ECEN 667
Power System Stability

Lecture 10: Exciters

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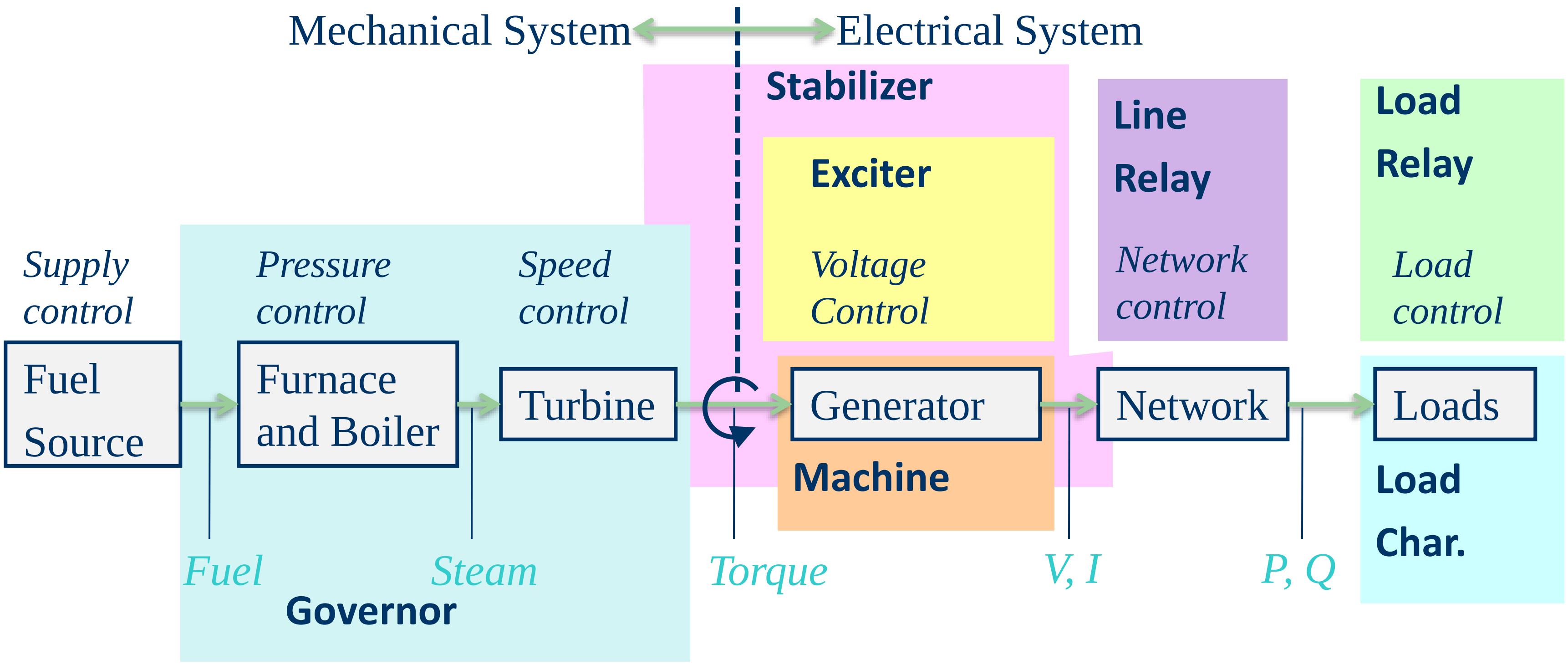
Announcements

- Read Chapter 4
- Homework 3 is due on Thursday Oct 7
- Homework 4 is assigned today, but will not need to be turned in (just done before the first exam)
- Exam 1 will be on Oct 14 in class
  - For the distance learners we usually use Honorlock (though I know for some that won't work)
  - Exams are closed book, closed notes, but you can bring in one 8.5 by 11 inch note sheet and can use calculators

