ECEN 667
Power System Stability

Lecture 13: Generator Governors

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Announcements

- Read Chapter 4
- Homework 4 is posted; it should be done before the first exam but need not be turned in
- Midterm exam is on Tuesday Oct 17 in class; closed book, closed notes, one 8.5 by 11 inch hand written notesheet allowed; calculators allowed

Compensation Example 1

- Added EXST1 model to 4 bus GENROU case with compensation of 0.05 pu (on gen's 100 MVA base) (using negative sign convention)
  - This is looking into step-up transformer
  - Initial voltage value is

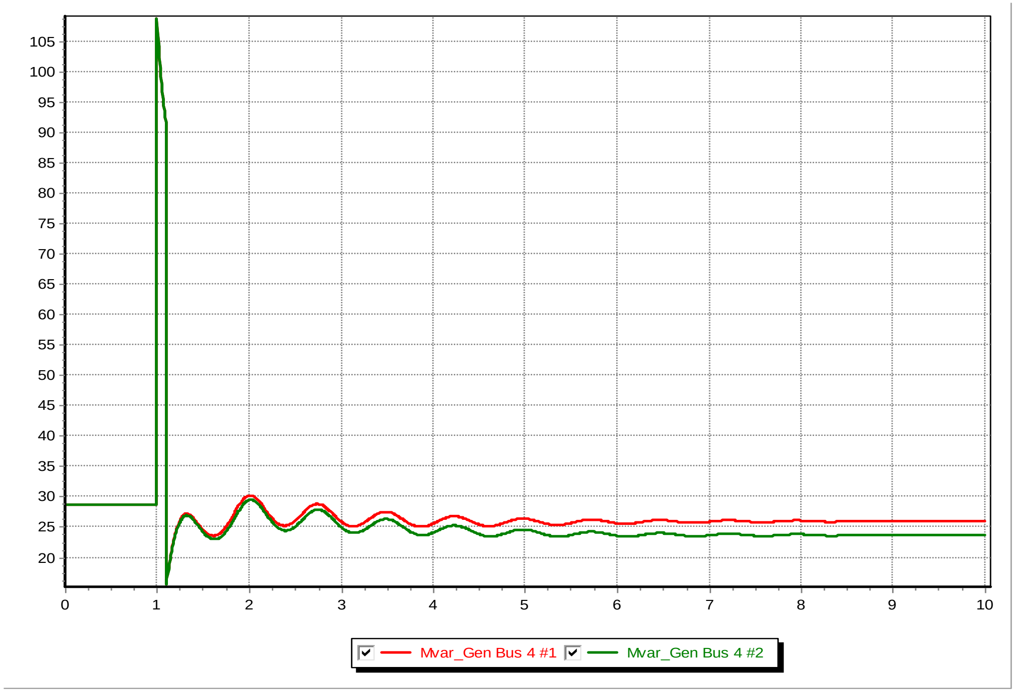
$$V_t = 1.072 + j0.22, \quad I_t = 1.0 - j0.3286$$

$$E_c = \left|1.072 + j0.22 - (j0.05)(1.0 - j0.3286)\right| = \left|1.0557 + j0.17\right| = 1.069$$

Case is b4_comp1

Compensation Example 2

- B4 case with two identical generators, except one in Xc = -0.1, one with Xc=-0.05; in the power flow the Mvars are shared equally (i.e., the initial value)

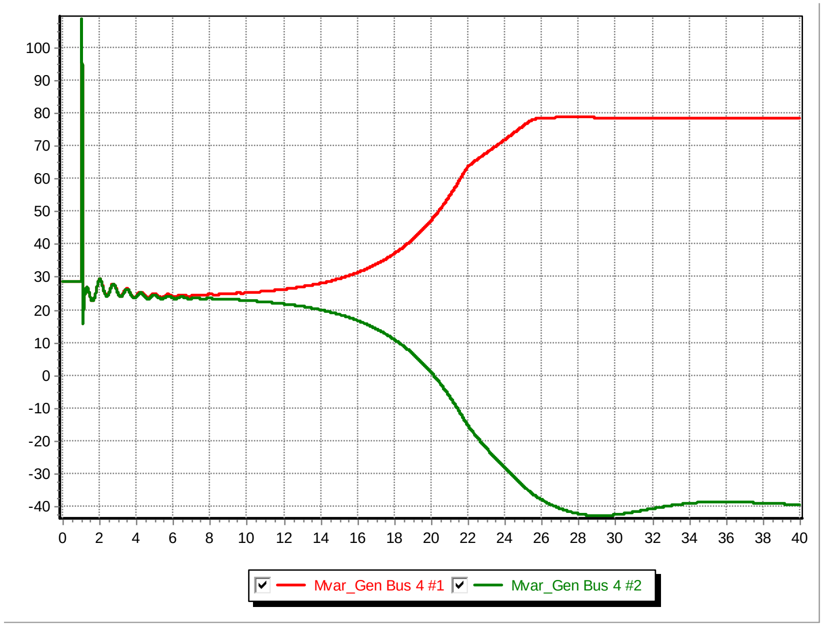


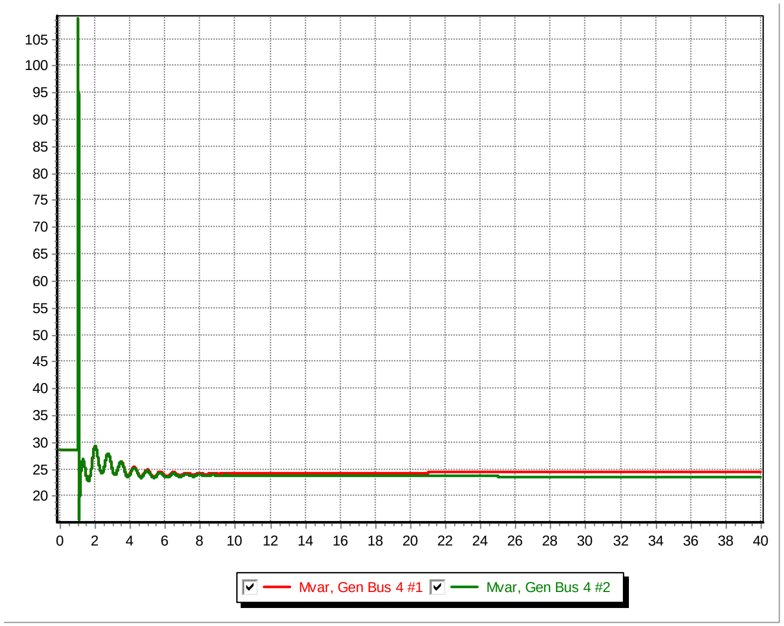
Plot shows the reactive power output of the two units, which start out equal, but diverage because of the difference values for X_c

Case is b4_comp2

Compensation Example 3

- B4 case with two identical generators except with slightly different Xc values (into net) (0.05 and 0.048)
- Below graphs show reactive power output if the currents from the generators not coordinated (left) or are coordinated (right); PowerWorld always does the right

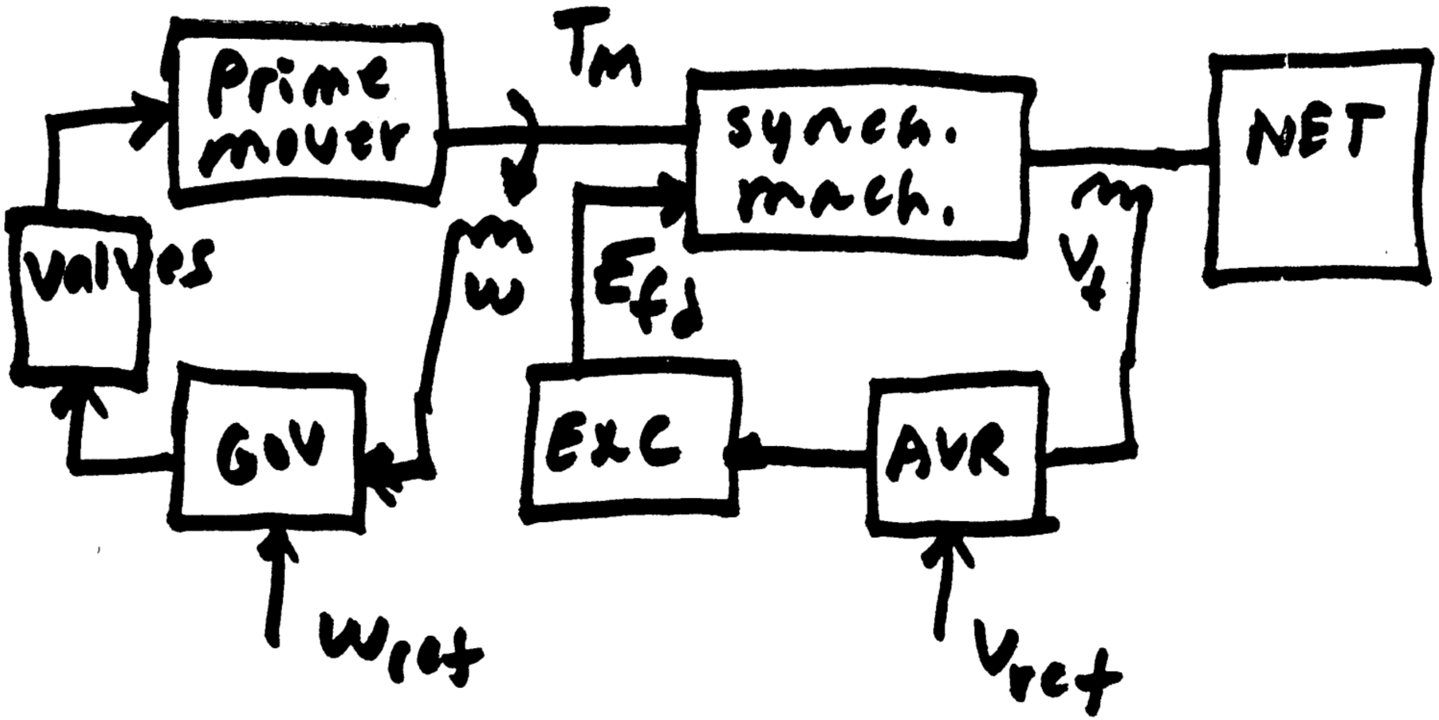




Initial Limit Violations

- Since many models have limits and the initial state variables are dependent on power flow values, there is certainly no guarantee that there will not be initial limit violations
- If limits are not changed, this does not result in an equilibrium point solution
- PowerWorld has several options for dealing with this, with the default value to just modify the limits to match the initial operating point
  - If the steady-state power flow case is correct, then the limit must be different than what is modeled

Speed and Voltage Control



(P,θ) (Q,V)

Prime Movers and Governors

- Synchronous generator is used to convert mechanical energy from a rotating shaft into electrical energy
- The "prime mover" is what converts the orginal energy source into the mechanical energy in the rotating shaft
- Possible sources: 1) steam (nuclear, coal, combined cycle, solar thermal), 2) gas turbines, 3) water wheel (hydro turbines), 4) diesel/ gasoline, 5) wind (which we'll cover separately)
- The governor is used to control the speed

