

Exciter and Governor Modeling

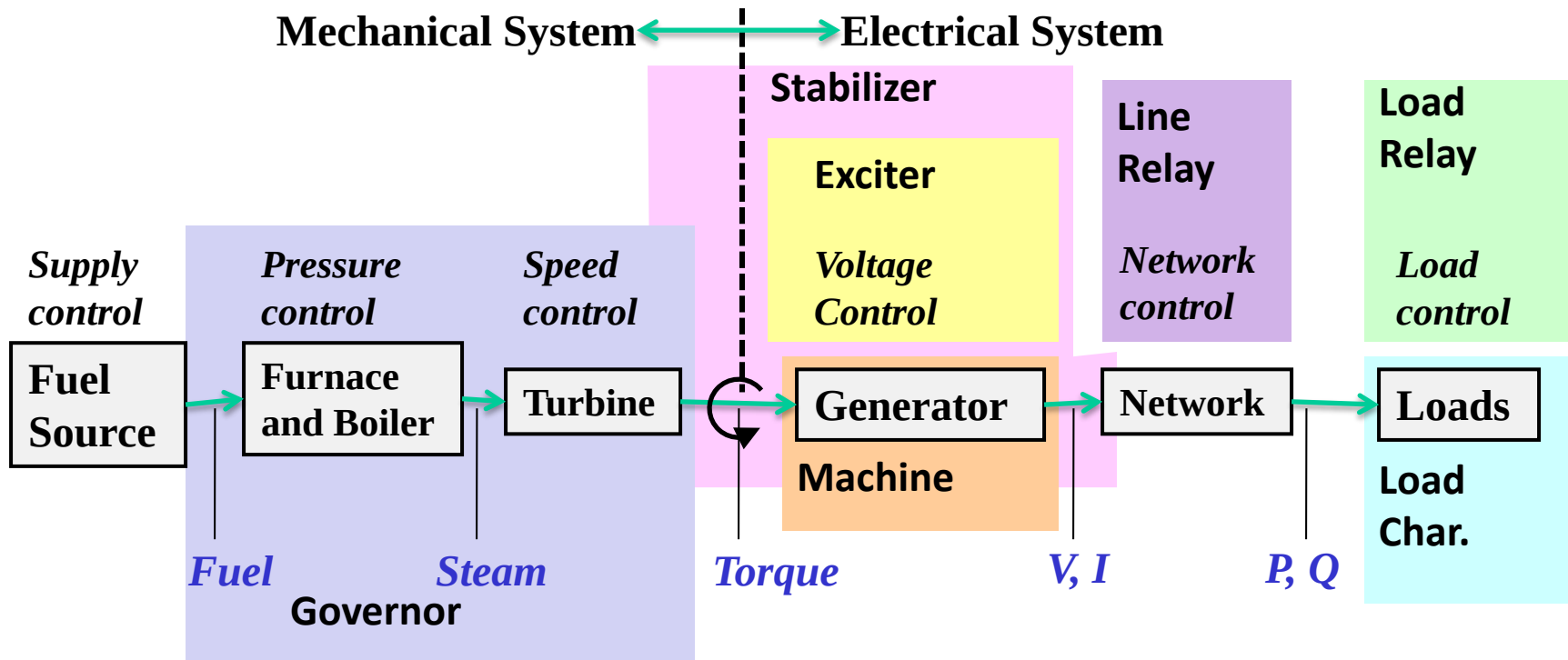


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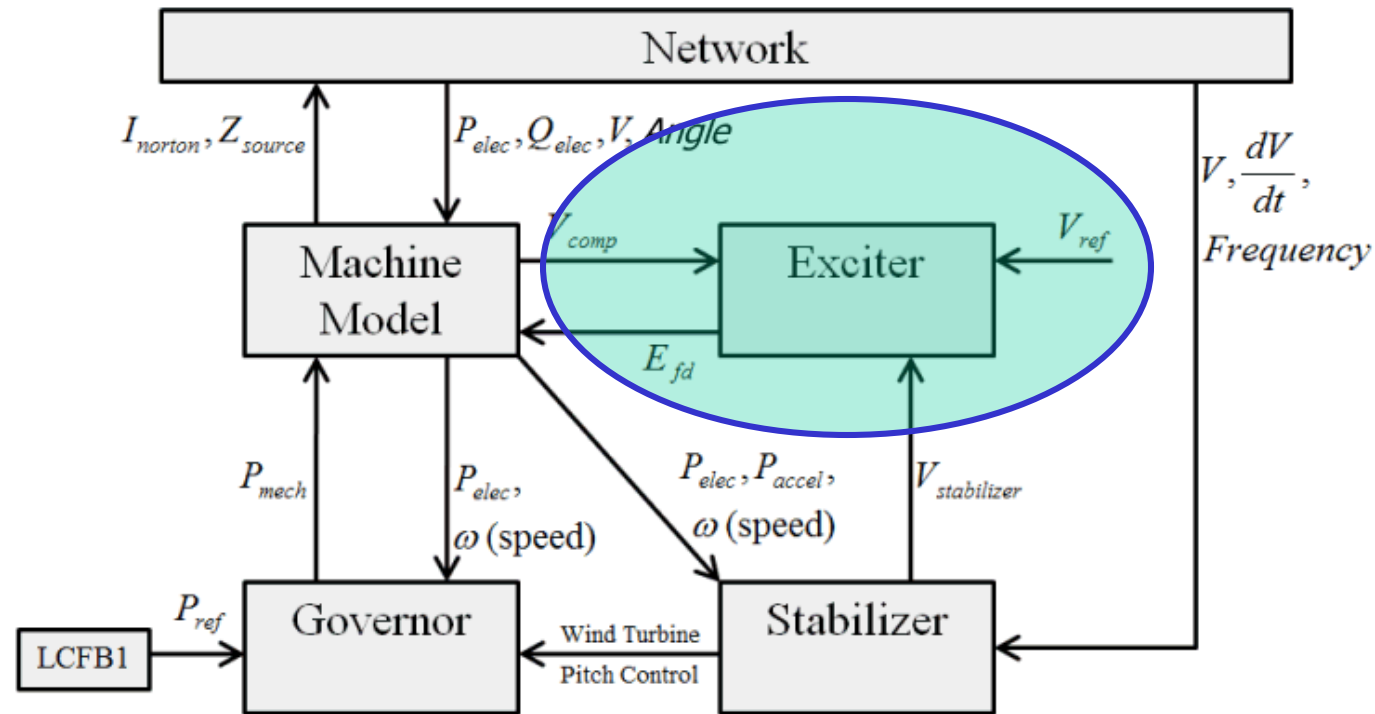
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Dynamic Models in the Physical Structure



P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Exciter 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)

Exciters, Including AVR



- Exciters are used to control the synchronous machine field voltage and current
 - Usually modeled with automatic voltage regulator included
- A useful reference is IEEE Std 421.5-2016
 - Updated from the 2005 edition
 - Covers the major types of exciters used in transient stability
 - Continuation of standard designs started with "Computer Representation of Excitation Systems," IEEE Trans. Power App. and Syst., vol. pas-87, pp. 1460-1464, June 1968
- Another reference is P. Kundur, Power System Stability and Control, EPRI, McGraw-Hill, 1994
 - Exciters are covered in Chapter 8 as are block diagram basics

Functional Block Diagram

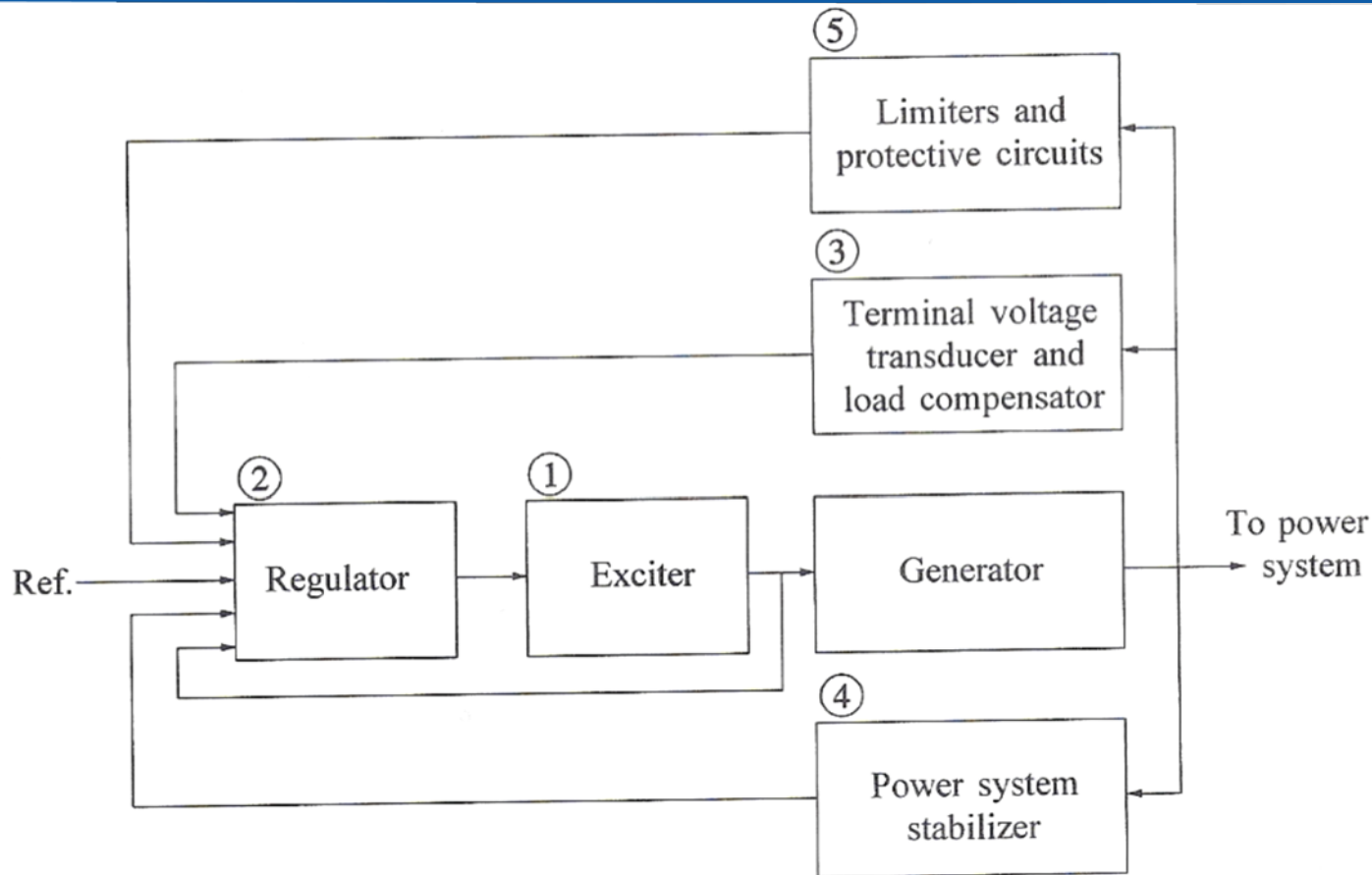


Image source: Fig 8.1 of Kundur, *Power System Stability and Control*

Types of Exciters



- None, which would be the case for a permanent magnet generator
 - primarily used with wind turbines with ac-dc-ac converters
- DC: Utilize a dc generator as the source of the field voltage through slip rings
- AC: Use an ac generator on the generator shaft, with output rectified to produce the dc field voltage; brushless with a rotating rectifier system
- Static: Exciter is static, with field current supplied through slip rings

IEEET1 Exciter



- We'll start with a common exciter model, the IEEET1 based on a dc generator, and develop its structure

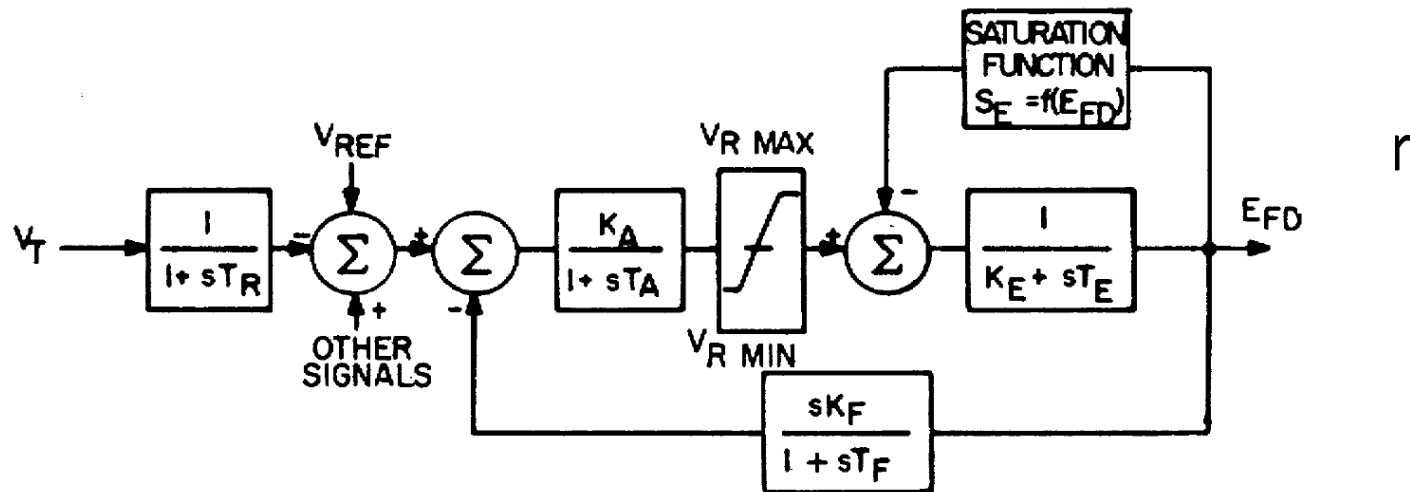


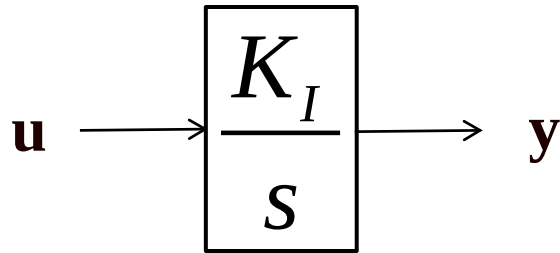
Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

Block Diagram Basics



- The following slides will make use of block diagrams to explain some of the models used in power system dynamic analysis. The next few slides cover some of the block diagram basics.
- To simulate a model represented as a block diagram, the equations need to be represented as a set of first order differential equations
- Also the initial state variable and reference values need to be determined

Integrator Block

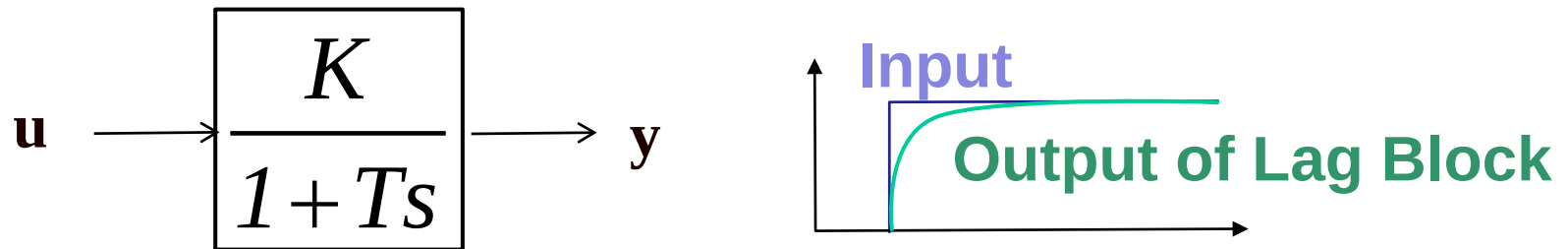


- Equation for an integrator with u as an input and y as an output is

$$\frac{dy}{dt} = K_I u$$

- In steady-state with an initial output of y_0 , the initial state is y_0 and the initial input is zero

First Order Lag Block

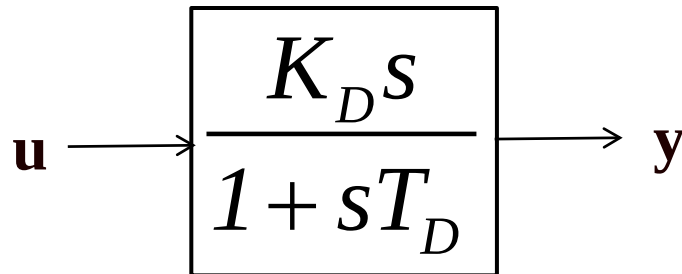


- Equation with u as an input and y as an output is

$$\frac{dy}{dt} = \frac{1}{T}(Ku - y)$$

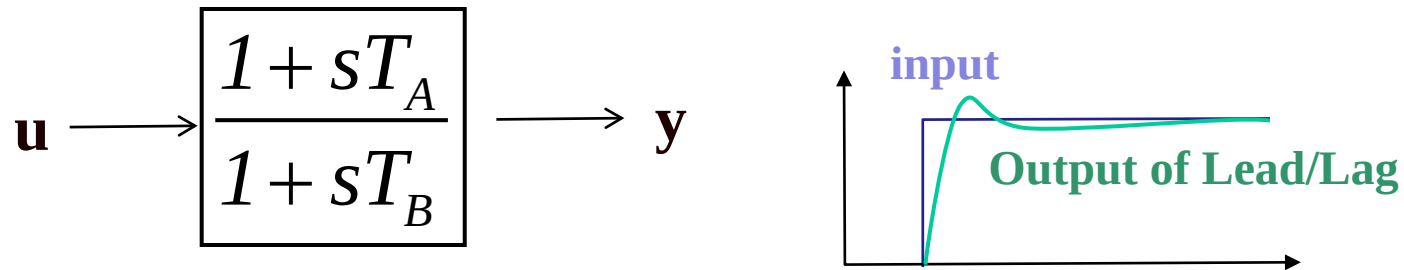
- In steady-state with an initial output of y_0 , the initial state is y_0 and the initial input is y_0/K
- Commonly used for measurement delay (e.g., TR block with IEEE T1)

Derivative Block



- Block takes the derivative of the input, with scaling K_D and a first order lag with T_D
 - Physically we can't take the derivative without some lag
- In steady-state the output of the block is zero
- State equations require a more general approach

Lead-Lag Block



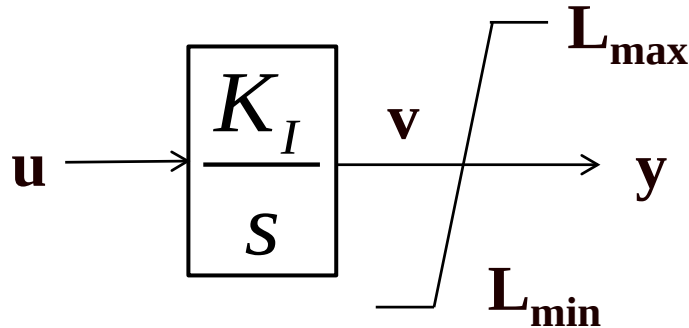
- In exciters such as the EXDC1 the lead-lag block is used to model time constants inherent in the exciter; the values are often zero (or equivalently equal)
- In steady-state the input is equal to the output
- To get equations write in form with $b_0=1/T_B$, $b_1=T_A/T_B$, $a_0=1/T_B$

$$\frac{1 + sT_A}{1 + sT_B} = \frac{\frac{1}{T_B} + s \frac{T_A}{T_B}}{\frac{1}{T_B} + s}$$

Limits: Windup versus Nonwindup



- When there is integration, how limits are enforced can have a major impact on simulation results
- Two major flavors: windup and non-windup
- Windup limit for an integrator block



$$\frac{dv}{dt} = K_I u$$

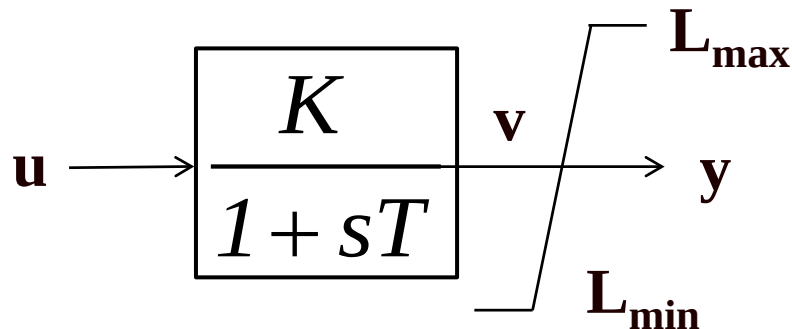
If $L_{\min} \leq v \leq L_{\max}$ then $y = v$
else If $v < L_{\min}$ then $y = L_{\min}$,
else if $v > L_{\max}$ then $y = L_{\max}$

The value of v is NOT limited, so its value can "windup" beyond the limits, delaying backing off of the limit

Limits on First Order Lag



- Windup and non-windup limits are handled in a similar manner for a first order lag



$$\frac{dv}{dt} = \frac{1}{T}(Ku - v)$$

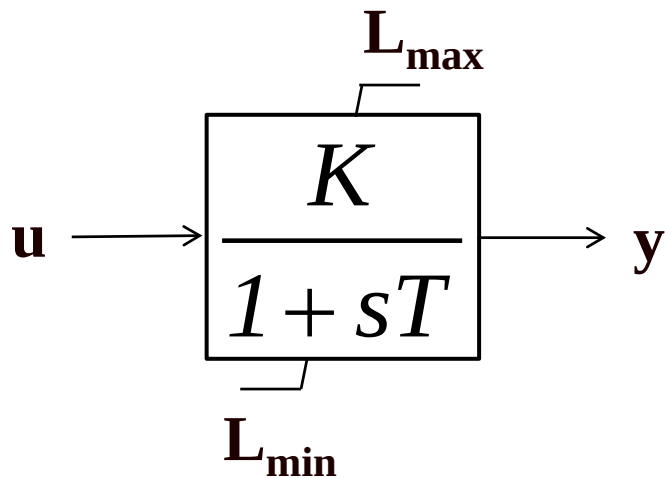
If $L_{\min} \leq v \leq L_{\max}$ then $y = v$
else If $v < L_{\min}$ then $y = L_{\min}$,
else if $v > L_{\max}$ then $y = L_{\max}$

Again the value of v is NOT limited, so its value can "windup" beyond the limits, delaying backing off of the limit

Non-Windup Limit First Order Lag



- With a non-windup limit, the value of y is prevented from exceeding its limit



$$\frac{dy}{dt} = \frac{1}{T}(Ku - y)$$

(except as indicated below)

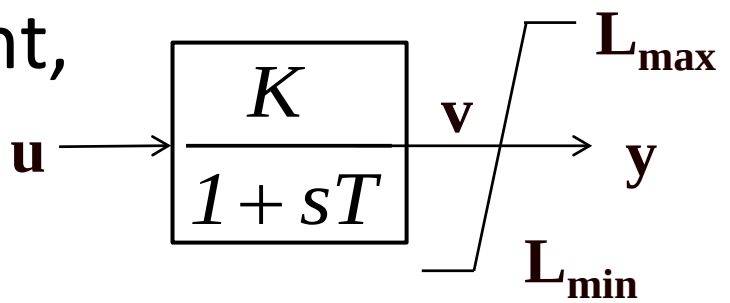
$$\text{If } L_{\min} \leq y \leq L_{\max} \text{ then normal } \frac{dy}{dt} = \frac{1}{T}(Ku - y)$$

$$\text{If } y \geq L_{\max} \text{ then } y = L_{\max} \text{ and if } u > 0 \text{ then } \frac{dy}{dt} = 0$$

$$\text{If } y \leq L_{\min} \text{ then } y = L_{\min} \text{ and if } u < 0 \text{ then } \frac{dy}{dt} = 0$$

Ignored States



- When integrating block diagrams often states are ignored, such as a measurement delay with $TR=0$
- In this case the differential equations just become algebraic constraints
- Example: For block at right, as $T \rightarrow 0$, $v = Ku$ 
- With lead-lag it is quite common for $T_A = T_B$, resulting in the block being ignored

Brief Review of DC Machines



- Prior to widespread use of machine drives, dc motors had a important advantage of easy speed control
- On the stator a dc machine has either a permanent magnet or a single concentrated winding
- Rotor (armature) currents are supplied through brushes and commutator
- Equations are

$$v_f = i_f R_f + L_f \frac{di_f}{dt}$$

$$v_a = i_a R_a + L_a \frac{di_a}{dt} + G \omega_m i_f$$

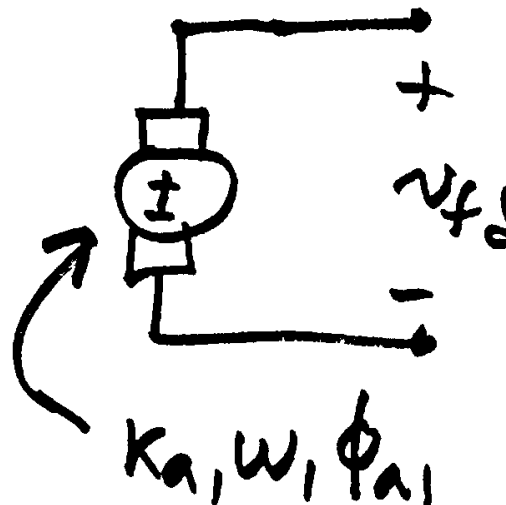
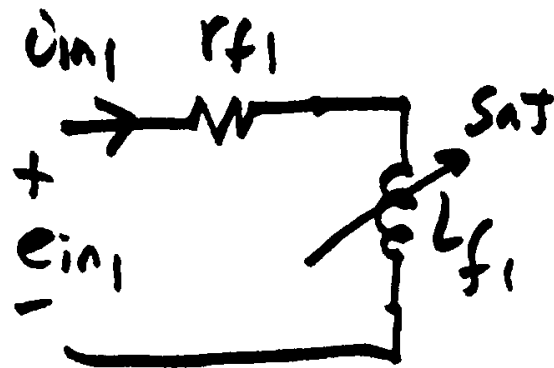
The f subscript refers to the field, the a to the armature; ω is the machine's speed, G is a constant. In a permanent magnet machine the field flux is constant, the field equation goes away, and the field impact is embedded in a equivalent constant to $G i_f$

