# ECEN 667
# Power System Stability

## Lecture 13: Governors

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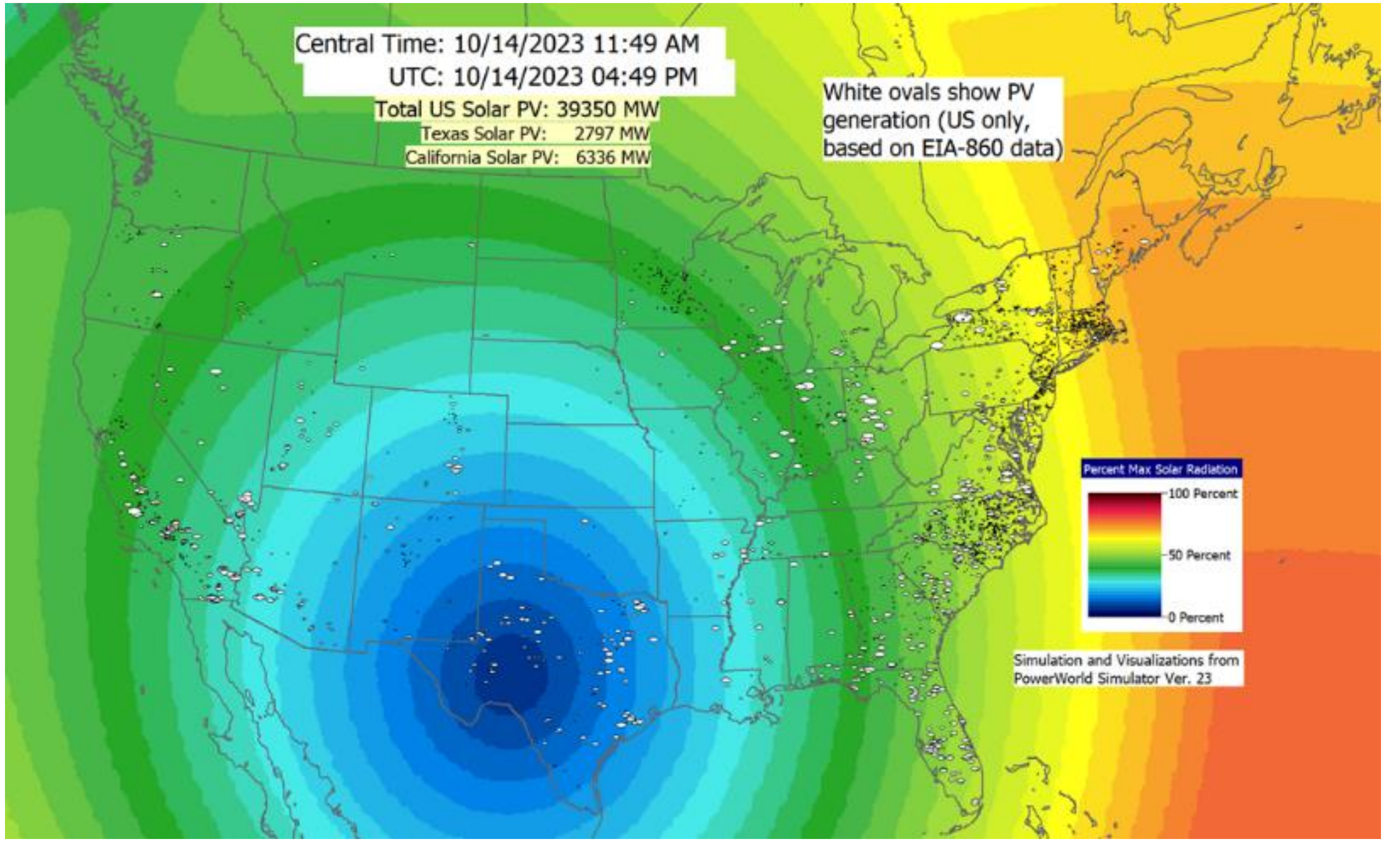
# Announcements

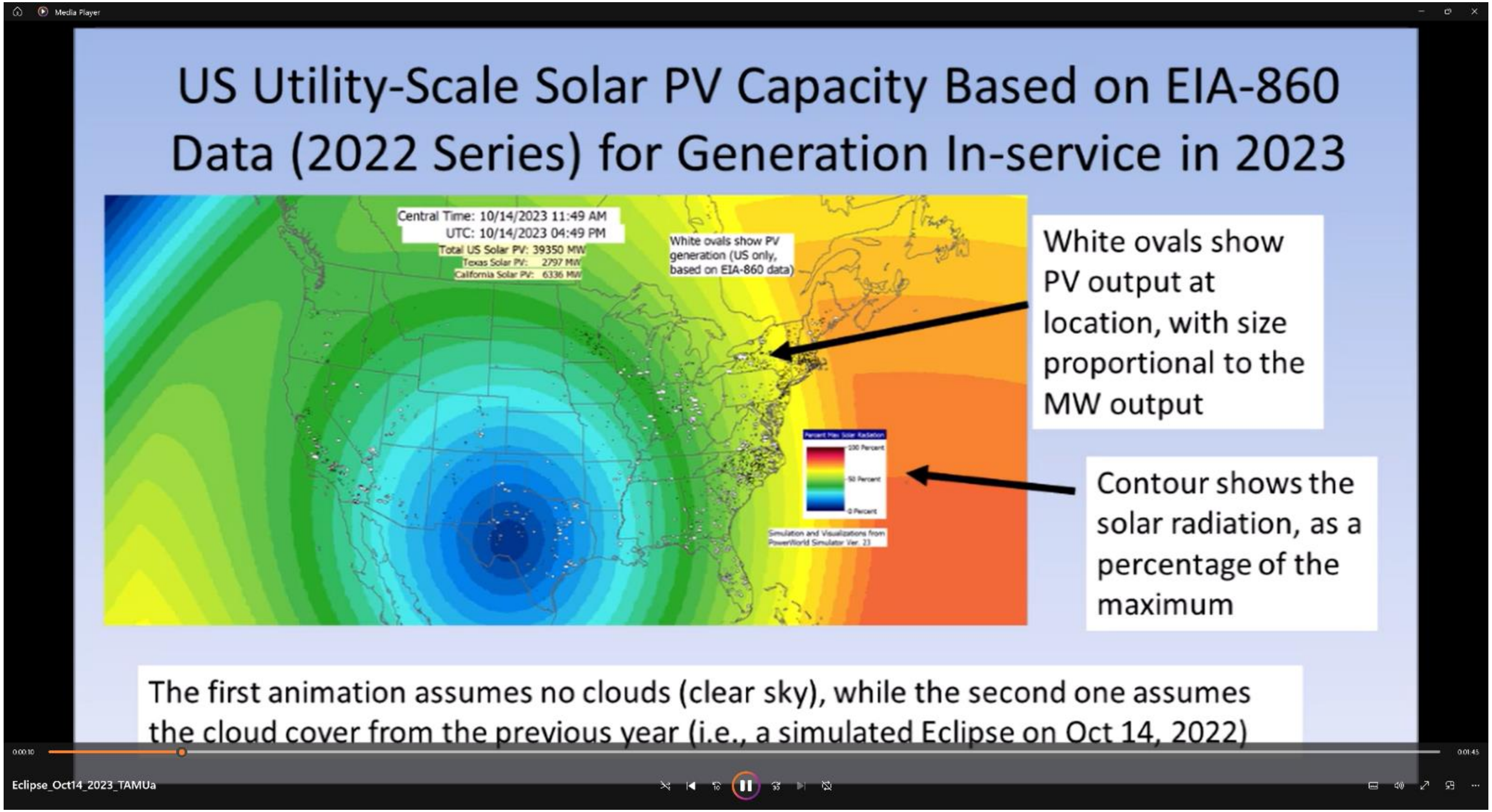
- Read Chapters 4 and 7
- Homework 4 is Thursday October 19
- Exam 1 average 86.9

# Electric Grid Impacts of Oct 14, 2023 Eclipse

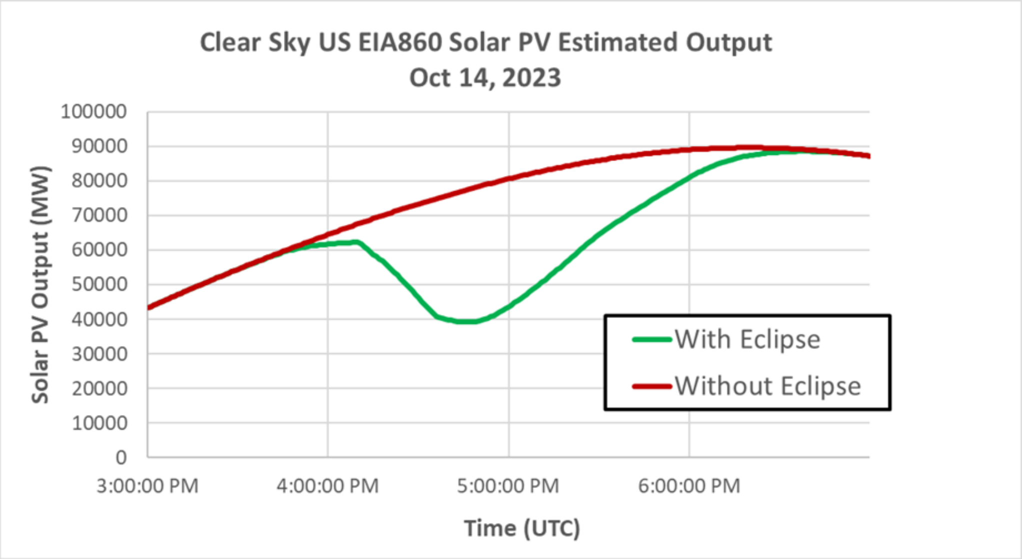
- There will be an annular eclipse on October 14, 2023 that will pass right over Texas; we recently released a video showing the estimated impact on US PV generation

