Synchronous Machines - Structure
Synchronous Machines - Structure

- rotates at constant speed.
- primary energy conversion devices of the word’s electric power system.
- both generator and motor operations
- can draw either a lagging or a leading reactive current from the supply system.

Non-salient pole generator

- high speed (2 - 4 poles)
- large power (100 - 400 MVA)
- steam and nuclear power plants

Salient pole generator

- small and mid-size power (0 - 100 MVA)
- small motors for electrical clocks and other domestic devices
- mid size generators for emergency power supply
- mid size motors for pumps and ship propulsion
- large size generators in hydro-electric power plants
Synchronous Generators – No-load

- excitation voltages

\[ f = \frac{np}{120} \quad n = \frac{120f}{p} \]

- open circuit characteristics
- magnetization characteristics

\[ E_f = 4.44f\Phi_fNK_w \quad E_f \propto n\Phi_f \]
Synchronous Generators - loaded

- the stator currents will establish a rotating field in the air-gap
- armature reaction flux $\Phi_a$
- resultant air-gap flux

$$\Phi_r = \Phi_f + \Phi_a$$
Synchronous Machines – The Infinite Bus

Hydro

Transformer

Thermal

Transformer

Nuclear

Transformer

Oil

Transformer

Interruptible Tie-line to other states or countries

230 kV grid

Load centers

Transformer 44 kV

Transformer 4.16 kV

Transformer

230 V load

115 V load

600 V or 480 V Industrial loads

Domestic loads

Pole transformer
Synchronous Machines – Paralleling with The Infinite Bus

- same
  - voltage
  - frequency
  - phase sequence
  - phase

- synchronizing lamps

1. Same f and phase sequence

2. Same V and phase sequence

1. Same V and f

![Diagram](image-url)
Synchronous Motor - Starting

- high inertia of the rotor prohibits direct connection into supply net

![Diagram of synchronous motor starting process](image)

- variable-frequency supply

- start as an induction motor
Synchronous Machines – Per Phase Equivalent Circuit Model

- armature flux, armature reaction flux, armature leakage flux

\[ \Phi_a = \Phi_{ar} + \Phi_{al} \]

\[ \Phi_r = \Phi_f(I_f) + \Phi_{ar}(I_a) \]

\[ E_r = E_{ar} + E_f \]

\[ -E_{ar} = jX_{ar}I_a \]

\[ E_f = I_a jX_{ar} + E_r \]

- magnetizing reactance \( X_{ar} \), (reactance of armature)

- synchronous reactance \( X_s = X_{ar} + X_{al} \)

- synchronous impedance \( Z_s = R_a + jX_s \)
Synchronous Machines – Equivalent Circuit Model

- Norton equivalent circuit

\[ I'_f = \frac{E_f}{X_s} \quad \left| I'_f \right| = \frac{X_{ar}}{X_s} n I_f \quad n = \frac{\sqrt{2}}{3} \frac{N_{re}}{N_{se}} \]
Equivalent Circuit Model – Determination of the Synchronous Reactance

• open circuit test
  • synchronous speed
  • stator open-circuited
  • measure $V_t(I_t)$
  • open-circuit characteristic
  • air-gap line

• short circuit test
  • synchronous speed
  • stator short-circuited
  • measure $I_a(I_t)$
  • short-circuit characteristic
  • straight line
  • flux remains at low level

• $I_a$ lags the $E_f$ by almost 90 because $R_a \ll X_S$
Equivalent Circuit Model – Determination of the Synchronous Reactance

- unsaturated value from the air-gap line

\[
Z_{s(\text{unsat})} = \frac{E_{da}}{I_{ba}} = R_a + jX_{s(\text{unsat})} \quad \quad X_{s(\text{unsat})} \approx \frac{E_{da}}{I_{ba}}
\]
Equivalent Circuit Model – Determination of the Synchronous Reactance – Saturated

\[ E_r = V_t + I_a (R_a + jX_{al}) \approx V_t \]

- at infinite bus operation the saturation level is defined by terminal voltage
- operation point c
- if the field current is changed the excitation voltage will change along modified air-gap line OC

\[ Z_{s(sat)} = \frac{E_{ca}}{I_{ba}} = R_a + jX_{s(sat)} \]

\[ X_{s(sat)} \approx \frac{E_{ca}}{I_{ba}} \]
Synchronous Machines – Phasor Diagram

- terminal voltage taken as the reference vector
- generator
  - power angle positive

\[ E_f = V_t + I_a R_a + I_a jX_s = |E_f| |\delta| \]