Types of DC Machines



- If there is a field winding (i.e., not a permanent magnet machine) then the machine can be connected in the following ways
 - Separately-excited: Field and armature windings are connected to separate power sources
 - For an exciter, control is provided by varying the field current (which is stationary), which changes the armature voltage
 - Series-excited: Field and armature windings are in series
 - Shunt-excited: Field and armature windings are in parallel

Separately Excited DC Exciter



(to sync
mach)

$$e_{in_1} = r_{f1} i_{in_1} + N_{f1} \frac{d\phi_{f1}}{dt}$$

$$\phi_{a1} = \frac{1}{\sigma_1} \phi_{f1}$$

σ_1 is coefficient of dispersion,
modeling the flux leakage

Separately Excited DC Exciter



- Relate the input voltage, e_{in1} , to v_{fd}

$$v_{fd} = K_{a1} \omega_1 \phi_{a1} = K_{a1} \omega_1 \frac{\phi_{f1}}{\sigma_1}$$

Assuming a constant speed ω_1

$$\phi_{f1} = \frac{\sigma_1}{K_{a1} \omega_1} v_{fd}$$

Solve above for ϕ_{f1} which was used in the previous slide

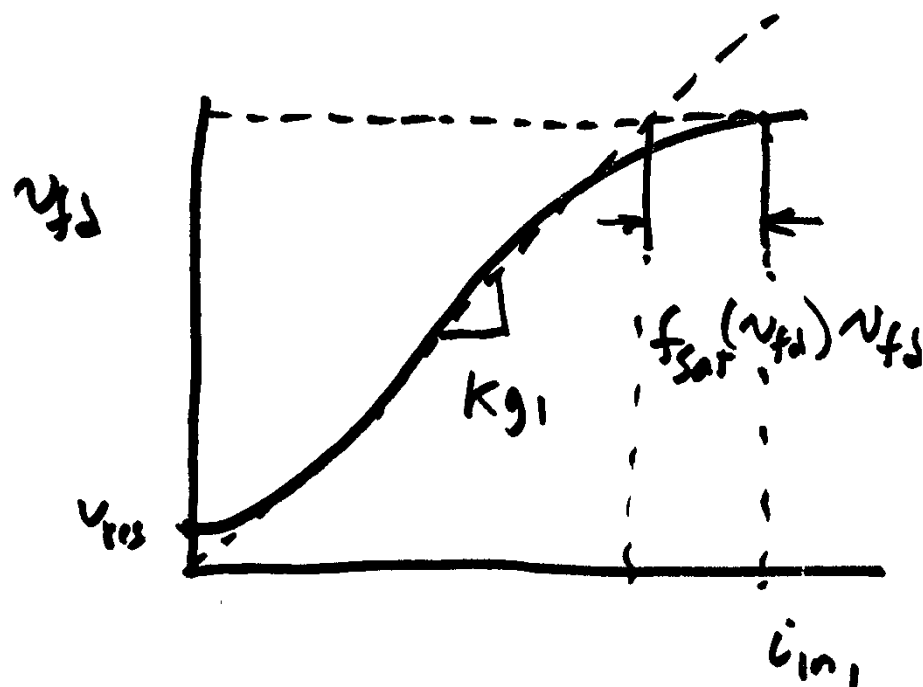
$$\frac{d\phi_{f1}}{dt} = \frac{\sigma_1}{K_{a1} \omega_1} \frac{dv_{fd}}{dt}$$

$$e_{in1} = i_{in1} r_{f1} + \frac{N_{f1} \sigma_1}{K_{a1} \omega_1} \frac{dv_{fd}}{dt}$$

Separately Excited DC Exciter



- If it was a linear magnetic circuit, then v_{fd} would be proportional to i_{n1} ; for a real system we need to account for saturation



$$i_{n1} = \frac{v_{fd}}{K_{g1}} + f_{sat}(v_{fd})v_{fd}$$

Without saturation we can write

$$K_{g1} = \frac{K_{a1}\omega_1}{N_{f1}\sigma_1} L_{f1us}$$

Where L_{f1us} is the unsaturated field inductance

Separately Excited DC Exciter



$$e_{in_1} = r_{f1} i_{in1} + N_{f1} \frac{d\phi_{f1}}{dt}$$

Can be written as

$$e_{in_1} = \frac{r_{f1}}{K_{g1}} v_{fd} + r_{f1} f_{sat}(v_{fd}) v_{fd} + \frac{L_{f1us}}{K_{g1}} \frac{dv_{fd}}{dt}$$

This equation is then scaled based on the synchronous machine base values

$$E_{fd} = \frac{X_{md}}{R_{fd}} V_{fd} = \frac{X_{md}}{R_{fd}} \frac{v_{fd}}{V_{BFD}}$$

Separately Excited Scaled Values



$$K_{E_{sep}} \triangleq \frac{r_{f1}}{K_{g1}} \quad T_E \triangleq \frac{L_{f1us}}{K_{g1}}$$

$$V_R \triangleq \frac{X_{md}}{R_{fd} V_{BFD}} e_{in1}$$

$$S_E(E_{fd}) \triangleq r_{f1} f_{sat} \left(\frac{V_{BFD} R_{fd}}{X_{md}} E_{fd} \right)$$

V_R is the scaled output of the voltage regulator amplifier

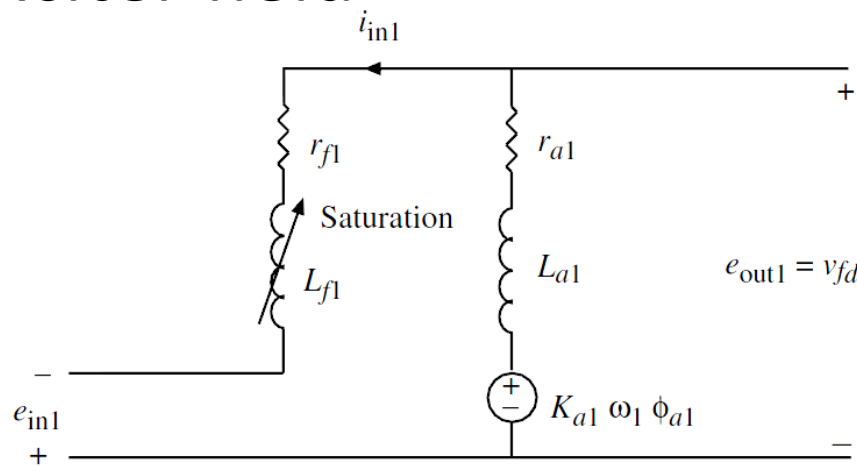
Thus we have

$$T_E \frac{dE_{fd}}{dt} = - \left(K_{E_{sep}} + S_E(E_{fd}) \right) E_{fd} + V_R$$

The Self-Excited Exciter



- When the exciter is self-excited, the amplifier voltage appears in series with the exciter field



Note the additional E_{fd} term on the end

$$T_E \frac{dE_{fd}}{dt} = - \left(K_{E_{sep}} + S_E(E_{fd}) \right) E_{fd} + V_R + E_{fd}$$

Self and Separated Excited Exciters



- The same model can be used for both by just modifying the value of K_E

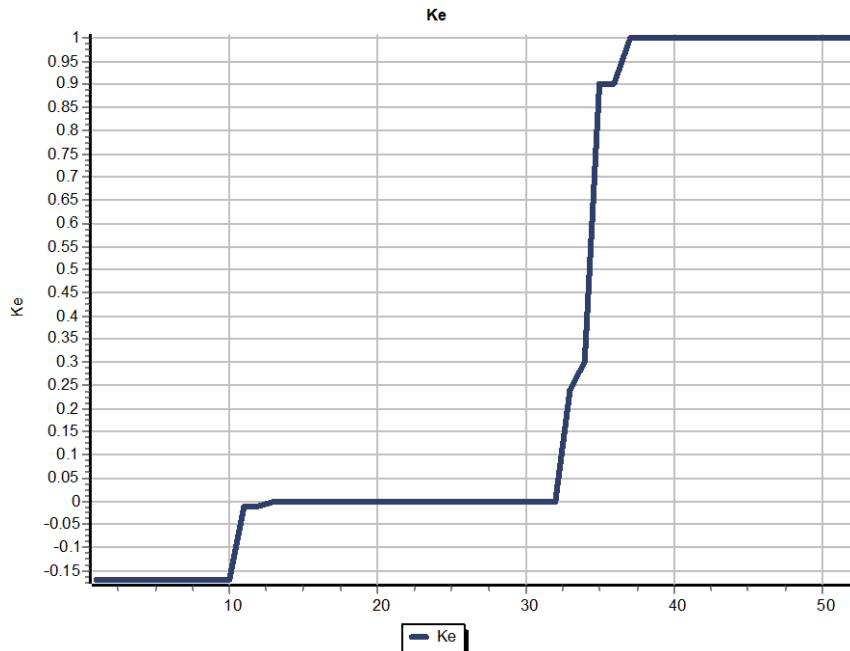
$$T_E \frac{dE_{fd}}{dt} = -\left(K_E + S_E(E_{fd})\right)E_{fd} + V_R$$

$$K_{E_{self}} = K_{E_{sep}} - 1 \quad \left(\text{typically } K_{E_{self}} = -.01 \right)$$

Exciter Model IEEEET1 KE Values



Example IEEEET1 Values from a large system



ctions ▾

als	Tr	Ka	Ta	Vrmax	Vrmin	Kr▲	Te	Kf	Tf	Switch	E1	SE1	E2	SE2	Spdm
	0.03333334	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0.03333334	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0.03333334	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0.03333334	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0.03333334	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0.03333334	50	0.05	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0.03333334	50	0.06	3.5	-3.5	-0.17	0.95	0.04	1	0	3.37	0.22	4.49	0.95	
	0.03333334	17	0.03333334	5	-5	-0.01	0.8	0.08	2.5	0	2.1635	0.28	3.245	0.42	
	0.03333334	20	0.03333334	5	-5	-0.01	1	0.08	2.7	0	2.1635	0.28	3.245	0.42	
	0.05	25	0.18	1	-1	0	0.35	0.0289	0.3	0	3.46	0.089	4.63	0.25	
	0	20	0.05	3.5	-3.5	0	1.1	0.06	1	0	2.73	0.22	3.64	0.95	
	0.05	2.2	0.07	5	-5	0	0.2	0.01	1	0	2.36	0.28	3.54	0.42	
	0.05	200	0.25	3.24	-3.24	0	0.85	0.11	1.25	0	3.12	0.22	4.16	0.95	
	0.06	23	0.2	1	-1	0	0.26	0.03	0.29	0	3.46	0.089	4.6	0.25	
	0.05	2.2	0.07	5	-5	0	0.2	0.01	1	0	2.36	0.28	3.54	0.42	
	0.05	2.7	0.03333334	5	-5	0	0.63	0.01	1	0	2.36	0.28	3.54	0.42	
	0	112	0.05	3.2	-3.2	0	0.85	0.036	1.1	0	3.3225	0.22	4.43	0.72	
	0.05	1.7	0.03333334	5	-5	0	0.63	0.01	1	0	2.36	0.28	3.54	0.42	
	0.05	2.2	0.07	5	-5	0	0.2	0.01	1	0	2.36	0.28	3.54	0.42	
	0.05	200	0.25	3.22	-3.22	0	0.85	0.11	1.25	0	3.09	0.22	4.12	0.95	
	0.03333334	50	0.03333334	3.5	-3	0	1	0.01	0.5	0	2.5	0.22	3.5	0.95	
	0.05	2.7	0.03333334	5	-5	0	0.63	0.01	1	0	2.36	0.28	3.54	0.42	
	0	130	0.04	3.42	-3.42	0	2	0.028	1	0	2.7	0.22	3.6	0.95	
	0	130	0.04	3.42	-3.42	0	2.5	0.033	1	0	2.7	0.22	3.6	0.95	

The K_E equal 1 are separately excited, and K_E close to zero are self excited

Saturation



- A number of different functions can be used to represent the saturation
- The quadratic approach is now quite common

$$S_E(E_{fd}) = B(E_{fd} - A)^2$$

An alternative model is
$$S_E(E_{fd}) = \frac{B(E_{fd} - A)^2}{E_{fd}}$$

This is the same function used with the machine models

- Exponential function could also be used

$$S_E(E_{fd}) = A_x e^{B_x E_{fd}}$$

Voltage Regulator Model



Amplifier $T_A \frac{dV_R}{dt} = -V_R + K_A V_{in}$

$$V_R^{\min} \leq V_R \leq V_R^{\max}$$

Modeled
as a first
order
differential
equation

In steady state $V_{ref} - V_t = V_{in} = \frac{V_R}{K_A}$

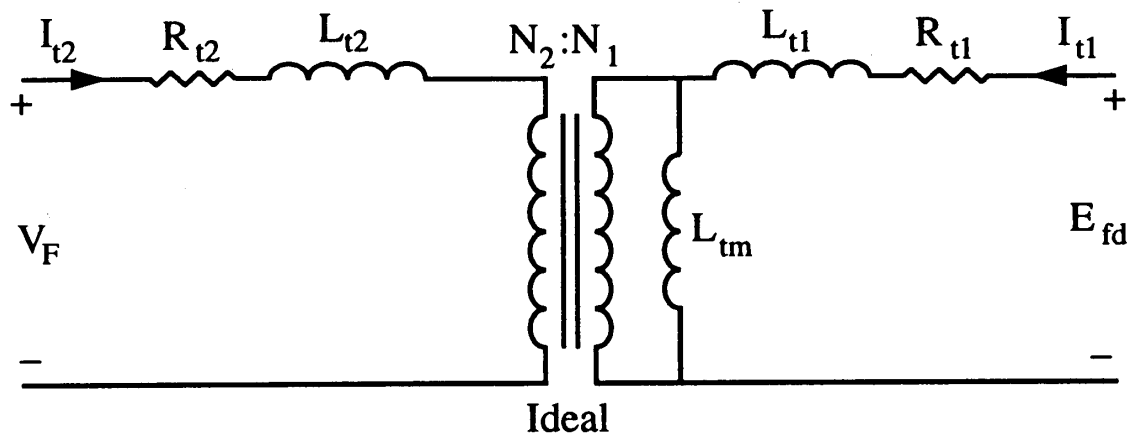
As K_A is increased $K_A \rightarrow V_t \approx V_{ref}$

There is often a droop in regulation

Feedback



- This control system can often exhibit instabilities, so some type of feedback is used
- One approach is a stabilizing transformer



Designed with a large L_{t2} so $I_{t2} \approx 0$

$$V_F = \frac{N_2}{N_1} L_{tm} \frac{dI_{t1}}{dt}$$

Feedback



$$E_{fd} = R_{t1}I_{t1} + (L_{t1} + L_{tm})\frac{dI_{t1}}{dt}$$

$$\frac{dV_F}{dt} = \frac{R_{t1}}{(L_{t1} + L_{tm})} \left(-V_F + \frac{N_2}{N_1} \frac{L_{tm}}{R_{t1}} \frac{dE_{fd}}{dt} \right)$$

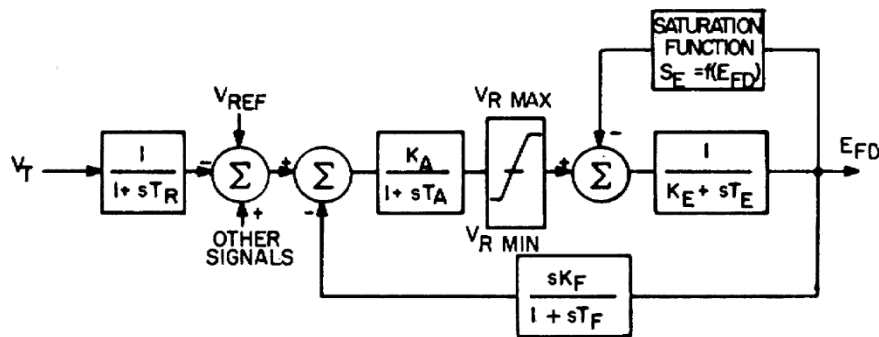
$$\downarrow$$
$$\frac{1}{T_F}$$

$$\downarrow$$
$$K_F$$

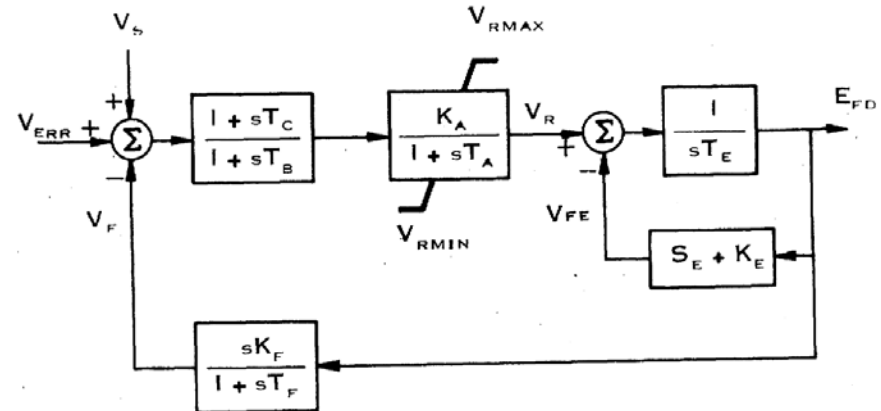
IEEET1 Model Evolution



- The original IEEET1, from 1968, evolved into the EXDC1 in 1981



1968



1981

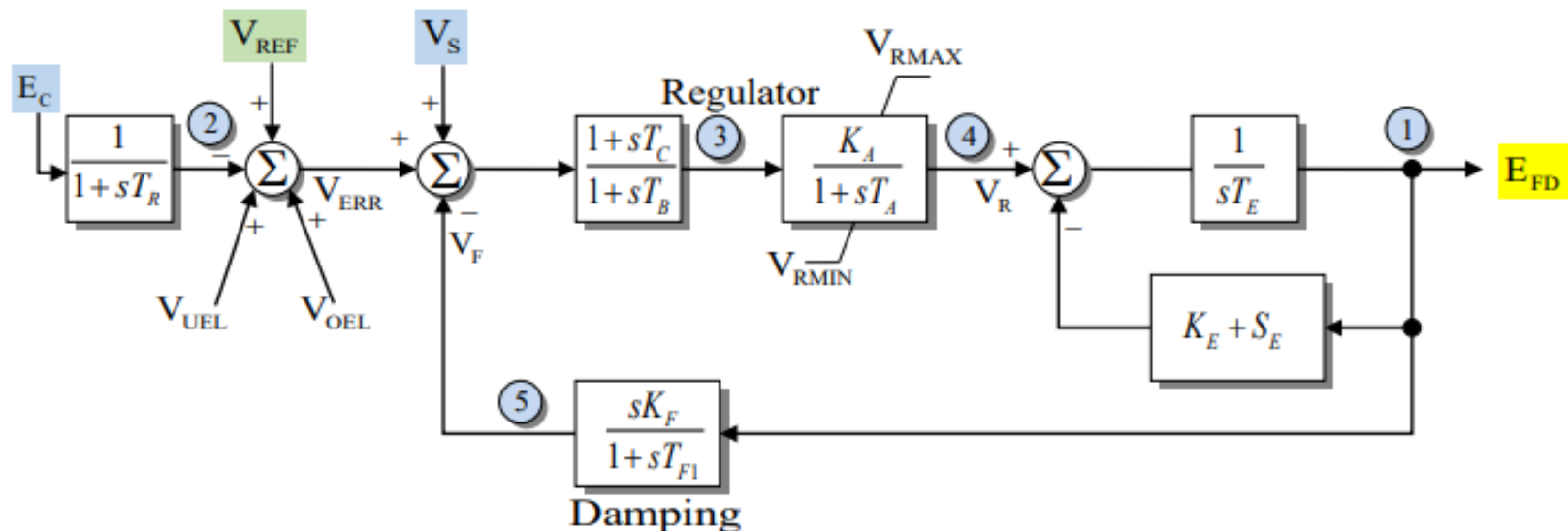
Note, K_E in the feedback is the same in both models

Image Source: Fig 3 of "Excitation System Models for Power Stability Studies,"
IEEE Trans. Power App. and Syst., vol. PAS-100, pp. 494-509, February 1981

IEEEEX1



- This is from 1979, and is the EXDC1 with the potential for a measurement delay and inputs for under or over excitation limiters



IEEEET1 Evolution



- In 1992 IEEE Std 421.5-1992 slightly modified the EXDC1, calling it the DC1A (modeled as ESDC1A)

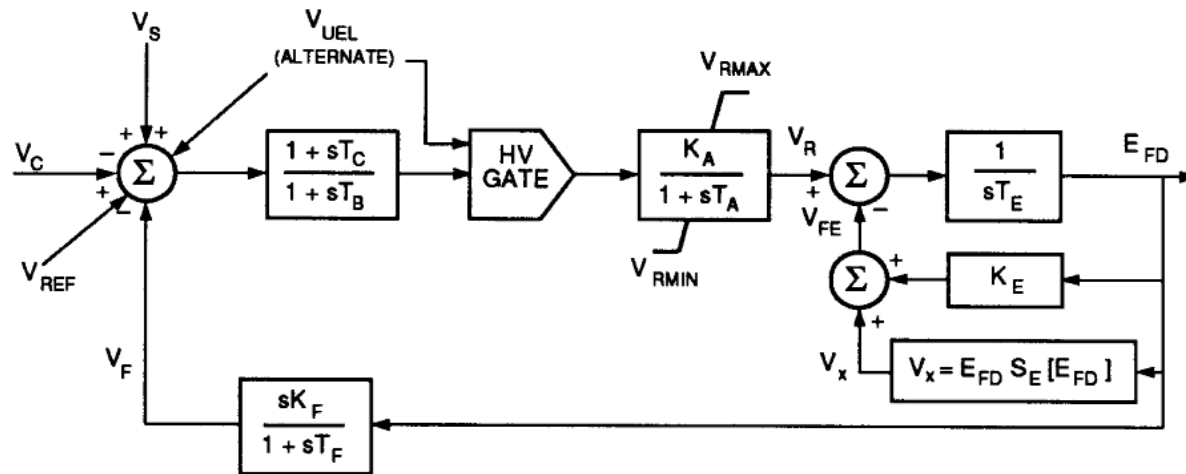


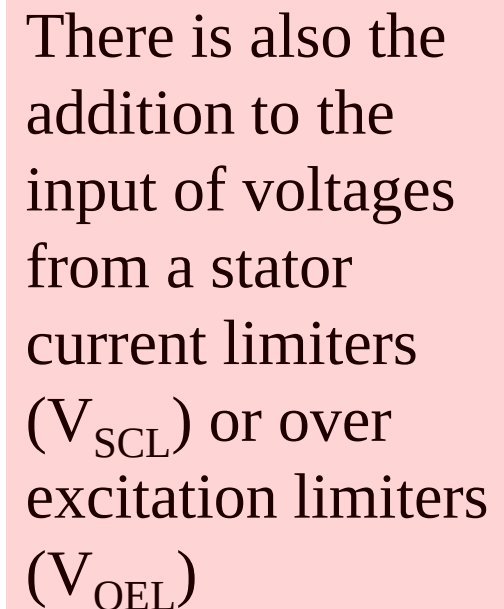
Figure 3—Type DC1A — DC Commutator Exciter

Same model is in 421.5-2005

Image Source: Fig 3 of IEEE Std 421.5-1992

V_{UEL} is a signal from an under-excitation limiter, which we'll cover later

- Note the minimum
limit on E_{FD}


$$(a) \quad V_x = E_{\text{FD}} \cdot S_F(E_{\text{FD}})$$

34

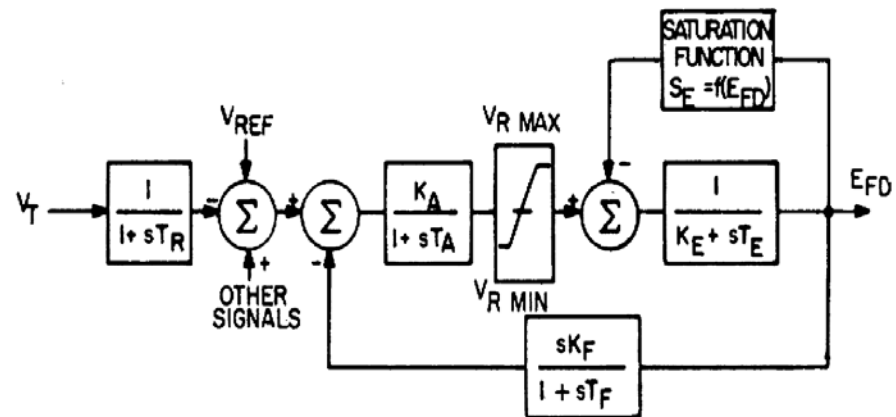
IEEET1 Example



- Assume previous GENROU case with saturation. Then add a IEEE T1 exciter with $K_a=50$, $T_a=0.04$, $K_e=-0.06$, $T_e=0.6$, $V_{r_{\max}}=1.0$, $V_{r_{\min}}=-1.0$ For saturation assume $Se(2.8) = 0.04$, $Se(3.73)=0.33$
- Saturation function is $0.1621(E_{fd}-2.303)^2$ (for $E_{fd} > 2.303$); otherwise zero

- E_{fd} is initially 3.22
- $Se(3.22)*E_{fd}=0.437$
- $(V_r-Se*E_{fd})/K_e=E_{fd}$
- $V_r=0.244$