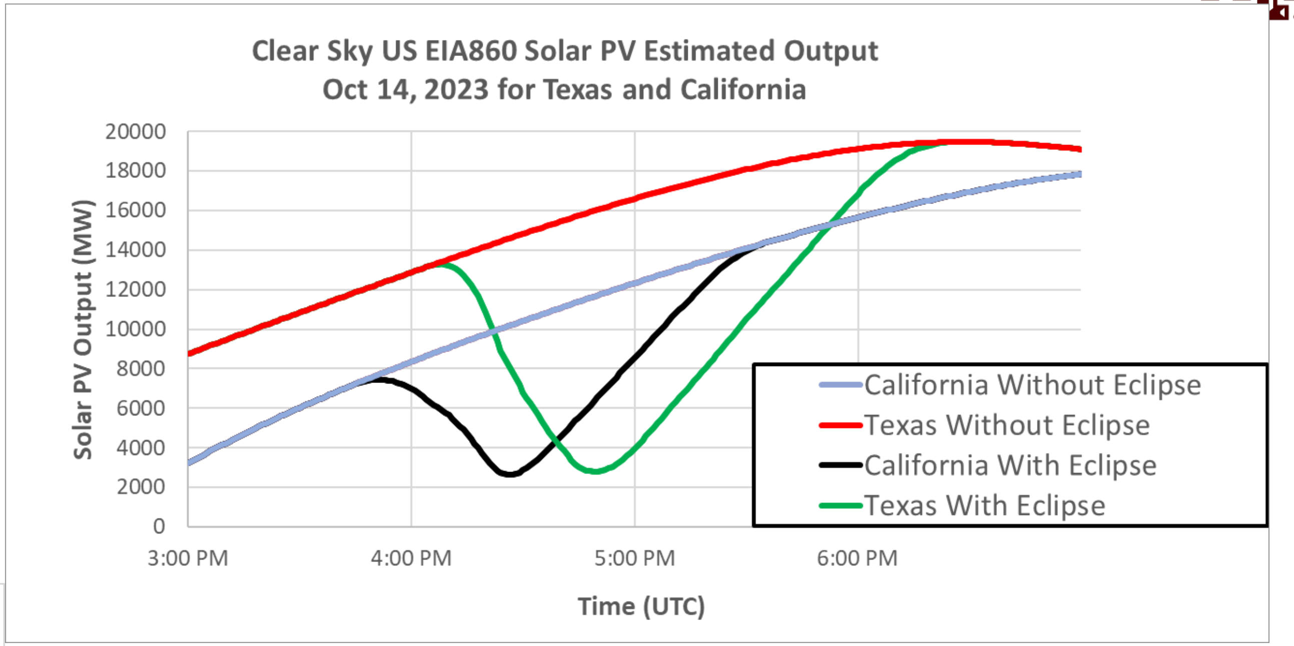



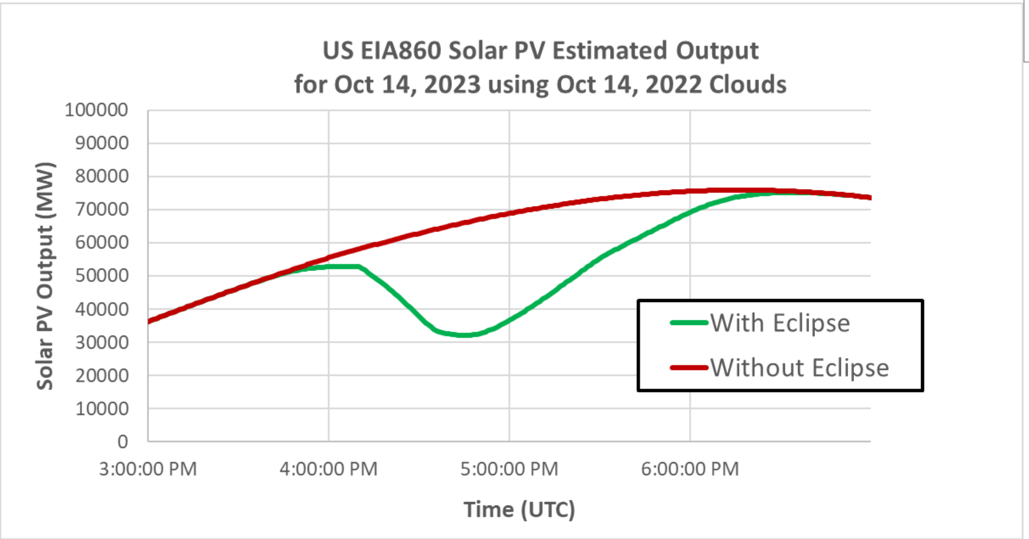
# Eclipse Video



# Clear Sky Impact of Oct 14, 2023 Eclipse



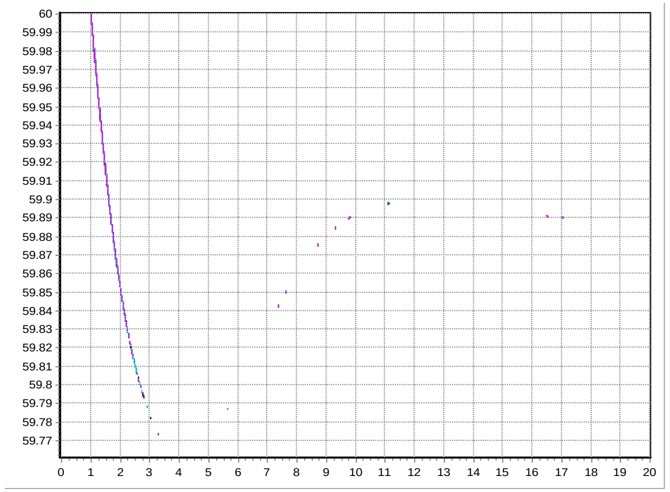



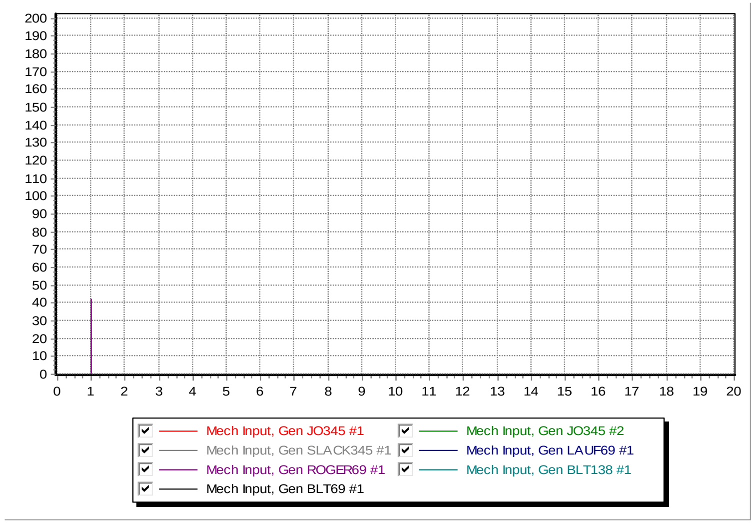



# Larger System Example

- 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

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

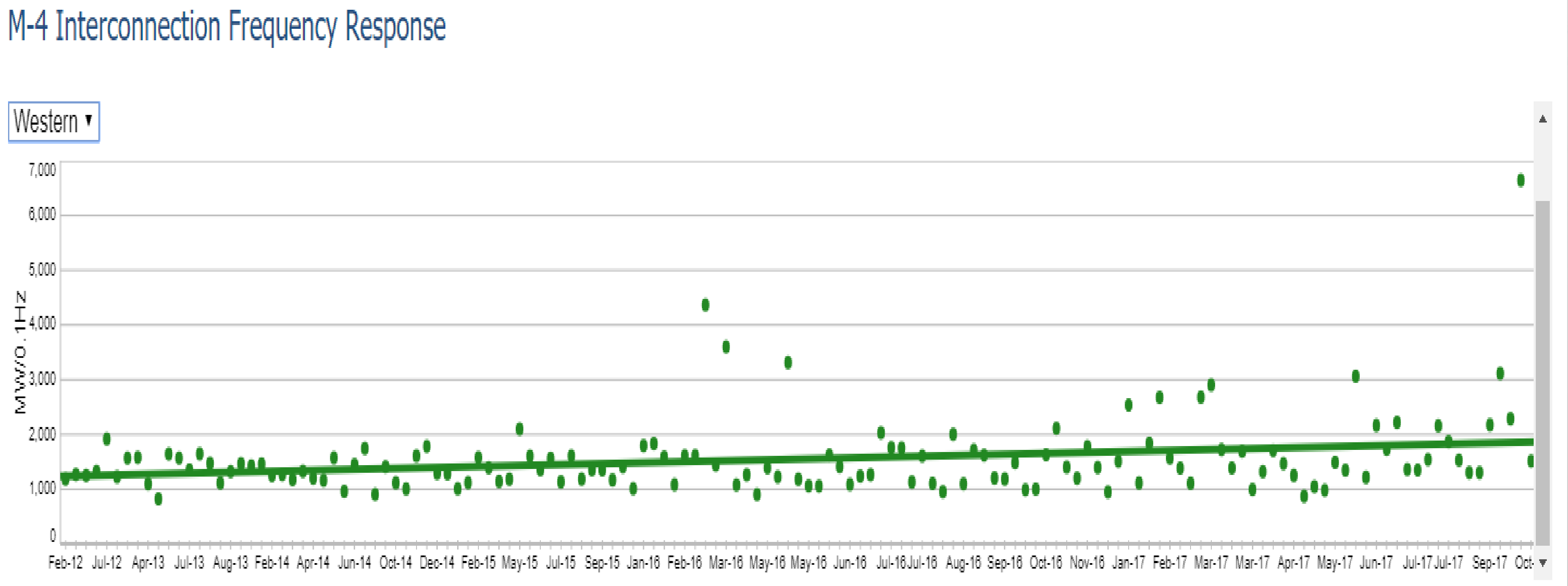





Case is **Bus37_TGOV1**

# WECC Interconnect Frequency Response

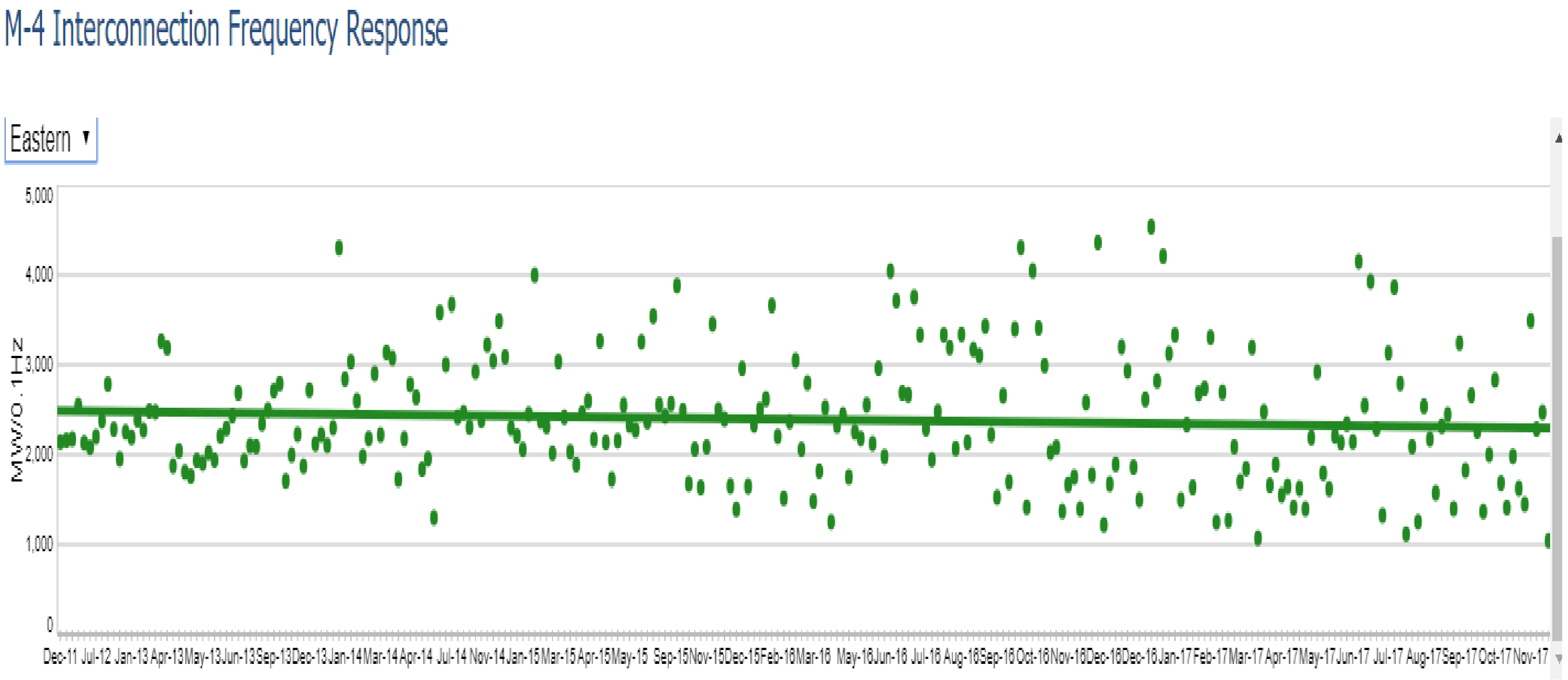
- Data for the four major interconnects had been available from NERC; these are the values between points A and B




A higher value is better (more generation for a 0.1 Hz change)