Dynamic Models in the Physical Structure: Exciters



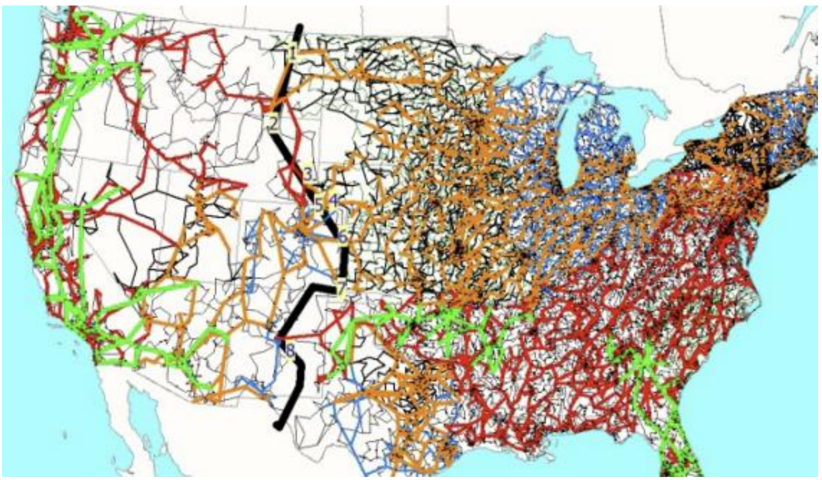
P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Larger Scale Stability Study

- An example of a larger scale stability study we did is available on my website
  - overbye.engr.tamu.edu/publications/
  - See the first paper in 2022 (from HICSS) or the PSERC report (number 18 in 2021)
- The study looked a stability aspects of a synchronous connection of the North American East and WECC grids
- The power flow model had 110,000 buses and 13,700 generators; for stability it had 246 different types of dynamic models, 61,000 model instances and more than 200,000 differential equations
- We also studied an 82,000 bus synthetic grid