- $V_{ref} = 0.244/K_a + V_T = 0.0488 + 1.0946 = 1.09948$

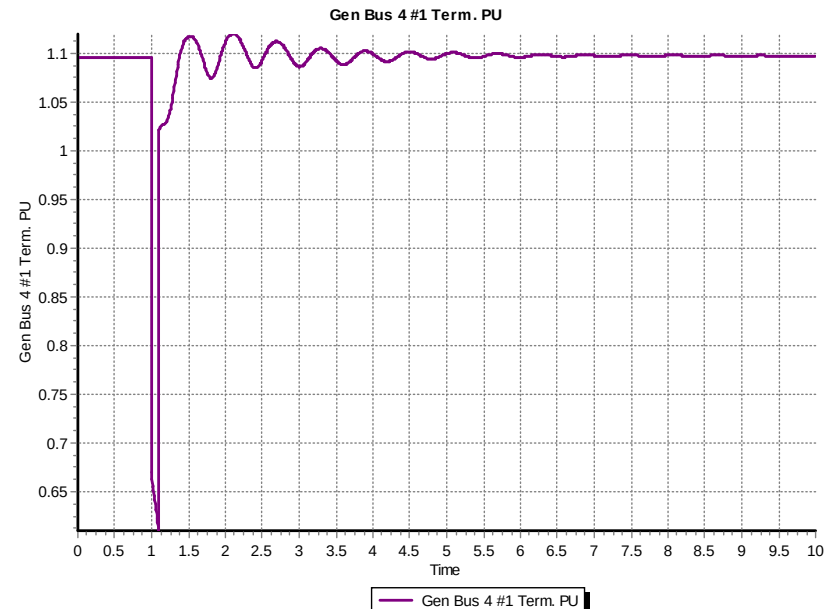
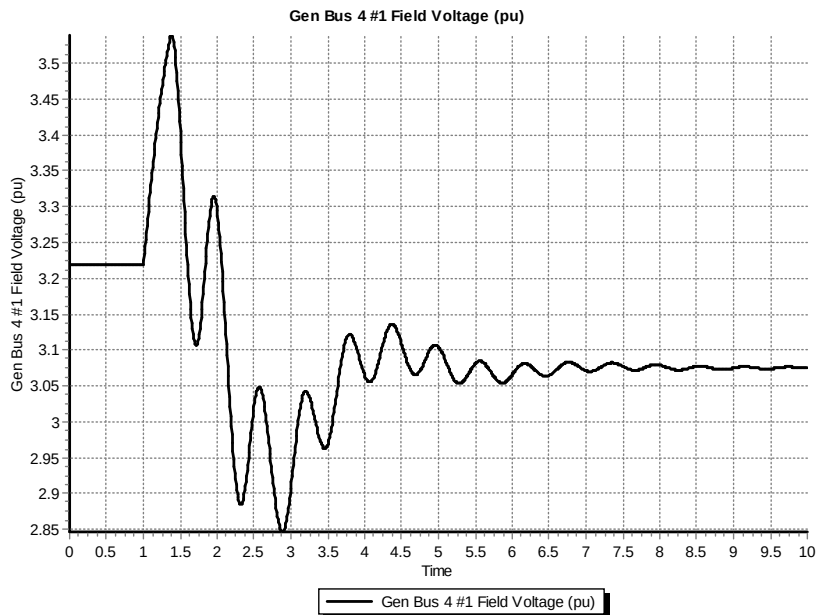


Case B4_GENROU_Sat_IEEET1

IEEE T1 Example



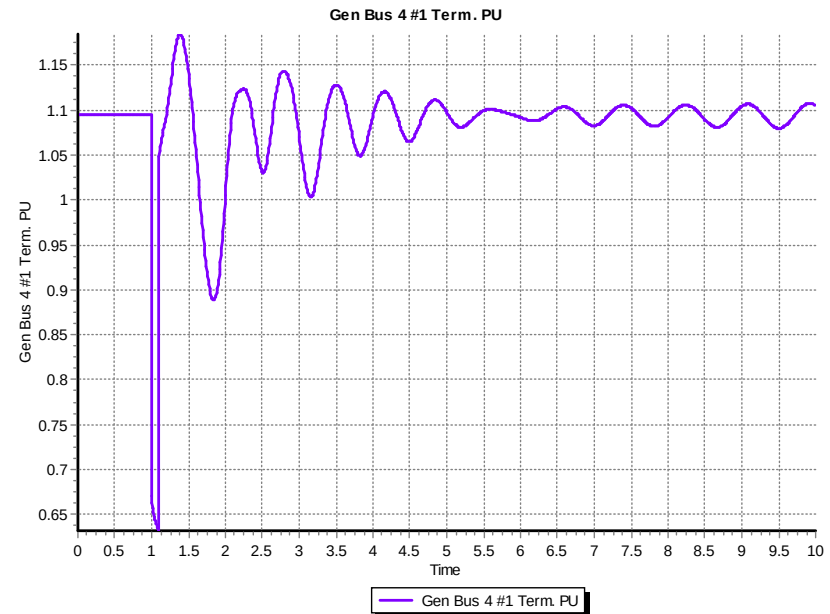
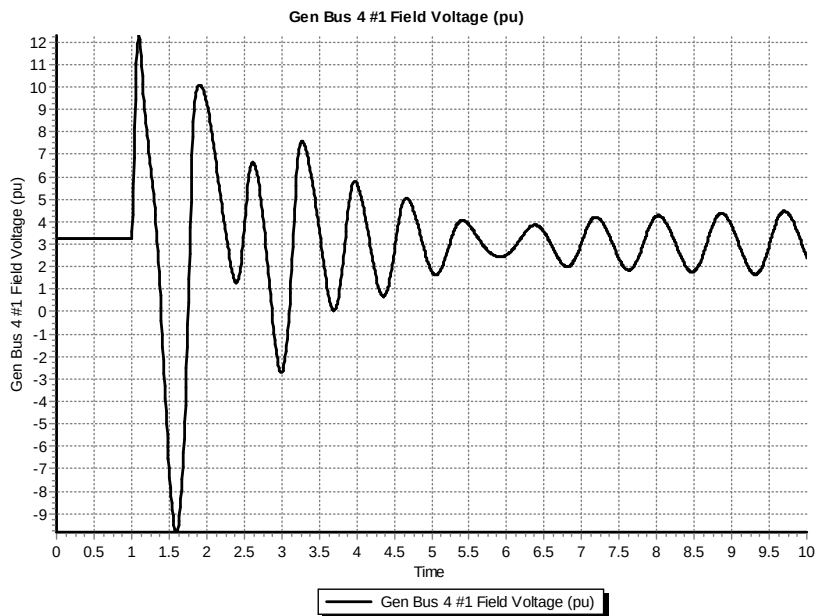
- For 0.1 second fault (from before), plot of Efd and the terminal voltage is given below
- Initial $V_4=1.0946$, final $V_4=1.0973$
 - Steady-state error depends on the value of K_a



IEEE1 Example



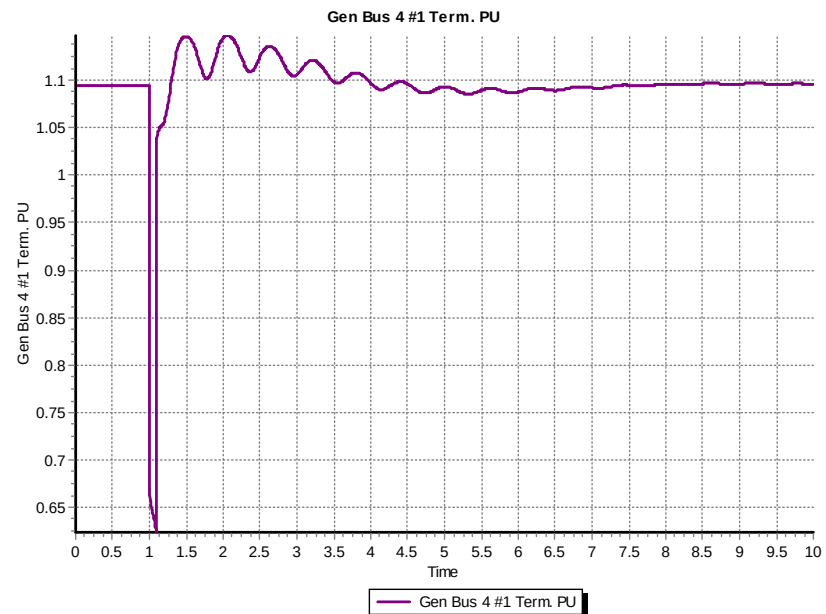
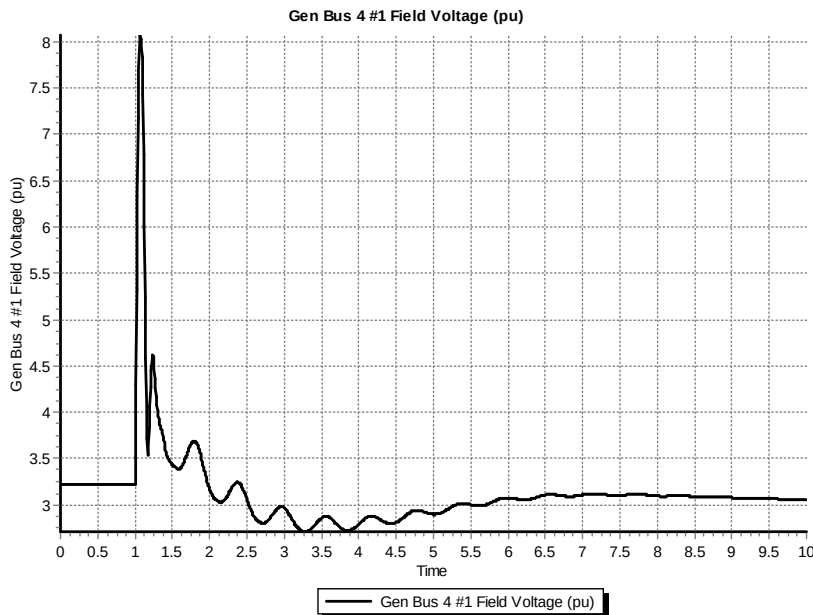
- Same case, except with $K_a=500$ to decrease steady-state error, no V_r limits; this case is actually unstable



IEEE1 Example



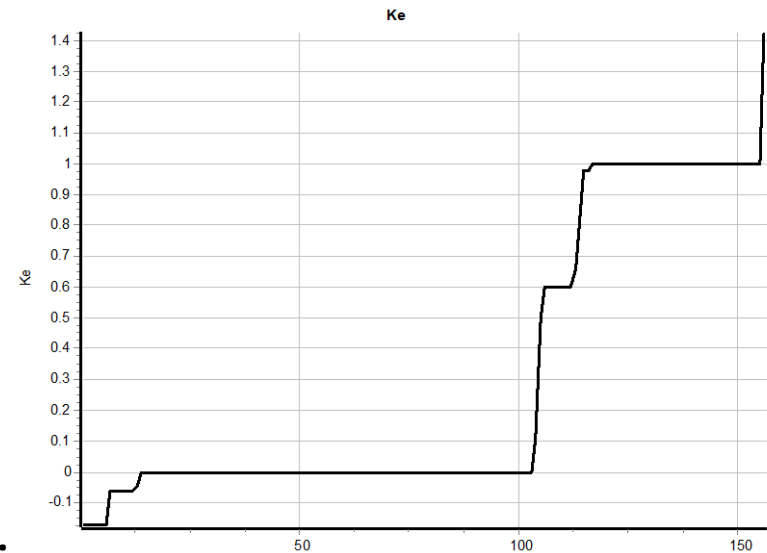
- With $K_a=500$ and rate feedback, $K_f=0.05$, $T_f=0.5$
- Initial $V_4=1.0946$, final $V_4=1.0957$



WECC Case Type 1 Exciters



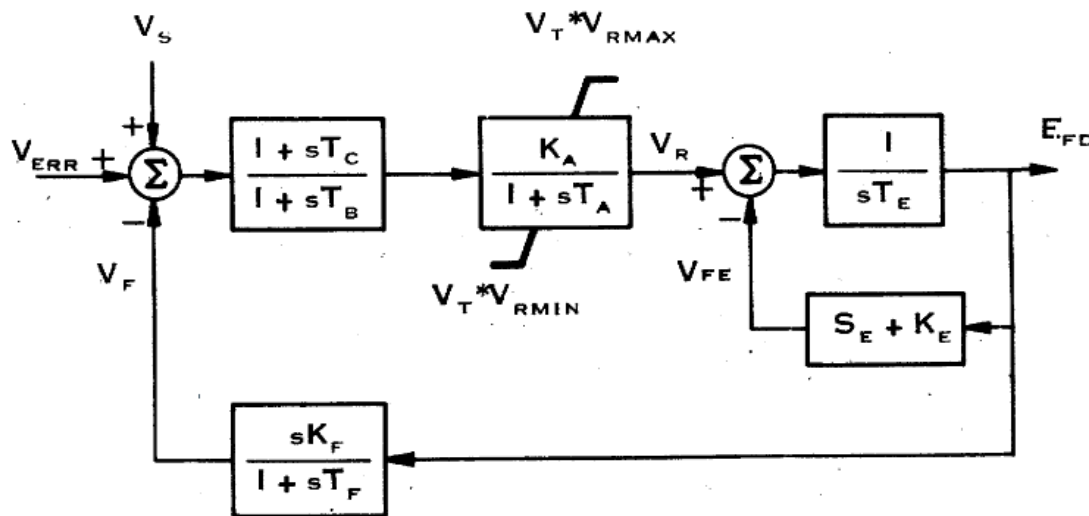
- In a recent WECC case with 3519 exciters, 20 are modeled with the IEEE T1, 156 with the EXDC1 20 with the ESDC1A (and none with IEEEX1)
- Graph shows K_E value for the EXDC1 exciters in case;
about 1/3 are separately excited, and the rest self excited
 - A value of K_E equal zero indicates code should set K_E so V_r initializes to zero; this is used to mimic the operator action of trimming this value



DC2 Exciters



- Other dc exciters exist, such as the EXDC2, which is quite similar to the EXDC1



Vr limits are multiplied by the terminal voltage

Fig. 4. Type DC2 - DC Commutator Exciter

Image Source: Fig 4 of "Excitation System Models for Power Stability Studies,"
IEEE Trans. Power App. and Syst., vol. PAS-100, pp. 494-509, February 1981

ESDC4B



- A newer dc model introduced in 421.5-2005 in which a PID controller is added; might represent a retrofit

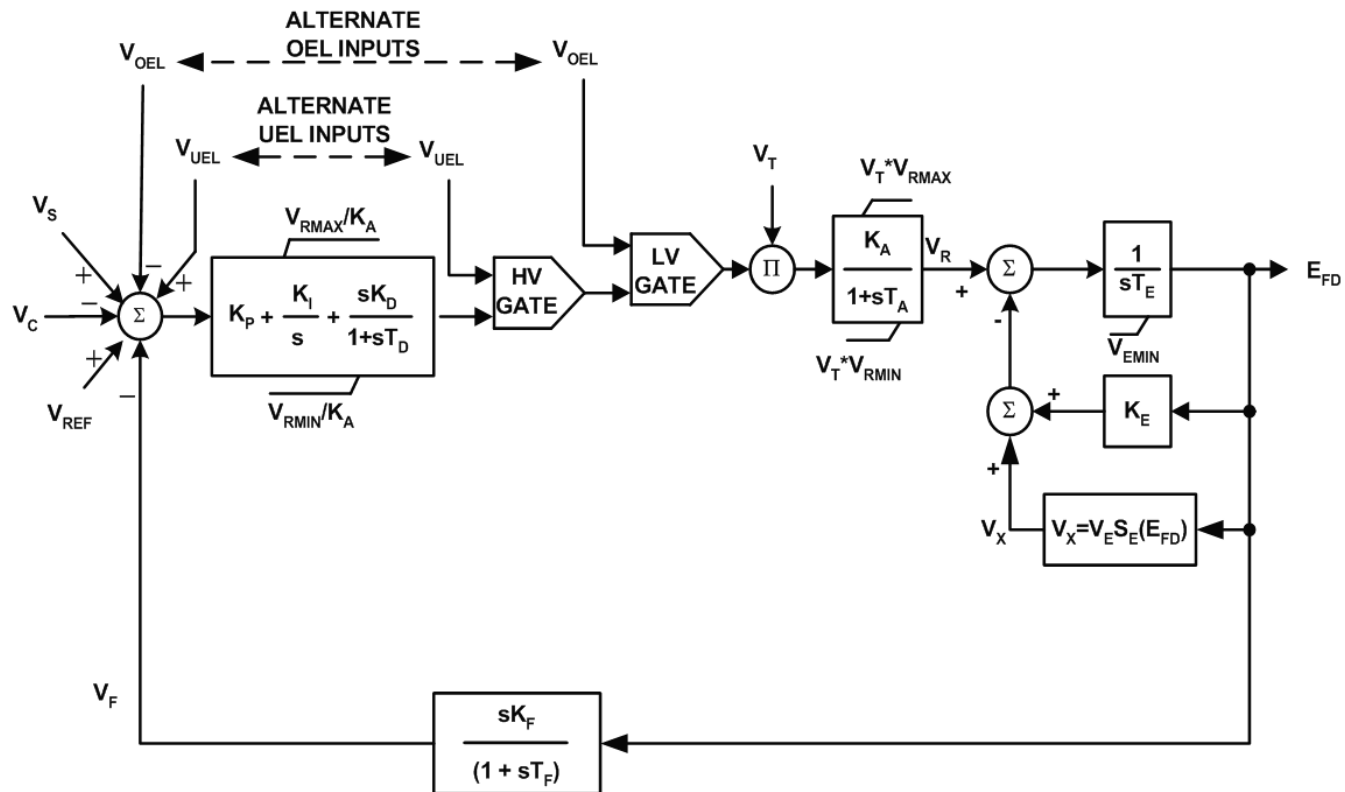


Image Source: Fig 5-4 of IEEE Std 421.5-2005

Desired Performance



- A discussion of the desired performance of exciters is contained in IEEE Std. 421.2-2014 (update from 1990)
- Concerned with
 - large signal performance: large, often discrete change in the voltage such as due to a fault; nonlinearities are significant
 - Limits can play a significant role
 - small signal performance: small disturbances in which close to linear behavior can be assumed
- Increasingly exciters have inputs from power system stabilizers, so performance with these signals is important

Transient Response



- Figure shows typical transient response

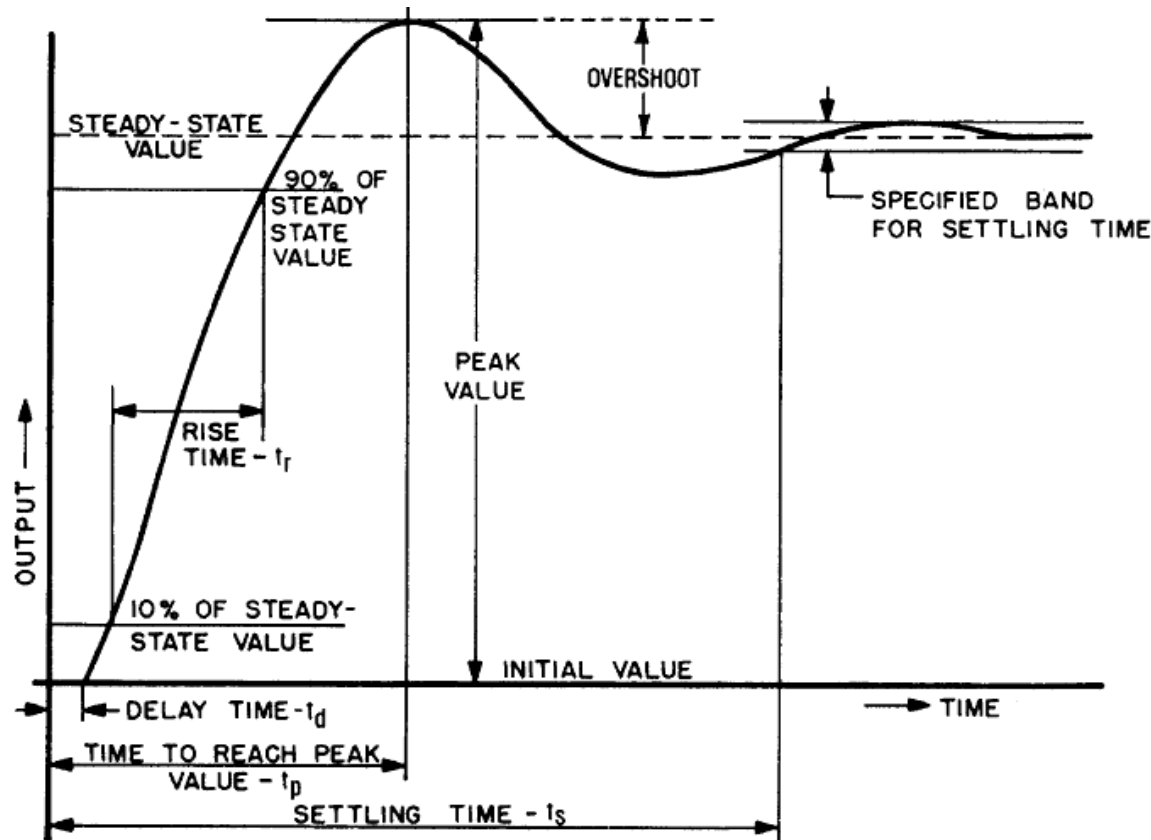


Image Source: IEEE Std 421.2-1990, Figure 3

Small Signal Performance



- Small signal performance can be assessed by either the time responses, frequency response, or eigenvalue analysis
- Figure shows the typical open loop performance of an exciter and machine in the frequency domain

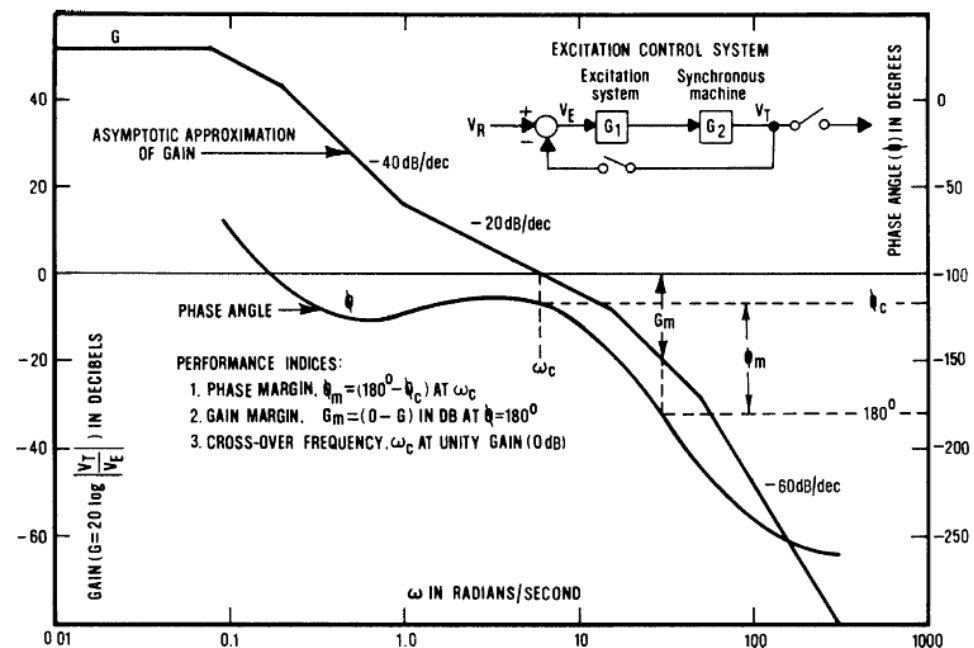


Image Source: IEEE Std 421.2-1990, Figure 4

Figure 4—Typical Open-Loop Frequency Response of an Excitation Control System with the Synchronous Machine Open-Circuited

AC Exciters



- Almost all new exciters use an ac source with an associated rectifier (either from a machine or static)
- AC exciters use an ac generator and either stationary or rotating rectifiers to produce the field current
 - In stationary systems the field current is provided through slip rings
 - In rotating systems since the rectifier is rotating there is no need for slip rings to provide the field current
 - Brushless systems avoid the anticipated problem of supplying high field current through brushes, but these problems have not really developed