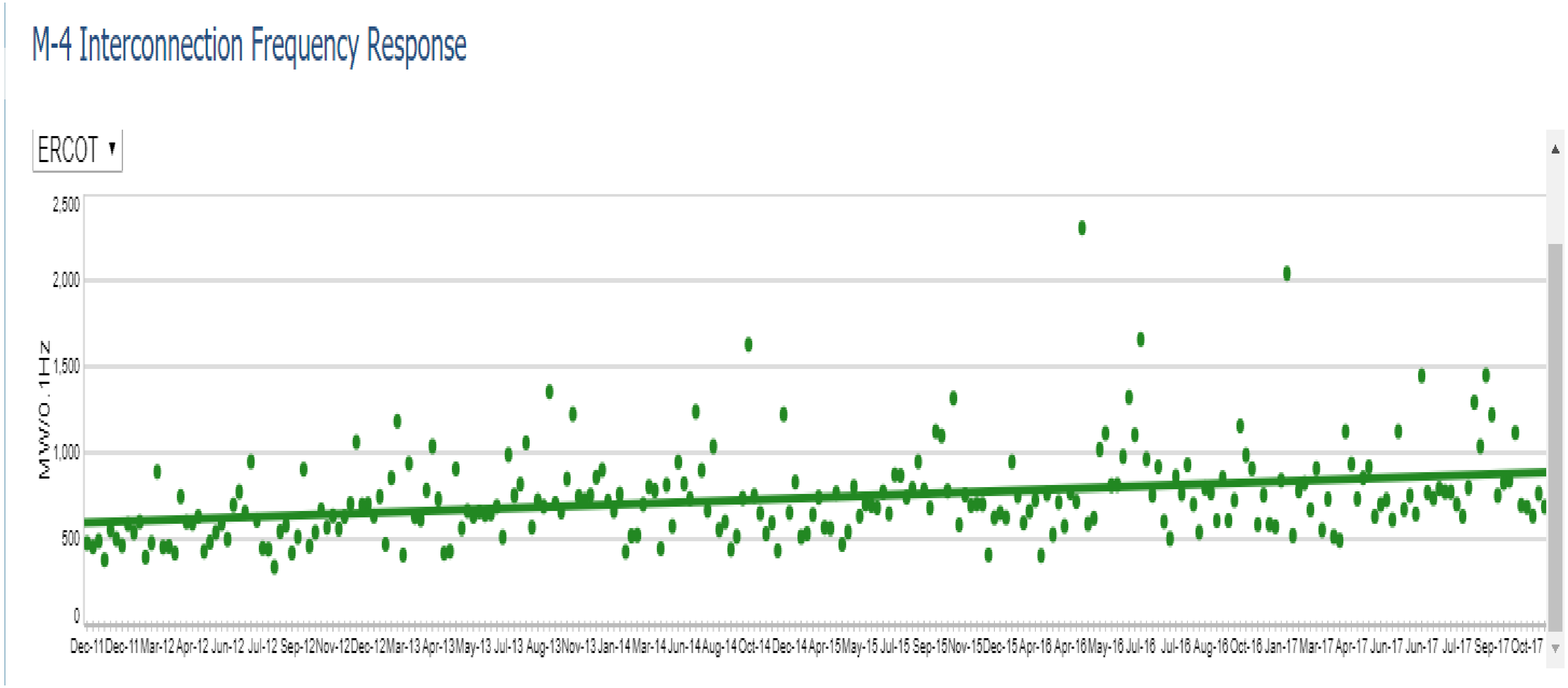
Source: www.nerc.com/pa/RAPA/ri/Pages/InterconnectionFrequencyResponse.aspx

# Eastern Interconnect Frequency Response




The larger Eastern Interconnect on average has a higher value

# ERCOT Interconnect Frequency Response




The ERCOT values are usually lower

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

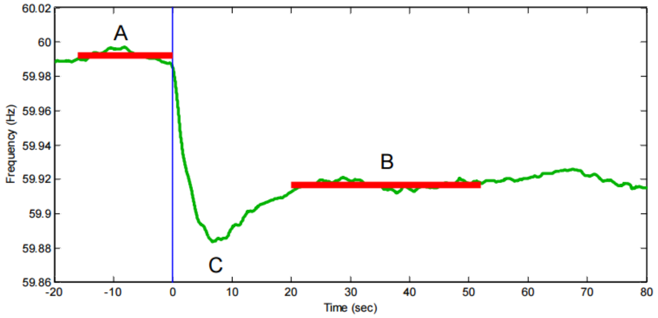
# NERC M-4 Interconnection Frequency Response

- Now it is use easily available in summary form

| 2022 Frequency Response Performance Statistics for Stabilizing Period | | | | | | |
|---|---|---|---|---|---|---|
| | 2022 Operating Year Stabilizing Period Performance | | | | | |
| | Mean $IFRM_{A\text{-}B}$ (MW/0.1Hz) | Median $IFRM_{A\text{-}B}$ (MW/0.1Hz) | Lowest $IFRM_{A\text{-}B}$ (MW/0.1Hz) | Maximum $IFRM_{A\text{-}B}$ (MW/0.1Hz) | Number of Events | 2018–2022 OY Trend |
| Eastern | 2,648 | 2,423 | 1,594 | 5,342 | 46 | Stable |
| Texas | 1,287 | 1,163 | 511 | 2,955 | 32 | Improving |
| Québec | 1,009 | 859 | 512 | 2,331 | 22 | Stable |
| Western | 1,934 | 1,763 | 1,114 | 4,917 | 30 | Stable |

| 2022 Frequency Response Performance Statistics for Arresting Period | | | | | | |
|---|---|---|---|---|---|---|
| | 2022 Operating Year Arresting Period Performance | | | | | |
| | Mean $IFRM_{A\text{-}C}$ (MW/0.1Hz) | Median $IFRM_{A\text{-}C}$ (MW/0.1Hz) | Lowest $IFRM_{A\text{-}C}$ (MW/0.1Hz) | Mean UFLS Margin (Hz) | Lowest UFLS Margin (Hz) | 2018–2022 $IFRM_{A\text{-}C}$ OY Trend |
| Eastern | 2,050 | 1,921 | 1,202 | 0.455 | 0.419 | Stable |
| Texas | 575 | 532 | 305 | 0.584 | 0.486 | Improving |
| Québec | 157 | 148 | 95 | 1.121 | 0.938 | Stable |
| Western | 886 | 846 | 535 | 0.413 | 0.330 | Stable |

The Arresting Period is up to 12 seconds after the event; the Stabilizing Period is between 20 and 52 after the event.



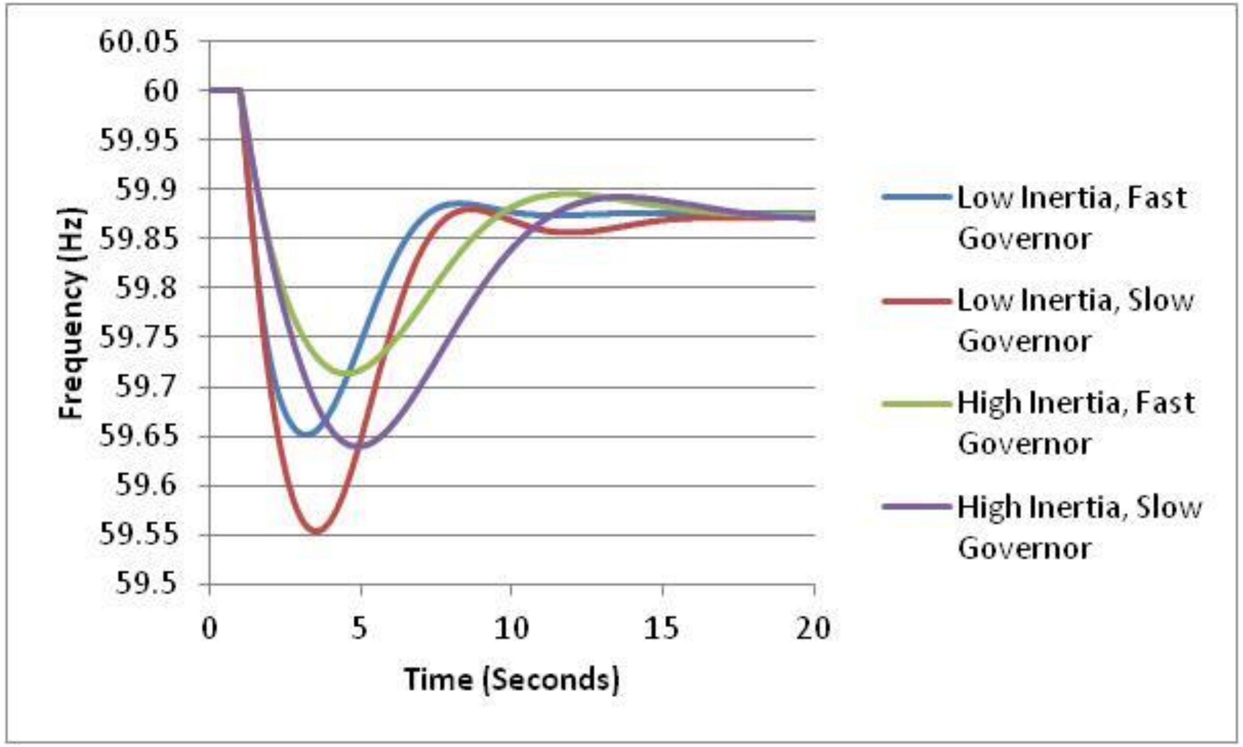

**NERC FRM BAL-003-1: Frequency difference between Point A and Point B**

LBNL Metrics: Frequency difference between Point A and Point C

Image source: www.nerc.com/pa/RAPA/ri/Pages/InterconnectionFrequencyResponse.aspx

# 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

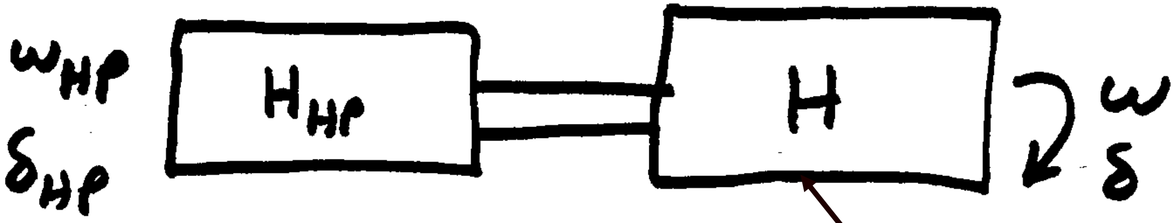
- In an interconnected power system the governors to not automatically restore the frequency to 60 Hz
- Rather this done via the ACE (area control error) calculation. Previously we defined ACE as the difference between the actual real power exports from an area and the scheduled exports. But it has an additional term

  $$ACE = P_{actual} - P_{sched} - 10\beta(freq_{act} - freq_{sched})$$

- $\beta$ is the balancing authority frequency bias in MW/0.1 Hz with a negative sign. It is about 0.8% of peak load/generation

This slower ACE response is usually not modeled in most stability simulations

# 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

$$\frac{d\delta_{HP}}{dt} = \omega_{HP} - \omega_s$$

$$\frac{2H_{HP}}{\omega_s}\frac{d\omega_{HP}}{dt} = T_{IN} - T_{OUT}$$

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

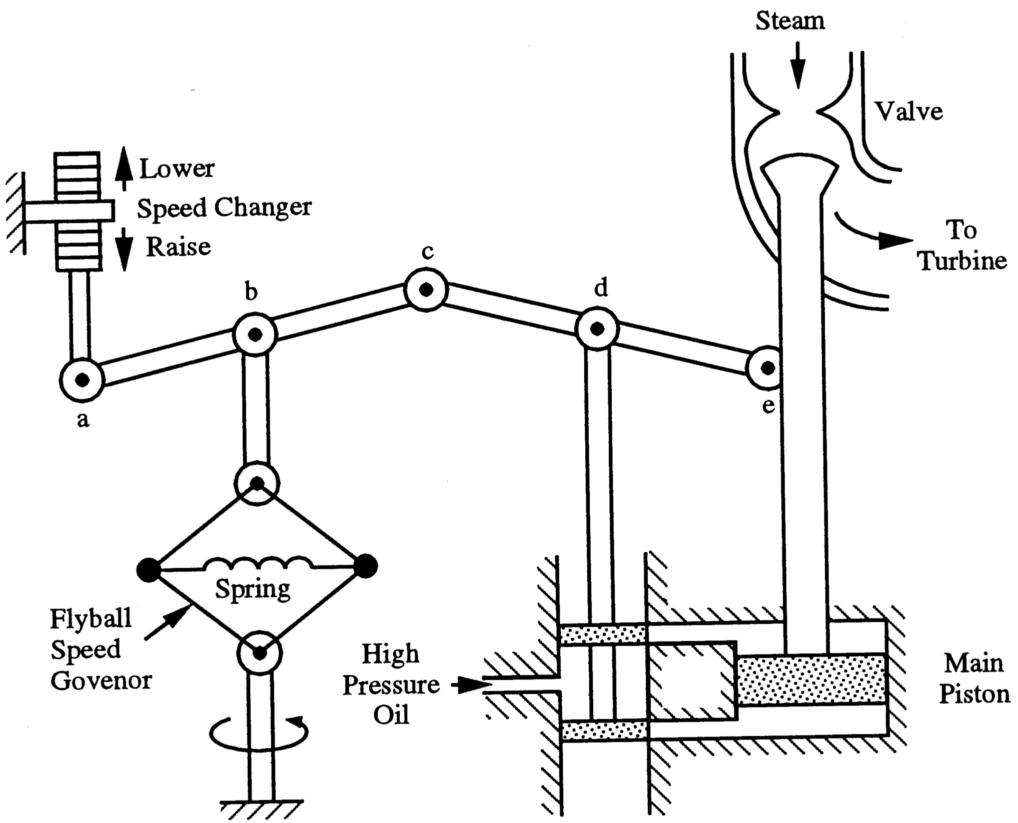
$$T_{SV}\frac{dP_{SV}}{dt} = -P_{SV} + P_C - \frac{1}{R}\Delta\omega$$

