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Instructor: Zhenyu (Henry) Huang
(509) 438-7235, h_zyu@yahoo.com

EE 521: Analysis of Power Systems

Lecture 21
Frequency Control

Fall 2009

Mondays & Wednesdays 5:45-7:00

August 24 – December 18

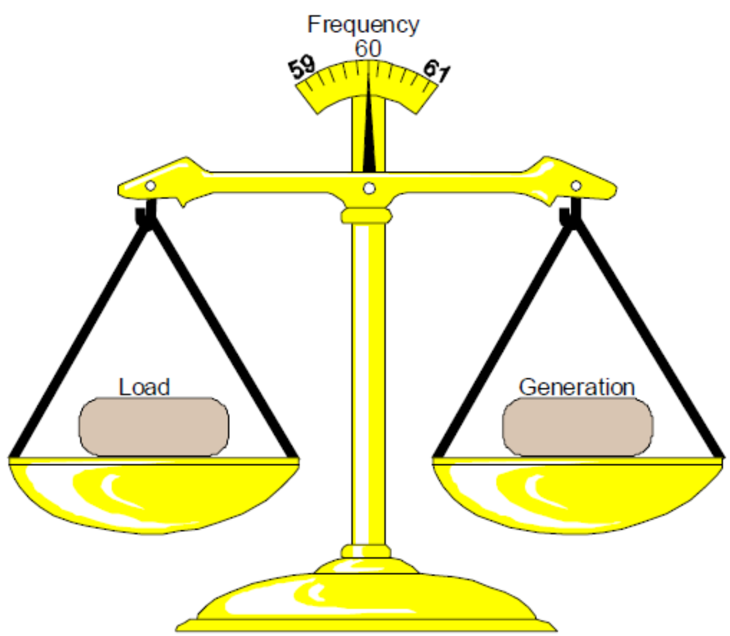
Test 216

Topics

- Governor Control
  - Droop
  - Load distribution among generators
- Automatic Generation Control
- Area Control Error
  - ACE calculation per three AGC modes

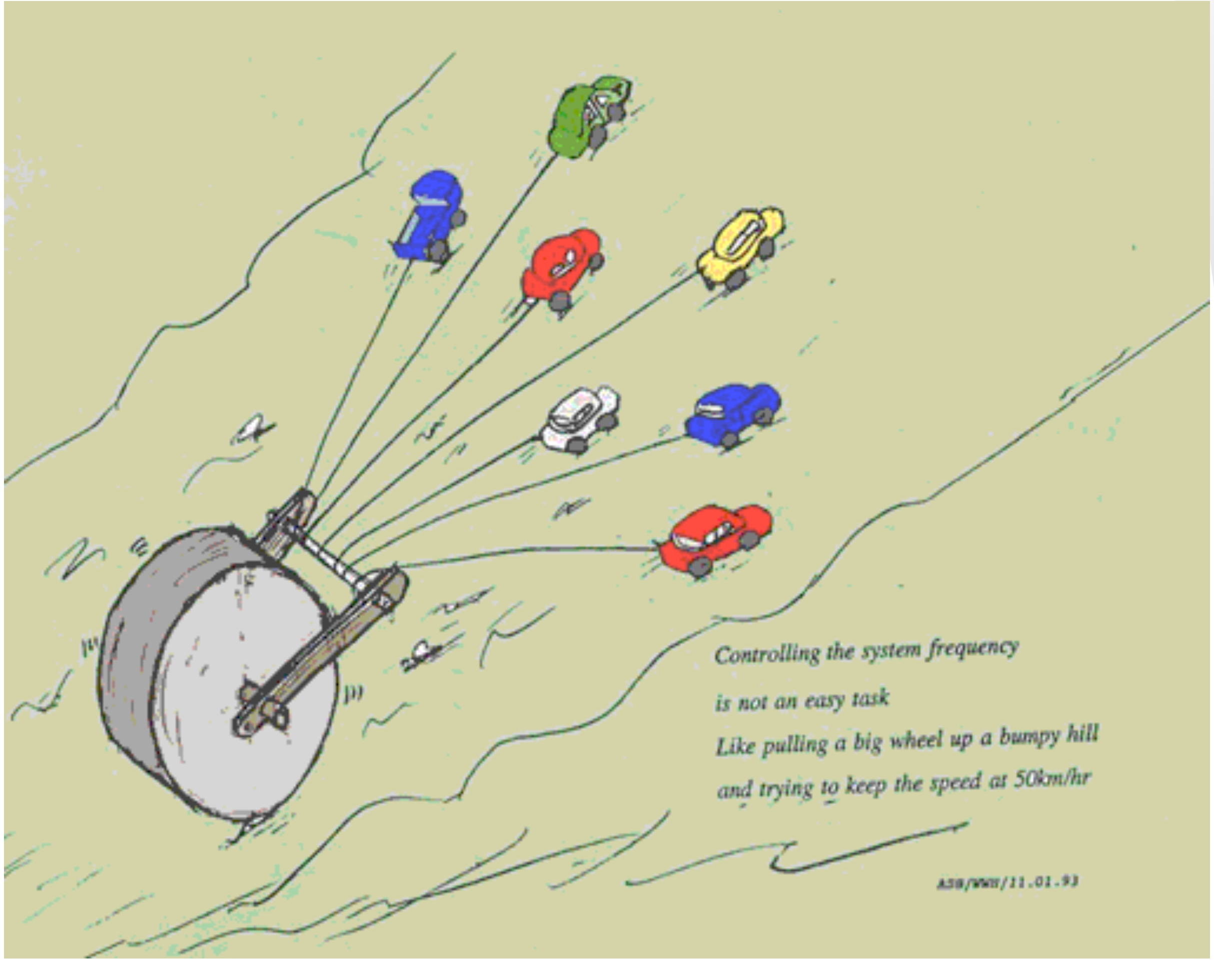
Why Frequency Control?

