# ECEN 667
# Power System Stability

## Lecture 11: Exciter Modeling

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

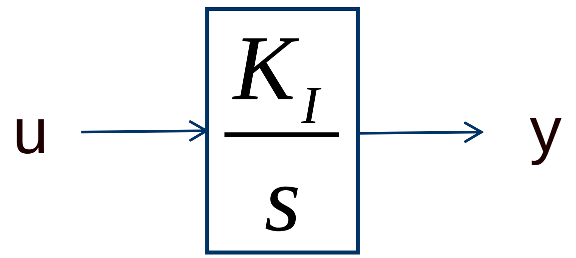
# Announcements

- Read Chapter 5; look at Appendix A
- Homework 3 should be done before the first exam, but does not need to be turned in.
- First exam is on Tuesday October 3 during class (except for the distance education students)
  - It is closed-book and closed-notes, but one 8.5 by 11 inch hand written note sheet and calculators allowed
  - My first exam from ECEN 667 in Fall 2021 has been posted to Canvas

# 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

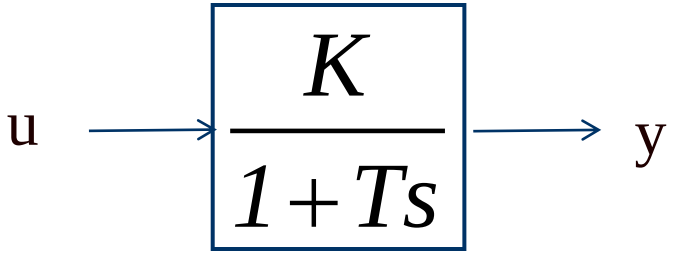


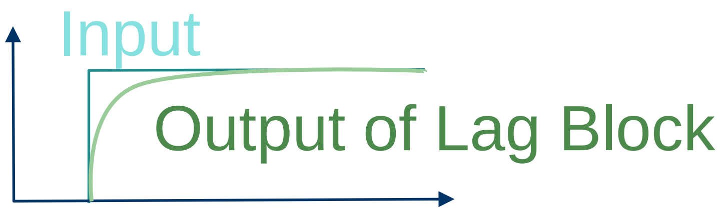

- Equation for an integrator with u as an input and y as an output is

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

- 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



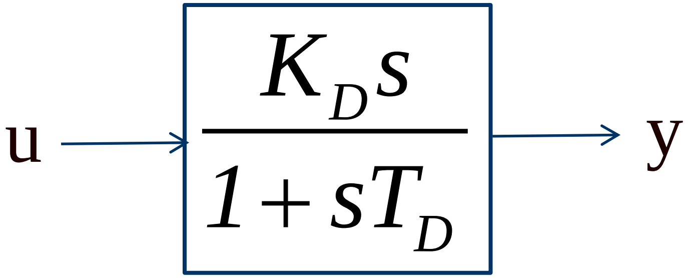




- Equation with u as an input and y as an output is

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

- 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., $T_R$ 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
  - An example is the feedback block in the IEEET1 model
- In steady-state the output of the block is zero
- State equations require a more general approach

# State Equations for More Complicated Functions

- There is not a unique way of obtaining state equations for more complicated functions with a general form

$$\beta_0 u + \beta_1 \frac{du}{dt} + \cdots + \beta_m \frac{d^m u}{dt^m} =$$

$$\alpha_0 y + \alpha_1 \frac{dy}{dt} + \cdots + \alpha_{n-1} \frac{d^{n-1} y}{dt^{n-1}} + \frac{d^n y}{dt^n}$$

- To be physically realizable we need n >= m

# General Block Diagram Approach

- One integration approach is illustrated in the below block diagram

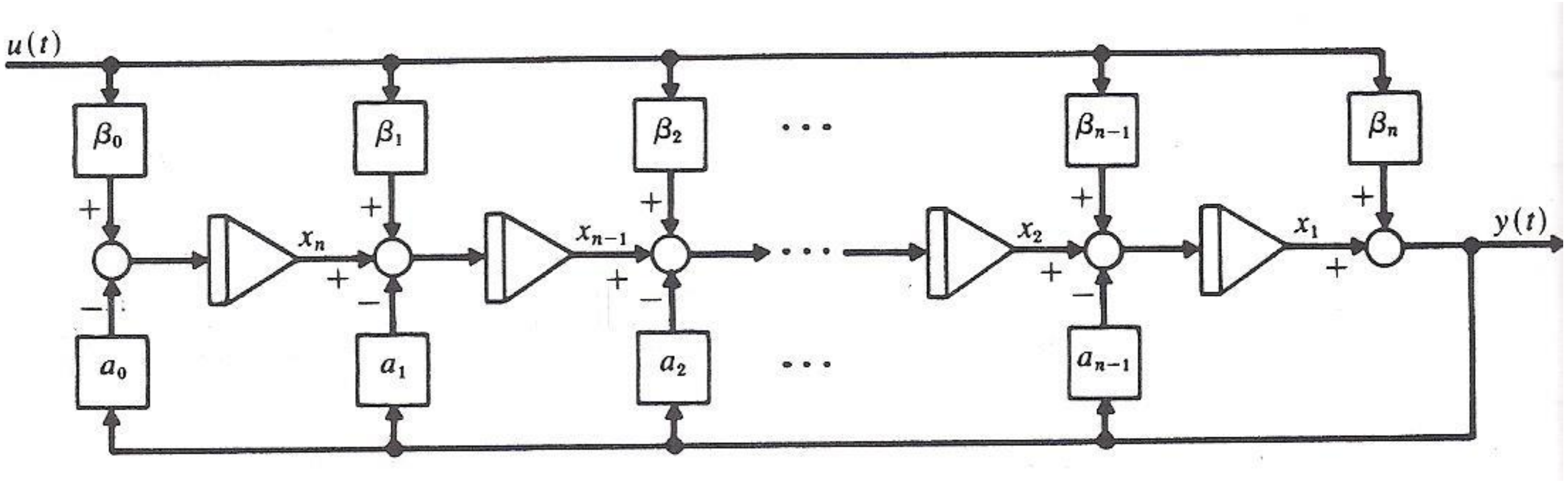
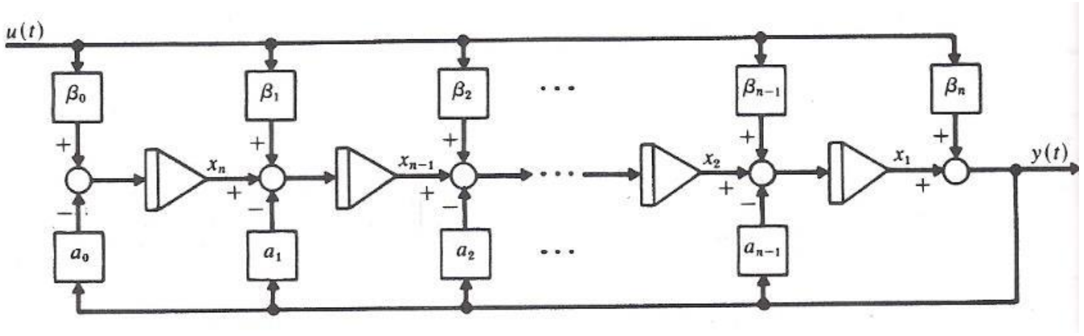



Image source: W.L. Brogan, *Modern Control Theory*, Prentice Hall, 1991, Figure 3.7

# Derivative Example

- Write in form

$$\frac{\frac{K_D}{T_D}s}{1/T_D + s}$$




- Hence $\beta_0=0$, $\beta_1=K_D/T_D$, $\alpha_0=1/T_D$
- Define single state variable x, then

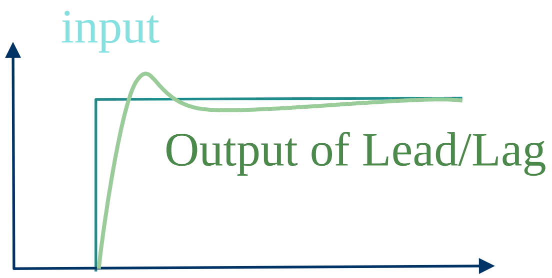
$$\frac{dx}{dt} = \beta_0 u - \alpha_0 y = -\frac{y}{T_D}$$

$$y = x + \beta_1 u = x + \frac{K_D}{T_D}u$$

Initial value of
x is found by recognizing
y is zero so $x = -\beta_1 u$

# Lead-Lag Block

$$u \rightarrow \boxed{\frac{1+sT_A}{1+sT_B}} \rightarrow y$$




The steady-state requirement that u = y is readily apparent

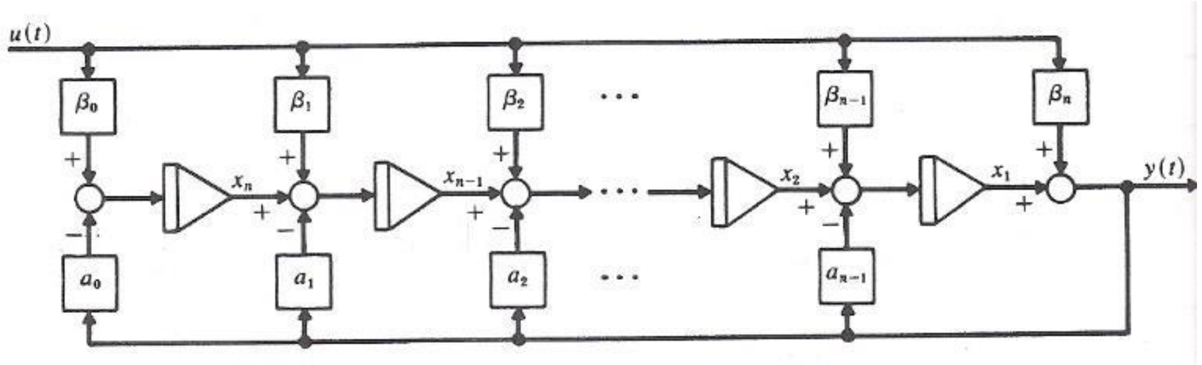
- In exciters such as the EXDC1 the lead-lag block is used to model time constants inherent in the exciter; the values are often zero (or equivalently equal)
- In steady-state the input is equal to the output
- To get equations write
  in form with $\beta_0=1/T_B$, $\beta_1=T_A/T_B$,
  $\alpha_0=1/T_B$

