ECEN 667
Power System Stability

Lecture 13: Governors, PID Controllers

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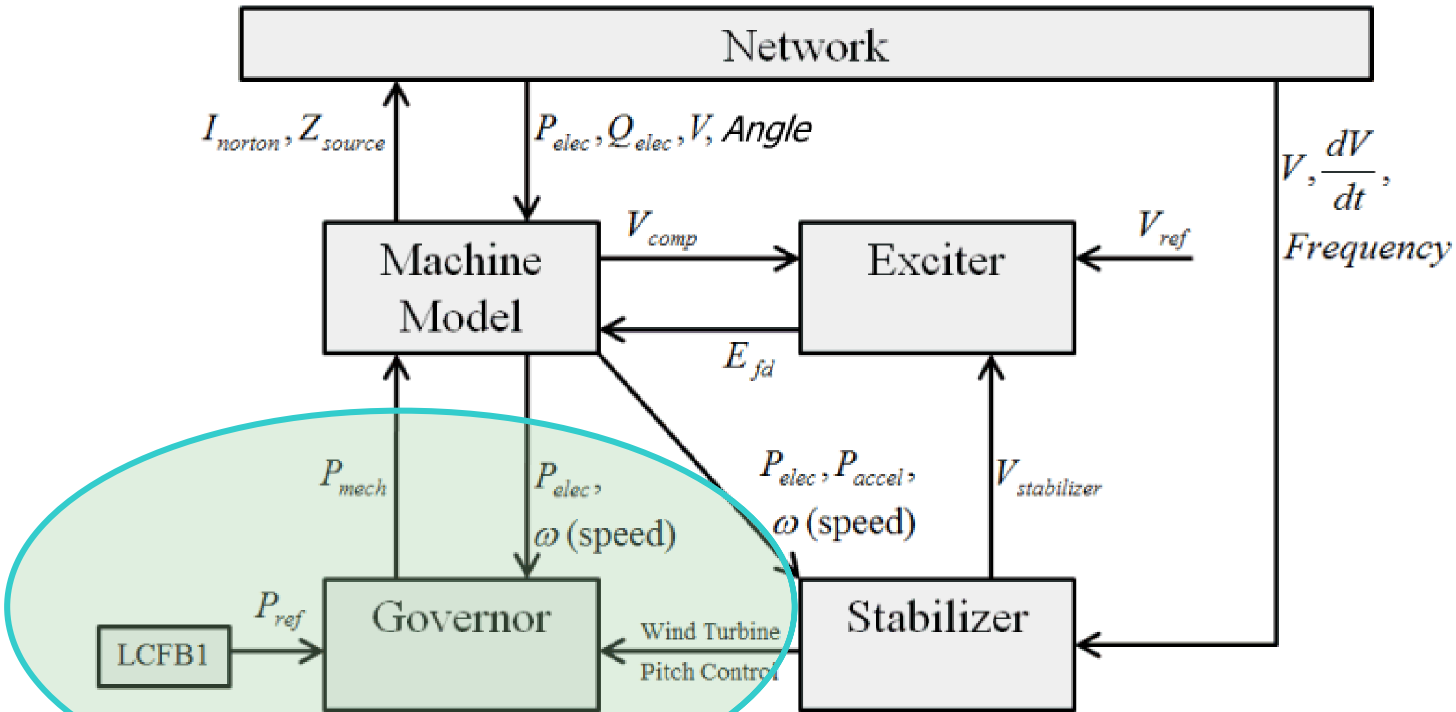
Announcements

- Read Chapter 4
- Homework 4 will not need to be turned in (but should be completed before the first exam)
- Exam 1 will be on Oct 14 in class
  - For the distance learners we usually use Honorlock (though I know for some that won't work)
  - Exams are closed book, closed notes, but you can bring in one 8.5 by 11 inch note sheet and can use calculators
  - My first exam from 2019 (with the solution) is available on Canvas, keeping in mind, Past performance is no guarantee of future results."
  - Covers through the end of Lecture 12

Governor Models



P_{elec} = Electrical Power

Q_{elec} = Electrical Reactive Power

V = Voltage at Terminal Bus

$\frac{dV}{dt}$ = Derivate of Voltage

V_{comp} = Compensated Voltage

P_{mech} = Mechanical Power

ω(speed) = Rotor Speed (often it's deviation from nominal speed)

P_{accel} = Accelerating Power

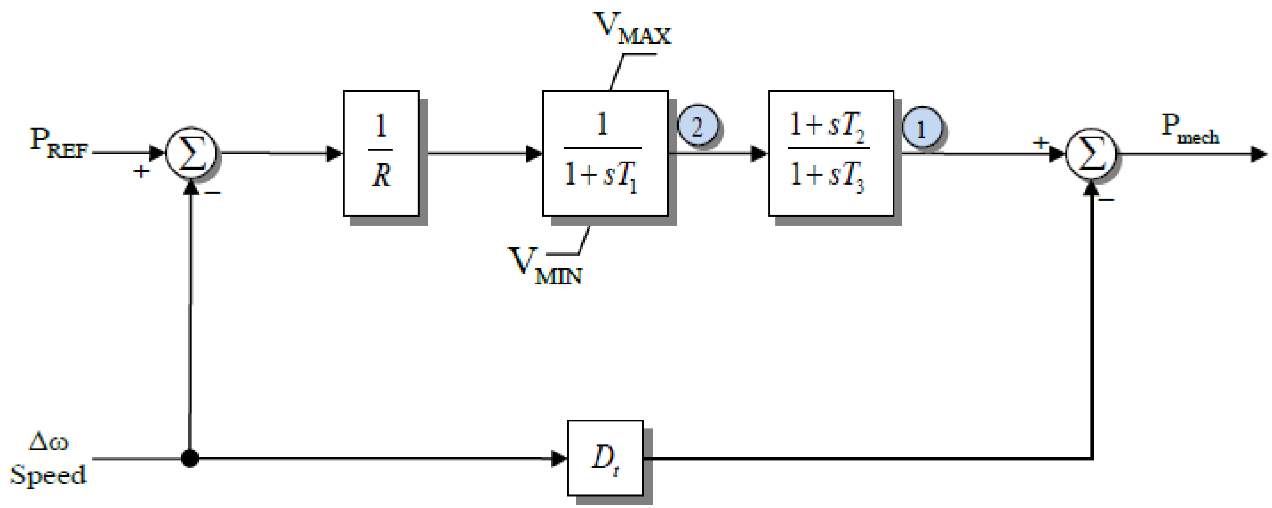
$V_{stabilizer}$ = Output of Stabilizer

V_{ref} = Exciter Control Setpoint (determined during initialization)

P_{ref} = Governor Control Setpoint (determined during initialization)

TGOV1 Model

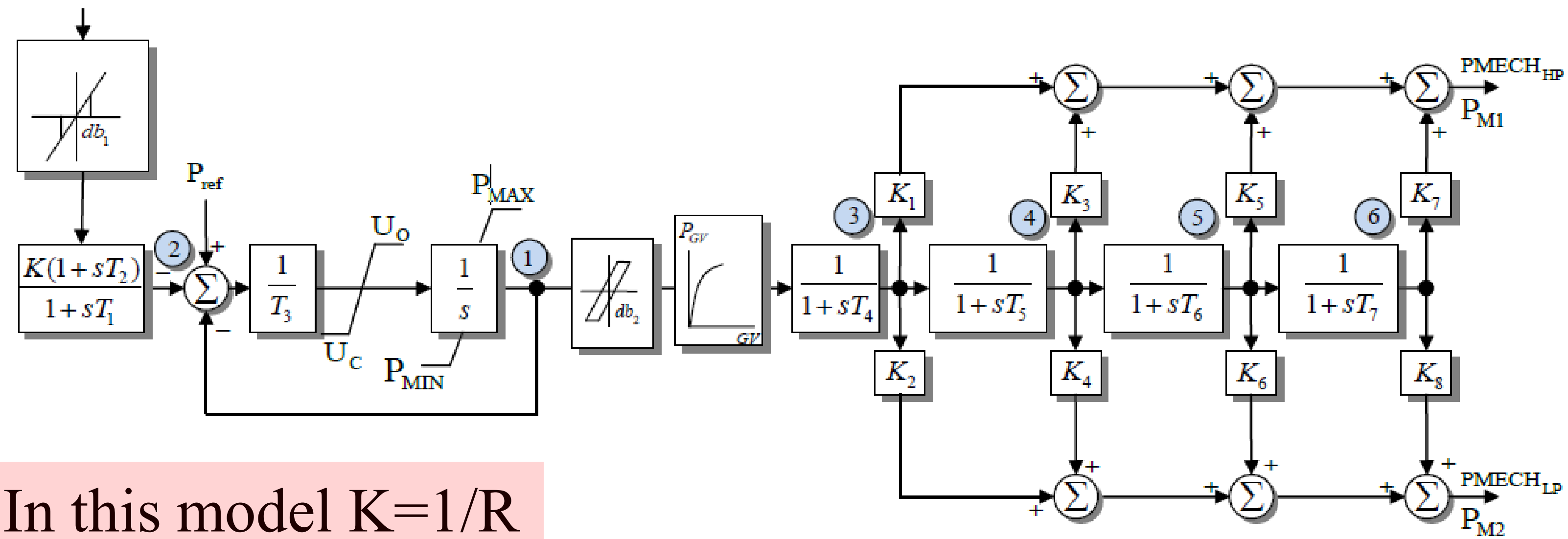
- Standard model that is close to this is TGOV1



About 12% of governors in a 2015 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 Model

