# ECEN 667
# Power System Stability

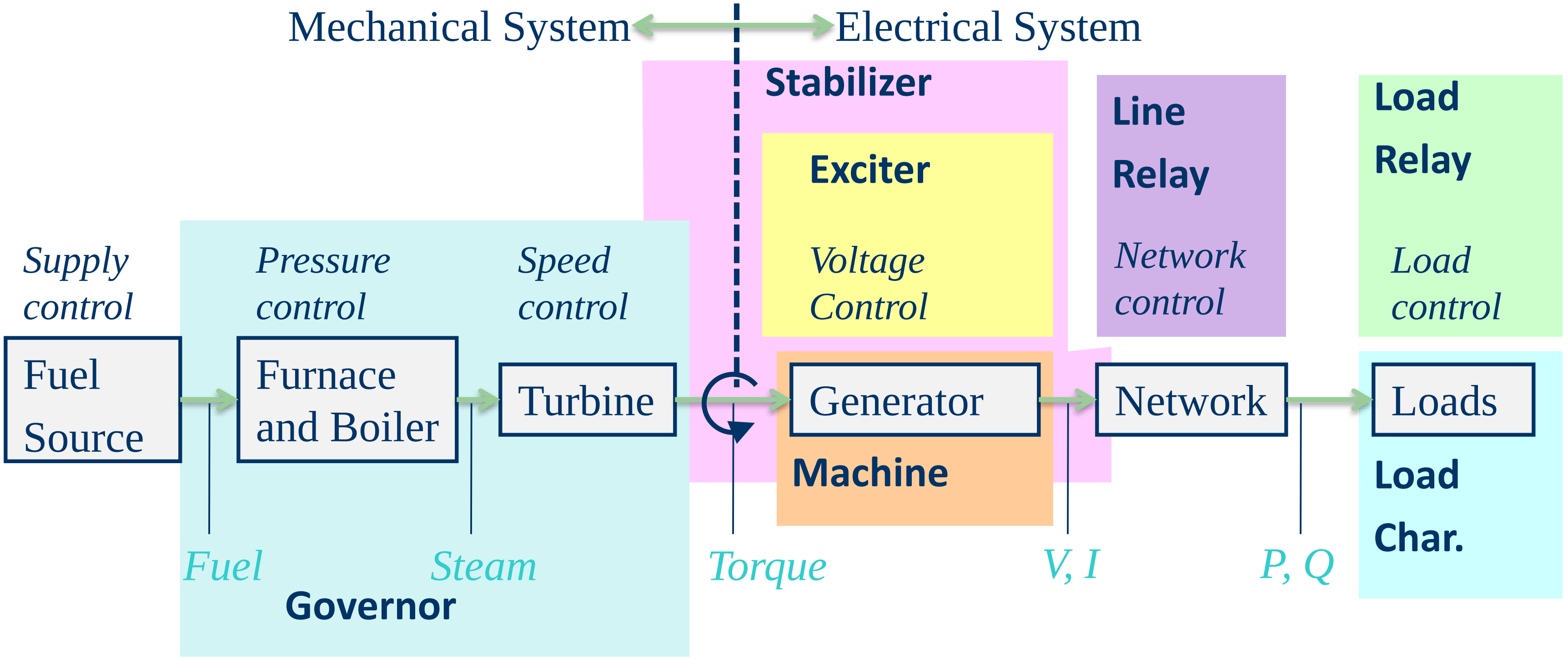
## Lecture 10: Exciters and Governors

Prof. Tom Overbye
Dept. of Electrical and Computer Engineering
Texas A&M University
overbye@tamu.edu

# Announcements

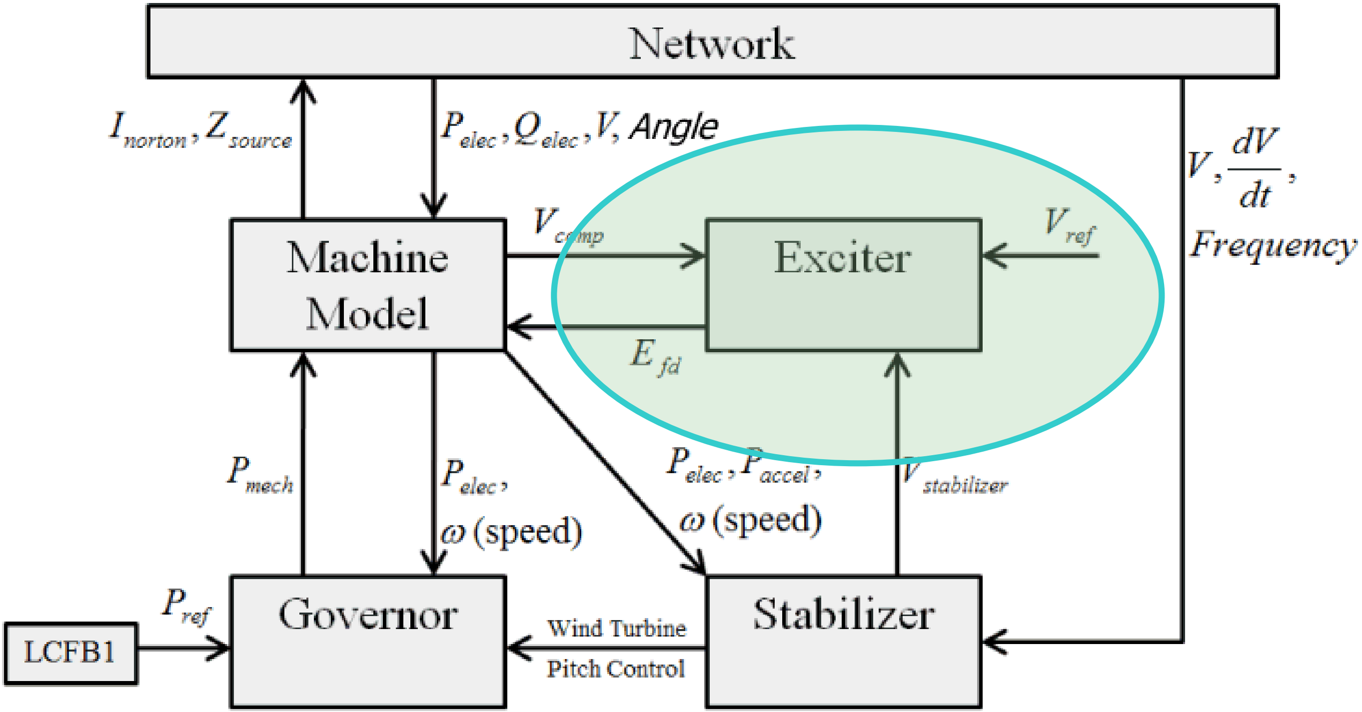
- Read Chapter 4
- Homework 3 is due on Tuesday October 1
- Exam 1 is Thursday October 10 during class; closed book, closed notes. One 8.5 by 11 inch note sheet and calculators allowed.

# Dynamic Models in the Physical Structure: Exciters



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

# Exciter Models



Network

$I_{norton}, Z_{source}$

$P_{elec}, Q_{elec}, V$, *Angle*

Machine Model

$V_{comp}$

Exciter

$V_{ref}$

$E_{fd}$

$V, \frac{dV}{dt}$, *Frequency*

$P_{mech}$

$P_{elec}$, $\omega$ (speed)

$P_{elec}, P_{accel}$, $\omega$ (speed)

$V_{stabilizer}$

LCFB1

$P_{ref}$

Governor

Wind Turbine Pitch Control

Stabilizer

$P_{elec}$ = 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

$\omega$(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)

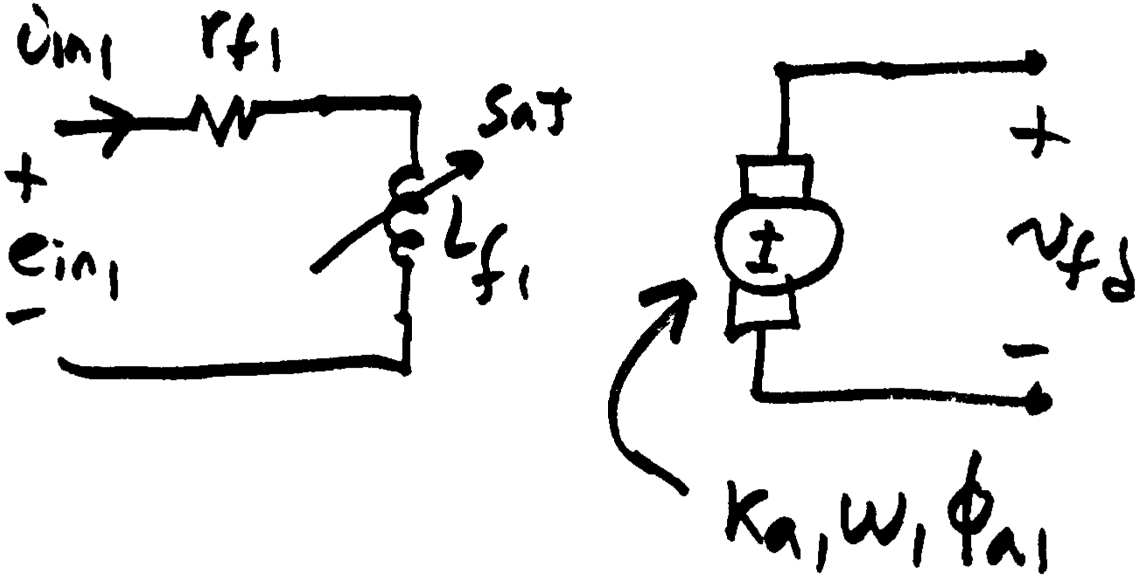
# Exciters, Including AVR

- 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

# 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)

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

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

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

# Separately Excited DC Exciter

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

Assuming a constant speed $\omega_1$

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

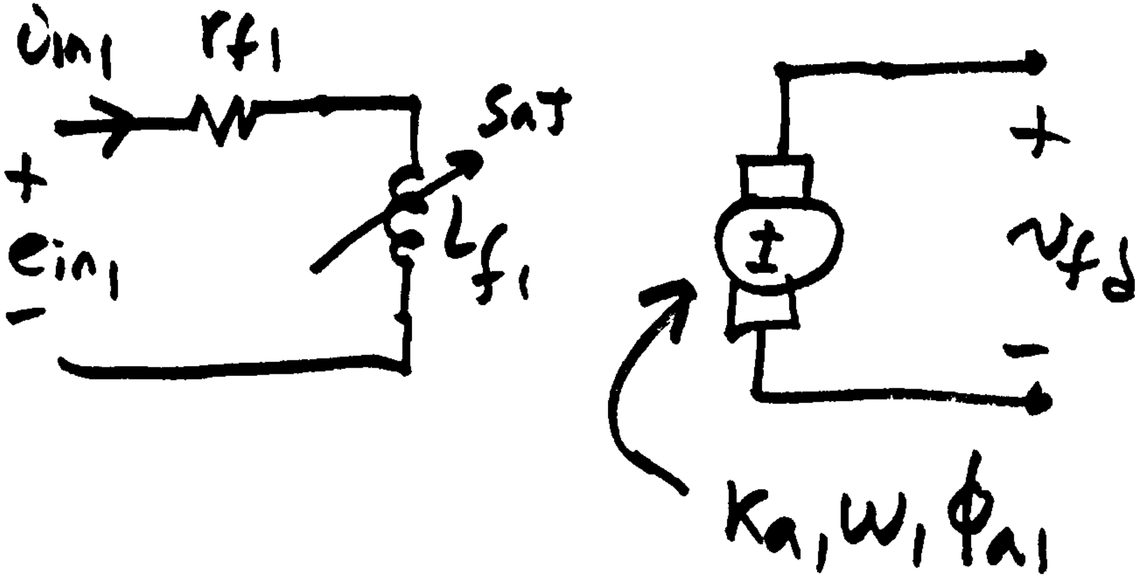
Solve above for $\phi_{f1}$ which was used in the previous slide