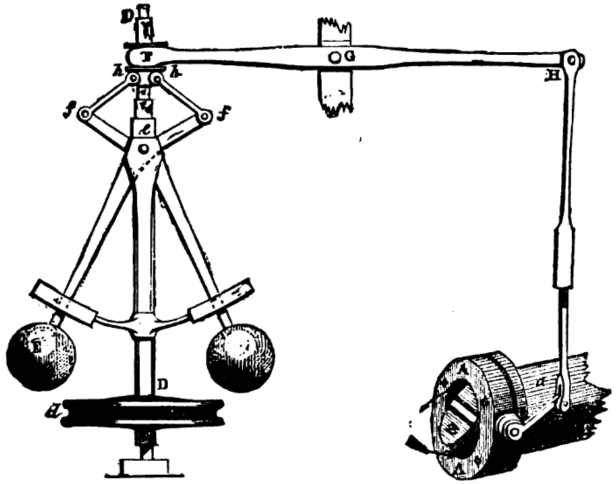


FIG. 4.—*Governor and Throttle-Valve.*

Image source: http://upload.wikimedia.org/wikipedia/commons/1/1e/Centrifugal_governor.png

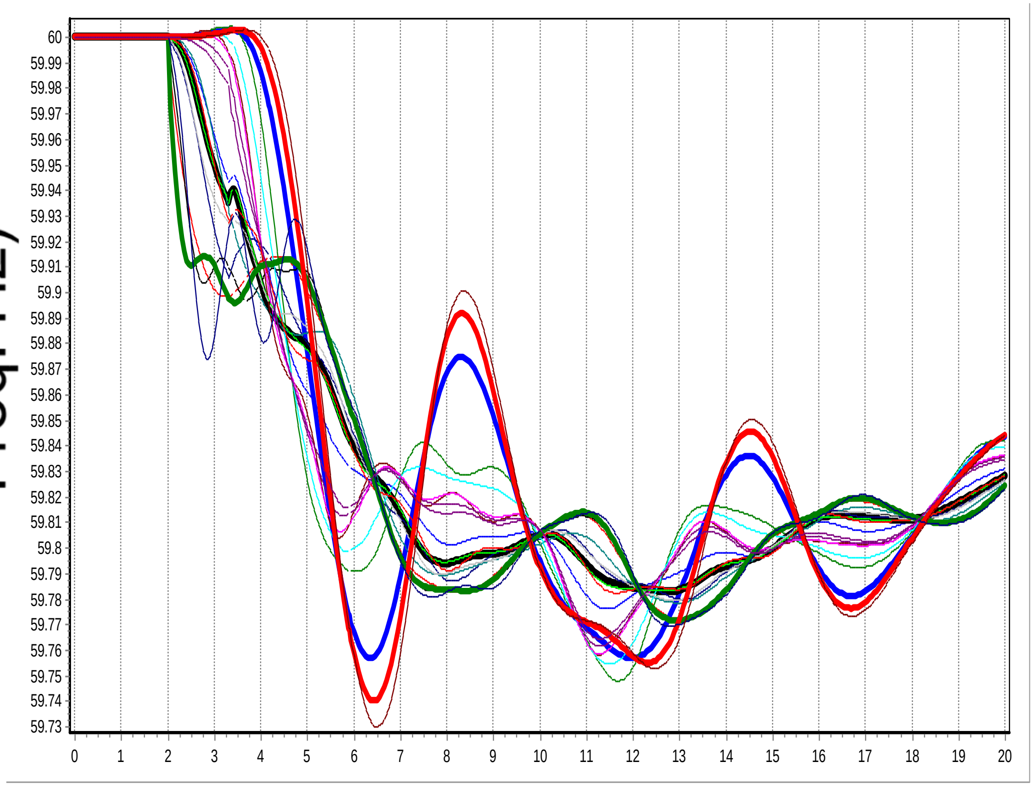
Prime Movers and Governors

- In transient stability collectively the prime mover and the governor are called the "governor"
- As has been previously discussed, models need to be appropriate for the application
- In transient stability the response of the system for seconds to perhaps minutes is considered
- Long-term dynamics, such as those of the boiler and automatic generation control (AG), are usually not considered
- These dynamics would need to be considered in longer simulations (e.g. dispatcher training simulator (DTS)

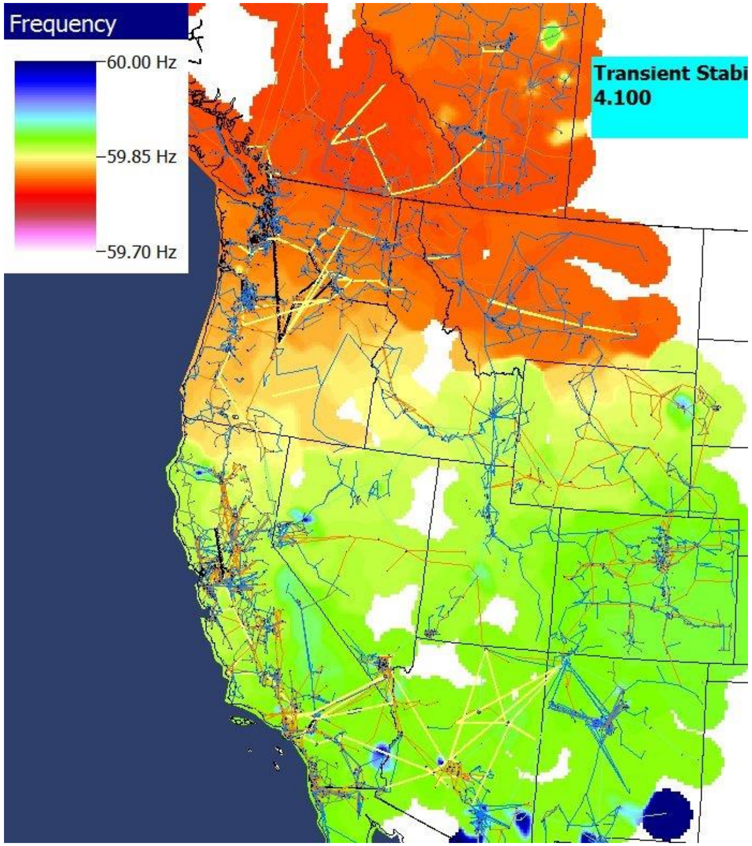
Power Grid Disturbance Example

Figures show the frequency change as a result of the sudden loss of a large amount of generation in the Southern WECC

Freq. Hz)



Time in Seconds



Frequency Contour

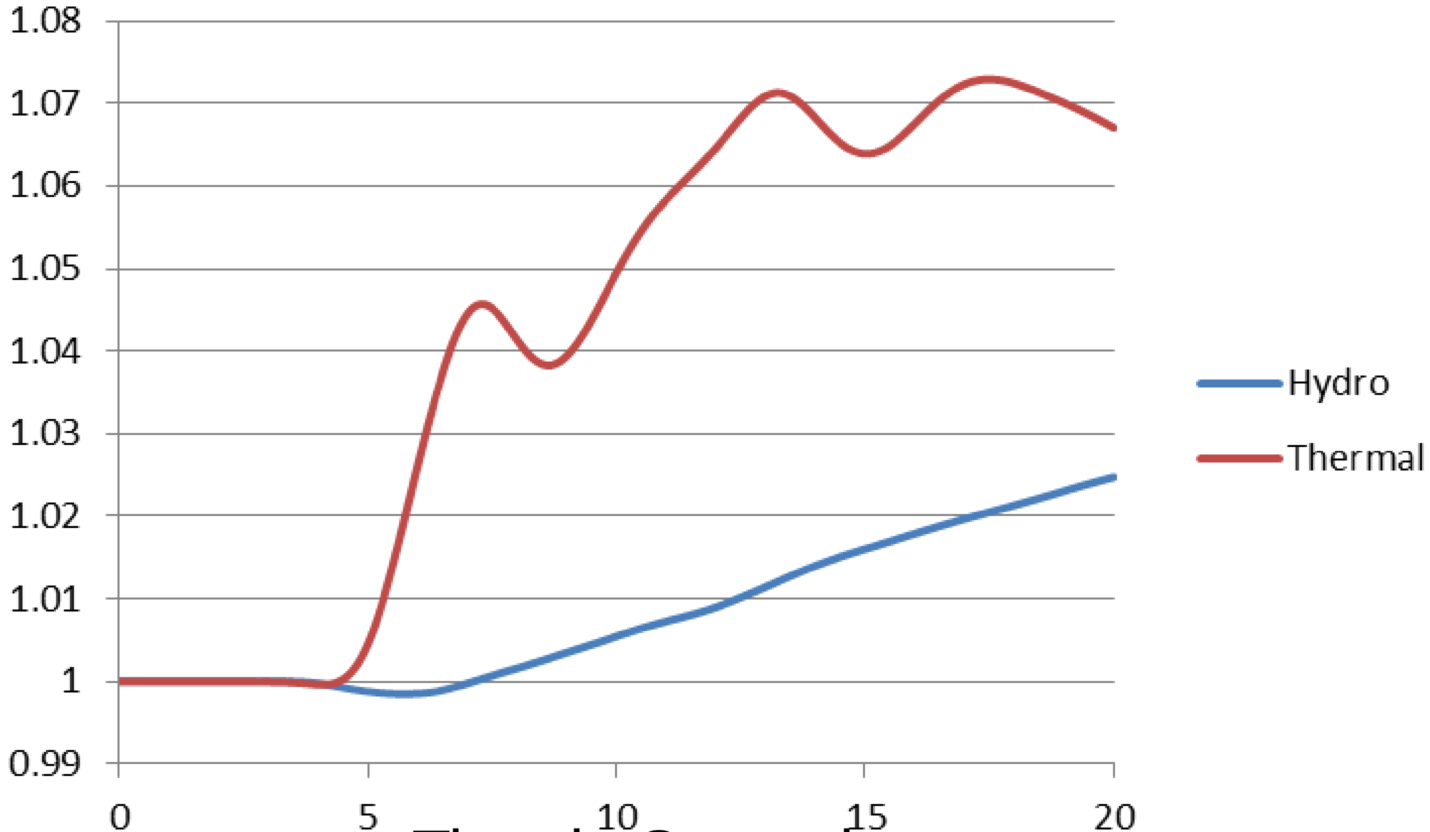
Frequency Response for Generation Loss

- In response to a rapid loss of generation, in the initial seconds the system frequency will decrease as energy stored in the rotating masses is transformed into electric energy
  - Solar PV has no inertia, and for most new wind turbines the inertia is not seen by the system
- Within seconds governors respond, increasing the power output of controllable generation
  - Many conventional units are operated so they only respond to over frequency situations
  - Solar PV and wind are usually operated in North America at maximum power so they have no reserves to contribute

Governor Response: Thermal Versus Hydro

Thermal units respond quickly, hydro ramps slowly (and goes down initially), wind and solar usually do not respond. And many units are set to not respond!