AC Exciter System Overview

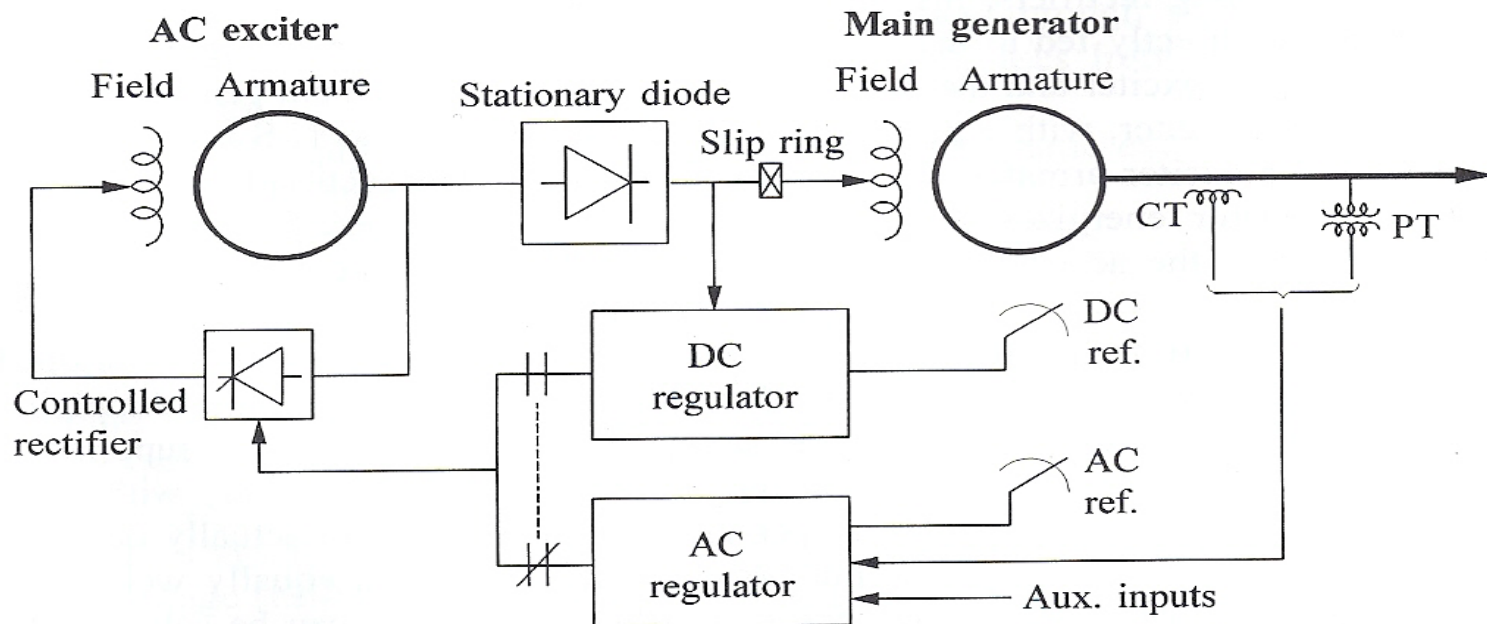


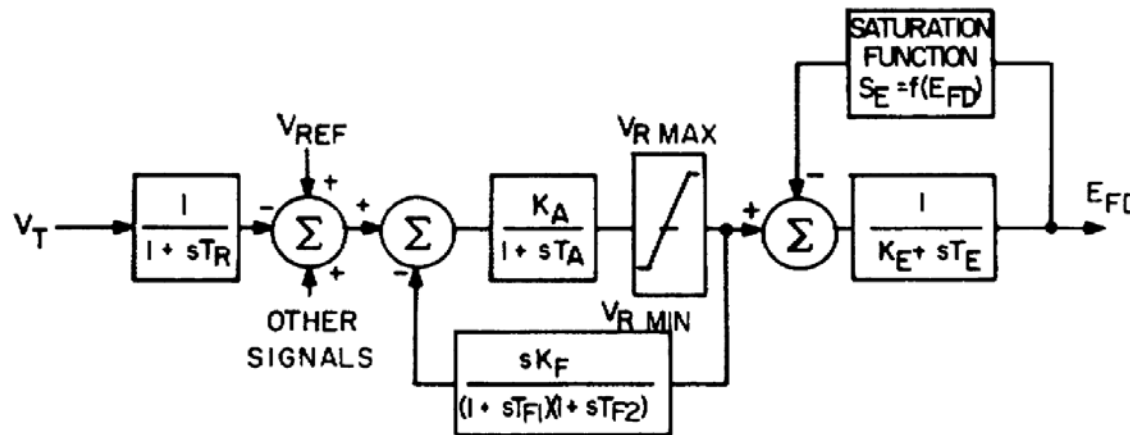
Figure 8.3 Field-controlled alternator rectifier excitation system

Image source: Figures 8.3 of Kundur, *Power System Stability and Control*, 1994

AC Exciter Modeling



- Originally represented by IEEE T2 shown below



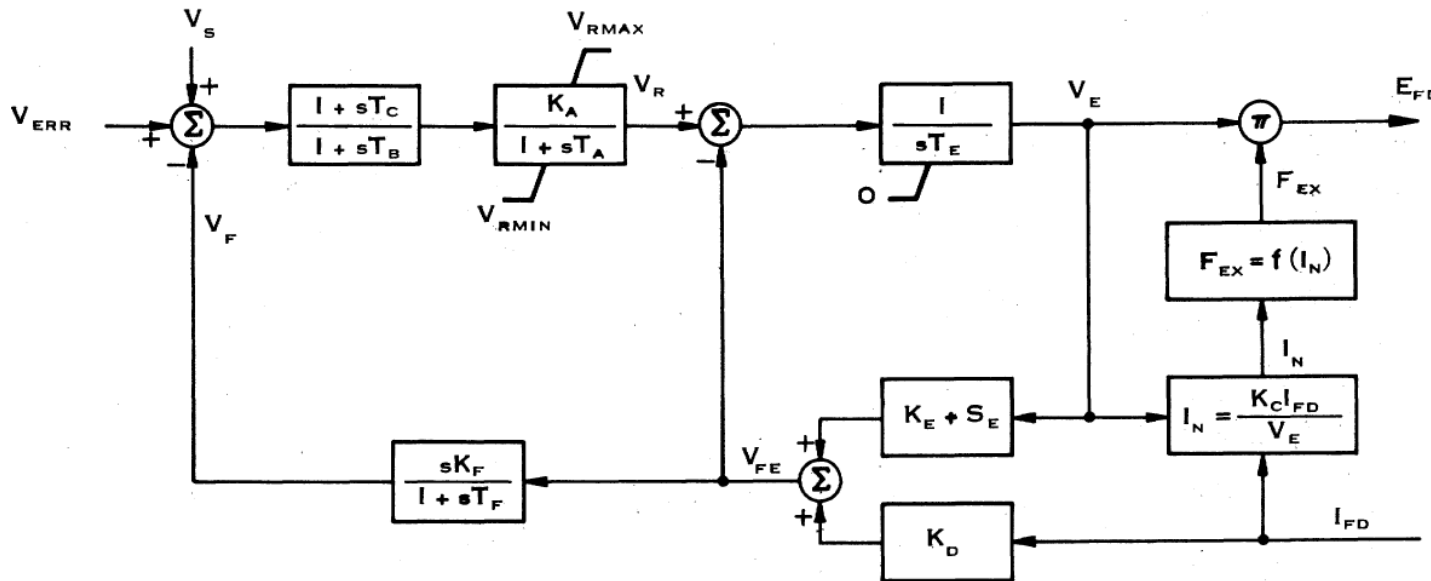
Exciter model is quite similar to IEEE T1

Image Source: Fig 2 of "Computer Representation of Excitation Systems,"
IEEE Trans. Power App. and Syst., vol. PAS-87, pp. 1460-1464, June 1968

EXAC1 Exciter



- The F_{EX} function represent the rectifier regulation, which results in a decrease in output voltage as the field current is increased



About 5% of WECC exciters are EXAC1

K_D models the exciter machine reactance

EXAC1 Rectifier Regulation

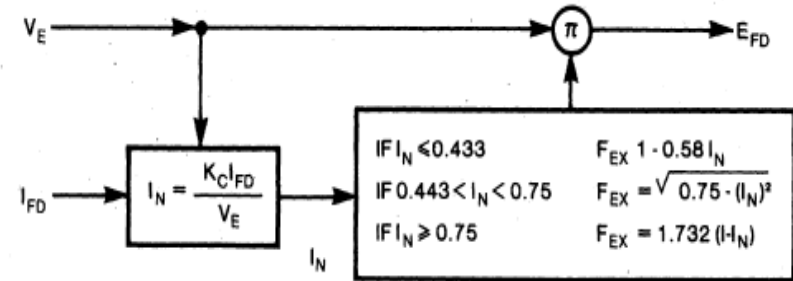
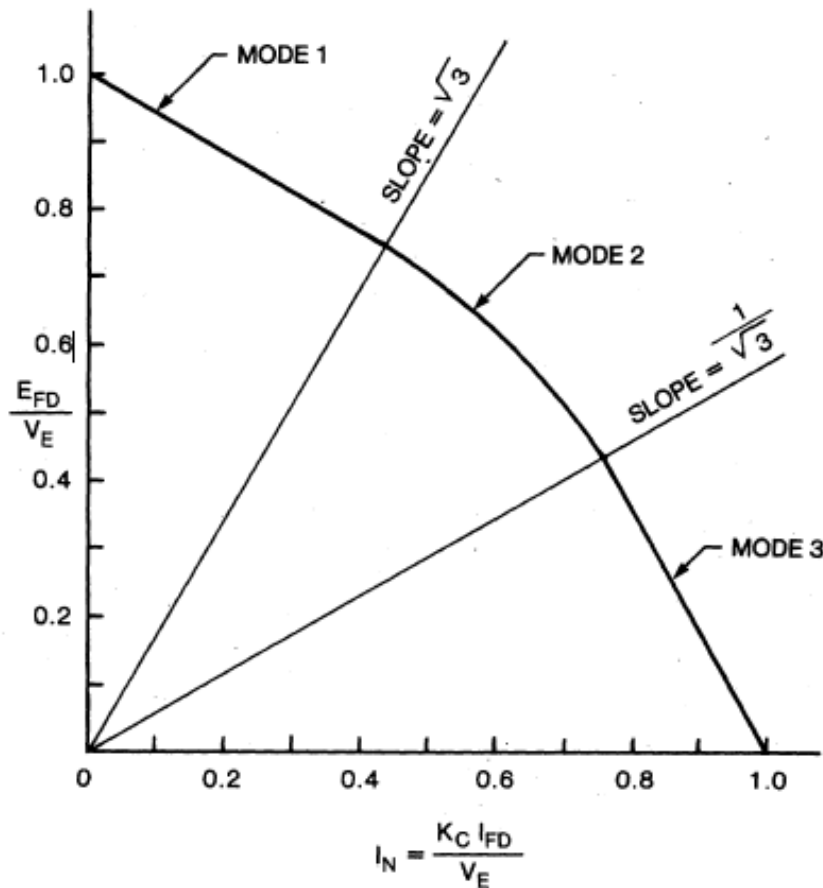


Fig. E.2. Rectifier Regulation Equations

K_C represents the
commuting reactance

There are about
6 or 7 main types
of ac exciter
models

Image Source: Figures E.1 and E.2 of "Excitation System Models for Power Stability Studies,"
IEEE Trans. Power App. and Syst., vol. PAS-100, pp. 494-509, February 1981

Static Exciters

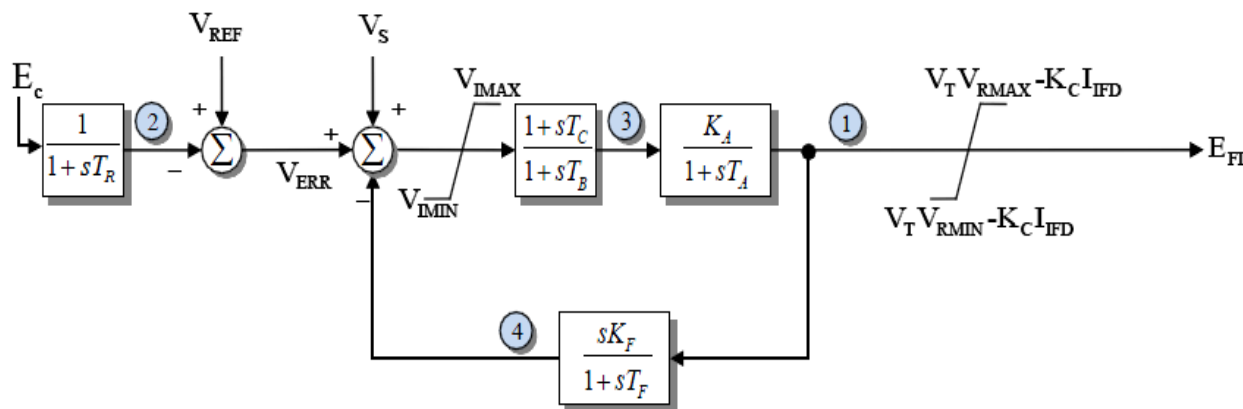


- In static exciters the field current is supplied from a three phase source that is rectified (i.e., there is no separate machine)
- Rectifier can be either controlled or uncontrolled
- Current is supplied through slip rings
- Response can be quite rapid

EXST1 Block Diagram



- The EXST1 is intended to model rectifier in which the power is supplied by the generator's terminals via a transformer
 - Potential-source controlled-rectifier excitation system
- The exciter time constants are assumed to be so small they are not represented



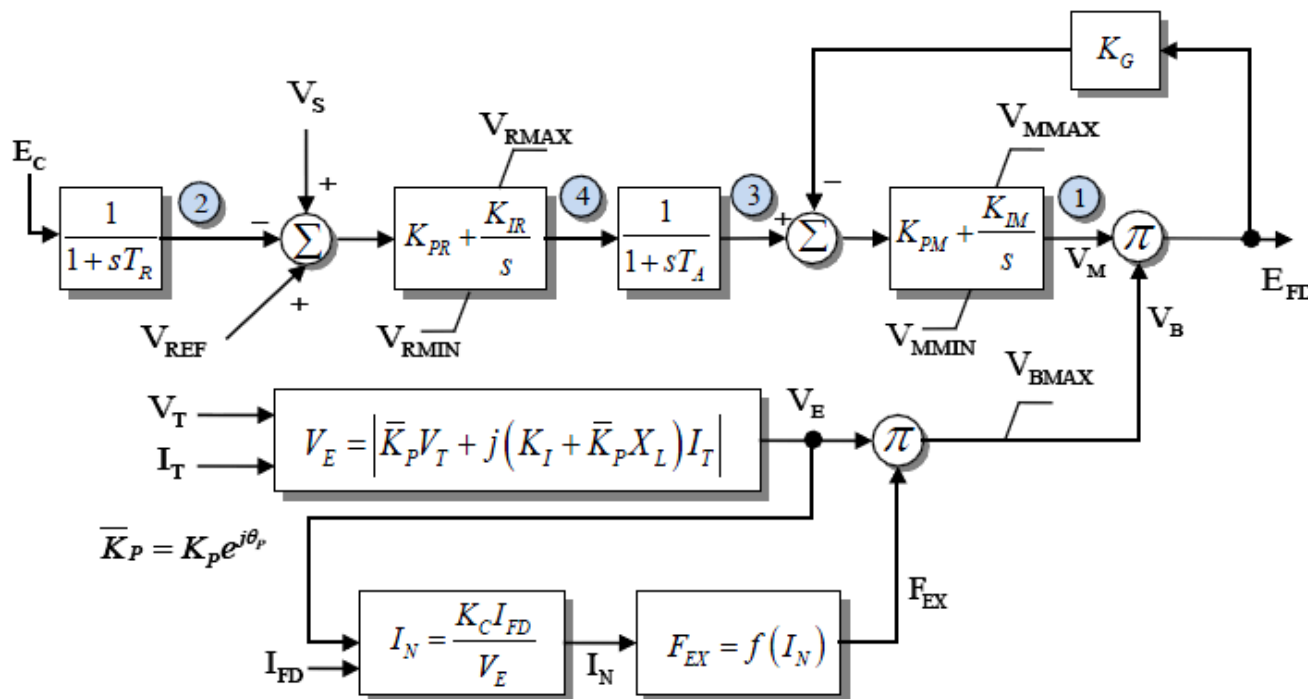
Most common exciter in WECC with about 14% modeled with this type

K_C represents the commuting reactance

EXST4B



- EXST4B models a controlled rectifier design; field voltage loop is used to make output independent of supply voltage



Second most common exciter in WECC with about 13% modeled with this type, though V_e is almost always independent of I_T

Compensation



- Often times it is useful to use a compensated voltage magnitude value as the input to the exciter
 - Compensated voltage depends on generator current; usually R_c is zero

$$E_c = \left| \bar{V}_t + (R_c + jX_c) I_T \right|$$

Sign convention is from IEEE 421.5

- PSLF and PowerWorld model compensation with the machine model using a minus sign
 - Specified on the machine base

$$E_c = \left| \bar{V}_t - (R_c + jX_c) I_T \right|$$

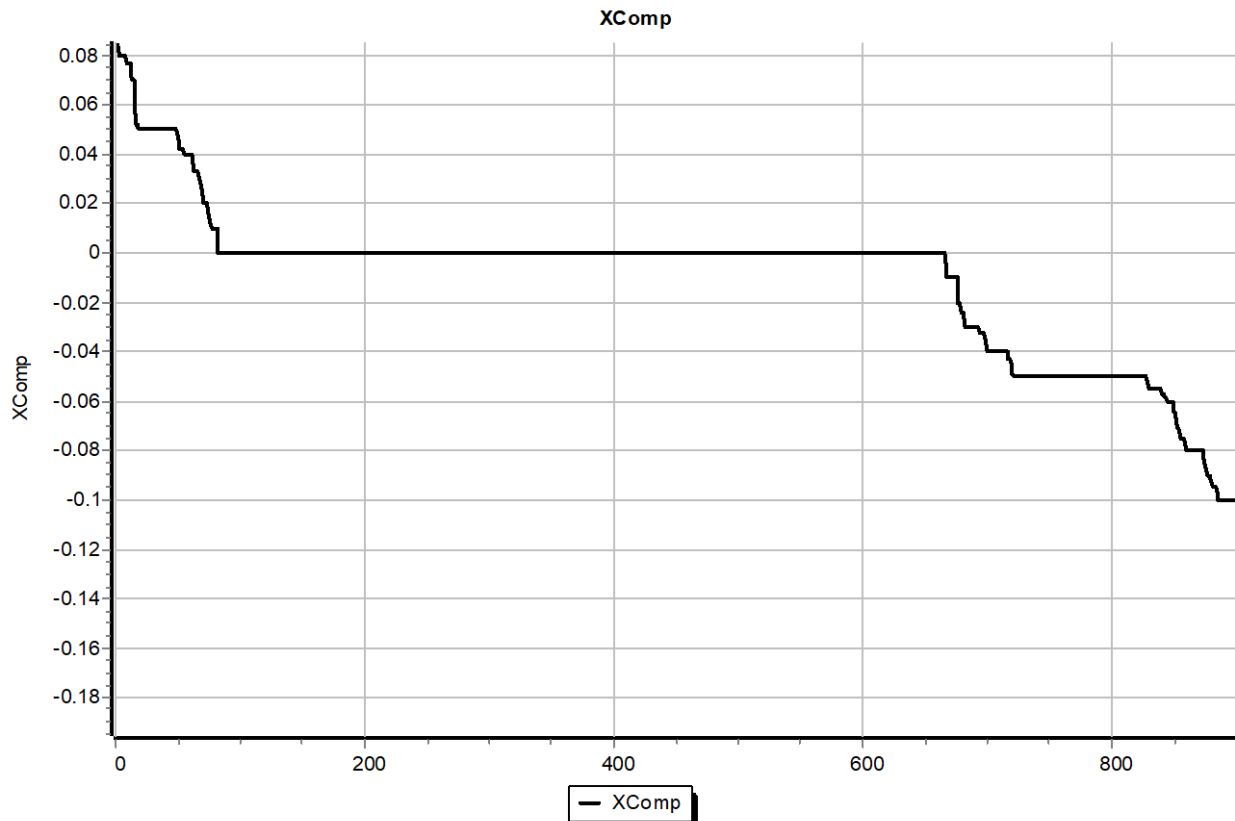
- PSSE requires a separate model with their COMP model also using a negative sign

Compensation



- Using the negative sign convention
 - if X_c is negative then the compensated voltage is within the machine; this is known as droop compensation, which is used reactive power sharing among multiple generators at a bus
 - If X_c is positive then the compensated voltage is partially through the step-up transformer, allowing better voltage stability
 - A nice reference is C.W. Taylor, "Line drop compensation, high side voltage control, secondary voltage control – why not control a generator like a static var compensator," IEEE PES 2000 Summer Meeting

Example Compensation Values



Negative values are within the machine

Graph shows example compensation values for large system; overall about 30% of models use compensation

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

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

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

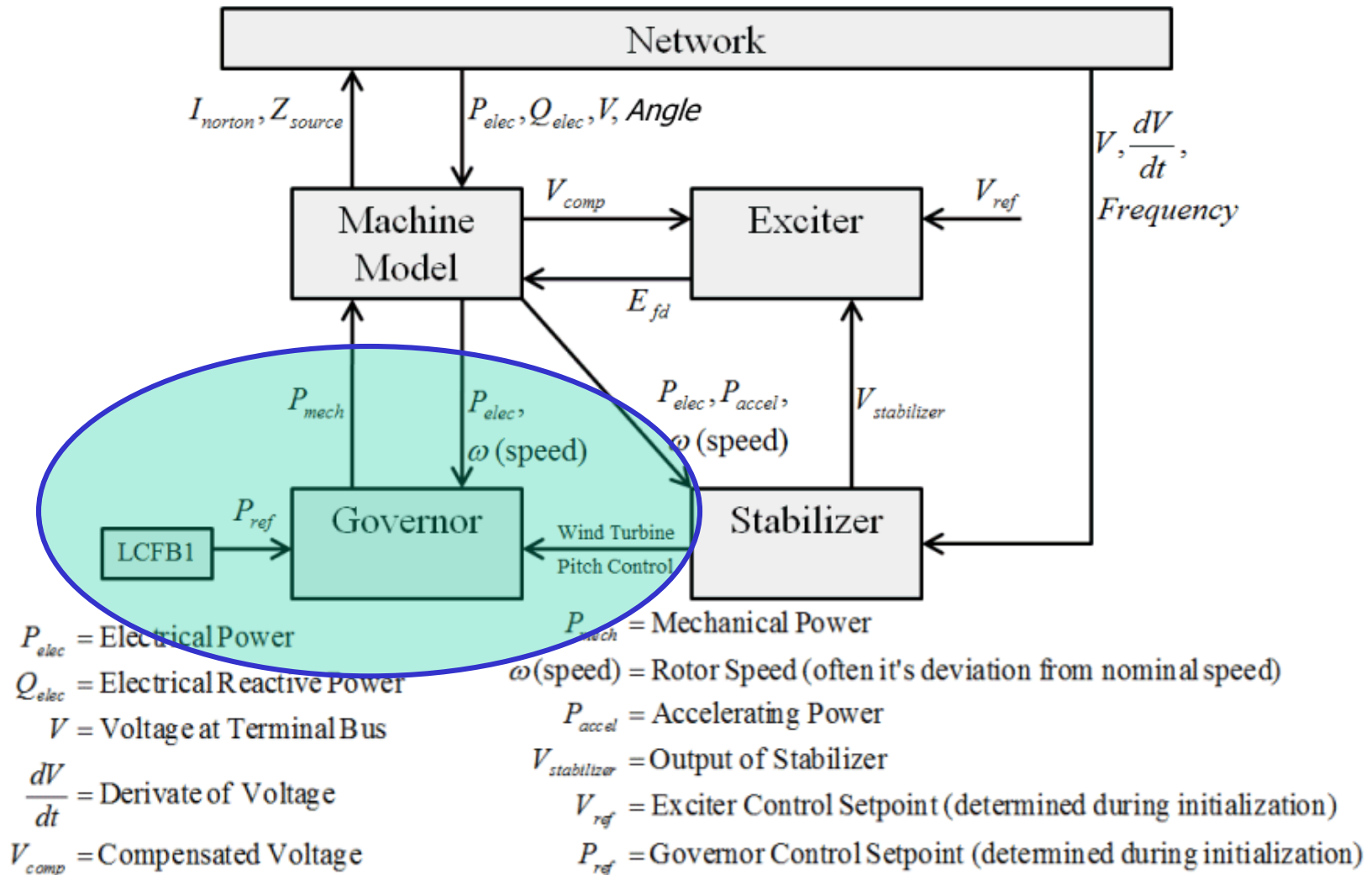
Case is **B4_comp1**

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

Governor Models



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 original 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

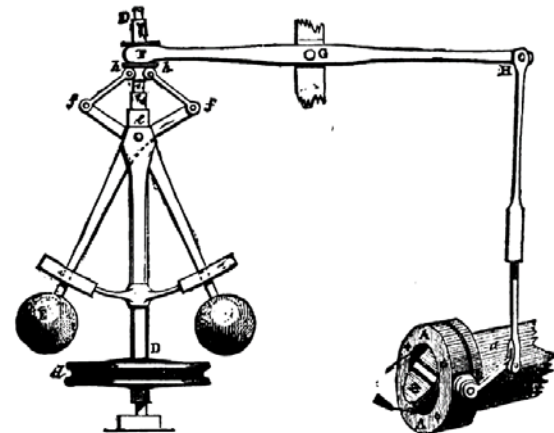


FIG. 4.--Governor and Throttle-Valve.