Larger Scale Stability Study

- The below figures are for the 82,000 bus synthetic grid



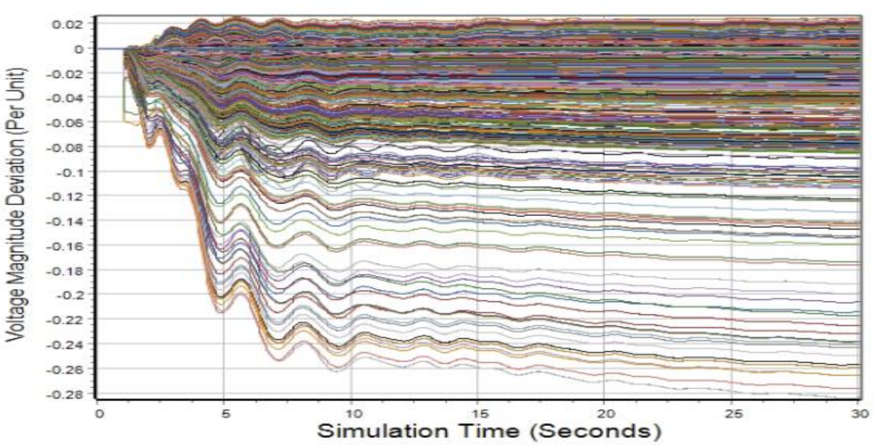
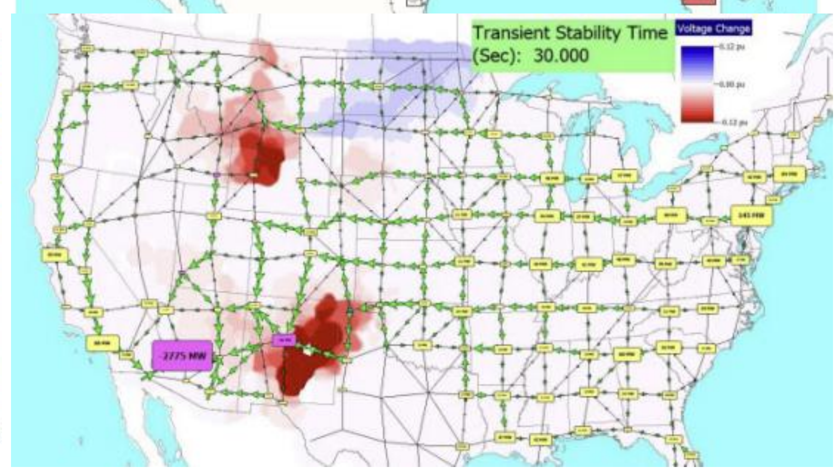
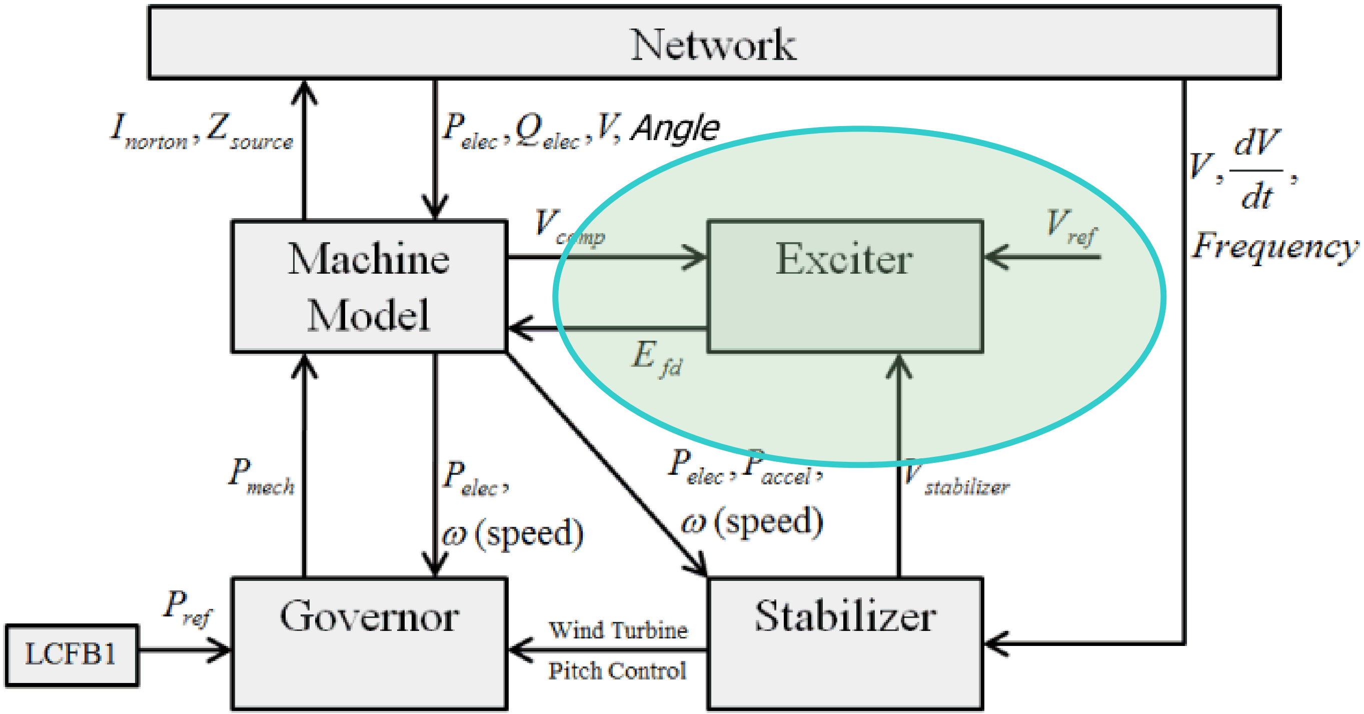