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



In this model K=1/R

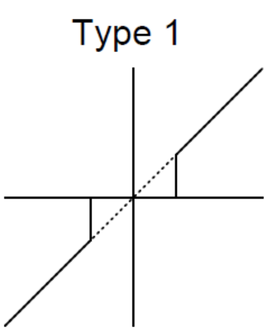
U_o and U_c are rate limits

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

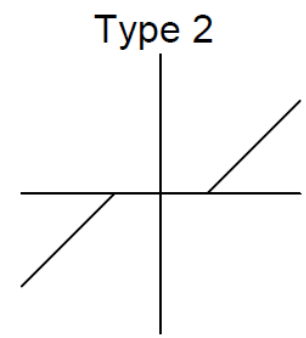
Deadbands

- 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

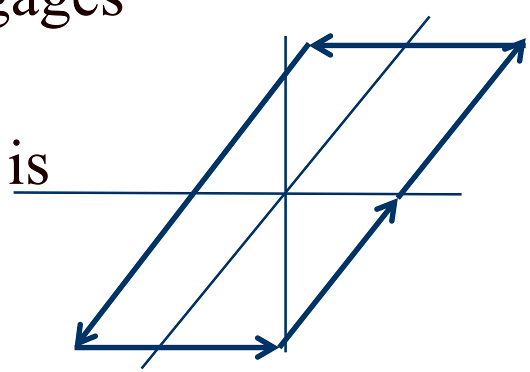


Deadbands

- 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



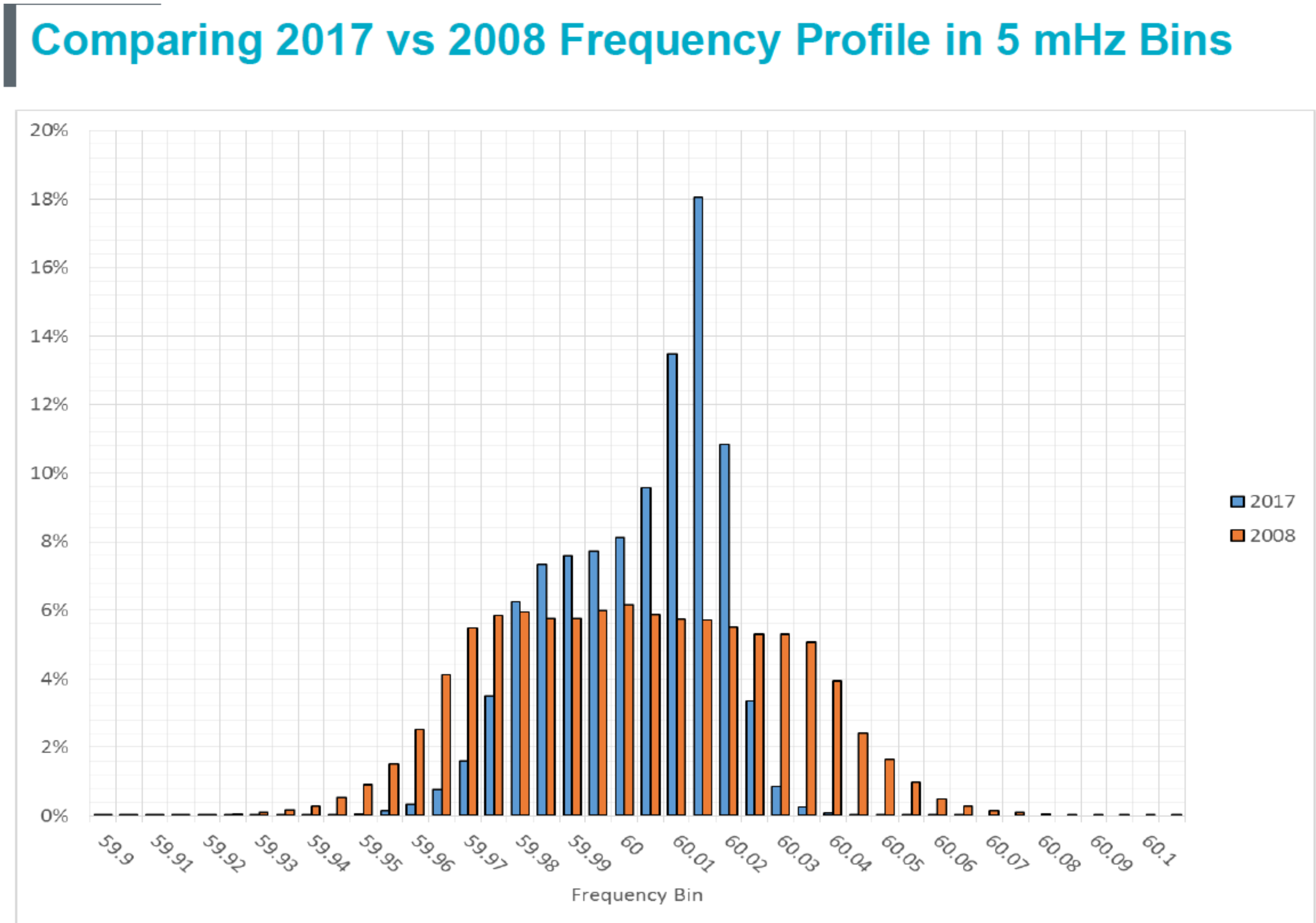
When starting simulations deadbands usually start at their origin

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)



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

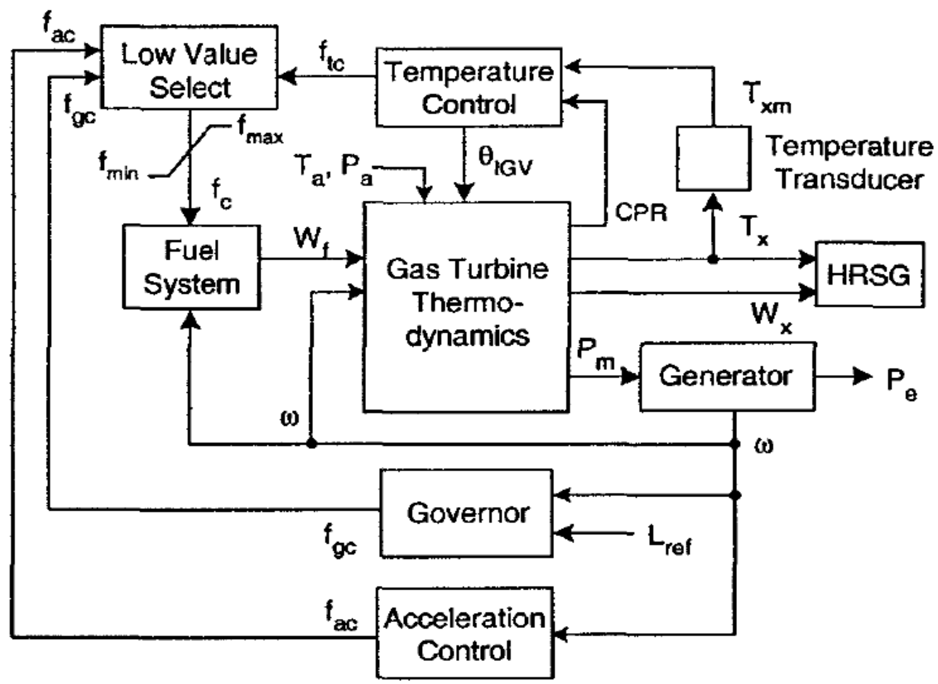
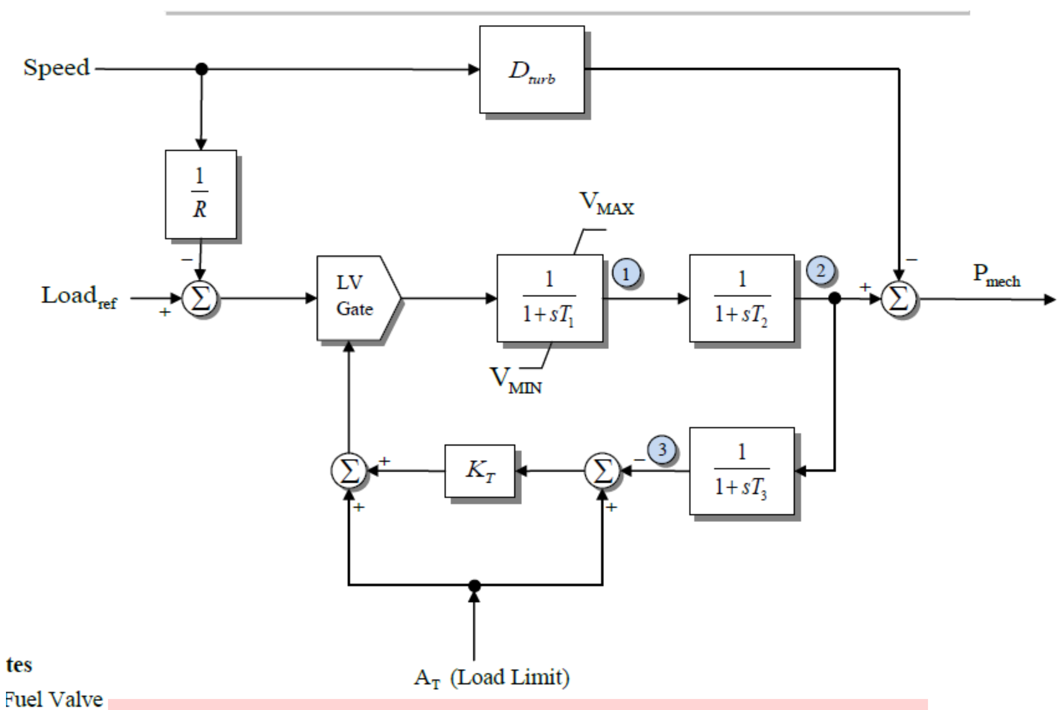


Figure 3-3: Gas turbine controls [17] (IEEE© 2001).