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

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

$$e_{in_1} = i_{in_1} r_{f1} + \frac{N_{f1}\sigma_1}{K_{a1}\omega_1}\frac{dv_{fd}}{dt}$$

# Separately Excited DC Exciter



(to sync mach)

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

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

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

# Separately Excited DC Exciter

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

Assuming a constant speed $\omega_1$

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

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

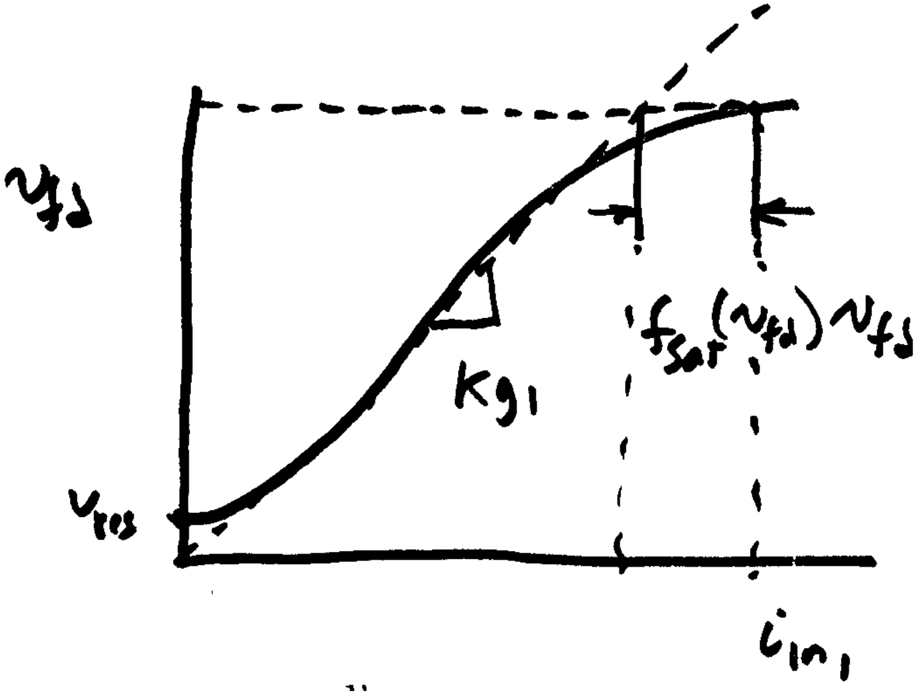
$$\phi_{f1} = \frac{\sigma_1}{K_{a1}\omega_1} v_{fd}$$

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

$$e_{in_1} = i_{in_1} r_{f1} + \frac{N_{f1}\sigma_1}{K_{a1}\omega_1} \frac{dv_{fd}}{dt}$$

# 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



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

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

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

Can be written as

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

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

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

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

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

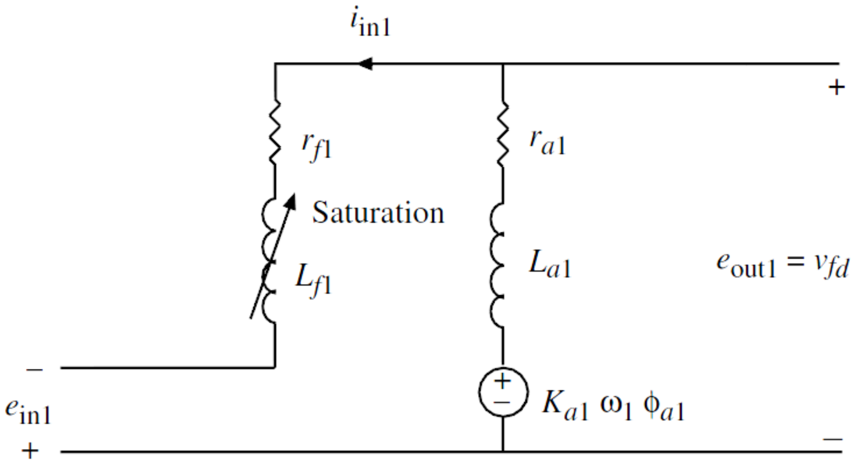
Thus we have

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

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

# The Self-Excited Exciter

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



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

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

# Self and Separated Excited Exciters

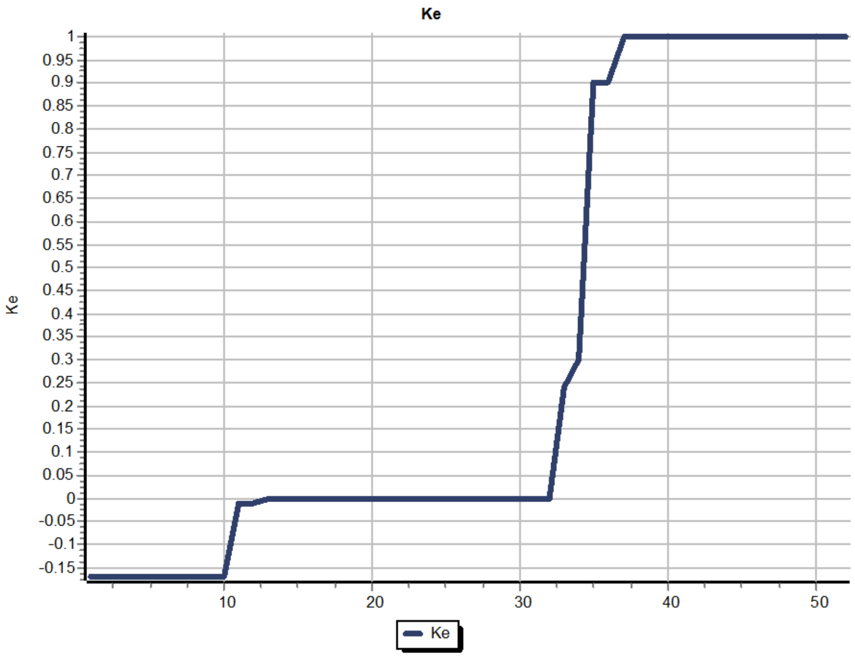
- The same model can be used for both by just modifying the value of $K_E$

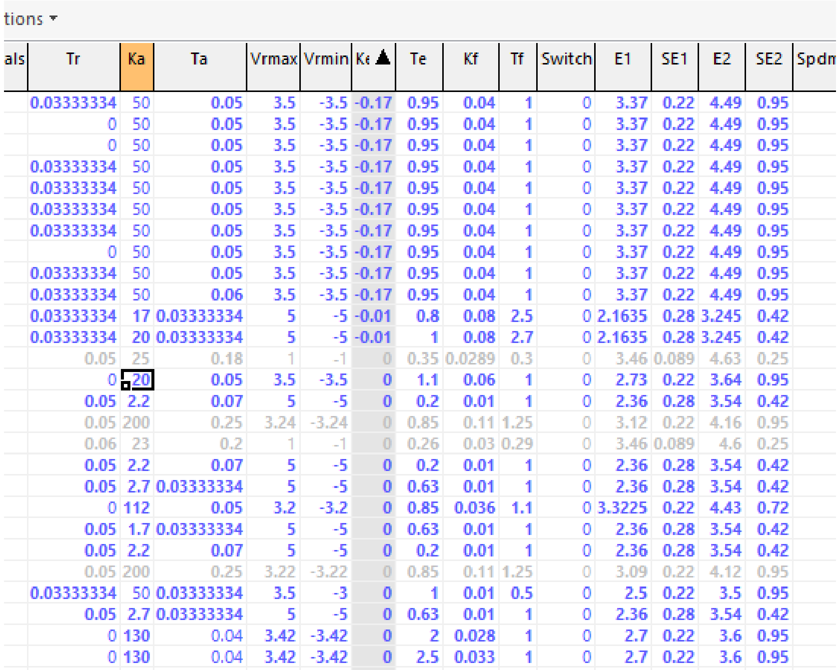
$$T_E \frac{dE_{fd}}{dt} = -\left(K_E + S_E\left(E_{fd}\right)\right)E_{fd} + V_R$$

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

# Exciter Model IEEET1 $K_E$ Values

Example IEEET1 Values from a large system





| als | Tr | Ka | Ta | Vrmax | Vrmin | Ke ▲ | 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 $S_E(E_{fd}) = \dfrac{B(E_{fd} - A)^2}{E_{fd}}$

This is the same function used with the machine models

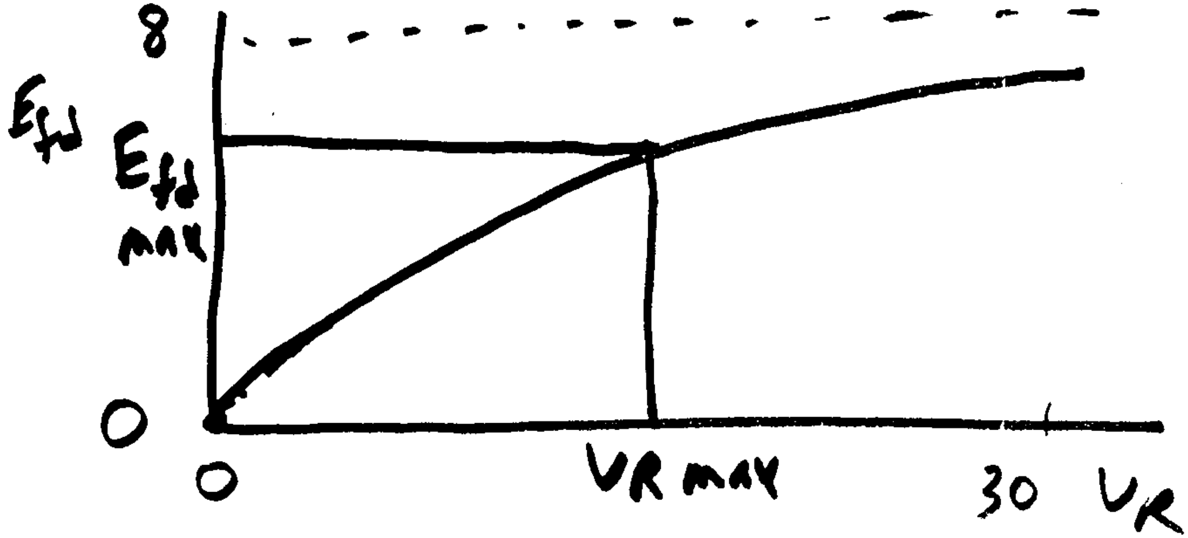
- Exponential function could also be used

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

# Exponential Saturation

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

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



# Exponential Saturation Example

Given: $K_E = -.05$

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

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

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

Find: $A_x, B_x$ and $E_{fd_{\max}}$

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

$$\Rightarrow \left\{ \begin{aligned} E_{fd_{\max}} &= 4.6 \\ A_x &= .0015 \\ B_x &= 1.14 \end{aligned} \right.$$

