

# ECEN 667

## Power System Stability

### Lecture 8: Excitation Systems and Voltage Control

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TEXAS A&M  
UNIVERSITY

# Announcements

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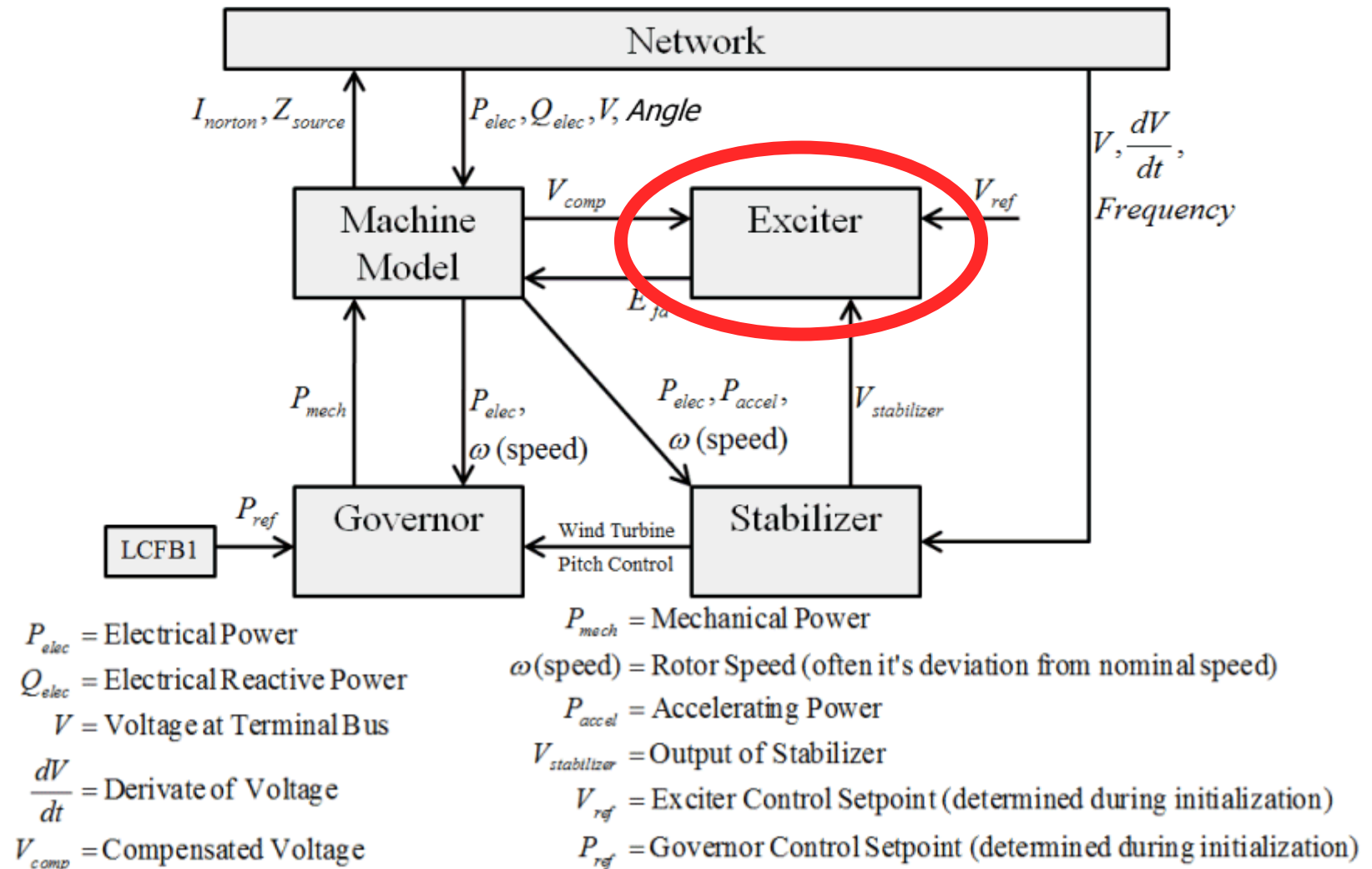


- Homework Assignment #2 is due Thursday, Sept. 25<sup>th</sup> at 8 AM. Email me your solution as a single PDF.
- Read book chapters 3, 4, and 5
- Review the slides and PowerWorld examples

# Synchronous Machine Controllers



- The excitation system is the part that provides the field voltage  $E_{fd}$  to the synchronous machine
- It is really two parts in one
  - The physical exciter, which generates the field voltage
  - The voltage regulator, a control system measuring and controlling terminal  $V$



# Exciters, Including AVR

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- 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

# Potential Types of Exciters

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- 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
  - This model was standardized in a 1968 IEEE Committee Paper with Fig 1. from the paper shown below

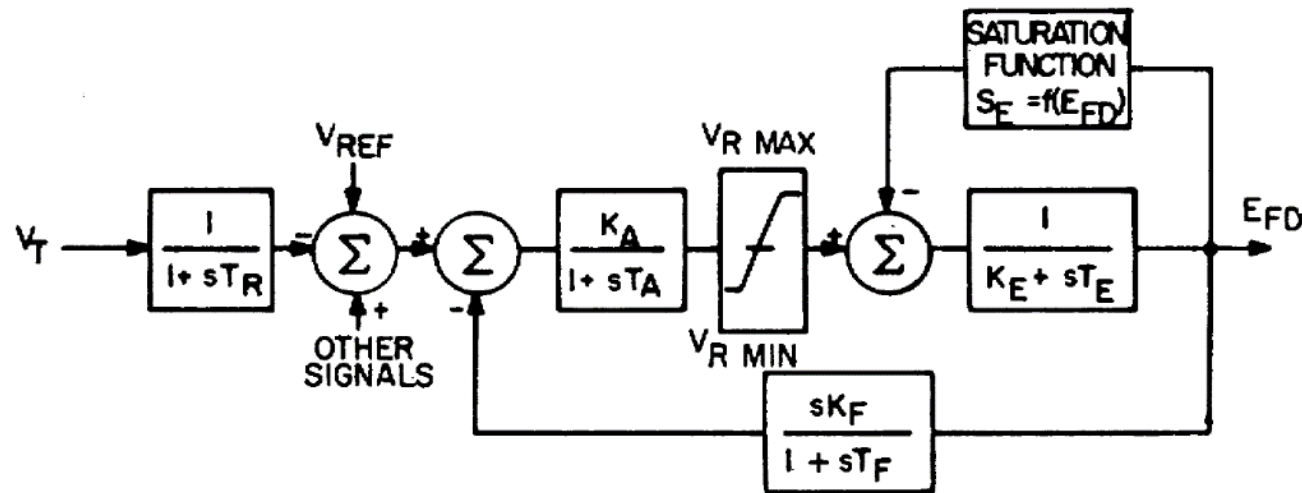


Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

# Brief Review of DC Machines



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

# Overview of DC Machines



- The purpose of the next few slides is to provide insight into the source of portions of the block diagrams for various types of exciters

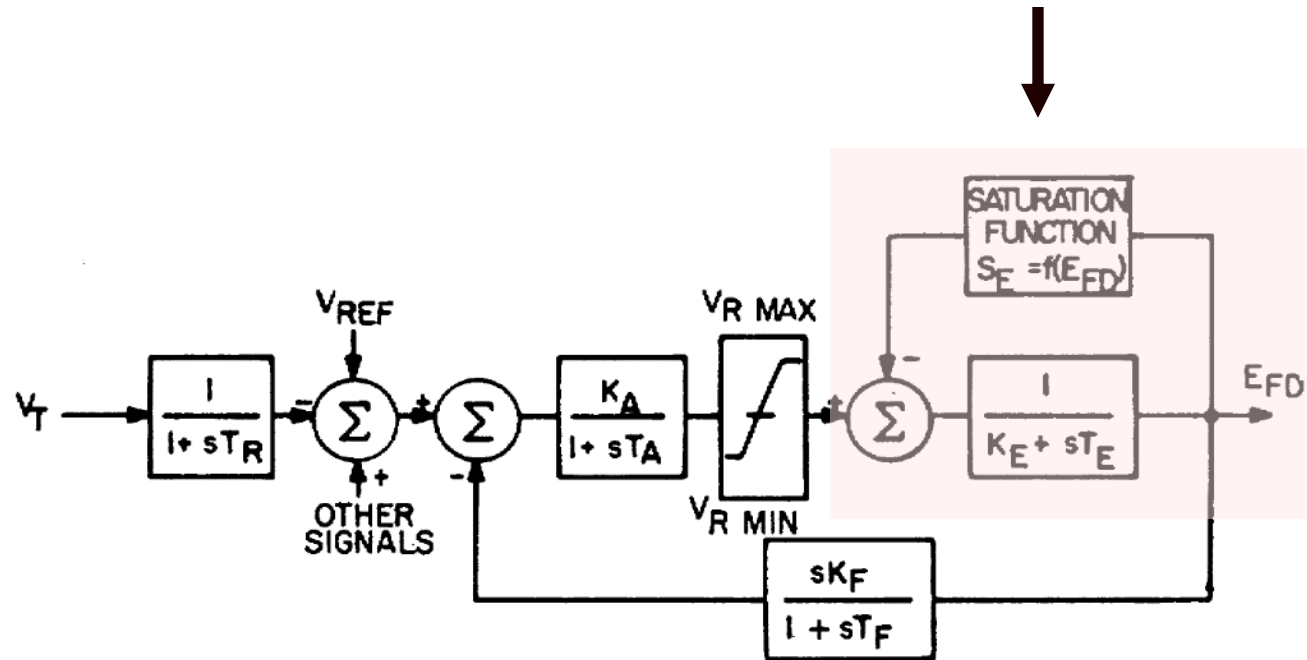


Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

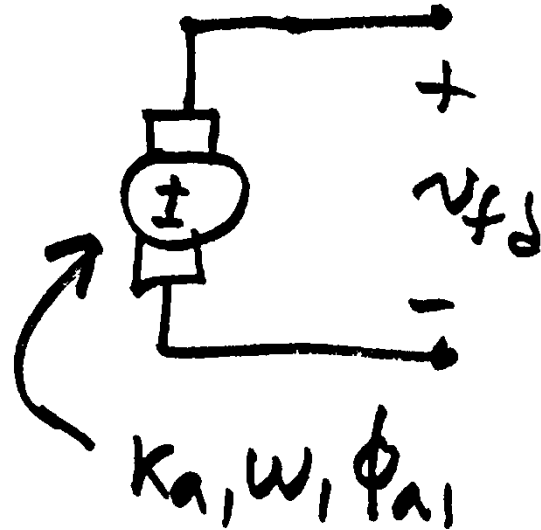
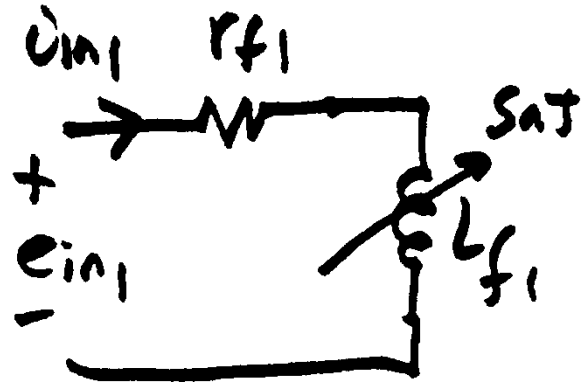
# Types of DC Machines

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- 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 the  
synchronous  
machine)

