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)
• Voltage levels:
  – Generation: 12-25 kV
  – Transmission: above 138 kV
  – Sub-transmission: 69-138 kV
  – Distribution: 4.16-69 kV
  – Utilization: below 4.16 kV
What is U.S. electricity generation by energy source?

In 2014, the United States generated about 4,093 billion kilowatthours of electricity. About 67% of the electricity generated was from fossil fuels (coal, natural gas, and petroleum).

Major energy sources and percent share of total U.S. electricity generation in 2014:

- Coal = 39%
- Natural gas = 27%
- Nuclear = 19%
- Hydropower = 6%
- Other renewables = 7%
  - Biomass = 1.7%
  - Geothermal = 0.4%
  - Solar = 0.4%
  - Wind = 4.4%
- Petroleum = 1%
- Other gases < 1%
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%
Utilities learned the benefits in reliability and reduced operating reserves by connecting to neighboring systems.

There are over 3,000 electric utilities in the US.

Some provide service in multiple states.

Over 1,700 non-utility power producers.

Utilities are either investor-owned, publicly-owned, and Federal utilities.

Electric utilities are regulated by local, State, and Federal authorities.
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
North American Interconnections

- The power system of North America is divided into four major Interconnections which can be thought of as independent islands.
- Western – Generally everything west of the Rockies.
- Texas - Also known as Electric Reliability Council of Texas (ERCOT).
- Eastern – Generally everything east of the Rockies except Texas and Quebec.
- Quebec.
North American Balancing Authorities

- The actual operation of the Interconnections is handled by over 100 Balancing Authorities (BA’s). The BA’s dispatch generators in order to meet their individual needs. Some BA’s also control load to maintain balance.
Demand

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

- As electricity itself cannot presently be stored on a large scale, changes in customer demand throughout the day and over the seasons are met by controlling conventional generation, using stored fuels.
- Frequency is maintained as long as there is a balance between resources and customer demand (plus losses). An imbalance causes a frequency deviation.
- The overall daily profile of load in a given area can be predicted reasonably well using forecasting tools.
- A day-ahead generating schedule can be developed based on the predicted next-day load profile.
Frequency: the heartbeat of a power System

– The figure below shows a sample time history of the frequency on the grid in the western United States, sampled six times a second. The slope of the frequency trace is a measure of the overall imbalance of generation and load at any given moment.

– The actual grid frequency tends to oscillate slightly around 60 Hz. The frequency error from 60 Hz is used to fine-tune the generation level through regulation.

Source: Alec Brooks, Ed Lu, Dan Reicher, Charles Spirakis, and Bill Weihl, ”Demand Dispatch” IEEE Power & Energy magazine, May/June 2010
Optimal generator scheduling & Dispatching

- Given a power system with $n$ generators, and a load forecast, the problem is to determine the optimal schedule of each generator while recognizing generating unit limits and output capability.
Generation fleet characteristics

• Each generating unit has specific (fixed) physical characteristics that determine the capability of each unit to respond to changes in system load in the up or down direction:
  – Minimum generation – $P_{\text{min}}$ (MW)
  – Maximum generation – $P_{\text{max}}$ (MW)
  – Maximum ramp rate – $R$ (MW/min)
  – Scheduled operating point - $P_{\text{sched}}$ (MW)
  – Regulation reserve (MW)
  – Load following reserve (MW)
  – Contingency reserve – $P_{\text{cont}}$ (MW)
Reserve allocation in scheduling process

- Contingency Reserve
- Regulation Up
- LF Up
- LF Down
- Regulation Down

Contingency Reserve Activation

Dispatch

AGC

LF - Load Following
AGC - Automatic Generation Control
Operating Reserve Requirements

- **BA’s** are required to maintain the following types of reserves (typically 10-15% of peak load) to provide for regulation, balance against the load forecasting error and to maintain local area reliability:
  - **Spinning Reserve** – Unloaded generation that is synchronized, automatically responsive to frequency deviations (AGC), and ready to serve an additional demand.
  - **Non-Spinning Reserve** – (1) The generating reserve, which is not connected to the system but capable of serving the demand within a specified time from its activation; and (2) loads that can be removed from the system within a specified time.
Interchange error

- Customer demand and generation are constantly changing within all BA’s.
- → BA’s will have some unintentional outflow or inflow at any given instant.

- A Balancing Authority’s internal obligations is to control an instantaneous value called the Area Control Error (ACE) by keeping it within acceptable limit that is proportional to the BA size (44 MW for NV Energy South?).
- Conceptually, the ACE informs the Balancing Authority what the frequency is doing in the Interconnected system. For example, over-generation makes ACE go positive and puts upward pressure on Interconnection frequency.

```
Scheduled net flow: 350 MW
Actual net flow: 340 MW (due to load reduction)
ACE goes positive
Frequency goes up
Reduce generation
```
In real time, the level of generation is adjusted to meet differences between actual loads and the hourly schedules. This real-time adjustment, can be separated into “load following” (within-hour resource dispatching) and “regulation” (sub-minute adjustments of generation) processes according to their respective time scales.