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

# Lead-Lag Block

- The equations are with

  $\beta_0=1/T_B$, $\beta_1=T_A/T_B$,
  $\alpha_0=1/T_B$



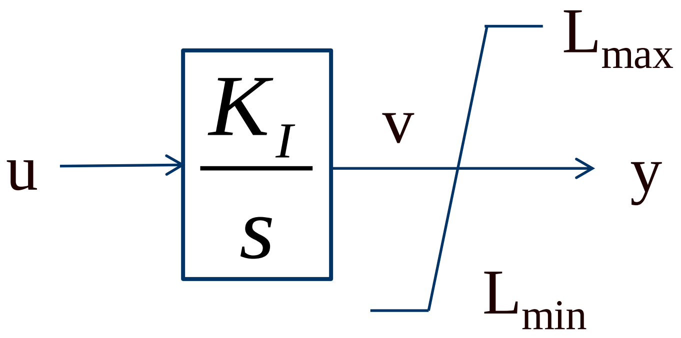

then

$$\frac{dx}{dt}=\beta_0 u-\alpha_0 y=\frac{1}{T_B}\left(u-y\right)$$

$$y=x+\beta_1 u=x+\frac{T_A}{T_B}u$$

# 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



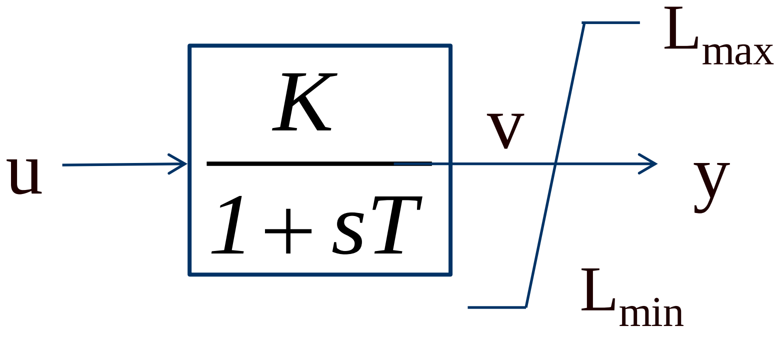

The value of v is NOT limited, so its value can "windup" beyond the limits, delaying backing off of the limit

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

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 $y = L_{max}$

# 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 $y = v$

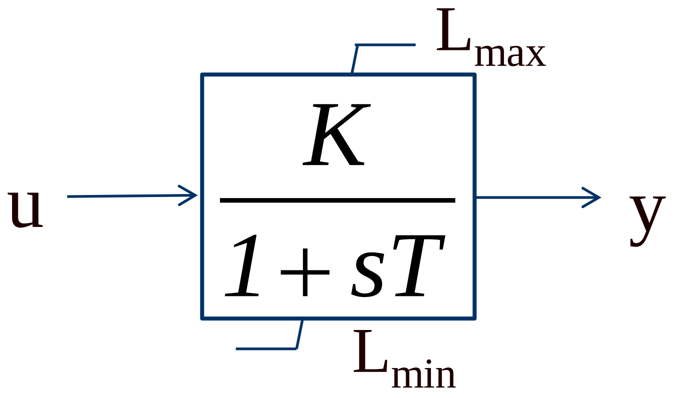
else If $v < L_{min}$ then $y = L_{min}$,

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




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

(except as indicated below)

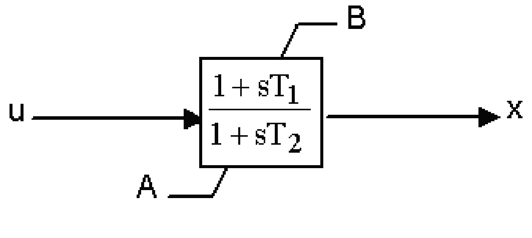
If $L_{min} \leq y \leq L_{max}$ then normal $\frac{dy}{dt} = \frac{1}{T}\left(Ku - y\right)$

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

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

# Lead-Lag Non-Windup Limits

- There is not a unique way to implement non-windup limits for a lead-lag. This is the one from IEEE 421.5-1995 (Figure E.6)



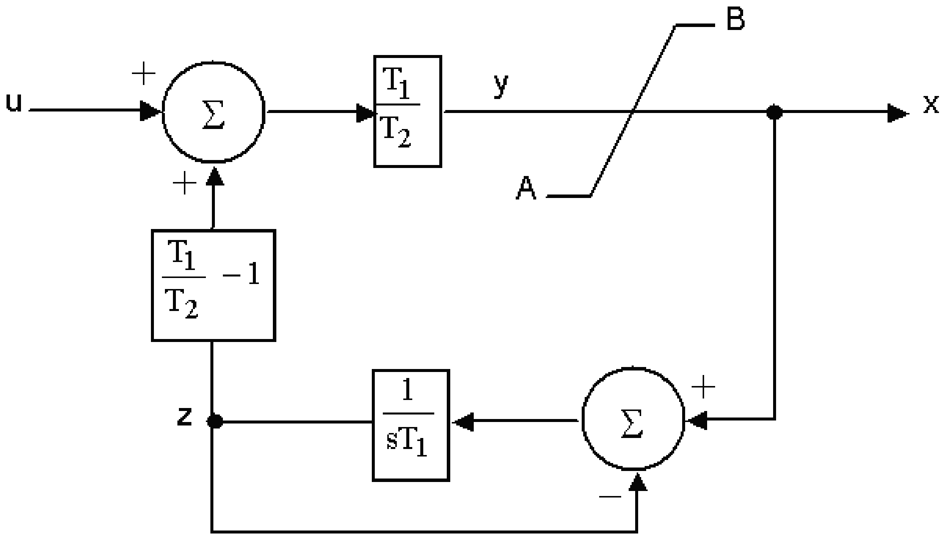

(a) Model

$T_2 > T_1, T_1 > 0, T_2 > 0$

If $y > B$, then $x = B$

If $y < A$, then $x = A$

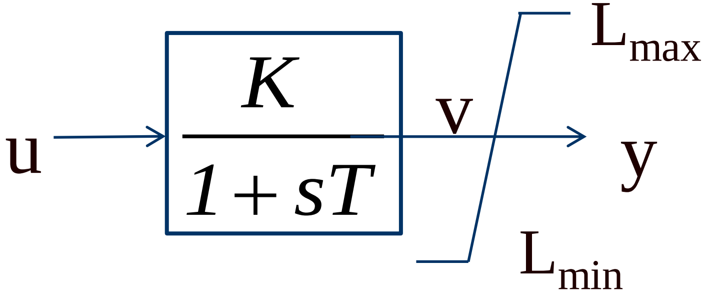
If $B \geq y \geq A$, then $x = y$




(b) Implementation

# Ignored States

- When integrating block diagrams often states are ignored, such as a measurement delay with $T_R$=0
- In this case the differential equations just become algebraic constraints
- Example: For block at right, as T→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 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 $i_f$

# Review 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

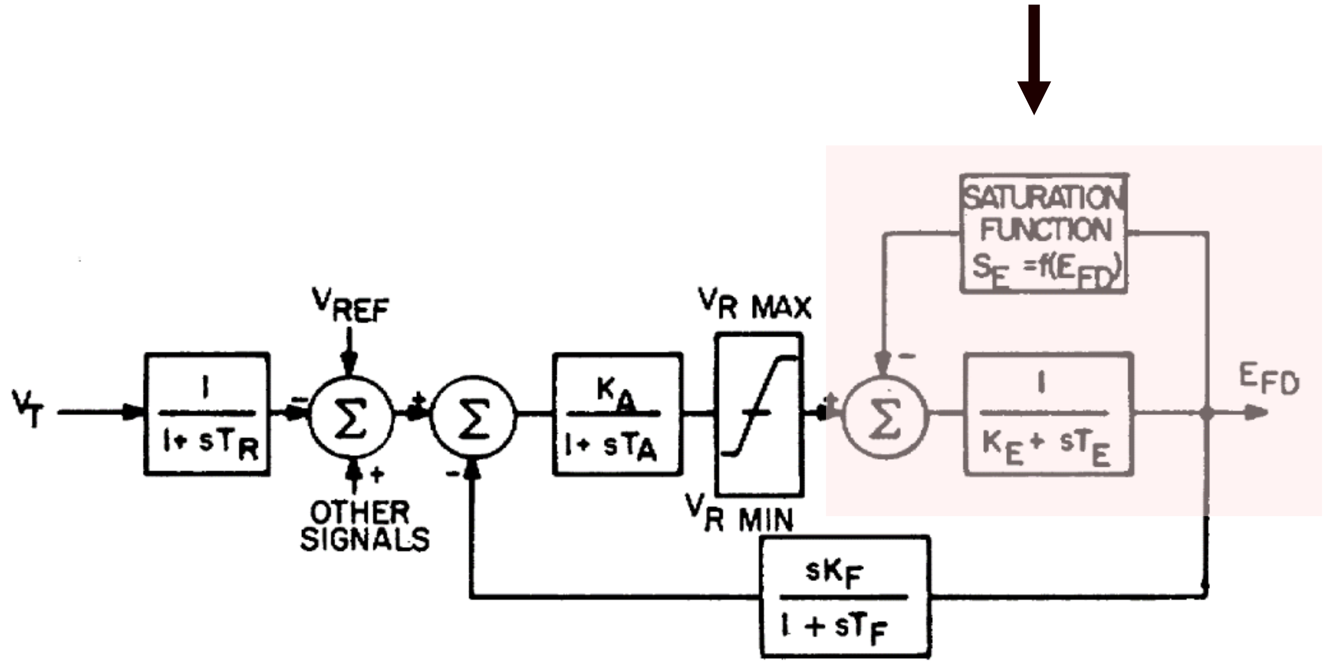
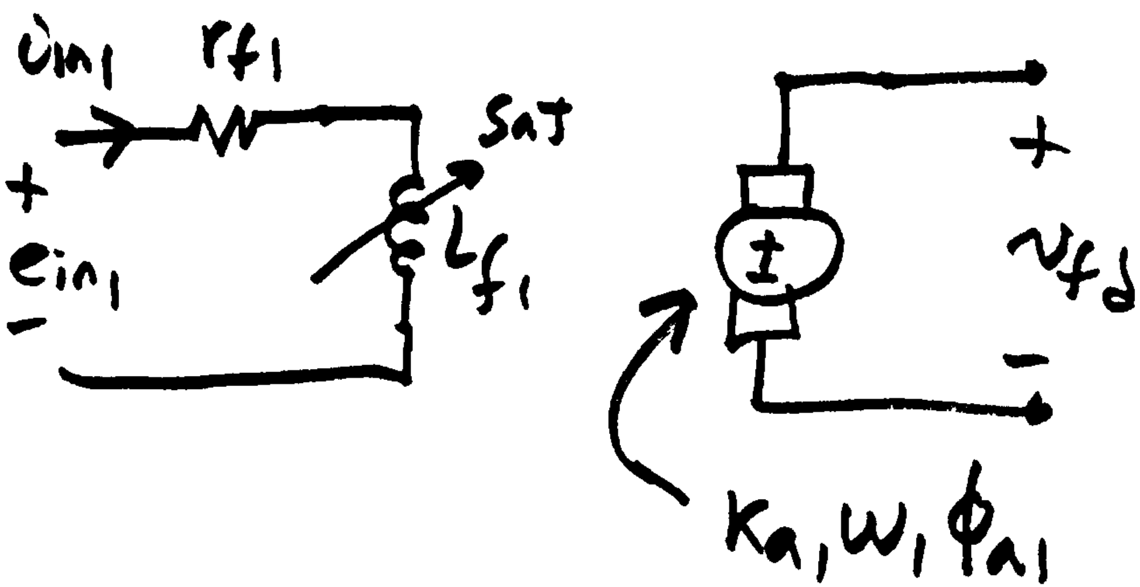



Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

# Types of DC Machines

- 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)