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

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

$\sigma_1$  is coefficient of dispersion,  
modeling the flux leakage

# Separately Excited DC Exciter, Cont.



- 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  $\omega_1$

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

Solve above for  $\phi_{f1}$  which was used in the previous slide

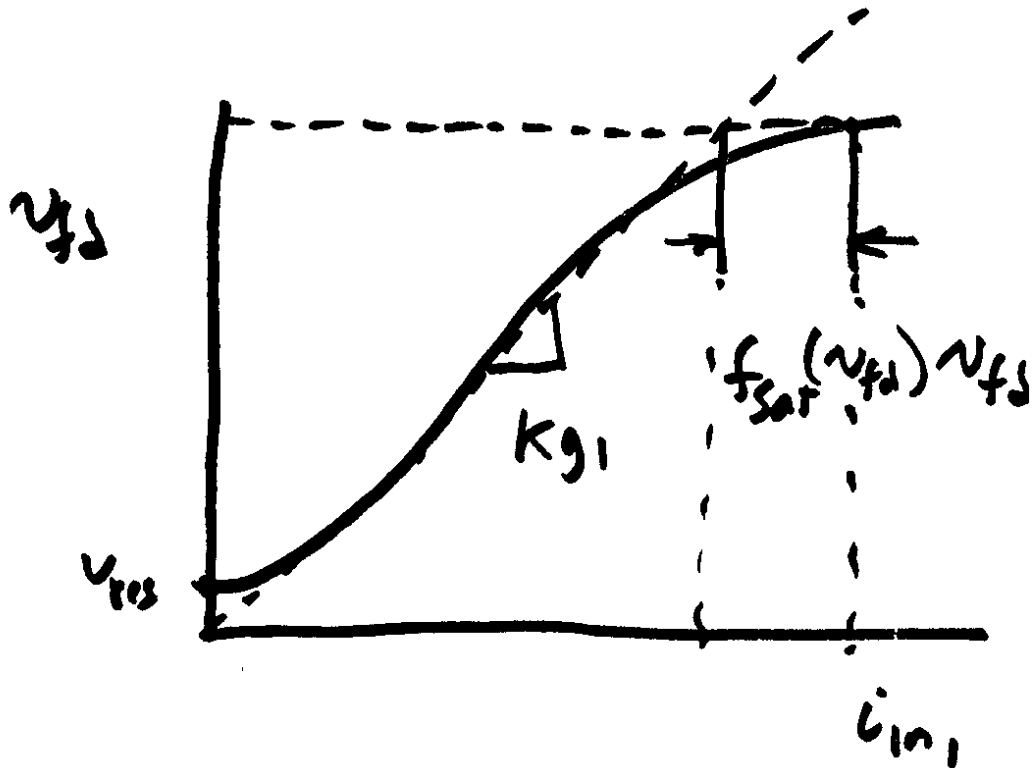
$$\frac{d\phi_{f1}}{dt} = \frac{\sigma_1}{K_{a1} \omega_1} \frac{dv_{fd}}{dt}$$

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

# Separately Excited DC Exciter, Cont.



- 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



$$i_{in_1} = \frac{v_{fd}}{K_{g1}} + f_{sat}(v_{fd}) v_{fd}$$

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, Cont.



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

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



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

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

$V_R$  is the scaled output of the voltage regulator amplifier

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

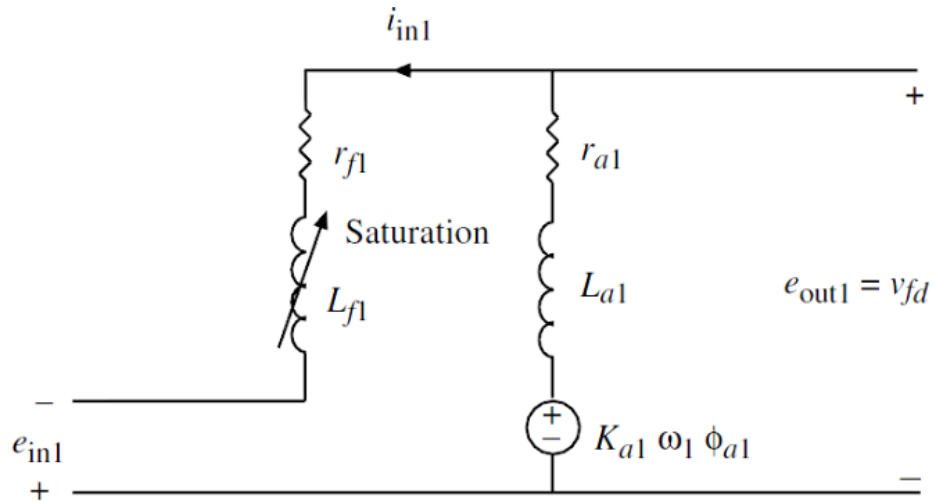
Thus we have

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

# The Self-Excited Exciter



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



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

Note the additional  $E_{fd}$  term on the end

# Self and Separated Excited Exciters



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

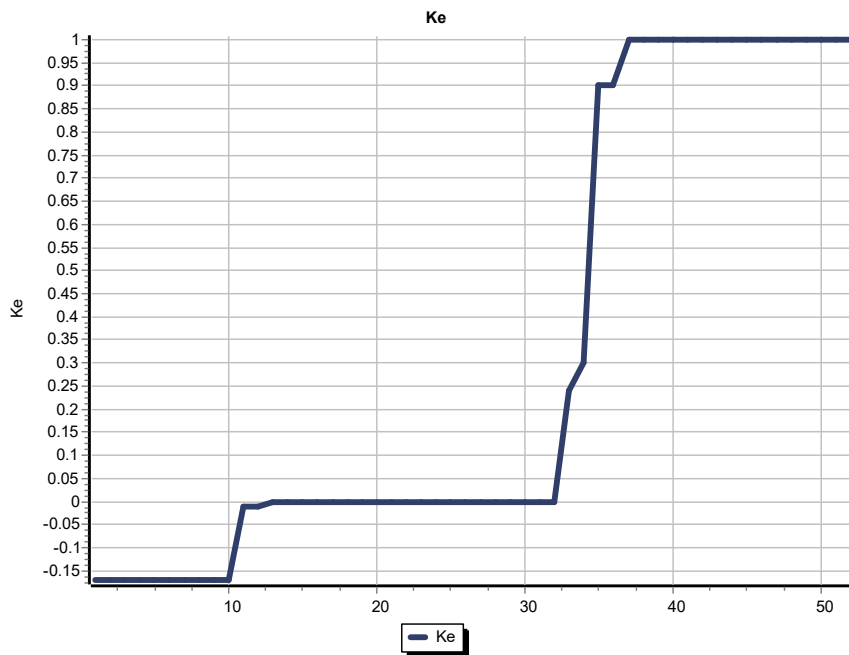
$$T_E \frac{dE_{fd}}{dt} = -\left(K_E + S_E(E_{fd})\right)E_{fd} + V_R$$

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

# Exciter Model IEEE11 K<sub>E</sub> Values



Example IEEE11 Values from a large system



als	Tr	Ka	Ta	Vrmax	Vrmin	Kr▲	Te	Kf	Tf	Switch	E1	SE1	E2	SE2	Spdr
0.03333334	50	0.05	3.5	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	-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	-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	-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	-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	-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	-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	-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	-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<sub>E</sub> equal 1 are separately excited, and K<sub>E</sub> 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 
$$S_E(E_{fd}) = \frac{B(E_{fd} - A)^2}{E_{fd}}$$

- Exponential function could also be used

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

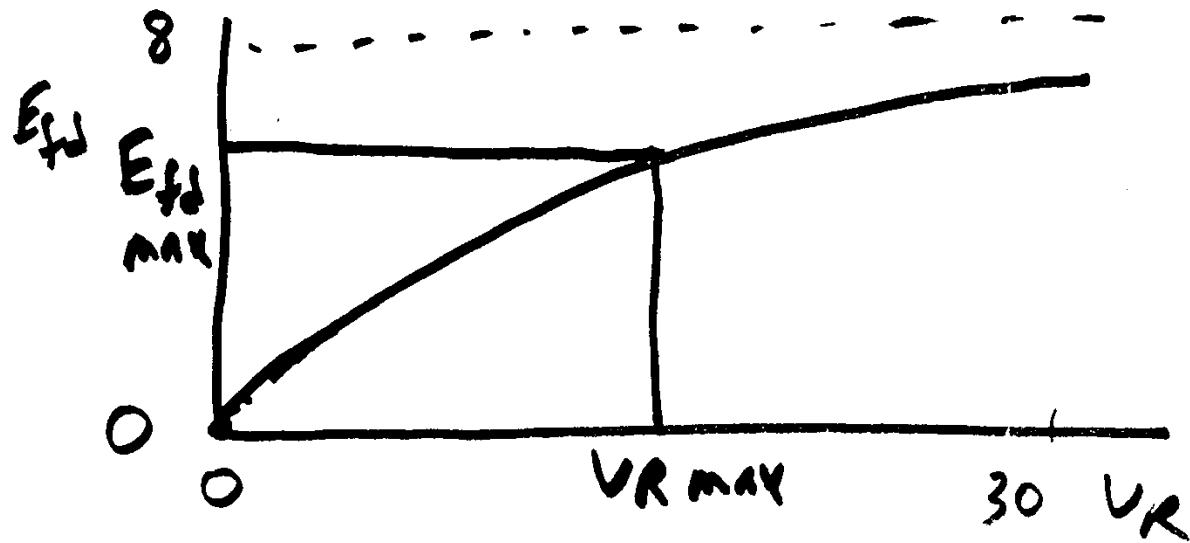
This is the same function used with the machine models

# Exponential Saturation



$$K_E = 1 \quad S_E(E_{fd}) = 0.1e^{0.5E_{fd}}$$

$$\text{In Steady state} \quad V_R = \left(1 + .1e^{.5E_{fd}}\right)E_{fd}$$



# Exponential Saturation Example



Given:

$$K_E = -.05$$

$$S_E \left( E_{fd_{\max}} \right) = 0.27$$

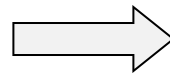
$$S_E \left( .75 E_{fd_{\max}} \right) = 0.074$$

$$V_{R_{\max}} = 1.0$$

Find:

$$A_x, B_x \text{ and } E_{fd_{\max}}$$

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



$$E_{fd_{\max}} = 4.6$$

$$A_x = .0015$$

$$B_x = 1.14$$

# Voltage Regulator Model



Amplifier

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

Modeled as a first order differential equation

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

In steady state

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

As  $K_A$  is increased

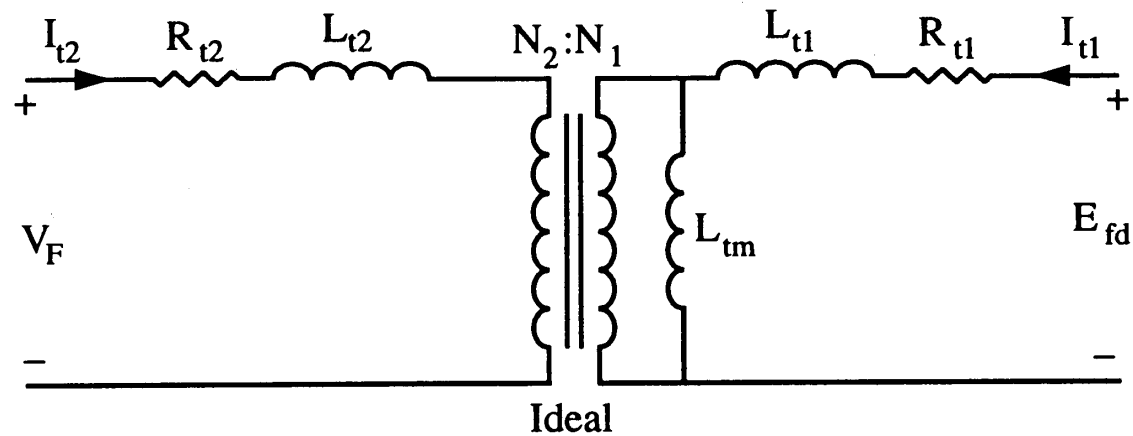
$$K_A \rightarrow V_t \approx V_{ref}$$

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, Cont.