# Voltage Regulator Model

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

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

Modeled as a first order differential equation

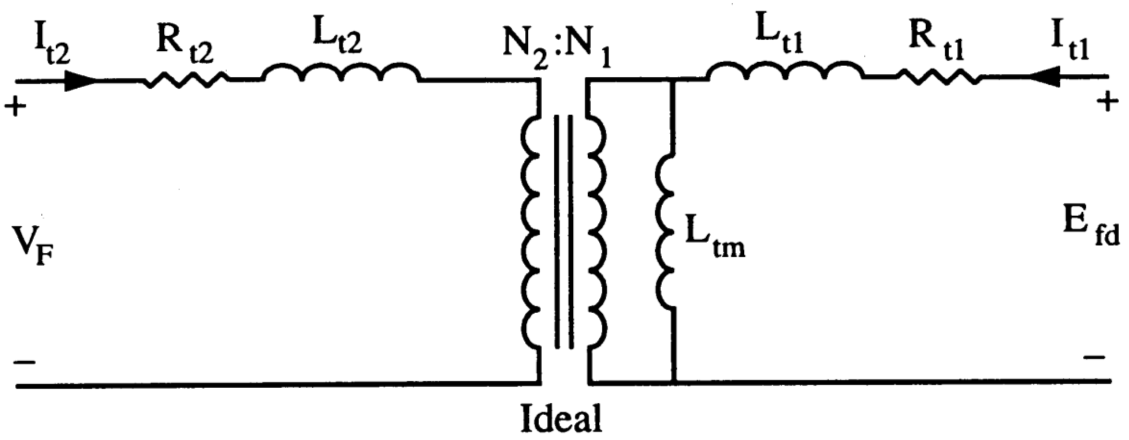
In steady state $$V_{ref} - V_t = V_{in} = \frac{V_R}{K_A}$$

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

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 $I_{t2} \approx 0$

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

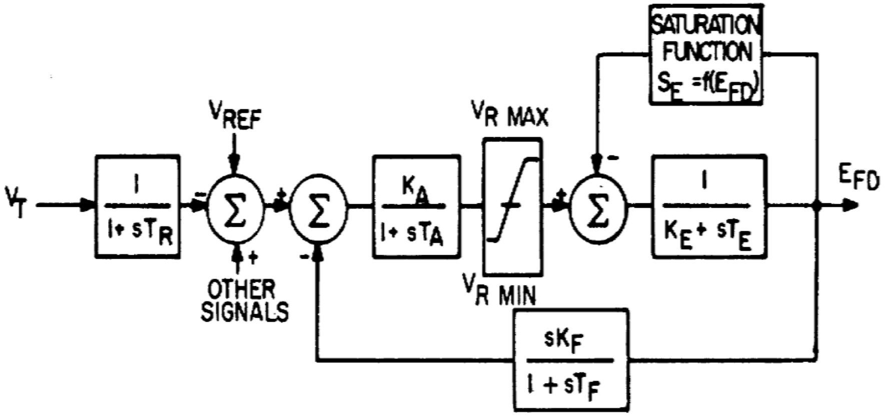
# Feedback

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

$$\frac{dV_F}{dt} = \underbrace{\frac{R_{t1}}{\left(L_{t1} + L_{tm}\right)}}_{\displaystyle \downarrow \; \frac{1}{T_F}} \left( -V_F + \underbrace{\frac{N_2}{N_1} \frac{L_{tm}}{R_{t1}}}_{\displaystyle \downarrow \; K_F} \frac{dE_{fd}}{dt} \right)$$

# IEEET1 Example

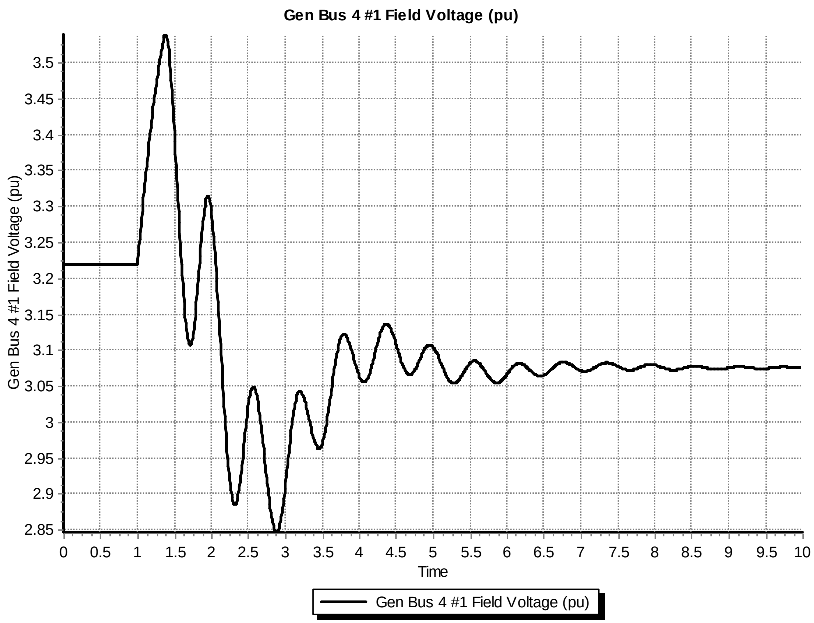
- Assume previous GENROU case with saturation. Then add a IEEE T1 exciter with Ka=50, Ta=0.04, Ke=-0.06, Te=0.6, $Vr_{max}$=1.0, $Vr_{min}$= -1.0 For saturation assume Se(2.8) = 0.04, Se(3.73)=0.33
- Saturation function is $0.1621(Efd-2.303)^2$ (for Efd > 2.303); otherwise zero
- Efd is initially 3.22
- Se(3.22)*Efd=0.437
- (Vr-Se*Efd)/Ke=Efd
- Vr =0.244
- Vref = 0.244/Ka +$V_T$ =0.0488 +1.0946=1.09948

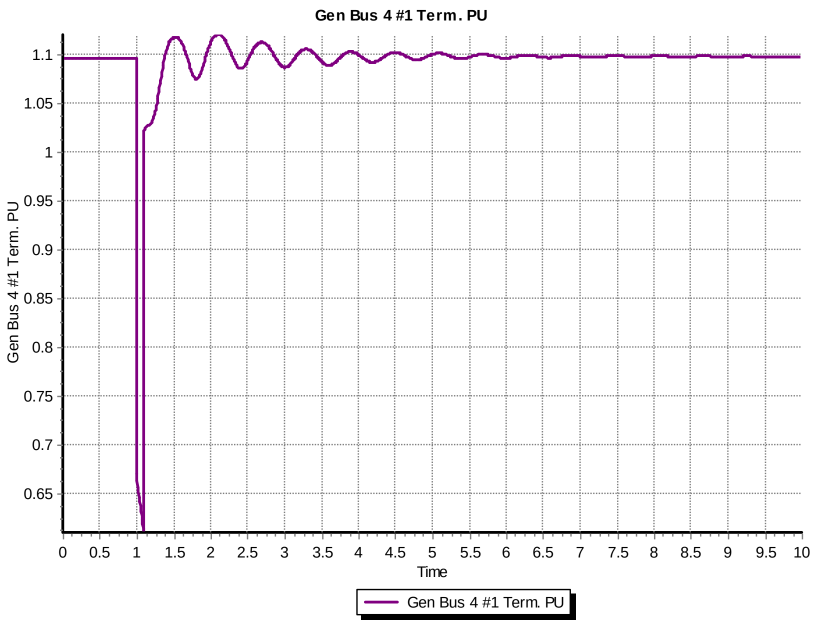


Case **B4_GENROU_Sat_IEEET1**

# IEEE T1 Example

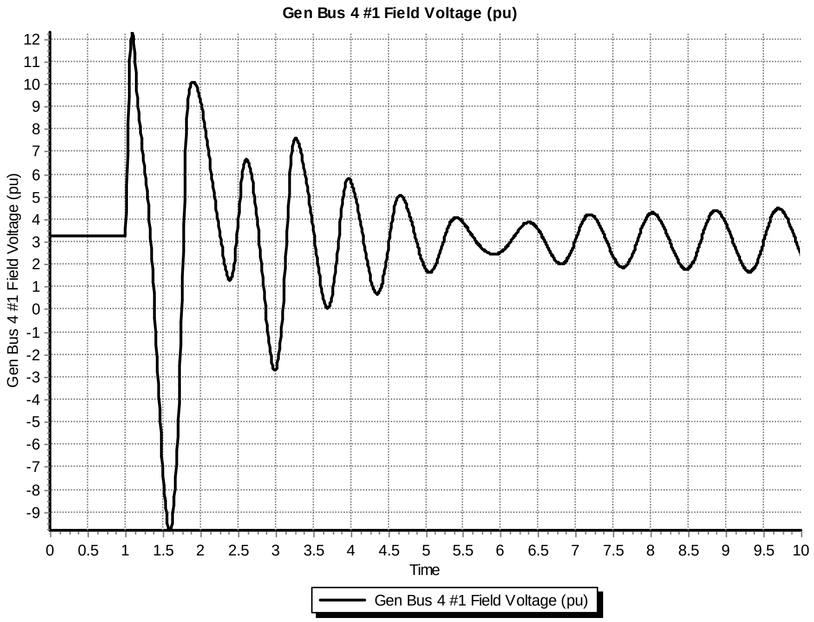
- For 0.1 second fault (from before), plot of Efd and the terminal voltage is given below
- Initial $V_4$=1.0946, final $V_4$=1.0973
  - Steady-state error depends on the value of Ka

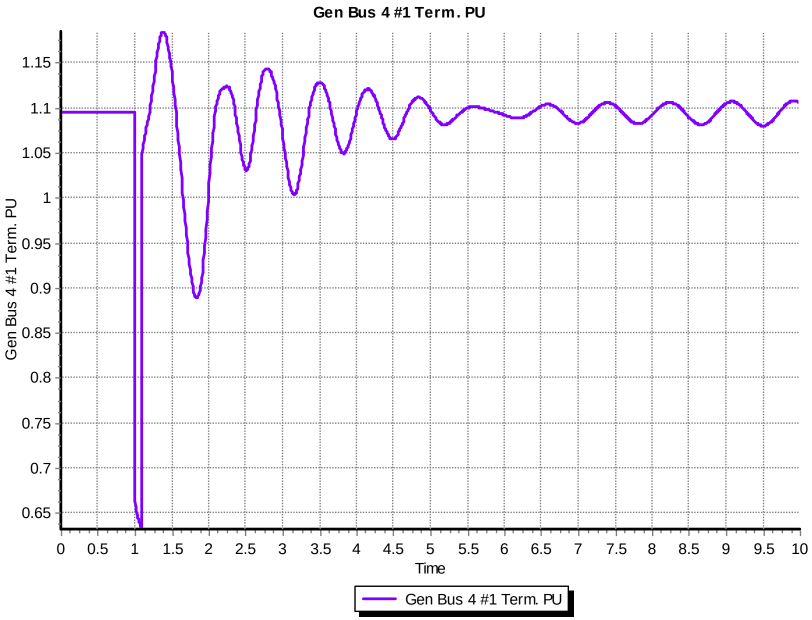




# IEEET1 Example

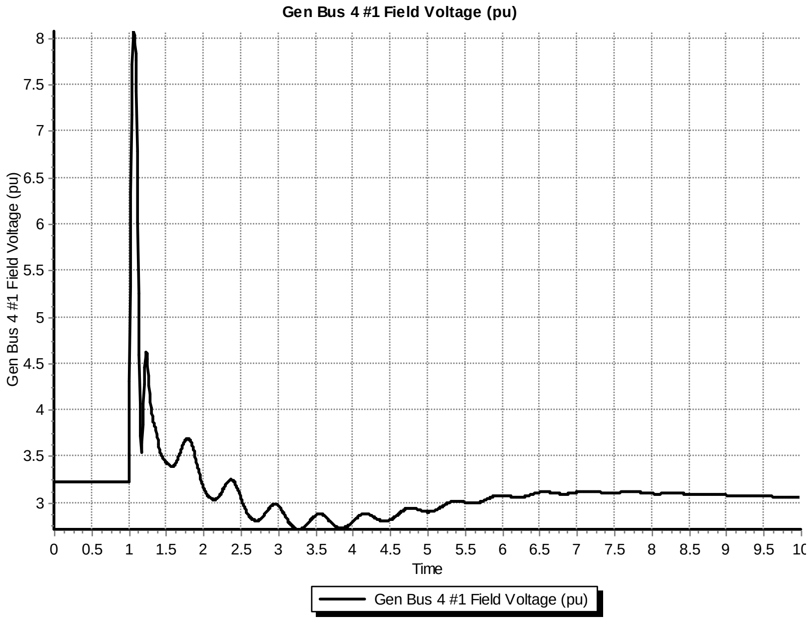
- Same case, except with Ka=500 to decrease steady-state error, no Vr limits; this case is actually unstable