- **Load following** typically requires adjustments every 10 minutes. This is accomplished through a re-dispatch of on-line generation via automatic adjustments by computerized control systems.

- **Regulation** is effected by making sub-minute output adjustments exclusively through an automatic generation control (AGC) system.

- During real time operation, generators under AGC are adjusted every 2 or 4 seconds (although their actual responses are slower) to keep the ACE close to zero.
Illustration of Regulation and Load Following

- Load following is the difference between 10-minute interval average and 60-minute average (both with ramps) of load, depicting the variation of load within the hour at a 10-minute time scale.
  - Load Following = [real-time schedule] – [hourly schedule]
  - Regulation = [actual load] – [real-time schedule]
- Note that the regulation ramps (i.e. slopes) are significantly higher than those of load following
Assessing Adequacy of Ramping Capability

• Insufficient ramping capability is identified when the ramp requirements exceed generation fleet ramping limits.
• The figure below illustrates how such a deficiency could occur: the area in red highlights the magnitude and duration of the interval when regulation ramp requirements exceed fleet capability.
• More units and capacity are needed if composite unit ramping capability is insufficient,
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
HW # 2

• Assume the following transfer function relating the generator terminal voltage to the reference voltage:

\[
\frac{V(S)}{V_{ref}(S)} = \frac{100}{S^2 + 10S + 100}
\]

• Determine the rise time, time to reach peak value, settling time, and overshoot for a step change in reference voltage (i.e., \(v_{ref}(t) = u(t)\)). Allow the error \(\varepsilon = \pm 1\%\)
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 that is controlled by a pilot valve.
- Main and reheat stop valves are normally fully open. They 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 ≈ 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

- Head: vertical distance between upper reservoir and level of turbine
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) \( \rho \):

\[
\frac{\Delta \omega}{\omega_n} = -\rho \frac{\Delta P_m}{P_n} \quad \text{or} \quad \frac{\Delta P_m}{P_n} = -K \frac{\Delta \omega}{\omega_n}.
\]

- **Effective gain** (reciprocal of droop) \( K \):

\[K = 1/ \rho\]
**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 \((\omega, P)\) plane.
- At the equilibrium point, the opposing electromagnetic and mechanical torques acting on the shaft are equal in magnitude.
- In Fig. (a) with small positive droop, a change of frequency brings the system back to the equilibrium point.
- In Fig. (b) with a small negative droop, a change on frequency results in system instability.
Block Diagram Transformation

<table>
<thead>
<tr>
<th>Original block diagrams</th>
<th>Equivalent block diagrams</th>
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<tr>
<td>1</td>
<td>A (-\rightarrow) A-B (-\rightarrow) A-B+C</td>
</tr>
<tr>
<td>2</td>
<td>A (-\rightarrow) A-B (-\rightarrow) A-B+C</td>
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<tr>
<td>3</td>
<td>A (-\rightarrow) G (-\rightarrow) G1 G2</td>
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<td>4</td>
<td>A (-\rightarrow) G (-\rightarrow) G1 G2</td>
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<td>6</td>
<td>A (-\rightarrow) G (-\rightarrow) A G-B</td>
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<td>7</td>
<td>A (-\rightarrow) A-B (-\rightarrow) A-B (-\rightarrow) G (-\rightarrow) A G-B</td>
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<td>13</td>
<td>A (-\rightarrow) G (-\rightarrow) A</td>
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Derive the transfer function of the system below.
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 $R$ represent 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 ($t \to \infty$, $s \to 0$), Fig. (b) is simplified to Fig. (c). Assuming linearity between valve position and mechanical power, 

$$\frac{\Delta \omega}{\omega_n} = -(R/\omega_n) \Delta c = -\rho \Delta c = -\rho \Delta P_m / P_n$$
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 ±10% with 32 steps - each corresponds to (5/8)%. 

Diverter and Selector Switch Combined into One Unit.
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 lightly-loaded 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

- TCR/TSR (a)
- TSC (b)
- TCR/FC (c)
- TSC/TCR (d)
FACTS Devices: STATCOM
FACTS Devices: BESS
FACTS Devices: TCBR
FACTS Devices: UPFC
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** (for short line) uses pilot wires and analog signals.
- **Interlock scheme** (for longer lines) uses power line carrier (PLC) - high frequency (20-200 kHz) logic signals – need for line traps.
- **Phase comparison scheme** (i.e., phase angle between currents at both ends of the line) 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.
  - 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 (pole-slip 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 non-electrical 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.
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.