Normalized output

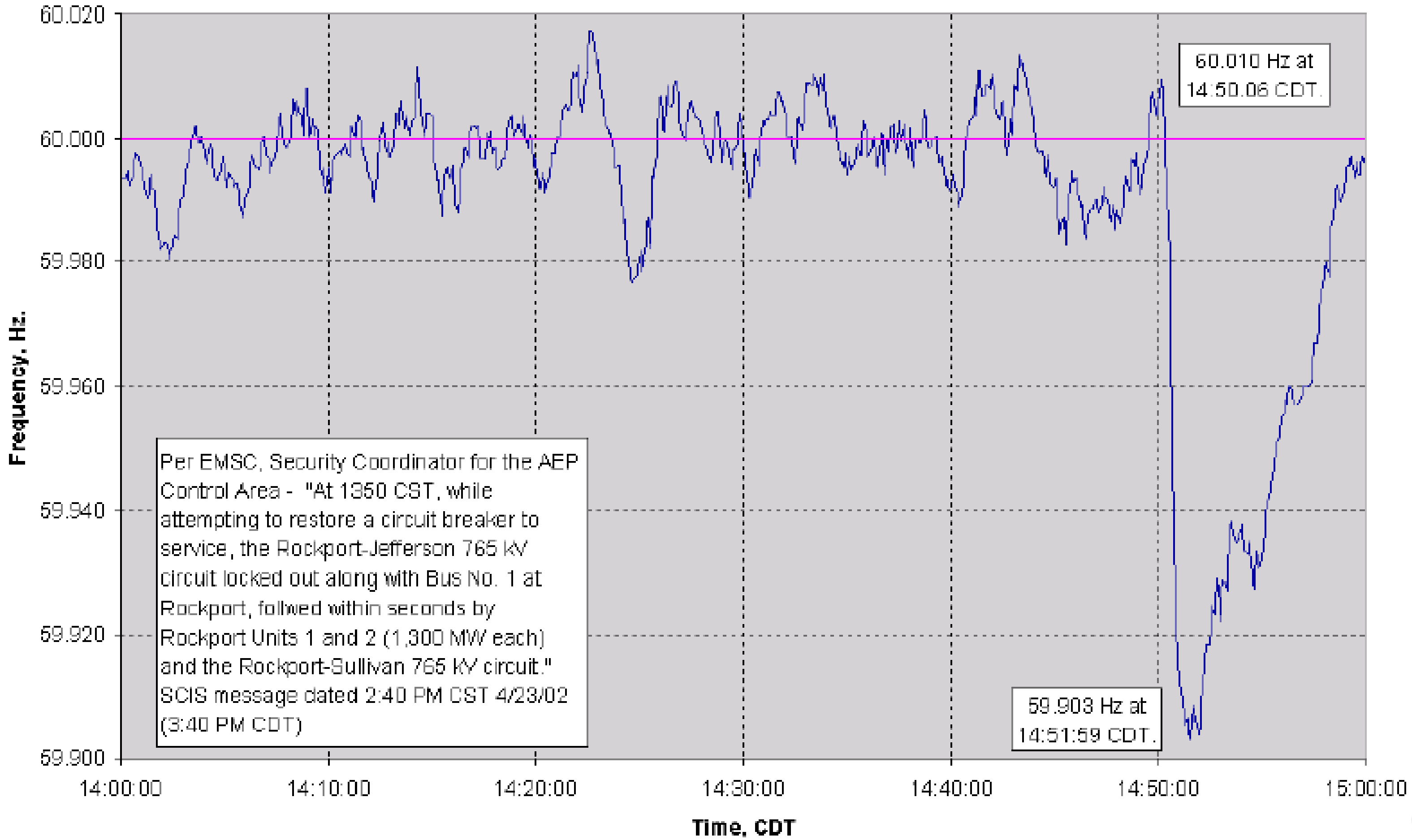


Time in Seconds

Some Good References

- Kundur, *Power System Stability and Control*, 1994
- Wood, Wollenberg and Sheble, *Power Generation, Operation and Control* (2nd edition, 1996, 3rd in 2013)
- IEEE PES, "Dynamic Models for Turbine-Governors in Power System Studies," Jan 2013
- "Dynamic Models for Fossil Fueled Steam Units in Power System Studies," *IEEE Trans. Power Syst.*, May 1991, pp. 753-761
- "Hydraulic Turbine and Turbine Control Models for System Dynamic Studies," *IEEE Trans. Power Syst.*, Feb 1992, pp. 167-179

2600 MW Loss Frequency Recovery



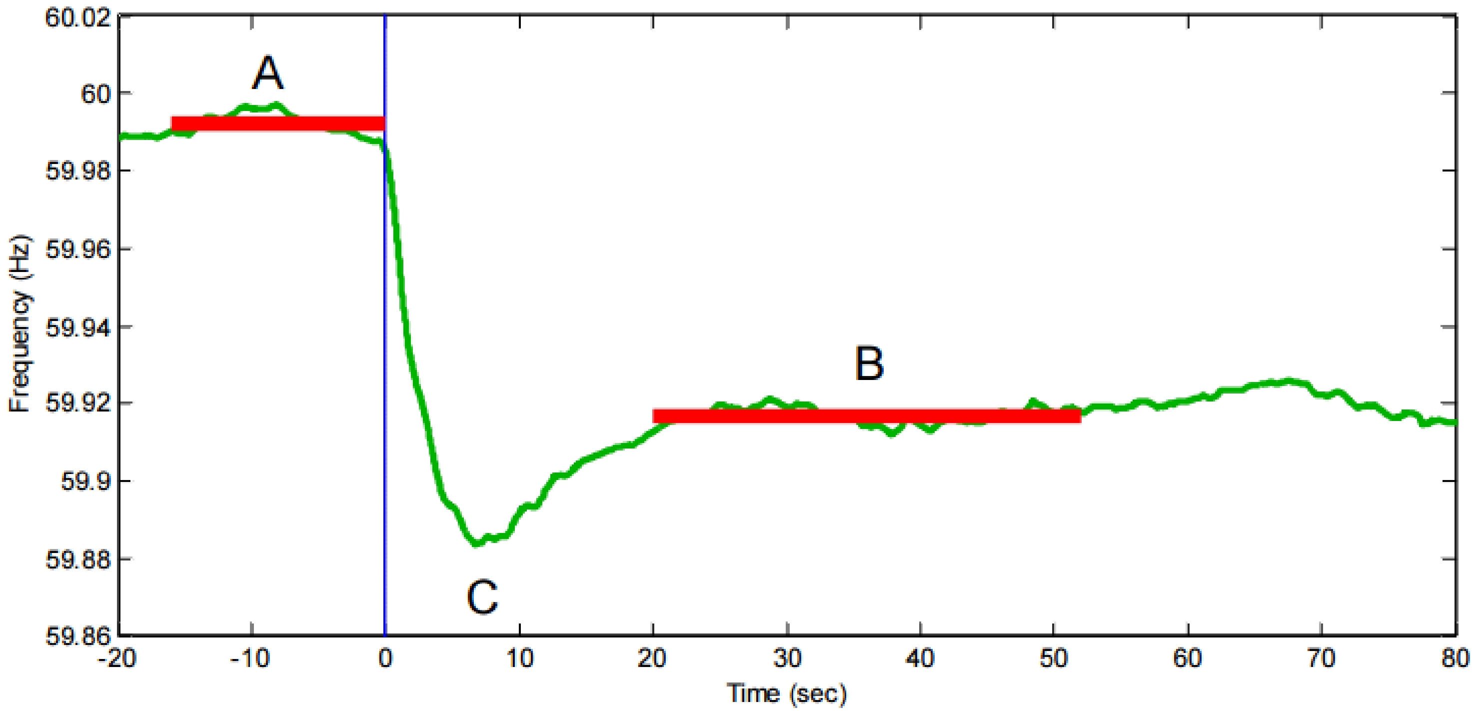
Frequency recovers in about ten minutes

Frequency Response Definition

- FERC defines in RM13-11: "Frequency response is a measure of an Interconnection's ability to stabilize frequency immediately following the sudden loss of generation or load, and is a critical component of the reliable operation of the Bulk-Power System, particularly during disturbances and recoveries."
- Design Event for WECC is N-2 (Palo Verde Outage) not to result in UFLS (59.5 Hz in WECC)

Source: wecc.biz/Reliability/Frequency%20Response%20Analysis%20-%20Dmitry%20Kosterev.pdf

Frequency Response Measure



NERC FRM BAL-003-1: Frequency difference between Point A and Point B

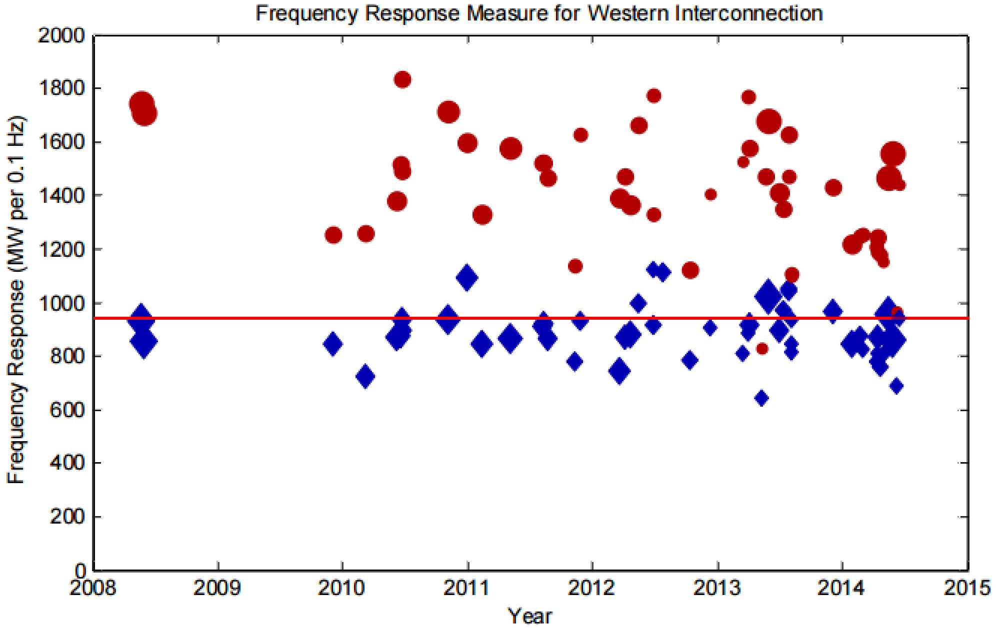
LBNL Metrics: Frequency difference between Point A and Point C

Source: wecc.biz/Reliability/Frequency%20Response%20Analysis%20-%20Dmitry%20Kosterev.pdf

WECC Interconnection Performance

Western Interconnection Performance

WECC IFRO ~950 MW per 01. Hz, WECC IFRM is trending ~ 1,400 to 1,600 MW per 0.1 Hz
Response at nadir: required ~580 MW per 0.1 Hz, actual is about 800 MW per 0.1 Hz



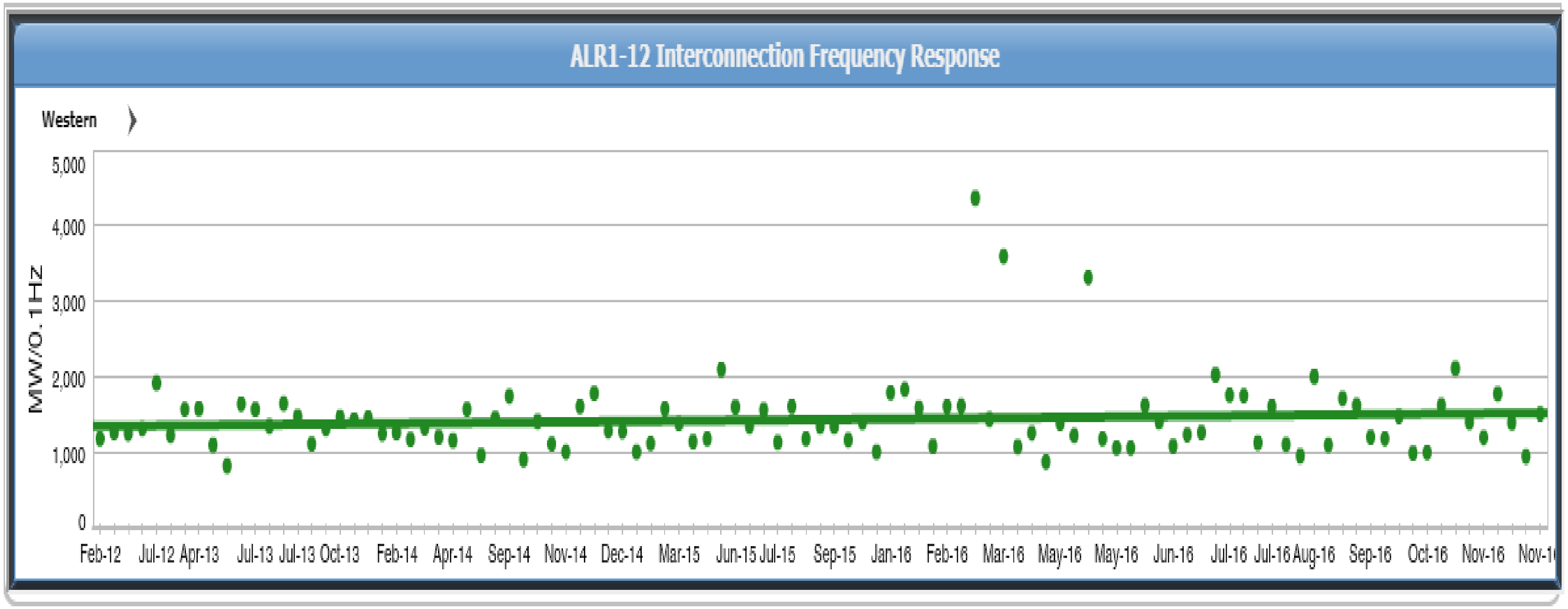
- Red dots – frequency response measured at point B (settling) using NERC FRM methodology
- Blue diamonds – frequency response is measured at point C (nadir)