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

Prime Movers and Governors

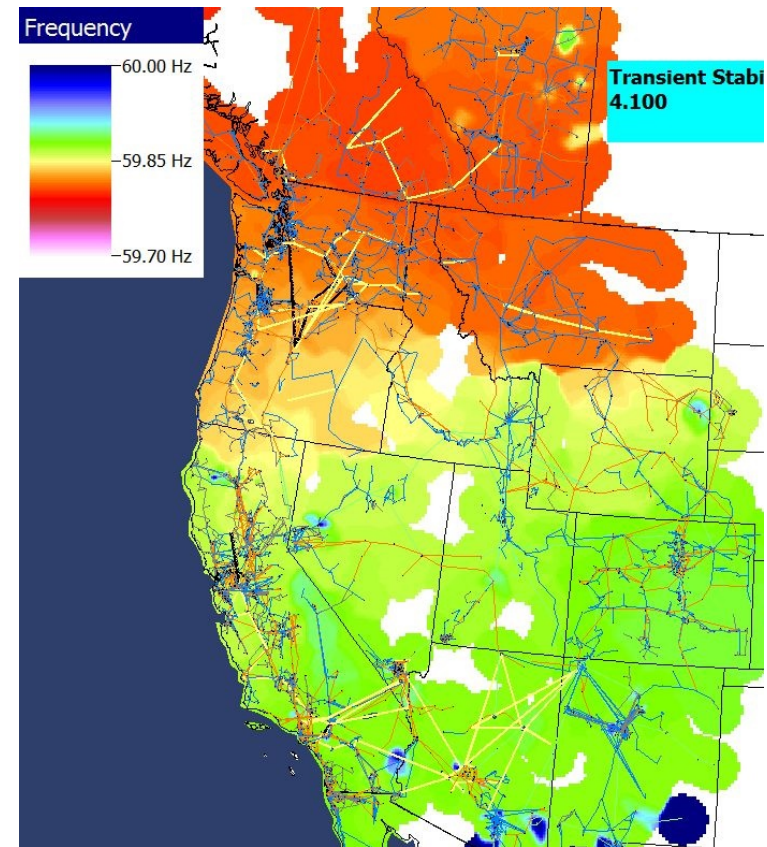
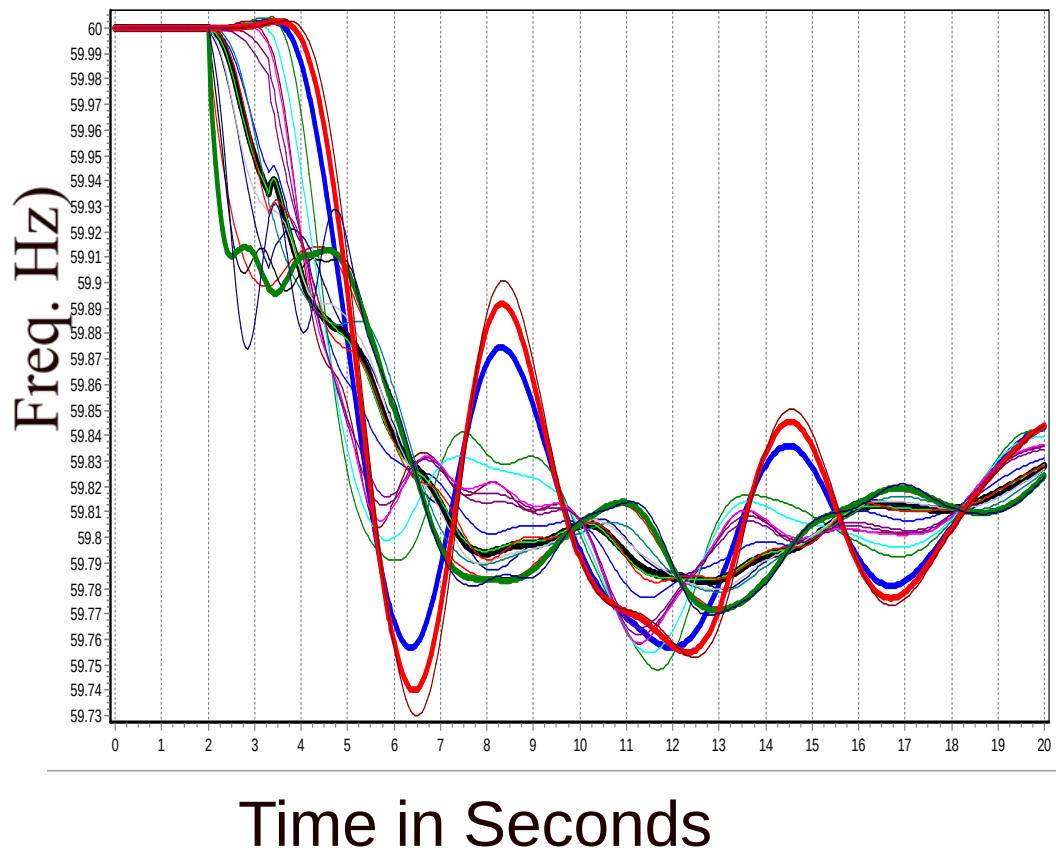


- In transient stability collectively the prime mover and the governor are called the "governor"
- As has been previously discussed, models need to be appropriate for the application
- In transient stability the response of the system for seconds to perhaps minutes is considered
- Long-term dynamics, 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



Frequency Contour

Frequency Response for Generation Loss



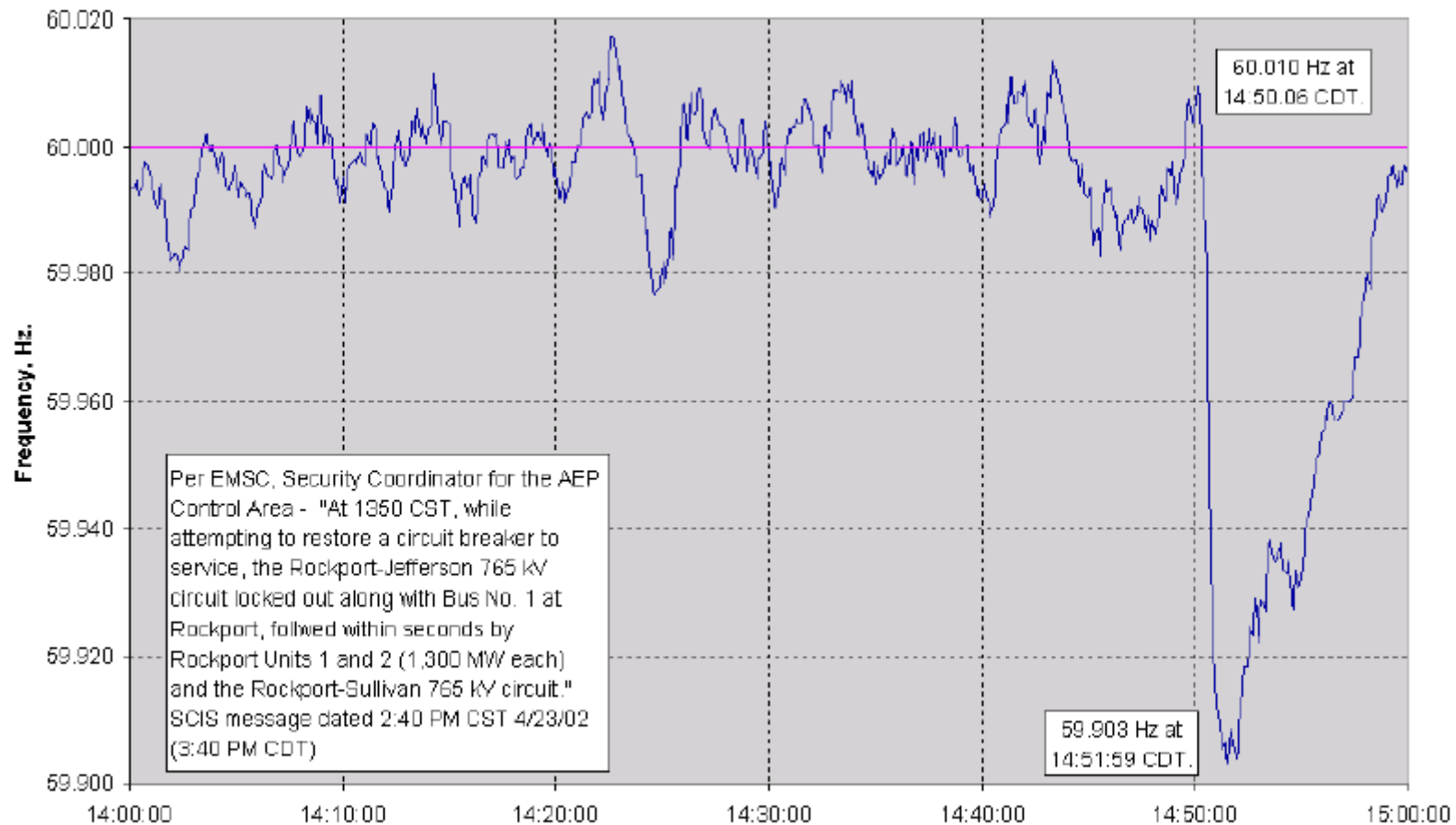
- In response to a rapid loss of generation, in the initial seconds the system frequency will decrease as energy stored in the rotating masses is transformed into electric energy
 - Some generation, such as solar PV has no inertia, and for most new wind turbines the inertia is not seen by the system
- 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

Some Good References



- Kundur, *Power System Stability and Control*, 1994
- Wood, Wollenberg and Sheble, *Power Generation, Operation and Control*, third edition, 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

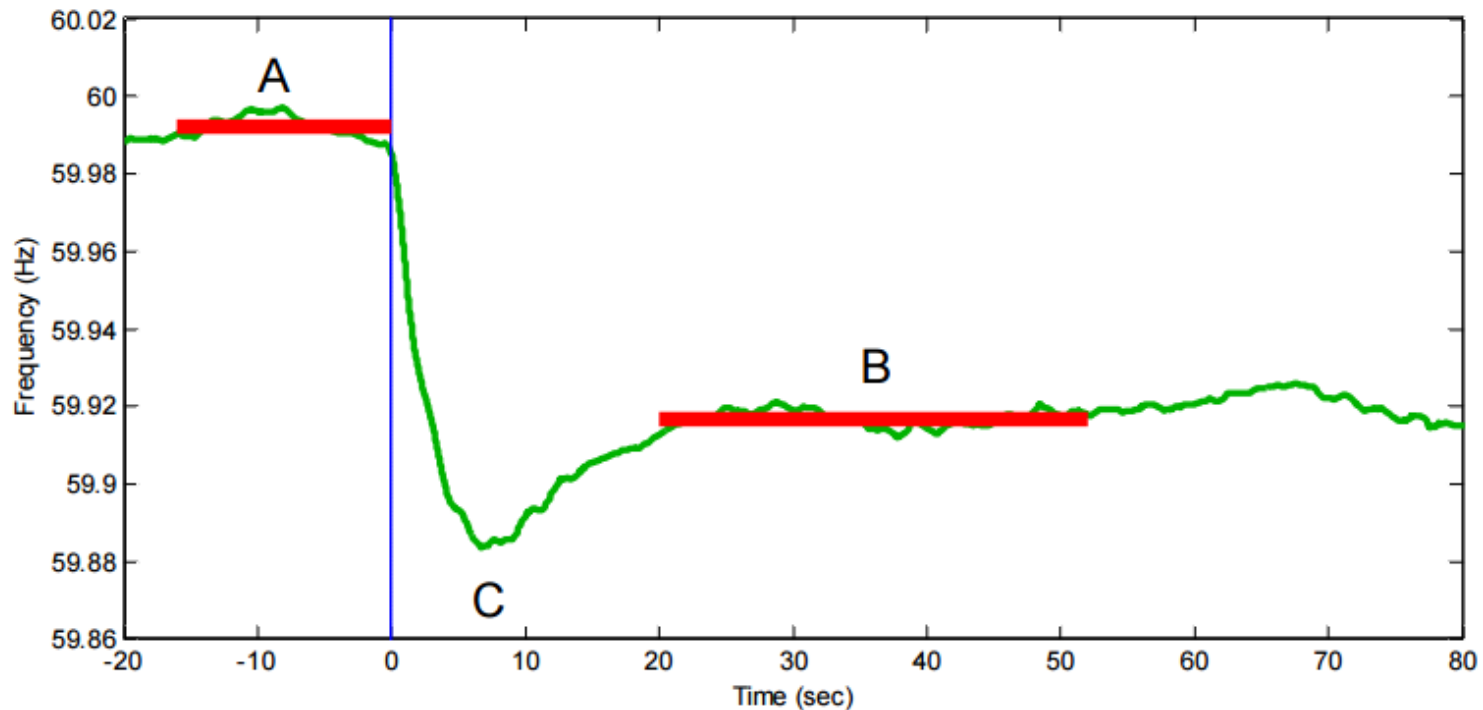
Frequency Response Definition



- 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

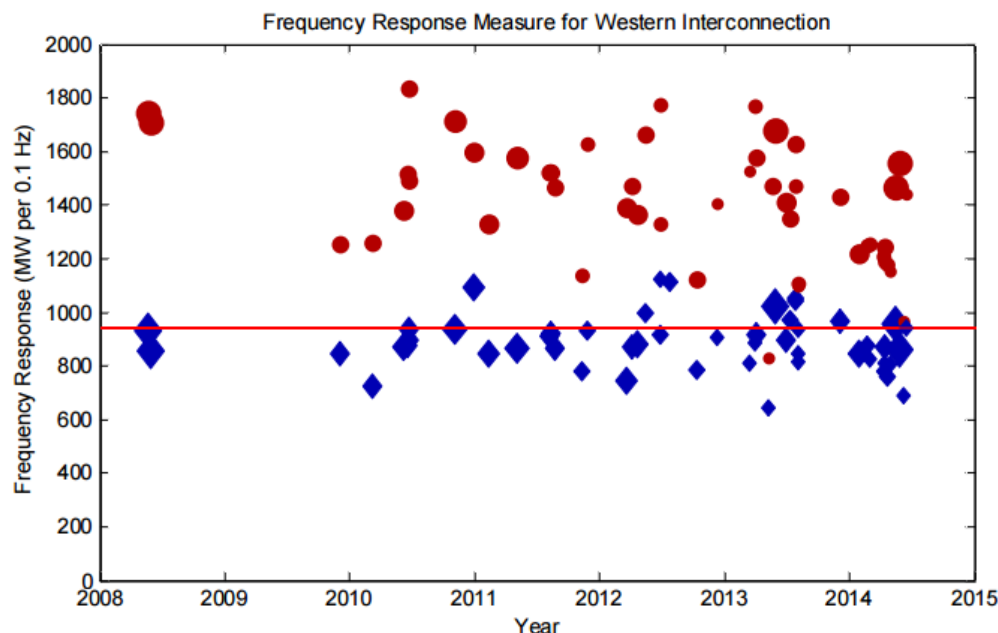
Source: [wecc.biz/Reliability/Frequency%20Response%20Analysis%20-%20Dmitry%20Kosterev.pdf](https://www.wecc.biz/Reliability/Frequency%20Response%20Analysis%20-%20Dmitry%20Kosterev.pdf)

WECC Interconnection Performance



Western Interconnection Performance

WECC IFRO ~950 MW per 0.1 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)

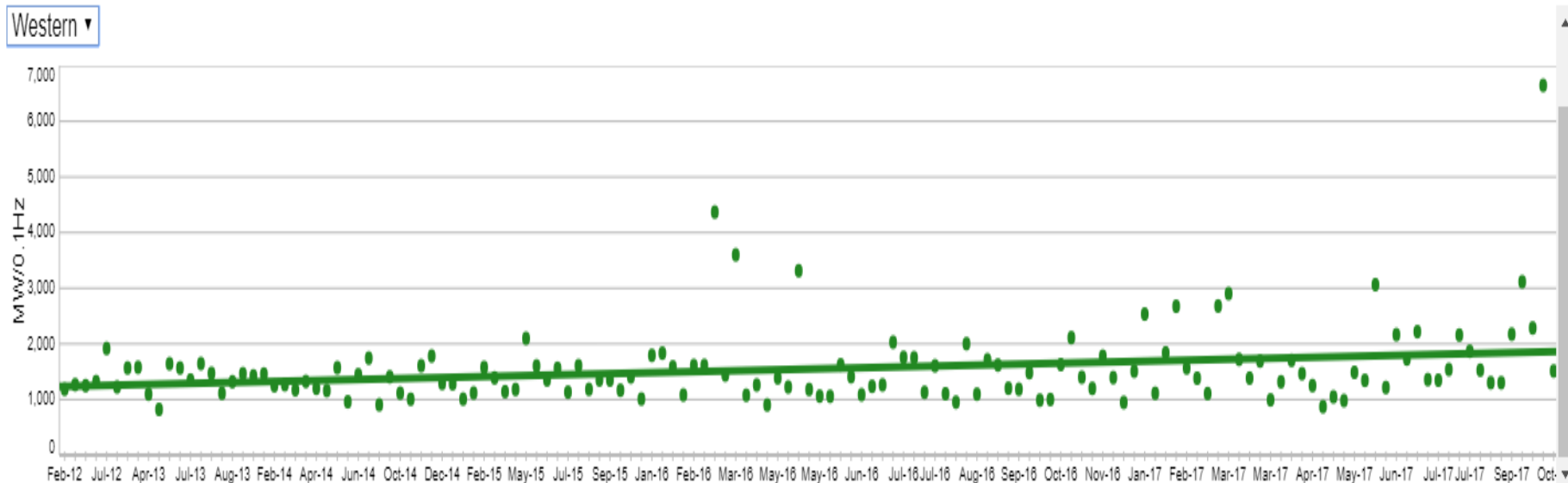
Source: wecc.biz/Reliability/Frequency%20Response%20Analysis%20-%20Dmitry%20Kosterev.pdf

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



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

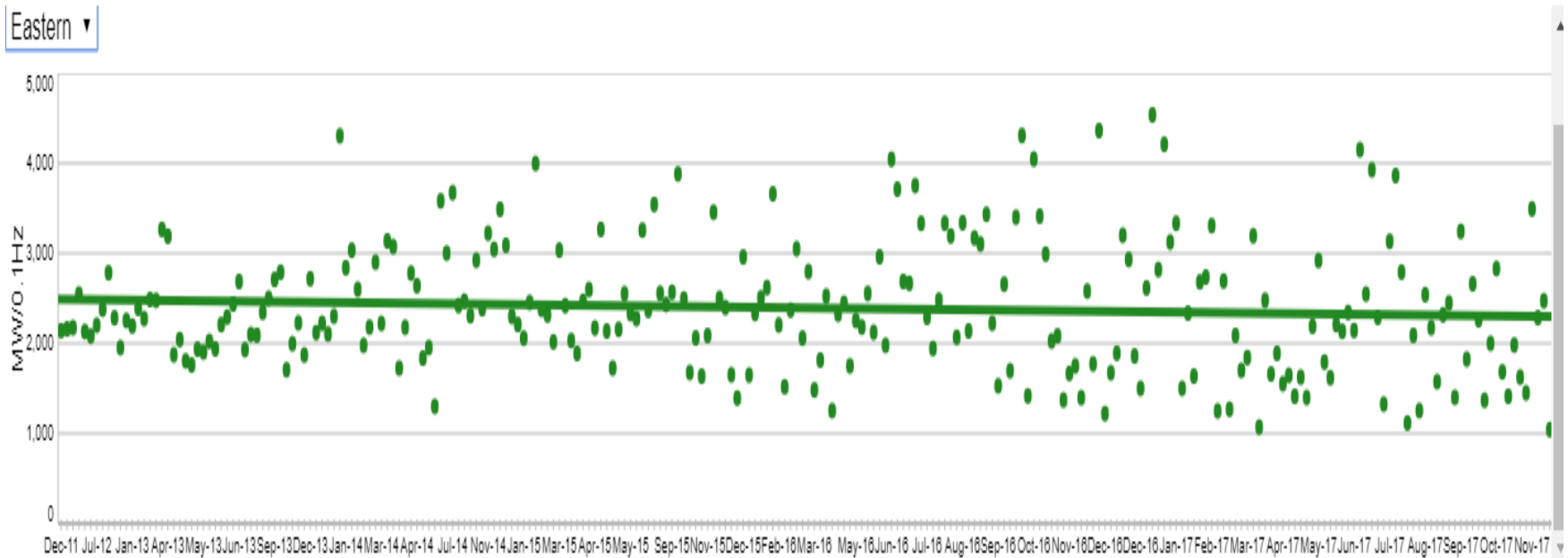
Source:

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

Eastern Interconnect Frequency Response



M-4 Interconnection Frequency Response

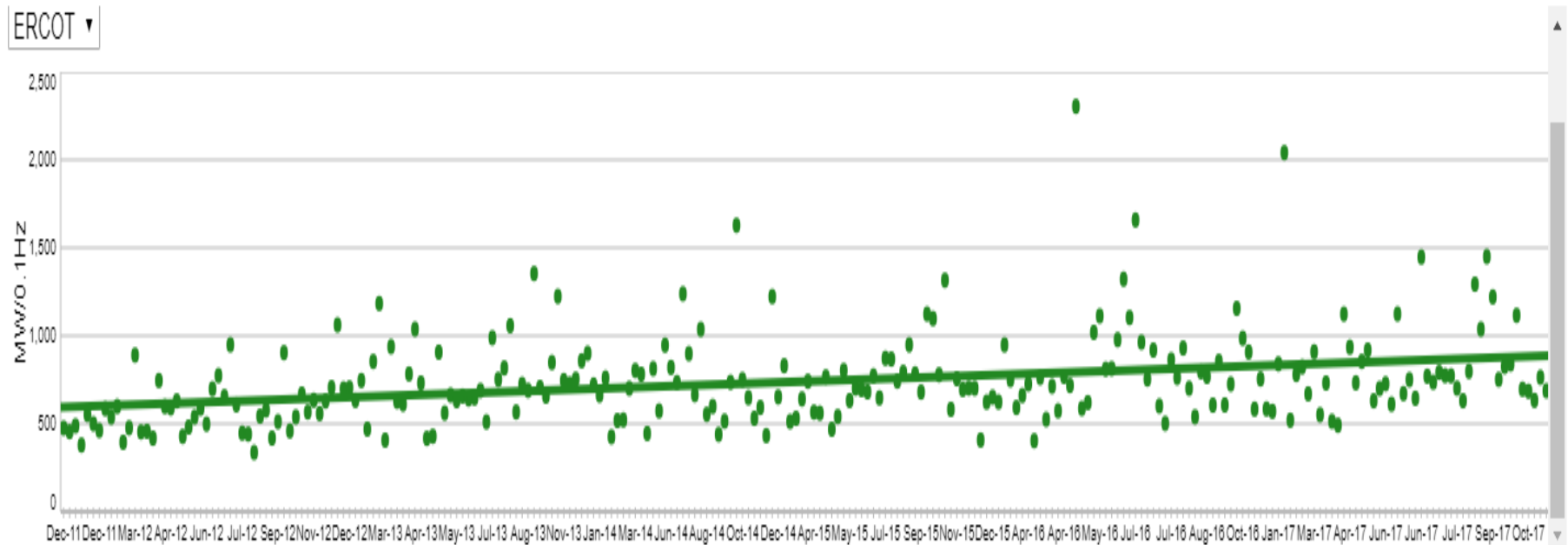


The larger Eastern Interconnect on average has a higher value

ERCOT Interconnect Frequency Response



M-4 Interconnection Frequency Response



An ERCOT a lower value

Source: 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 ensure frequency goes back to the desired value
 - Cannot be used with interconnected systems because of "hunting"

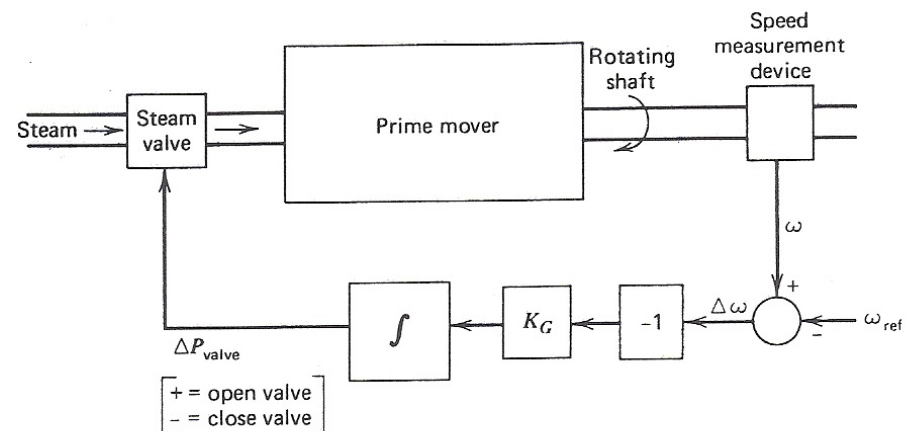


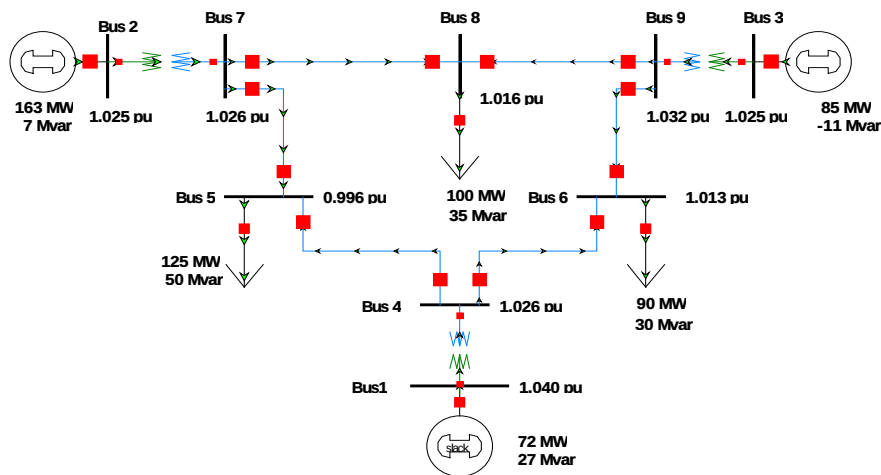
FIG. 9.9 Isochronous governor.

