EE 742 Power System Components

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Desire to have a system with high reliability and power quality

- High reliability ensured by
 - High quality of components
 - High level of system security
 - Reserve of generation
 - Interconnection with large systems
- High power quality ensured by
 - Well regulated voltage levels
 - Well regulated frequency
 - Minimal waveform distortion (low harmonics)

Structure of a Power System

- Voltage levels:
 - Transmission: above 138 kV
 - Sub-transmission: 69-138kV
 - Distribution: 4.16-69 kV
 - Utilization: below 4.16 kV
- Unbundled utility broken into:
 - Generation Co.
 - Transmission (TSO)
 - Distribution (wire) Co.
 - Supply Co.
- The above re-organization creates challenges at the way the system is planned and operated.



US Sources of Electricity Generation, 2017



Note: Electricity generation from utility-scale facilities.



US Electric Power Generating Plants

https://www.eia.gov/state/maps.php



Transmission, Sub-transmission and Distribution

- Common transmission voltages: 138kV, 245kV, 345kV, 500kV, 765kV
- Common sub-transmission voltages: 69kV
- Common distribution voltages: 34.5kV, 25kV, 13.8kV, 13.2kV, 12.47kV, 4.16k
- Transmission power loss: ≈ 0.5%-1.5%
- Distribution power loss: ≈ 4%-6%









Electric Utilities in Nevada

90% of the state's electric load is served by NV Energy 10% of the load is served by 15 small rural electric utilities









Load Demand

- Changes in demand of individual customers is fast and frequent
- The aggregated demand is smoother, and total load fluctuations are usually small.



Power Generation Unit (hydro/steam/gas)



Rotating and Static Excitation Systems

- Power rating: typically less than 1% of generator rating.
- Voltage rating: less than 1 kV











Block diagram of excitation and AVR system

- The AVR regulates generator voltage by controlling the amount of field current.
- Regulation is stabilized using feedback loops.
- Limiters are used to protect the system from excessive currents and voltages.
- The PSS helps with the damping of power swings in the system.





Dynamic voltage response to step change in reference value

- For small disturbances, the quality of voltage regulation can be assessed by observing the voltage response of a generator to a step change in the reference value.
- The quality of regulation is assessed by four indices for a given accuracy:
 - Rise time
 - Time to reach peak value
 - Settling time
 - Overshoot



Turbines and their Governors

- Steam turbines can have non-reheat, single-reheat or double-reheat.
- The steam flow is controlled by the governor. The main amplifier of the governing system and valve mover is an oil servomotor controlled by a pilot valve.
- Main and reheat stop valves are normally fully open. The are used only during generator start-up and shut down.



Open- and Combined-Cycle Gas turbines

- Open cycle gas turbine plant efficiency ≈ 35%
- Combined cycle gas turbine plant efficiency $\approx 60\%$
- Combined cycle gas turbine plants have shorter construction time, lower capital construction, relatively clean, little staffing and the materials handling problem is much simpler than coal fired plants.
- Some plants use heat exhaust for process industry in the vicinity, while others use steam for district heating.



Hydro turbines



Block diagram of mechanical-hydraulic and electro-hydraulic speed governing systems



Turbine Characteristics

- See graph below: unregulated turbine (line 1-2), regulated turbine (line 4-3-2)
- Role of turbine governor: stable operation in line 3 (with small droop).
- *Droop* (or speed droop coefficient) *ρ*:

$$\frac{\Delta\omega}{\omega_{\rm n}} = -\rho \frac{\Delta P_{\rm m}}{P_{\rm n}} \quad \text{or} \quad \frac{\Delta P_{\rm m}}{P_{\rm n}} = -K \frac{\Delta\omega}{\omega_{\rm n}}$$

• *Effective gain* (reciprocal of droop) *K*:

$$K = 1/\rho$$



Simplified model of turbine governing system

- Ignore steam flow feedback (in electro-hydraulic governing system) and governor response is dominated by the time constant of the servomotor.
- Fig. (a) below (where K_A and R correspond to the gain in servomotor amplification and gain in the feedback loop) can be simplified to Fig. (b) where the effective time constant $T_G = 1/(K_A R)$
- At steady-state (t→∞, s→0), Fig. (b) is simplified to Fig. (c). Assuming linearity between valve position and mechanical power,

$$\Delta \omega / \omega_n = -(R / \omega_n) \Delta c = -\rho \Delta c = -\rho \Delta P_m / P_n$$



Equilibrium point between turbine and load power

- The droop should be made small (but cannot be zero or negative)
- Load power has a very high positive slope in the (ω , P) plane.
- At the equilibrium point, the opposing electromagnetic and mechanical torques acting on the shaft are equal in magnitude.
- With a small positive droop, a change in frequency brings the system back to the equilibrium point.