- Generation and Load Balance
  - By maintaining 60 Hz, we can make sure that the power produced is equal to the power consumed without measuring generation, loads, and losses on a real time basis.
- Equipment Protection
  - Abnormal frequencies can damage electrical equipment, especially high-speed turbines.



Source: WECC Operator Training.

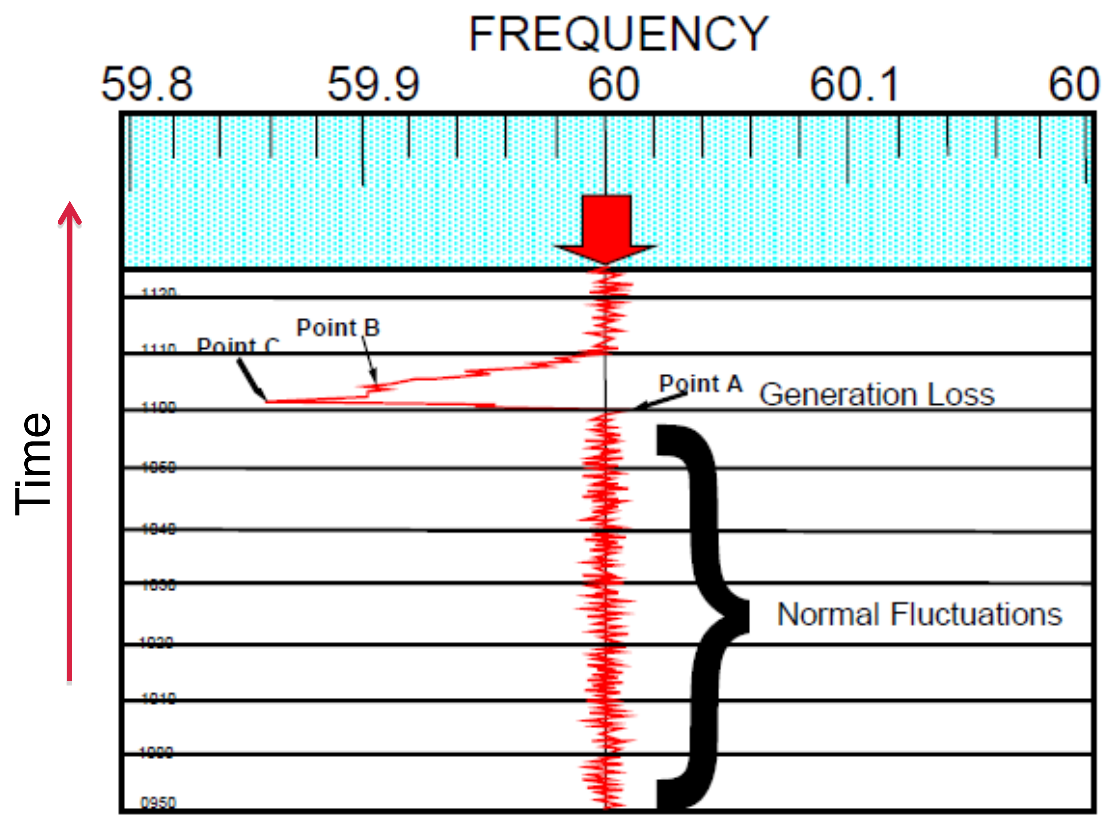
The Challenge of Frequency Control



Source: The Automatic Earth blog.

Typical Frequency Deviation

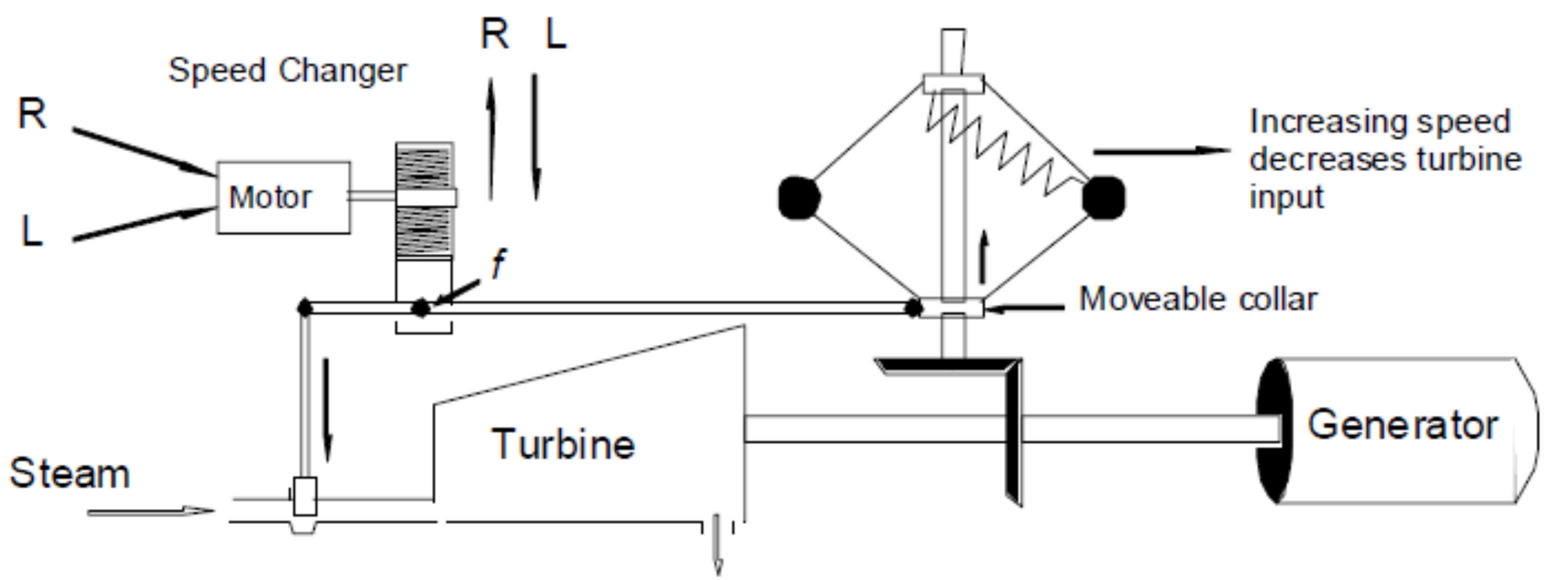
- Rotor dynamic response (Swing Equation)
  - Point A → C
- Governor response
  - Point C → B
- AGC response
  - Point B → steady state