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

$$0 \le P_{SV} \le P_{SV}^{\max}$$

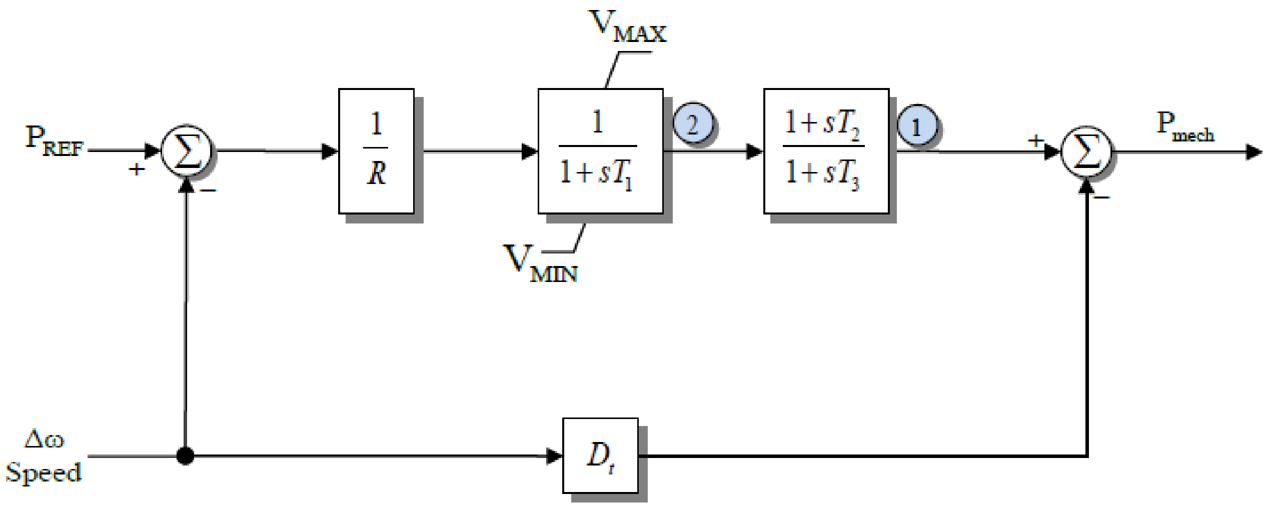
Steam valve limits

$R$ = .05 (5% droop)



# TGOV1 Model

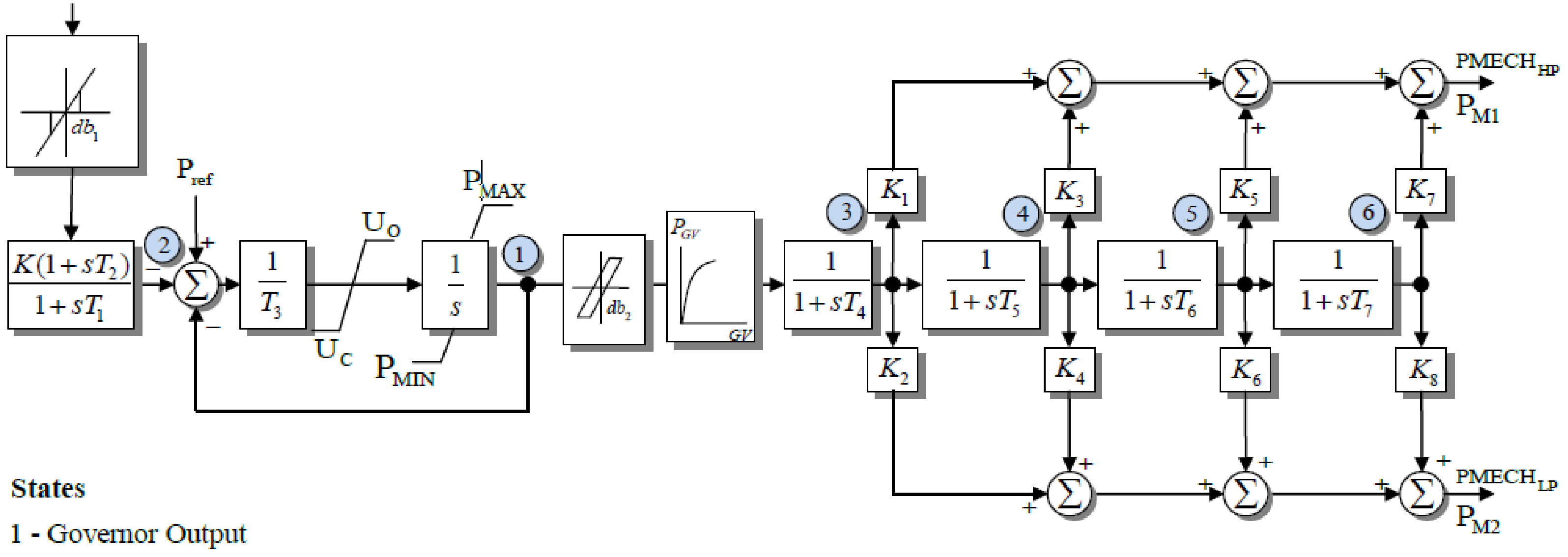
- The standard model that is close to this is the TGOV1




About 3% of governors in the 2022 EI/WECC model are TGOV1; R is about 0.05, $T_1$ is less than 0.5 (except for one 999!), $T_3$ has an average of 6, average $T_2/T_3$ is 0.34; $D_t$ is used to model turbine damping and is often zero (about 90% of the time)

# IEEEG1 Model

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




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

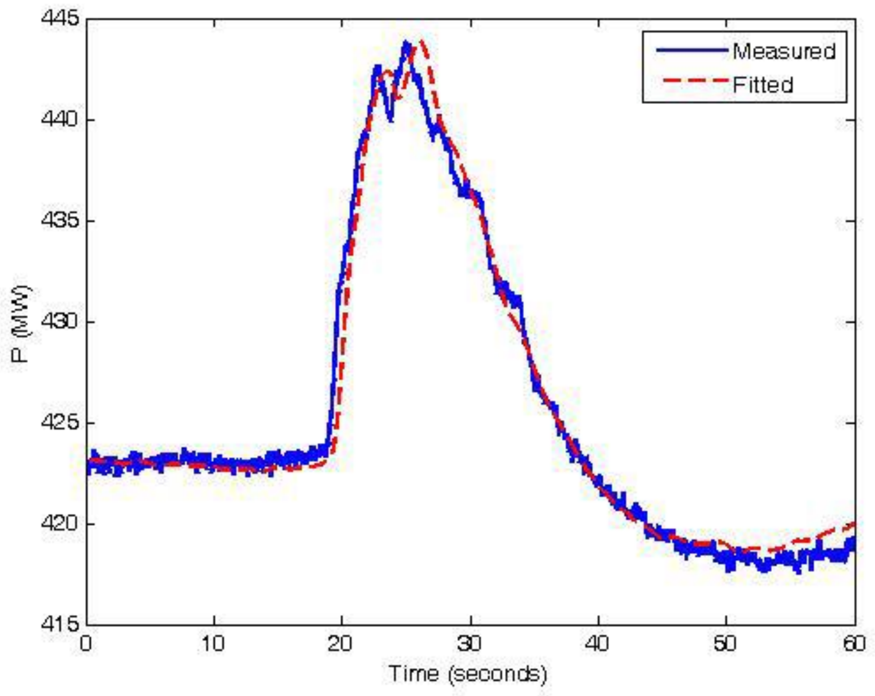
$U_o$ and $U_c$ are rate limits

In this model K=1/R

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 16% of WECC and EI governors are currently IEEEG1s
- Below figures show two test comparison with this model



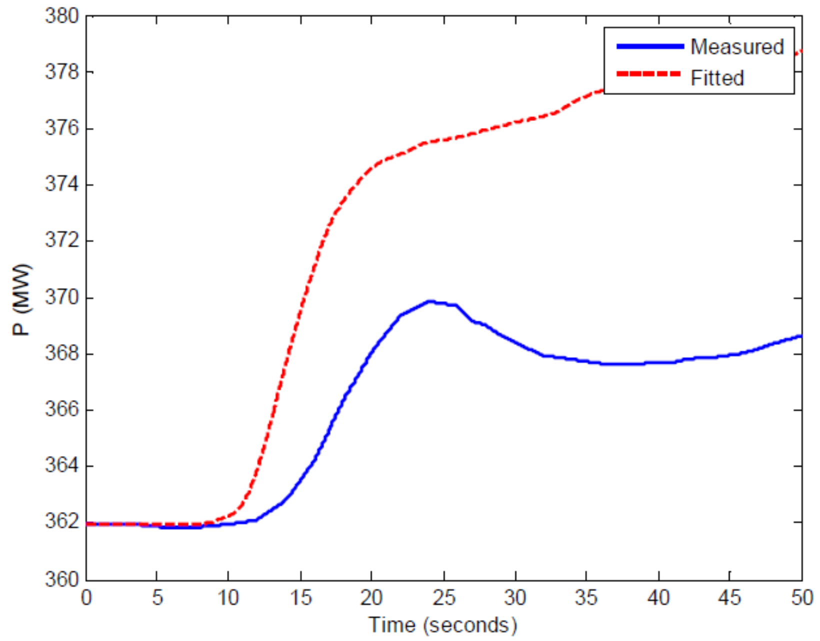
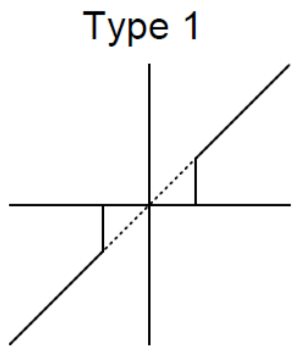




Image Source: Figs 2-4, 2-6 of IEEE PES, "Dynamic Models for Turbine-Governors in Power System Studies," Jan 2013

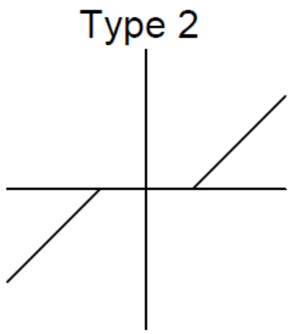
# Deadbands

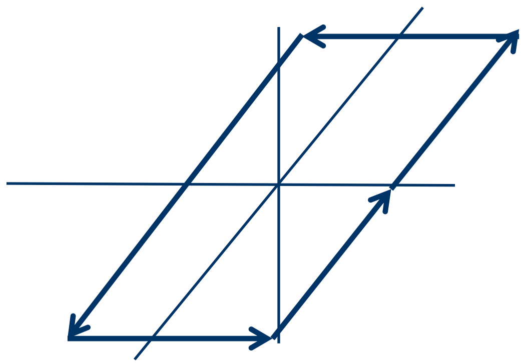
- Before going further, it is useful to briefly consider deadbands, with two types shown with IEEEG1 and described in the 2013 IEEE PES Governor Report
- The type 1 is an intentional deadband, implemented to prevent excessive response
  - Until the deadband activates there is no response, then normal 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 the deadbands usually start at their origin