Figure 14: 82K Voltage Magnitude Response



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

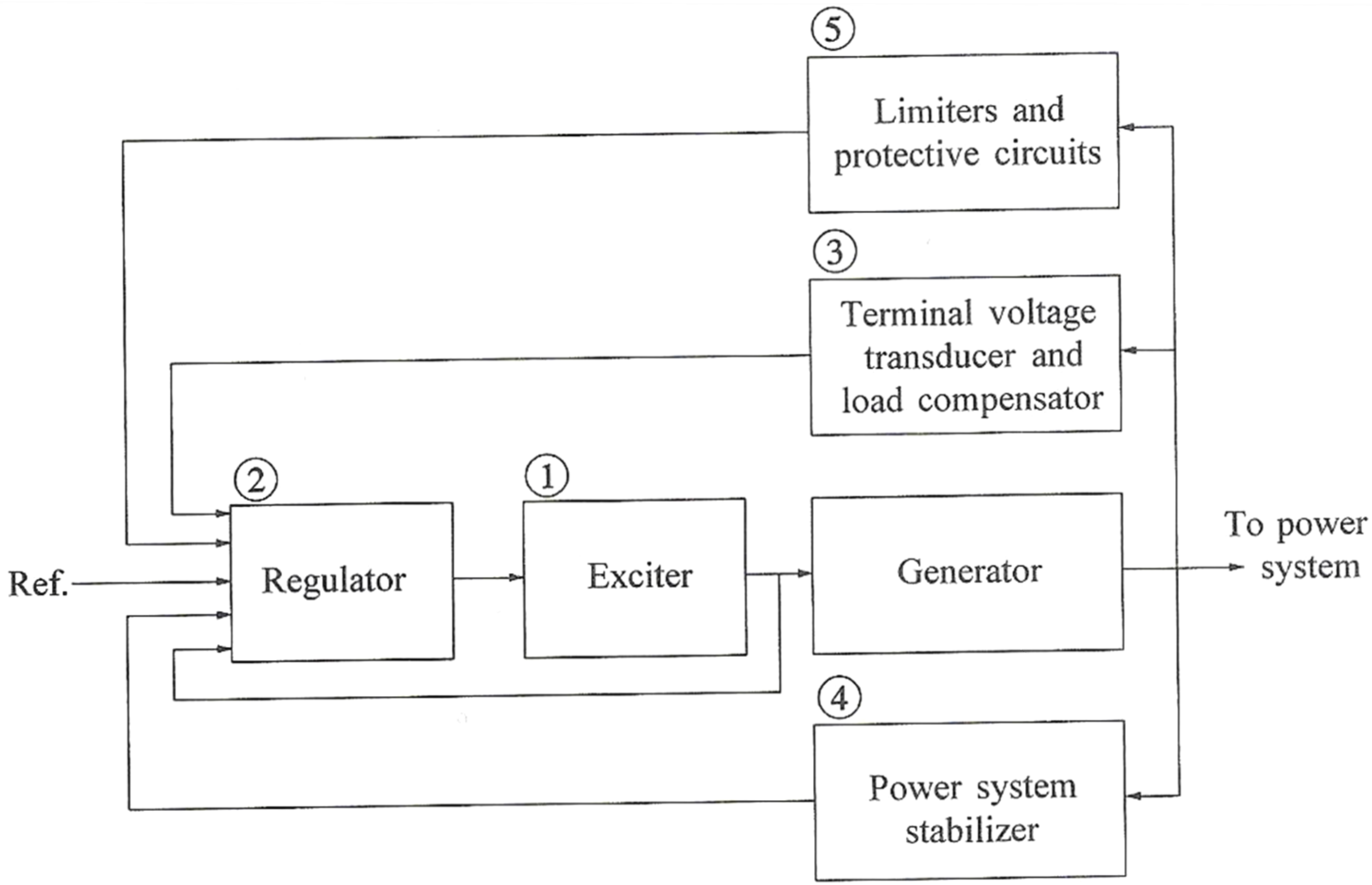


Image source: Fig 8.1 of Kundur, *Power System Stability and Control*

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

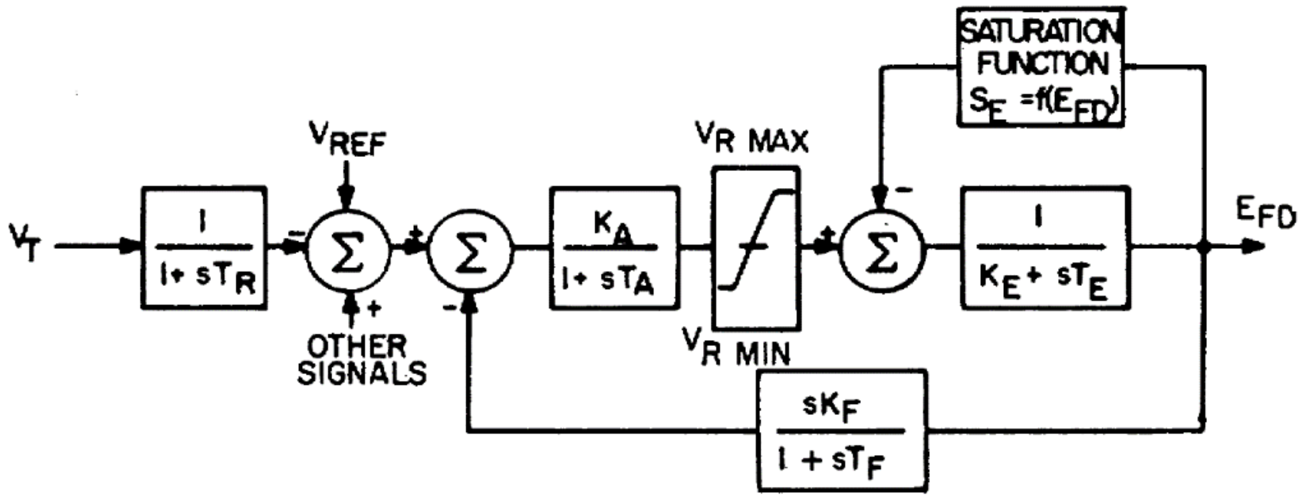