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

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

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

# Separately Excited DC Exciter

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

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

Assuming a constant speed $\omega_1$

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

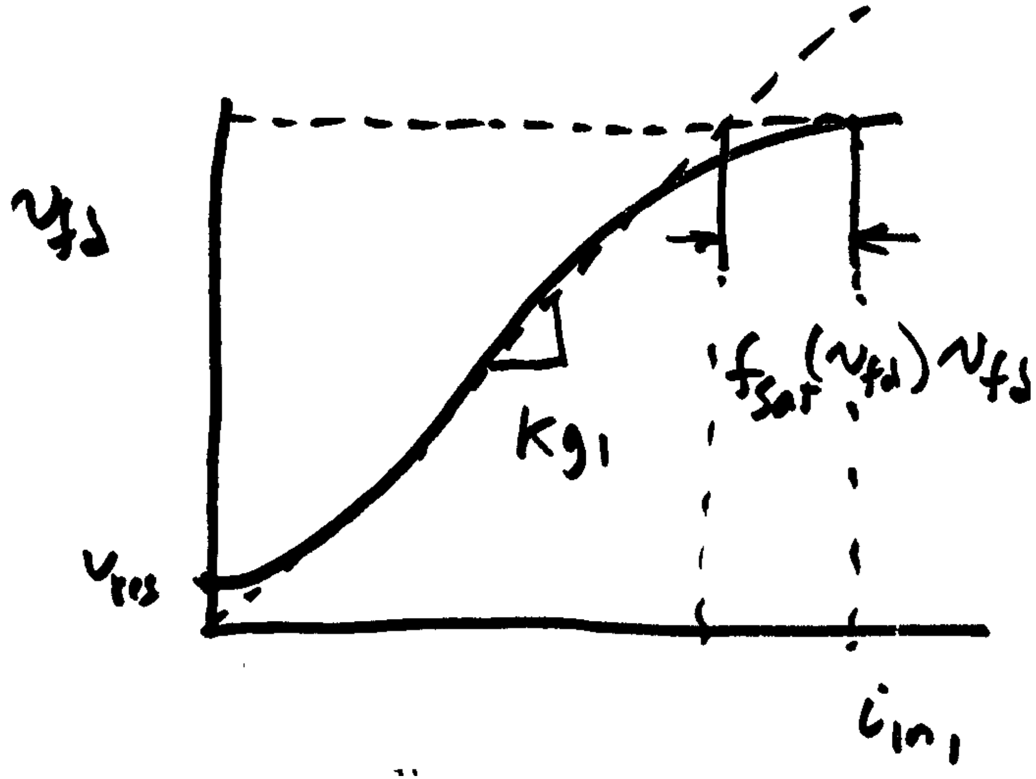
Solve above for $\phi_{f1}$ which was used in the previous slide

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

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

# 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




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

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

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

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

VR is the scaled output of the voltage regulator amplifier

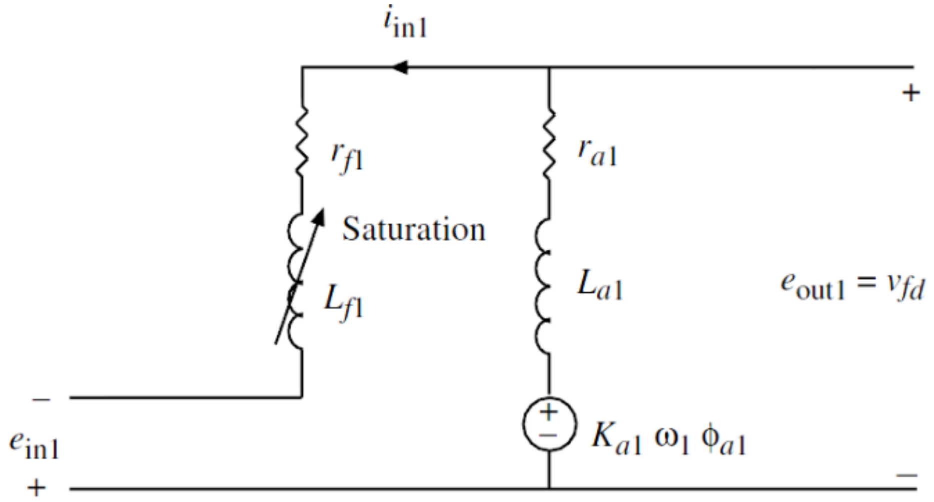
$$S_E\left(E_{fd}\right) \triangleq r_{f1} f_{sat}\left(\frac{V_{BFD} R_{fd}}{X_{md}} E_{fd}\right)$$

Thus we have

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

# 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

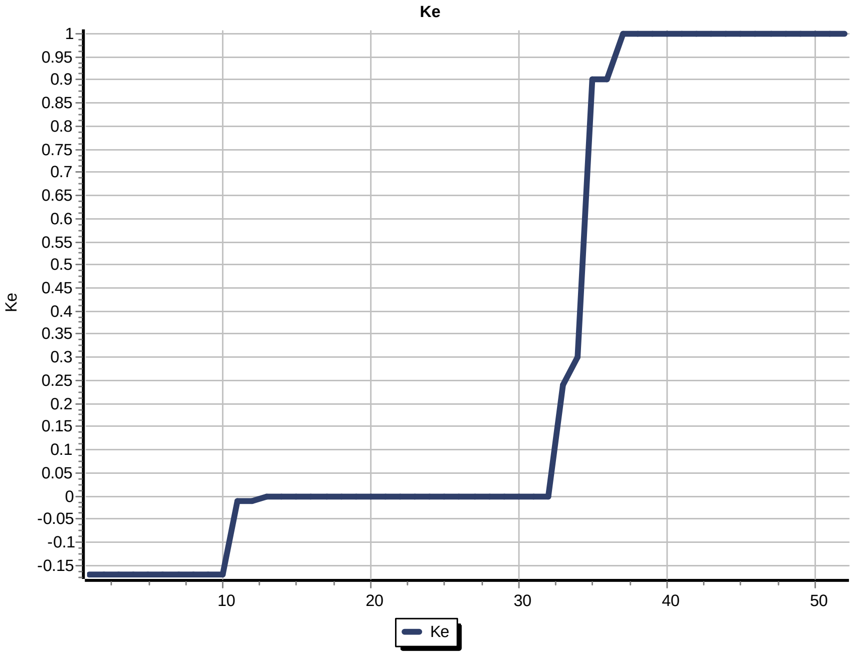
- The same model can be used for both by just modifying the value of $K_E$

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

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

# Exciter Model IEEET1 $K_E$ Values

Example IEEET1 Values from a large system




tions

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

This is the same function used with the machine models

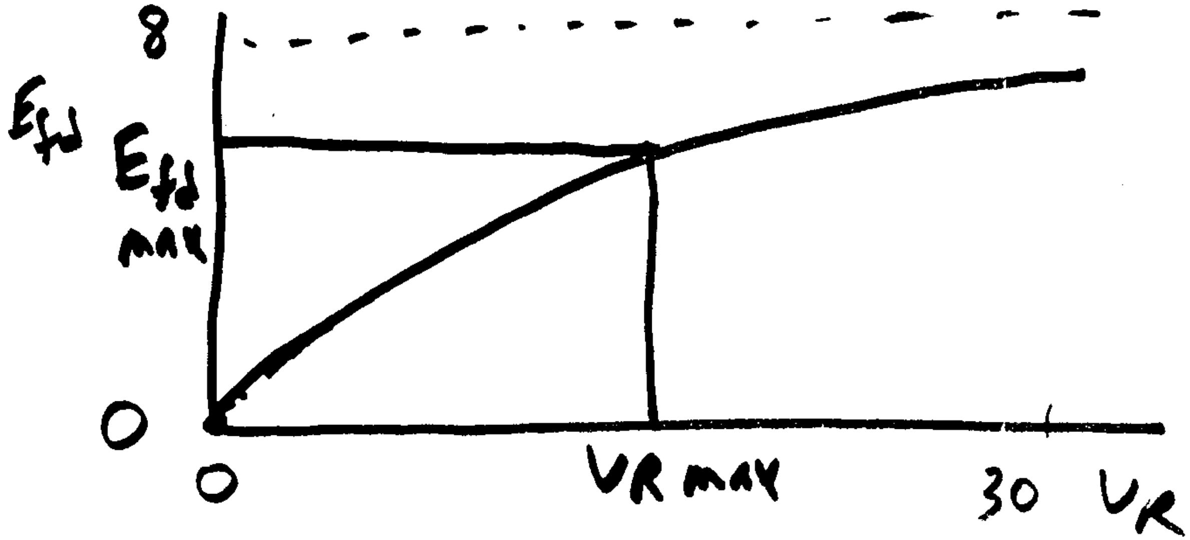
- Exponential function could also be used

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

# 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 $E_{fd_{\max}}$

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

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

$$A_x = .0015$$

$$B_x = 1.14$$

# Voltage Regulator Model

Amplifier

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

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

Modeled as a first order differential equation

In steady state

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

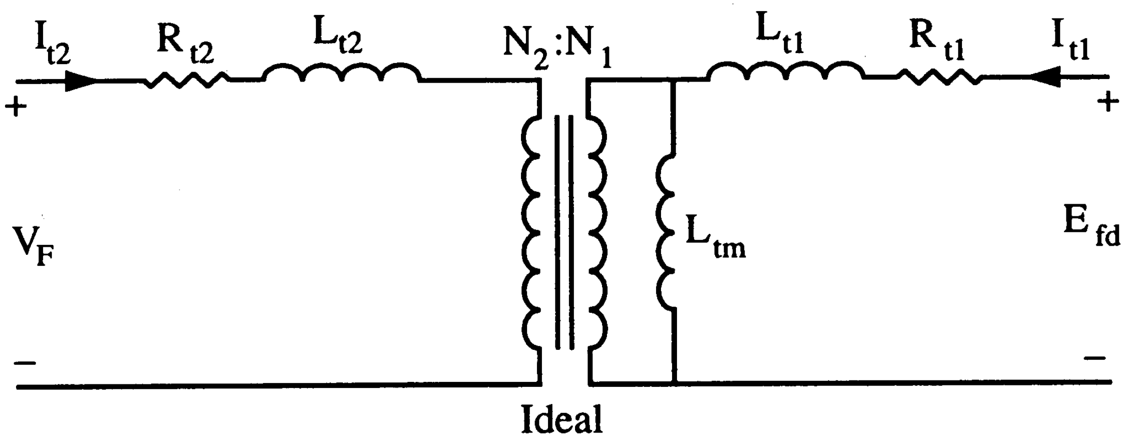
As $K_A$ is increased

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

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

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

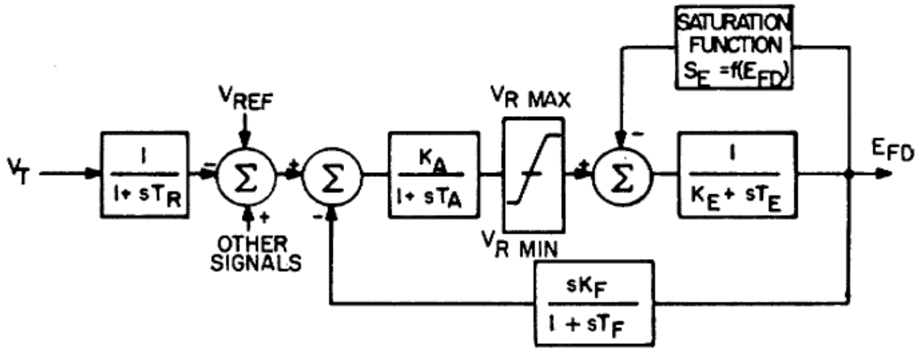
$$\frac{dV_F}{dt} = \frac{R_{t1}}{\left(L_{t1} + L_{tm}\right)} \left( -V_F + \frac{N_2}{N_1} \frac{L_{tm}}{R_{t1}} \frac{dE_{fd}}{dt} \right)$$