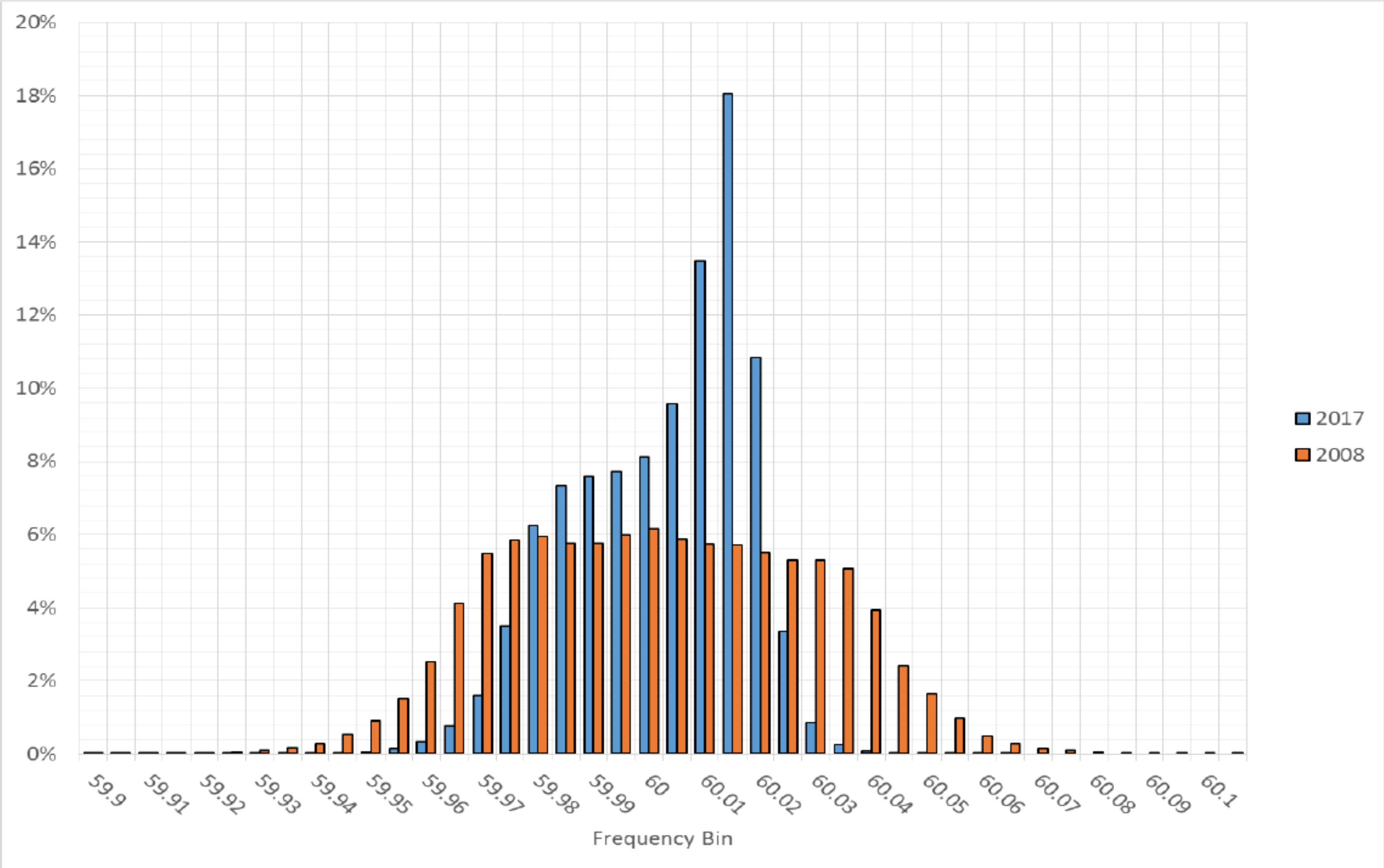
# Frequency Deadbands in ERCOT

- In ERCOT NERC BAL-001-TRE-1 ("Primary Frequency Response in the ERCOT Region") has the purpose "to maintain interconnection steady-state frequency within defined limits"
- The deadband requirement is ±0.034 Hz for steam and hydro turbines with mechanical governors; ±0.017 Hz for all other generating units
  - Controllable load resources used ±0.036 Hz
- The maximum droop setting is 5% for all units except it is 4% for combined cycle combustion turbines

Source: www.ercot.com/content/wcm/libraries/224011/February_1_2021_Nodal_Operating_Guide.pdf

# Comparing ERCOT 2017 Versus 2008 Frequency Profile (5 mHz bins)

## Comparing 2017 vs 2008 Frequency Profile in 5 mHz Bins




A good NERC document that addresses deadbands is "Reliability Guideline: Primary Frequency Control," Jan 2023 (Draft)

# 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

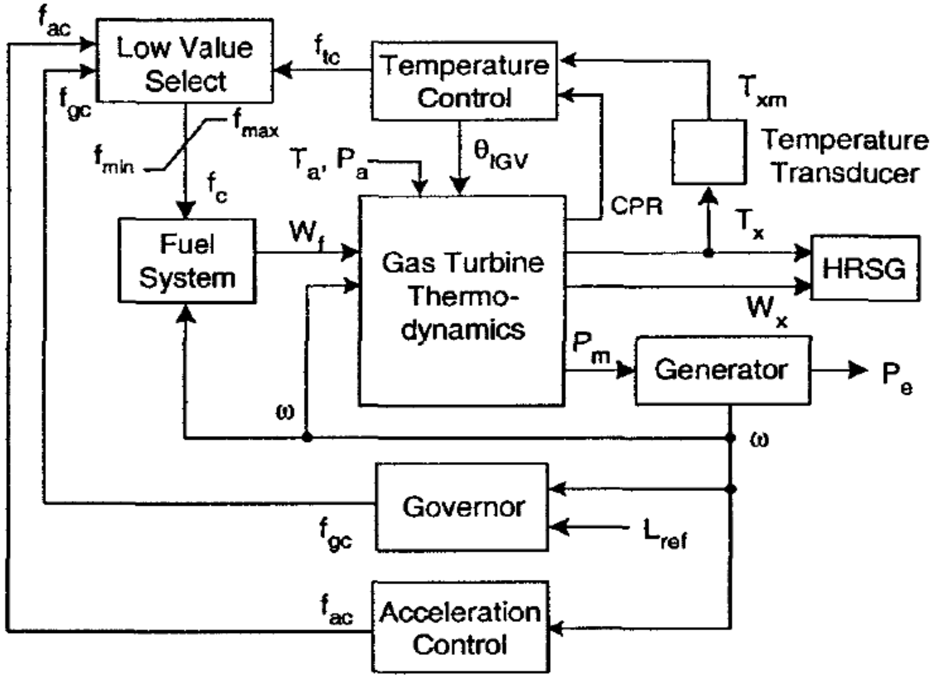


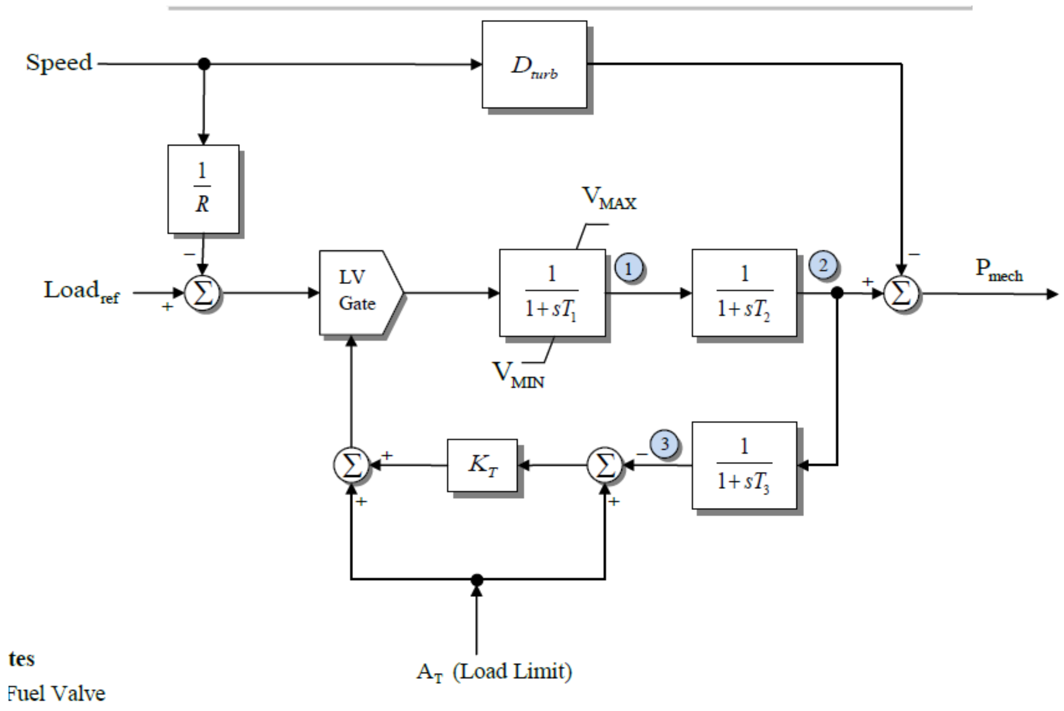

Figure 3-3: Gas turbine controls [17] (IEEE© 2001).

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 (about 6% of 2022 EI/WECC governors; not recommended for new models though)




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

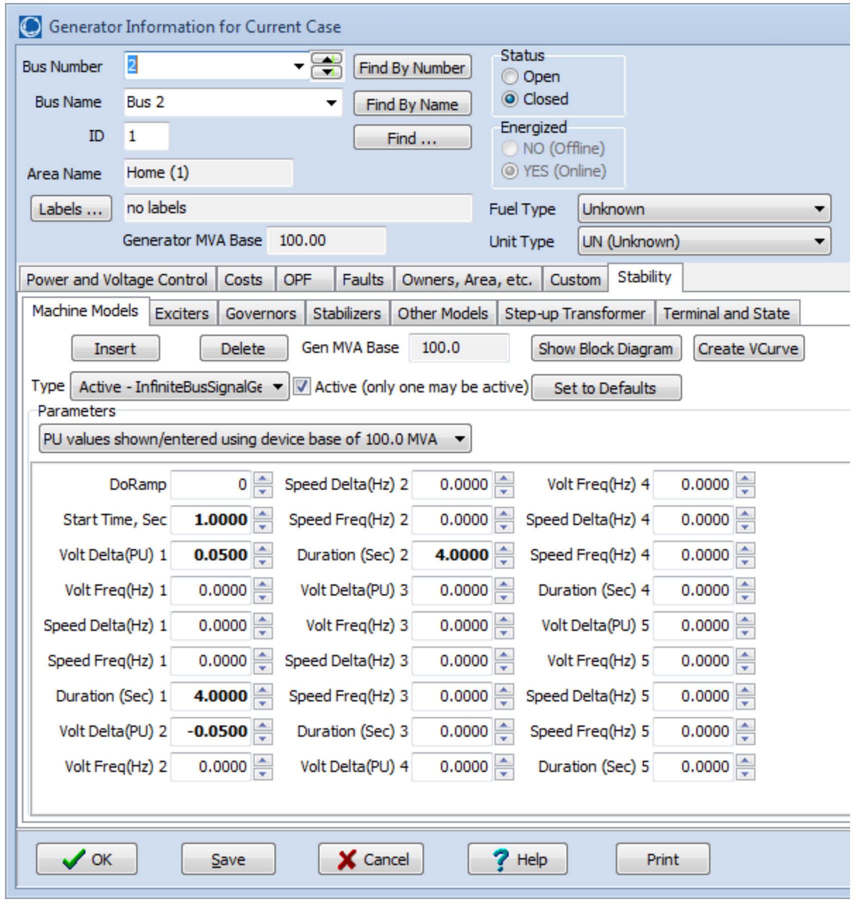
$T_1$ average is 0.9, $T_2$ is 0.6 sec

# Play-in (Playback) Models

- Often time in system simulations there is a desire to test the response of units (or larger parts of the simulation) to particular changes in voltage or frequency
  - These values may come from an actual system event
- "Play-in" or playback models can be used to vary an infinite bus voltage magnitude and frequency, with data specified in a file
- PowerWorld allows both the use of files (for say recorded data) or auto-generated data
  - Machine type GENCLS_PLAYBACK can play back a file
  - Machine type InfiniteBusSignalGen can auto-generate a signal

