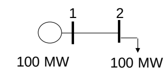
24: Frequency Control

text: 11.6 – 11.12

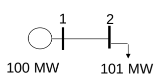
Frequency Control

- We now look at how the frequency is controlled in the network
- Consider the lossless system operating at 60 Hz with:
  - P_{G1} = 100 MW
  - P_{D2} = 100 MW



Frequency Control

- What happens if the load suddenly increases to 101 MW?
- If the power supplied to the generator's prime mover does not change, we have a mismatch of power between load and generation
- Where does this power come from?



Frequency Control

- Answer: the power is extracted from the rotating mass of the generator itself, causing it to slow in rotation (and eventually stop, if nothing is done)

$$T_m - T_e = J\frac{d\omega_{rm}}{dt}$$

  - T_m: mechanical torque from the prime mover
  - T_e: electromagnetic counter torque
  - J: mass polar moment of inertia of all rotating parts
  - ω_{rm}: rotor shaft velocity in mechanical rad/s

Frequency Control

- Multiply by ω_{rm} to get:

$$P_m - P_e = \omega_{rm} J\frac{d\omega_{rm}}{dt}$$

  - P_m: mechanical power from the prime mover
  - P_e: electromagnetic power torque
- So, if $P_e > P_m$, then the rotor slows down
  - frequency drops
- What happens to the frequency if the load decreases to 99 MW ?
  - frequency increases

Frequency Control

- Fluctuating frequency is not desirable
  - damages equipment
  - output power of pumps, fans, etc depend on system frequency
  - etc
- How do we prevent frequency deviations?
  - use deviation as a control signal to cause increases or decreases in prime mover power
  - essentially, we match generation with load
  - primary control: governor action to increase or decrease valve positions

Frequency Control

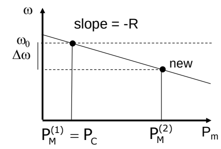
- Governor: see figure 11.1 in text for physical description of the governor
- The action of the governor can be simplified as

$$\Delta P_m = \Delta P_c - \frac{1}{R}\Delta\omega$$

  - ΔP_c : change in command input
  - R: regulation constant (Hz/MW) or (rad/sec/p.u. power) or just p.u.
  - $\Delta\omega$: change in system frequency

Frequency Control

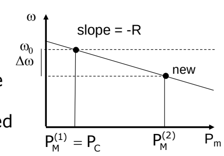
- Let ω_0 be the nominal frequency
- Let $P_m = P_c$ (the generator is operating at its set-point)
- Now, the load increases causing decrease in frequency of $\Delta\omega$
- The governor action increases the P_m to settle on a new operating point



$$\Delta P_m = \Delta P_c - \frac{1}{R}\Delta\omega$$

Frequency Control

- A common term is "droop": the variation of frequency with P_m and is related to R
- The less droop, the better the regulation
- If all the generators in the system are properly controlled, the power in the system returns to balance
- Additional control is required to increase the frequency back to nominal (and P_C changes)



$$\Delta P_m = \Delta P_c - \frac{1}{R}\Delta\omega$$

Example

- Let R = 0.05 p.u. (also expressed as a percent)
- Suppose the frequency changes from 60 Hz to 59 Hz, what is the corresponding change in P_m? (assume there is no change in control signal)

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$$\Delta P_m = \Delta P_c - \frac{1}{R}\Delta\omega$$

← since R is in per unit, so should $\Delta\omega$

$$\Delta P_m = 0 - \frac{1}{0.05}\left(\frac{-1}{60}\right)$$

$$\Delta P_m = 0.3333 \text{ p.u.}$$

Example

- If it was a 100 MW unit, the new power output would be 133 MW
- At what change in frequency would P_m change from 0 to 1 p.u. (no load to full load)?

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$$\Delta P_m = \Delta P_c - \frac{1}{R}\Delta\omega$$