$$\downarrow \qquad \qquad \downarrow$$

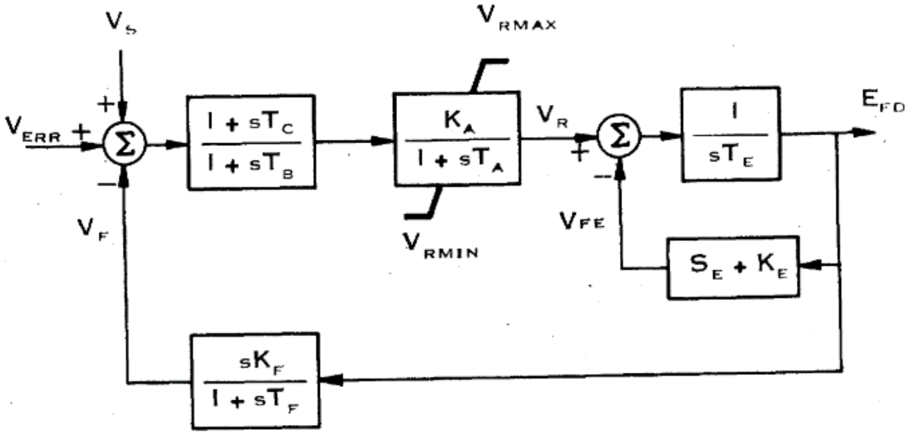
$$\frac{1}{T_F} \qquad \qquad K_F$$

# IEEET1 Model Evolution

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




1968



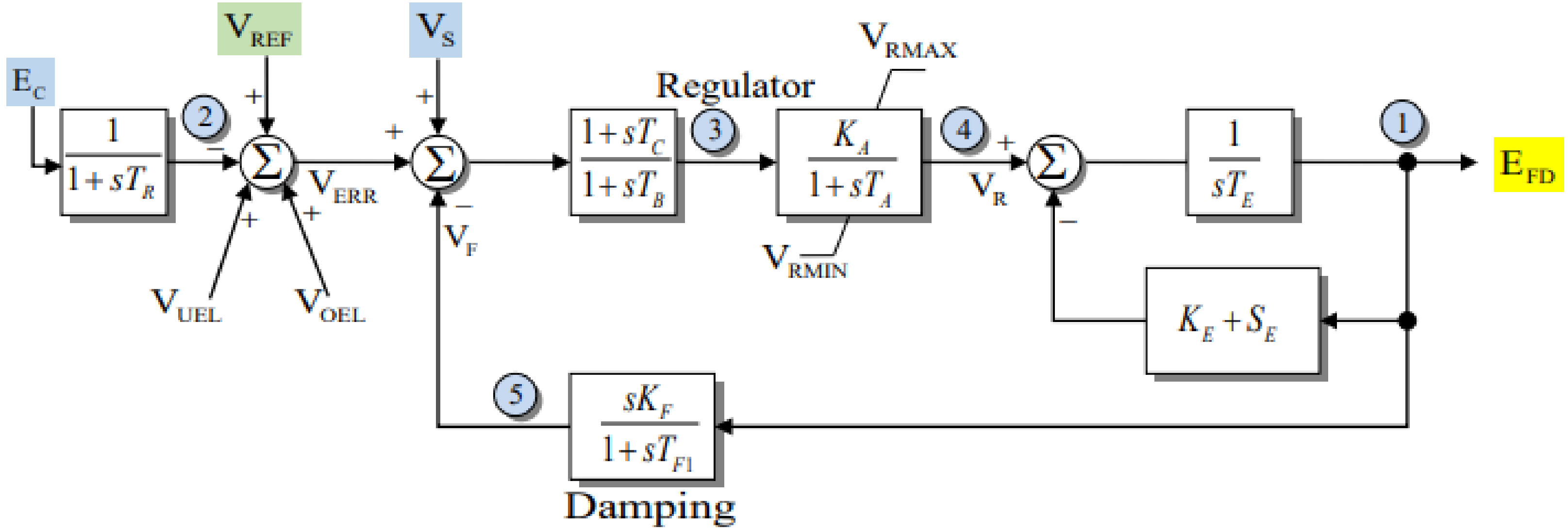

1981

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

# IEEEX1

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



# IEEET1 Evolution

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

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

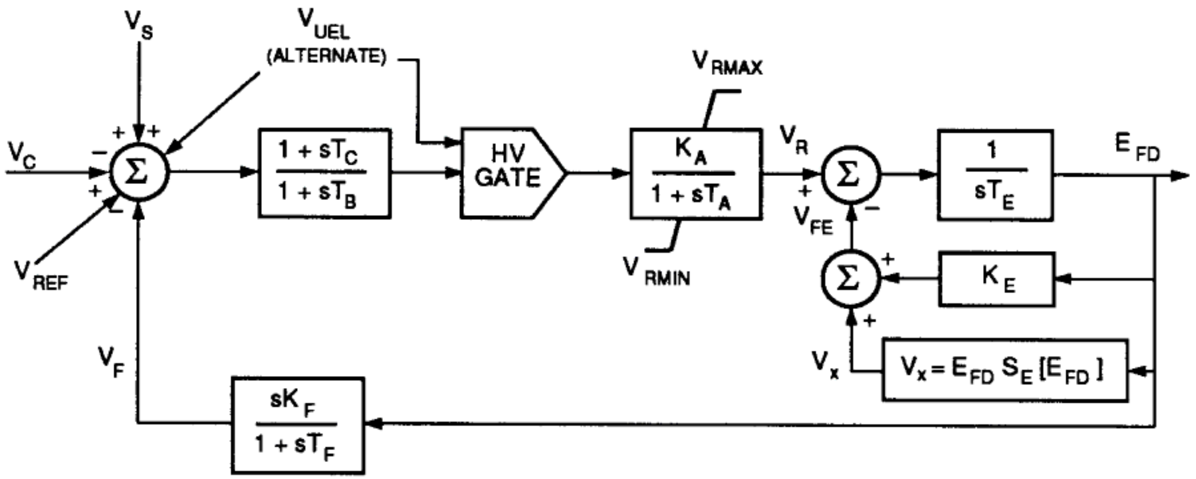



**Figure 3—Type DC1A — DC Commutator Exciter**

Same model is in 421.5-2005

Image Source: Fig 3 of IEEE Std 421.5-1992

# IEEET1 Evolution

- Slightly modified in Std 421.5-2016

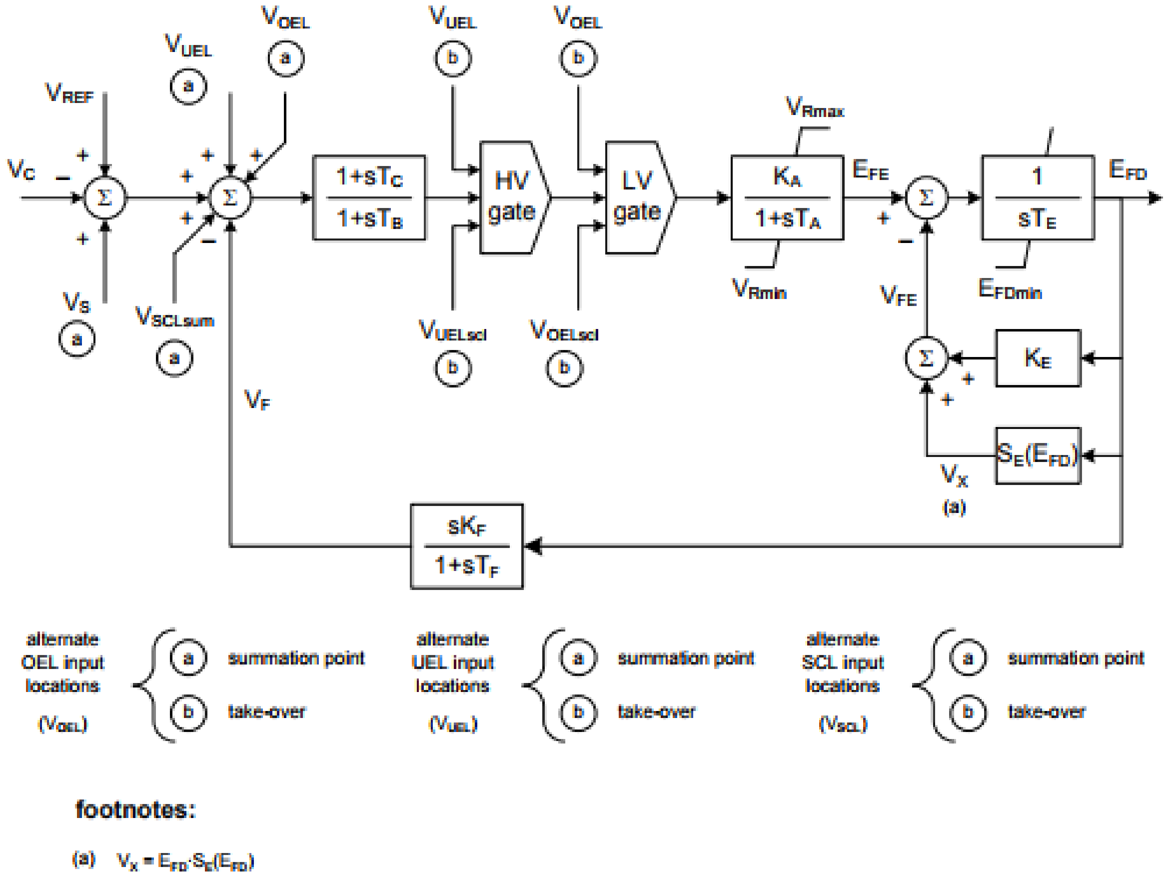


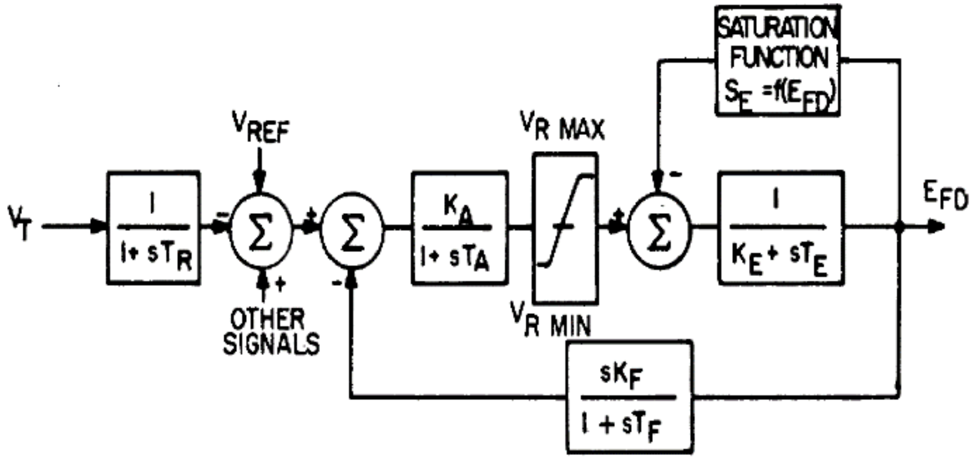

Figure 4—Type DC1C dc commutator exciter

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 ($V_{OEL}$)