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

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

↓

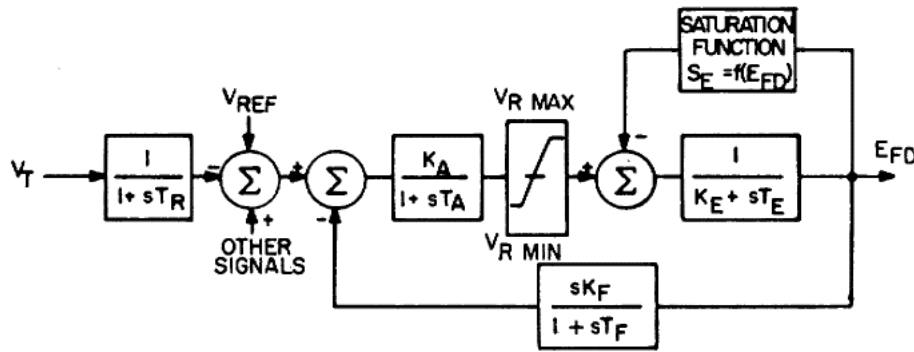
$\frac{1}{T_F}$

↓

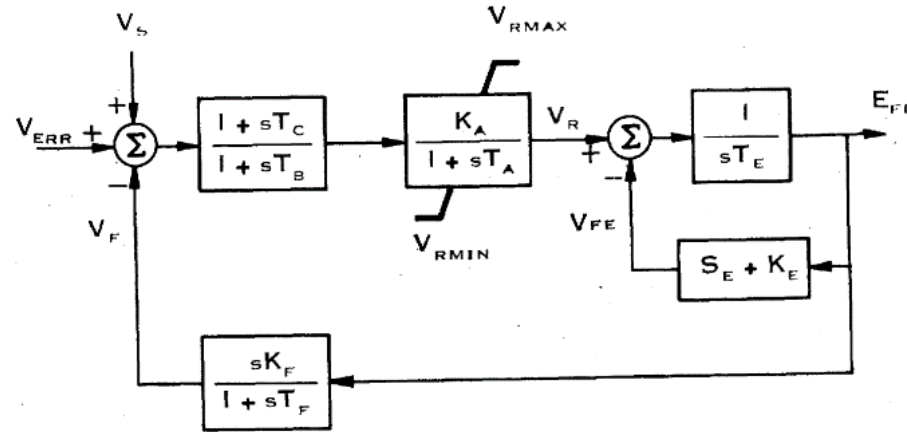
$K_F$

# IEEEET1 Model Evolution

- The original IEEEET1, from 1968, evolved into the EXDC1 in 1981



1968



1981

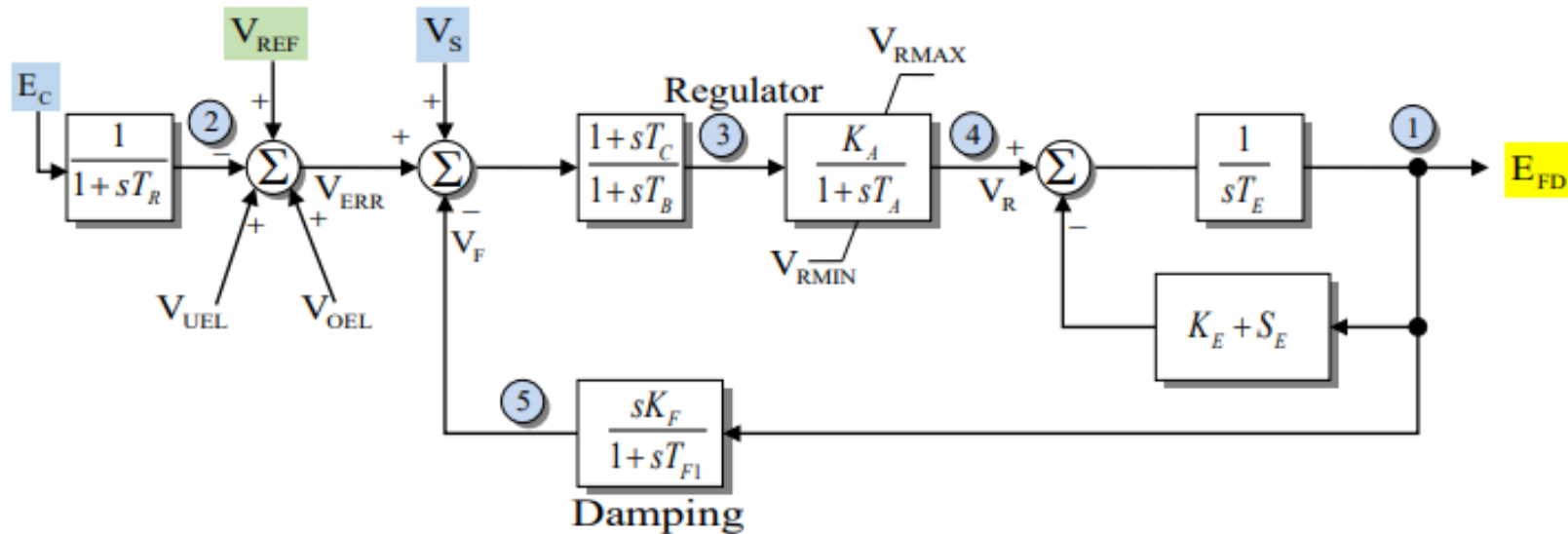
Note,  $K_E$  in the feedback is the same in both models

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

# IEEEX1



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



# IEEE1 Evolution



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

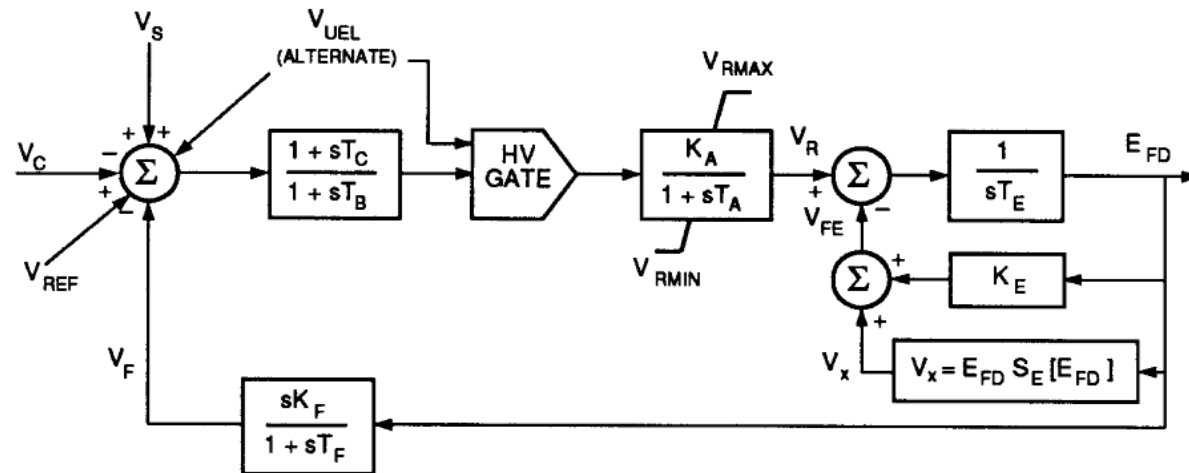


Figure 3—Type DC1A — DC Commutator Exciter

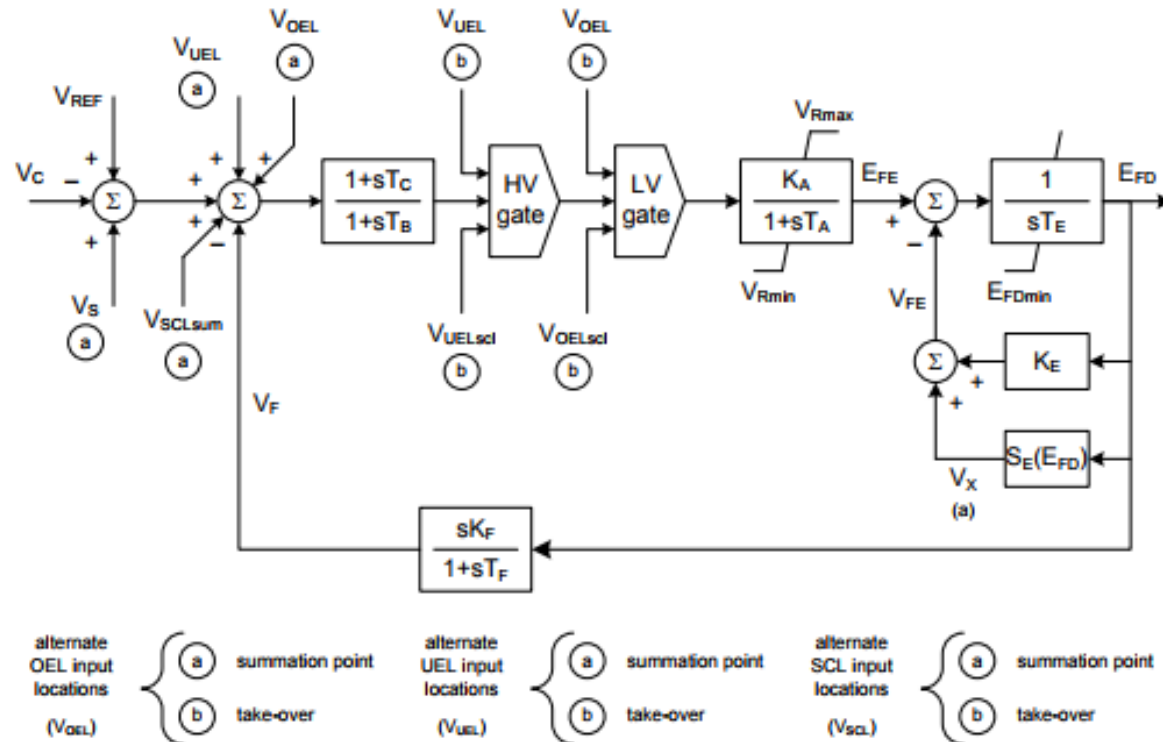
$V_{UEL}$  is a signal from an under-excitation limiter, which we'll cover later

Same model is in 421.5-2005

# IEEE T1 Evolution, Cont.



- Slightly modified in Std 421.5-2016



#### footnotes:

(a)  $V_x = E_{FD} \cdot S_E(E_{FD})$

Note the minimum limit on  $E_{FD}$

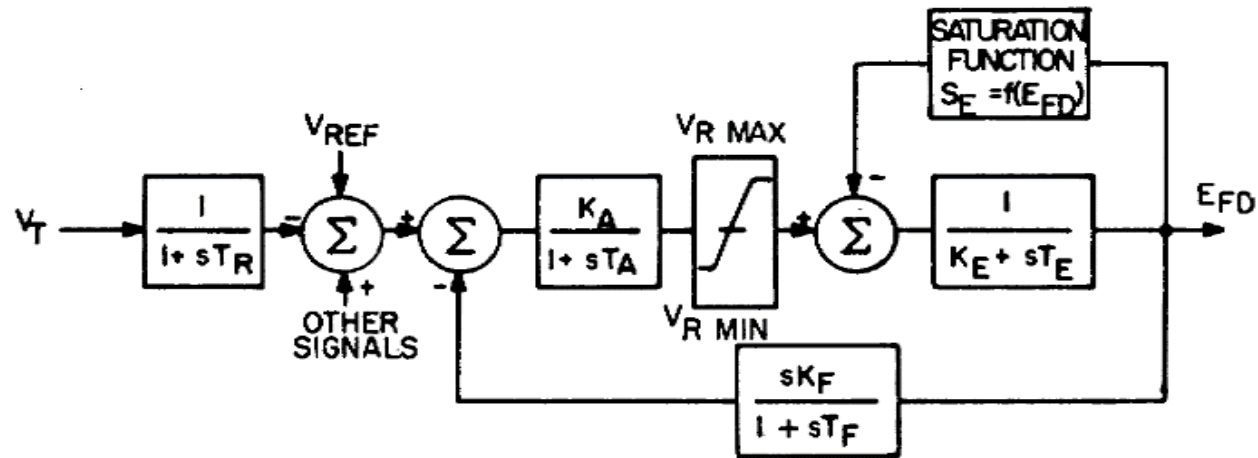
There is also the addition to the input of voltages from a stator current limiters ( $V_{SCL}$ ) or over excitation limiters ( $V_{OEL}$ )