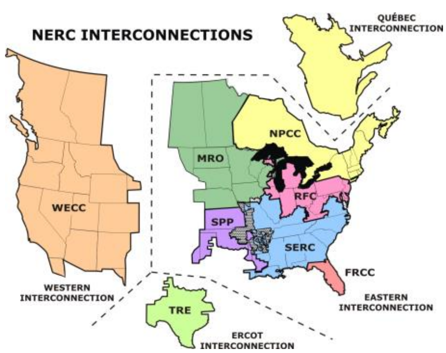
$$1 = \frac{1}{0.05}(\Delta\omega)$$

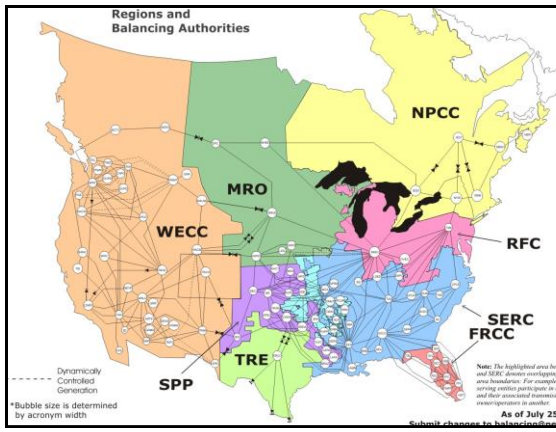
$$\Delta\omega = 0.05 \text{ p.u.}$$

$$\omega = 57 \text{ Hz}$$

Frequency Control

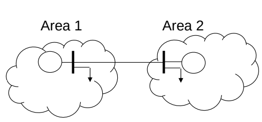
- How are the power command are determined by control area
- Control areas: groups of closely coupled generators
  - each control area is weakly coupled to other control areas
  - this greatly simplifies the model of the interconnected power system





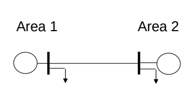
Frequency Control

- Consider two control areas
- Each control area can have many generators and loads, though they are not explicitly modeled. However, tie line connections are.
- Control areas can be used in the analysis of power pools



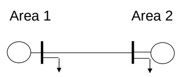
Frequency Control

- A power pool is an interconnection of utilities
- Each operates independently within its jurisdiction, but there exist contractual agreements regarding inter-company exchanges of power and operating procedures to maintain system frequency



Frequency Control

- Basic principles of pool operation:
  - scheduled tie-line power interchanges are maintained
  - each area absorbs its own load changes
- These objectives do not apply to transients (faults, etc)

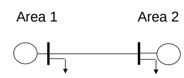


Frequency Control

- A slight digression…
- Assume that the tie-line carrying P_{12} from Area 1 to Area 2 is lost
- Change in frequency in Area 1 is

$$\Delta\omega_{1ss} = \frac{P_{12}}{\beta_1}$$

  - ω_{1ss}: steady state frequency
  - β_1: frequency characteristic of Area 1



Frequency Control

- A similar expression for the change in steady state frequency in Area 2 can be found to be:

$$\Delta\omega_{2ss} = \frac{-P_{12}}{\beta_2}$$

- Now assume the line is added and the frequency in both areas is returned to normal
- If there is a sudden change in load in Area 2, P_{L2} and the tie-line power flow is not allowed to change then

$$\Delta\omega_2 = \frac{-\Delta P_{L2}}{\beta_2}$$

$$\Delta\omega_1 = 0$$

Frequency Control

- If we allow the power to change, then

$$\Delta\omega_2 = \Delta\omega_1 = \frac{-\Delta P_{L2}}{\beta_1 + \beta_2}$$

and the tie-line power flow will also increase
- We can restore the system frequency to nominal by adjusting P_C^1 and P_C^2 (the command signals for each area)
- To determine the values, we are guided by the principles of pool operation

Frequency Control

- The adjustment of P_C^1 and P_C^2 is done automatically based on tie-line or secondary control
- The control is such that they drive the Area Control Error (ACE) to zero

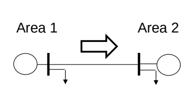
$$ACE_1 = \Delta P_{12} + B_1\Delta\omega$$

$$ACE_2 = \Delta P_{21} + B_2\Delta\omega$$

  - ΔP_{12}, ΔP_{21} are the deviations from the scheduled interchange
  - B_1, B_2 are the frequency bias settings and are positive
  - If load damping is ignored, then $B_1 = 1/R_1$ and $B_2 = 1/R_2$

Frequency Control

- Consider the following scenario with:
- P_{12} positive
- Now assume the load P_{D2} in Area 2 increases



Frequency Control

- In the considered scenario with ΔP_{D2} positive, P_{12} tends to increase above its scheduled value
  - ΔP_{12} is positive
  - ΔP_{21} is negative
- Since frequency is dropping, $\Delta\omega$ is negative

$$ACE_1 = \Delta P_{12} + B_1 \Delta\omega$$

$$ACE_2 = \Delta P_{21} + B_2 \Delta\omega$$

- ACE_2 is negative
- ACE_1 should have a small magnitude

Frequency Control

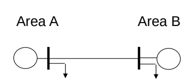
- Since ACE_2 is negative, P_C^2 should increase
- We expect a smaller change for P_C^1
- ACE is used as metric for measuring area performance