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

GAST Model

- Quite detailed gas turbine models exist; we'll just consider the simplest, which is still used some



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

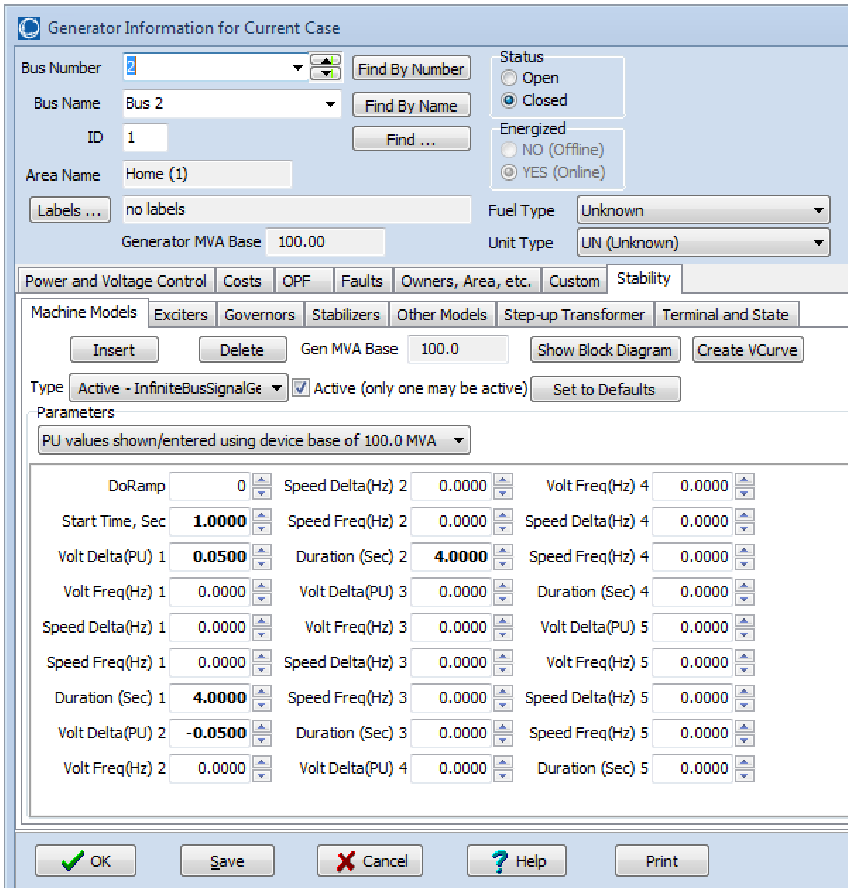
T_1 average is 0.9, T_2 is 0.6 sec

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

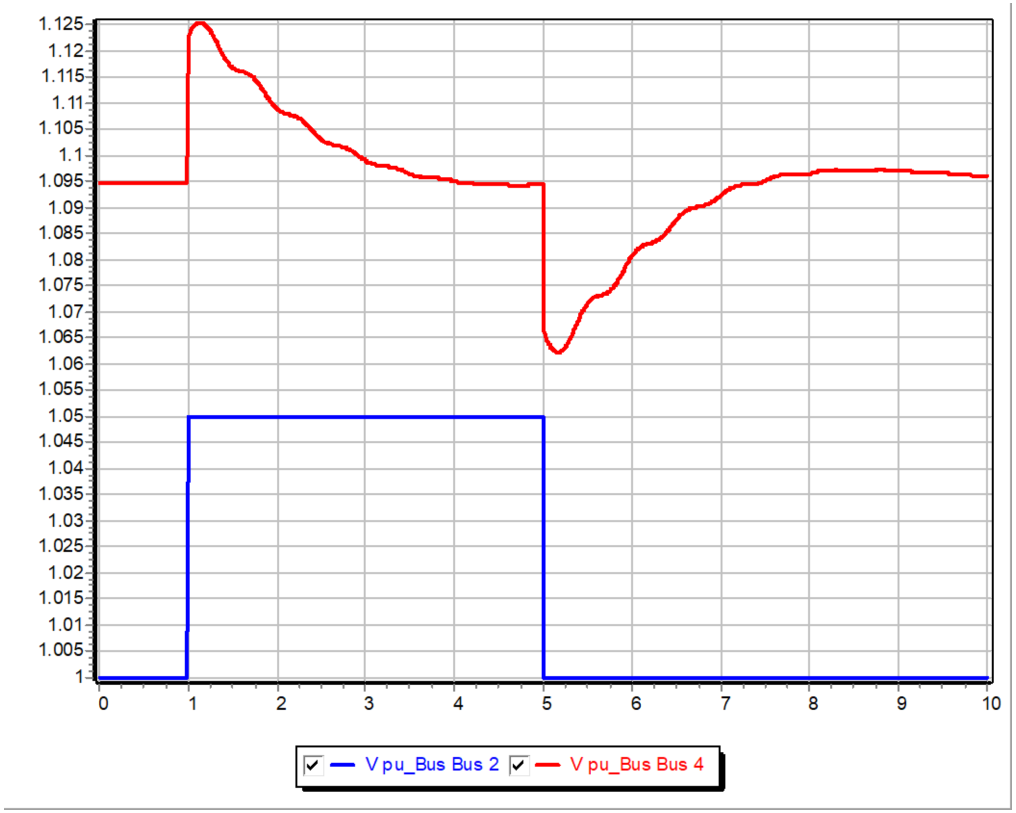
Volt Delta is the magnitude of the pu voltage deviation; **Volt Freq** is the frequency of the voltage deviation in Hz (zero for dc)

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

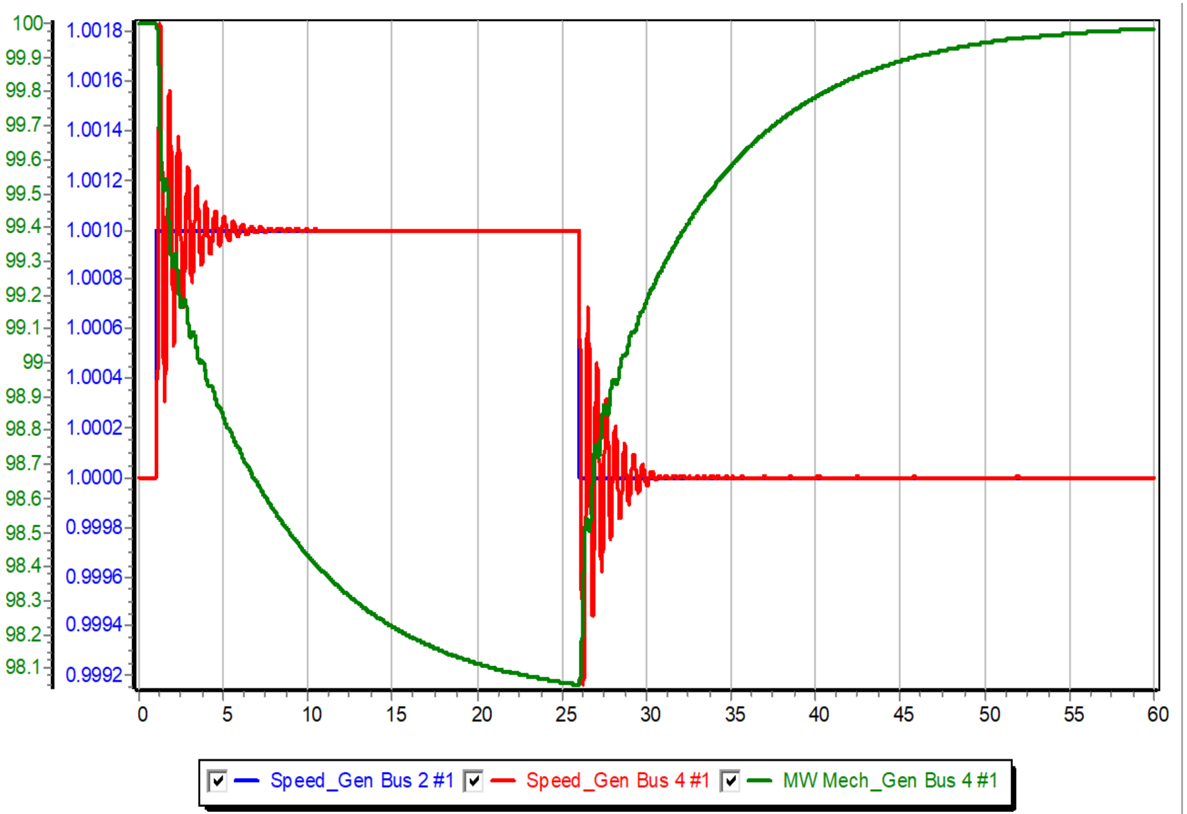
- Below graph shows the voltage response for the four bus system for a change in the infinite bus voltage