Source: WECC Operator Training.

Governor

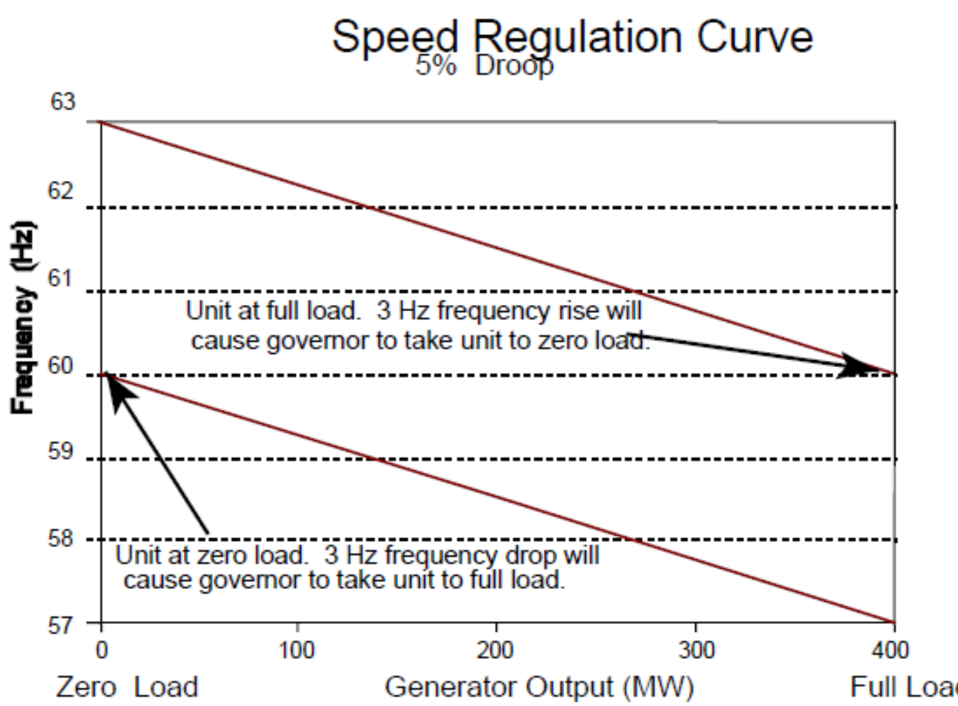
- To maintain generation-load balance
- NOT to restore frequency to 60 Hz!



Source: WECC Operator Training.

Droop

- R: Frequency change w.r.t. MW change: Hz/MW
- R_u: Per-unit Droop: x% (e.g. 3%, 5%, …)
- Relative to operating point!



$$R = -\frac{\Delta f}{\Delta P_G} \quad \text{in Hz/MW}$$

$$R_u = -\frac{\Delta f / f_{Base}}{\Delta P_G / P_{G,Base}} \quad \text{in \%}$$

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Example: Droop (Single Generator Case)

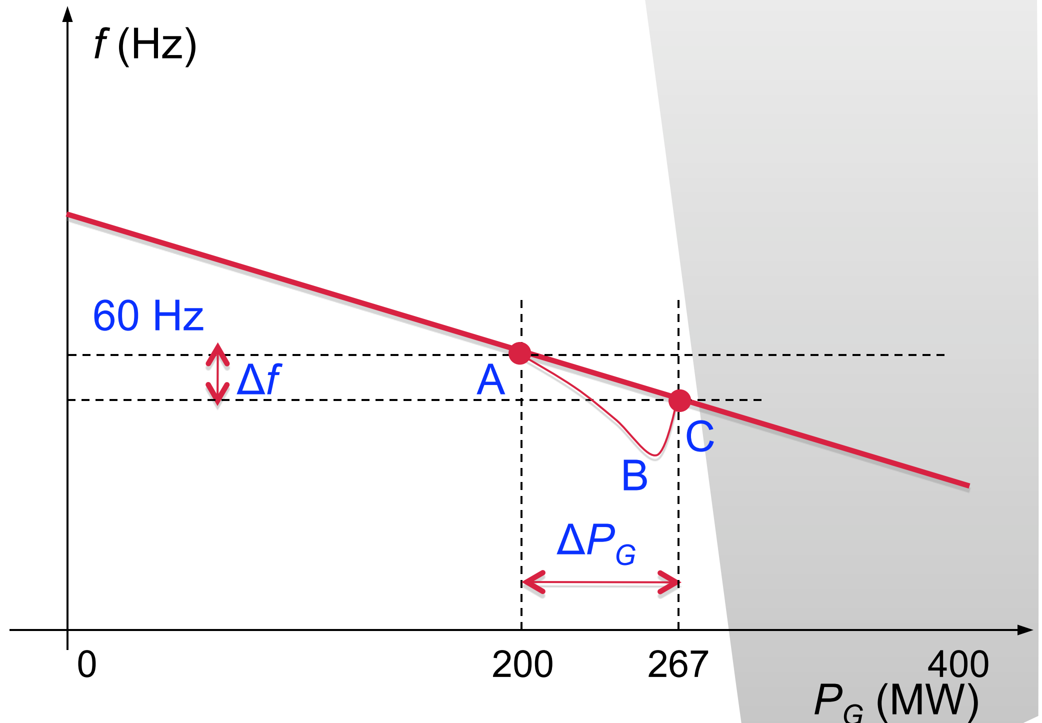
Problem: A generator with 5% droop as shown in the figure serves a load. In the condition of a sudden load increase of 67 MW, describe the frequency deviation and governor response.