Figure 4—Type DC1C dc commutator exciter

# 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  $S_E(2.8) = 0.04$ ,  $S_E(3.73)=0.33$
- Saturation function is  $0.1621(E_{FD}-2.303)^2$  (for  $E_{FD} > 2.303$ ); otherwise zero
- $E_{FD}$  is initially 3.22
- $S_E(3.22)*E_{FD}=0.437$
- $(V_R-S_E*E_{FD})/K_E=E_{FD}$
- $V_R=0.244$
- $V_{REF} = 0.244/K_a + V_T = 0.0488$

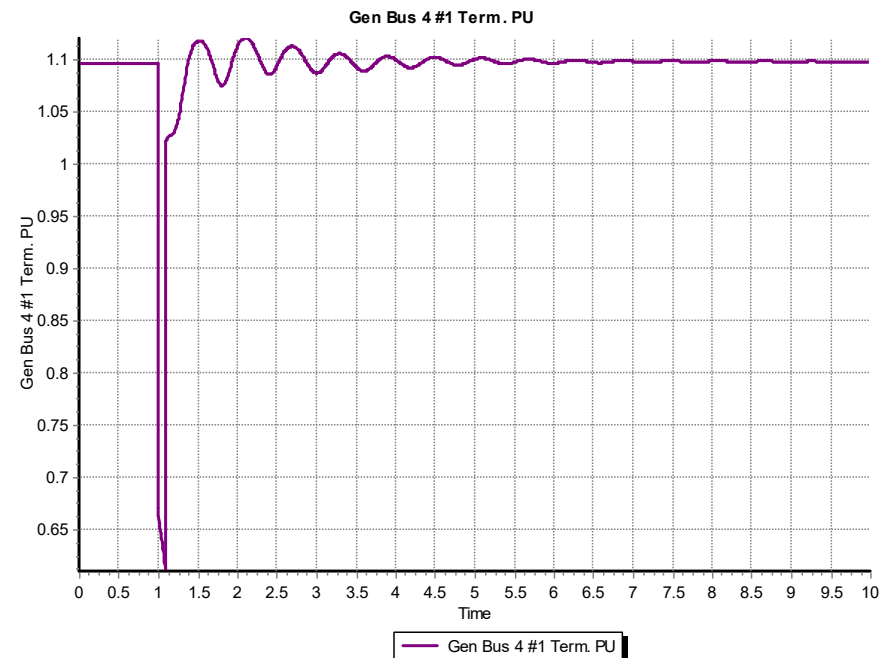
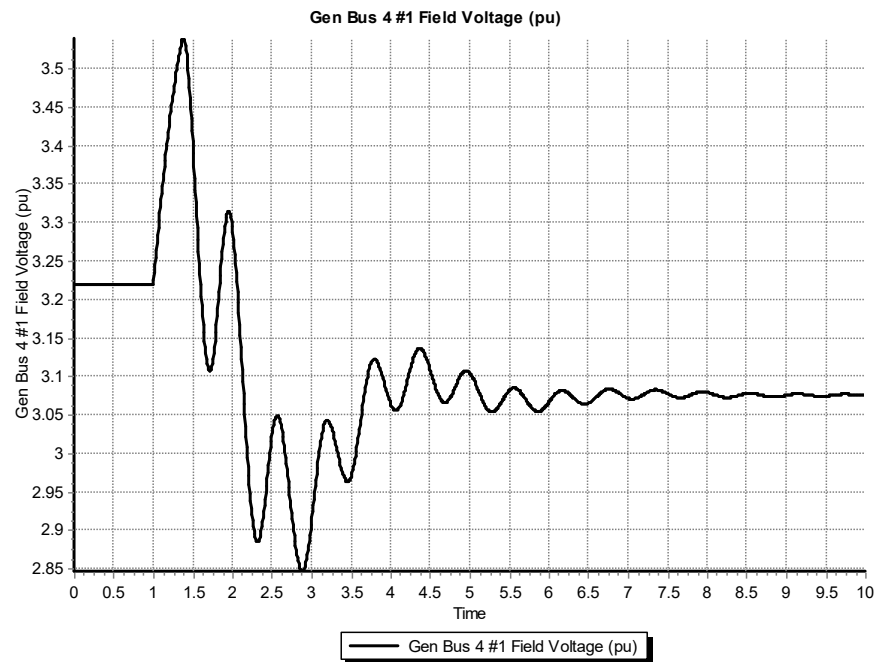


Case B4\_GENROU\_Sat\_IEEET1

# IEEE T1 Example



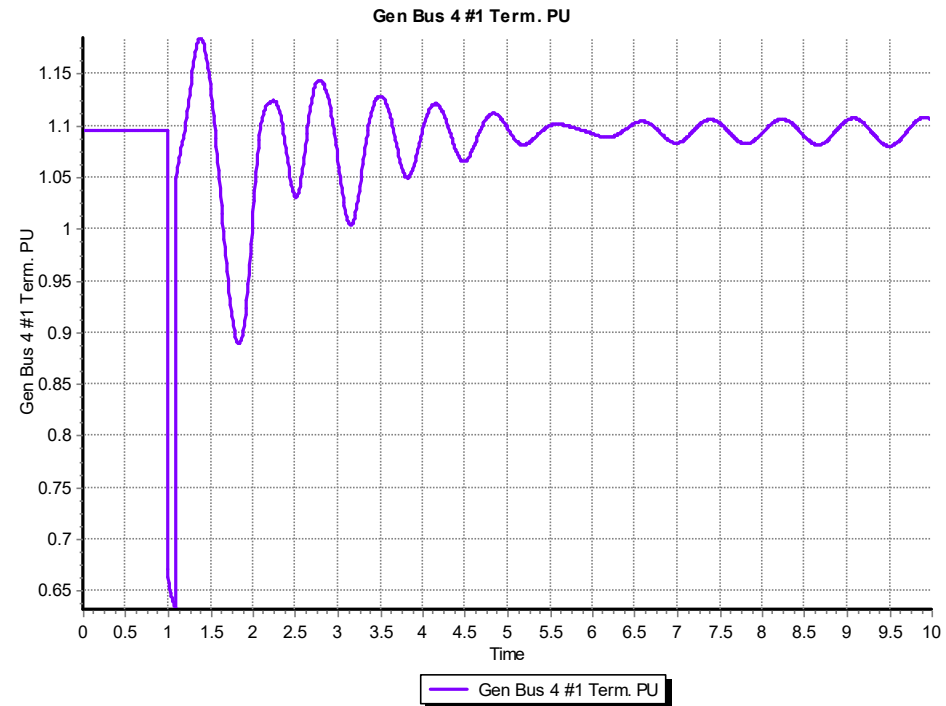
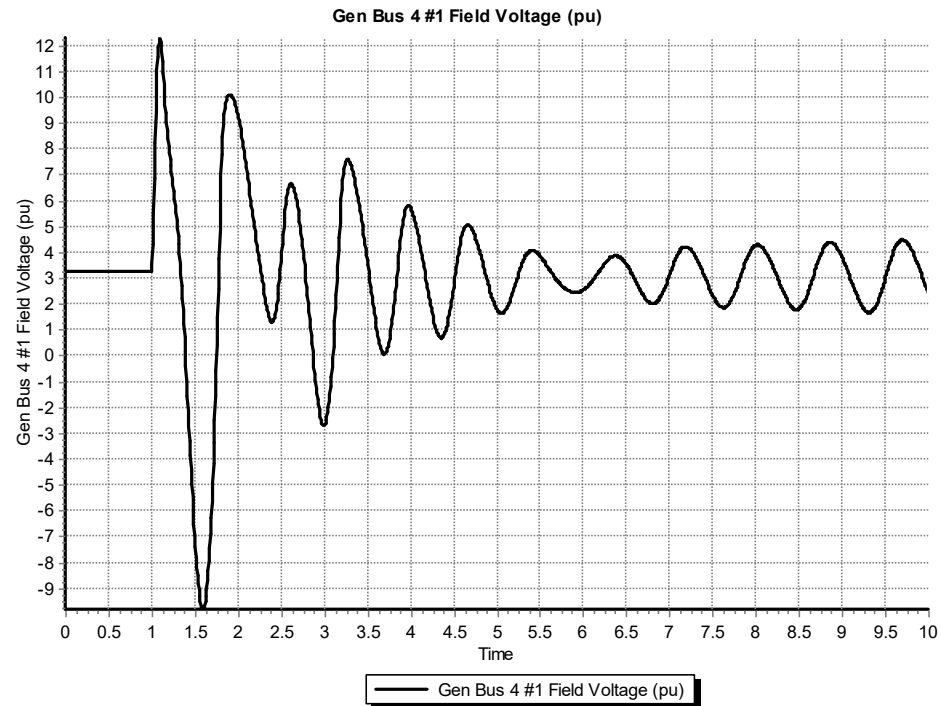
- For 0.1 second fault (from before), plot of  $E_{FD}$  and the terminal voltage is given below
- Initial  $V_4=1.0946$ , final  $V_4=1.0973$ 
  - Steady-state error depends on the value of  $K_A$