# IEEET1 Example

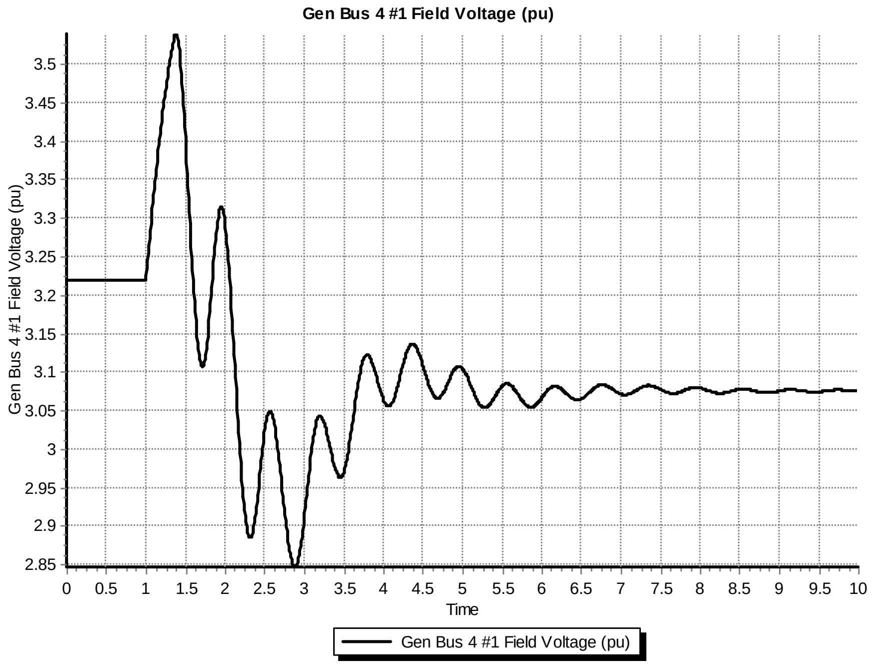
- Assume previous GENROU case with saturation. Then add a IEEE T1 exciter with $K_A$=50, $T_A$=0.04, $K_E$=-0.06, $T_E$=0.6, $V_{R,max}$=1.0, $V_{R,min}$= -1.0 For saturation assume $S_E(2.8) = 0.04$, $S_E(3.73)=0.33$
- Saturation function is $0.1621(E_{FD}-2.303)^2$ (for $E_{FD} > 2.303$); otherwise 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/Ka +$V_T$ =0.0488 +1

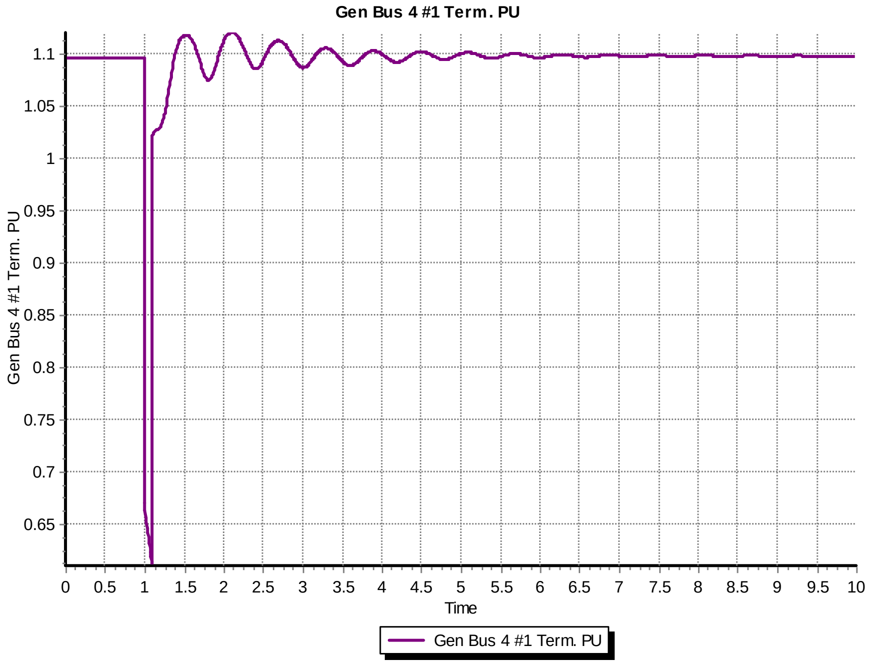



Case **B4_GENROU_Sat_IEEET1**

# IEEE T1 Example

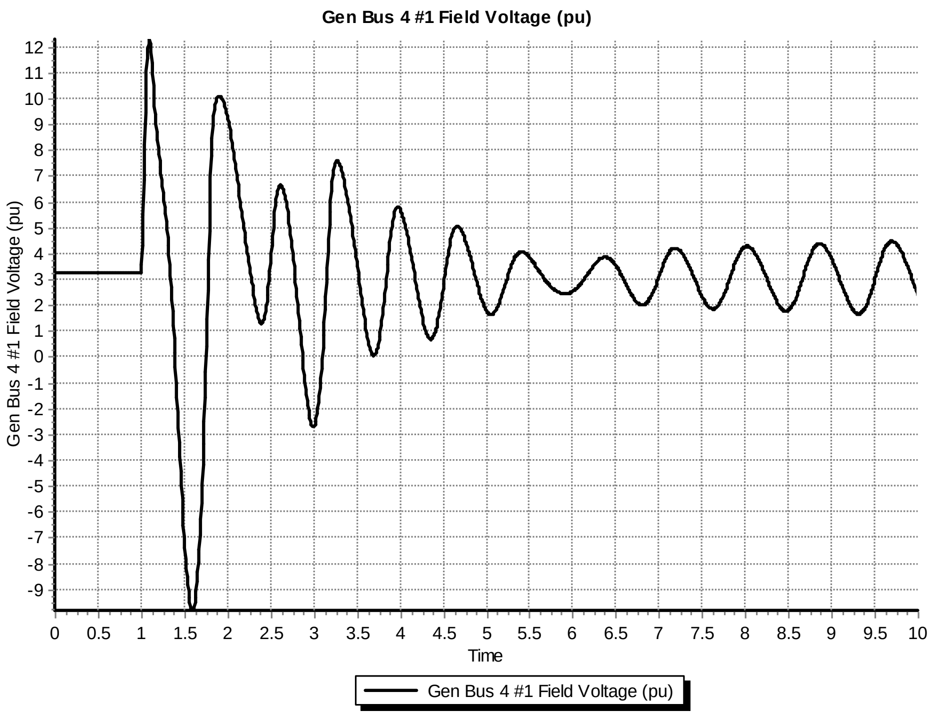
- For 0.1 second fault (from before), plot of $E_{FD}$ and the terminal voltage is given below
- Initial $V_4$=1.0946, final $V_4$=1.0973
  - Steady-state error depends on the value of $K_A$

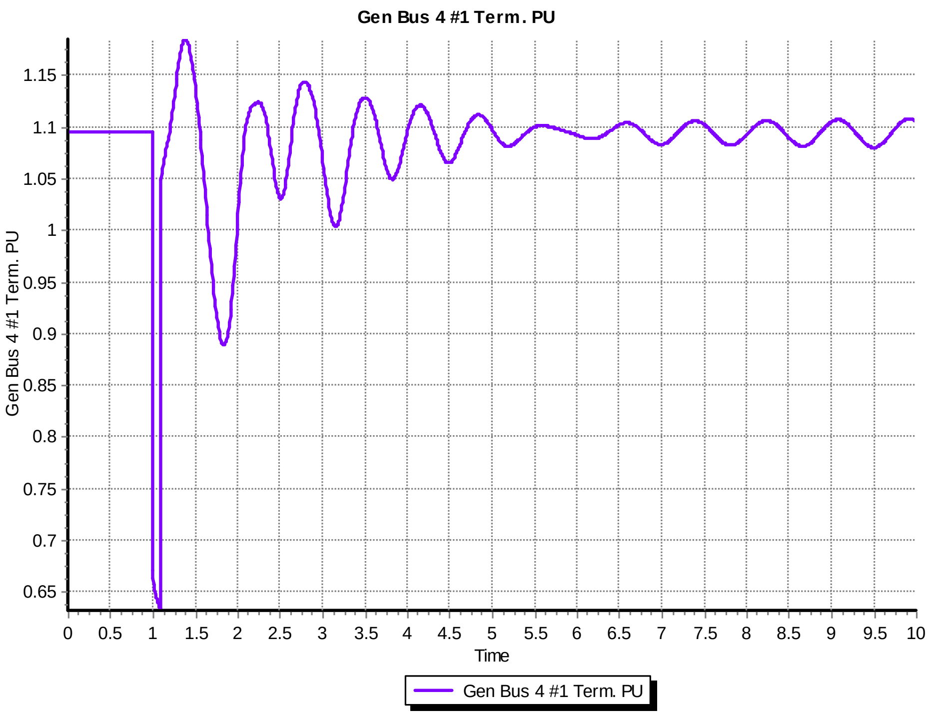


# IEEET1 Example

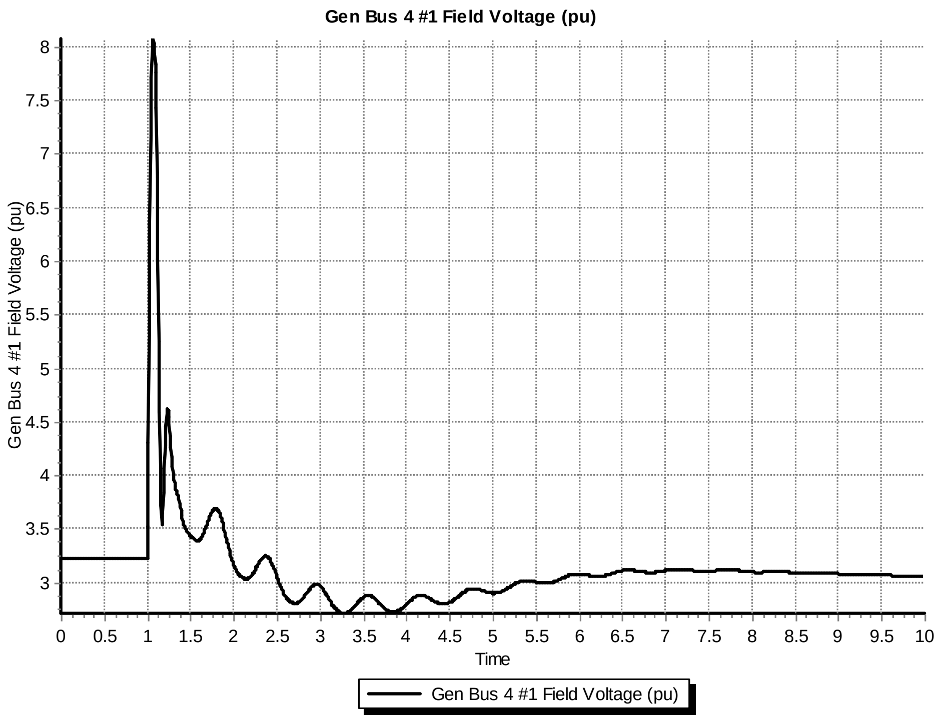
- Same case, except with $K_A$=500 to decrease steady-state error, no $V_R$ limits; this case is actually unstable