Solution:

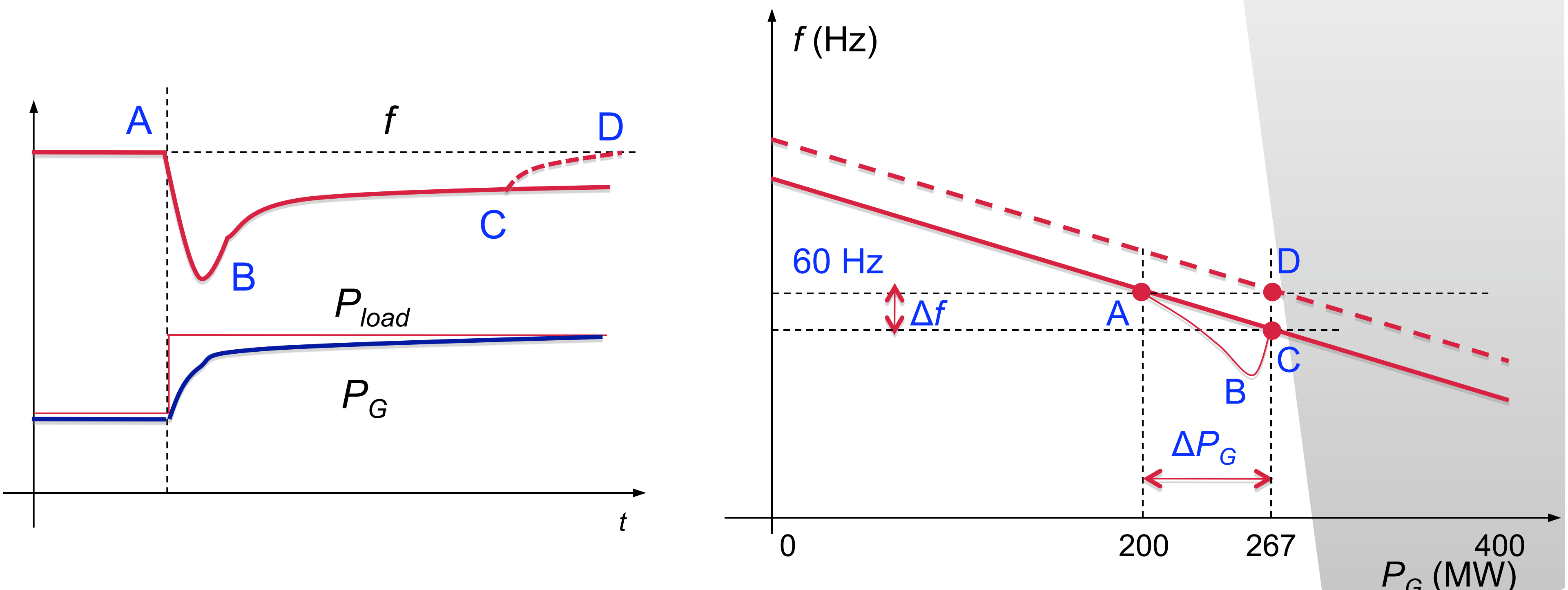
1. Prior to governor response, the generator decreases its speed and releases kinetic energy to meet load demand. (Point B)
2. Governor responds per the droop curve. (Point C)

$$R_u = -\frac{\Delta f / f_{Base}}{\Delta P_G / P_{G,Base}} \quad \text{in } \%$$

$$\Delta f = -R_u\left(\Delta P_G / P_{G,Base}\right) f_{Base}$$
$$= -5\%(67/400)60 = -0.5 \text{ Hz}$$



Time-Domain Picture of Droop Characteristics



Question: How to restore frequency to 60 Hz? (Point D)

Load Division

- For multiple generators in a system, load will be divided per their respective droop characteristics.