# IEEE1 Example, Cont.



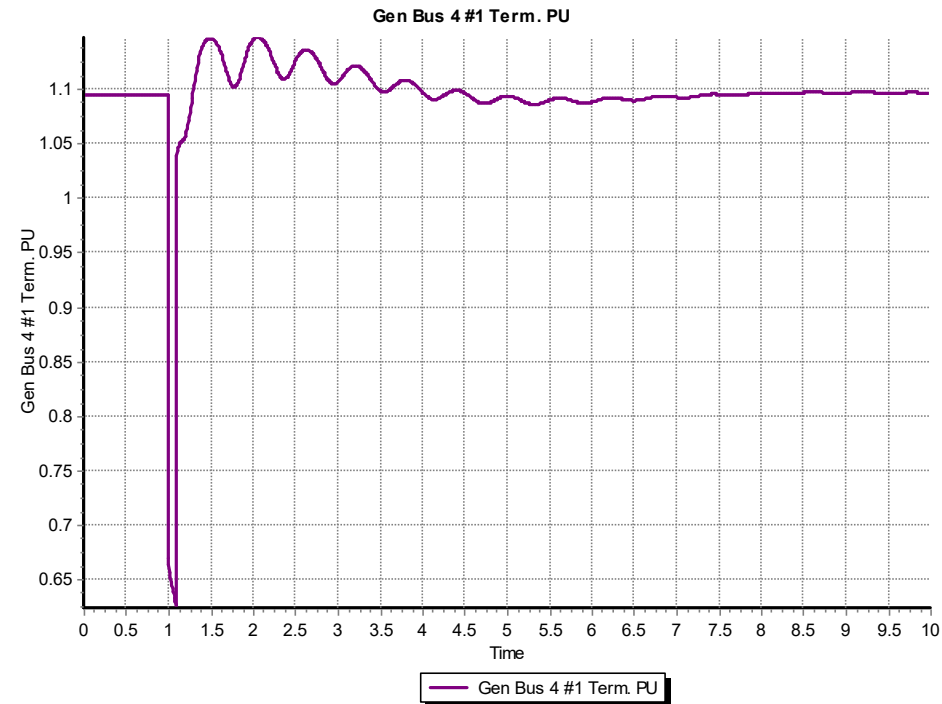
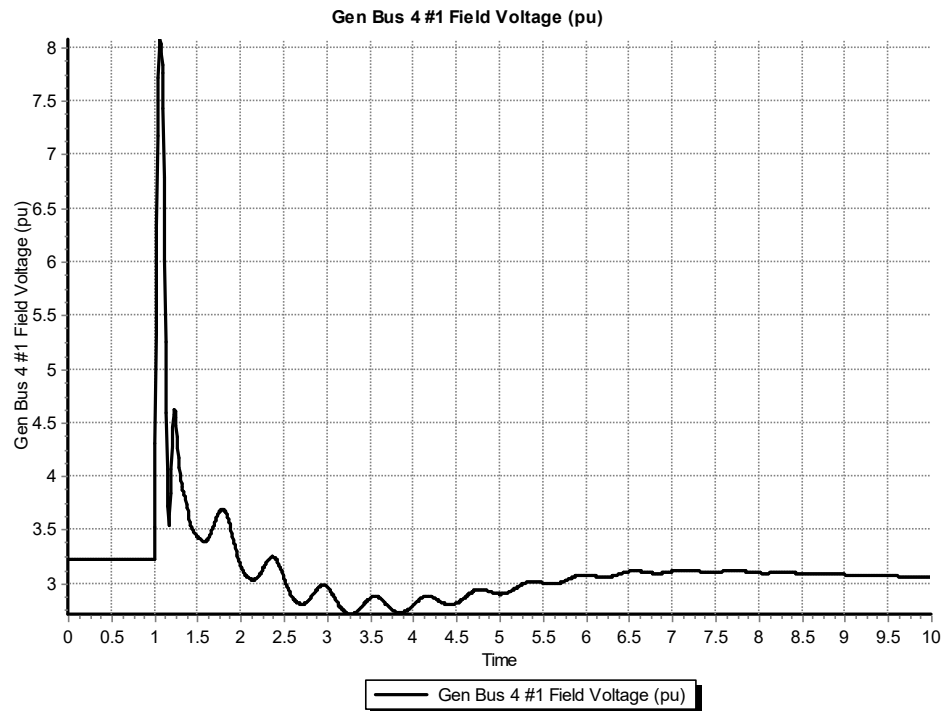
- Same case, except with  $K_A=500$  to decrease steady-state error, no  $V_R$  limits; this case is actually unstable



# IEEE1 Example, Cont.



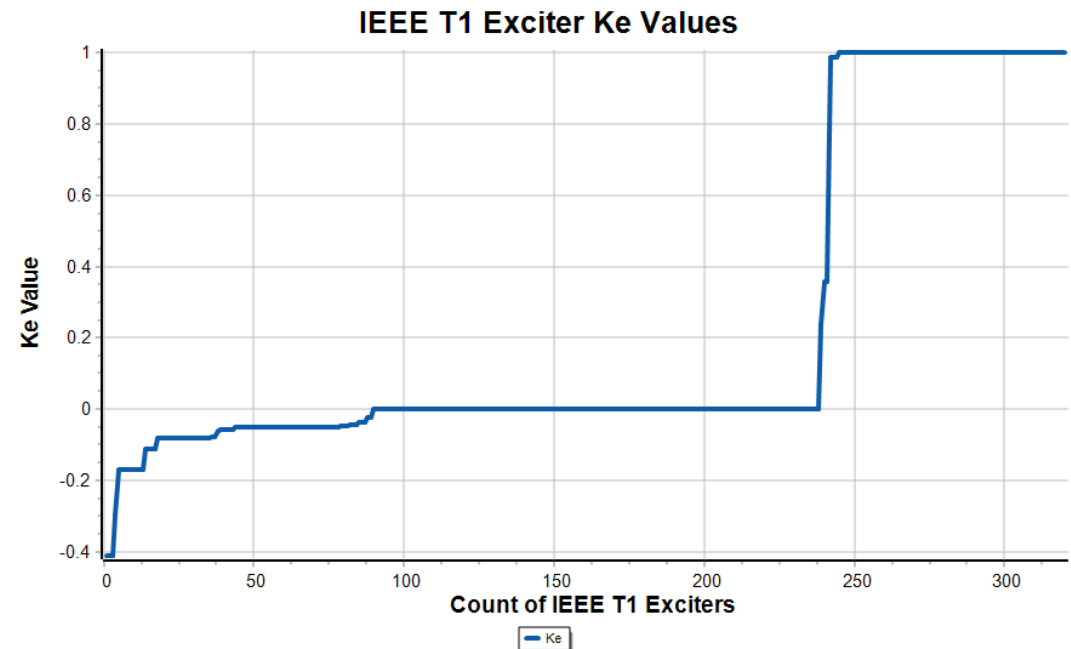
- With  $K_A=500$  and rate feedback,  $K_F=0.05$ ,  $T_F=0.5$
- Initial  $V_4=1.0946$ , final  $V_4=1.0957$



# Combined EI/WECC Case Type 1 Exciters



- In a recent combined EI/WECC case with about 11,000 exciters, 320 are modeled with the IEEE T1, 129 with IEEE X1, 147 with the EXDC1, and 162 with the ESDC1A
- Graph shows  $K_E$  value for the IEEE T1 exciters in case; about 1/4 are separately excited ( $K_E = 1$ ), 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

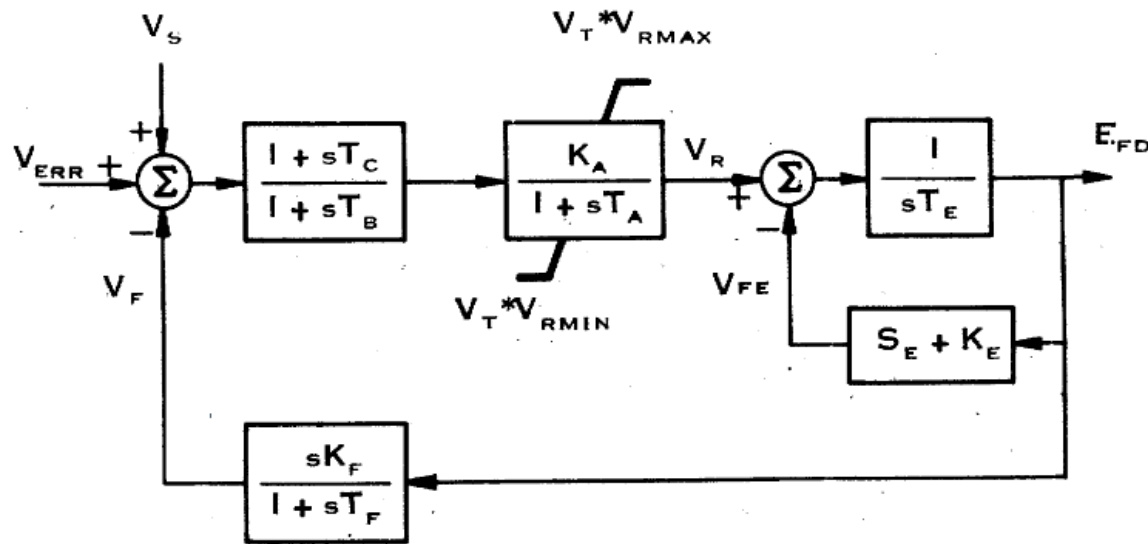


Fig. 4. Type DC2 - DC Commutator Exciter

$V_r$  limits are multiplied by the terminal voltage

# ESDC4B



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

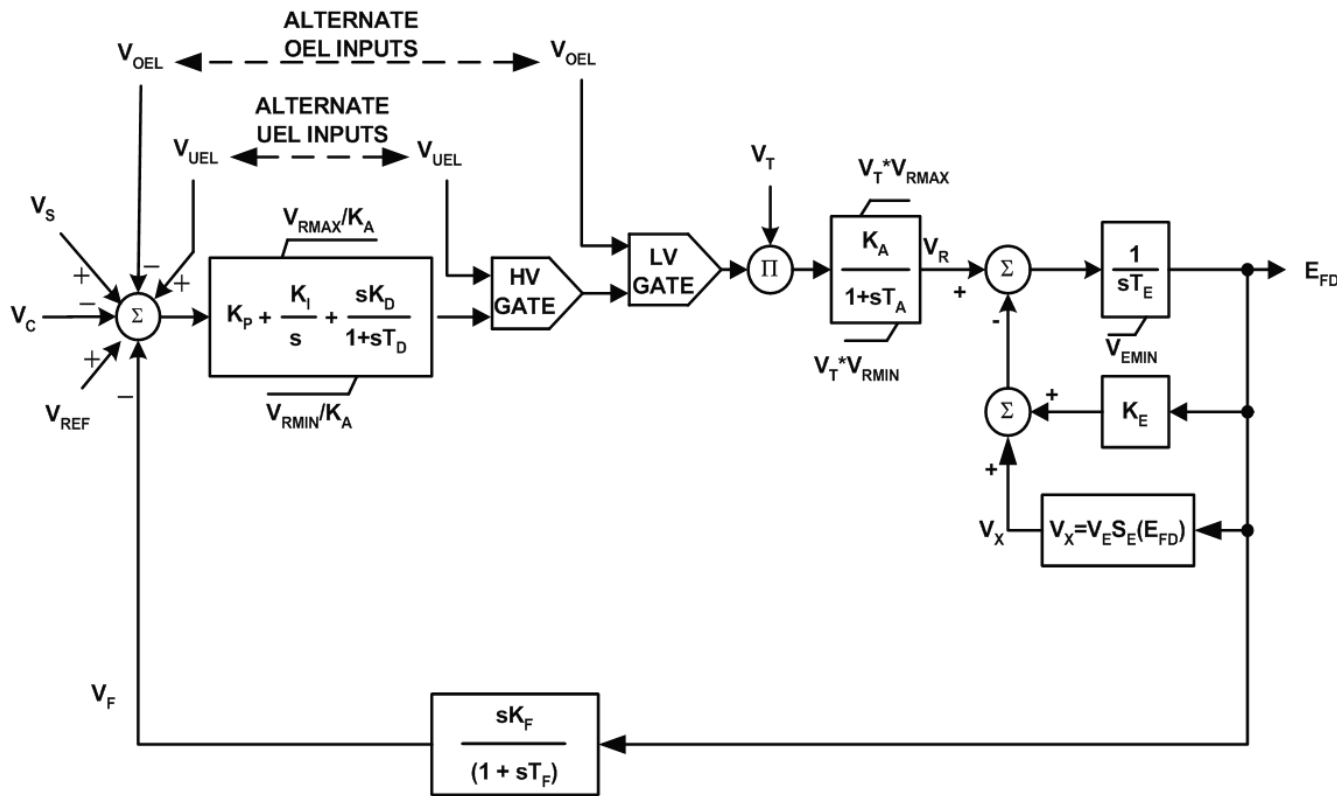


Image Source: Fig 5-4 of IEEE Std 421.5-2005

# AC Exciters

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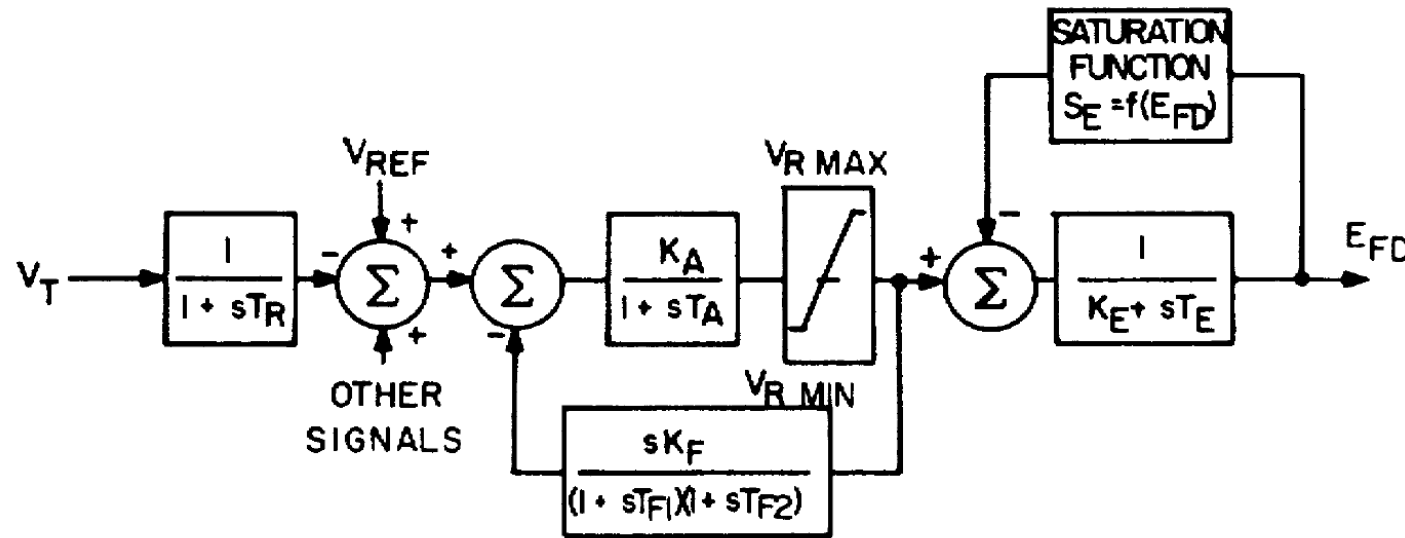