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

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

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

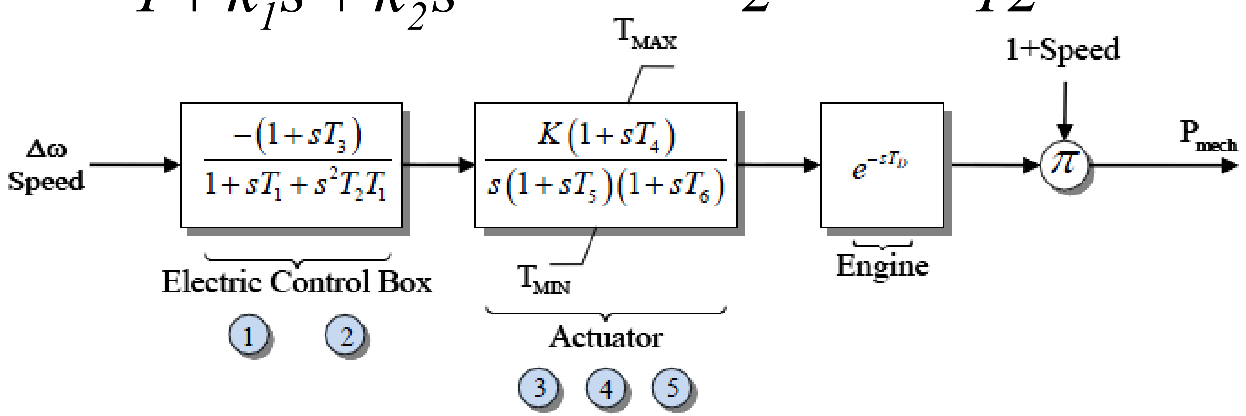
$$\Delta P_{gen,MW} = -2$$

Case name: **B4_SignalGen_Freq**

Simple Diesel Model: DEGOV

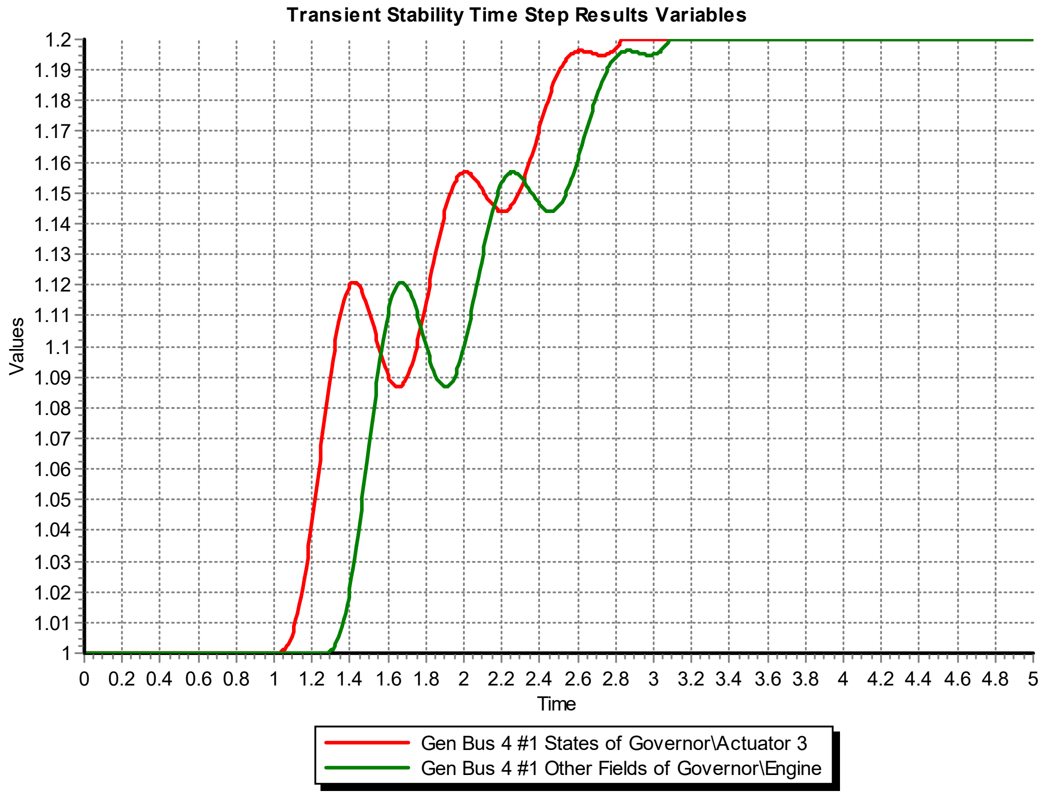
- Sometimes models implement time delays (DEGOV)
  - Often delay values are set to zero
- Delays can be implemented either by saving the input value or by using a Pade approximation, with a 2nd order given below; a 4th order is also common

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



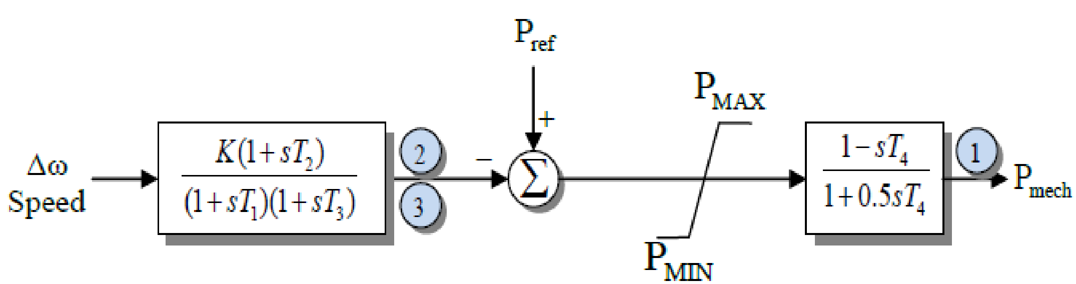
DEGOV Delay Approximation

- 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

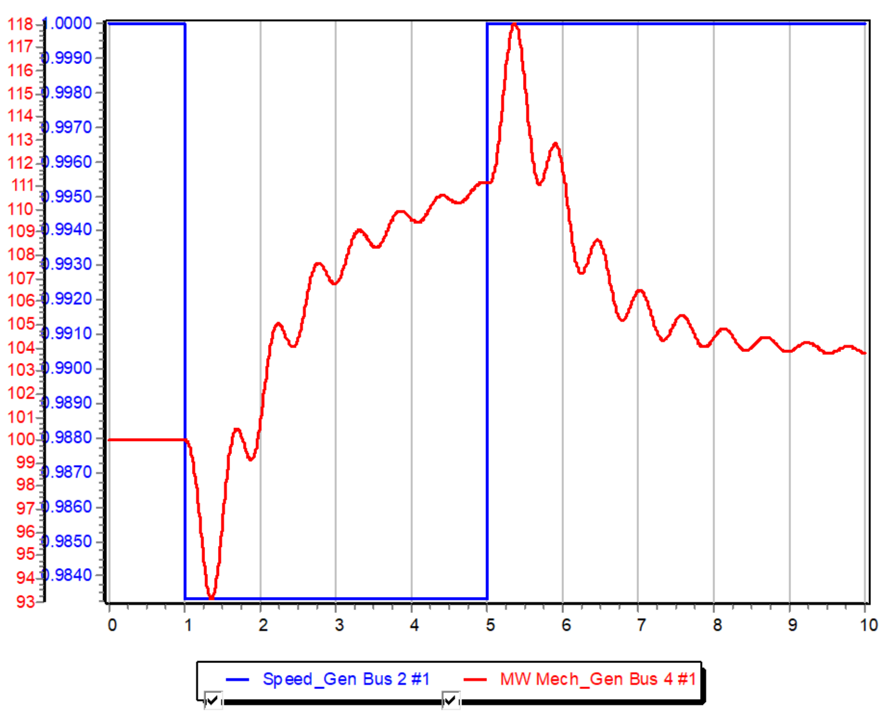
- Hydro units tend to respond slower than steam and gas units; since early transient stability studies focused on just a few seconds (first or second swing instability), detailed hydro units were not used
  - The original IEEEG2 and IEEEG3 models just gave the linear response; now considered obsolete
- 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; flows does not change instantaneously because of the water's inertia.

Case name: **B4_SignalGen_IEEEG2**

Washout Filters

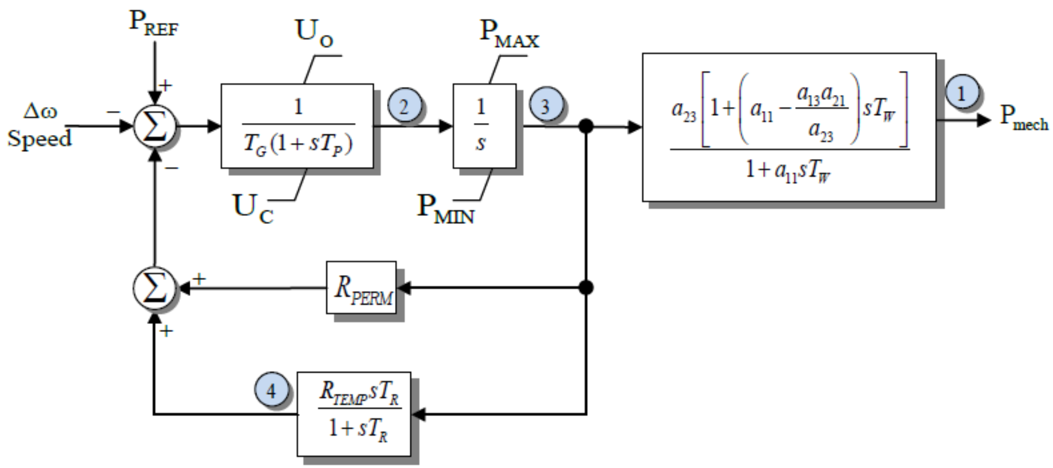
- A washout filter is a high pass filter that removes the steady-state response (i.e., it "washes it out") while passing the high frequency response

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

- 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 2019 it is about 5%

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

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

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

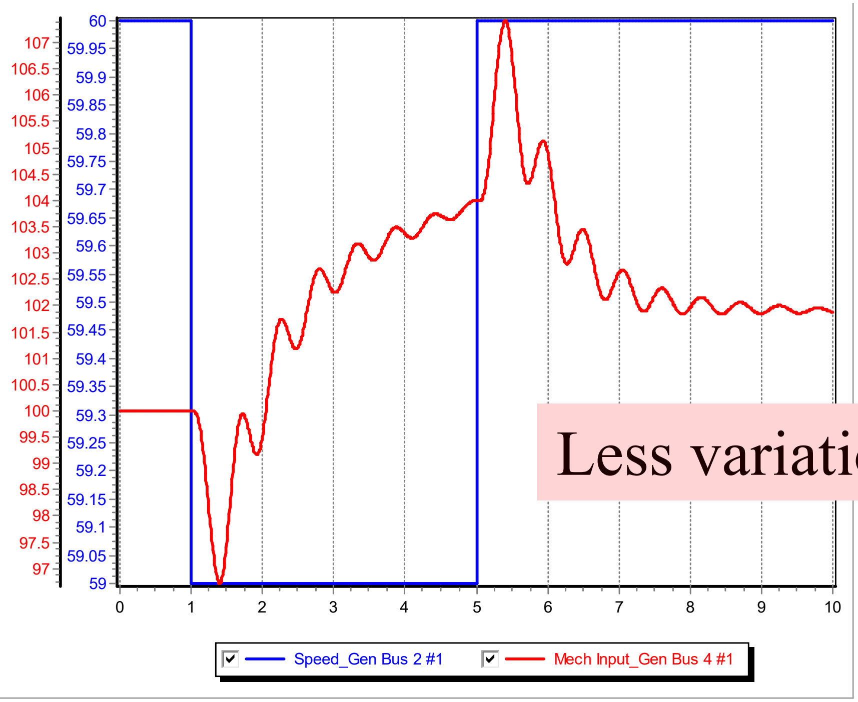
where T_M=2H (called the mechanical starting time)