Source: wecc.biz/Reliability/Frequency%20Response%20Analysis%20-%20Dmitry%20Kosterev.pdf

WECC Interconnect Frequency Response

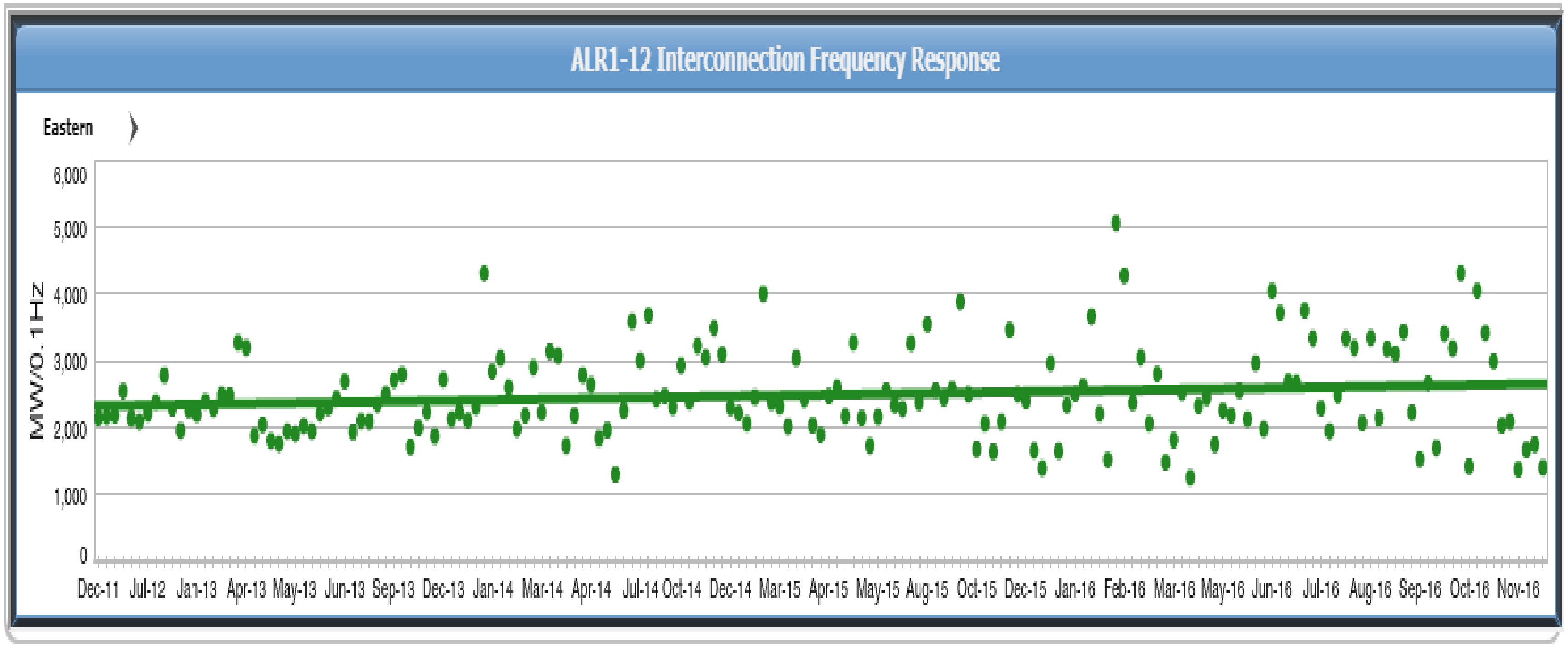
- Data for the four major interconnects is available from NERC; these are the values between points A and B

M-4 Interconnection Frequency Response



Eastern Interconnect Frequency Response

M-4 Interconnection Frequency Response

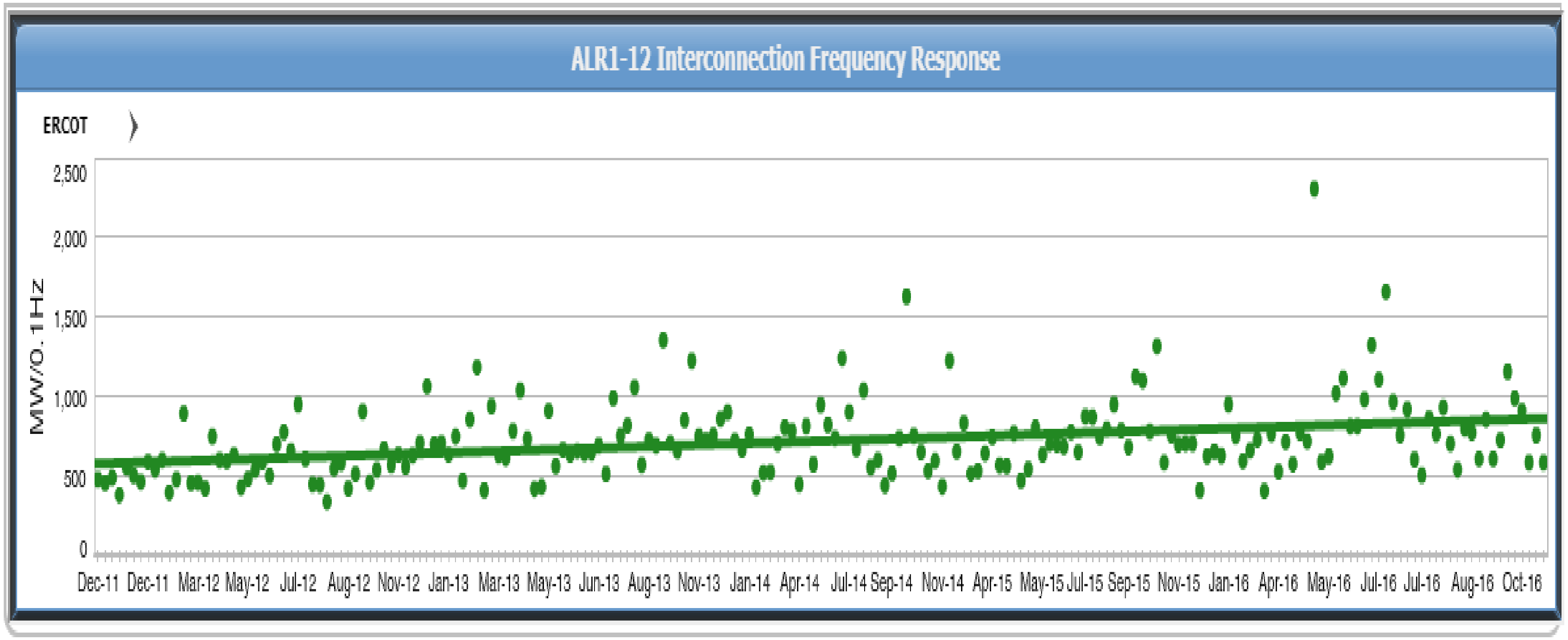


www.nerc.com/pa/RAPA/ri/Pages/InterconnectionFrequencyResponse.aspx

ERCOT Frequency Response

- As expected, smaller grids have greater frequency sensitivity

M-4 Interconnection Frequency Response



www.nerc.com/pa/RAPA/ri/Pages/InterconnectionFrequencyResponse.aspx

Control of Generation Overview

- Goal is to maintain constant frequency with changing load
- If there is just a single generator, such with an emergency generator or isolated system, then an isochronous governor is used
  - Integrates frequency error to insure frequency goes back to the desired value
  - Cannot be used with interconnected systems because of "hunting"

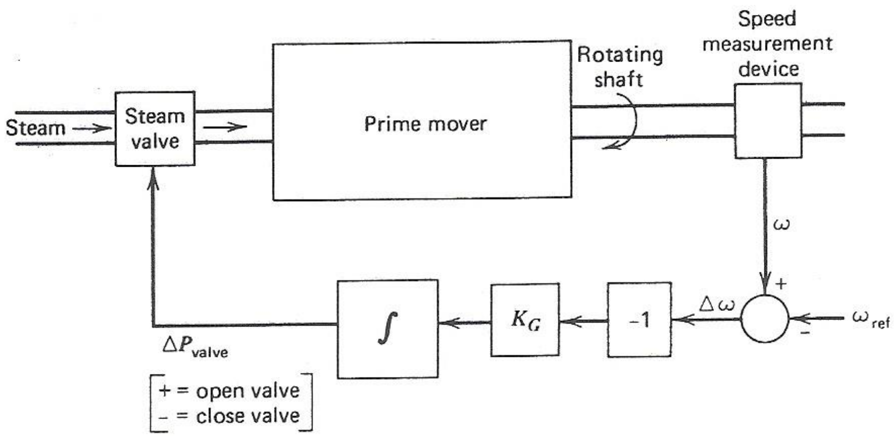


FIG. 9.9 Isochronous governor.