- Almost all new exciters use an ac source with an associated rectifier (either from a machine or static)
- AC exciters use an ac generator and either stationary or rotating rectifiers to produce the field current
  - In stationary systems the field current is provided through slip rings
  - In rotating 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 Modeling



- Originally represented by IEEE T2 shown below

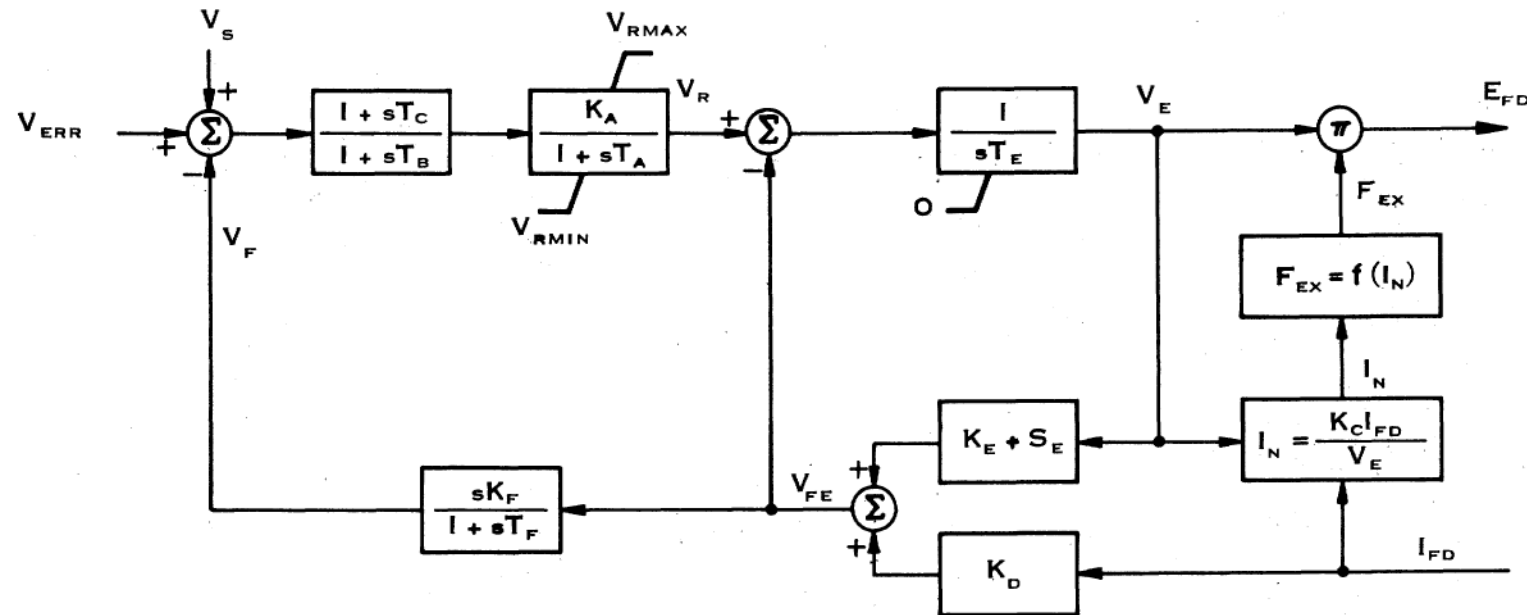


Exciter model is quite similar to IEEE T1; in the EI/WECC case there are 105 IEEE T2 exciters (about 1%)

# EXAC1 Exciter



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



$K_D$  models the exciter machine reactance

About 1% of the  
EI/WECC exciters  
are EXAC1

# EXAC1 Rectifier Regulation

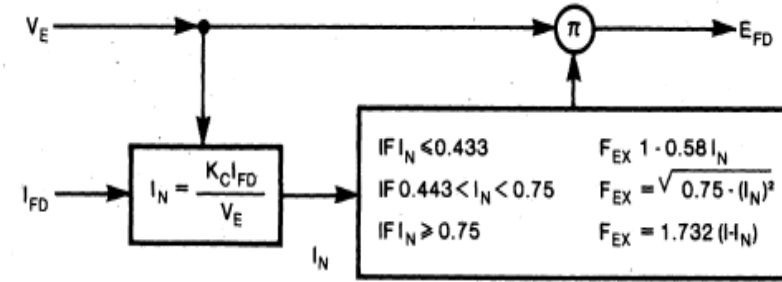
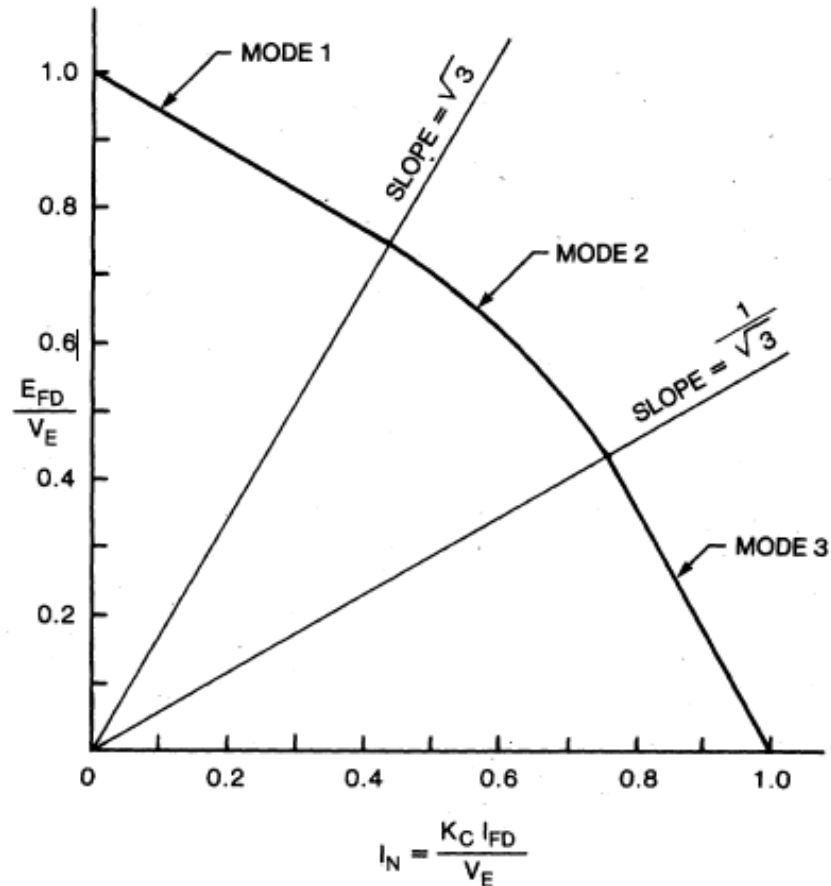


Fig. E.2. Rectifier Regulation Equations

$K_c$  represents the  
commuting reactance

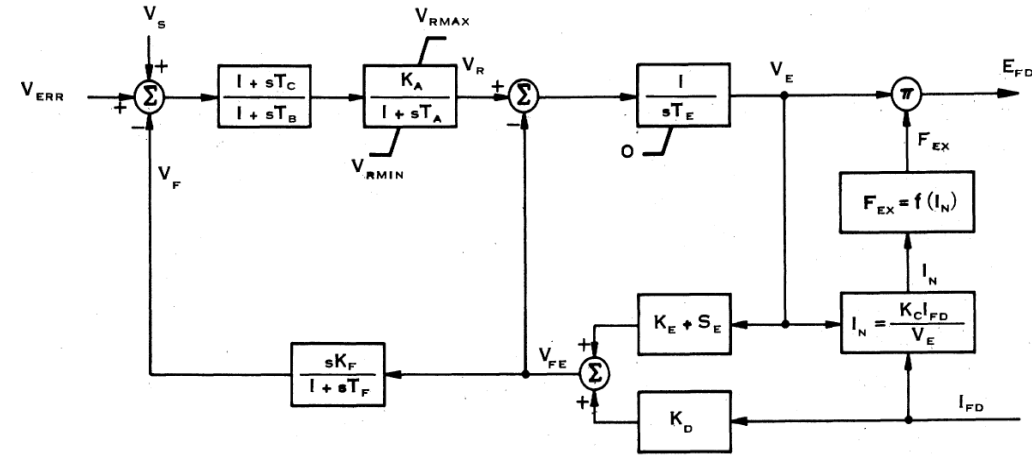
There are about 6 or 7 main  
types of ac exciter models

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

# Initial State Determination, EXAC1



- To get initial states  $E_{fd}$  and  $I_{fd}$  would be known and equal
- Solve  $V_e * F_{ex}(I_{fd}, V_e) = E_{fd}$ 
  - Easy if  $K_c=0$ , then  $I_n=0$  and  $F_{ex} = 1$
  - Otherwise the  $F_{EX}$  function is represented by three piecewise functions; need to figure out the correct segment; for example for Mode 3



$$F_{ex} = \frac{E_{fd}}{V_e} = 1.732(I_{fd} - I_n) = 1.732 \left( 1 - \frac{K_c I_{fd}}{V_e} \right)$$

$$\text{Rewrite as } \frac{E_{fd}}{1.732} = V_e - K_c I_{fd} \rightarrow \frac{E_{fd}}{1.732} + K_c I_{fd}$$

Need to check to make sure we are on this segment

# Static Exciters

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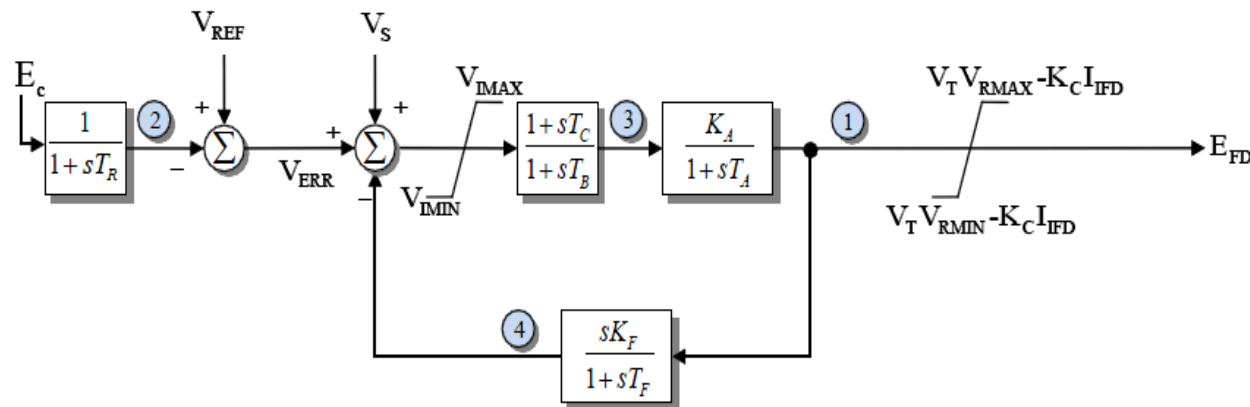