Transformers

- Step-up transformer: connects generator to the transmission network.
- Transmission transformer: connects transmission networks with different voltage levels
- *Substation transformer:* connects the transmission network to the distribution network
- *Distribution transformers:* connects the distribution network to customers
- *Auto-transformer*: typically used when the voltage ratio is less than 2.

Two-winding Transformer

Auto-Transformer





Regulating Transformer

The under-load-tap-changing transformer(ULTC), also called the on-load tap Changer (OLTC) or load tap changer(LTC), allows the taps to be changed while the transformer is energized. A typical range of regulation is $\pm 10\%$ with 32 steps - each corresponds to (5/8)%.



Phase-Shifting Transformer

Phase shifting transformers change the phase angle between the primary and secondary voltages in order to control the flow of real power. They can also be used to control the voltage ratio, hence reactive power flow.



Series and Shunt Elements

- Shunt reactors are used in long and lightlyloaded transmission lines to lower the voltage.
- Shunt capacitors are used in heavily loaded transmission lines to raise the voltage.
- Series capacitors are used in long transmission lines to offset some of the line inductance thus allowing more power flow.
 - Capacitor overvoltage protection during faults is provided by either spark gaps (G) or Zinc-Oxide Varistors (R) with a breaker switch (S).







FACTS Devices: SVC

(Static Var Compensator)













FACTS Devices: STATCOM (or SVG)

(Stattic Var Generator)



busbar





FACTS Devices: BESS

(battery energy storage system)







FACTS Devices: TSBR

(Thyristor switched breaking resistor)



FACTS Devices: SSC, CSC and SSSC

(Switched series capacitors, Controlled series capacitor, Static synchronous series compensator)







FACTS Devices: TCPAR, UPFC

(Thyristor controlled phase angle regulator, Unified power flow controller)



System Protection

- Protective equipment needs to detect a fault and disconnect the faulty element.
- Protection equipment consists of current and/or potential transformers, relays, auxiliary power supplies for the relays, and circuit breakers.
- Operation of the protection scheme must be
 - fast,
 - reliable,
 - and selective.





Protection of transmission lines

- Differential current protection uses pilot wires and analog signals. Interlock scheme (for longer lines) uses power line carrier (PLC) - high frequency logic signals – need for line traps.
- Directional or phase comparison schemes also use PLC.
- Fiber optics placed inside the ground wire are replacing pilot wires and power line carriers.





Transformer Protection

- The main form of transformer protection is differential current protection (similar to the current differential protection used to protect a transmission line).
- The protection scheme takes into account
 - The magnitude and phase angle of the current on each side are different.
 - The presence of large magnetizing inrush currents
- The transformer is protected against inter-turn faults by the Buchholz protection – a safety device that detects the build-up of gases inside the transformer.
- Transformers are also equipped with ground fault protection (supplied with zero-sequence current), overload protection, and thermal protection.

Generator Protection

- Differential protection against faults inside the generator,
- Over-current and asymmetry protection of stator windings,
- Over-current protection of rotor windings
- Additional protection systems are used to protect the generator from loss of excitation, loss of synchronism (poleslip protection), faults in stator windings (under impedance protection), earth faults in the rotor windings and from failure of the prime mover (motoring protection).
- The generator is also equipped with protection from nonelectrical disturbances due to lubrication oil failure, loss of boiler fire, over speeding, rotor distortion, excessive vibration and difference in expansion between rotating and stationary parts.

Wide Area Measurement, Protection & Control

 The possibility of measuring synchronized voltage and current phasors using GPS/GIS has led to new innovative ways of monitoring, protecting, and controlling power systems.

Structure of a WAMPAC