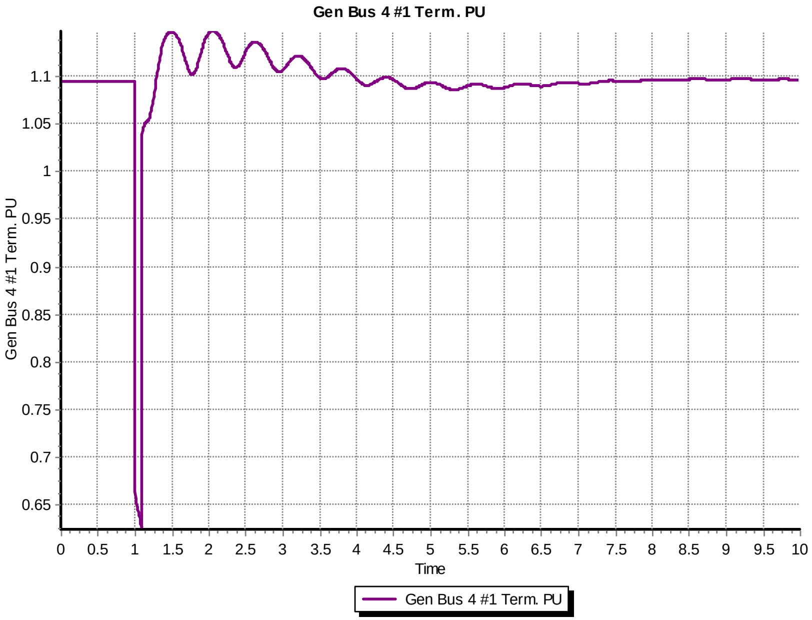




# IEEET1 Example

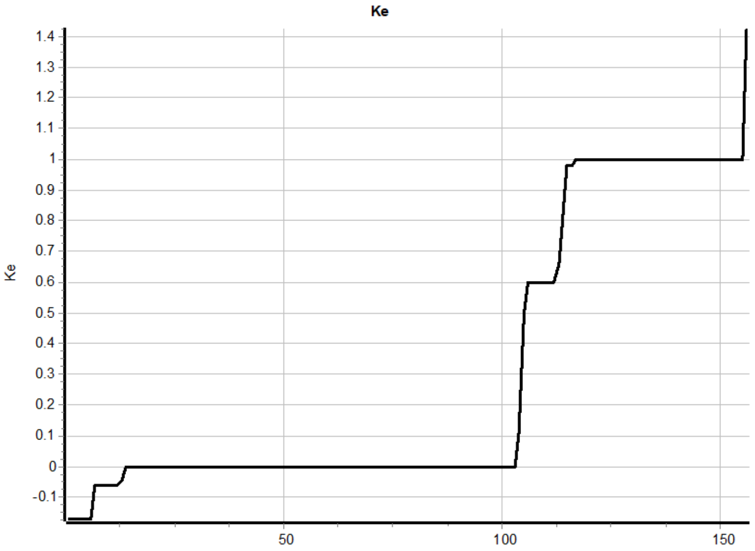
- With Ka=500 and rate feedback, Kf=0.05, Tf=0.5
- Initial $V_4$=1.0946, final $V_4$=1.0957