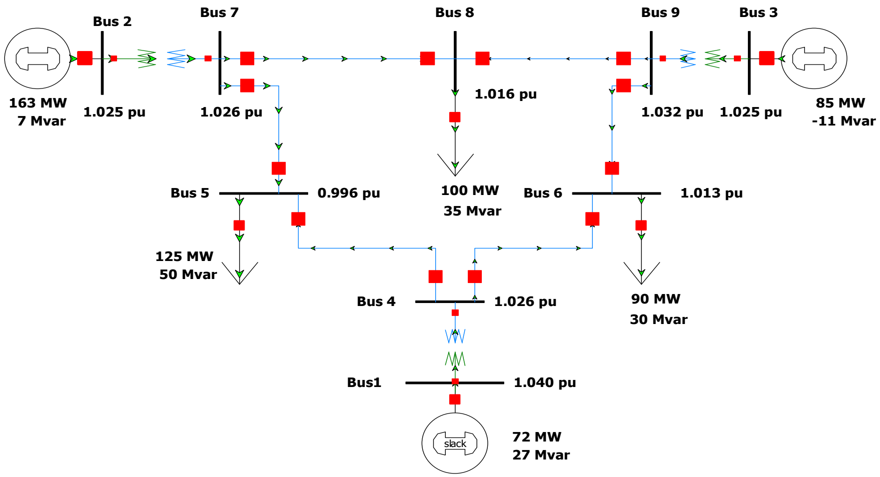
Image source: Wood/Wollenberg, 2nd edition

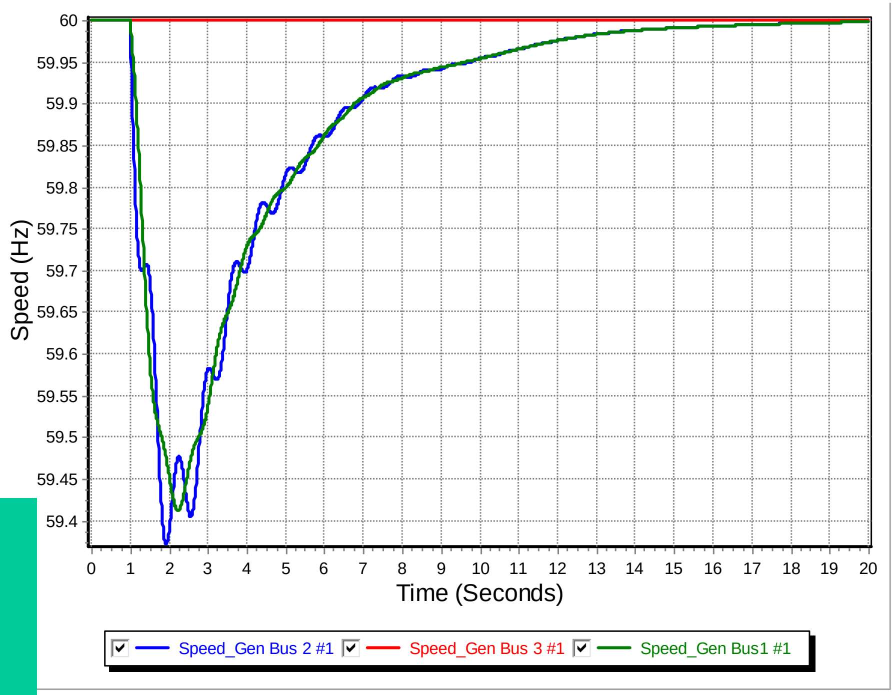
Generator "Hunting"

- Control system "hunting" is oscillation around an equilibrium point
- Trying to interconnect multiple isochronous generators will cause hunting because the frequency setpoints of the two generators are never exactly equal
  - One will be accumulating a frequency error trying to speed up the system, whereas the other will be trying to slow it down
  - The generators will NOT share the power load proportionally.

Isochronous Gen Example

- WSCC 9 bus from before, gen 3 dropping (85 MW)
  - No infinite bus, gen 1 is modeled with an isochronous generator (PW ISOGov1 model)

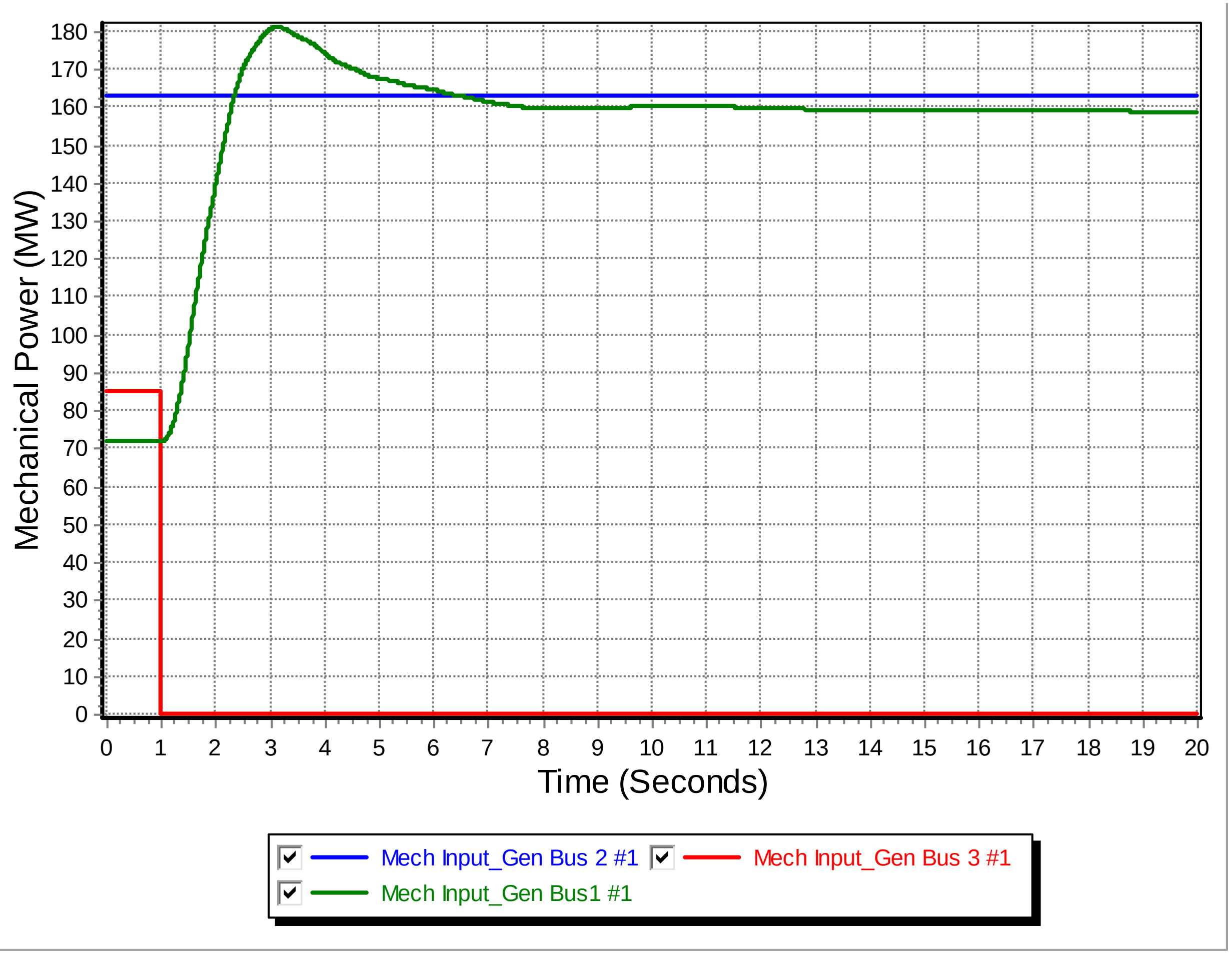




Gen 2 is modeled with no governor, so its mechanical power stays fixed

Isochronous Gen Example

- Graph shows the change in the mechanical output

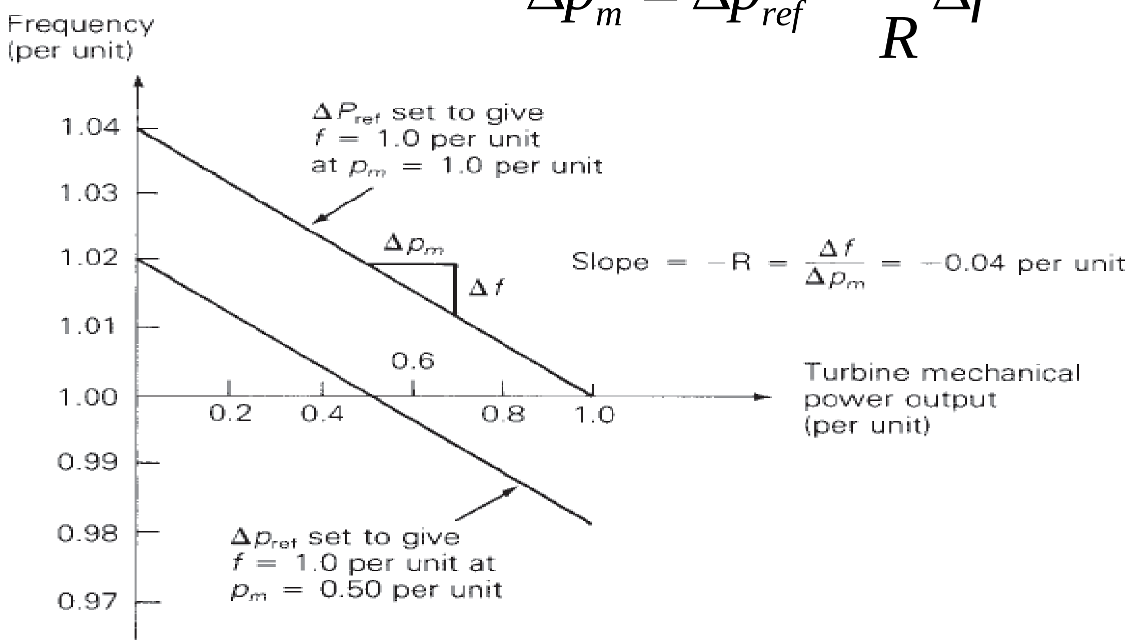


All the change in MWs due to the loss of gen 3 is being picked up by gen 1

Droop Control

- To allow power sharing between generators the solution is to use what is known as droop control, in which the desired set point frequency is dependent upon the generator's output

$$\Delta p_m = \Delta p_{ref} - \frac{1}{R}\Delta f$$



R is known as the regulation constant or droop; a typical value is 4 or 5%. At 60 Hz and a 5% droop, each 0.1 Hz change would change the output by 0.1/(60*0.05)= 3.33%

WSCC 9 Bus Droop Example

- Assume the previous gen 3 drop contingency (85 MW), and that gens 1 and 2 have ratings of 500 and 250 MVA respectively and governors with a 5% droop. What is the final frequency (assuming no change in load)?

To solve the problem in per unit, all values need to be on a common base (say 100 MVA)

$$\Delta p_{m1} + \Delta p_{m2} = 85/100 = 0.85$$

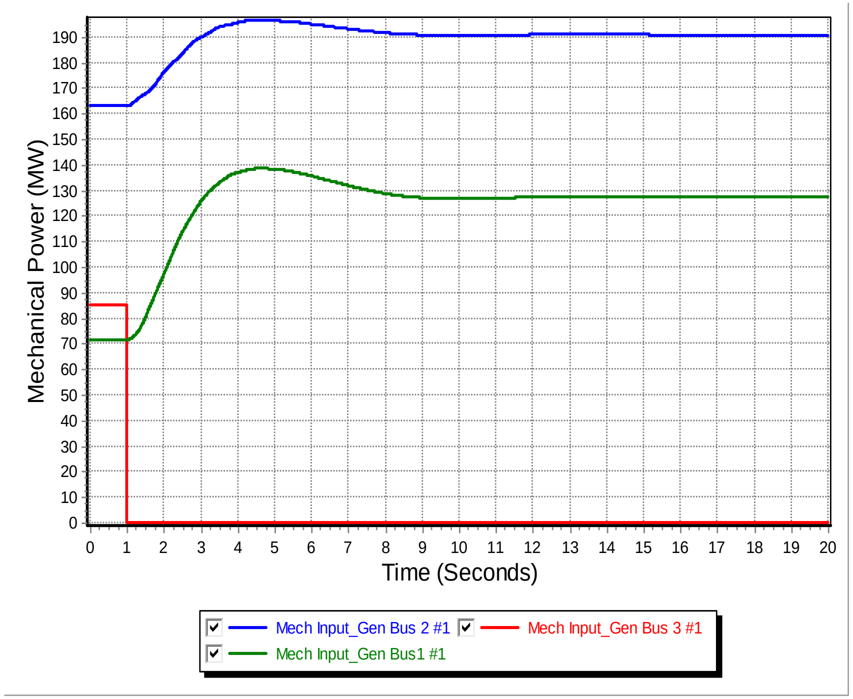
$$R_{1,100MVA} = R_1 \frac{100}{500} = 0.01, \quad R_{2,100MVA} = R_2 \frac{100}{250} = 0.02$$