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

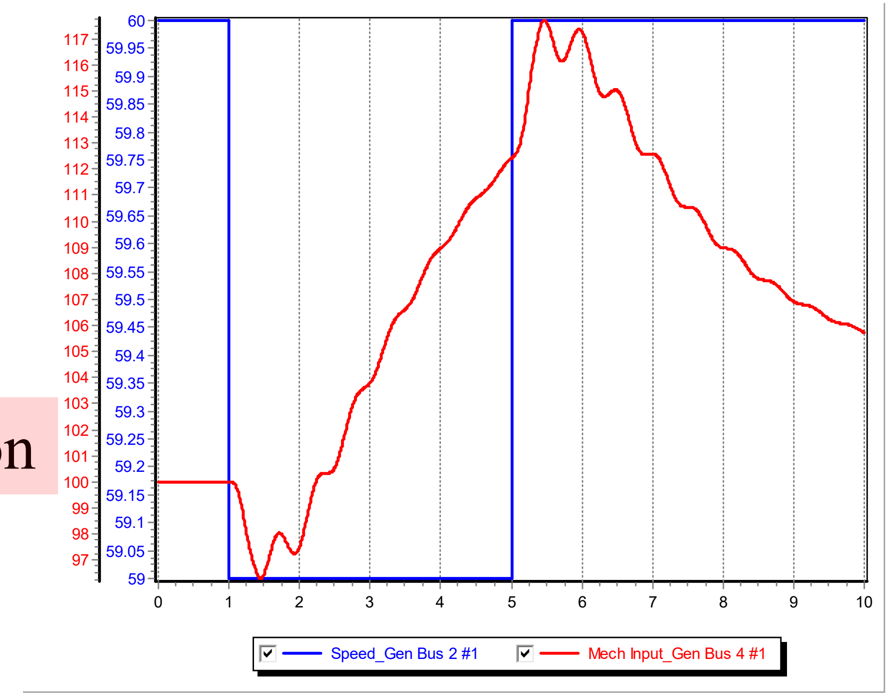
IEEEG3 Four Bus Frequency Change

- 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;

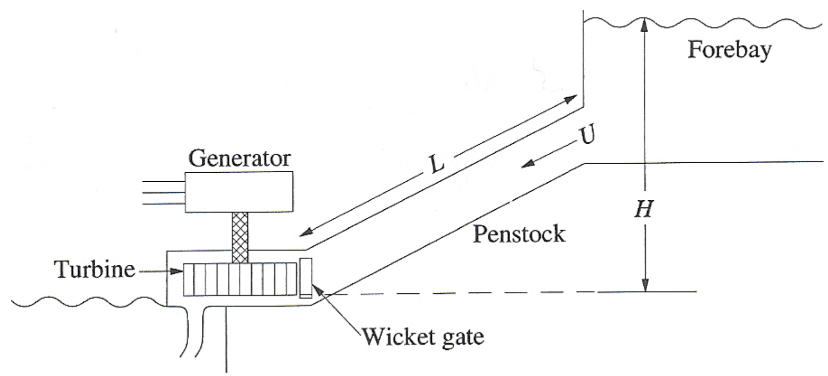


Figure 9.2 Schematic of a hydroelectric plant

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 ρ 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)

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

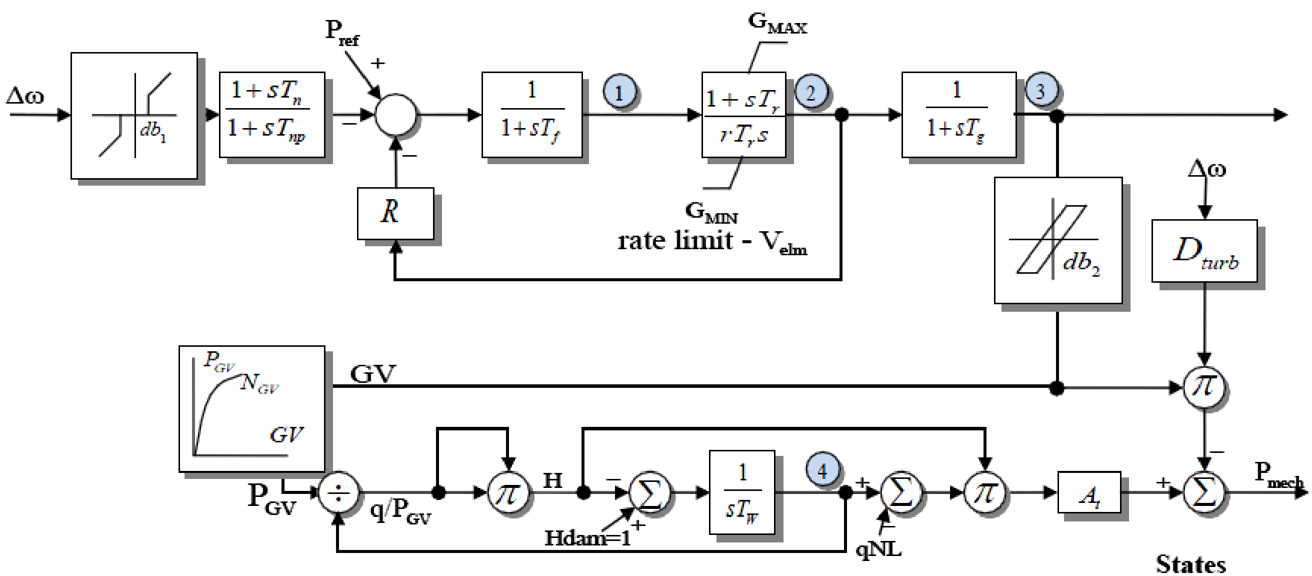
Basic Nonlinear Hydro Turbine Model

- 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 2 seconds

H_{loss} is assumed small and not included

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

Linearized Model Derivation

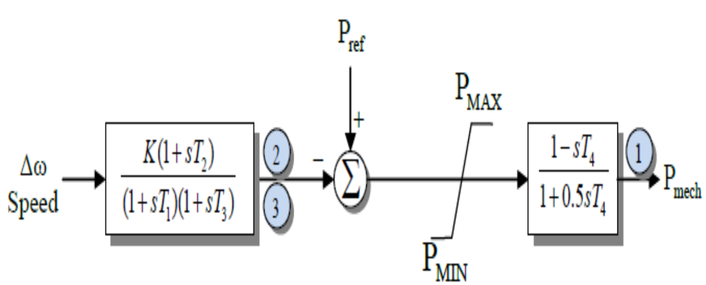
- The previously mentioned linearized model can now be derived as

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

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

And for the linearized power

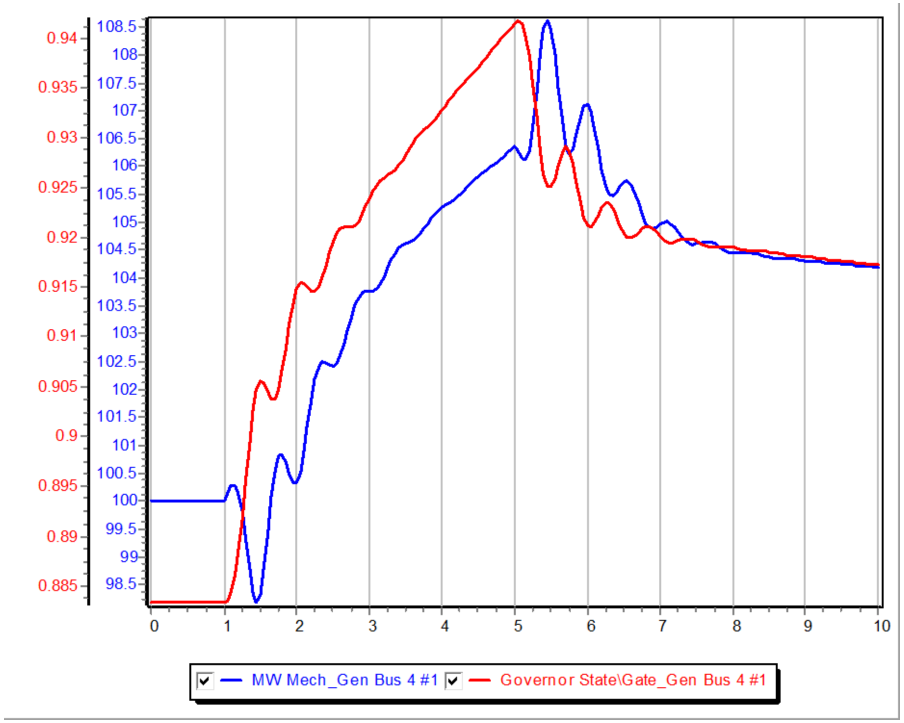
$$\Delta P_m = \frac{\partial P_m}{\partial h}\Delta h + \frac{\partial P_m}{\partial q}\Delta q$$



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**

PID Controllers

- Governors and exciters often use proportional-integral-derivative (PID) controllers
  - Developed in 1890's for automatic ship steering by observing the behavior of experienced helmsman
- PIDs combine
  - Proportional gain, which produces an output value that is proportional to the current error
  - Integral gain, which produces an output value that varies with the integral of the error, eventually driving the error to zero
  - Derivative gain, which acts to predict the system behavior. This can enhance system stability, but it can be quite susceptible to noise

PID Controller Characteristics

- Four key characteristics of control response are 1) rise time, 2) overshoot, 3) settling time and 4) steady-state errors

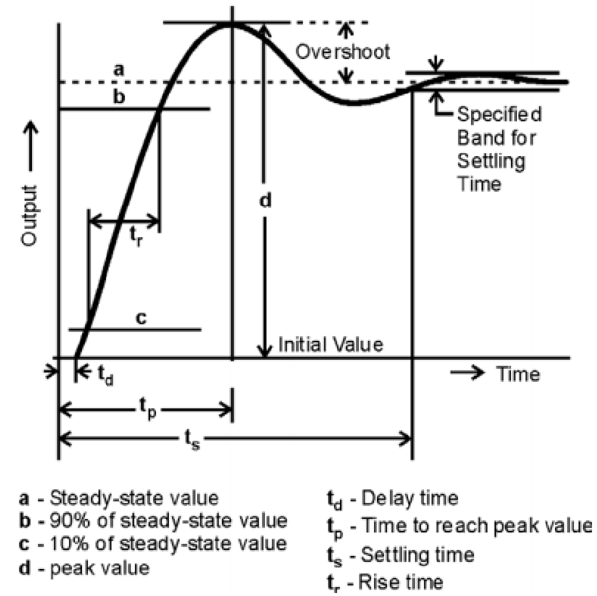


Figure F.1—Typical dynamic response of a turbine governing system to a step change

Increasing Gain	Rise Time	Overshoot	Setting Time	Steady-State Error
K_P	Decreases	Increases	Little impact	Decreases
K_I	Decreases	Increases	Increases	Zero
K_D	Little impact	Decreases	Decreases	Little Impact