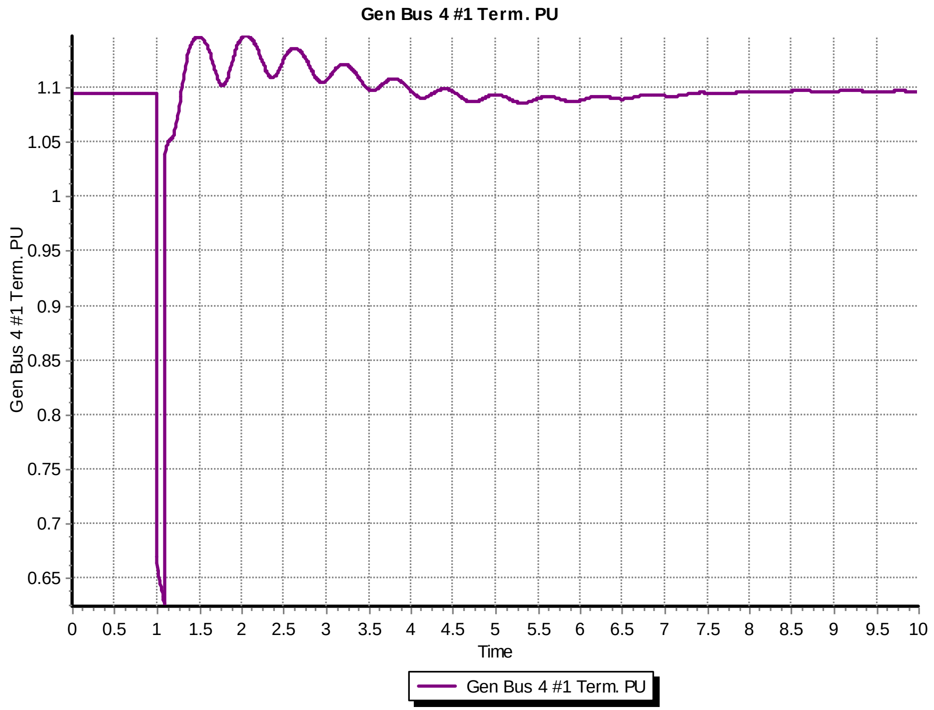


# IEEET1 Example

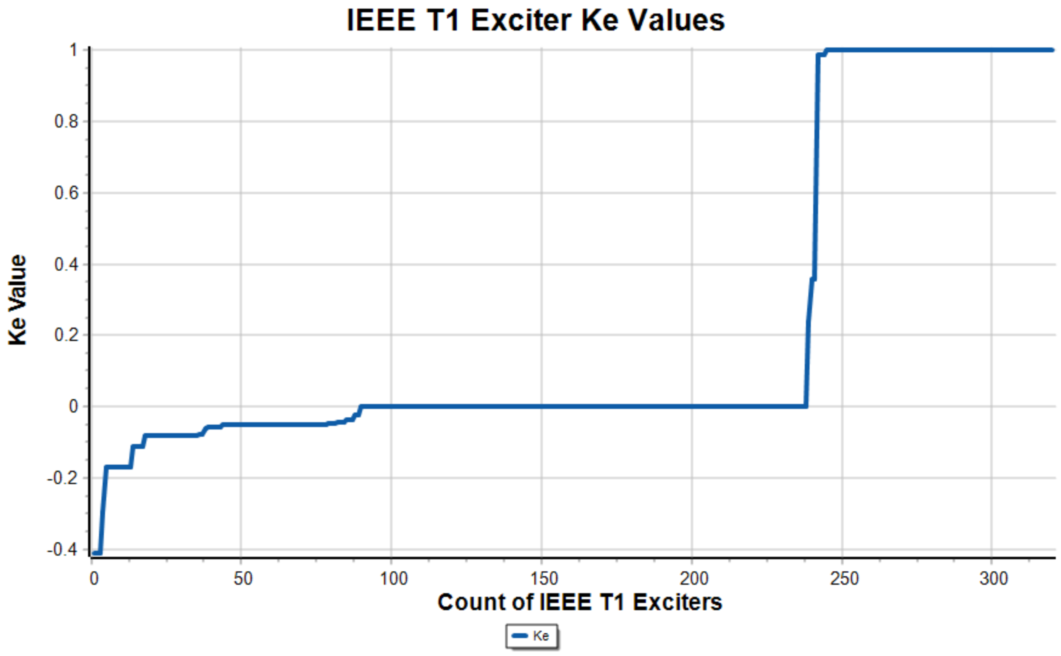
- With $K_A$=500 and  rate feedback, $K_F$=0.05, $T_F$=0.5
- Initial $V_4$=1.0946, final $V_4$=1.0957