Image source: Wood/Wollenberg, 2nd edition

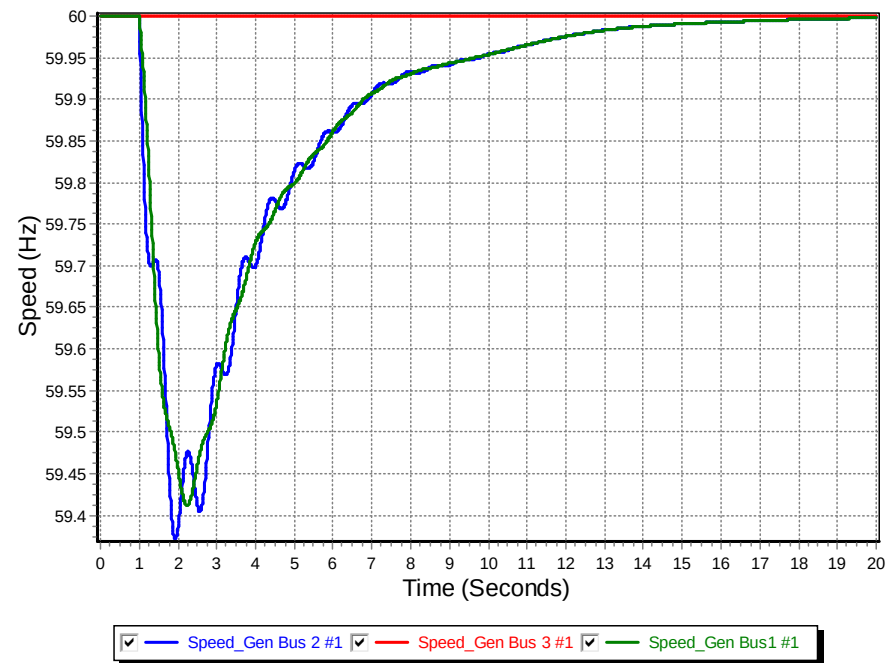
Isochronous Gen Example



- WSCC 9 bus from before, gen 3 dropping (85 MW)



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

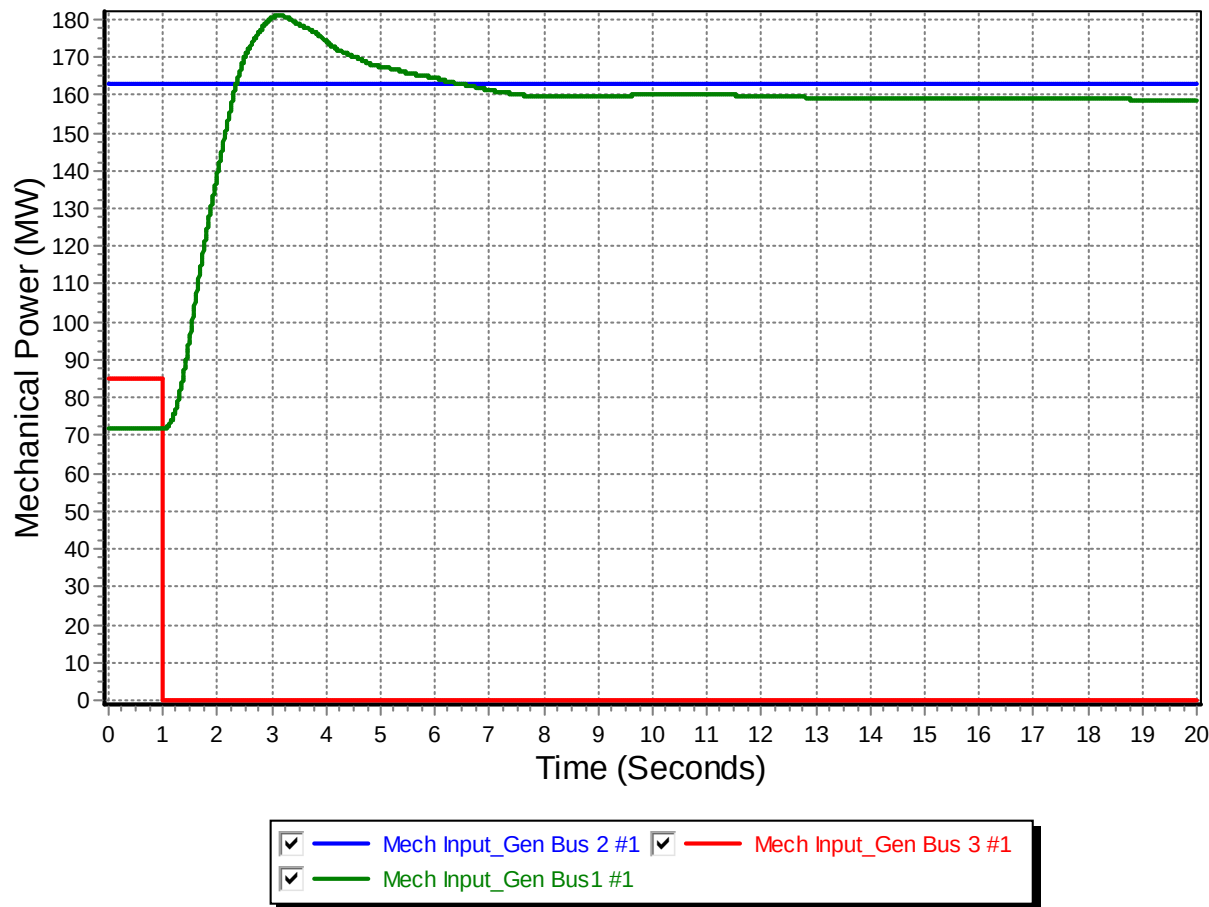


Case is wsc9bus_IsoGov

Isochronous Gen Example



- Graph shows the change in the mechanical output



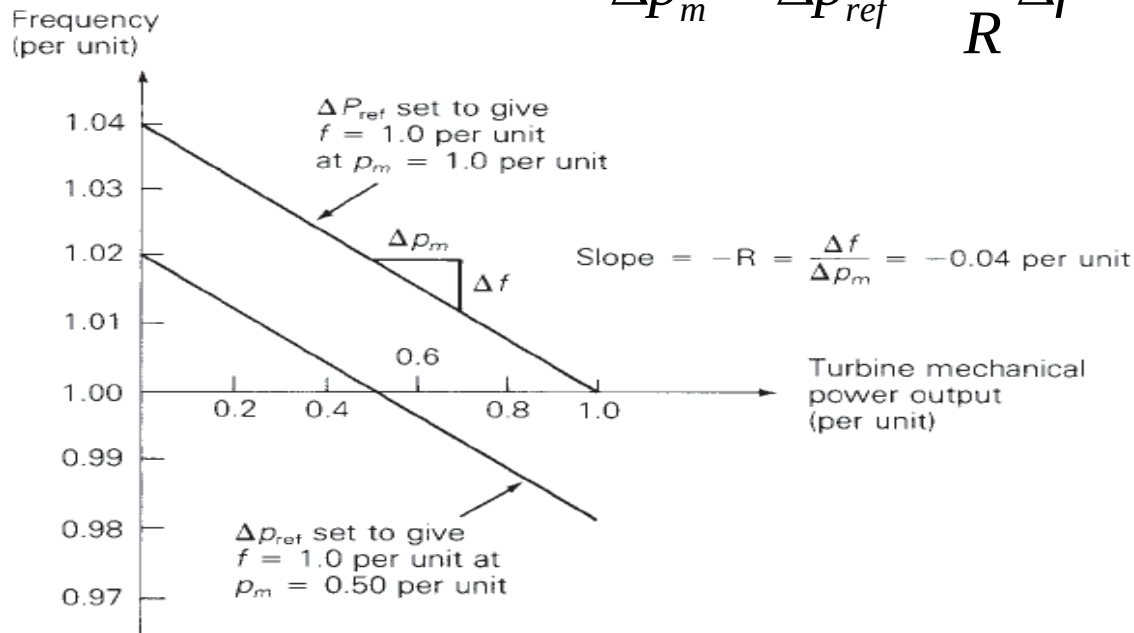
All the change in MWs due to the loss of gen 3 is being picked up by gen 1

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 $0.1/(60 \times 0.05) = 3.33\%$

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)

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

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

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

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

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 generator group obviously does not include the contingency generator(s) that are opened

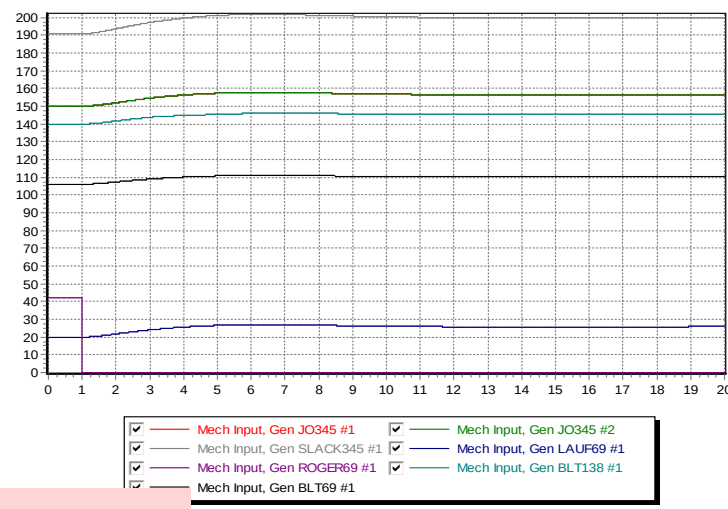
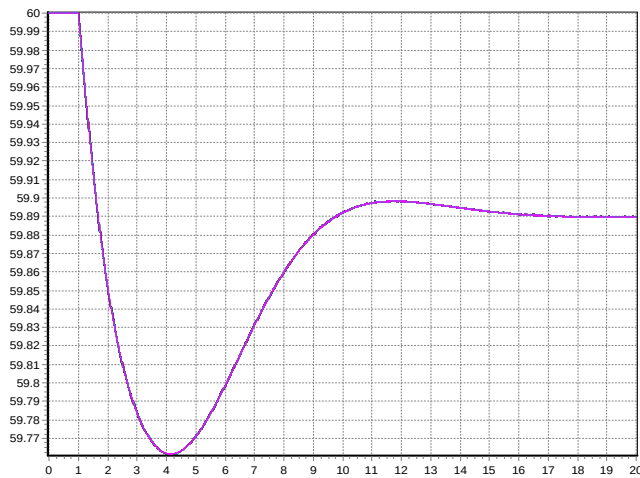
- The online generator summation should only include generators that actually have governors that can respond, and does not take into account generators hitting their limits

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 $R=0.05$

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

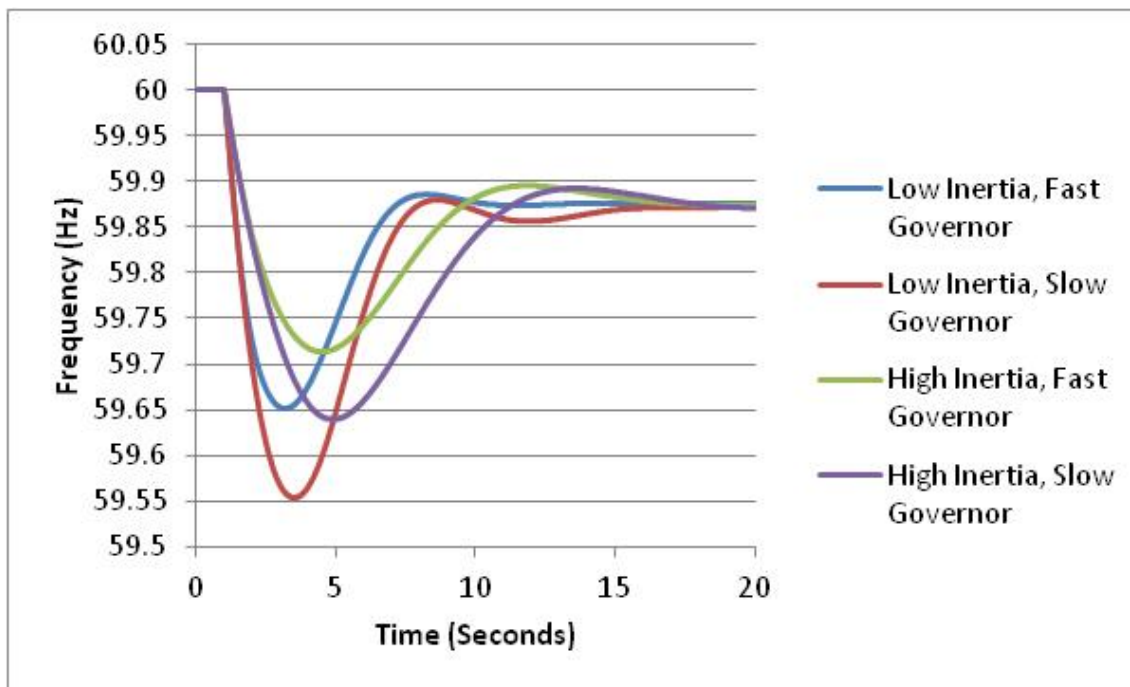


Case is Bus37_TGOV1

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



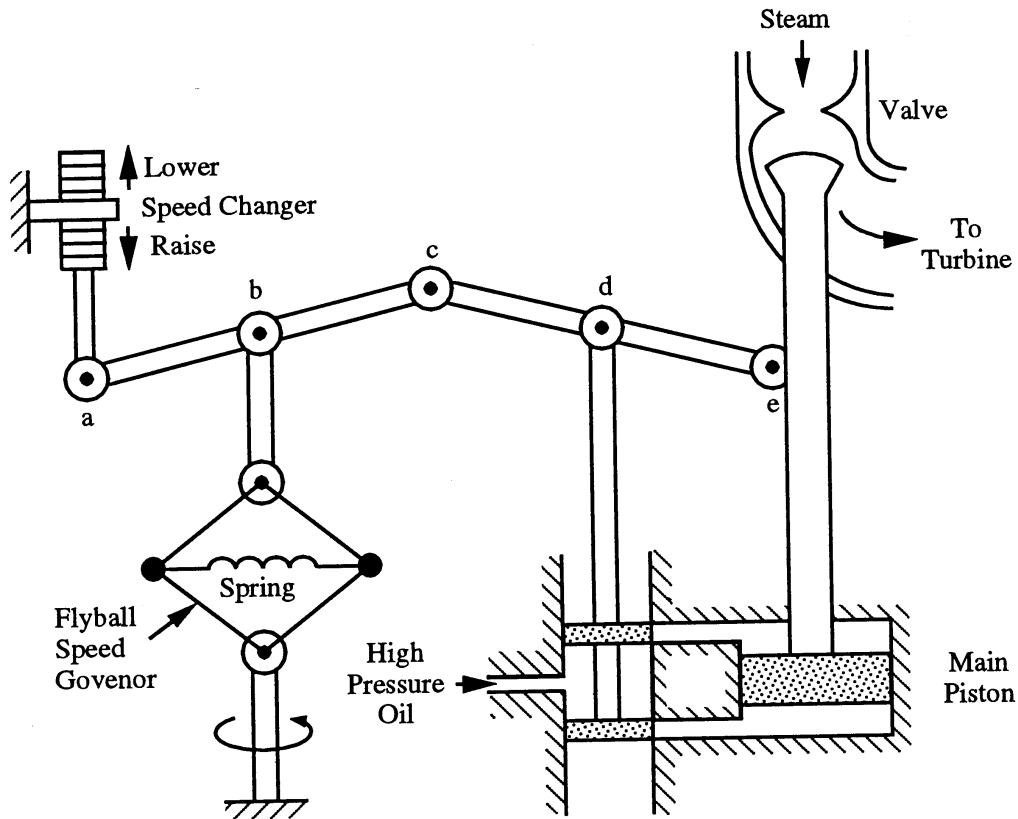
- In an interconnected power system the governors to not automatically restore the frequency to 60 Hz
- Rather done via the ACE (area control area calculation). Previously we defined ACE as the difference between the actual real power exports from an area and the scheduled exports. But it has an additional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

$$ACE = P_{\text{actual}} - P_{\text{sched}} - 10\beta(\text{freq}_{\text{act}} - \text{freq}_{\text{sched}})$$

- 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

This slower ACE response is usually not modeled in transient stability

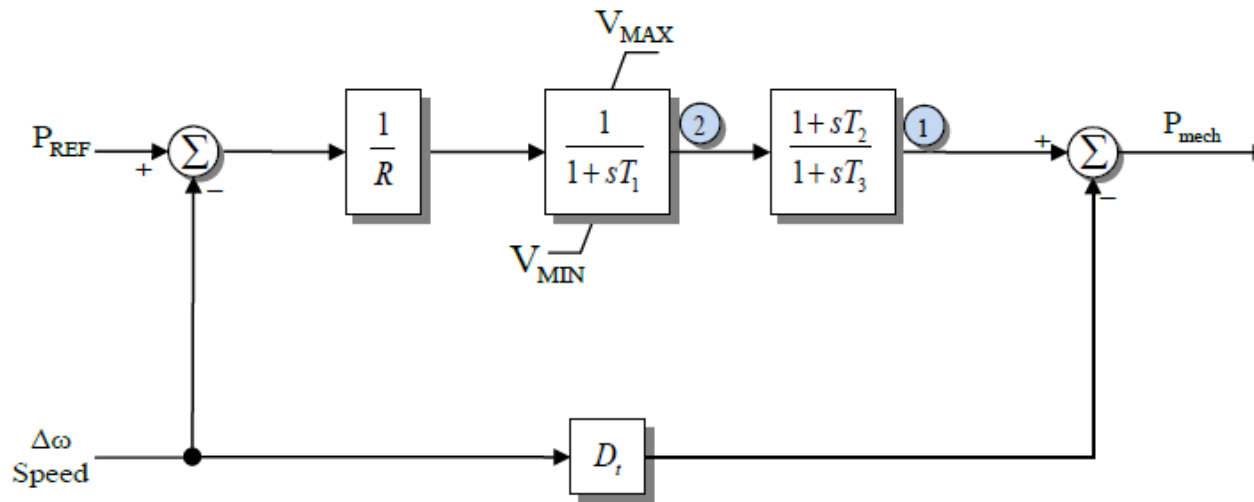
Steam Governor Model



TGOV1 Model



- A simple turbine/governor model is TGOV1

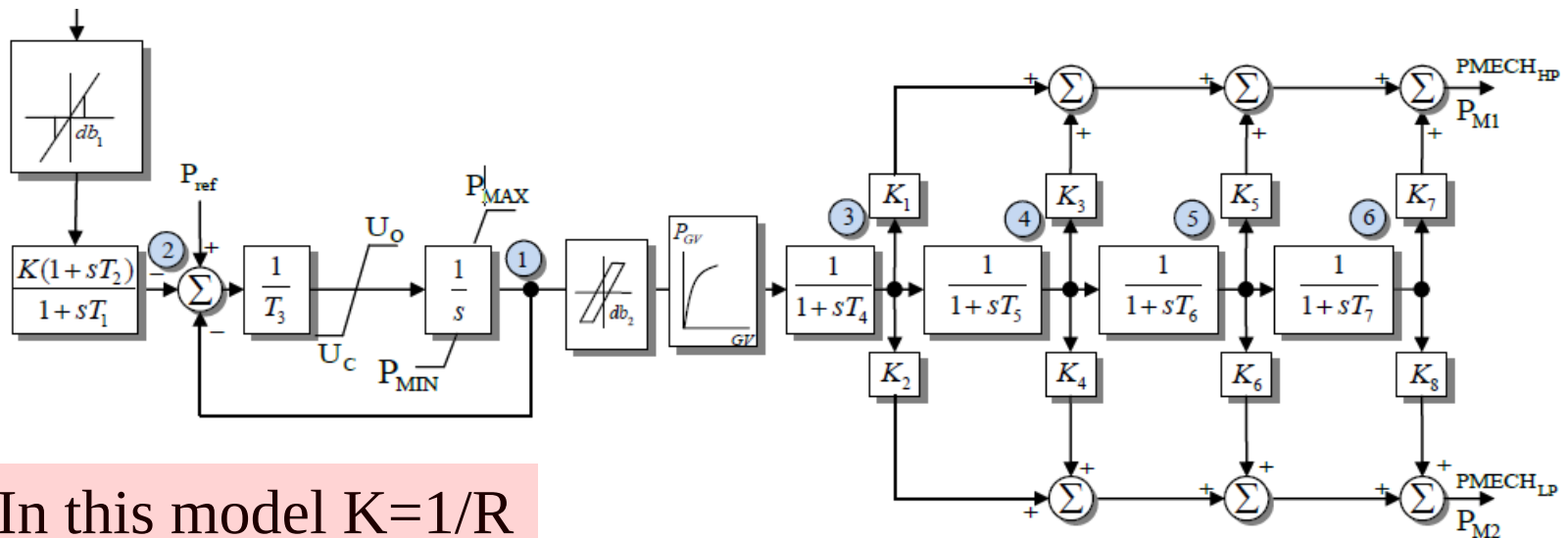


About 12% of governors in a 2015 EI model are TGOV1; $R = 0.05$, T_1 is less than 0.5 (except a few 999's!), T_3 has an average of 7, average T_2/T_3 is 0.34; D_t is used to model turbine damping and is often zero (about 80% of time in EI)

IEEEG1 Model



- A common steam 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

IEEEG1



- Blocks on the right model the various steam stages
- About 12% of WECC and EI governors are

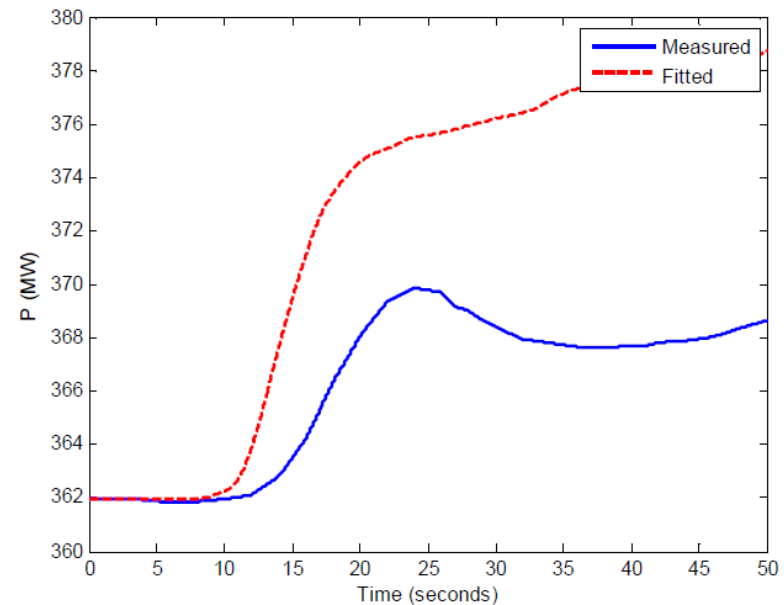
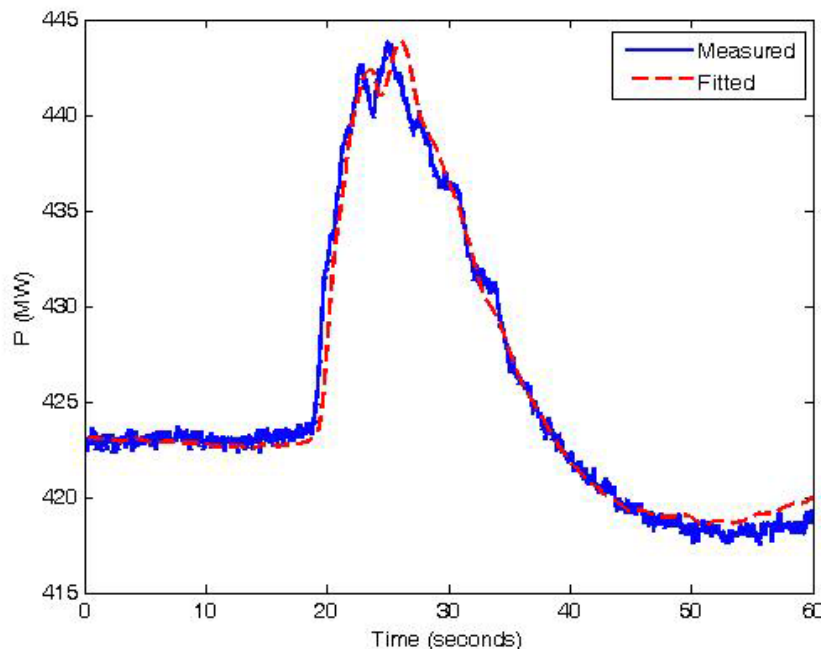
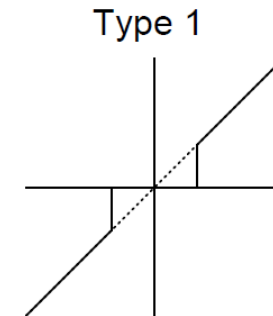


Image Source: Figs 2-4, 2-6 of IEEE PES, "Dynamic Models for Turbine-Governors in Power System Studies," Jan 2013

Deadbands



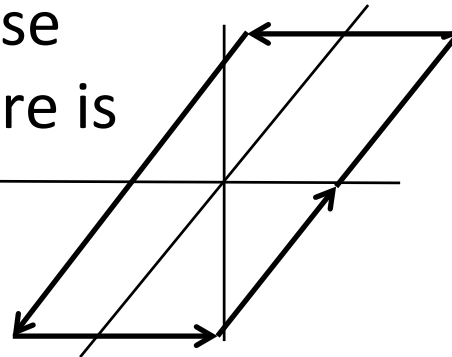
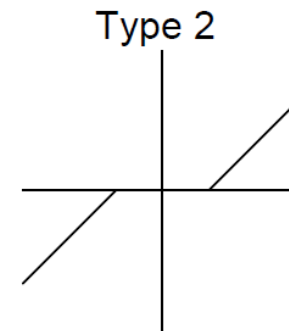
- Before going further, it is useful to briefly consider deadbands, with two types shown with IEEE1 and described in the 2013 IEEE PES Governor Report
- The type 1 is an intentional deadband, implemented to prevent excessive response
 - Until the deadband activates there is no response, then normal response 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 IEEE1



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 r
- Another type of deadband is t unintentional, such as will occ 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
- The maximum droop setting is 5% for all units except it is 4% for combined cycle combustion turbines