- In static exciters the field current is supplied from a three phase source that is rectified (i.e., there is no separate machine)
- Rectifier can be either controlled or uncontrolled
- Current is supplied through slip rings
- Response can be quite rapid

# 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



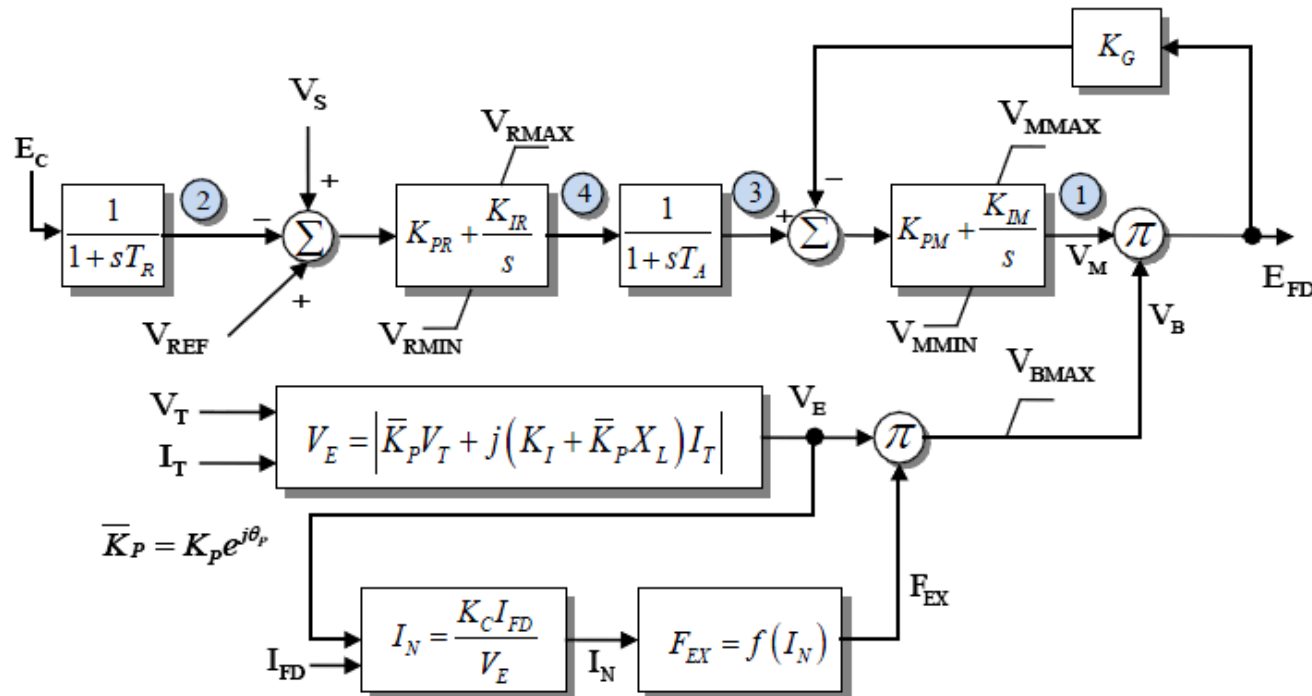
This (and the related ESST1A) is a very common exciter (about 14% of EI/WECC total)

$K_c$  represents the commuting reactance

# EXST4B



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



This (and the related ESST4B) are the most common exciters (about 20% of the total);  $V_e$  is almost always independent of  $I_T$

# Desired Performance

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- 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 performance to a step change in input

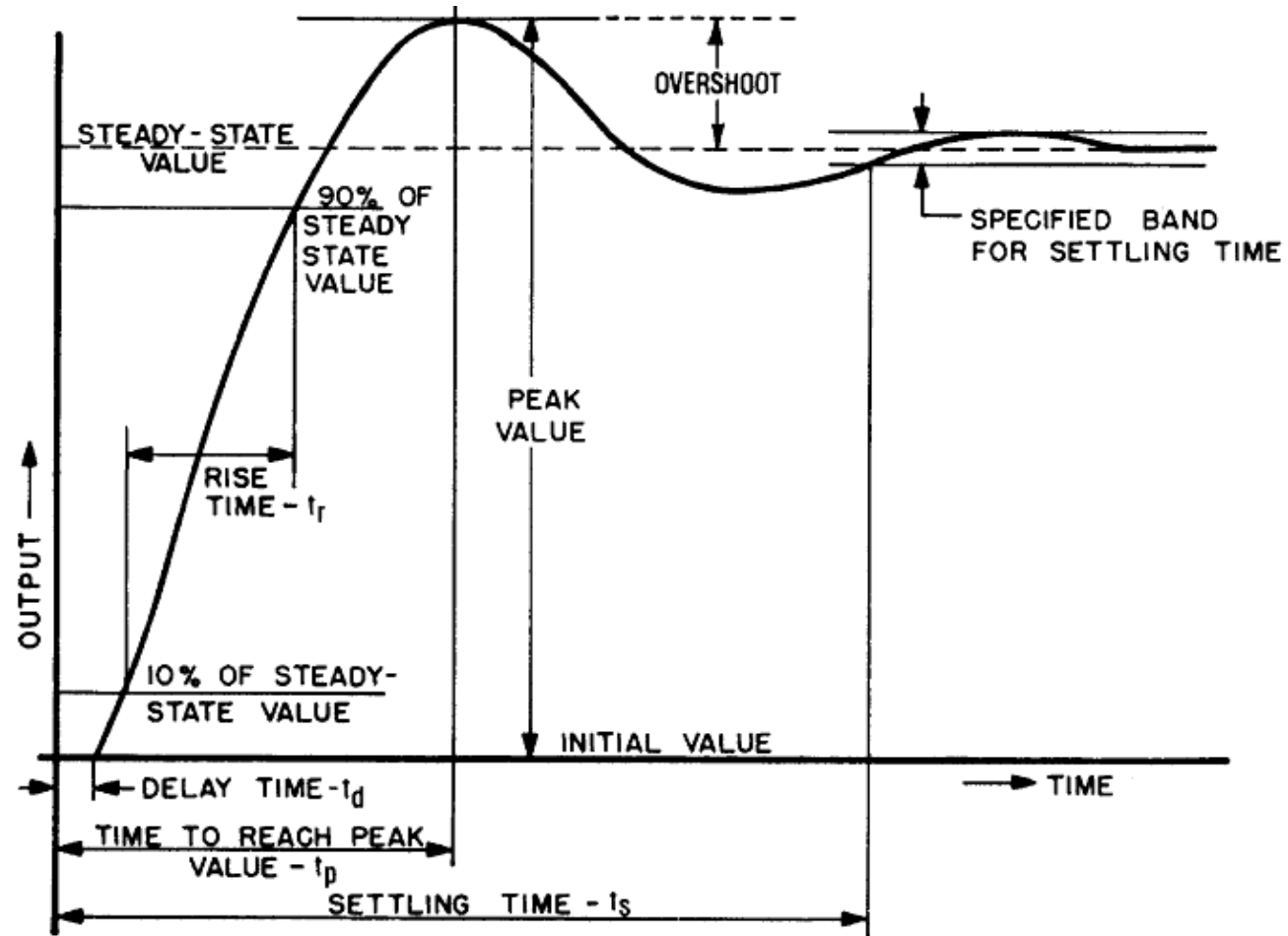
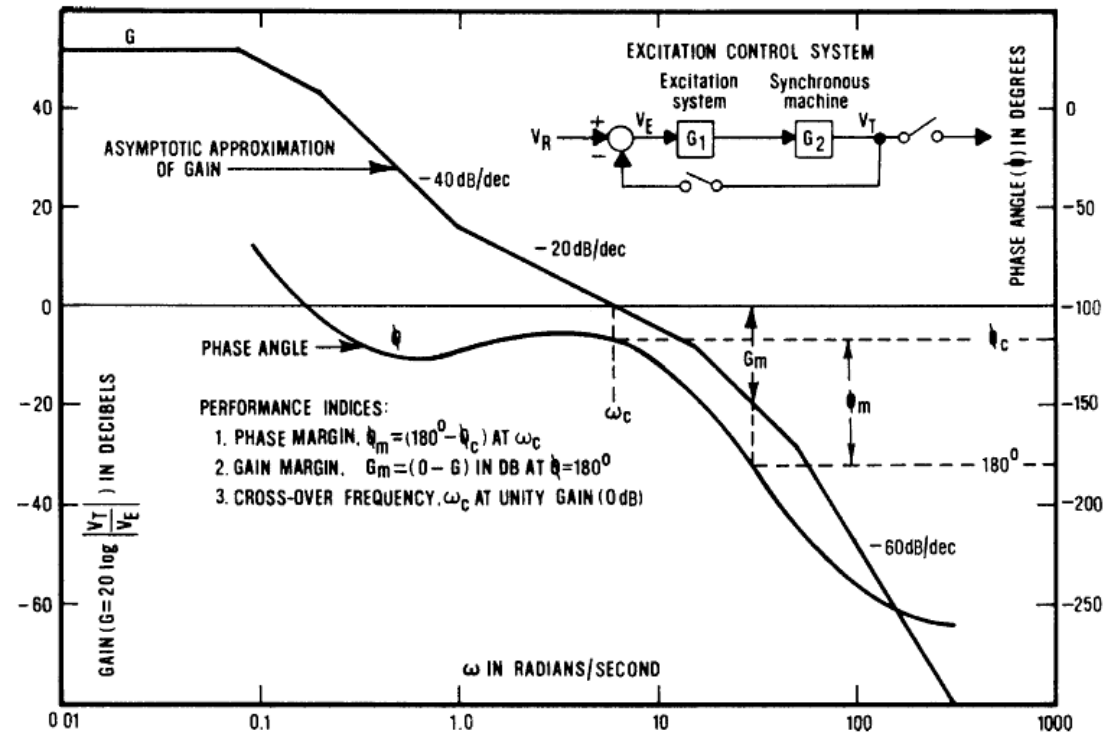


Image Source: IEEE Std 421.2-1990, Figure 3.