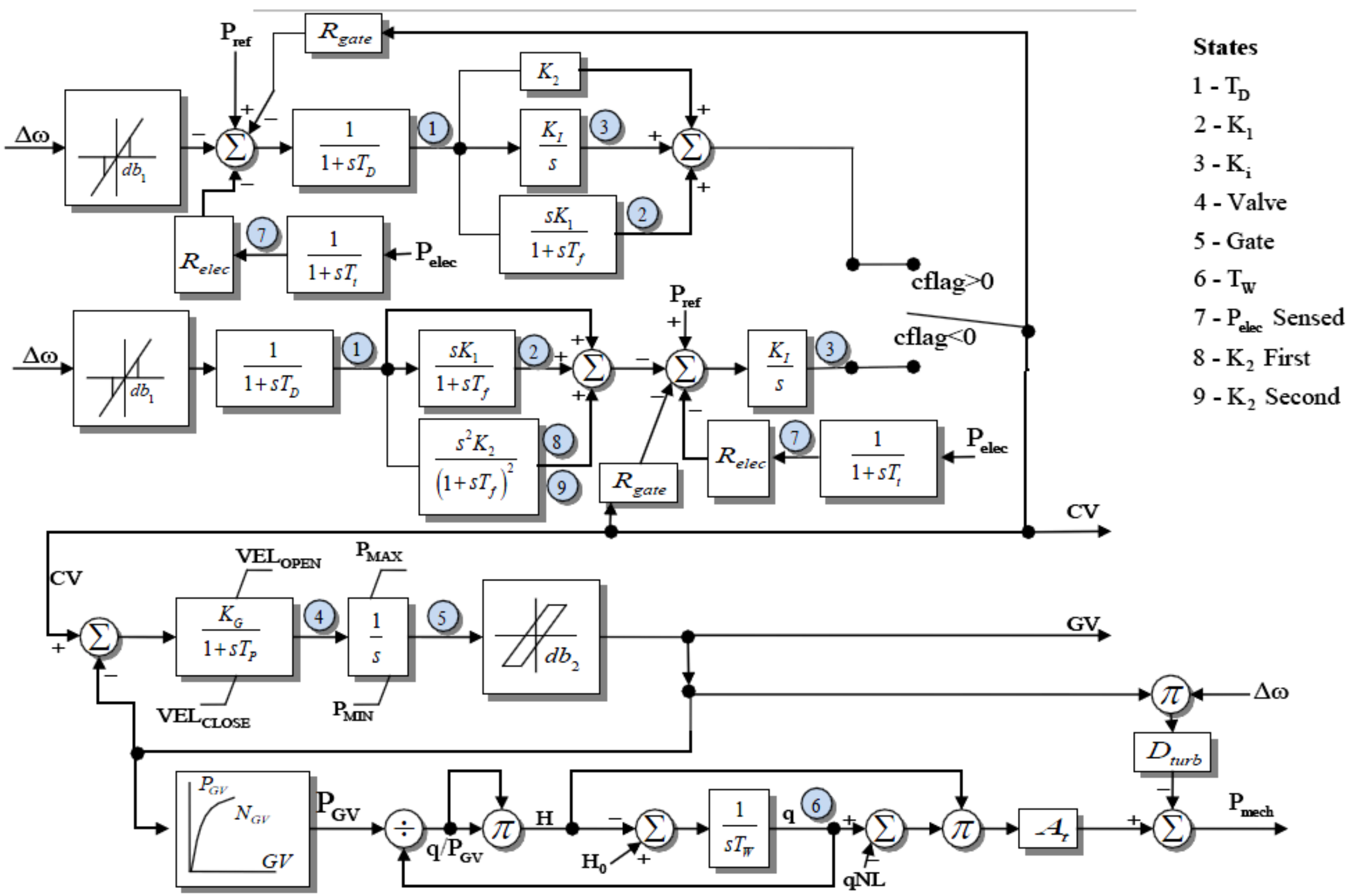
Image source: Figure F.1, IEEE Std 1207-2011

PID Example: Car Cruise Control

- Say we wish to implement cruise control on a car by controlling the throttle position
  - Assume force is proportional to throttle position
  - Error is difference between actual speed and desired speed
- With just proportional control we would never achieve the desired speed because with zero error the throttle position would be at zero
- The integral term will make sure we stay at the desired point
- With derivative control we can improve control, but as noted it can be sensitive to noise

HYG3

- The HYG3 models has a PID or a double derivative



Looks more complicated than it is since depending on cflag only one of the upper paths is used

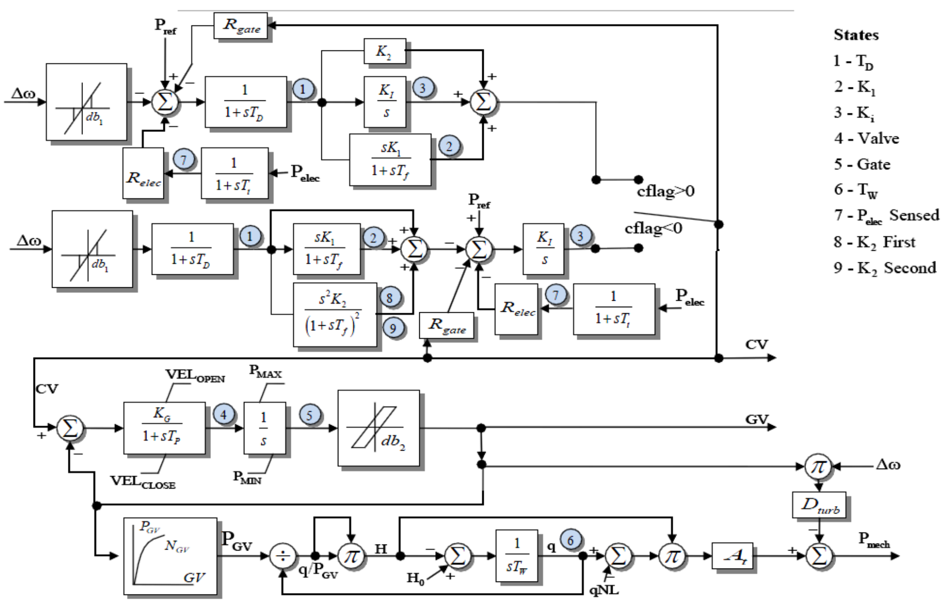
About 15% of current WECC governors at HYG3

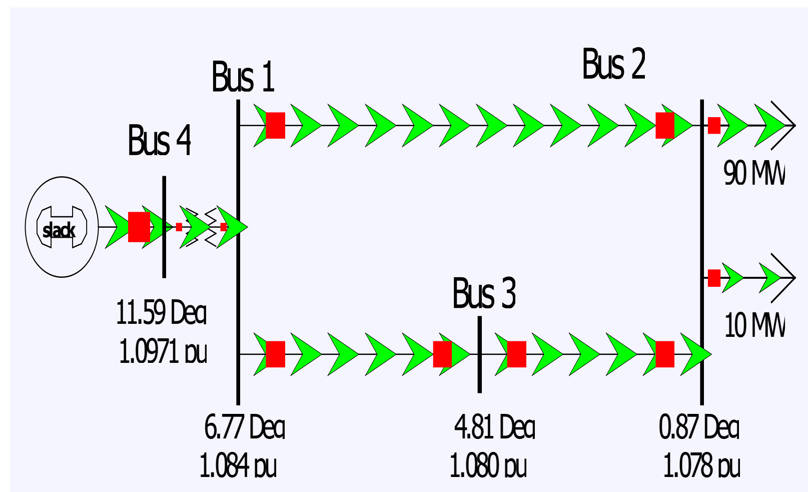
Tuning PID Controllers

- Tuning PID controllers can be difficult, and there is no single best method
  - Conceptually simple since there are just three parameters, but there can be conflicting objectives (rise time, overshoot, setting time, error)
- One common approach is the Ziegler-Nichols method
  - First set K_I and K_D to zero, and increase K_P until the response to a unit step starts to oscillate (marginally stable); define this value as K_u and the oscillation period at T_u
  - For a P controller set $K_p = 0.5K_u$
  - For a PI set $K_P = 0.45\ K_u$ and $K_I = 1.2^*\ K_p/T_u$
  - For a PID set $K_P=0.6\ K_u$, $K_I=2^*\ K_p/T_u$, $K_D=K_pT_u/8$

Tuning PID Controller Example

- Use the four bus case with infinite bus replaced by load, and gen 4 has a HYG3 governor with cflag > 0; tune K_P, K_I and K_D for full load to respond to a 10% drop in load (K_2, K_I, K_1 in the model; assume T_f=0.1)