Generator 1 Generator 2 Generator *N*

$$R_{u1} = -\frac{\Delta f / f_{Base}}{\Delta P_{G1} / P_{G1,Base}} \qquad R_{u2} = -\frac{\Delta f / f_{Base}}{\Delta P_{G2} / P_{G2,Base}} \qquad \cdots \qquad R_{uN} = -\frac{\Delta f / f_{Base}}{\Delta P_{GN} / P_{GN,Base}}$$

$$\Rightarrow \Delta P_{G1} = -\frac{\Delta f / f_{Base}}{R_{u1} / P_{G1,Base}}$$

$$\Rightarrow \Delta P = \sum \Delta P_{Gi} = -(\Delta f / f_{Base}) \sum \left(\frac{1}{R_{ui} / P_{Gi,Base}} \right) \quad \Rightarrow \quad \Delta f = -f_{Base} \, \Delta P \Big/ \sum \left(\frac{1}{R_{ui} / P_{Gi,Base}} \right)$$

$$\Rightarrow \Delta P_{G1} = \Delta P \frac{1}{R_{u1} / P_{G1,Base}} \Big/ \sum \left(\frac{1}{R_{ui} / P_{Gi,Base}} \right) \qquad \cdots$$

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Example: Droop (Multi-Generator Case)

Problem (Textbook 13.6): Two generators serve 700 MW load.

Unit 1: rated 600 MW, output 400 MW, 4% droop

Unit 2: rated 500 MW, output 300 MW, 5% droop

If load increases to 800 MW, determine new unit loading and new system frequency.

Solution:

Generator loading change:

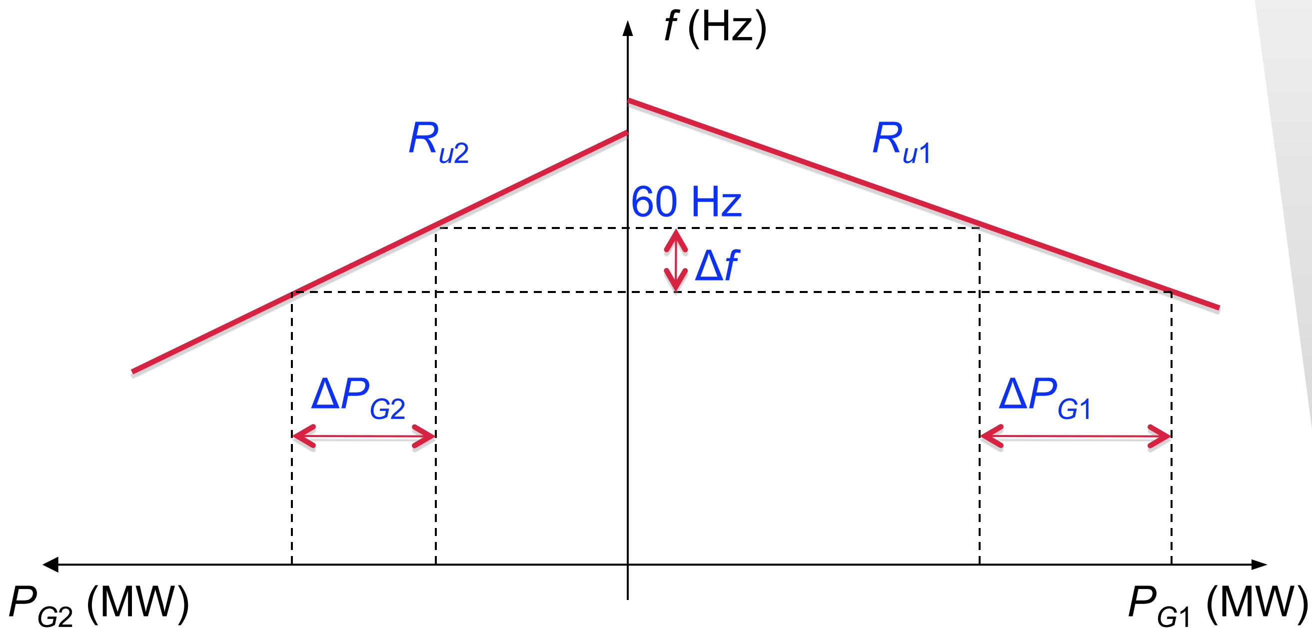
$$\Delta P_{G1} = \Delta P \frac{1}{R_{u1}/P_{G1,Base}} \Big/ \sum\left(\frac{1}{R_{ui}/P_{Gi,Base}}\right) = 100\frac{1}{4\%/600} \Big/ \left(\frac{1}{4\%/600} + \frac{1}{5\%/500}\right) = 60\ \text{MW}$$

$$\Delta P_{G2} = \Delta P \frac{1}{R_{u2}/P_{G2,Base}} \Big/ \sum\left(\frac{1}{R_{ui}/P_{Gi,Base}}\right) = 100\frac{1}{5\%/500} \Big/ \left(\frac{1}{4\%/600} + \frac{1}{5\%/500}\right) = 40\ \text{MW}$$

System frequency change:

$$\Delta f = -f_{Base}\,\Delta P \Big/ \sum\left(\frac{1}{R_{ui}/P_{Gi,Base}}\right) = -60 \bullet 100 \Big/ \left(\frac{1}{4\%/600} + \frac{1}{5\%/500}\right) = -0.24\ \text{Hz}$$

Load Division (Graphic Explanation)



Question: How to restore frequency to 60 Hz?