# 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



# 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 (negative convention)
  - Specified on the machine base
- PSSE requires a separate model with their COMP model also using a negative sign

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

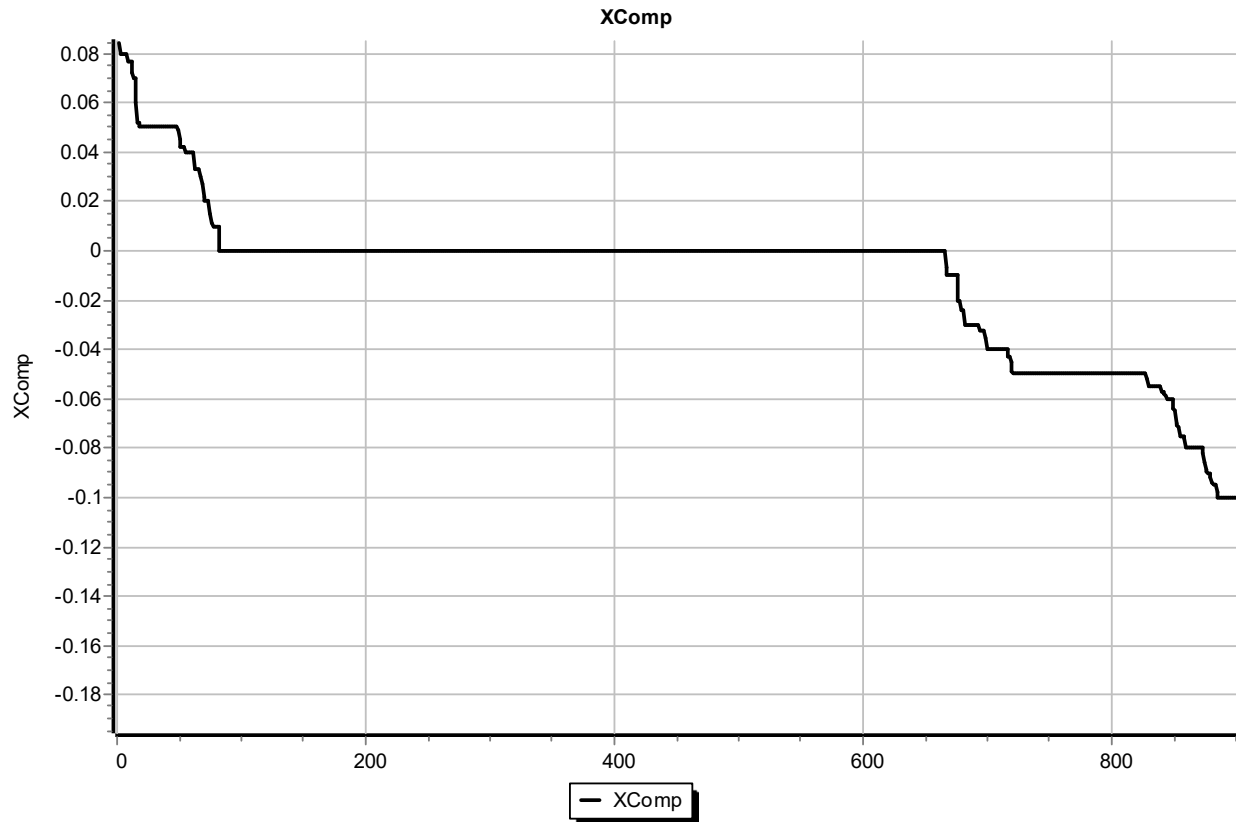
# Compensation, Cont.

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- 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

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

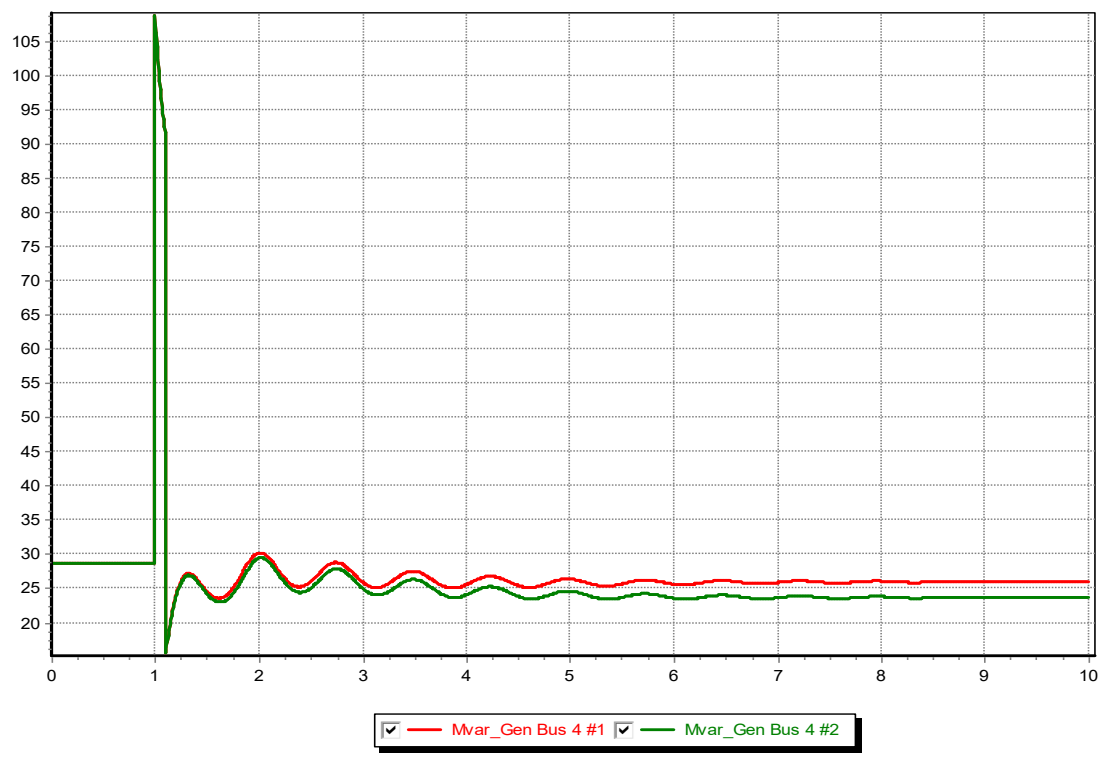
$$E_c = |1.072 + j0.22 - (j0.05)(1.0 - j0.3286)| = |1.0557 + j0.17| = 1.069$$

Case is **B4\_comp1**

# Compensation Example 2



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



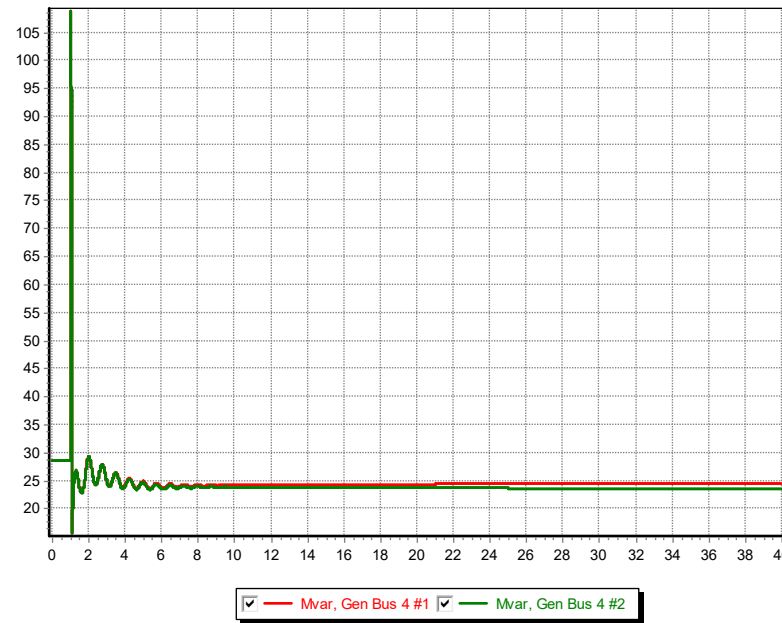
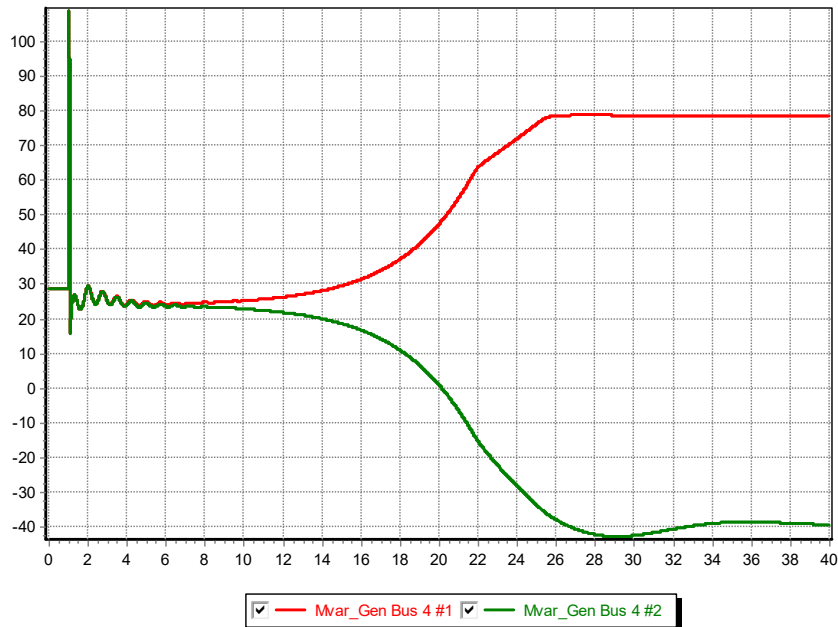
Plot shows the reactive power output of the two units, which start out equal, but diverge because of the difference values for  $X_c$

Case is **B4\_comp2**

# Compensation Example 3



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



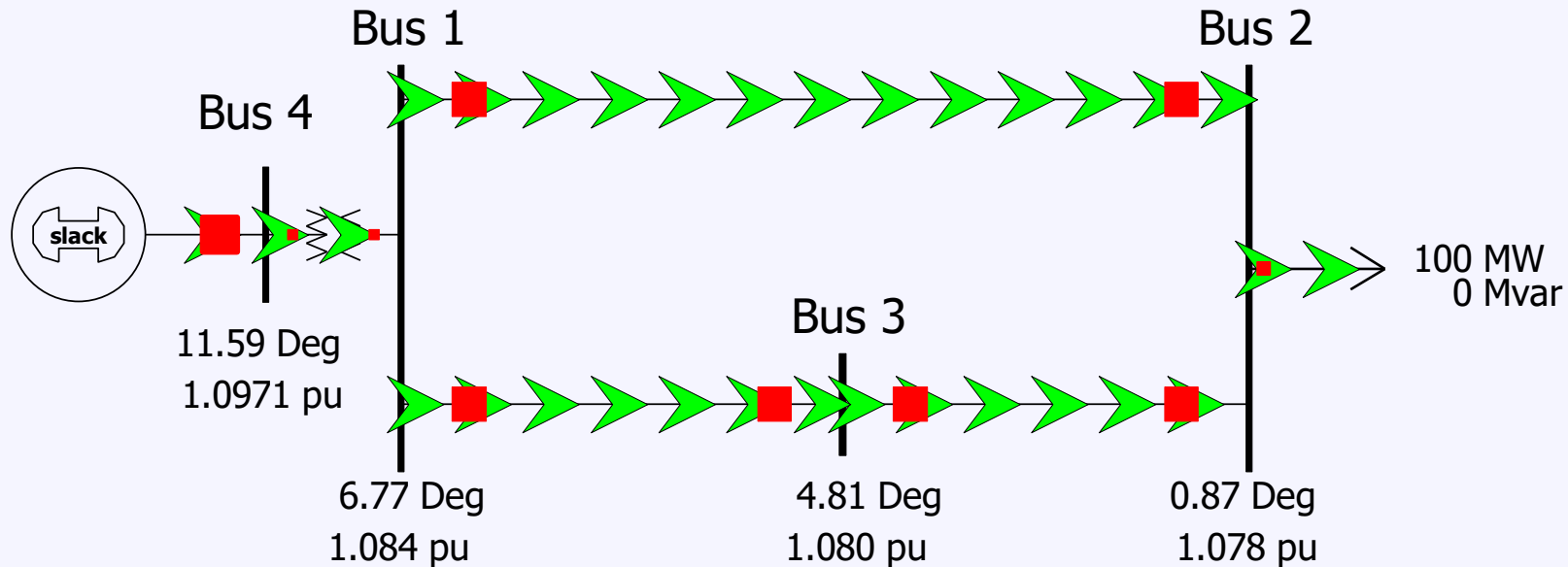
Case is **B4\_comp3**

# Compensation Benefits



- A reason for using compensation to control voltages in the transmission system is to move the source of voltage support closer to the load

Case is **B4\_comp\_voltagestability**



# Initial Limit Violations

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- 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