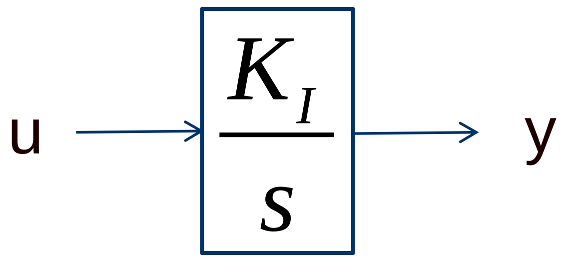


Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

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

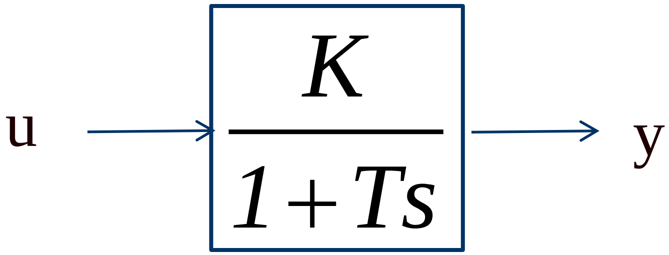


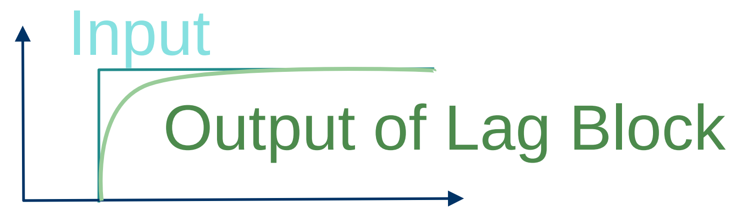
- Equation for an integrator with u as an input and y as an output is