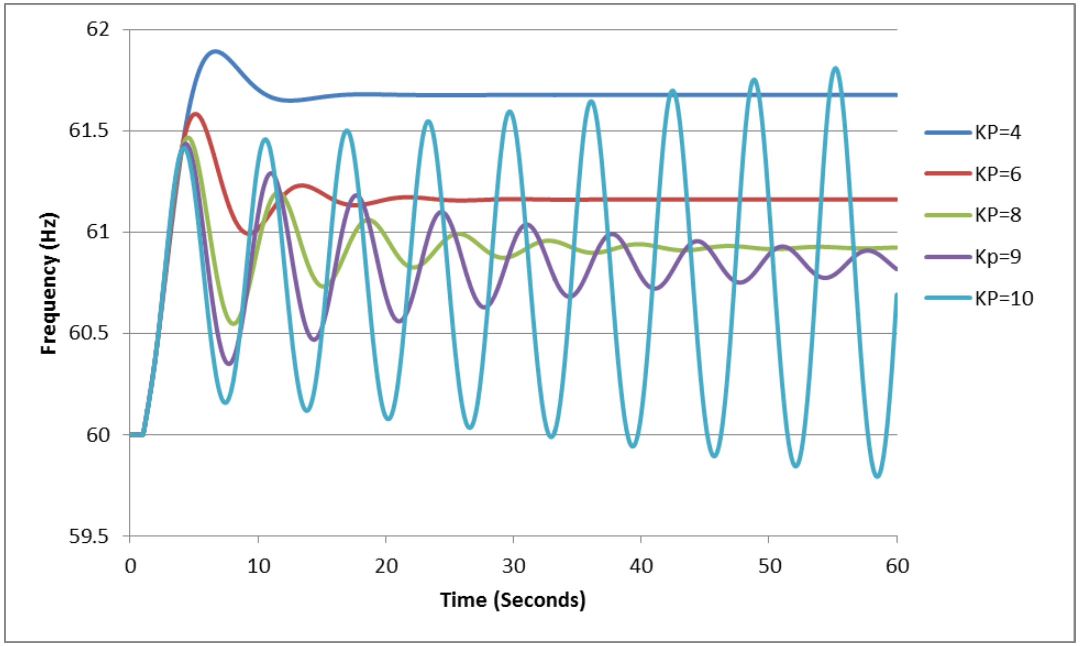




Case name: **B4_PIDTuning**

Tuning PID Controller Example

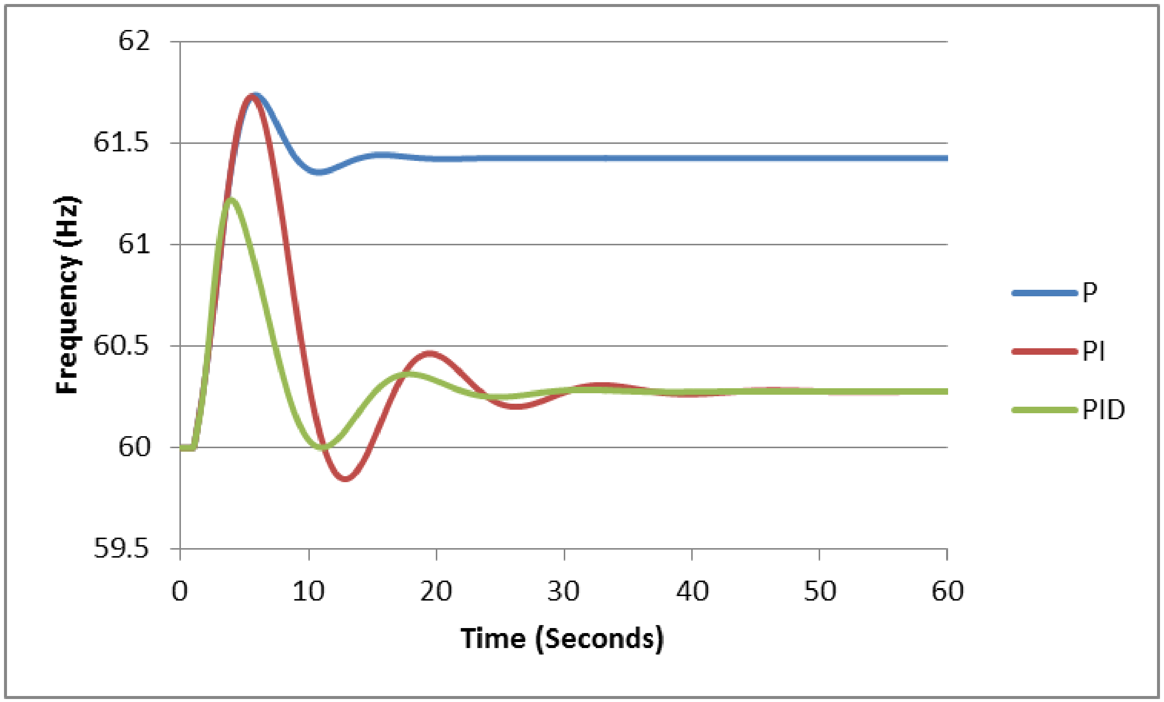
- Based on testing, K_u is about 9.5 and T_u is 6.4 seconds
- Using Ziegler-Nichols a good P value 4.75, is good PI values are $K_P = 4.3$ and $K_I = 0.8$, while good PID values are $K_P = 5.7$, $K_I = 1.78$, $K_D=4.56$



Further details on tuning are covered in IEEE Std. 1207-2011

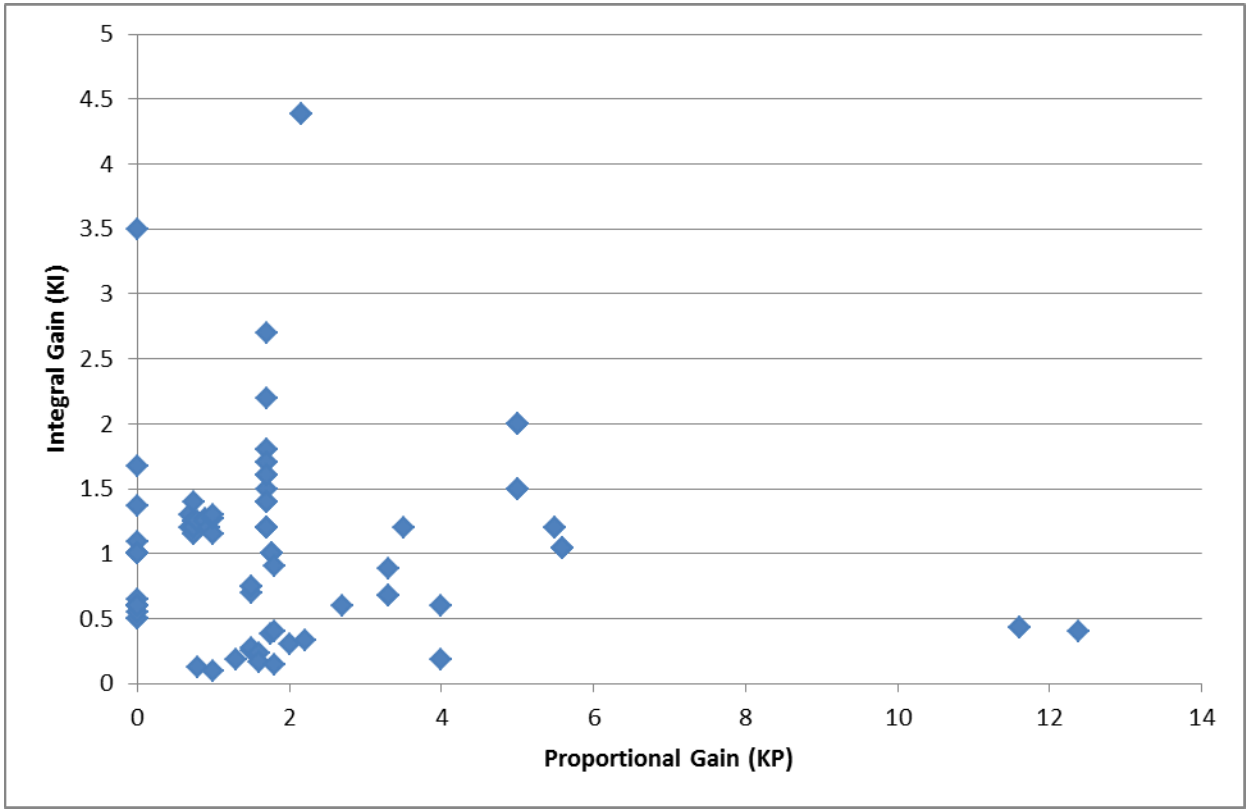
Tuning PID Controller Example

- Figure shows the Ziegler-Nichols for a P, PI and PID controls. Note, this is for stand-alone, not interconnected operation



Example K_I and K_P Values

- Figure shows example K_I and K_P values from an actual system case



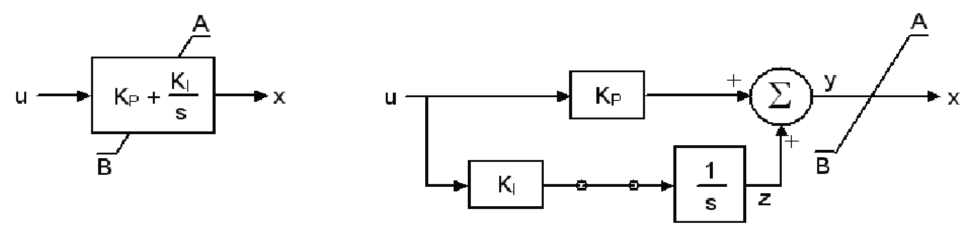
About 60% of the models also had a derivative term with an average value of 2.8, and an average T_D of 0.04 sec

Non-windup Limits

- An important open question is whether the governor PI controllers should be modeled with non-windup limits
  - Currently models show no limit, but transient stability verification seems to indicate limits are being enforced
- This could be an issue if frequency goes low, causing governor PI to "windup" and then goes high (such as in an islanding situation)
  - How fast governor backs down depends on whether the limit winds up

PI Non-windup Limits

- There is not a unique way to handle PI non-windup limits; the below shows two approaches from IEEE Std 421.5



$y > A$, then $x = A$ and $dz/dt = 0$

$y < B$, then $x = B$ and $dz/dt = 0$

Figure E.7—Non-windup proportional-integral block

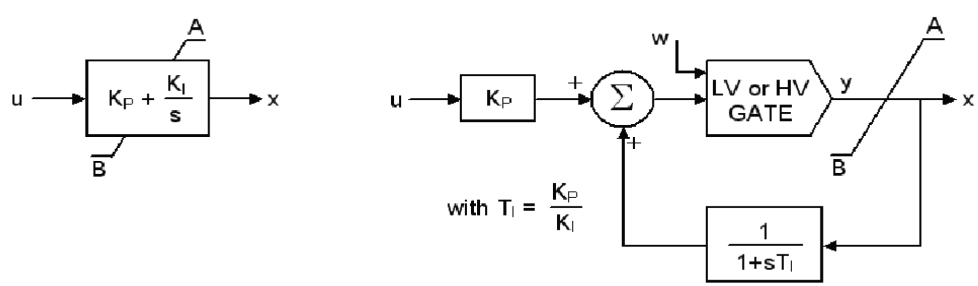
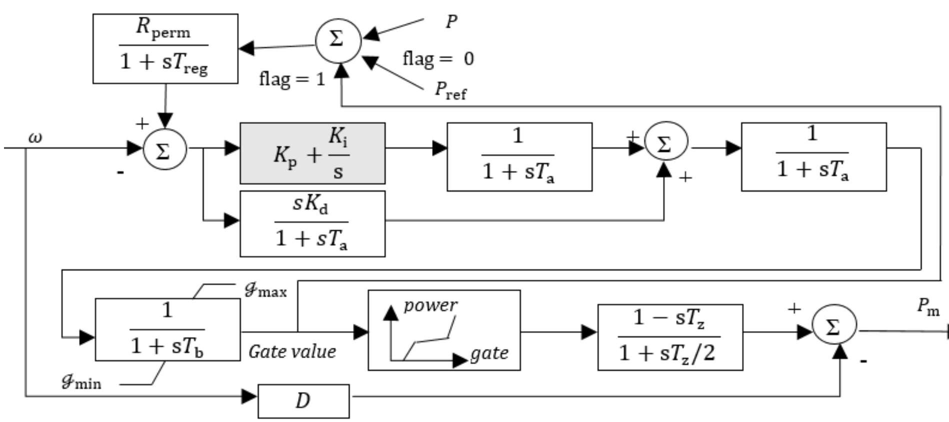