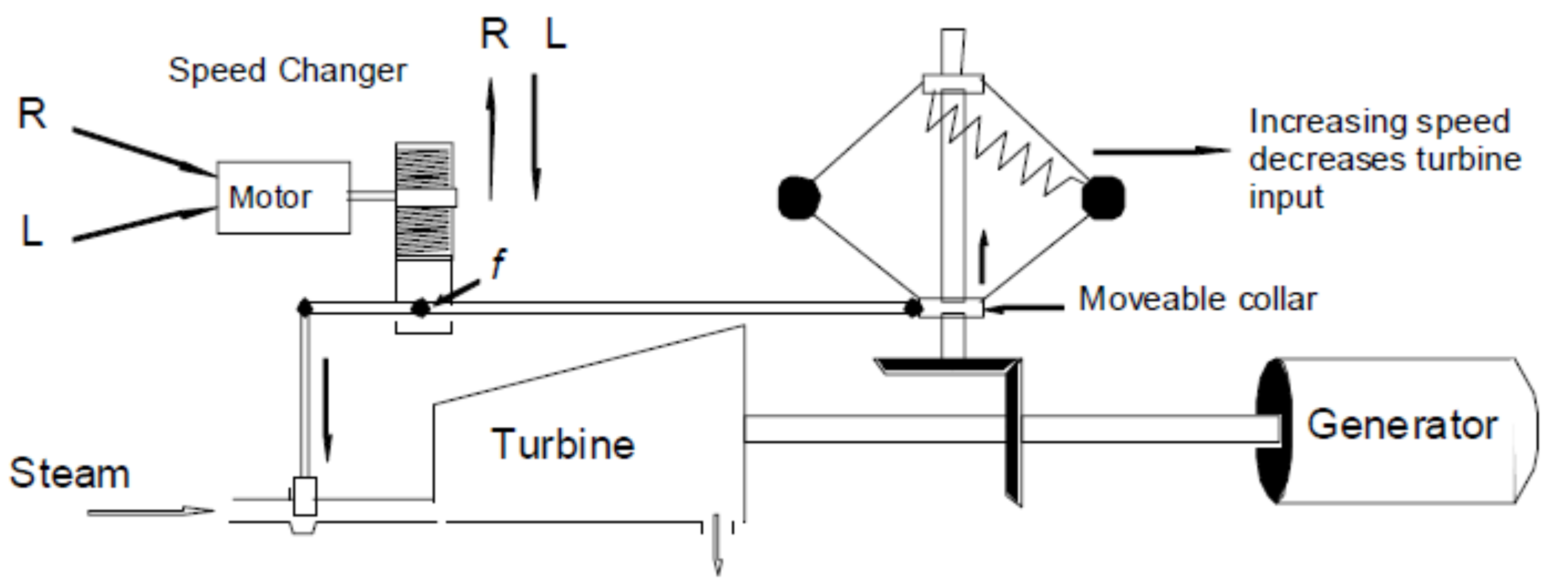
Automatic Generation Control

- Restore frequency to 60 Hz!
  - With objective to optimize cost through economic dispatch.
- Maintain scheduled interchange.

- Other AGC functions:
  - Hydrothermal optimization
  - Inter-area exchange negotiation
  - Transfer generation
  - Interconnected system balance

Speed Changer

- AGC resets the governor reference point by raising/ lowering the pivotal point.

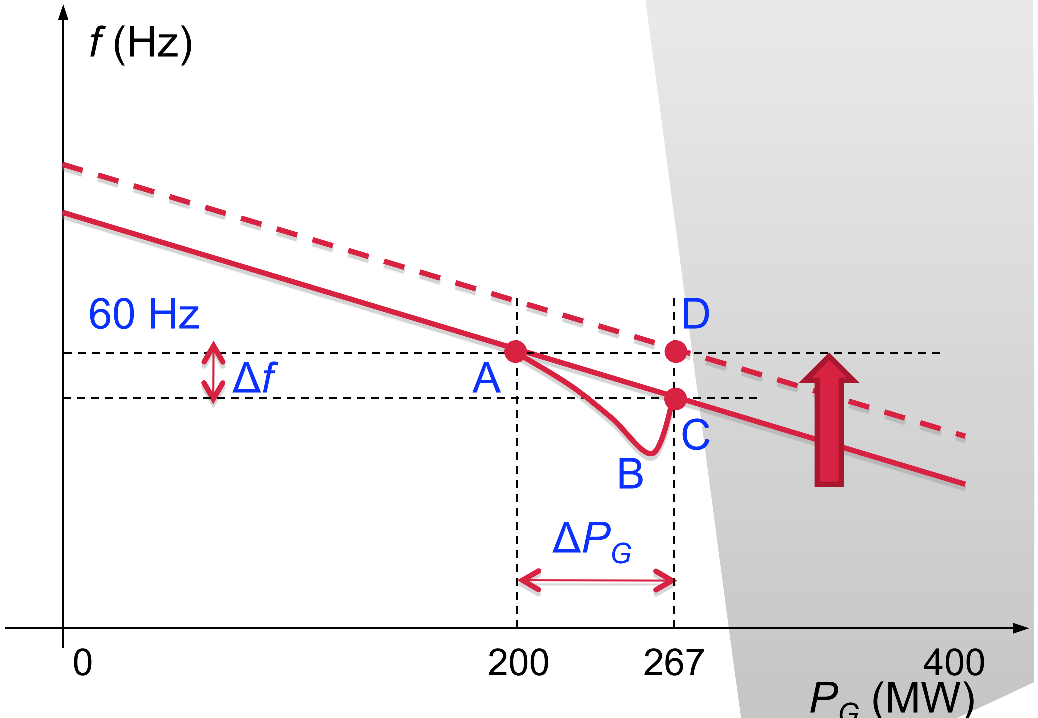


Source: WECC Operator Training.

AGC (One-Generator Case)

- Speed changer raises/lowers the droop curve so the speed restores to ensure frequency to be 60 Hz.