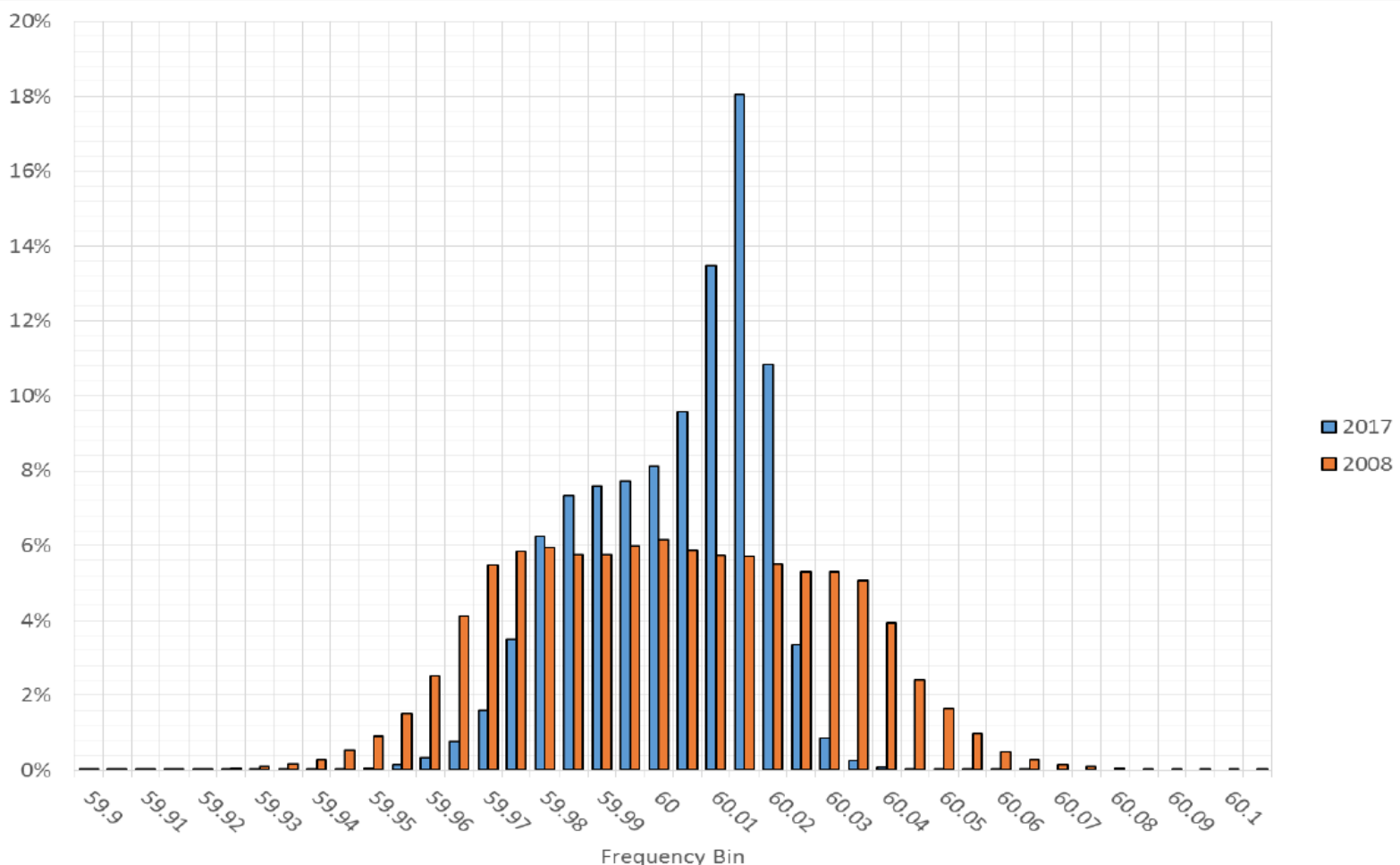
Source: NERC BAL-001-TRE-1 and ERCOT, Demonstration of PFR Improvement,

ERCOT Operations Planning, Sept. 2017 presentation

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



Comparing 2017 vs 2008 Frequency Profile in 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

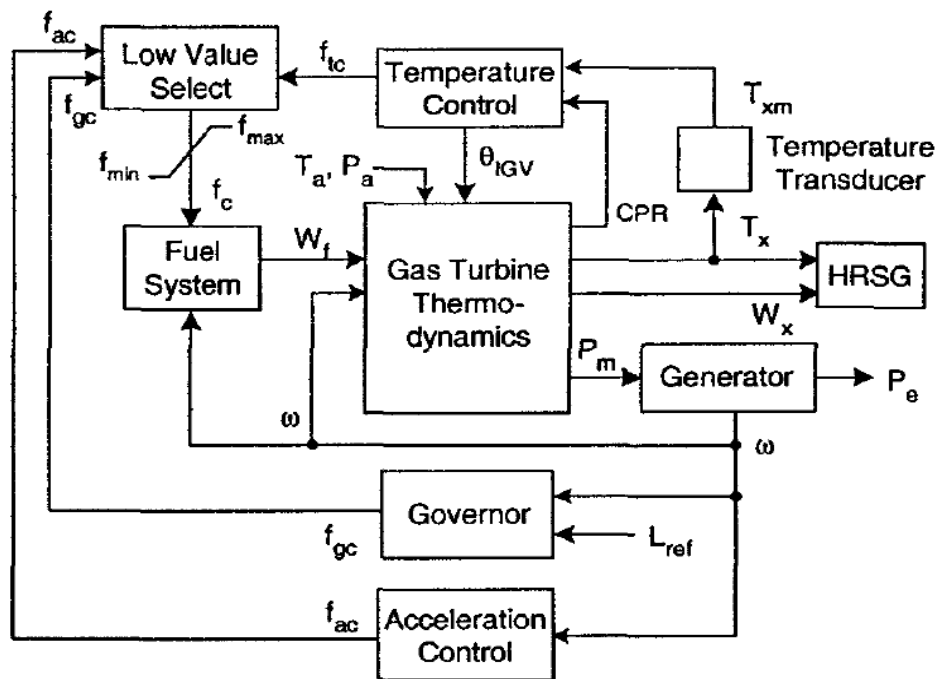


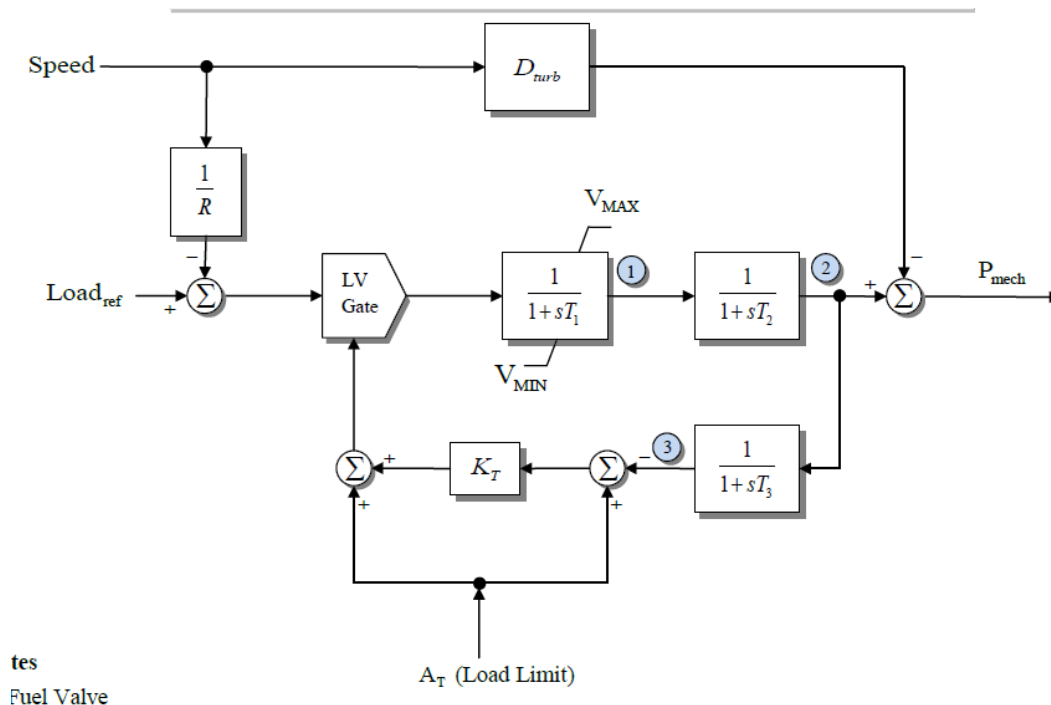
Figure 3-3: Gas turbine controls [17] (IEEE© 2001).

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



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 (A_t); T_3 is the delay in measuring the exhaust temperature

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

Generator Information for Current Case

Bus Number: 2 (Find By Number) | Bus Name: Bus 2 (Find By Name) | ID: 1 (Find ...)

Area Name: Home (1) | Labels: no labels | Generator MVA Base: 100.00

Status: ☐ Open, ☒ Closed | Energized: ☐ NO (Offline), ☒ YES (Online)

Fuel Type: Unknown | Unit Type: UN (Unknown)

Machine Models: Exciters, Governors, Stabilizers, Other Models, Step-up Transformer, Terminal and State

Type: Active - InfiniteBusSignalGe (Active (only one may be active)) | Set to Defaults

Parameters: PU values shown/entered using device base of 100.0 MVA

Parameter	Value	Parameter	Value	Parameter	Value
DoRamp	0	Speed Delta(Hz) 2	0.0000	Volt Freq(Hz) 4	0.0000
Start Time, Sec	1.0000	Speed Freq(Hz) 2	0.0000	Speed Delta(Hz) 4	0.0000
Volt Delta(PU) 1	0.0500	Duration (Sec) 2	4.0000	Speed Freq(Hz) 4	0.0000
Volt Freq(Hz) 1	0.0000	Volt Delta(PU) 3	0.0000	Duration (Sec) 4	0.0000
Speed Delta(Hz) 1	0.0000	Volt Freq(Hz) 3	0.0000	Volt Delta(PU) 5	0.0000
Speed Freq(Hz) 1	0.0000	Speed Delta(Hz) 3	0.0000	Volt Freq(Hz) 5	0.0000
Duration (Sec) 1	4.0000	Speed Freq(Hz) 3	0.0000	Speed Delta(Hz) 5	0.0000
Volt Delta(PU) 2	-0.0500	Duration (Sec) 3	0.0000	Speed Freq(Hz) 5	0.0000
Volt Freq(Hz) 2	0.0000	Volt Delta(PU) 4	0.0000	Duration (Sec) 5	0.0000

Buttons: OK, Save, Cancel, Help, Print

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)

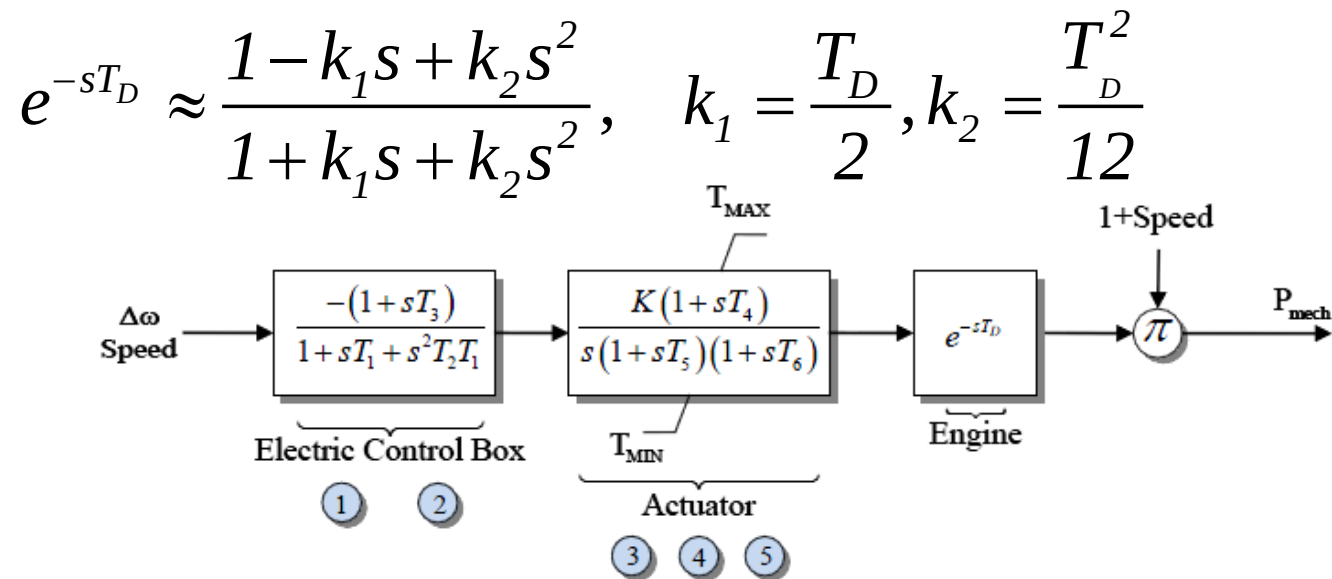
Speed Delta is the magnitude of the frequency deviation in Hz; **Speed Freq** is the frequency of the frequency deviation

Duration is the time in seconds for the time period

Simple Diesel Model: DEGOV



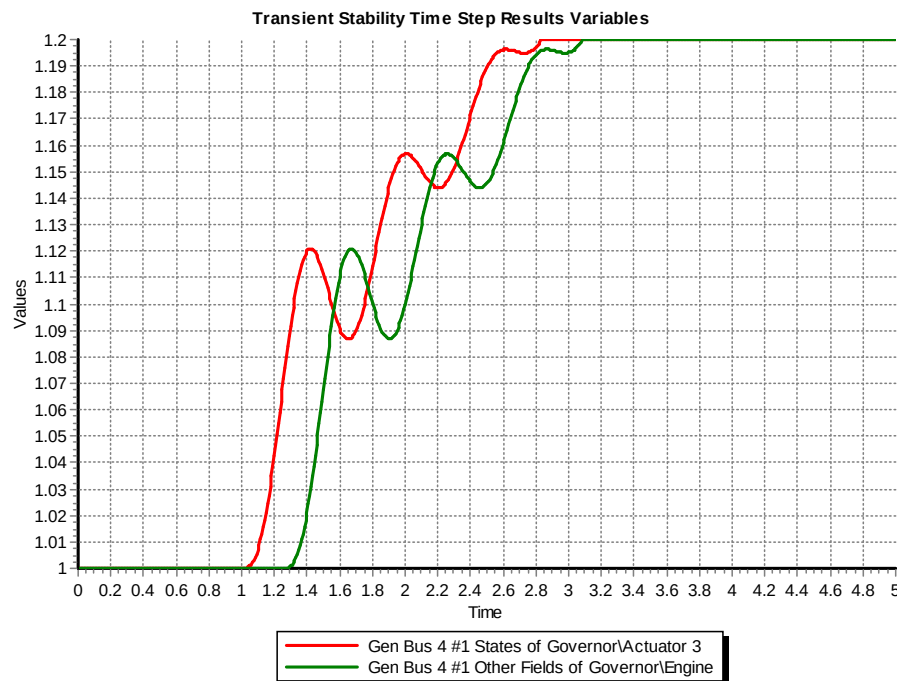
- Sometimes models implement time delays (DEGOV)
 - Often delay values are set to zero
- Delays can be implemented either by saving the input value or by using a Pade approximation, with a 2nd order given below; a 4th order is also common



DEGOV Delay Approximation



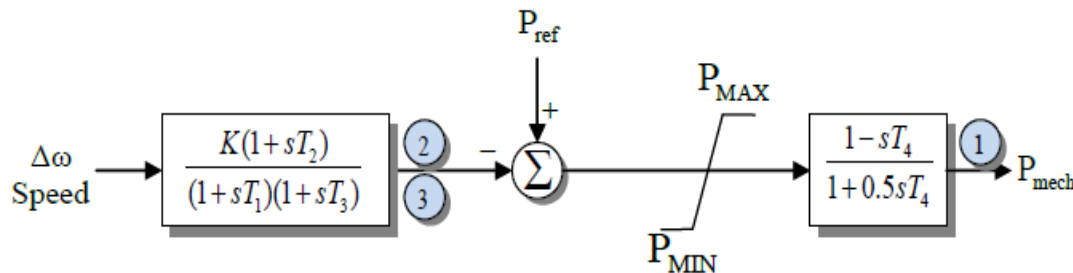
- With TD set to 0.5 seconds (which is longer than the normal of about 0.05 seconds in order to illustrate the delay)



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 IEEE2 and IEEE3 models just gave the linear response; now considered obsolete
- Below is the IEEE2; left side is the governor, right side is the turbine and water column

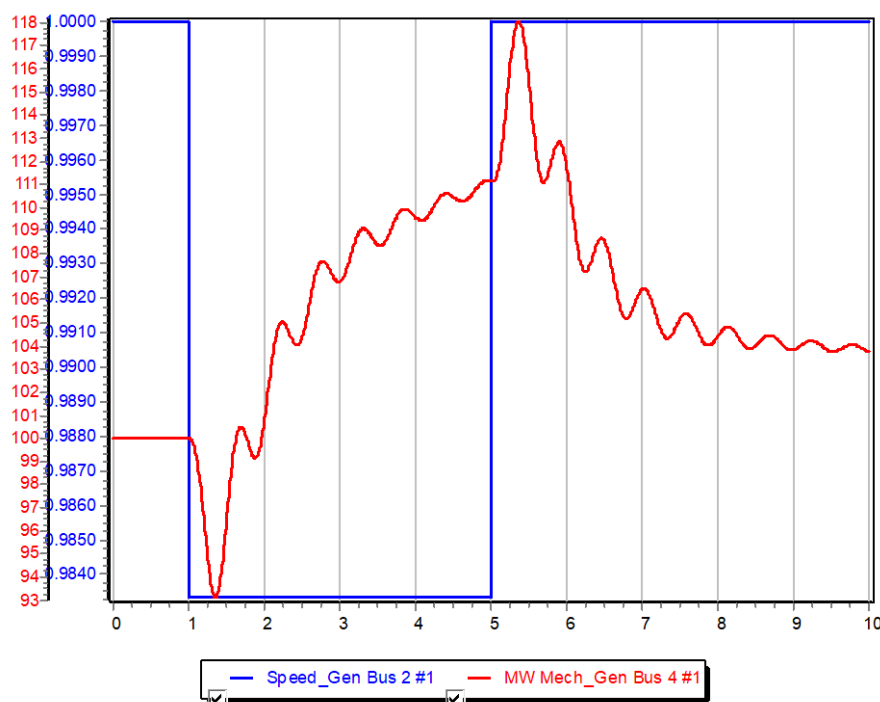


For sudden changes there is actually an inverse change in the output power

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

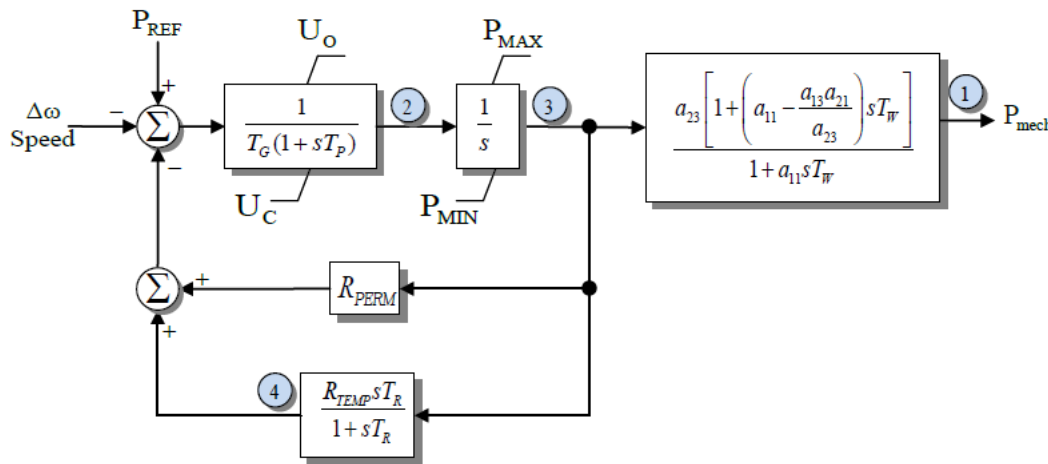
$$\frac{sT_w}{1 + sT_w}$$

- 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 Kundur (1994) the transient droop should be tuned so

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

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

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

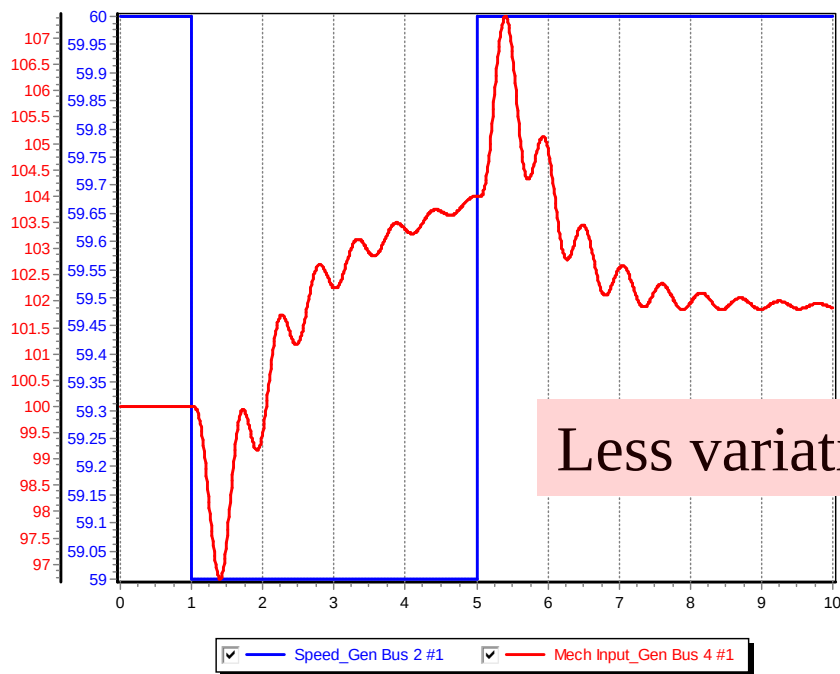
In comparing an average H is about 4 seconds, so T_M is 8 seconds, an average T_W is about 1.3, giving an calculated average R_{TEMP} of 0.37 and T_R of 6.3; the actual averages in a WECC case are 0.46 and 6.15. So on average this is pretty good! R_{perm} is 0.05

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

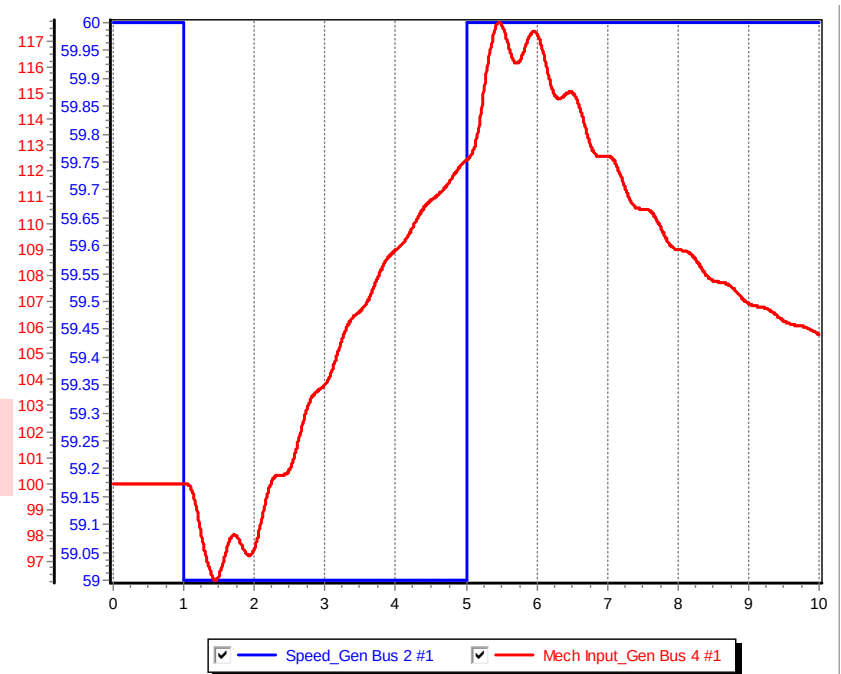
IEEEG3 Four Bus Frequency Change



- The two graphs compare the case response for the frequency change with different RTEMP values



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



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

Case name: **B4_SignalGen_IEEEG3**

Basic Nonlinear Hydro Turbine Model



- Basic hydro system is shown below
 - Hydro turbines work by 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 $A \cdot U = Q$;

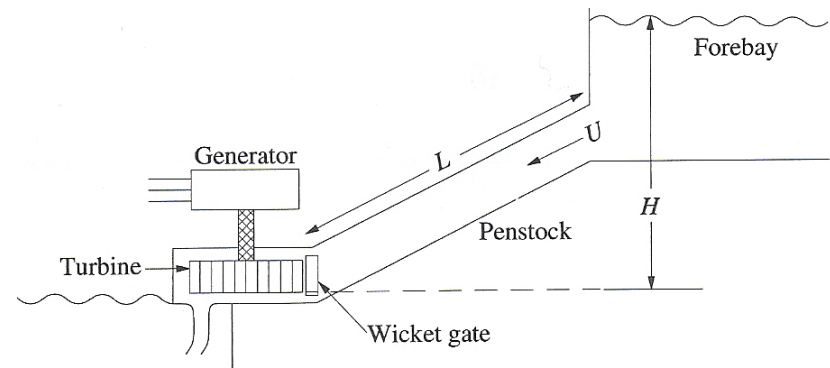


Figure 9.2 Schematic of a hydroelectric plant

Basic Nonlinear Hydro Turbine Model



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

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

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) and H_{loss} is the head loss due to friction in the penstock