Frequency Control

- North American Electric Reliability Corporation (NERC) criteria for control performance require that:
  - ACE must equal zero at least one time in all 10-minute periods
  - average deviation of ACE from zero for all 10-minute periods must be within specified limits based on a percentage of system generation
- Performance criteria for disturbance conditions:
  - ACE must be returned to zero within 10 minutes
  - corrective action must be forthcoming within one minute of a disturbance

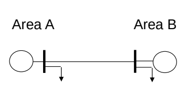
Example

- Area A: P_D = 1000 MW, P_G = 1000 MW, R = 0.015 rad per sec/MW
- Area B: P_D = 10,000 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
- P_{AB} = 0



Example

- A sudden load increase of 10 MW occurs in Area A
- Find the ACE in each area, the change in frequency and the appropriate control signals



Area A: P_D = 1000 MW, P_G = 1000 MW, R = 0.015 rad per sec/MW
Area B: P_D = 10,000 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
P_{AB} = 0

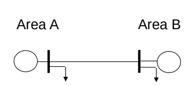
Example

- First find the frequency change:

$$\Delta\omega_A = \Delta\omega_B = \frac{-\Delta P_{DA}}{\beta_A + \beta_B}$$

$$\Delta\omega = \frac{-\Delta P_{DA}}{\beta_A + \beta_B} = \frac{-\Delta P_{DA}}{\frac{1}{R_A} + \frac{1}{R_B}} = \frac{-10}{\frac{1}{0.015} + \frac{1}{0.0015}}$$

$$= -0.0136 \text{ rad/sec}$$



Area A: P_D = 1000 MW, P_G = 1000 MW, R = 0.015 rad per sec/MW
Area B: P_D = 10,000 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
P_{AB} = 0
Load change: 10 MW increase in Area A

Example

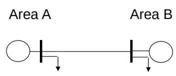
- The generators in each area respond:

$$\Delta P_{GA} = -\frac{1}{R_A}\Delta\omega = -\frac{1}{0.015}(-0.0136) = 0.9091 \text{ MW}$$

$$\Delta P_{GB} = -\frac{1}{R_B}\Delta\omega = -\frac{1}{0.0015}(-0.0136) = 9.091 \text{ MW}$$

- The tie-line change:

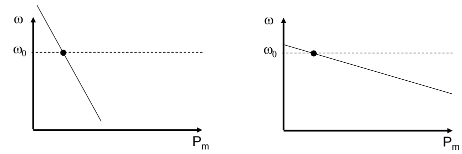
$$\Delta P_{AB} = -\Delta P_{AB} = \Delta P_{GA} - \Delta P_{LA}$$
$$= 0.9091 - 10 = -9.091\text{MW}$$



Area A: P_D = 1000 MW, P_G = 1000 MW, R = 0.015 rad per sec/MW
Area B: P_D = 10,000 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
P_{AB} = 0
Frequency change: -0.0136 rad/sec

Example

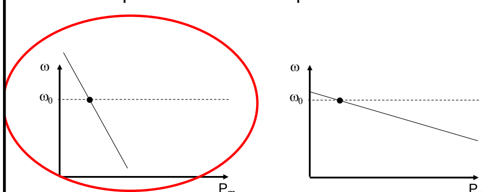
- Which plot shows the response of Area A?



Area A: R = 0.015 rad per MW
Area B: R= 0.0015 rad per MW

Example

- Which plot shows the response of Area A?

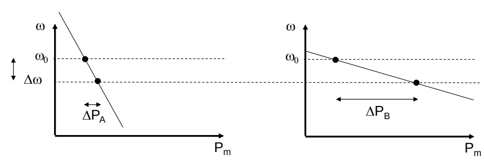


slope: = - R

Area A: R = 0.015 rad per MW
Area B: R= 0.0015 rad per MW

Example

- Area A has less load and generation so it is less capable of regulating large frequency changes

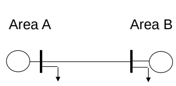


Example

- Now for the ACE

$$ACE_A = \Delta P_{AB} + \frac{1}{R_A}\Delta\omega$$
$$= -9.091 + \left(\frac{1}{0.015}\right)(-0.0136)$$
$$= -9.091 - 0.909 = -10\text{MW}$$

$$ACE_B = \Delta P_{BA} + \frac{1}{R_B}\Delta\omega$$
$$= 9.091 + \left(\frac{1}{0.0015}\right)(-0.0136)$$
$$= 9.091 - 9.091 = 0\text{MW}$$