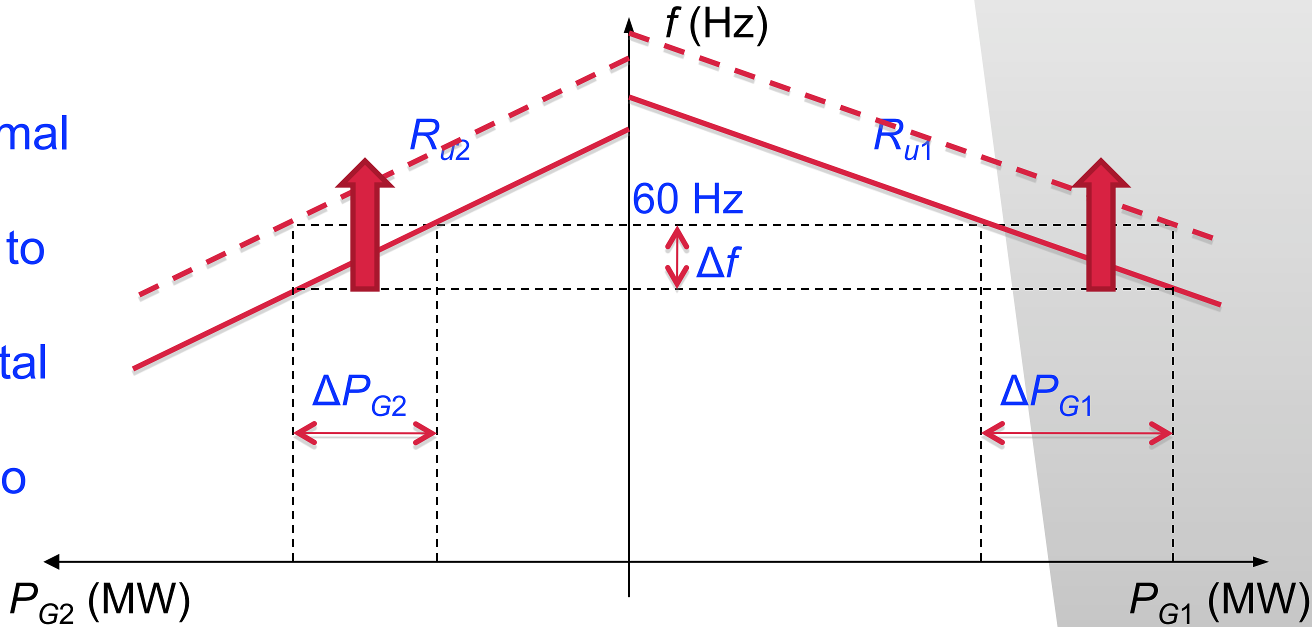
1. Prior to governor response, the generator decreases its speed and releases kinetic energy to meet load demand. (Point C)
2. Governor responds per the droop curve. (Point B)
3. AGC sends a signal to the speed changer to raise the pivotal point.
4. Frequency returns to 60 Hz. (Point D)



AGC (Multi-Generator Case)

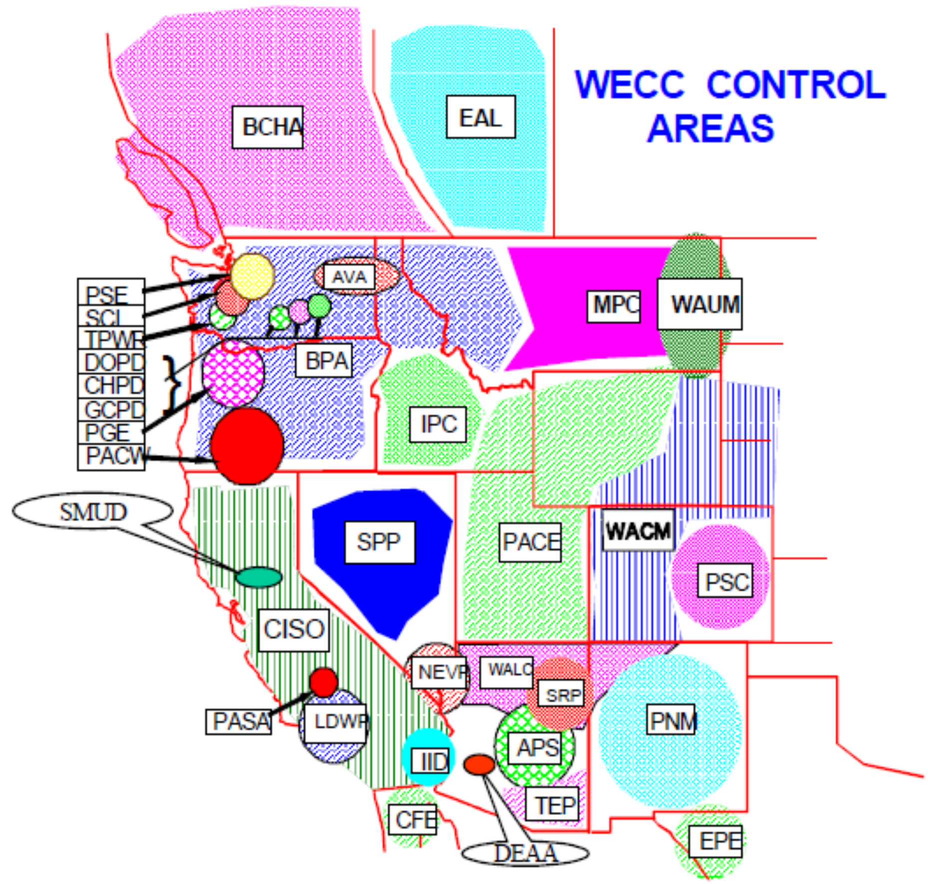
- Speed changer raises/lowers one or multiple droop curves so the speed restores to ensure frequency to be 60 Hz.