# PowerWorld Infinite Bus Signal Generation

- Below dialog shows some options for auto-generation of voltage magnitude and frequency variations




**Start Time** tells when to start; values are then defined for up to five separate time periods

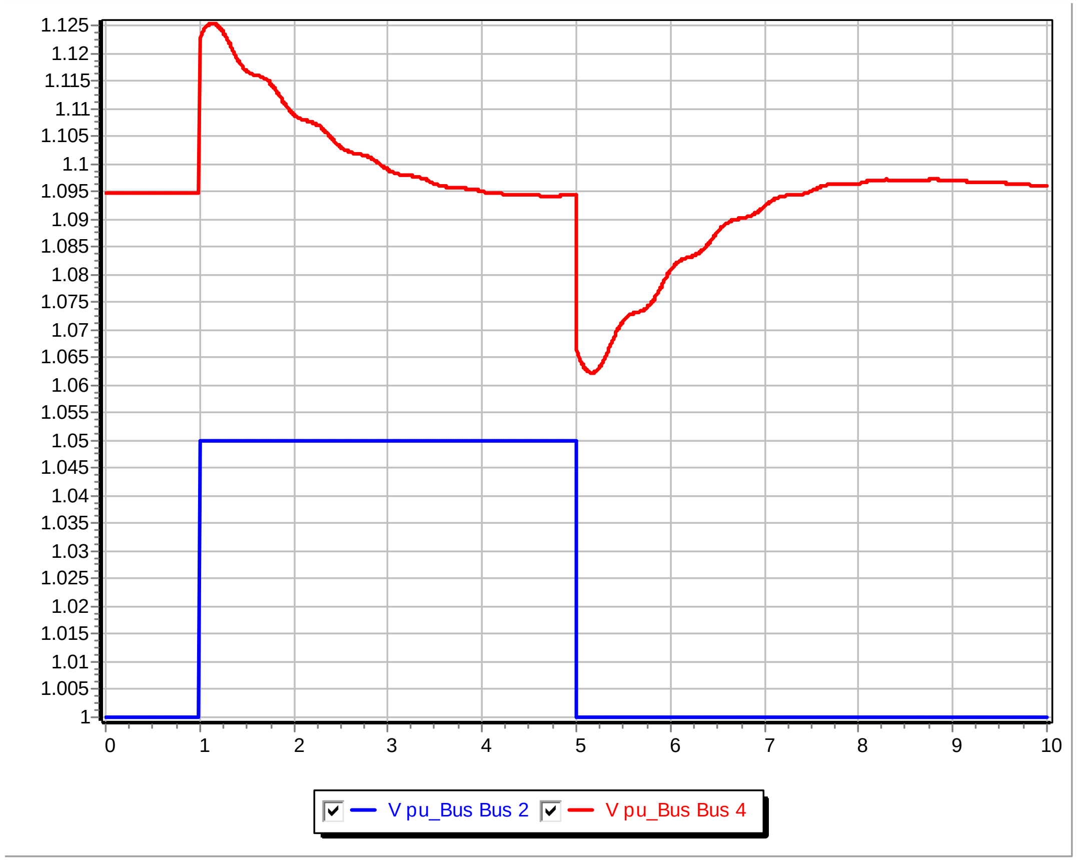
**Volt Delta** is the magnitude of the pu voltage deviation; **Volt Freq** is the frequency of the voltage deviation in Hz (zero for dc)

**Speed Delta** is the magnitude of the frequency deviation in Hz; **Speed Freq** is the frequency of the frequency deviation

**Duration** is the time in seconds for the time period

# Example: Step Change in Voltage Magnitude

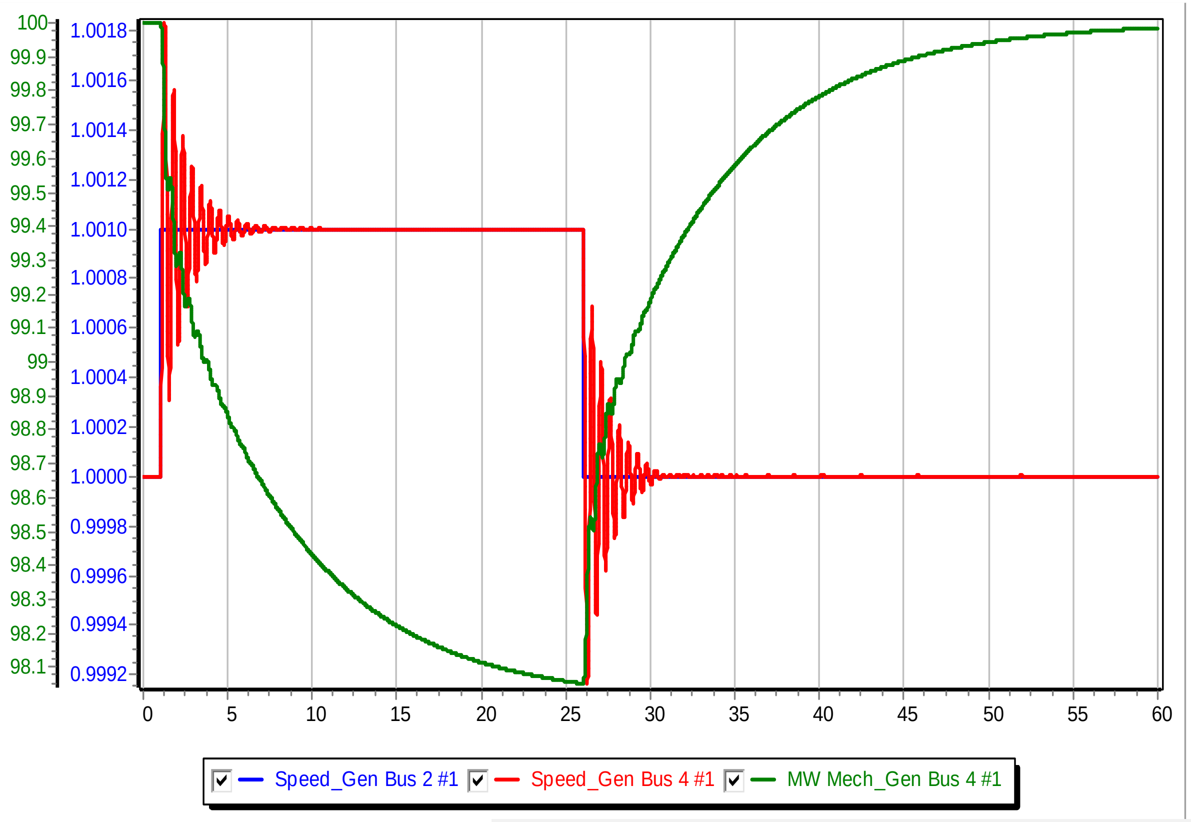
- Below graph shows the voltage response for the four bus system for a change in the infinite bus voltage




Case name:
**B4_SignalGen_Voltage**

# Example: Step Change Frequency Response

- Graph shows response in generator 4 output and speed for a 0.1% increase in system frequency




This is a 100 MVA unit with a per unit R of 0.05

$$\Delta f = -\frac{0.05 \times \Delta P_{gen,MW}}{100}$$

$$\frac{-0.001 \times 100}{0.05} = \Delta P_{gen,MW}$$

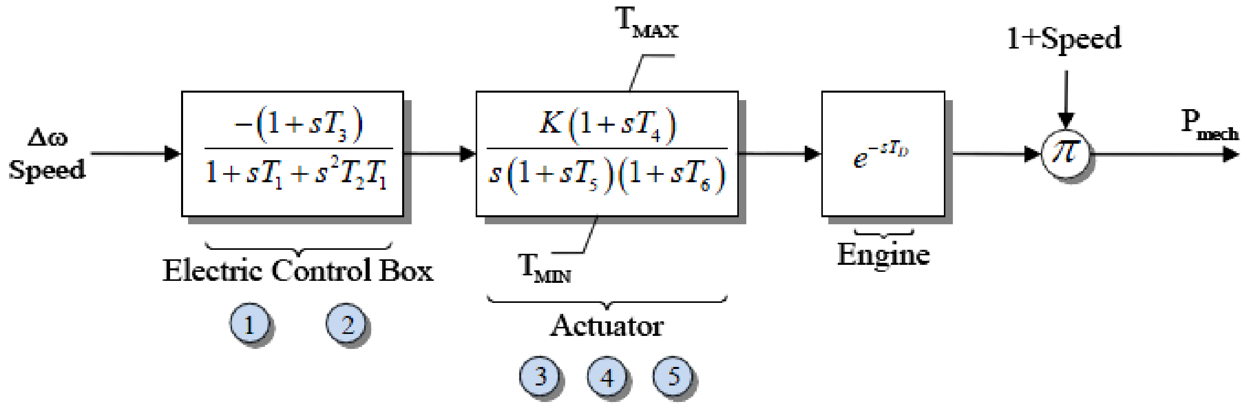
$$\Delta P_{gen,MW} = -2$$

Case name: **B4_SignalGen_Freq**

# Simple Diesel Model: DEGOV

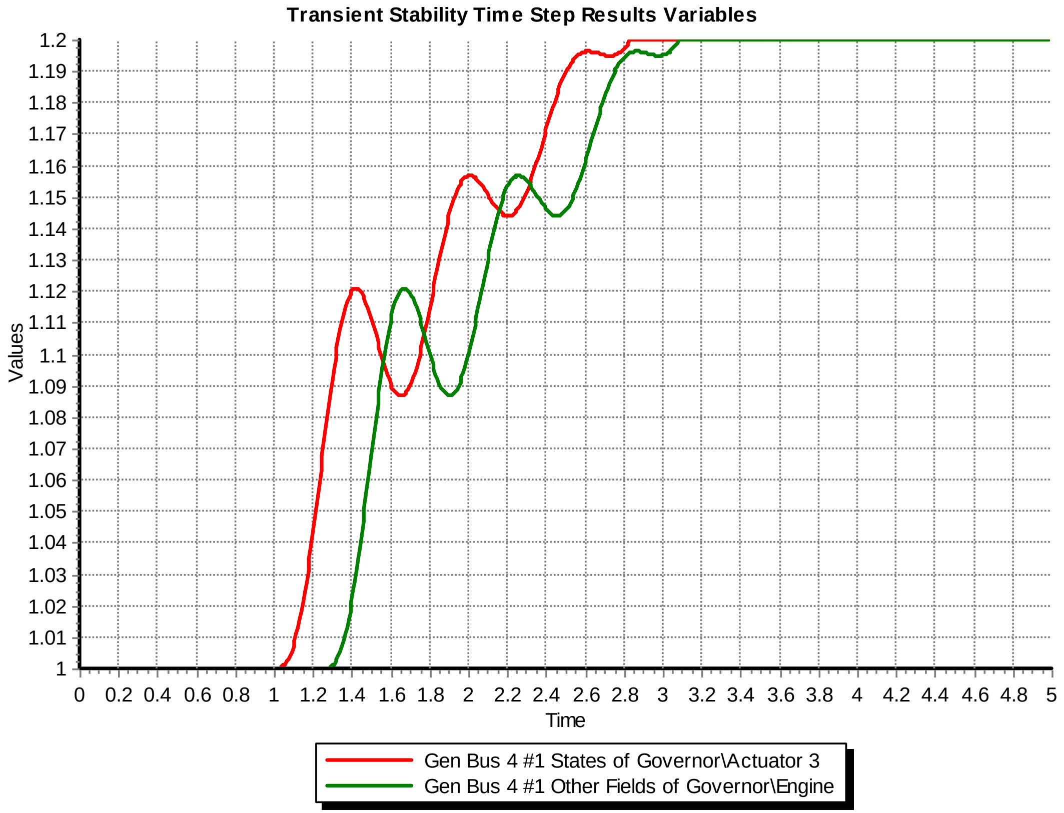
- Sometimes models implement time delays (DEGOV)
  - Often delay values are set to zero
- Delays can be implemented either by saving the input value or by using a Pade approximation, with a 2nd order given below; a 4th order is also common

$$e^{-sT_D} \approx \frac{1 - k_1 s + k_2 s^2}{1 + k_1 s + k_2 s^2}, \quad k_1 = \frac{T_D}{2}, k_2 = \frac{T_D^2}{12}$$