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

$$\frac{dq}{dt} = \frac{(1 - h_{gate} - h_{loss})}{T_w}$$

T_w is called the water time constant, or water starting time

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

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

- About
6% of
WECC
governors
use this
model;
average
 T_w is
2 seconds

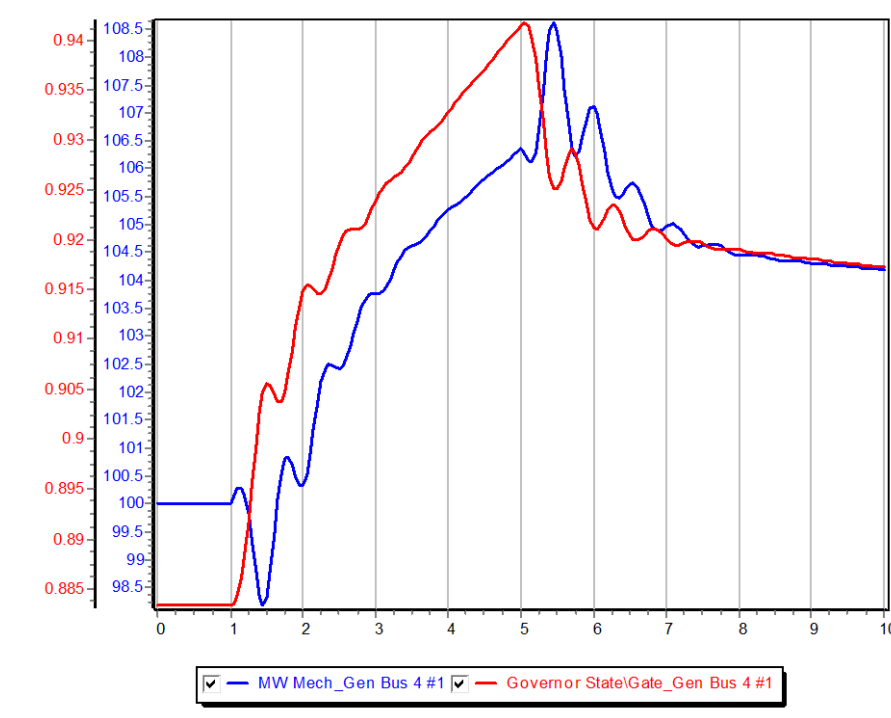


The gate position (gv) to gate power (pgv) is sometimes represented with a nonlinear curve

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

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

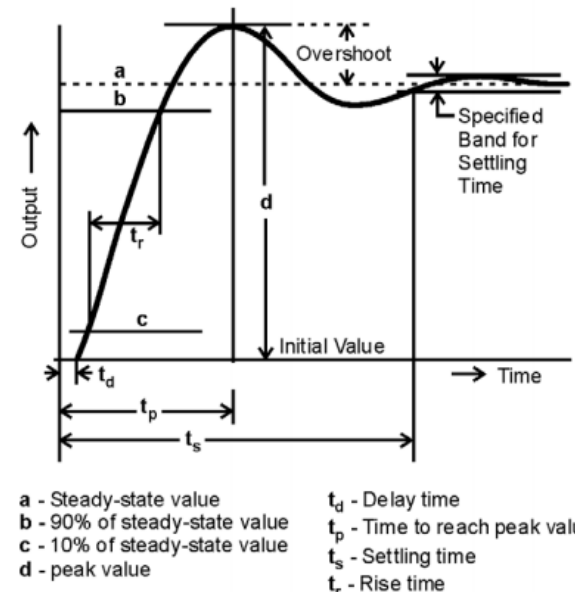


Figure F.1—Typical dynamic response of a turbine governing system to a step change

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

PID Example: Car Cruise Control

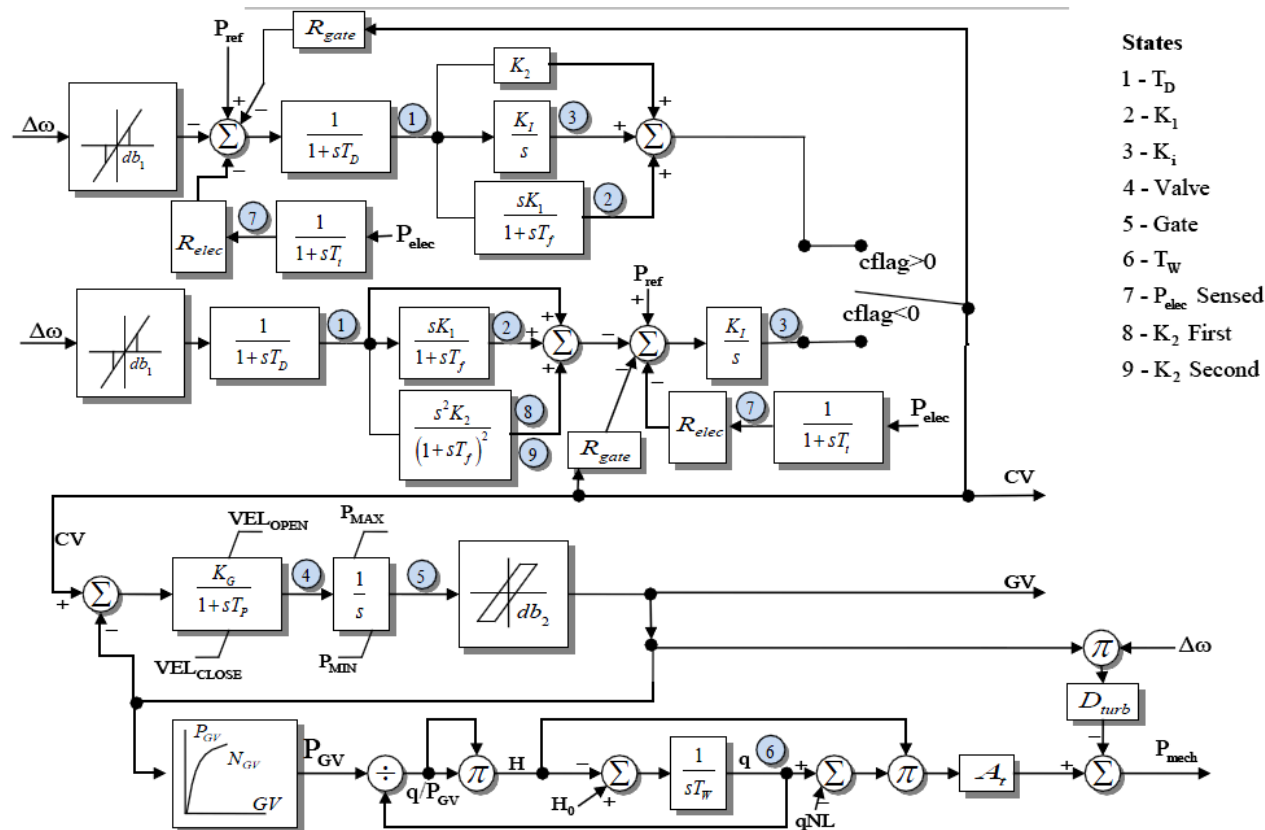


- Say we wish to implement cruise control on a car by controlling the throttle position
 - Assume force is proportional to throttle position
 - Error is difference between actual speed and desired speed
- With just proportional control we would never achieve the desired speed because with zero error 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

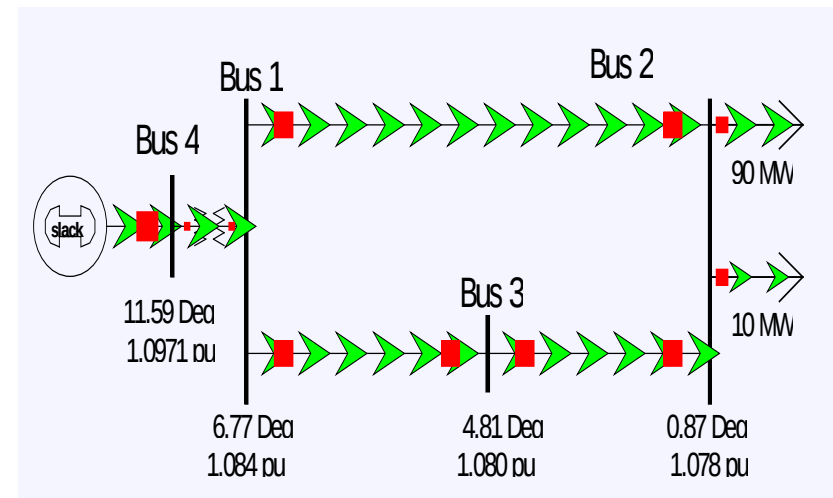
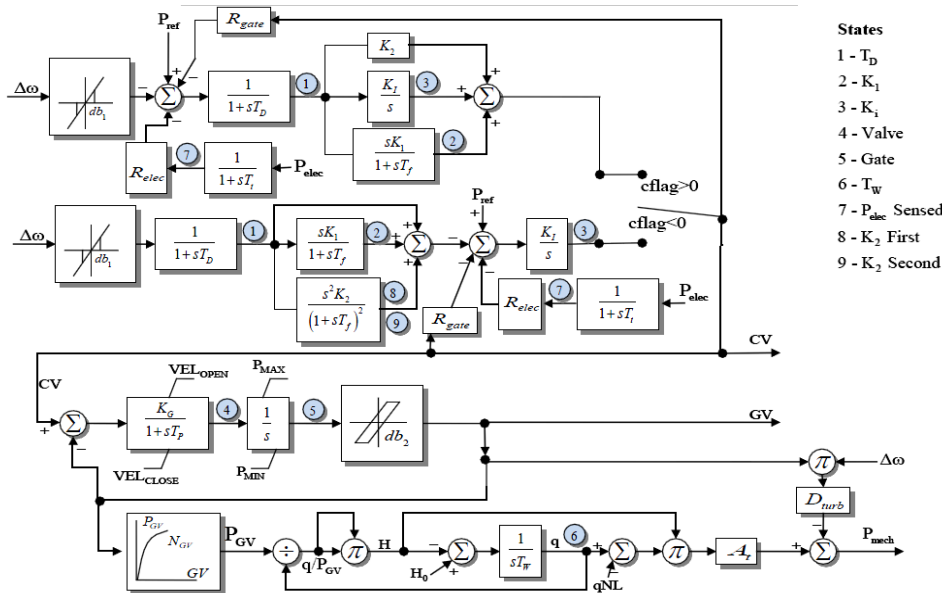


- Tuning PID controllers can be difficult, and there is no single best method
 - Conceptually simple since there are just three parameters, but there can be conflicting objectives (rise time, overshoot, setting time, error)
- One common approach is the Ziegler-Nichols method
 - First set K_I and K_D 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 $K_p=0.6 K_u$, $K_I=2 * K_p/T_u$, $K_D=K_p T_u/8$

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_1 , K_1 in the model; assume $T_f=0.1$)

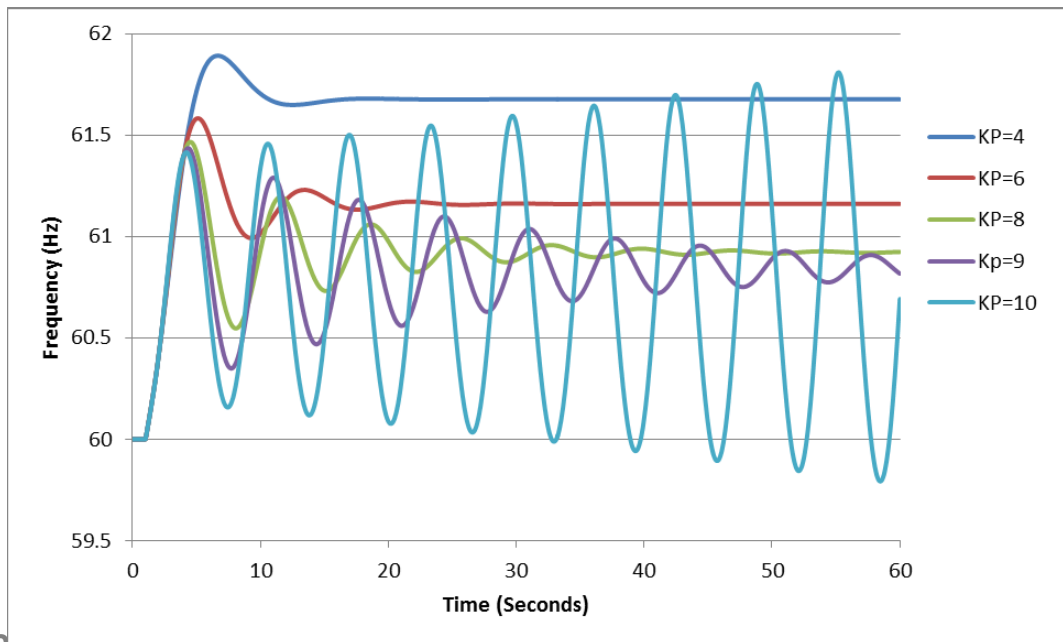


Case name: **B4_PIDTuning**

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 $K_p = 5.7$, $K_i = 1.78$, $K_D = 4.56$

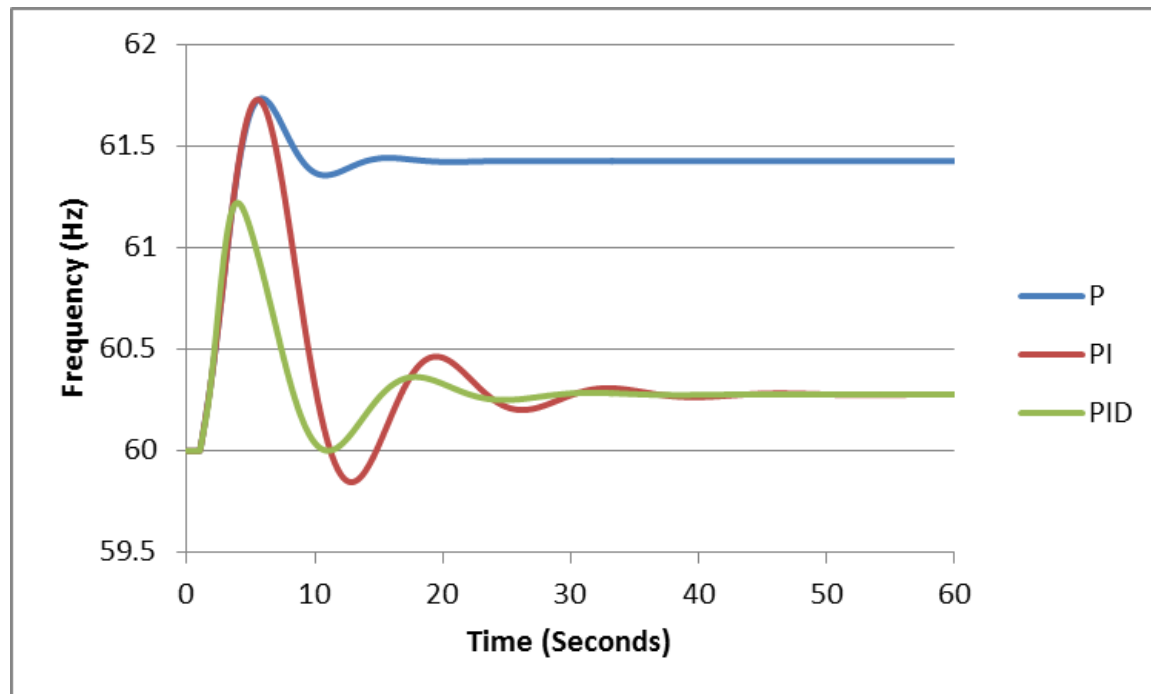


Further details on tuning are covered in IEEE Std. 1207-2011

Tuning PID Controller Example



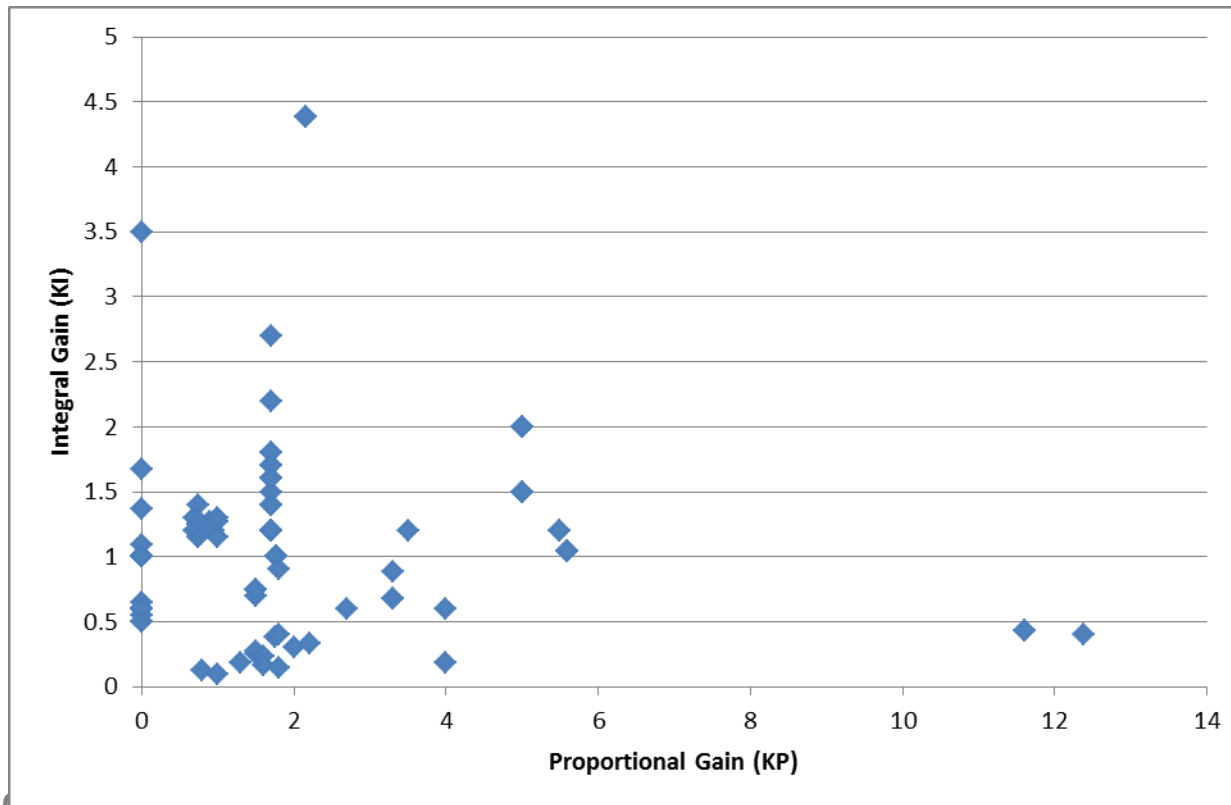
- Figure shows the Ziegler-Nichols for a P, PI and PID controls. Note, this is for stand-alone, not interconnected operation



Example KI and KP Values



- Figure shows example KI and KP 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

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

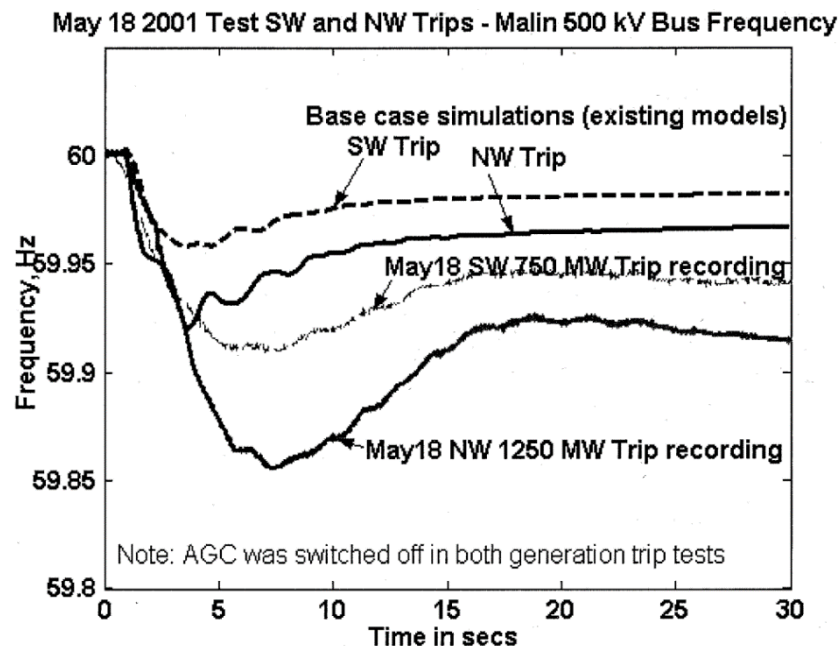
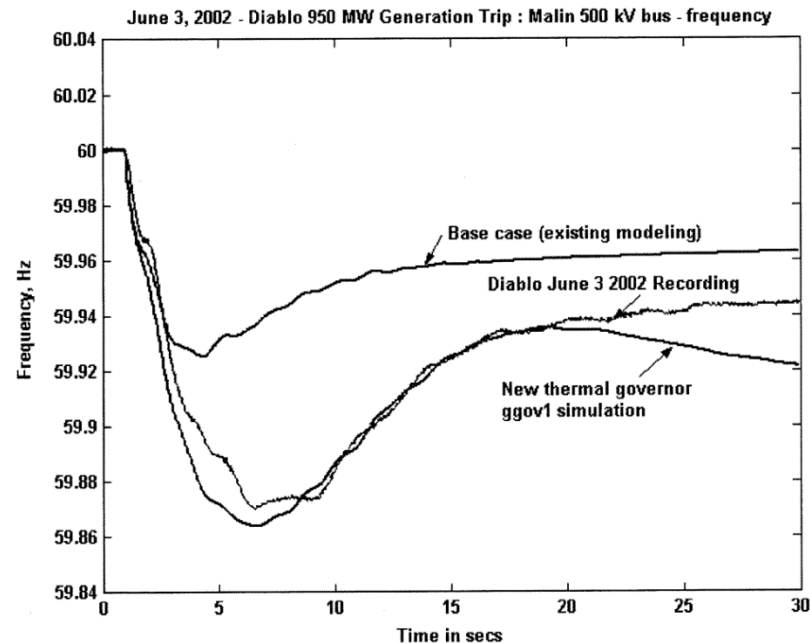


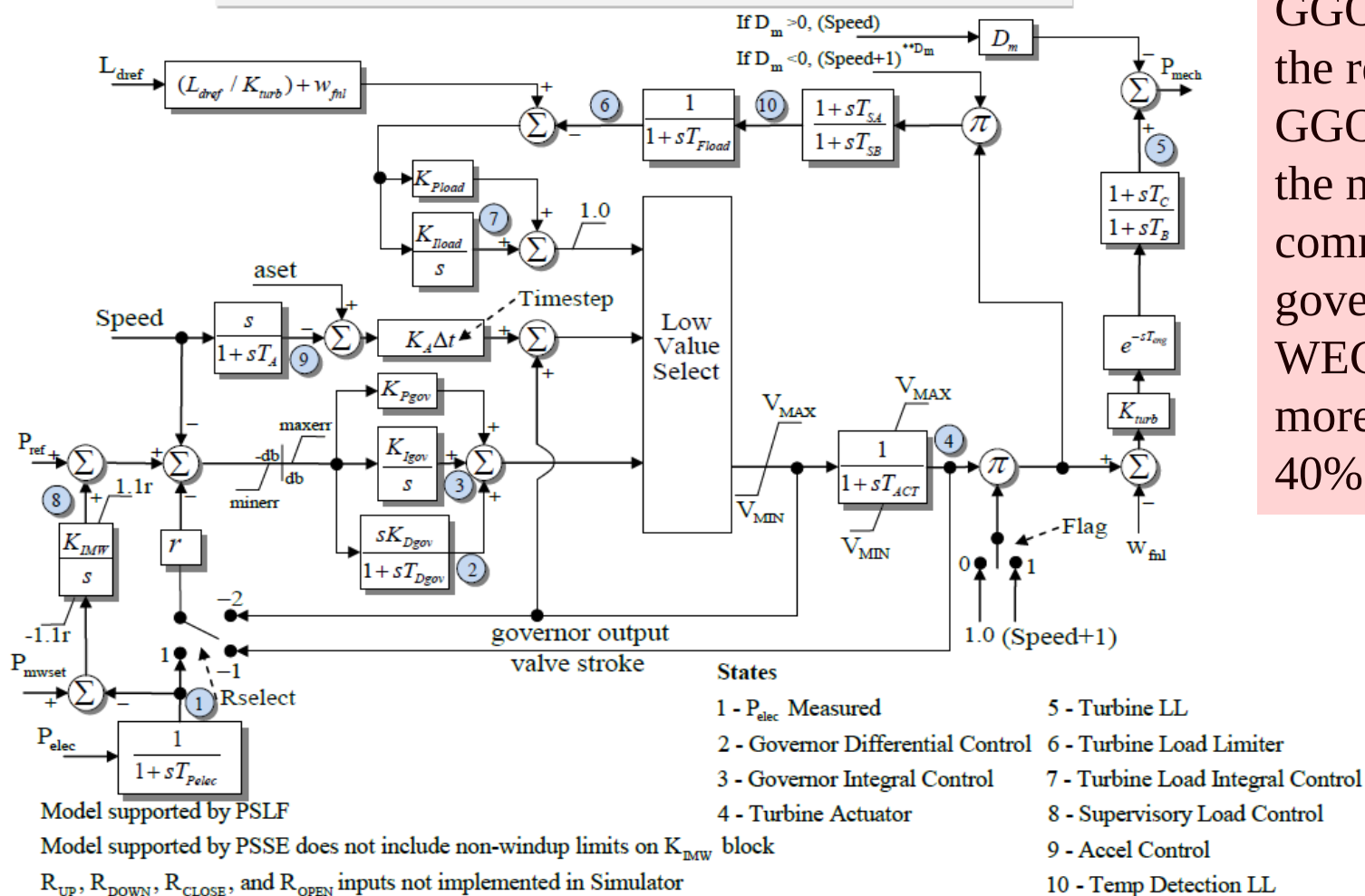
Fig. 1. Frequency recordings of the SW and NW trips on May 18, 2001. Also shown are simulations with existing modeling (base case).



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.

GGOV1 Block Diagram



GGOV1 and the related GGOV3 are the most common governors in WECC, with more than 40% in 2019