- motor
  - power angle negative

\[ V_t = E_f + I_a R_a + I_a jX_s \]

\[ E_f = V_t |0^\circ - I_a R_a - I_a jX_s \]

\[ = |E_f| |\delta| \]

convention: generating current flows out of the machine
Synchronous Machines – Power and Torque

\[ V_t = |V_t| 0^\circ \]

\[ E_f = |E_f| \delta \]

\[ Z_s = R_a + jX_s = |Z_s| \theta_s \]

\[ S = V_t I_a^* \]

\[ I_a^* = \left( \frac{E_f - V_t}{Z_s} \right)^* = \frac{E_f^*}{Z_s^*} - \frac{V_t^*}{Z_s^*} \]

\[ = \frac{|E_f| - \delta}{|Z_s| - \theta_s} - \frac{|V_t| 0}{|Z_s| - \theta_s} \]

\[ = \frac{E_f}{Z_s} |\theta_s - \delta| - \frac{V_t}{Z_s} |\theta_s| \]

convention: lagging reactive power positive
Synchronous Machines – Power and Torque

• complex power

\[ S = \frac{|V_t||E_f|}{|Z_s|} \theta_s - \delta - \frac{|V_t|^2}{|Z_s|} \theta_s \]

• real power

\[ P = \frac{|V_t||E_f|}{|Z_s|} \cos(\theta_s - \delta) - \frac{|V_t|^2}{|Z_s|} \cos \theta_s \]

• reactive power

\[ Q = \frac{|V_t||E_f|}{|Z_s|} \sin(\theta_s - \delta) - \frac{|V_t|^2}{|Z_s|} \sin \theta_s \]
Synchronous Machines – Power and Torque

- \( R_a \) neglected

- real power

\[
P_{3\phi} = \frac{3|V_t||E_f|}{|X_s|} \sin \delta = P_{\text{max}} \sin \delta
\]

- reactive power

\[
Q_{3\phi} = \frac{3|V_t||E_f|}{|X_s|} \cos \delta - \frac{3|V_t|^2}{|X_s|}
\]

- torque

\[
T = \frac{P_{3\phi}}{\omega_{\text{syn}}} = \frac{3}{\omega_{\text{syn}}} \frac{V_t|E_f|}{X_s} \sin \delta = T_{\text{max}} \sin \delta \quad \text{N} \cdot \text{m}
\]
Synchronous Machines – Complex Power Locus

\[ P_{3\phi} = \frac{3|V_t||E_f|}{|X_s|} \sin \delta = P_{\text{max}} \sin \delta \]

\[ Q_{3\phi} = \frac{3|V_t||E_f|}{|X_s|} \cos \delta - \frac{3|V_t|^2}{|X_s|} \]
Synchronous Machines – Capability Curves

- armature heating, length of OM
- field heating, length of YM
- steady-state stability $\delta$
Synchronous Machines – Power Factor Control

• machine connected to an infinite bus

\[ P = 3V_t I_a \cos \phi \]

• for constant power operation

\[ |I_a \cos \phi| = \text{const.} \]

• reactive current can be controlled by field current

\[ jX_s I_a = V_t - E_f \]

• also

\[ P = 3 \frac{V_t E_f}{X_s} \sin \delta \]

\[ E_f \sin \delta = \text{const} \]
Synchronous Machines – Independent Generators

• purely inductive load ($I_{sc}$ is short-circuit current)

\[ V_t = E_f - I_a X_s \]
\[ = I_{sc} X_s - I_a X_s \]
\[ = X_s (I_{sc} - I_a) \]

• purely resistive load

\[ I_a = \frac{E_f}{\sqrt{R_L^2 + X_s^2}} = \frac{X_s I_{sc}}{\sqrt{R_L^2 + X_s^2}} \]

\[ V_t = I_a R_L \]

• quarter ellipse

\[ \frac{V_t^2}{(X_s I_{sc})^2} + \frac{I_a^2}{I_{sc}^2} = 1 \]

• control curves
  • constant terminal voltage
Salient Pole Synchronous Machines

- the field mmf and flux are along the d-axis
- stator current is in phase with the excitation voltage
- armature mmf and flux are along the q-axis
- stator current is lagging the excitation voltage by 90 degrees
- armature mmf and flux act along the d-axis, directly opposing the field
- the same magnitude of the armature mmf produces more flux in d-direction than that in q-direction
- magnetizing reactance is not unique in a salient pole machine
Salient Pole Synchronous Machines

- the armature quantities can be resolved into two components – one acting along the d-axis \((F_d, I_d)\), and the other acting along the q-axis \((F_q, I_q)\),