# 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

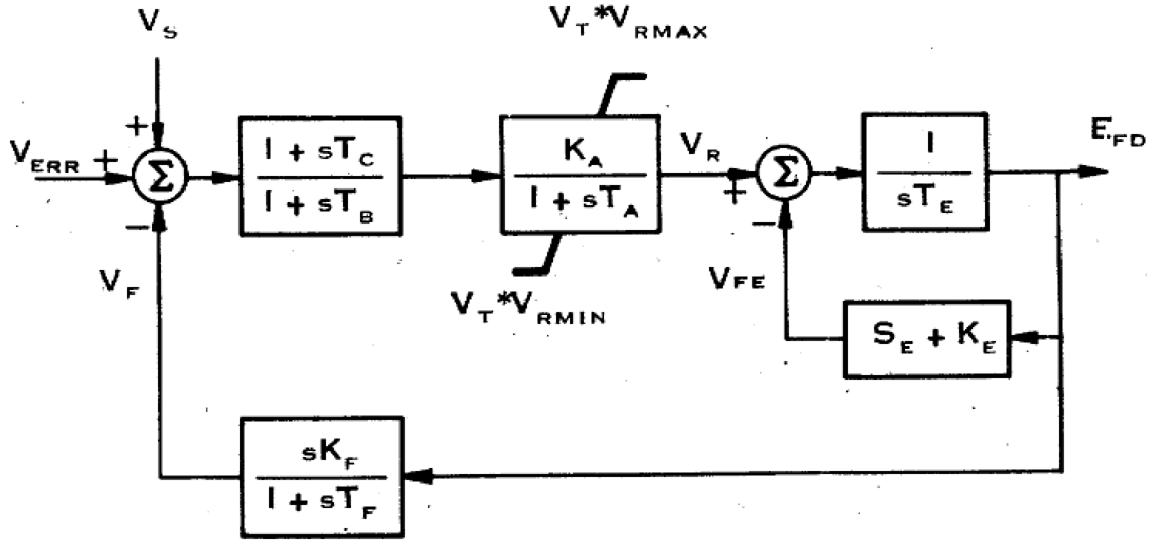



Fig. 4. Type DC2 - DC Commutator Exciter

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

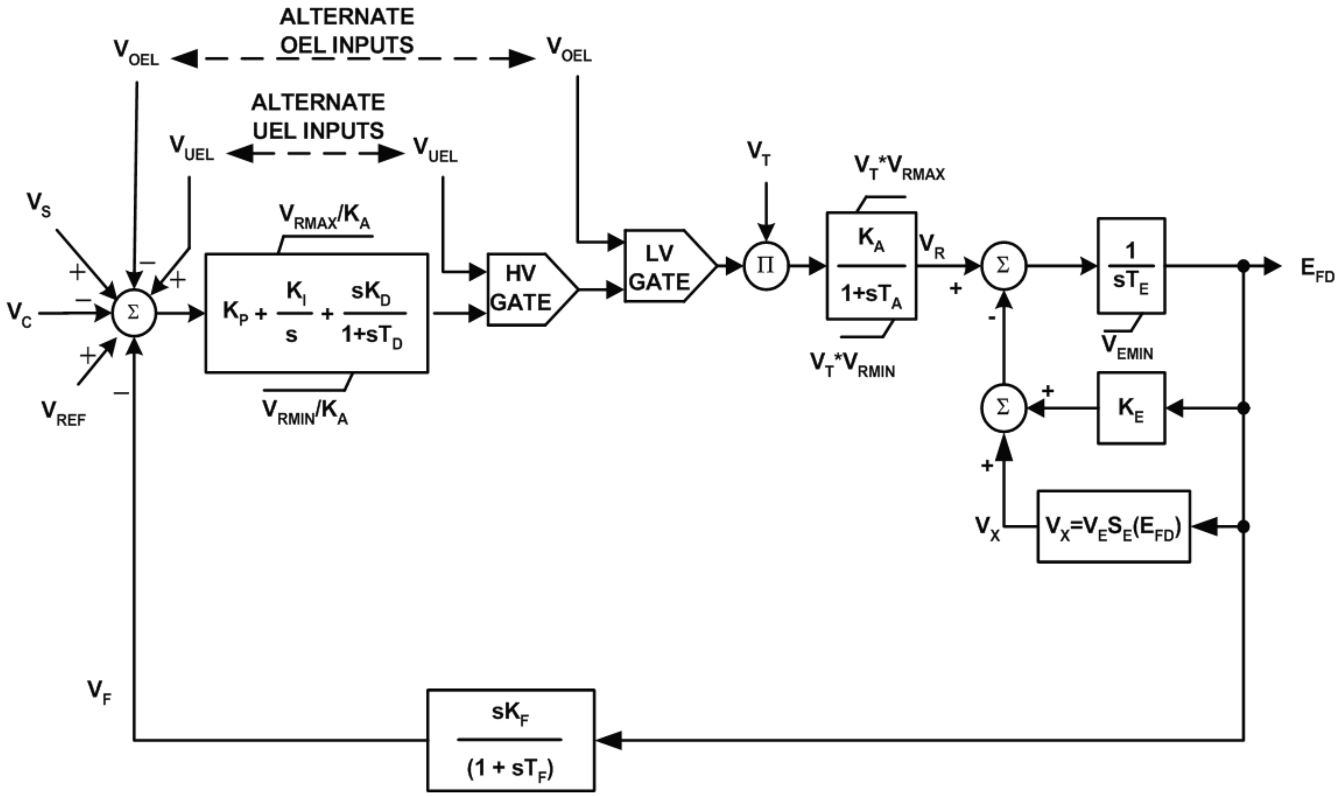


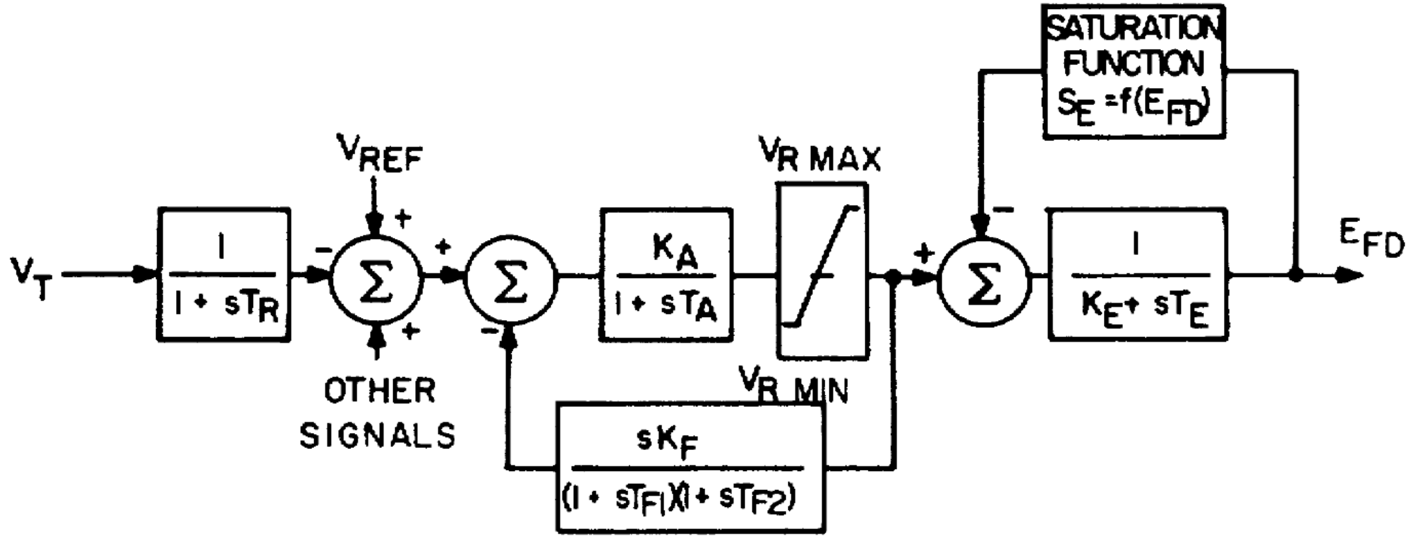

Image Source: Fig 5-4 of IEEE Std 421.5-2005

# 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 Modeling

- Originally represented by IEEE T2 shown below

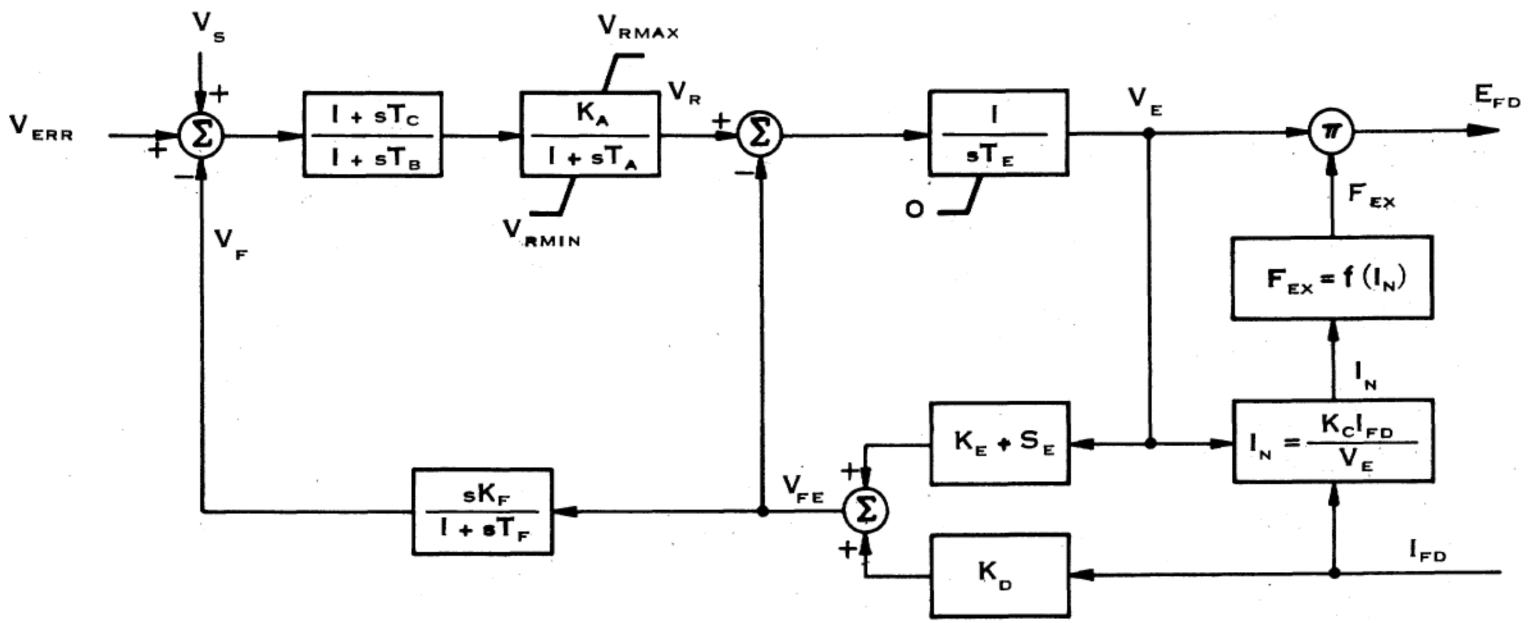



Exciter model is quite similar to IEEE T1; in the EI/WECC case there are 105 IEEE T2 exciters (about 1%)

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

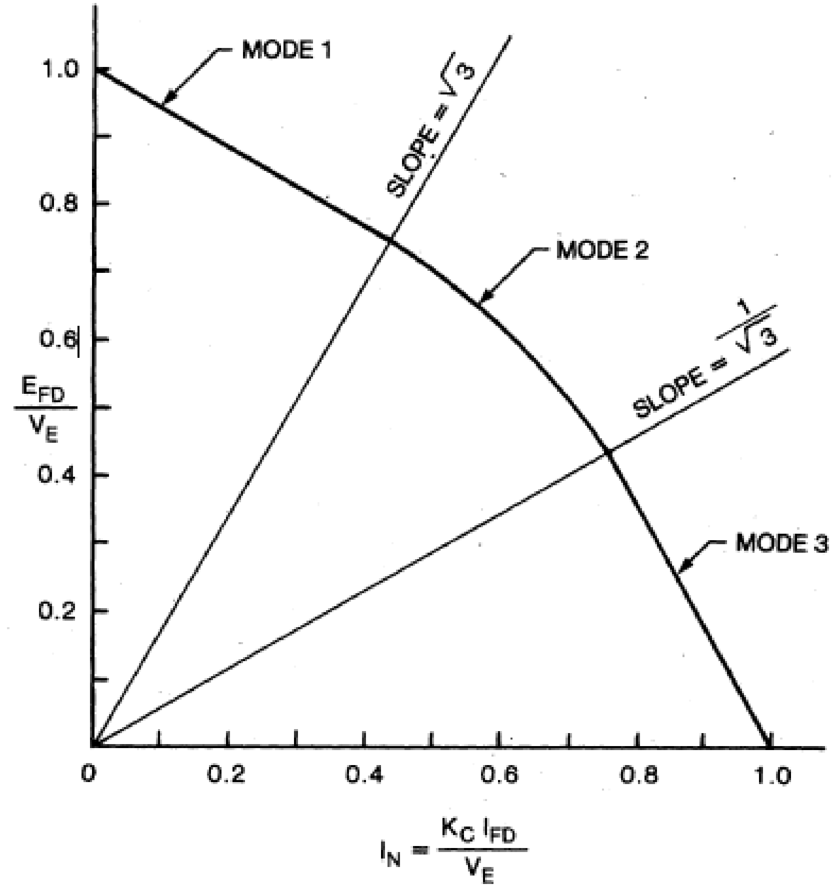



About 1% of the EI/WECC exciters are EXAC1

$K_D$ 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



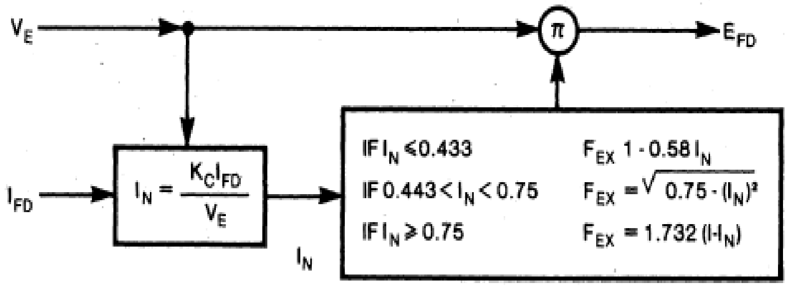



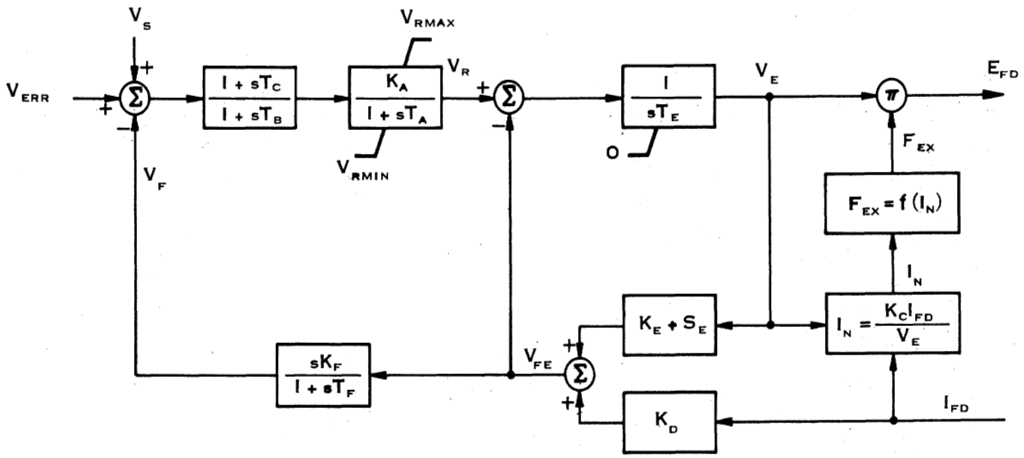

Fig. E.2. Rectifier Regulation Equations

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

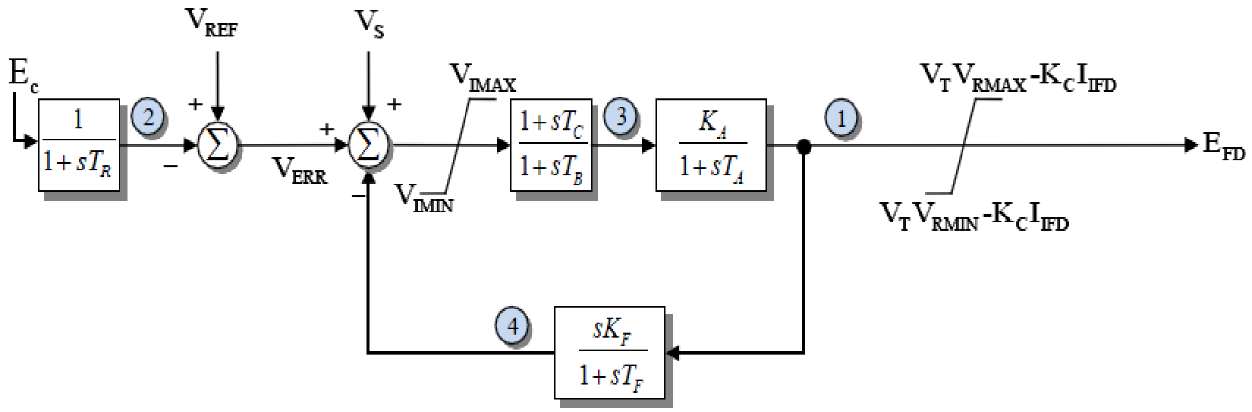
Need to check to make sure we are on this segment