1. Economic dispatch determines the optimal allocation of load.
2. AGC sends signals to speed changers to raise/lower the pivotal point.
3. Frequency returns to 60 Hz.



Control Area

- Control Area (NERC Definition)
  - A system which regulates its generation in order to maintain its interchange schedule with other systems and contributes its frequency bias obligation to the Interconnection



Source: WECC Operator Training.

Area Control Error (ACE)

- Area Control Error (ACE) is an error value to measure the difference between actual and desired conditions of frequency and interchange.
- Each control area has an ACE
  - ACE ≠ 0 ➔ AGC actions until ACE = 0
  - ACE < 0 ➔ insufficient generation in this control area ➔ AGC sends raise pulses to the units to increase generation in this control area.
  - ACE > 0 ➔ excessive generation in this control area ➔ AGC sends lower pulses to the units to decrease generation in this control area.

ACE Calculation

- ACE has a unit of MW.
- AGC Control Modes
  - Flat Tie-line Control: used only when system frequency resources are not available

$$ACE = P_A - P_S$$

  - Flat Frequency Control: used only when the control area is isolated from the system

$$ACE = -10B_f\left(f_A - f_S\right)$$

  - Tie-line Bias: normal operation mode

$$ACE = \left(P_A - P_S\right) - 10B_f\left(f_A - f_S\right)$$

Example: ACE Calculation I

Problem (Textbook 13.7): Three control areas with AGCs in tie-line bias mode.

Area A: rated 16,000 MW, 2% droop, B_{fA} = −1200 MW/0.1 Hz, P_{SA} = 0 MW
Area B: rated 12,000 MW, 1.25% droop, B_{fB} = −1500 MW/0.1 Hz, P_{SB} = 500 MW
Area C: rated 6,400 MW, 1% droop, B_{fC} = −950 MW/0.1 Hz, P_{SC} = −500 MW

If Area B loses 400-MW generation, determine frequency and generation change, and calculate ACE for each control area.

Solution:

System frequency change and generation change in each control area:

$$\Delta f = -f_{Base}\,\Delta P \Big/ \sum\left(\frac{1}{R_{ui}/P_{Gi,Base}}\right) = 0.01\ \text{Hz}$$

$$\Delta P_{GA} = \Delta P\frac{1}{R_{uA}/P_{GA,Base}} \Big/ \sum\left(\frac{1}{R_{ui}/P_{Gi,Base}}\right) = 133\ \text{MW} \qquad \Delta P_{GB} = 160\ \text{MW} \qquad \Delta P_{GC} = 107\ \text{MW}$$

ACEs:

$$ACE_A = \left(P_{A,A} - P_{SA}\right) - 10B_{fA}\left(f_A - f_S\right) = (133-0) - 10(-1200)(-0.01) = 13\ \text{MW}$$

$$ACE_B = \left(P_{A,B} - P_{SB}\right) - 10B_{fB}\left(f_A - f_S\right) = (260-500) - 10(-1500)(-0.01) = -390\ \text{MW}$$

$$ACE_C = \left(P_{A,C} - P_{SC}\right) - 10B_{fC}\left(f_A - f_S\right) = \left(-393-(-500)\right) - 10(-950)(-0.01) = 12\ \text{MW}$$

Example: ACE Calculation II

Problem: Conditions same as Textbook 13.7. Calculate ACE for each control area for 1) flat tie-line control mode; and 2) flat frequency control mode.

Solution:

1) Flat tie-line control mode:

$$
\begin{aligned}
ACE_A &= \left(P_{A,A} - P_{SA}\right) = \left(133 - 0\right) = 133 \text{ MW} \\
ACE_B &= \left(P_{A,B} - P_{SB}\right) = \left(260 - 500\right) = -240 \text{ MW} \\
ACE_C &= \left(P_{A,C} - P_{SC}\right) = \left(-393 - \left(-500\right)\right) = 107 \text{ MW}
\end{aligned}
$$

2) Flat frequency control mode:

$$
\begin{aligned}
ACE_A &= -10B_{fA}\left(f_A - f_S\right) = -10\left(-1200\right)\left(-0.01\right) = -120 \text{ MW} \\
ACE_B &= -10B_{fB}\left(f_A - f_S\right) = -10\left(-1500\right)\left(-0.01\right) = -150 \text{ MW} \\
ACE_C &= -10B_{fC}\left(f_A - f_S\right) = -10\left(-950\right)\left(-0.01\right) = -95 \text{ MW}
\end{aligned}
$$

Relevant Operating Standards

- Control Performance Standard
  - CPS1: Over a year, the average of the clock-minute averages of a control area's ACE divided by $-10B_f$ times the corresponding clock-minute averages of Interconnection's frequency error shall be less than a specific limit, ε.
  - CPS2: The average ACE for each of the six ten-minute periods during the hour (i.e., for the ten-minute periods ending at 10, 20, 30, 40, 50, and 60 minutes past the hour) must be within specific limits, referred to as L10.
- NERC Operating Policies and WECC Minimum Operating Reliability Criteria (MORC)
  - 1. Generation Control and Performance
  - 2. Transmission
  - 3. Interchange
  - 4. System Coordination
  - 5. Emergency Operations
  - 6. Operations Planning
  - 7. Telecommunications
  - 8. Operator Personnel and Training
  - 9. Security Coordinator Procedures

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Questions?