# 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

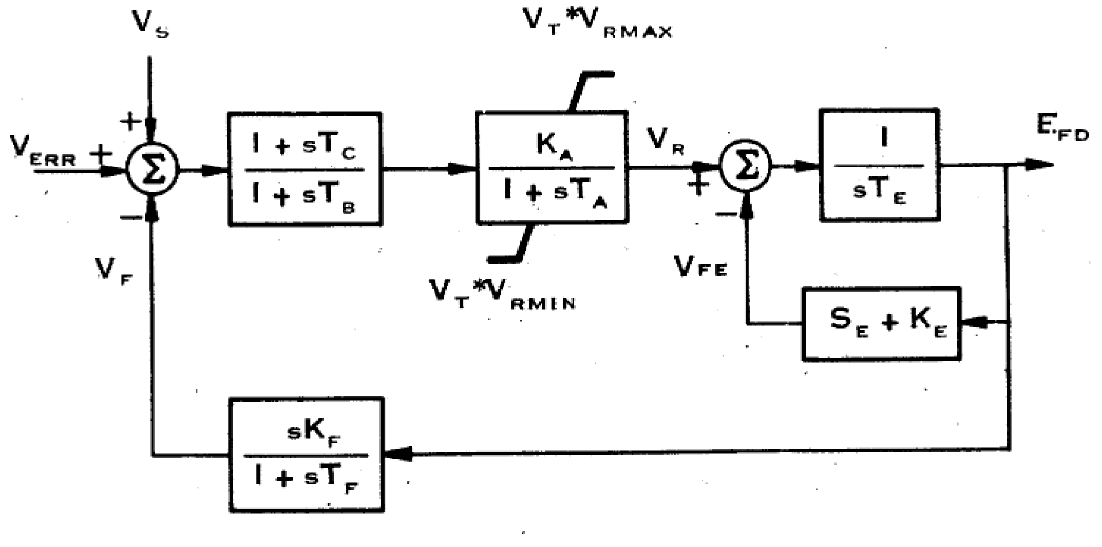


Fig. 4. Type DC2 - DC Commutator Exciter

Vr limits are multiplied by the terminal voltage

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

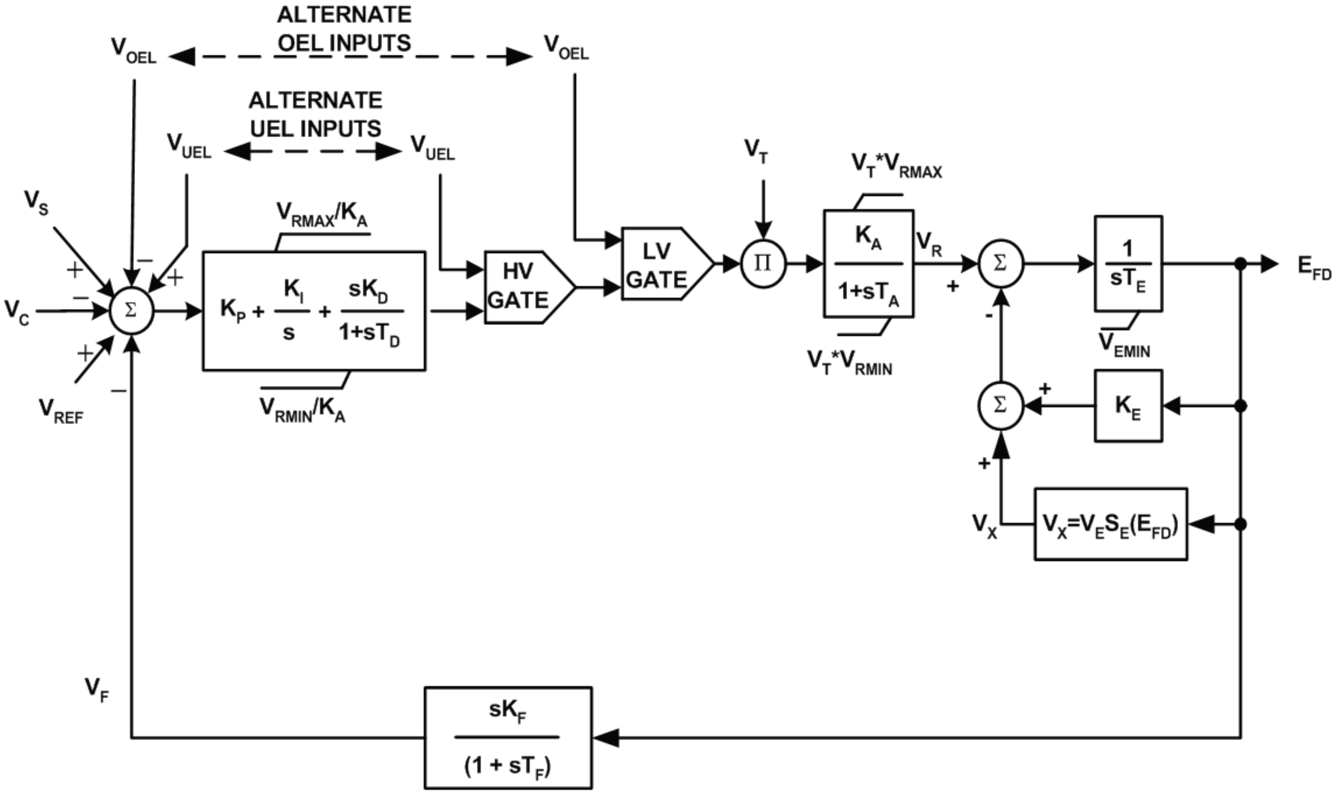


Image Source: Fig 5-4 of IEEE Std 421.5-2005

# 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 performance to a step change in input

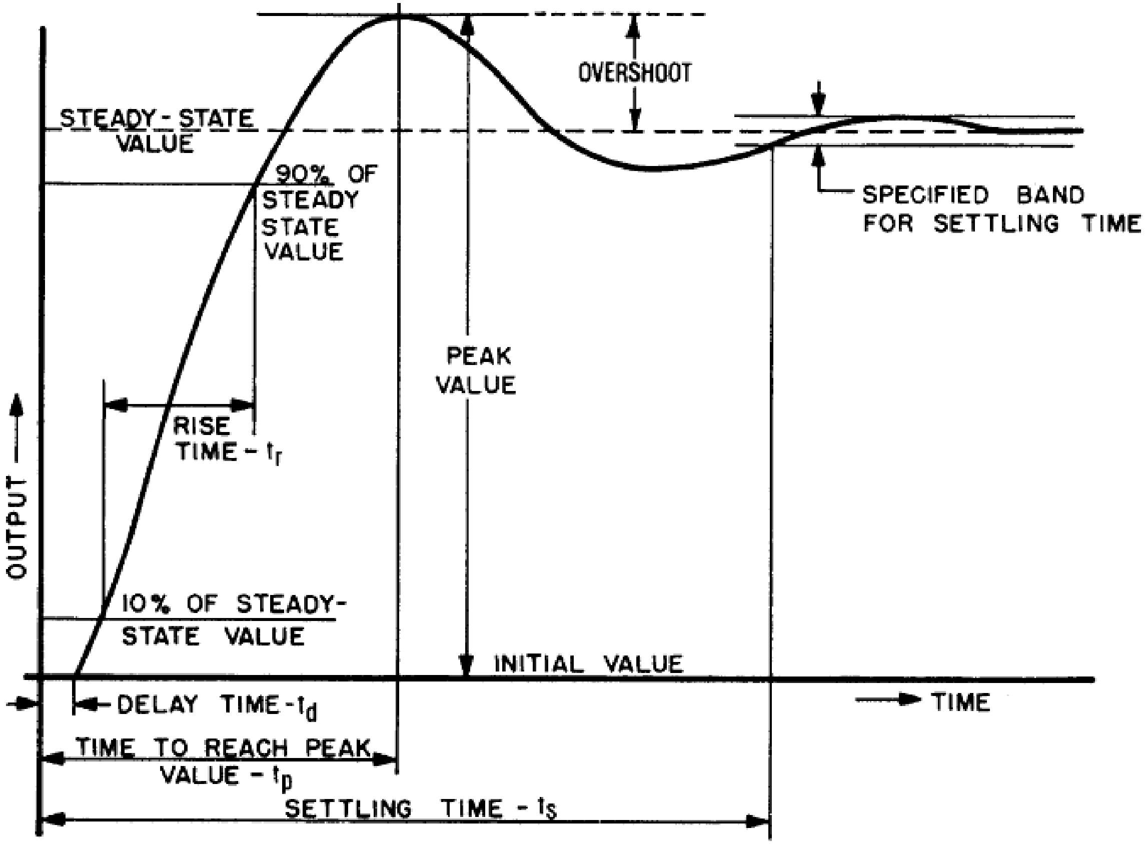


Image Source: IEEE Std 421.2-1990, Figure 3

# 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

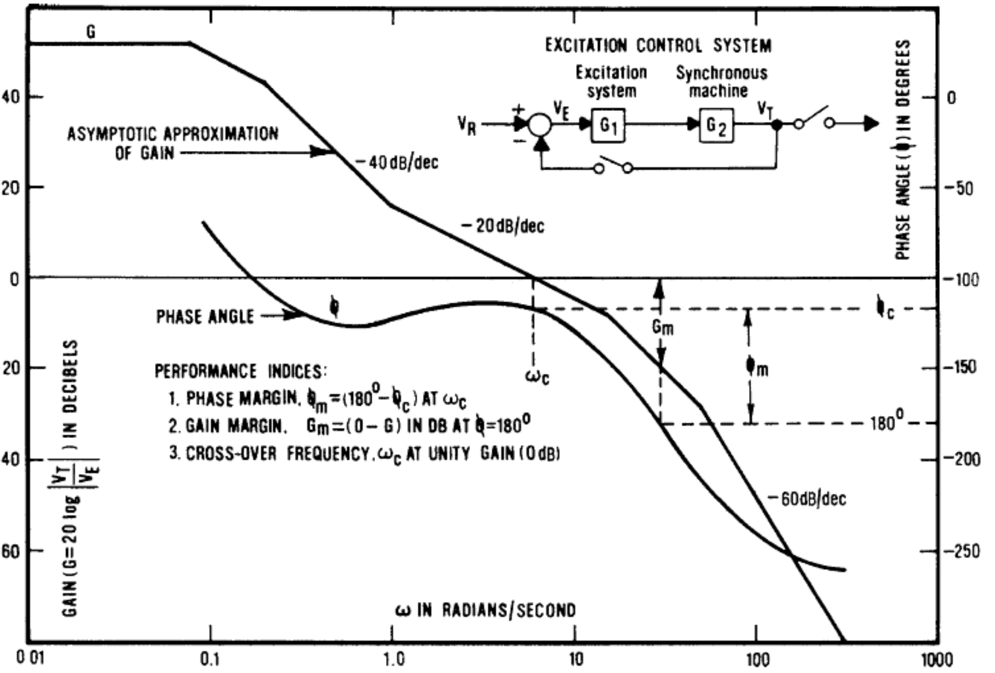


Figure 4—Typical Open-Loop Frequency Response of an Excitation Control System with the Synchronous Machine Open-Circuited

Image Source: IEEE Std 421.2-1990, Figure 4

# 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

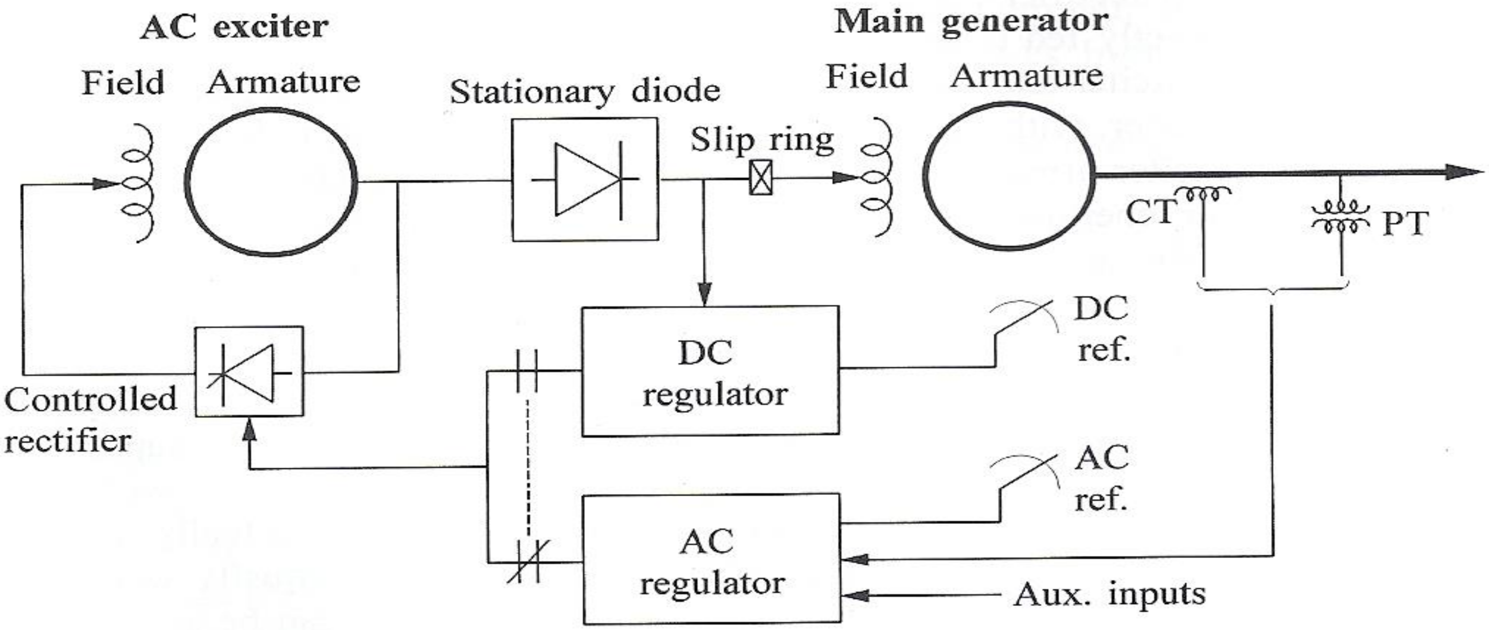
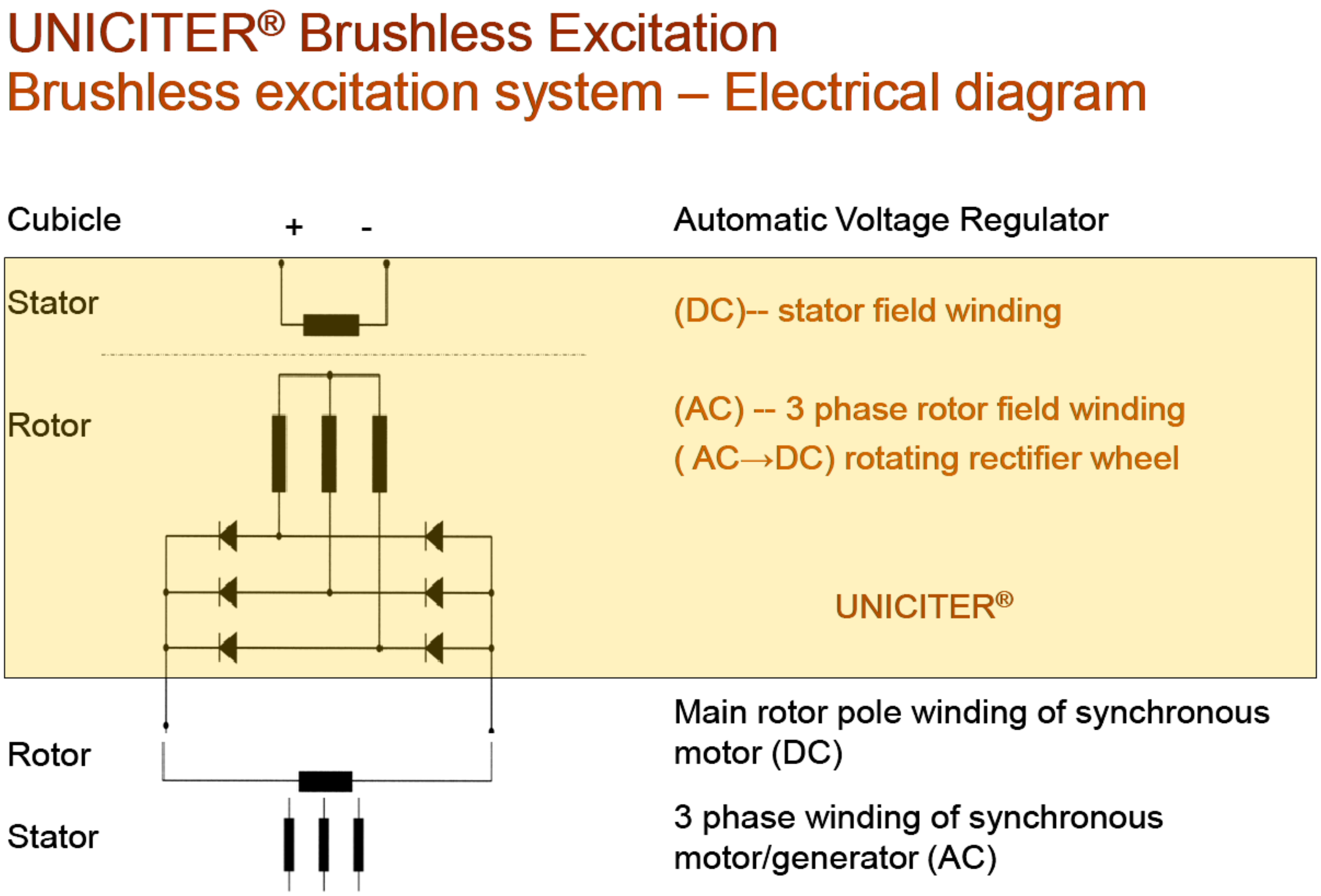