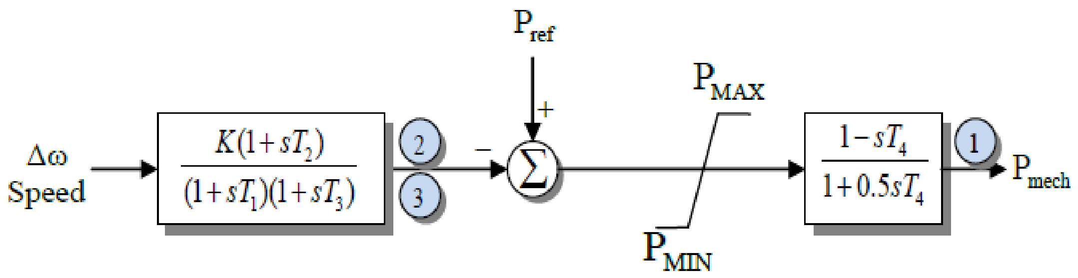
# DEGOV Delay Approximation

- With $T_D$ set to 0.5 seconds (which is longer than the normal of about 0.05 seconds in order to illustrate the delay)



# Hydro Units

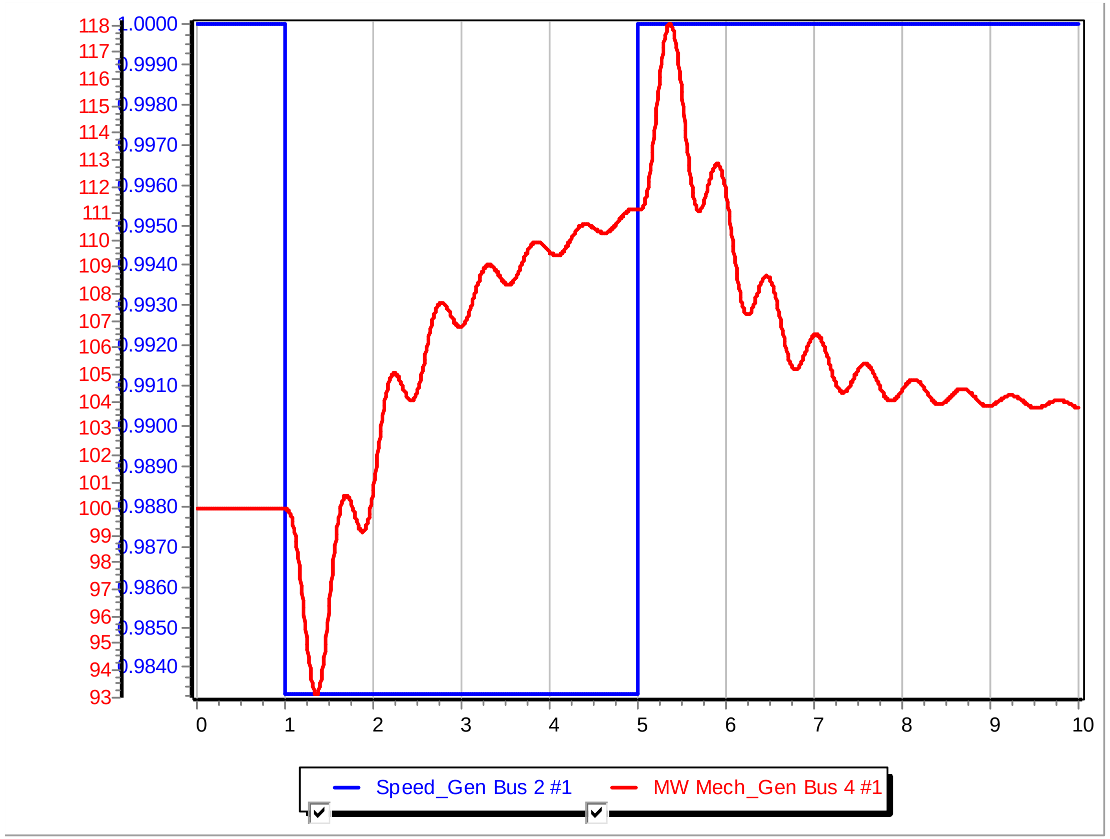
- Hydro units tend to respond slower than steam and gas units; since early transient stability studies focused on just a few seconds (first or second swing instability), detailed hydro units were not used
  - The original IEEEG2 and IEEEG3 models just gave the linear response; now considered obsolete
- Below is the IEEEG2; left side is the governor, right side is the turbine and water column




For sudden changes there is actually an inverse change in the output power

# Four Bus Example with an IEEEG2

- Graph below shows the mechanical power output of gen 2 for a unit step decrease in the infinite bus frequency; note the power initially goes down!




This is caused by a transient decrease in the water pressure when the valve is opened to increase the water flow; the flow does not change instantaneously because of the water's inertia.

Case name:
**B4_SignalGen_IEEEG2**

# Washout Filters

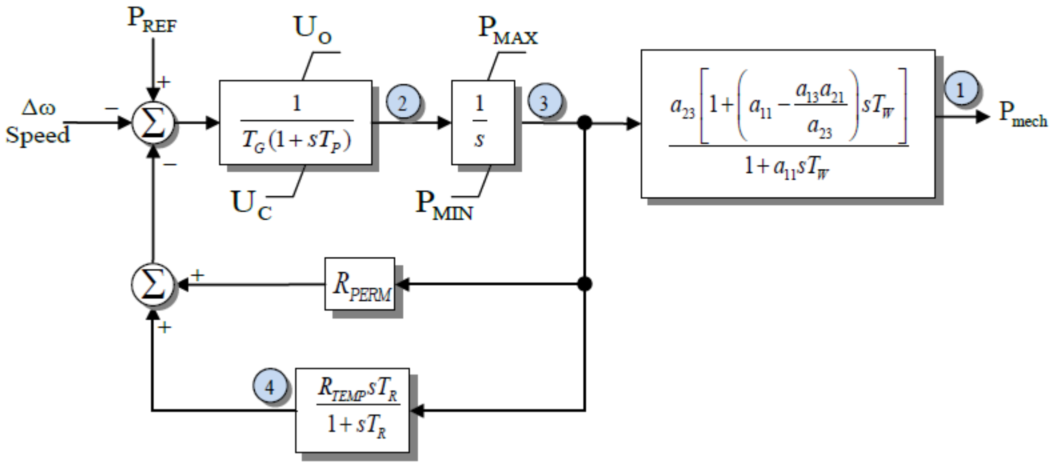
- A washout filter is a high pass filter that removes the steady-state response (i.e., it "washes it out") while passing the high frequency response

$$\frac{sT_w}{1+sT_w}$$

- They are commonly used with hydro governors and (as we shall see) with power system stabilizers
- With hydro turbines ballpark values for $T_w$ are around one or two seconds

# IEEEG3

- This model has a more detailed governor model, but the same linearized turbine/water column model
- Because of the initial inverse power change, for fast deviations the droop value is transiently set to a larger value (resulting in less of a power change)




Previously WECC had about 10% of their governors modeled with IEEEG3s; in 2022 it is less than 1%

Because of the washout filter at high frequencies $R_{TEMP}$ dominates (on average it is 10 times greater than $R_{PERM}$)

# Tuning Hydro Transient Droop

- As given in equations 9.41 and 9.42 from Kundar (1994) the transient droop should be tuned so

$$R_{TEMP} = \left(2.3 - (T_W - 1) \times 0.15\right) \frac{T_W}{T_M}$$

$$T_R = \left(5.0 - (T_W - 1) \times 0.5\right) T_W$$

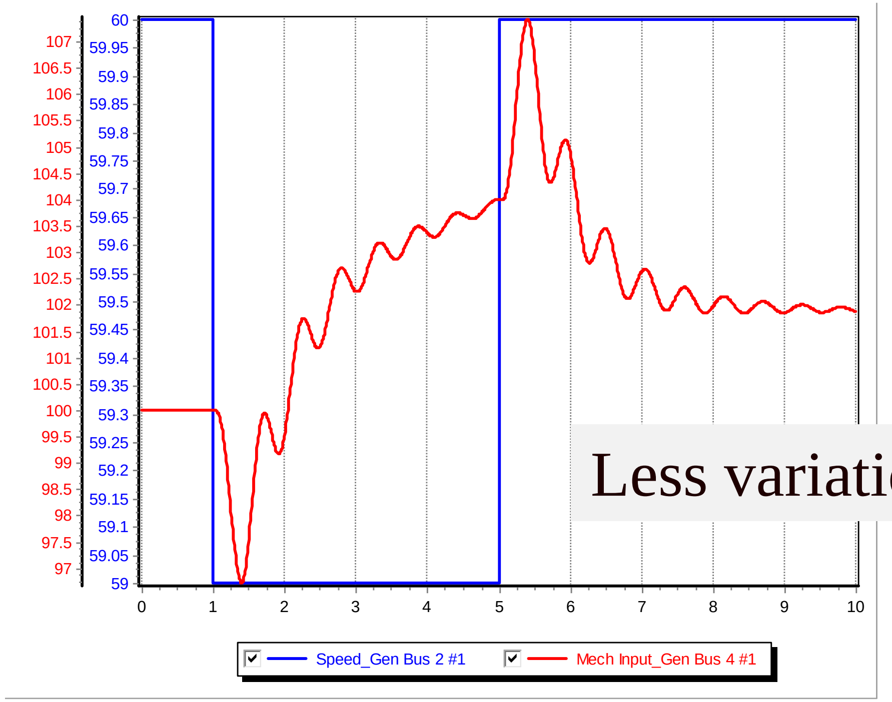
where $T_M$ =2H (called the mechanical starting time)

In comparing an average H is about 4 seconds, so $T_M$ is 8 seconds, an average $T_W$ is about 1.3, giving an calculated average $R_{TEMP}$ of 0.37 and $T_R$ of 6.3; the actual averages in a WECC case are 0.46 and 6.15. So on average this is pretty good! $R_{perm}$ is 0.05

Source: 9.2, Kundur, *Power System Stability and Control*, 1994

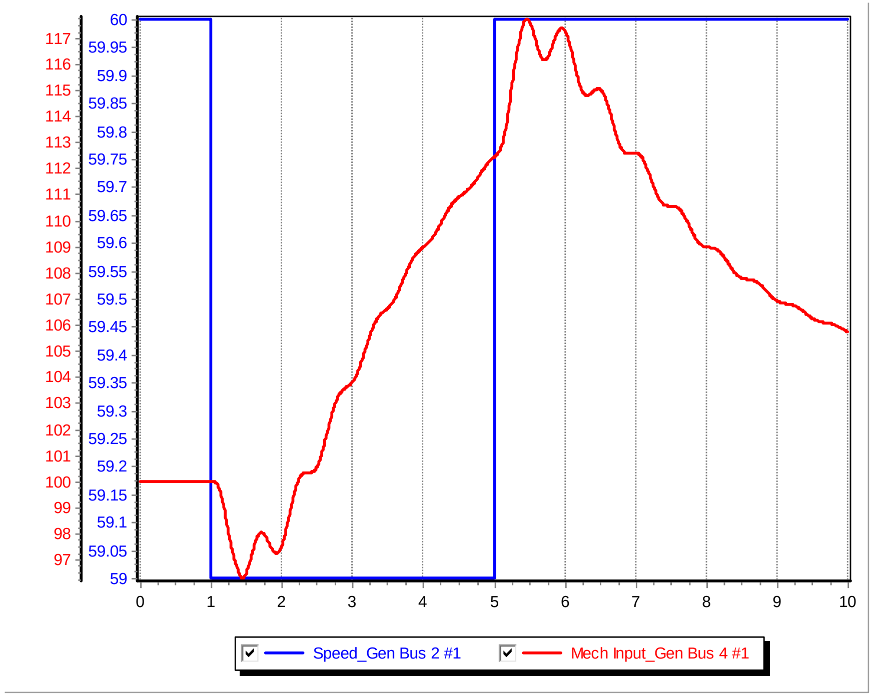
# IEEEG3 Four Bus Frequency Change

- The two graphs compare the case response for the frequency change with different $R_{TEMP}$ values




