34-Synchronous Generator Control

text: 7.13

ECEGR 450
Electromechanical Energy Conversion

Overview

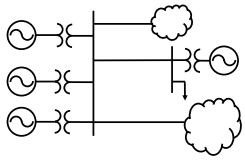
- Synchronization
- Infinite Bus
- Effects of Excitation
- Mechanical Power

Synchronization

- Generators must be synchronized with the grid before supplying power:
- Following conditions must be met
  1. Generator frequency must equal grid frequency
  2. Generator voltage must equal grid voltage (at connection point)
  3. Generator voltage must be in phase with grid voltage (at connection point)
  4. Generator phase sequence must match grid phase sequence

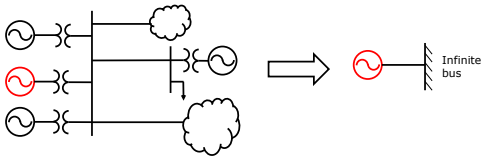
Synchronization

- Electric grid comprised of thousands of connected generators
- Single generator usually cannot significantly influence system voltage or frequency
  - $J_1 << J_2 + \ldots + J_M$



Infinite Bus

- Conceptual element representing a very large electric grid
- Infinite bus properties:
  - Constant voltage
  - Constant current
  - Sink or source infinite current (power) at any angle



Excitation Effects

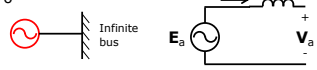
- Assume a lossless cylindrical rotor synchronous generator is connected to an infinite bus
- Assume $\mathbf{E}_a = \mathbf{V}_a$ ("floating")
- Therefore:

$$\mathbf{I}_a = \frac{\mathbf{E}_a - \mathbf{V}_a}{jX_s} = 0\angle 0°\text{A}$$

$$P_o = \text{Re}\{\mathbf{V}_a\mathbf{I}_a^*\} = 0\text{W}$$

$$Q_o = \text{Im}\{\mathbf{V}_a\mathbf{I}_a^*\} = 0\text{VAR}$$

$$\delta = 0°$$



Over-Excitation

What happens if i_f is increased?

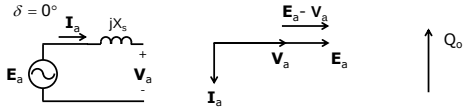
- $|\mathbf{E}_a|$ increases (> $|\mathbf{V}_a|$, overexcited)
- $|\mathbf{I}_a|$ non-zero

$$\mathbf{I}_a = \frac{\mathbf{E}_a - \mathbf{V}_a}{jX_s} = |\mathbf{I}_a| \angle -90°\text{A}$$

$P_o = \text{Re}\{\mathbf{V}_a\mathbf{I}_a^*\} = 0\text{W}$

$Q_o = \text{Im}\{\mathbf{V}_a\mathbf{I}_a^*\} > 0\text{VAR}$ (generator supplies reactive power)

$\delta = 0°$



Under-Excitation

What happens if i_f is decreased?

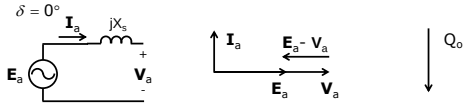
- $|\mathbf{E}_a|$ decreases (<$|\mathbf{V}_a|$, under-excited)
- $|\mathbf{I}_a|$ non-zero

$$\mathbf{I}_a = \frac{\mathbf{E}_a - \mathbf{V}_a}{jX_s} = |\mathbf{I}_a| \angle 90°\text{A}$$

$P_o = \text{Re}\{\mathbf{V}_a\mathbf{I}_a^*\} = 0\text{W}$

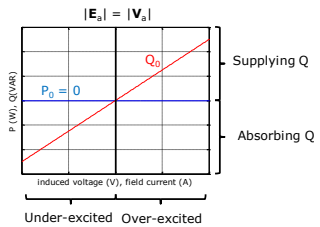
$Q_o = \text{Im}\{\mathbf{V}_a\mathbf{I}_a^*\} < 0\text{VAR}$ (generator consumes reactive power)

$\delta = 0°$



Excitation Effects

- Adjusting excitation alone does not influence real power supplied to grid
- Similar results for non-zero power output