- these components produce fluxes along the respective axes \((\Phi_{ad}, \Phi_{aq})\),

- d-axis armature reactance \(X_d\)
- q-axis armature reactance \(X_q\)
- leakage reactance \(X_{al}\)

- synchronous reactances

\[
X_d = X_{ad} + X_{al} \\
X_q = X_{aq} + X_{al}
\]
Salient Pole Synchronous Machines – Phasor Diagrams

- the component currents ($I_d$, $I_q$), produce component voltage drops ($jI_dX_d$, $jI_qX_q$)

$$E_f = V_t + I_aR_a + I_djX_d + I_qjX_q$$

$$I_a = I_d + I_q$$

- generator phasor diagram ($I_a$ lagging)

- $\psi$ internal power factor angle
- $\phi$ terminal power factor angle
- $\delta$ torque angle

- $R_a$ neglected
Salient Pole Synchronous Machines – Phasor Diagrams

• motoring phasor diagram ($I_a$ lagging)
  • $\psi$ internal power factor angle
  • $\phi$ terminal power factor angle
  • $\delta$ torque angle

\[ V_t = E_f + I_d jX_d + I_q jX_q \]
\[ \psi = \phi \pm \delta \]

\[ I_d = I_a \sin \psi = I_a \sin(\phi \pm \delta) \]
\[ I_q = I_a \cos \psi = I_a \cos(\phi \pm \delta) \]

\[ \tan \delta = \frac{I_a X_q \cos \phi}{V_t \pm I_a X_q \sin \phi} \]
\[ E_f = V_t \cos \delta \pm I_d X_d \]
Power Transfer

\[ S = V_t I_a^* \]
\[ = |V_t| - \delta (|I_q| - j|I_d|)^* \]
\[ = |V_t| - \delta (|I_q| + j|I_d|) \]

\[ |I_d| = \frac{|E_f| - |V_t| \cos \delta}{X_d} \]

\[ |I_q| = \frac{|V_t| \sin \delta}{X_q} \]
Power Transfer

\[ S = \frac{|V_t|^2}{X_q} \sin \delta \delta - \frac{|V_t||E_f|}{X_d} |90^\circ - \delta| - \frac{|V_t|^2}{X_d} \cos \delta |90^\circ - \delta| = P + jQ \]

\[ P = \frac{|V_t||E_f|}{X_d} \sin \delta + \frac{|V_t|^2 (X_d - X_q)}{2X_dX_q} \sin 2\delta = P_f + P_r \]

\[ Q = \frac{|V_t||E_f|}{X_d} \cos \delta - |V_t|^2 \left| \frac{\sin^2 \delta}{X_q} + \frac{\cos^2 \delta}{X_d} \right| \]

- if \( X_d = X_q \), then

\[ P = \frac{|V_t||E_f|}{X_d} \sin \delta \]

\[ Q = \frac{|V_t||E_f|}{X_d} \cos \delta - \frac{|V_t|^2}{X_d} \]
Power Transfer - Torque

\[ P = \frac{|V_t||E_f|}{X_d} \sin \delta + \frac{|V_t|^2 (X_d - X_q)}{2X_d X_q} \sin 2\delta = P_f + P_r \]
Determination of $X_d$ and $X_q$

- slip test
  - rotor is driven at a small slip
  - field winding open-circuited
  - stator is connected to a balanced three phase supply
  - stator encounters varying reluctance path
  - amplitude of the stator current varies

$$X_d = \frac{V_t}{i_{\text{min}}/\sqrt{2}}$$

$$X_q = \frac{V_t}{i_{\text{max}}/\sqrt{2}}$$
Speed Control of Synchronous Motors

- open-loop frequency control
Speed Control of Synchronous Motors

- frequency control

\[ P = T \omega_m = \frac{3V_t E_f}{X_s} \sin \delta \]

\[ \omega_m = \frac{4\pi f}{p} \]

\[ X_s = 2\pi f L_s \]

- field current kept constant

\[ E_f = K_1 f \]

\[ T = K \frac{V_t}{f} \sin \delta \]

- voltage is changed with the frequency
Speed Control of Synchronous Motors

• self-controlled synchronous motor
  • rotor position information is used to decrease the stator frequency

• open-loop / closed-loop control
Applications

- ac generator
- constant speed operation
- high efficiency
  - motor-generator set, air compressor, centrifugal pump, blower, crusher, mill
- power factor control, synchronous reactor, condenser

![Diagram showing hp vs rpm for synchronous and induction motors]