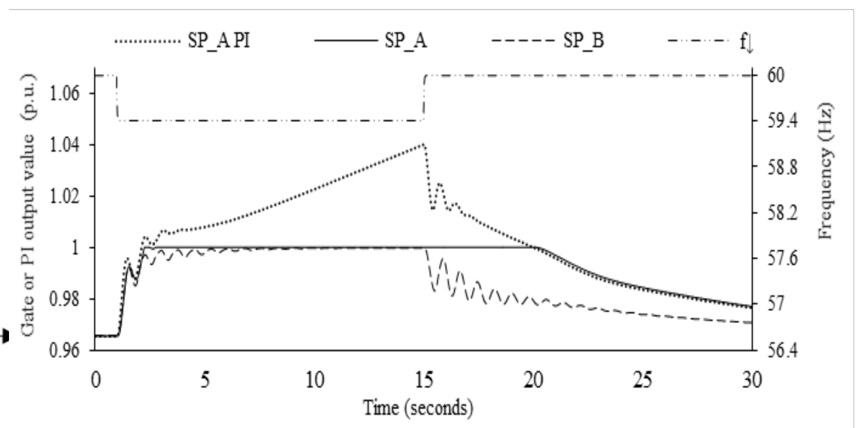
Figure E.8—Non-windup proportional-integral block

Another common approach is to cap the output and put a non-windup limit on the integrator

PI Limit Problems with Actual Hydro Models

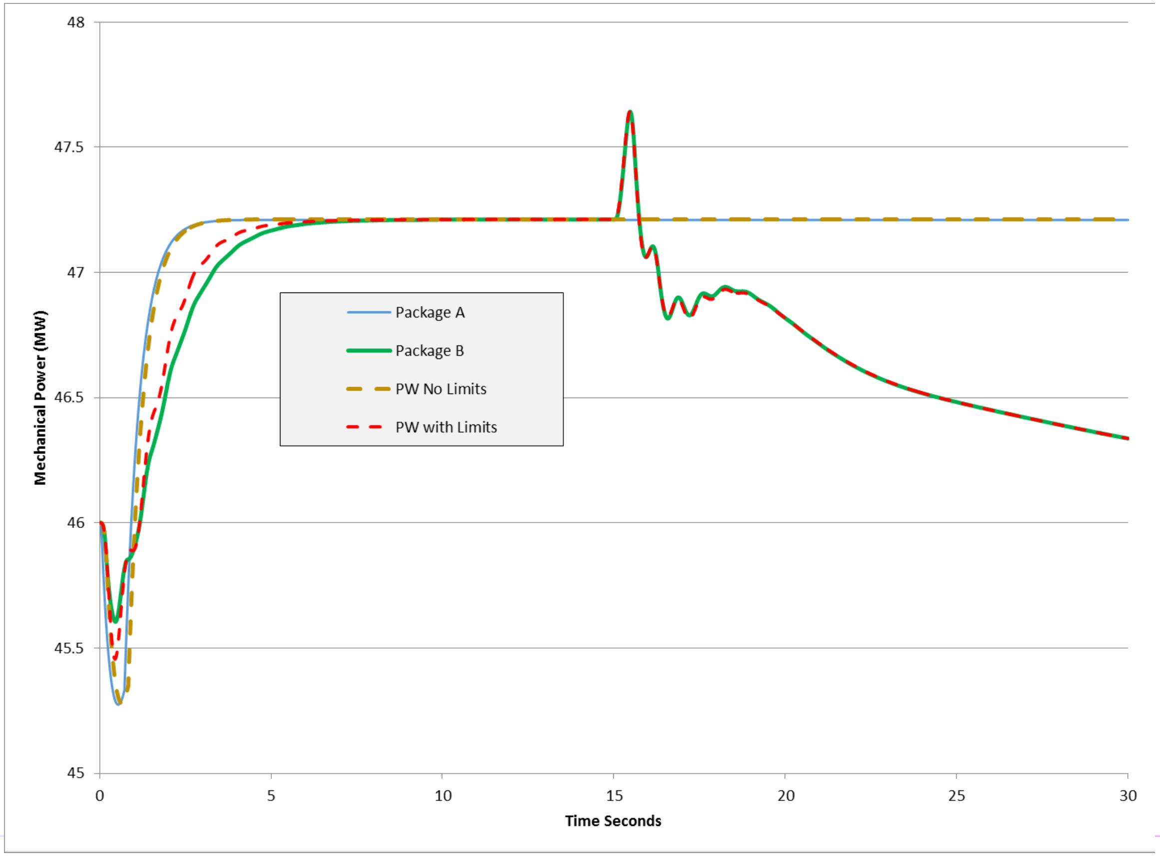
- A previous research project comparing transient stability packages found there were significant differences between hydro model implementations with respect to how PI limits were modeled
  - One package modeled limits but did not document them, another did not model them; limits were recommended at WECC MVWG in May 2014





PIDGOV Model Results

- Below graph compares the Pmech response for a two bus system for a frequency change, between three transient stability packages

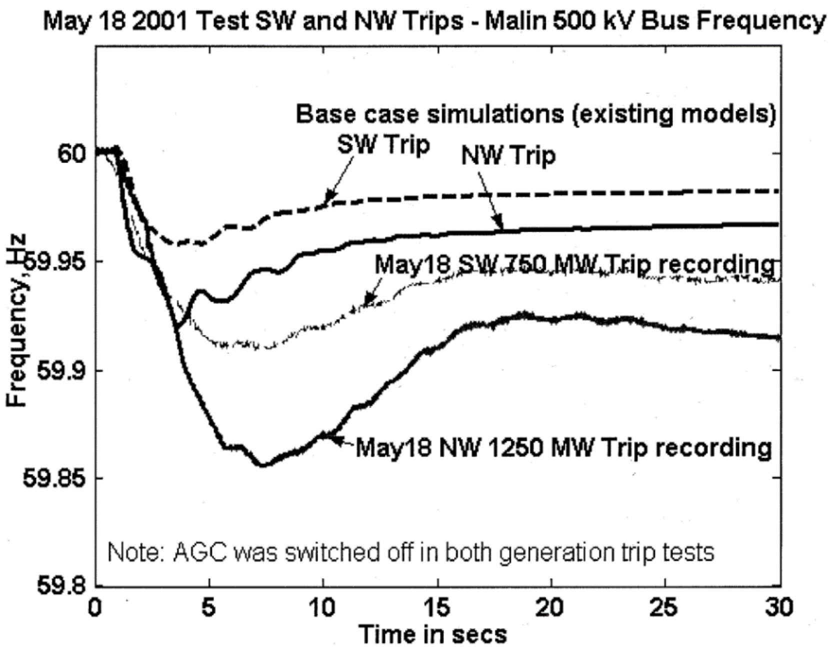


Packages A and B both say they have no governor limits, but B seems to; PowerWorld can do either approach

GGOV1

- GGOV1 is a relatively newer governor model introduced in early 2000's by WECC for modeling thermal plants
  - Existing models greatly under-estimated the frequency drop
  - GGOV1 is now the most common WECC governor, used with about 40% of the units
- A useful reference is L. Pereira, J. Undrill, D. Kosterev, D. Davies, and S. Patterson, "A New Thermal Governor Modeling Approach in the WECC," *IEEE Transactions on Power Systems*, May 2003, pp. 819-829

GGOV1: Selected Figures from 2003 Paper



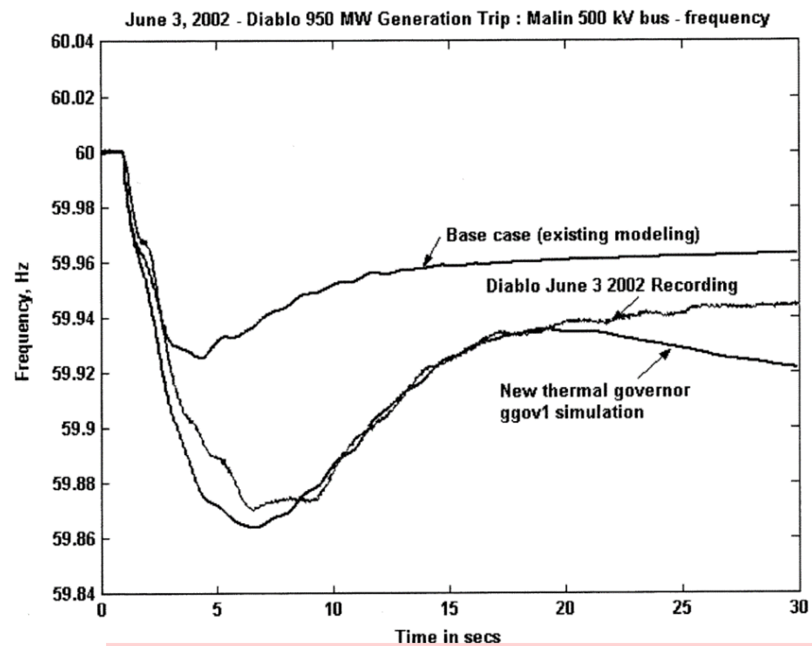


Fig. 1. Frequency recordings of the SW and NW trips on May 18, 2001. Also shown are simulations with existing modeling (base case).

Governor model verification—950-MW Diablo generation trip on June 3, 2002.

Diablo Canyon is California's last nuclear plant, with Unit 1 now scheduled to shutdown in 2024 and Unit 2 in 2025 (though there has been recent controversy about this)