  - the windings are usually connected in a wye configuration
    - the voltage per phase is only $\frac{1}{\sqrt{3}}$ or 58% of the line voltage, permitting a reduction in the amount of dielectric insulation
  - under load, the voltage can become distorted and no longer sinusoidal
    - the distortion is mainly due to third harmonic voltages (180 Hz)
    - with a wye connection, the third harmonic voltages cancel between the line-to-line voltages
    - with a delta connection, the third harmonic voltage add and appear on the line-to-line voltages
Rotor Construction

- Two general types
  - salient pole (slow speed) and cylindrical (high speed) rotors
- Coil layouts are designed to produce a fixed set of N and S magnetic poles
  - dc current is supplied to the coils to create the magnetic field
- Damper windings
  - in addition to the dc field windings, a squirrel-case winding is added
    - under normal conditions, this winding does not carry any current
    - when sharp changes in loading occurs, the rotor speed begins to fluctuate, producing momentary speed variations
    - large currents begin to flow, producing dampen forces
Field Excitation

• Three methods of excitation
  – slip rings link the rotor’s field winding to an external dc source
  – dc generator exciter
    • a dc generator is built on the same shaft as the ac generator’s rotor
    • a commutator rectifies the current that is sent to the field winding
  – brushless exciter
    • an ac generator with fixed field winding and a rotor with a three-phase circuit
    • diode/SCR rectification supplies dc current to the field windings
Field Excitation

Diagram of field excitation system with labels:
- Pilot exciter
- Main exciter
- Stationary field
- 3-phase bridge rectifier
- 3-phase rotor
- Alternator terminals
- Stator
- Pole
- Rotor
- Exciting coil
- 3-phase stator winding
- Air gap
- Currents $I_c$ and $I_x$
No-load Saturation Curve
Equivalent Circuit

- Induced voltage, $E_0$
  - voltage induced as flux cuts across windings
- Winding inductance $X_s = 2\pi f L$
- Winding resistance
  - usually 1/100 of the size of the reactance
  - often neglected in the equivalent circuit
Synchronous Reactance

- The value of $X_S$ can be determined by measurements of the open-circuit and short-circuit tests
  - Tests are conducted under an unsaturated core condition
  - Open-circuit test is conducted at rated speed with the exciting current $I_{xn}$ adjusted until the generator terminals are at rated voltage, $E_n$
  - Short-circuit test is conducted at rated speed with the exciting current $I_{xn}$ gradually raised from 0 amps up to the original value used in the open-circuit test
  - The resulting short-circuit current $I_{sc}$ is measured, allowing the calculation of $X_S$:
    $$X_S = \frac{E_n}{I_{sc}}$$
Synchronous Reactance

• Example
  – a 3-phase synchronous generator produces an open-circuit line voltage of 6928 V when the dc exciting current is 50 A
    • when the ac terminals are short-circuited under the same excitation, the three line currents are found to be 800 A
  – calculate
    • the per-phase synchronous reactance of the generator
    • the resulting terminal voltage if a 12-ohm, wye-connected load is connected to the generator
Per Unit Generator Impedance

- Generator nameplates denote the synchronous reactance, $X_S$, in per-units or percentage of the generator’s base impedance, $Z_B$
  - the impedance base is determined from the full-load power and rated line voltage

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Z_B = \frac{E_B^2}{S_B} = \frac{(E_{n-LL})^2}{S_{3\phi-FL}} = \frac{(\sqrt{3} E_{n-LN})^2}{3 \cdot S_{1\phi-FL}} = \frac{(E_{n-LN})^2}{S_{1\phi-FL}}
\]
Per Unit Generator Impedance

• Example
  – a 30 MVA, 15 kV 60 Hz generator has a synchronous reactance of 1.2 pu and a resistance of 0.02 pu
  – calculate
    • the generator’s base voltage, power, and impedance
    • the actual value of the synchronous reactance
    • the actual winding resistance, per phase.
    • the total full-load copper losses
Short-circuit Ratio

• Instead of expressing the synchronous reactance as a percent of base impedance on the generator’s nameplate, the short-circuit ratio is often used for larger machines
  – by definition, the short-circuit ratio is the value of the field current, $I_{x1}$, needed to generate the rated terminal voltage on an open circuit, divided by the field current, $I_{x2}$, needed to generate the rated full-load current with short-circuit terminals
  – the short-circuit ratio is equal to the reciprocal of the per-unit synchronous reactance value, $X_S$

$$\frac{I_{X1}}{I_{X2}} = \frac{1}{X_S} = \frac{I_{SC}}{E_n}$$
Homework

• Problems 16-13, 16-16, and 16-19