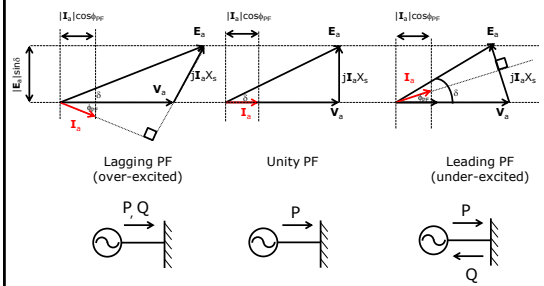


Excitation Effects

- How does varying the excitation affect δ, $\mathbf{I}_a$, ϕ_p for a constant real power and terminal voltage $\mathbf{V}_a$?
- To maintain constant power:
  - $|\mathbf{E}_a|\sin\delta$ is constant $\quad P_o = \frac{3|\mathbf{V}_a||\mathbf{E}_a|\sin\delta}{X_s}$
  - $|\mathbf{I}_a|\cos\phi_{PF}$ is constant $\quad P_o = 3|\mathbf{V}_a||\mathbf{I}_a|\cos\phi_{PF}$
- Increasing $|\mathbf{E}_a|$ decreases power angle δ
- Real part of $\mathbf{I}_a$ remains constant

Phasor Diagrams

Each diagram has same real power output, differing excitation

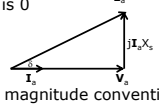


Side Note

- Two conventions for excitation
- Convention 1:Based on voltage magnitudes
  - $|\mathbf{V}_a| > |\mathbf{E}_a|$: under-excited
  - $|\mathbf{V}_a| = |\mathbf{E}_a|$: normally excited
  - $|\mathbf{V}_a| < |\mathbf{E}_a|$: over-excited
- Convention 2: Based on PF
  - Leading PF: under-excited
  - Unity PF: normally-excited
  - Lagging PF: over-excited

Side Note

- Conventions not always compatible
- Example: for unity power factor, $|\mathbf{E}_a| > |\mathbf{V}_a|$ unless armature current is 0

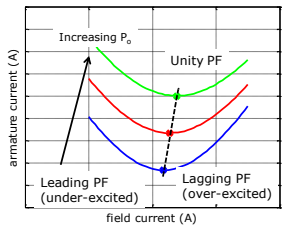


- Using the voltage magnitude convention:
  - Over-excited generators *tend* to supply power to the grid at lagging power factor (but could be unity power factor)
  - Under-excited generators *tend* to supply power to the grid at leading power factor
  - Normally-excited generators supply power to the grid at *nearly* unity power factor

Excitation (infinite bus)

- For synchronous generators connected infinite bus, adjusting excitation:
  - Does not promote real power output if power angle is zero, put reactive power will be affected
  - Increases real power output if power angle is held constant (non-zero)
  - May not affect real power output if power angle is adjusted such that $|\mathbf{E}_a|\sin\delta$ is constant, but reactive power will be affected

V-Curves



Increasing $|\mathbf{E}_a|$

Power Effects

- How does varying the power output effect δ, $\mathbf{I}_a$, ϕ_p for a constant excitation $|\mathbf{E}_a|$ and terminal voltage $\mathbf{V}_a$?
- To increase power:
  - $|\mathbf{E}_a|\sin\delta$ increases
  - $|\mathbf{I}_a|\cos\phi_{PF}$ increases

$$P_o = \frac{3|\mathbf{V}_a||\mathbf{E}_a|\sin\delta}{X_s}$$

$$P_o = 3|\mathbf{V}_a||\mathbf{I}_a|\cos\phi_{PF}$$

- Increasing P_o also increases power angle δ
- Real part of $\mathbf{I}_a$ also increases

Mechanical Power

- How do we change the real power?
- Power output described by:

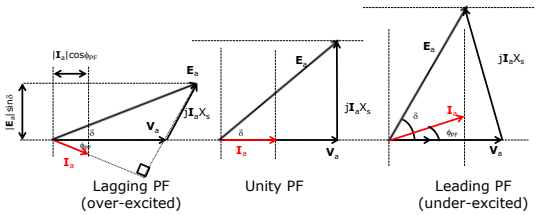
$$P_o = \frac{3|\mathbf{V}_a||\mathbf{E}_a|\sin\delta}{X_s}$$

$$P_o = 3|\mathbf{V}_a||\mathbf{I}_a|\cos\phi_{PF}$$

- If excitation and terminal voltage are held constant, then increasing the mechanical power into the generator results in:
  - Increase in power angle δ
  - Increase in $|\mathbf{I}_a|\cos\phi_{PF}$ (real part of armature current)

Phasor Diagrams

Each diagram has same excitation, differing power



Lagging PF (over-excited) | Unity PF | Leading PF (under-excited)

Increasing Power

Summary

- Generators must be properly synchronized to the electric grid prior to connection
- Infinite bus concept: constant voltage and frequency, capable of source or sinking any amount of current
- Excitation affects reactive power
  - Under-excited: generator absorbs reactive power
  - Over-excited: generator supplies reactive power
- Increasing mechanical power increases power angle, real part of armature current