Less variation

$R_{TEMP} = 0.5, R_{PERM} = 0.05$




$R_{TEMP} = 0.05, R_{PERM} = 0.05$

Case name: **B4_SignalGen_IEEEG3**

# Basic Nonlinear Hydro Turbine Model

- Basic hydro system is shown below
  - Hydro turbines work be converting the kinetic energy in the water into mechanical energy
  - assumes the water is incompressible
- At the gate assume a velocity of U, a cross-sectional penstock area of A; then the
  volume flow is A*U=Q;

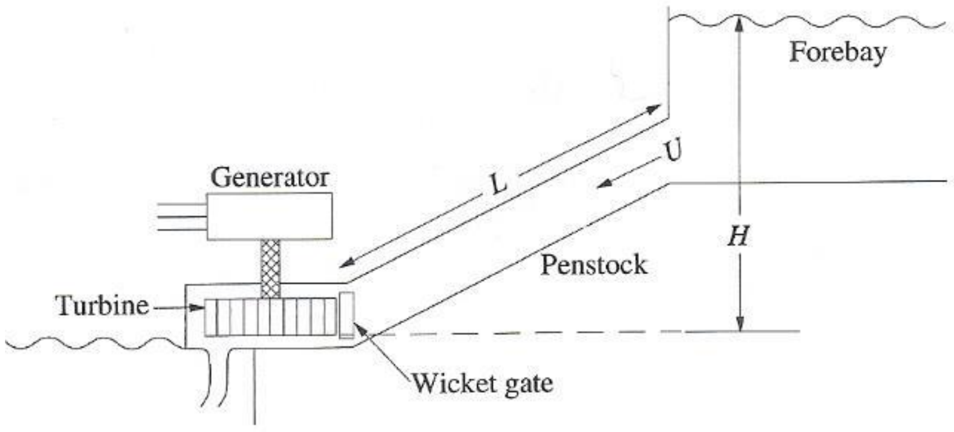



**Figure 9.2** Schematic of a hydroelectric plant

Source: 9.2, Kundur, *Power System Stability and Control*, 1994

# Basic Nonlinear Hydro Turbine Model

- From Newton's second law of motion the change in the flow volume Q

$$\rho L \frac{dQ}{dt} = F_{net} = A\rho g\left(H - H_{gate} - H_{\text{loss}}\right)$$

where $\rho$ is the water density, g is the gravitational constant, H is the static head (at the drop of the reservoir) and $H_{gate}$ is the head at the gate (which will change as the gate position is changed, $H_{loss}$ is the head loss due to friction in the penstock, and L is the penstock length.

- As per [a] paper, this equation is normalized to

$$\frac{dq}{dt} = \frac{\left(1 - h_{gate} - h_{\text{loss}}\right)}{T_W}$$

$T_W$ is called the water time constant, or water starting time

[a] "Hydraulic Turbine and Turbine Control Models for System Dynamic Studies," *IEEE Trans. Power Syst.*, Feb, 92

# Basic Nonlinear Hydro Turbine Model

- With $h_{base}$ the static head, $q_{base}$ the flow when the gate is fully open, an interpretation of $T_w$ is the time (in seconds) taken for the flow to go from stand-still to full flow if the total head is $h_{base}$
- If included, the head losses, $h_{loss}$, vary with the square of the flow
- The flow is assumed to vary as linearly with the gate position (denoted by c)

$$q = c\sqrt{h} \text{ or } h = \left(\frac{q}{c}\right)^2$$

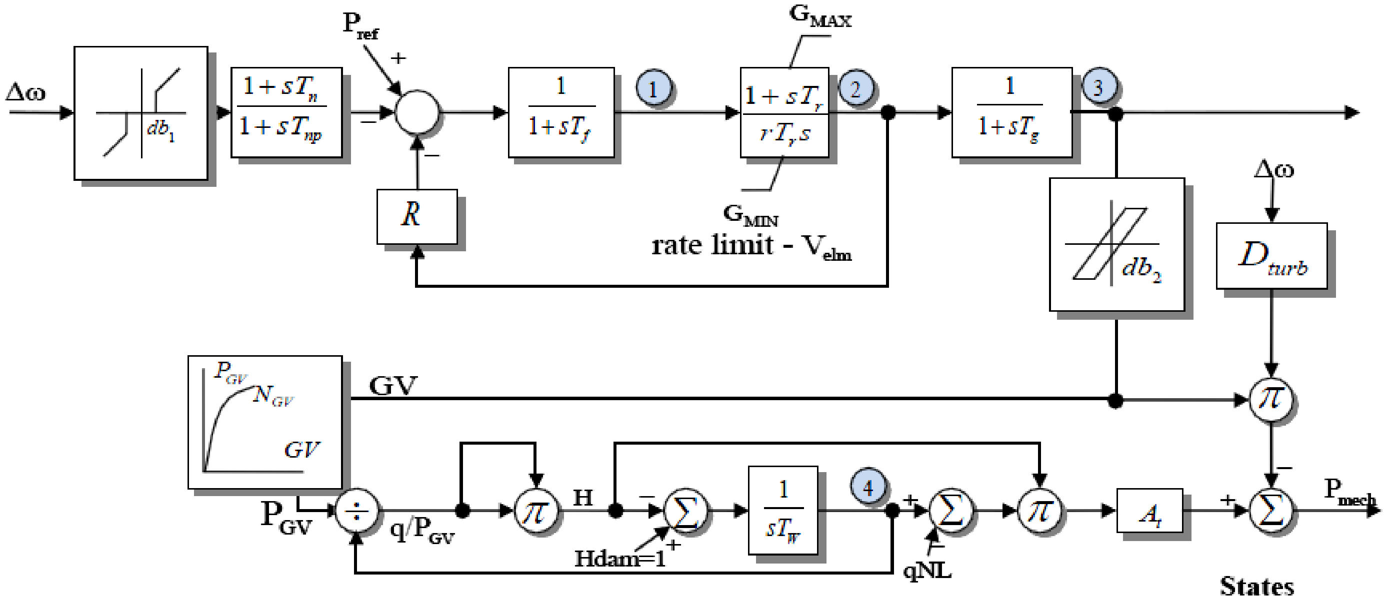
- Power developed is proportional to flow rate times the head, with a term $q_{nl}$ added to model the fixed turbine (no load) losses
  - The term $A_t$ is used to change the per unit scaling to that of the electric generator

$$P_m = A_t h\left(q - q_{nl}\right)$$

# Model HYGOV

- This simple model, combined with a governor, is implemented in HYGOV

About 6% of WECC governors use this model; average $T_W$ is two seconds

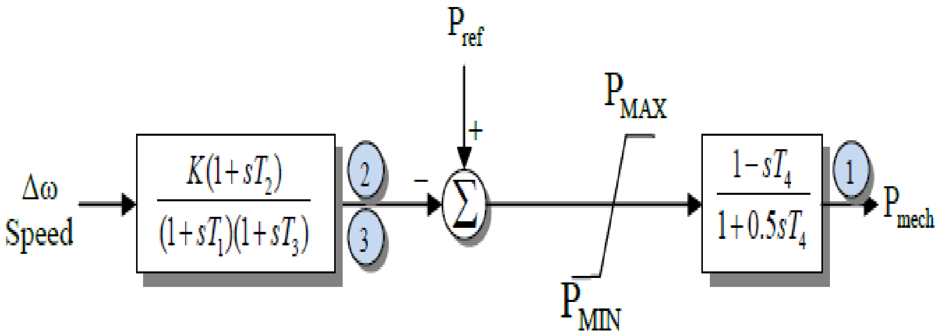



The gate position (GV) to gate power ($P_{GV}$) is sometimes represented with a nonlinear curve

$H_{loss}$ is assumed small and not included

# Linearized Model Derivation

- The previously mentioned linearized model can now be derived as




$$\frac{dq}{dt} = \frac{\left(1 - h(c)_{gate}\right)}{T_W}$$

$$\frac{d\Delta q}{dt} = -\frac{\Delta h(c)_{gate}}{T_W} \rightarrow \Delta q = \frac{\partial q}{\partial c}\Delta c + \frac{\partial q}{\partial h}\Delta h$$

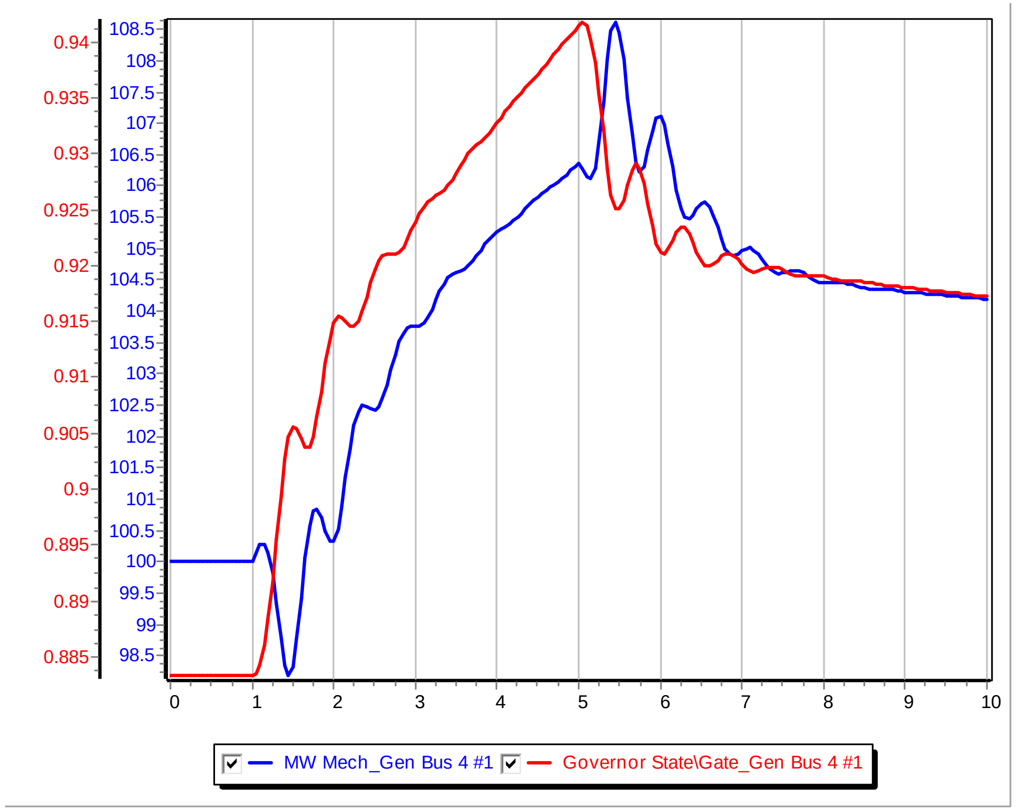
And for the linearized power

$$\Delta P_m = \frac{\partial P_m}{\partial h}\Delta h + \frac{\partial P_m}{\partial q}\Delta q$$

Then $$\frac{\Delta P_m}{\Delta c} = \frac{\left[\frac{\partial q}{\partial c}\frac{\partial P_m}{\partial q} - sT_w \frac{\partial P_m}{\partial h}\frac{\partial q}{\partial c}\right]}{1 + sT_w \frac{\partial q}{\partial h}}$$

# Four Bus Case with HYGOV

- The below graph plots the gate position and the power output for the bus 2 signal generator decreasing the speed then increasing it




Note that just like in the linearized model, opening the gate initially decreases the power output

Case name: **B4_SignalGen_HYGOV**