Lesson 11
Power System Controls
Generator Voltage Control
Turbine-Governor Control
Load-Frequency Control
Economic Dispatch

Introduction
• We look briefly at local generation control and system-wide load-frequency control and economic dispatch of generation

Generator Voltage Control
• Excitation system consists of
  – Exciter: a device that supplies field current to the generator
    • conventional dc generator
    • ac generator feeding a rectifier
    • controlled rectifier supplied from the main generator

– Voltage regulator:
  • Feedback controller that attempts to regulate the main ac generator terminal voltage by controlling the exciter through any amplifiers
  • Excitation system block diagram shown below
Excitation system block diagram shown below

Voltage Regulator → Exciter

Desired Voltage

---

Power system stabilizer

Helps stabilize system from small-signal instabilities, especially for systems with long heavily loaded lines.

\[ \Delta V_{\text{ref}} - \Delta V_{\text{meas}} \]

\[ \frac{k_{e}}{1+sT} \]

\[ s \]

\[ \Delta \delta \]

\[ \Delta E_{\text{fd}} \]

Generator connected to system

\[ \Delta \delta \]

\[ |V_a| \]

Speed deviations (measured)

---

Automatic Generation Control (AGC)

- Load Frequency Control (LFC)
  - Control of active power
- Economic Dispatch (ED)
  - At a slower rate, the production costs are minimized (within constraints) by ED

---

Load Frequency Control (LFC)

- Two components of control
  - Primary control is action of local unit speed governors:
    - As load increases, the speed drops slightly while the generated power increases
  - Secondary control is action of LFC
    - As load changes, maintain system frequency
    - Adjust generation so that each control area satisfies its own load
    - Both LFC functions performed by using Area Control Error (ACE)
Normal AC System Operation
• We assume the generating units run in step, and exchange synchronizing power over the transmission network
  – Synchronizing power tends to keep the units running in step at the same frequency
  – The system operates with all units at the same frequency and synchronized with each other

Power Control Modeling
• Speed Governor
  – Watt’s steam engine used a mechanical governor
  – Some generators use mechanical-hydraulic governors
  – Many recent generators use electro-hydraulic governors

Block diagram of governor-turbine system (small signal)
• Simplified models
  – governor, turbine, inertia, generator

Two generators (continued)
• Simplified equations (first-order effects):
  – Synchronizing power coefficients:
    \[ T_{21} = T_{12} = |V_1| |V_2| B_{12} \cos(\theta_1 - \theta_2) \]
  – Governor-turbine block diagram:
  – Generator block diagram:

Two generators (continued)
• Synchronizing power coefficients:
  – Governor-turbine block diagram:
    \[ G_{M1}(s) = \frac{1}{(1+sT_{G1})(1+sT_{T1})} \]
    \[ G_{M2}(s) = \frac{1}{(1+sT_{G2})(1+sT_{T2})} \]
  – Generator block diagram:
    \[ G_{P1}(s) = K_{p1} / (1+sT_{P1}) \]
    \[ G_{P2}(s) = K_{p2} / (1+sT_{P2}) \]
Control Areas

- Control area is a generating utility, a part or a group of utilities that operate as if one
- Some areas use Independent System Operators or regional Power Pools for control areas
- Others use individual operating companies and agencies (changes are imminent)

Area Control Error (ACE)

- Lump all generation in a control area into one equivalent generator (approximation)
  \[ \Delta P_{ij} \text{ is now the increase in power from area} \, i \, \text{to area} \, j \]

Area Control Error (ACE)

- Area control error (ACE) is defined:
  \[ ACE_i = \sum_k \Delta P_{ik} + B_i \Delta f \]
  - \( B_i \) is area \( i \)'s frequency bias setting \( [\text{MW}/0.1\text{Hz}] \)
  - This is called frequency biased tie-line control

Bias settings

- For each area, the frequency bias \( B \) is set equal to the \( \beta = -\Delta P_i/\Delta f \) = decrease in area load as frequency increases
- This forces each area to pick up its own load increases, while the system drives the frequency back to 60 Hz with integral control

Two-area block diagram
Example

- Simplified two-area system
  - Area 1 has a peak demand (load) of about 4 GW and $B_1 = 60$ MW/0.1Hz
  - Area 2 has a peak demand of about 18 GW and $B_2 = 180$ MW/0.1Hz

\[ \Delta P_{12} = \Delta P_{g1} - \Delta P_1 = -3.75 \text{ MW} \]
\[ \Delta P_{21} = \Delta P_g - \Delta P_2 = 3.75 \text{ MW} \]
\[ \text{ACE}_1 = \Delta P_{12} + B_1 \Delta f = -5 \text{ MW} \]
\[ \text{ACE}_2 = \Delta P_{21} + B_2 \Delta f = 0 \text{ MW} \]
\[ \Delta P_{g1} = -\text{ACE}_1 = 5 \text{ MW} \]
\[ \Delta P_{g2} = -\text{ACE}_2 = 0 \]

A new $\Delta f$ will put $f$ at 60 Hz and both ACE values at zero.

Example

- Simplified two-area system
  - Let $\Delta P_1 = 5$ MW and $\Delta P_2 = 0$ MW
  - $\Delta f = (\Delta P_1 + \Delta P_2)/(B_1 + B_2)$
    - $= -0.021$ (0.1 Hz)
  - $\Delta P_{g1} = -B_1 \Delta f = 1.25$ MW
  - $\Delta P_{g2} = -B_2 \Delta f = 3.75$ MW

Economic Dispatch (ED)

- Minimize fuel cost (all thermal generation), neglect transmission loss
- Assume incremental fuel cost is known
- Minimum fuel cost is when all units operate at the same incremental cost
- Units above max (below min) limits will operate fixed at the limit, dispatch others

Incremental cost [$/\text{MWhr}$]

\[ \text{IC}_1 \text{ IC}_2 \text{ IC}_3 \]

All units are being dispatched

Incremental cost [$/\text{MWhr}$]

\[ \text{IC}_1 \text{ IC}_2 \text{ IC}_3 \]

Units 1 and 2 are being dispatched while unit 3 is fixed at its upper limit
Equal IC Rule

- Constraint (generation=load):
  \[ P_{g1} + P_{g2} + P_{g3} = P_d \]
  or \[ P_{g3} = P_d - P_{g1} - P_{g2} \]
- Total fuel cost to be minimized
  \[ C_t = C_1 + C_2 + C_3 \]
  \[ \frac{\partial C_t}{\partial P_{g1}} = 0 = \frac{dC_1}{dP_{g1}} - \frac{dC_3}{dP_{g3}} \]
  where constraint was used in 2\text{nd} term

Equal IC rule

- Same analysis applies for each unit
  – Thus all units should operate at equal incremental cost to minimize the total fuel cost of the system
  – Reliability, pollution constraints, and other operating constraints may cause deviations from optimum
  – The derivation can be formalized by method of Lagrange multipliers

Line Losses

- Penalty factors are used for line losses
  \[ IC_i = dC_i/dP_{gi} \] = incremental cost of unit \( i \)
  \[ L_i = 1/(1 - \partial P_{loss}/\partial P_{gi}) \] = penalty factor \( i \)
  Except \( L_1 = 1 \) (since it is the slack bus)

Line Losses

- Penalty factors are used for line losses
  Equal penalized incremental costs
  \[ L_1 IC_1 = L_2 IC_2 = L_3 IC_3 \]
- Calculation of penalty factors and consideration of energy markets is beyond our scope