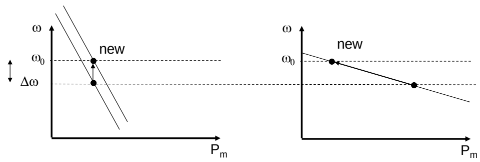
Area A: P_D = 1000 MW, P_G = 1000 MW, R = 0.015 rad per sec/MW
Area B: P_D = 10,000 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
P_{AB} = 0
Frequency change: -0.0136 rad/sec

Example

- power command signals based on the ACEs will result in the generation in Area A increasing by 10 MW
- this matches the change in load and the tie-line flow returns to zero

Example

After supplementary control:



and the frequency is returned to nominal

Example

- Area A: P_D = 1000 MW, P_G = 1100 MW, R = 0.015 rad per sec/MW
- Area B: P_D = 9,900 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
- The load in Area A decreases by 20 MW
- Find the ACE in each area, the change in frequency and the appropriate control signals

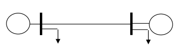
Example

- First find the frequency change:

$$\Delta\omega = \frac{-\Delta P_{DA}}{\beta_A + \beta_B} = \frac{-\Delta P_{DA}}{\frac{1}{R_A} + \frac{1}{R_B}} = \frac{20}{\frac{1}{0.015} + \frac{1}{0.0015}}$$

$$= 0.0273 \text{ rad/sec}$$

Area A Area B



Area A: P_D = 1000 MW, P_G = 1100 MW, R = 0.015 rad per sec/MW
Area B: P_D = 9,900 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
Load change: 20 MW decrease in Area A

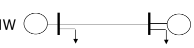
Example

- The generators in each area respond:

$$\Delta P_{GA} = -\frac{1}{R_A}\Delta\omega = -\frac{1}{0.015}(0.0273) = -1.818 \text{ MW}$$

$$\Delta P_{GB} = -\frac{1}{R_B}\Delta\omega = -\frac{1}{0.0015}(0.0273) = -18.18 \text{ MW}$$

Area A Area B



- Tie-line change:

$$\Delta P_{AB} = -\Delta P_{AB} = \Delta P_{GA} - \Delta P_{LA}$$

$$= -1.818 + 20 = 18.182\text{MW}$$

Area A: P_D = 1000 MW, P_G = 1000 MW, R = 0.015 rad per sec/MW
Area B: P_D = 9,900 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
Freq. Change: 0.0273

Example

- Now for the ACE

$$ACE_A = \Delta P_{AB} + \frac{1}{R_A}\Delta\omega$$

$$= 18.182 + \left(\frac{1}{0.015}\right)(0.0273)$$

$$= 18.182 + 1.82 = 20\text{MW}$$

$$ACE_B = \Delta P_{BA} + \frac{1}{R_B}\Delta\omega$$

$$= -18.182 + \left(\frac{1}{0.0015}\right)(0.0272)$$

$$= 0\text{MW}$$

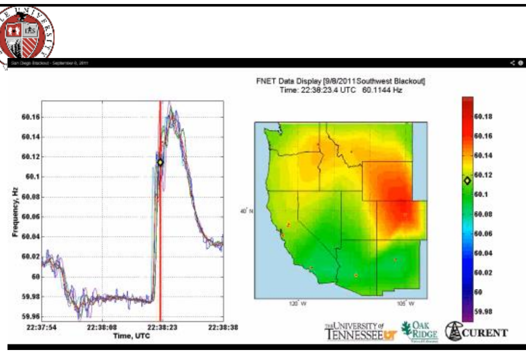
Area A Area B

Area A: P_D = 1000 MW, P_G = 1000 MW, R = 0.015 rad per sec/MW
Area B: P_D = 9,900 MW, P_G = 10,000 MW R= 0.0015 rad per sec/MW
Freq. Change: 0.0273
ΔP_{AB}: 18.182 MW

Frequency Control

- Extension to n-area case:

$$ACE_i = \sum_{j=1}^{n} \Delta P_{ij} + B_i\Delta\omega$$



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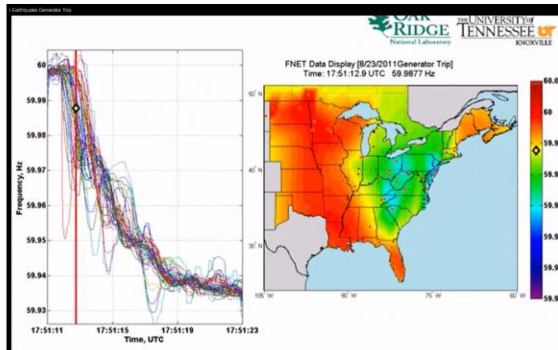

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