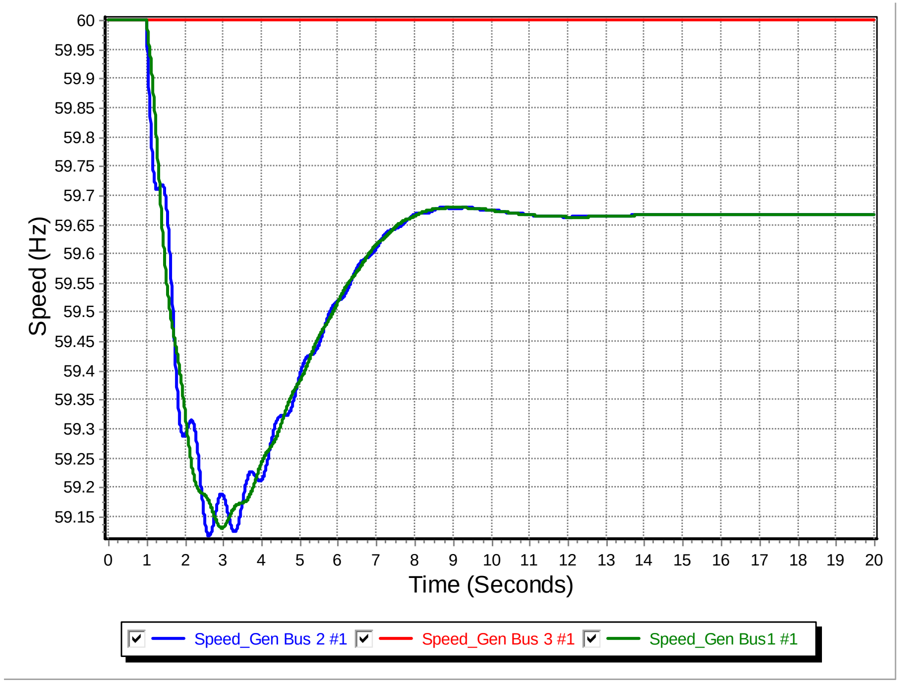
$$\Delta p_{m1} + \Delta p_{m2} = -\left(\frac{1}{R_{1,100MVA}} + \frac{1}{R_{2,100MVA}}\right)\Delta f = 0.85$$

$$\Delta f = -.85/150 = 0.00567 = -0.34 \text{ Hz} \rightarrow 59.66 \text{ Hz}$$

WSCC 9 Bus Droop Example

- The below graphs compare the mechanical power and generator speed; note the steady-state values match the calculated 59.66 Hz value





Case is wscc_9bus_TGOV1

Quick Interconnect Calculation

- When studying a system with many generators, each with the same (or close) droop, then the final frequency deviation is

$$\Delta f = -\frac{R \times \Delta P_{gen,MW}}{\sum_{OnlineGens} S_{i,MVA}}$$

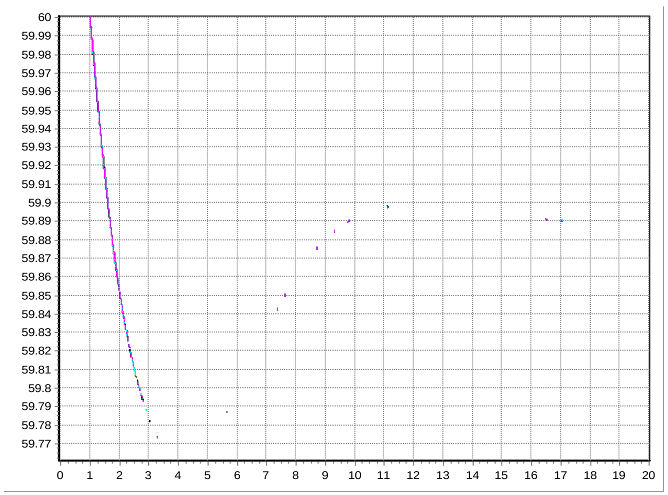
The online generators obviously does not include the contingency generator(s)

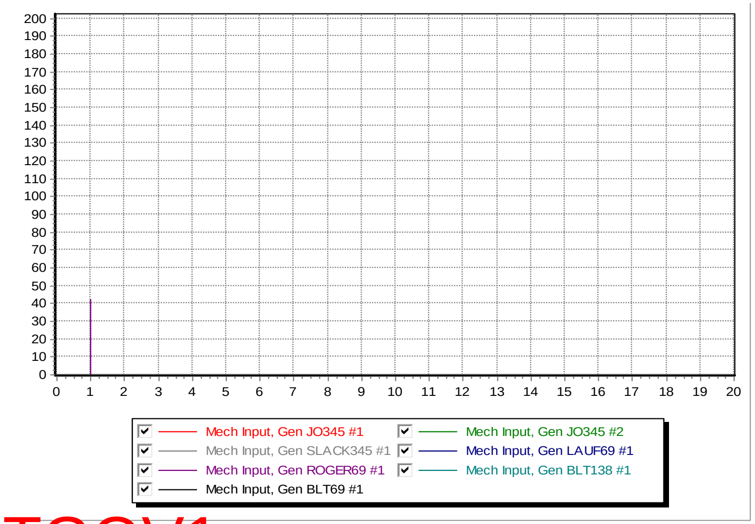
- The online generator summation should only include generators that actually have governors that can respond, and does not take into account generators hitting their limits

Larger System Example

- As an example, consider the 37 bus, nine generator example from earlier; assume one generator with 42 MW is opened. The total MVA of the remaining generators is 1132. With R=0.05

$$\Delta f = -\frac{0.05 \times 42}{1132} = -0.00186 \text{ pu} = -0.111 \text{ Hz} \rightarrow 59.889 \text{ Hz}$$

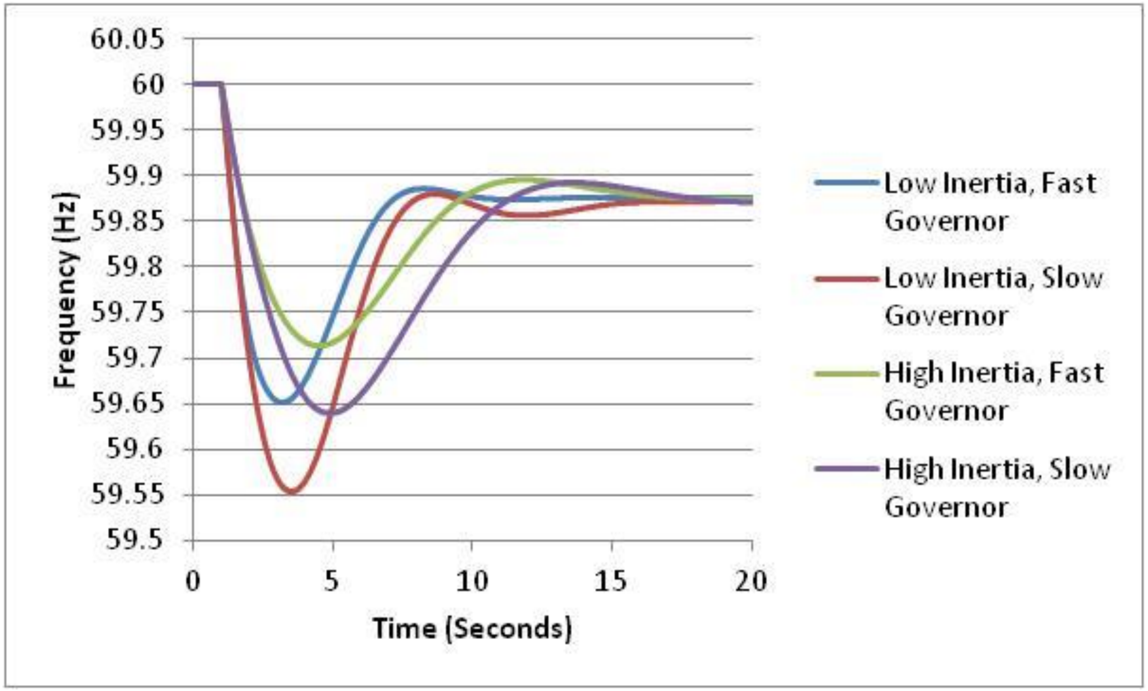




Case is Bus37_TGOV1

Impact of Inertia (H)

- Final frequency is determined by the droop of the responding governors
- How quickly the frequency drops depends upon the generator inertia values



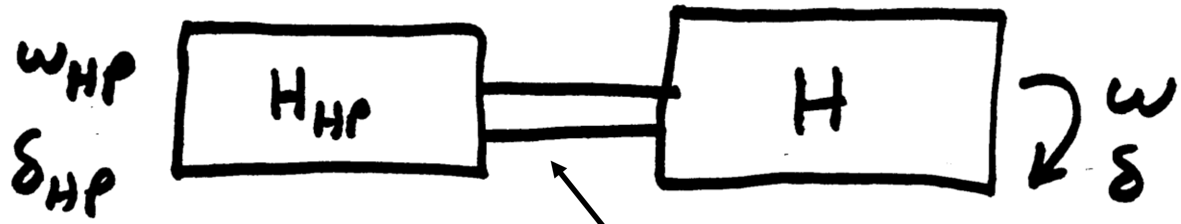
The least frequency deviation occurs with high inertia and fast governors

Restoring Frequency to 60 (or 50) Hz

- In an interconnected power system the governors to not automatically restore the frequency to 60 Hz
- Rather done via the ACE (area control area calculation). Previously we defined ACE as the difference between the actual real power exports from an area and the scheduled exports. But it has an additional term
  $ACE = P_{actual} - P_{sched} – 10\beta(freq_{act} - freq_{sched})$
- β is the balancing authority frequency bias in MW/0.1 Hz with a negative sign. It is about 0.8% of peak load/generation

ACE response is usually not modeled in transient stability

Turbine Models



model shaft "squishiness" as a spring

$$\frac{d\delta}{dt} = \omega - \omega_s$$

$$T_M = -K_{shaft}(\delta - \delta_{HP}) = T_{OUT}$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = T_M - T_{ELEC} - T_{FW}$$

Usually shaft dynamics are neglected

$$\left.\begin{aligned} \frac{d\delta_{HP}}{dt} &= \omega_{HP} - \omega_s \\ \frac{2H_{HP}}{\omega_s}\frac{d\omega_{HP}}{dt} &= T_{IN} - T_{OUT} \end{aligned}\right\}$$