**Figure 8.3** Field-controlled alternator rectifier excitation system

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

# ABB UNICITER



## UNICITER® Brushless Excitation
## Brushless excitation system – Electrical diagram

Cubicle — Automatic Voltage Regulator

Stator — (DC)-- stator field winding

Rotor — (AC) -- 3 phase rotor field winding

( AC→DC) rotating rectifier wheel

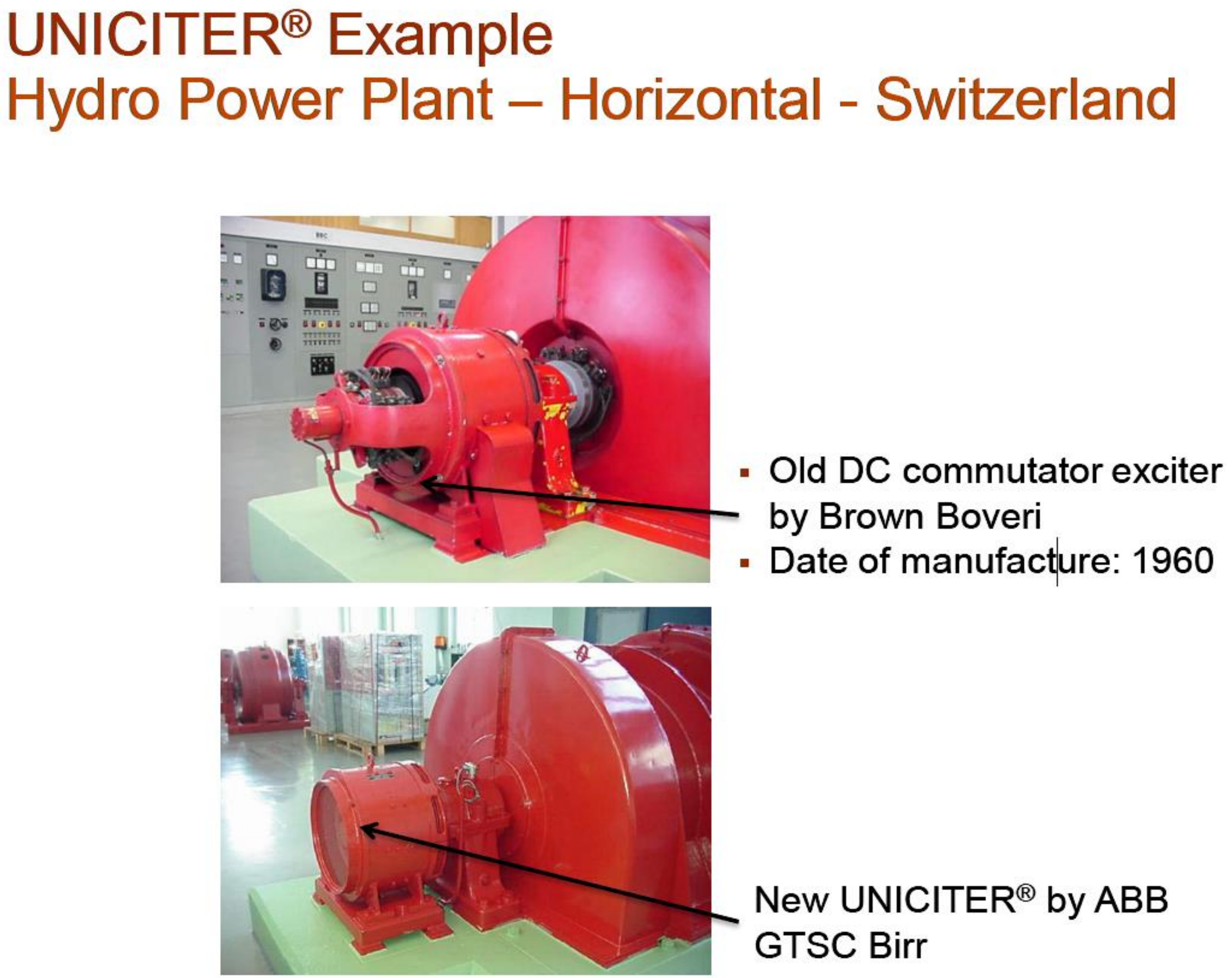
UNICITER®

Rotor — Main rotor pole winding of synchronous motor (DC)

Stator — 3 phase winding of synchronous motor/generator (AC)

Image source: www02.abb.com, Brushless Excitation Systems Upgrade,

# ABB UNICITER Example



## UNICITER® Example
## Hydro Power Plant – Horizontal - Switzerland

- Old DC commutator exciter by Brown Boveri
- Date of manufacture: 1960

New UNICITER® by ABB GTSC Birr

Image source: www02.abb.com, Brushless Excitation Systems Upgrade

# ABB UNICITER Rotor Field

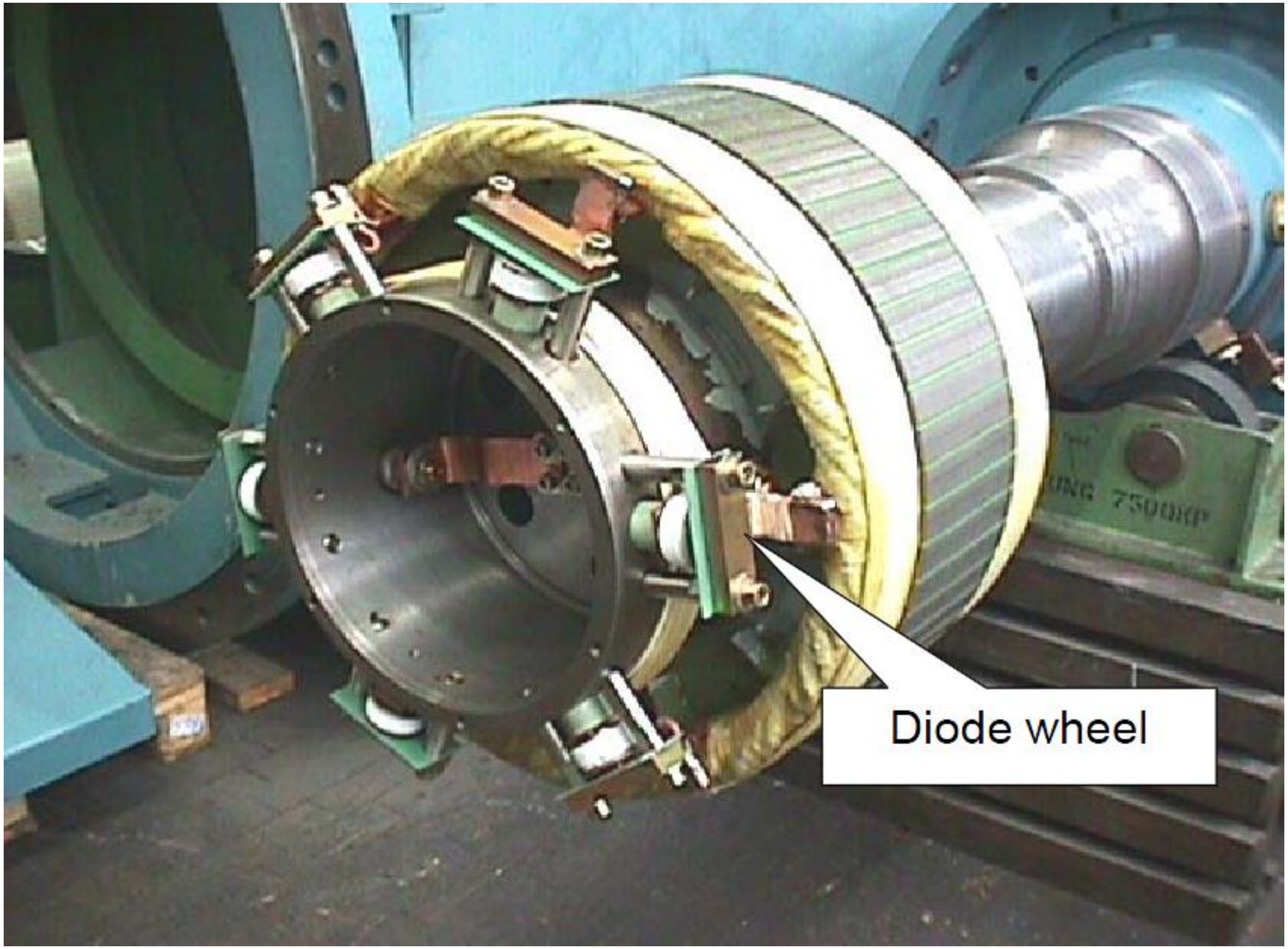
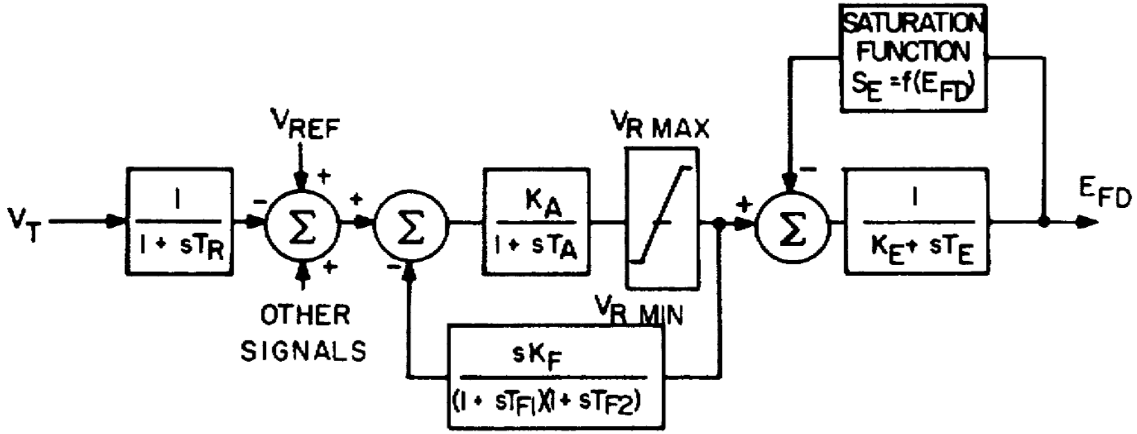


Image source: www02.abb.com, Brushless Excitation Systems Upgrade,

# AC Exciter Modeling

- Originally represented by IEEET2 shown below

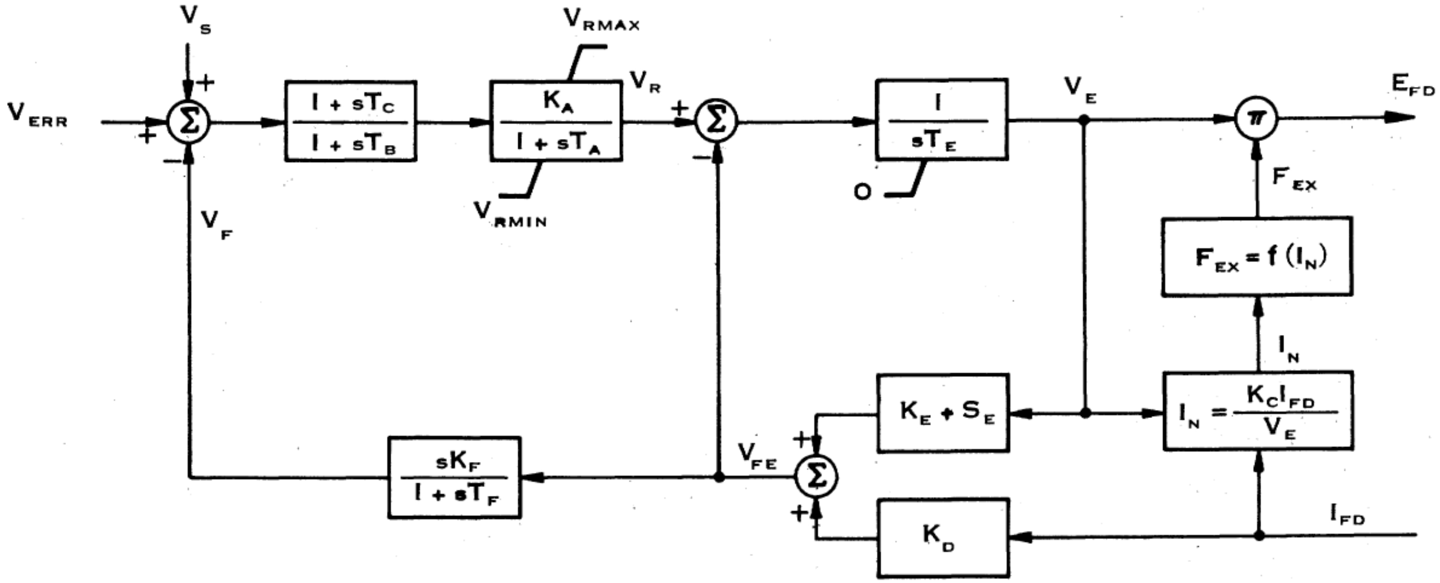


Exciter
model
is quite
similar
to IEEE T1

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

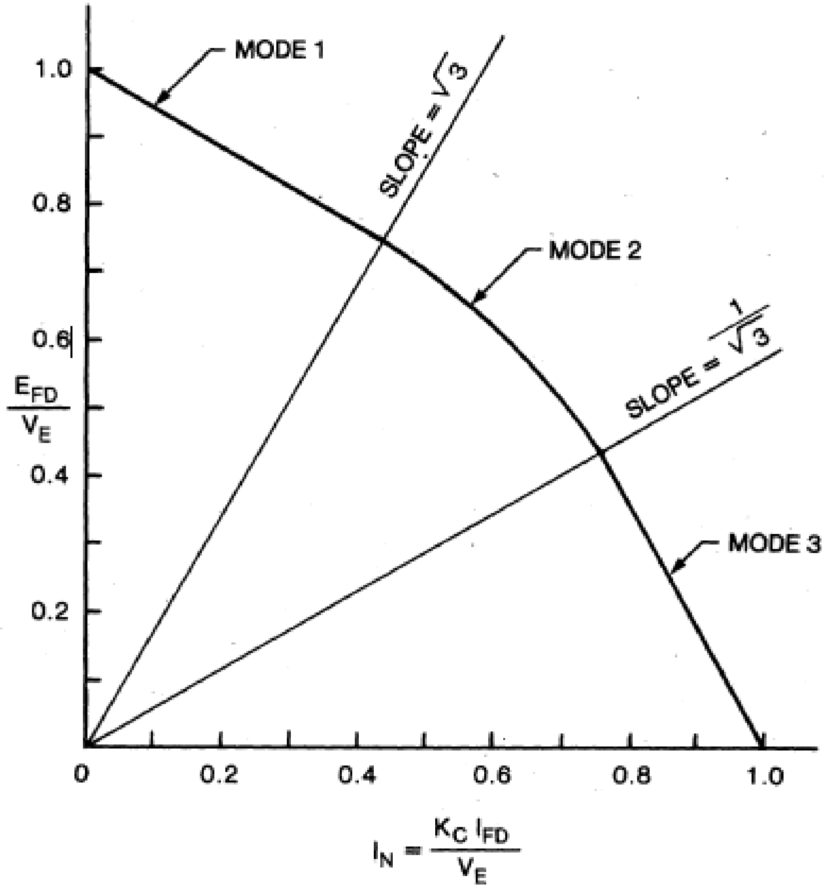


About 5% of WECC exciters are EXAC1

$K_D$ models the exciter machine reactance

Image Source: Fig 6 of "Excitation System Models for Power Stability Studies," IEEE Trans. Power App. and Syst., vol. PAS-100, pp. 494-509, February 1981