# Static Exciters

- 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

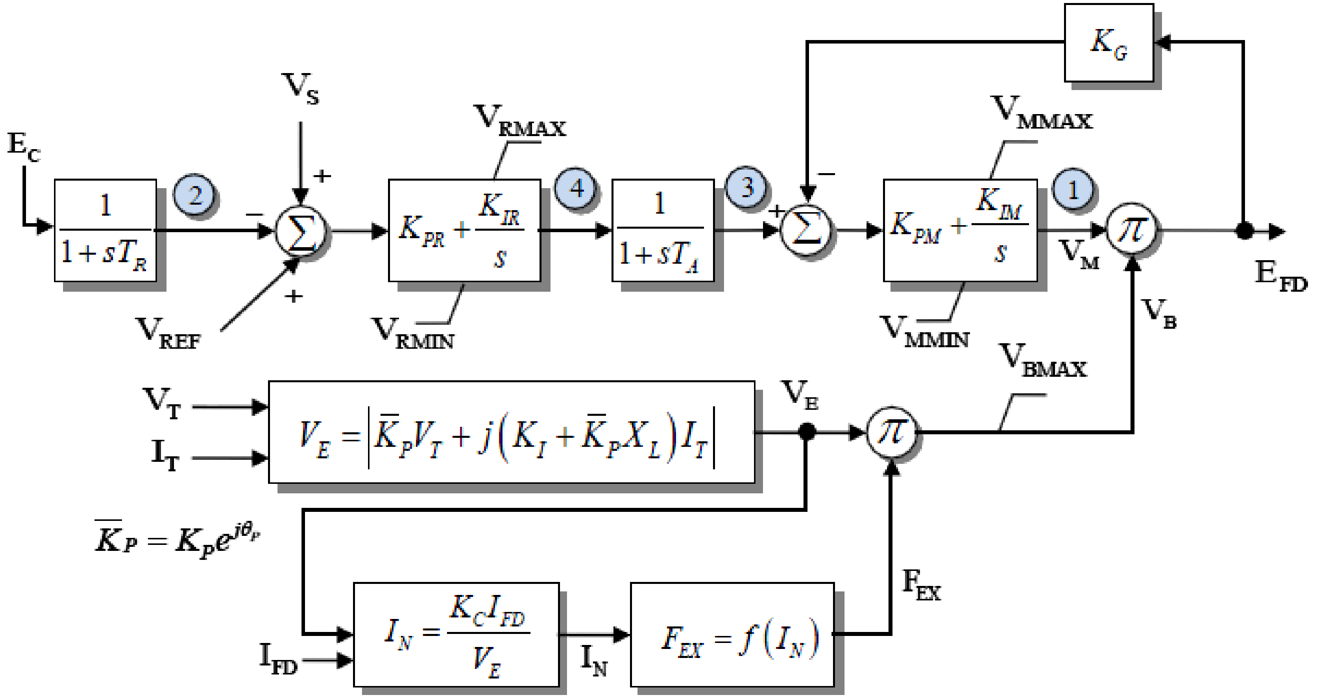



This (and the related ESST1A) is a very common exciter (about 14% of EI/WECC total)

Kc represents the commuting reactance

# EXST4B

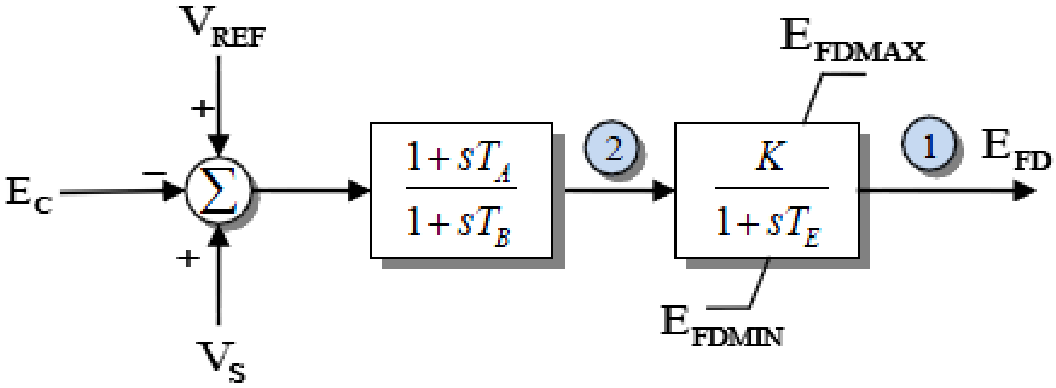
- EXST4B models a controlled rectifier design; field voltage loop is used to make output independent of supply voltage




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

# 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



# 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

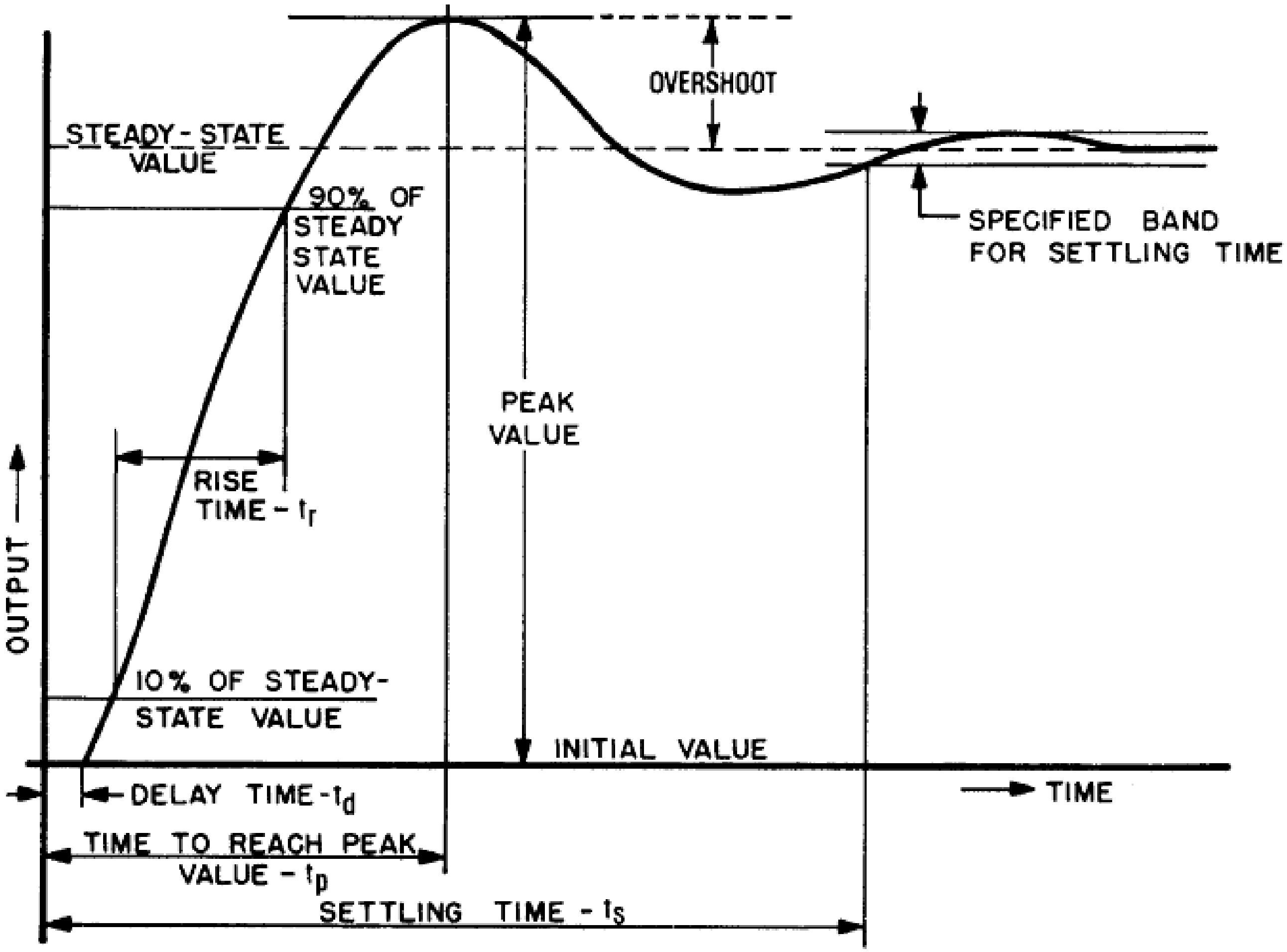



Image Source: IEEE Std 421.2-1990, Figure 3

# 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

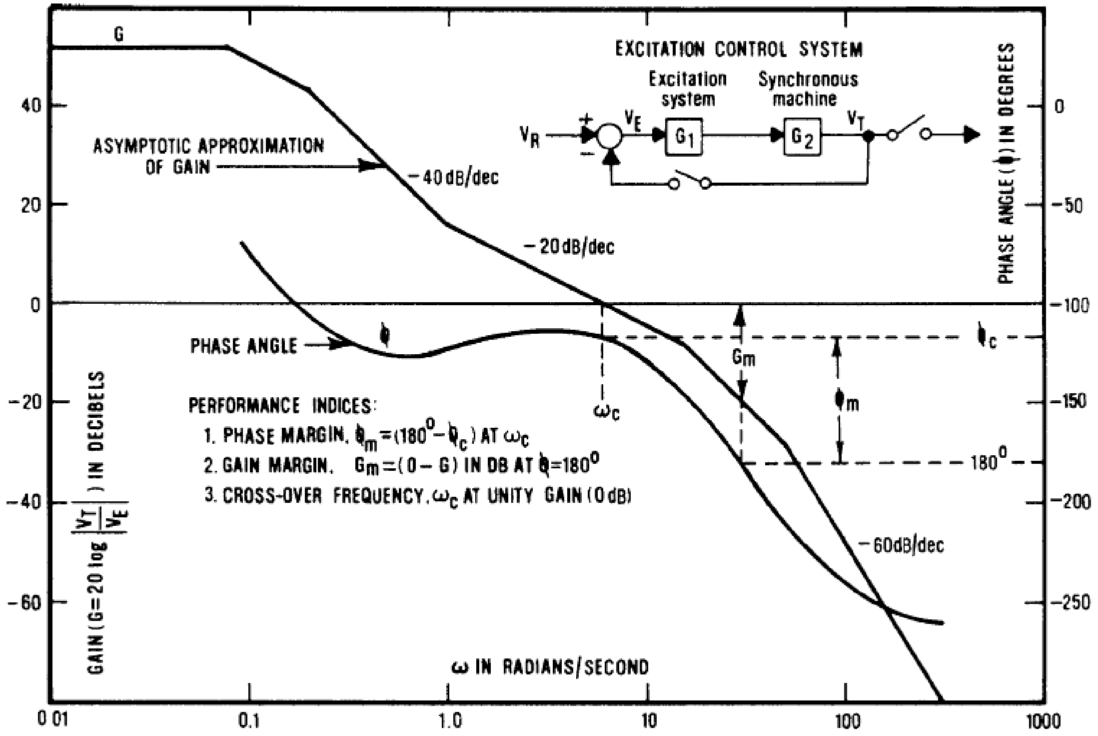



Figure 4—Typical Open-Loop Frequency Response of an Excitation Control System with the Synchronous Machine Open-Circuited

Image Source: IEEE Std 421.2-1990, Figure 4