High-pressure turbine shaft dynamics

Steam Turbine Models

Boiler supplies a "steam chest" with the steam then entering the turbine through a value

$$T_{CH}\frac{dP_{CH}}{dt} = -P_{CH} + P_{SV}$$

Assume $T_{in} = P_{CH}$ and a rigid shaft with $P_{CH} = T_M$

Then the above equation becomes

$$T_{CH}\frac{dT_M}{dt} = -T_M + P_{SV}$$

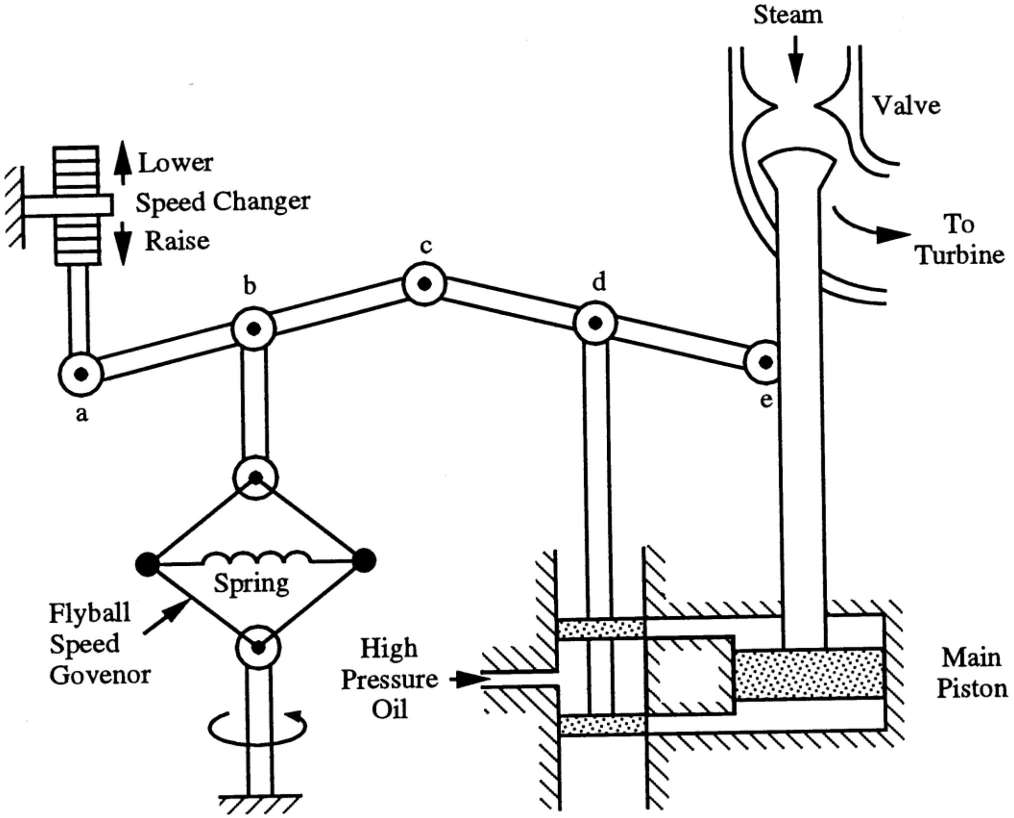
And we just have the swing equations from before

$$\frac{d\delta}{dt} = \omega - \omega_s$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = T_M - T_{ELEC} - T_{FW}$$

We are assuming $\delta=\delta_{HP}$ and $\omega=\omega_{HP}$

Steam Governor Model



Steam Governor Model

$$T_{SV}\frac{dP_{SV}}{dt} = -P_{SV} + P_C - \frac{1}{R}\Delta\omega$$

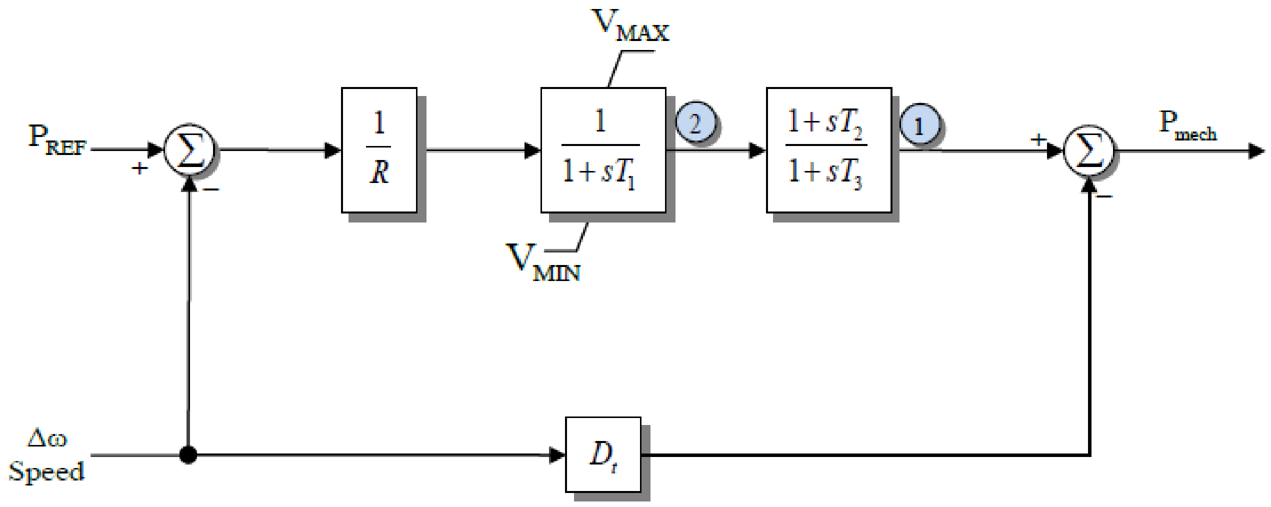
$$\text{where } \Delta\omega = \frac{\omega - \omega_s}{\omega_s}$$

$$0 \le P_{SV} \le P_{SV}^{\max}$$ Steam valve limits

R = .05 (5% droop)

TGOV1 Model

- Standard model that is close to this is TGOV1

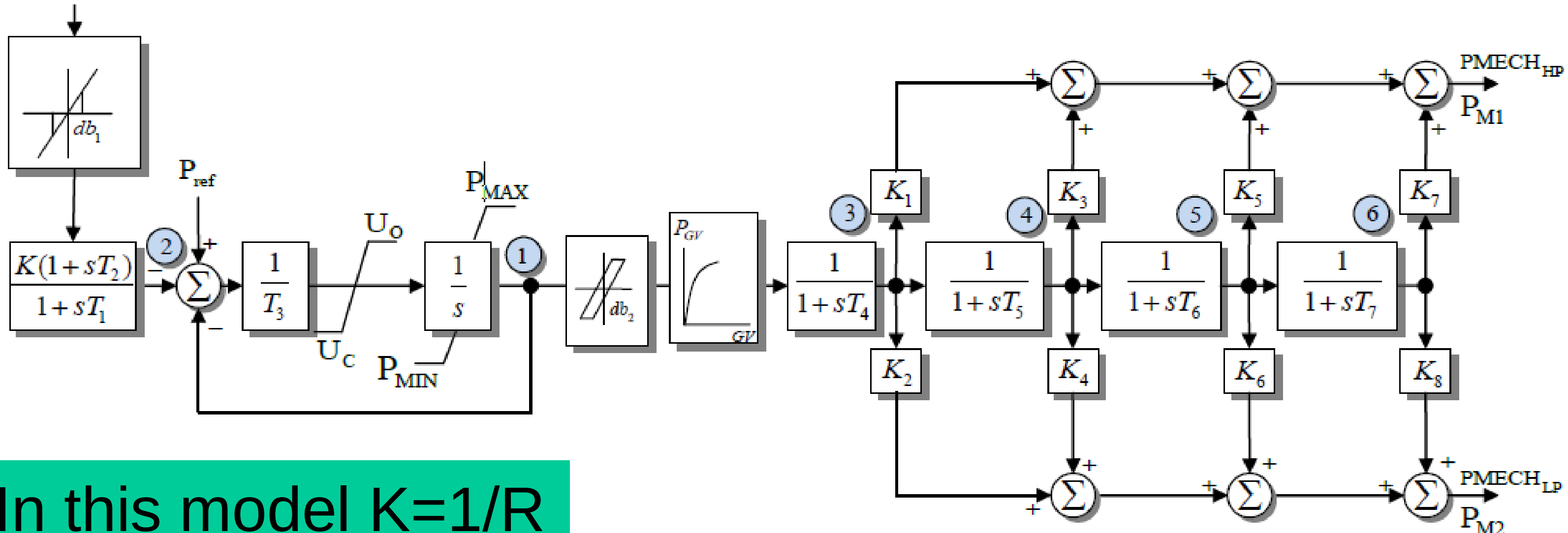


Here T_1 corresponds to T_{SV} and T_3 to T_{CH}

About 12% of governors in the EI model are TGOV1; R = 0.05, T_1 is less than 0.5 (except a few 999's!), T_3 has an average of 7, average T_2/T_3 is 0.34; D_t is used to model turbine damping and is often zero (about 80% of time in EI)

IEEEG1

- A common stream turbine model, is the IEEEG1, originally introduced in the below 1973 paper



In this model K=1/R

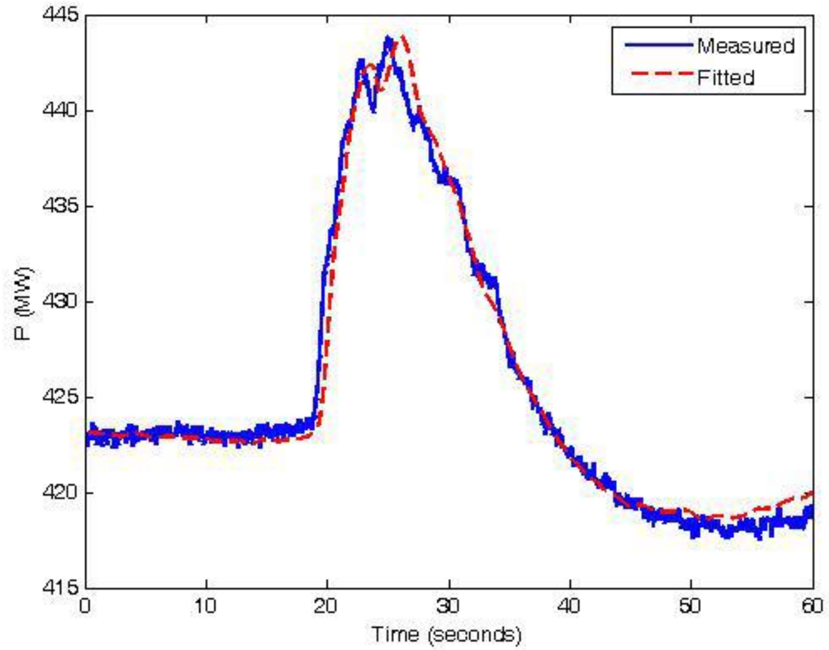
U_o and U_c are rate limits

It can be used to represent cross-compound units, with high and low pressure steam

IEEE Committee Report, "Dynamic Models for Steam and Hydro Turbines in Power System Studies," Transactions in Power Apparatus & Systems, volume 92, No. 6, Nov./Dec. 1973, pp 1904-15

IEEEG1

- Blocks on the right model the various steam stages
- About 12% of WECC and EI governors are currently IEEEG1s
- Below figures show two test comparison with this model



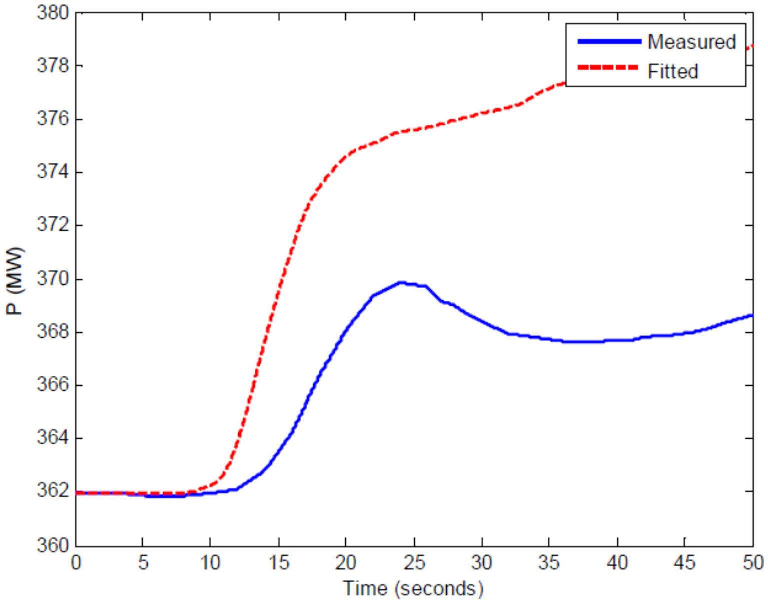
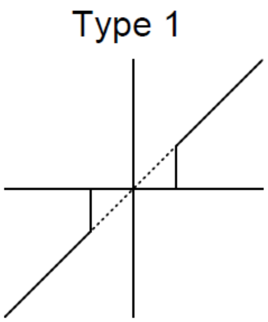