# EXAC1 Rectifier Regulation



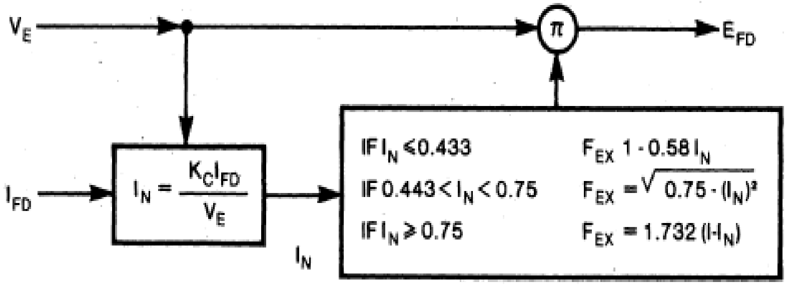


Fig. E.2. Rectifier Regulation Equations

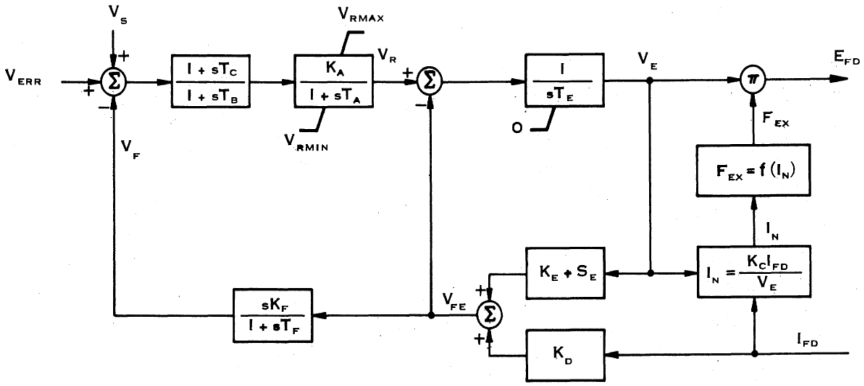
Kc represents the commuting reactance

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 Kc=0, then In=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



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

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

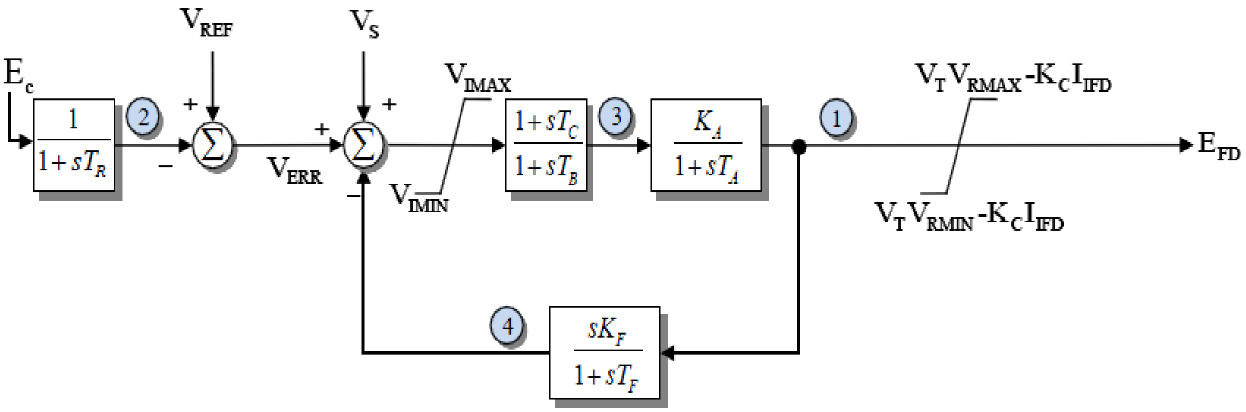
Need to check to make sure we are on this segment

# 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

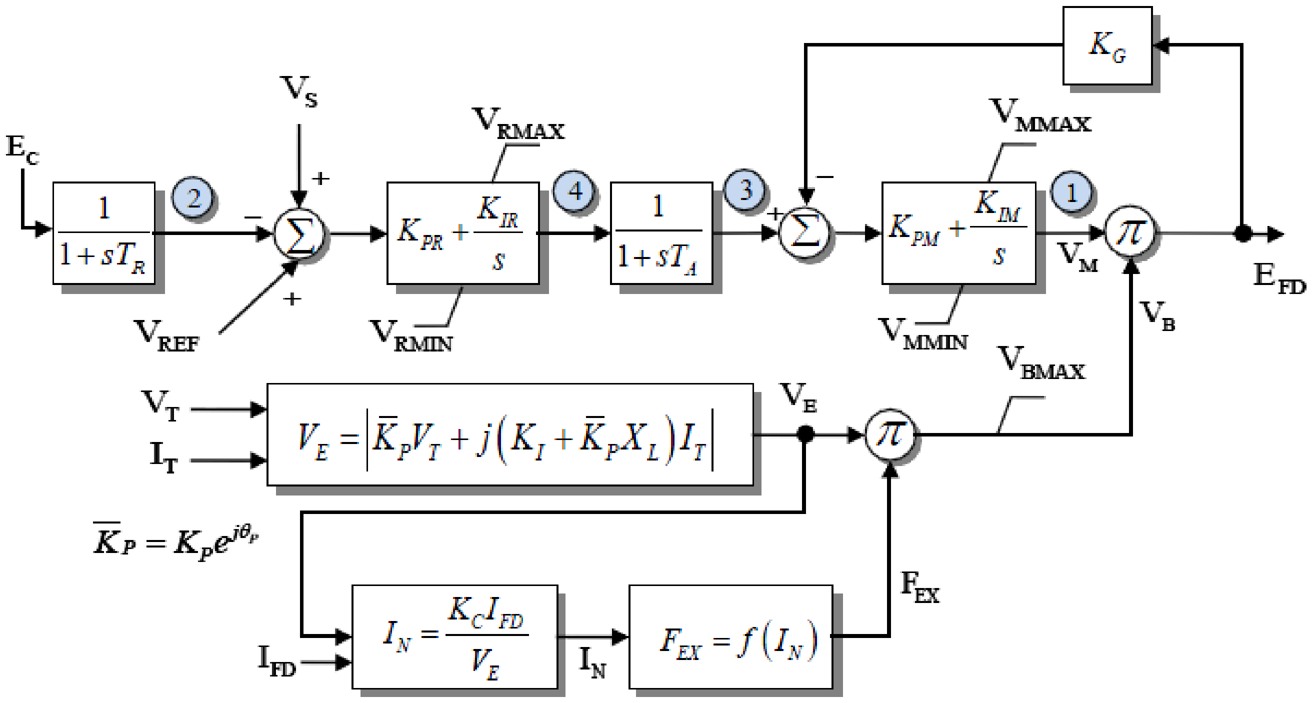


Most common exciter in WECC with about 14% modeled with this type

Kc represents the commuting reactance

# EXST4B

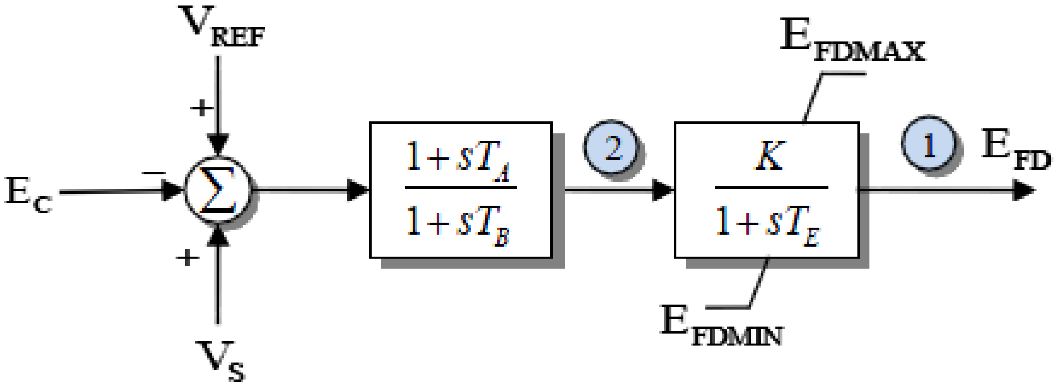
- EXST4B models a controlled rectifier design; field voltage loop is used to make output independent of supply voltage



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

# Simplified Excitation System Model

- A very simple model call Simplified EX System (SEXS) is available
  - Not now commonly used; also other, more detailed models, can match this behavior by setting various parameters to zero