Image Source: Figs 2-4, 2-6 of IEEE PES, "Dynamic Models for Turbine-Governors in Power System Studies," Jan 2013

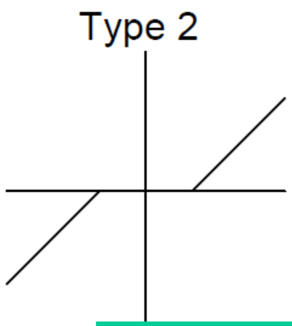
Deadbands

- Before going further, it is useful to briefly consider deadbands, with two types shown with IEEEG1 and described in the 2013 IEEE PES Governor Report
- The type 1 is an intentional deadband, implemented to prevent excessive response
  - Until the deadband activates there is no response, then normal response after that; this can cause a potentially large jump in the response
  - Also, once activated there is normal response coming back into range
  - Used on input to IEEEG1

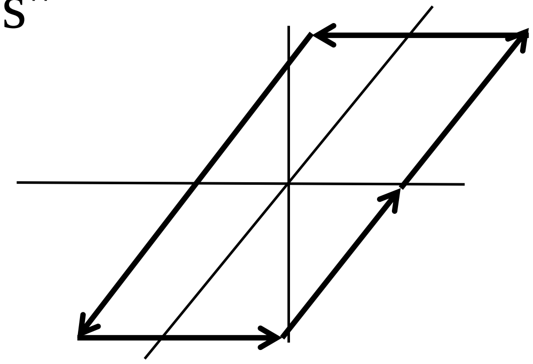


Deadbands

- The type 2 is also an intentional deadband, implemented to prevent excessive response
  - Difference is response does not jump, but rather only starts once outside of the range



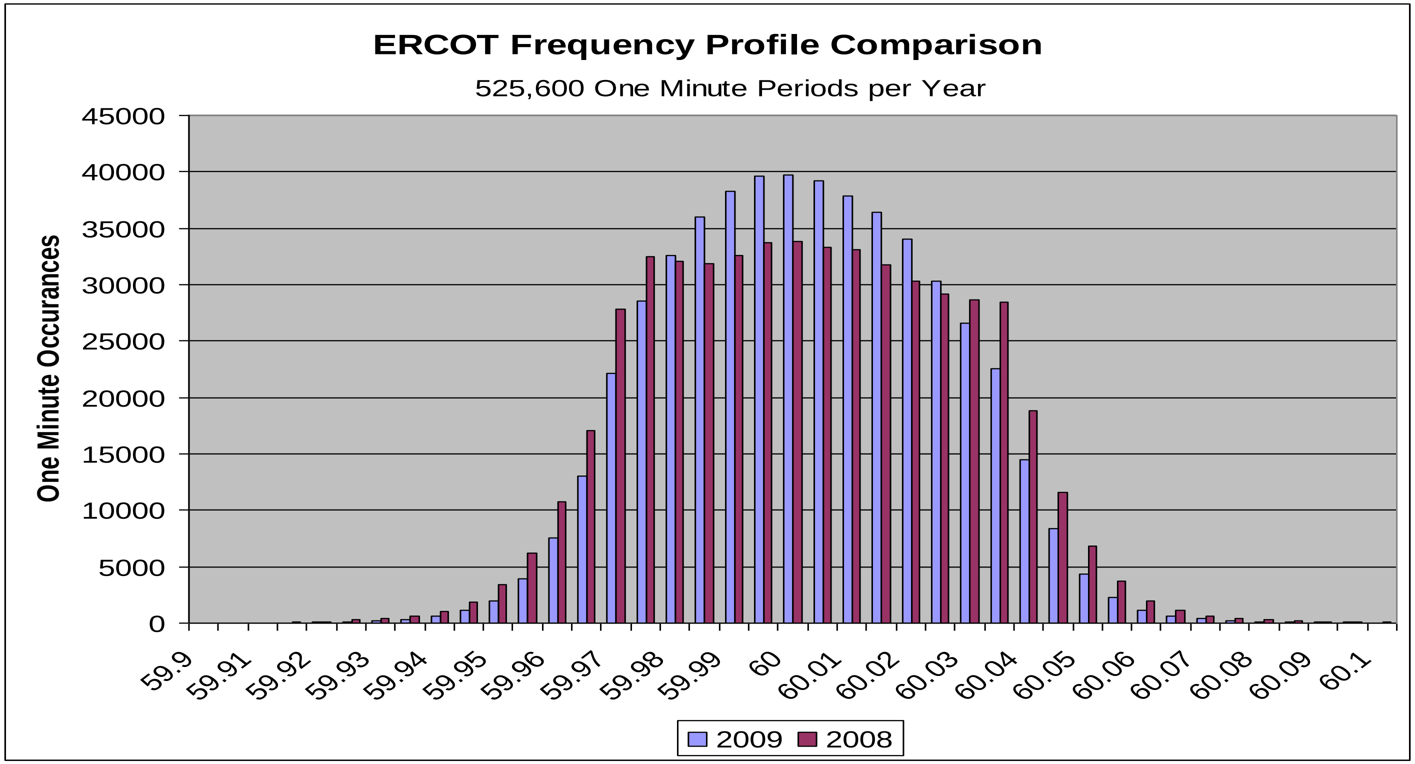
- Another type of deadband is the unintentional, such as will occur with loose gears
  - Until deadband "engages" there is no response
  - Once engaged there is a hysteresis in the response



When starting simulations deadbands usually start start at their origin

Deadband Example: ERCOT

- Prior to November 2008, ERCOT required that the governor deadbands be no greater than +/- 0.036 Hz
- After 11/3/08 deadbands were changed to +/- 0.0166 Hz



2008 did have two months with the lower values

Image Source: Sydney Niemeyer, NRG, 2/9/10 presentation to Texas Regional Entity (part of ERCOT)

Gas Turbines

- A gas turbine (usually using natural gas) has a compressor, a combustion chamber and then a turbine
- The below figure gives an overview of the modeling

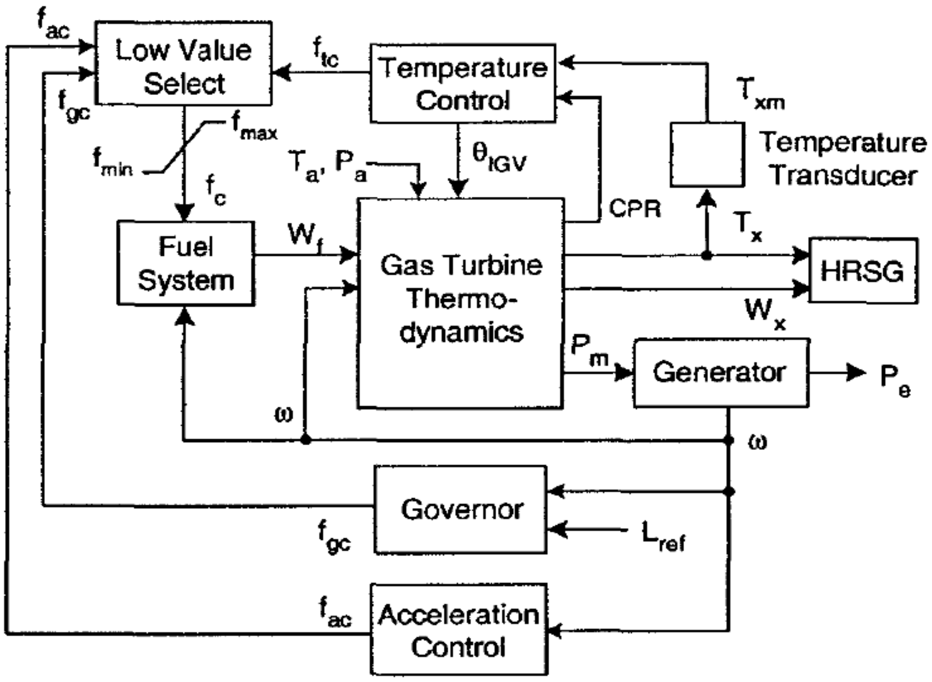


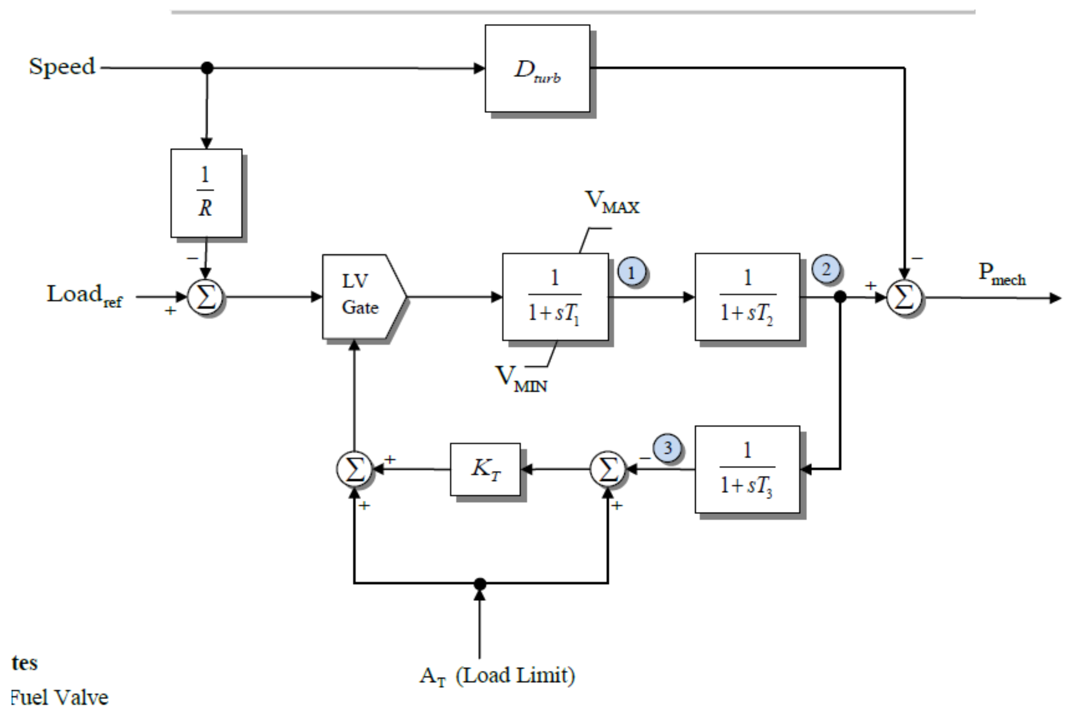
Figure 3-3: Gas turbine controls [17] (IEEE© 2001).

HRSG is the heat recovery steam generator (if it is a combined cycle unit)

Image from IEEE PES, "Dynamic Models for Turbine-Governors in Power System Studies," Jan 2013

GAST Model

- Quite detailed gas turbine models exist; we'll just consider the simplest, which is still used some (10% in EI)



T_1 average is 0.9, T_2 is 0.6 sec

It is somewhat similar to the TGOV1. T_1 is for the fuel valve, T_2 is for the turbine, and T_3 is for the load limit response based on the ambient temperature (At); T_3 is the delay in measuring the exhaust temperature