# 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 Rc is zero

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

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

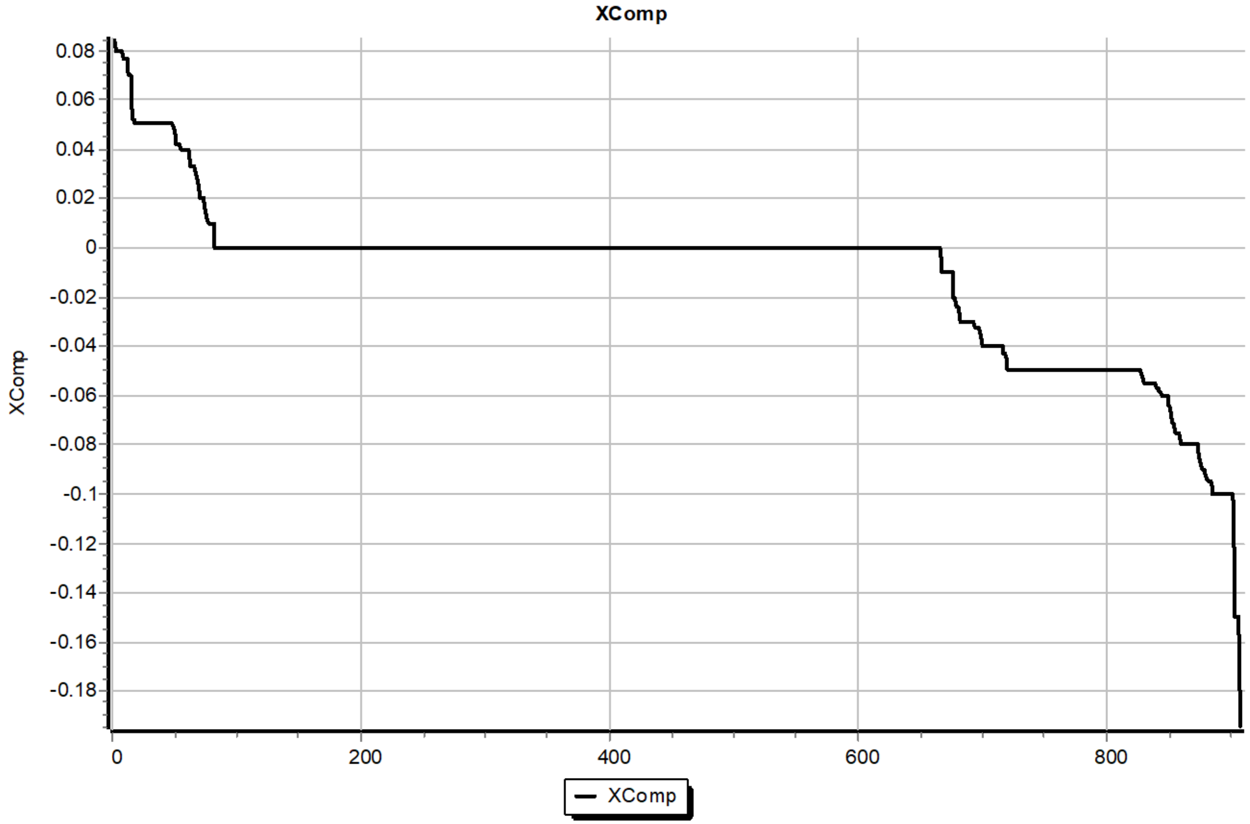
$$E_c = \left| \bar{V}_t - \left( R_c + jX_c \right) I_T \right|$$

- 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

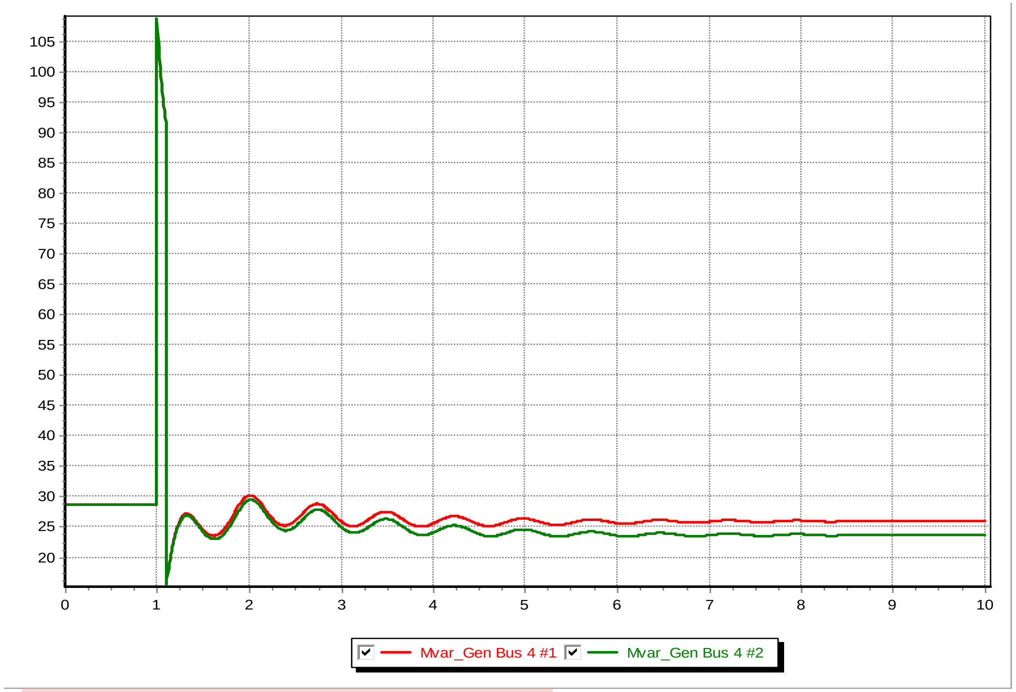
$$V_t = 1.072 + j0.22, \quad I_t = 1.0 - j0.3286$$

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

Case is **B4_comp1**

# Compensation Example 2

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



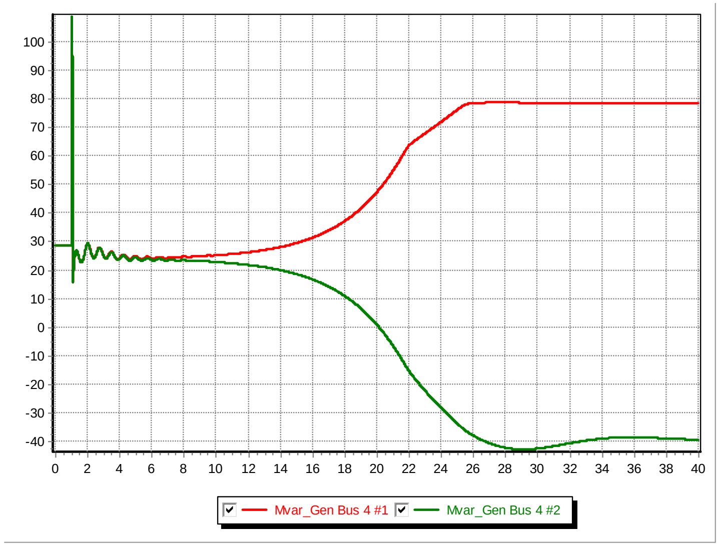
Plot shows the reactive power output of the two units, which start out equal, but diverage because of the difference values for $X_c$

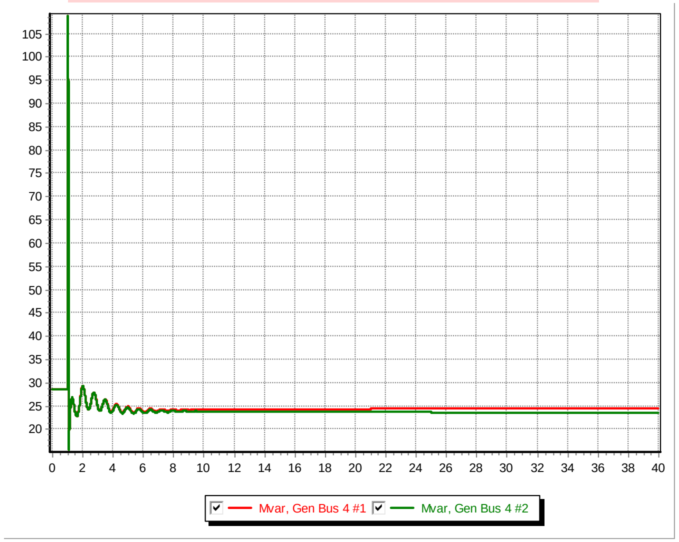
Case is **B4_comp2**

# Compensation Example 3

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

Case is **B4_comp3**

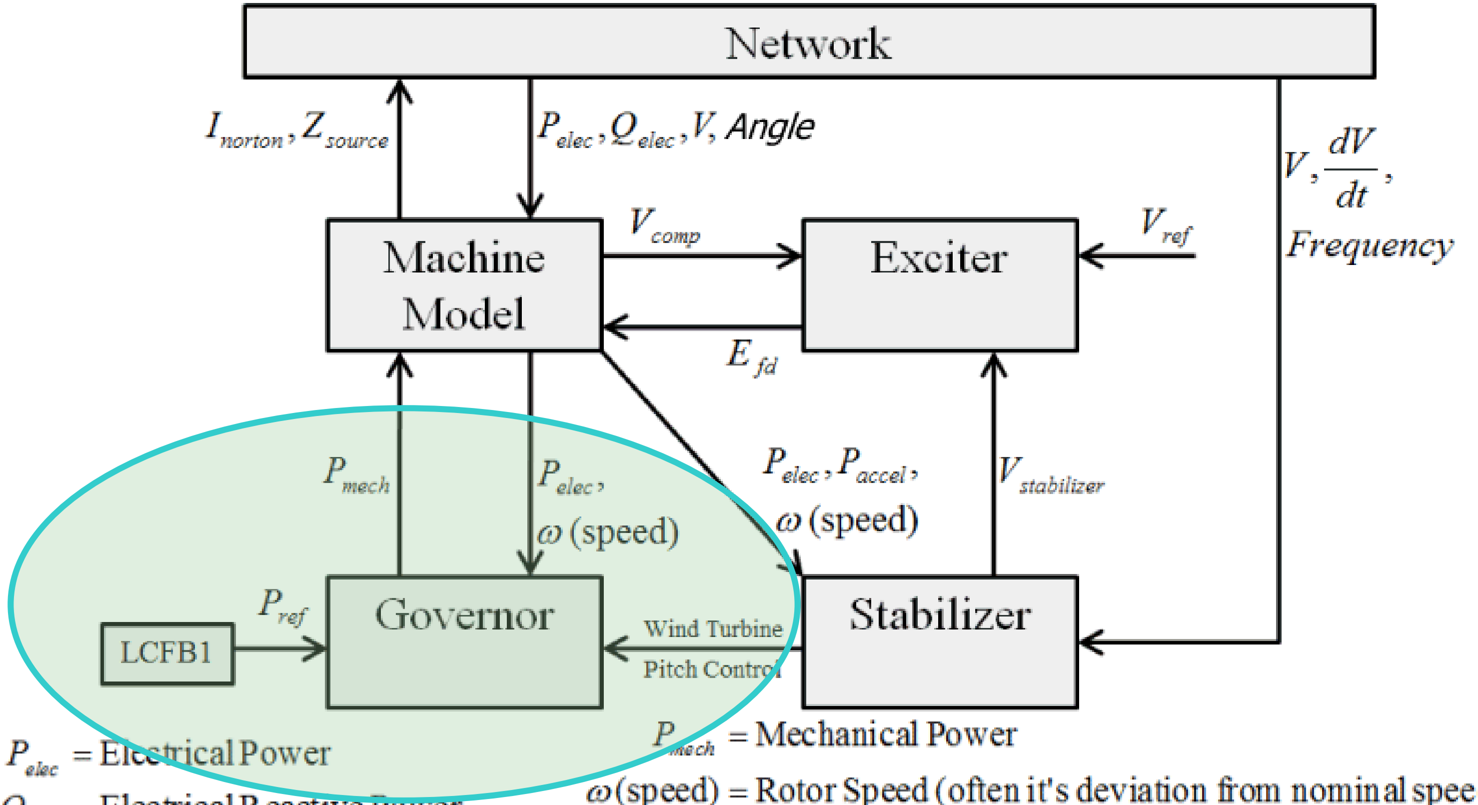




# Initial Limit Violations

- 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



$P_{elec}$ = 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
$\omega$(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)

# Prime Movers and Governors

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

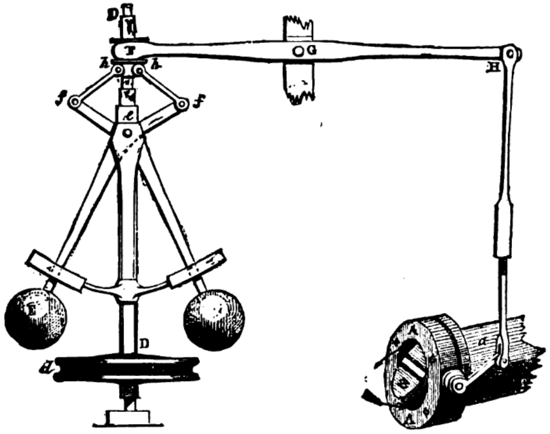


FIG. 4.—*Governor and Throttle-Valve.*

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

# Prime Movers and Governors

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