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

- 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

$$u \longrightarrow \boxed{\frac{K_D s}{1+sT_D}} \longrightarrow y$$

- 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

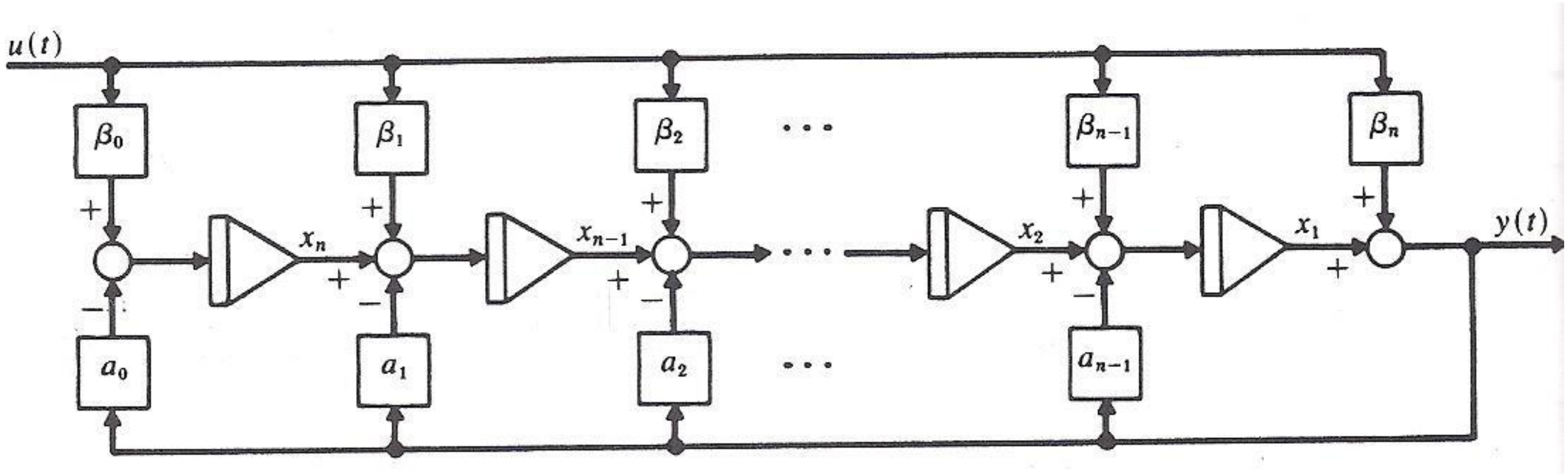
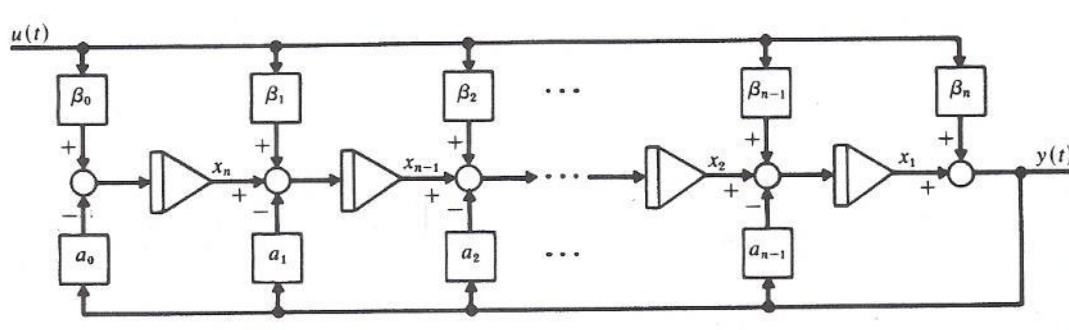


Image source: W.L. Brogan, *Modern Control Theory*, Prentice Hall, 1991, Figure 3.7

Derivative Example

- Write in form

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



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

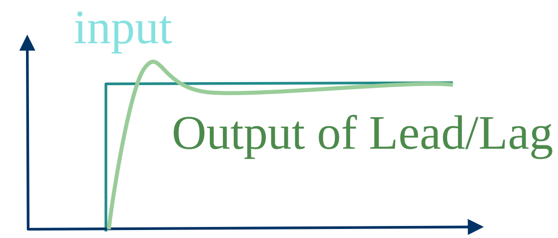
$$\frac{dx}{dt} = \beta_0 u - \alpha_0 y = -\frac{y}{T_D}$$

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

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

Lead-Lag Block

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



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

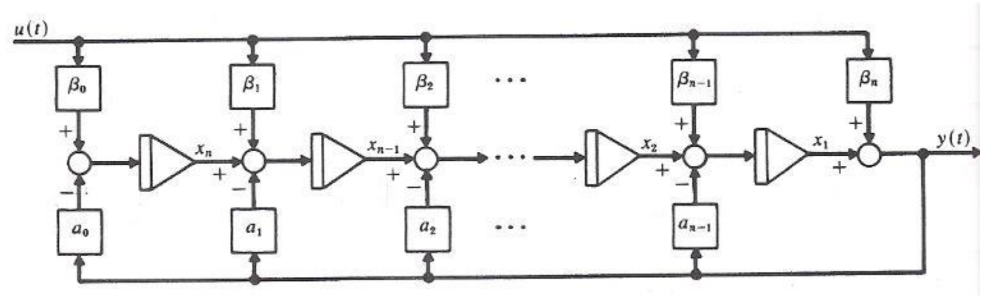
$$\boxed{\frac{1+sT_A}{1+sT_B}=\frac{\frac{1}{T_B}+s\frac{T_A}{T_B}}{1/T_B+s}}$$

Lead-Lag Block

- The equations are with

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

  then



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

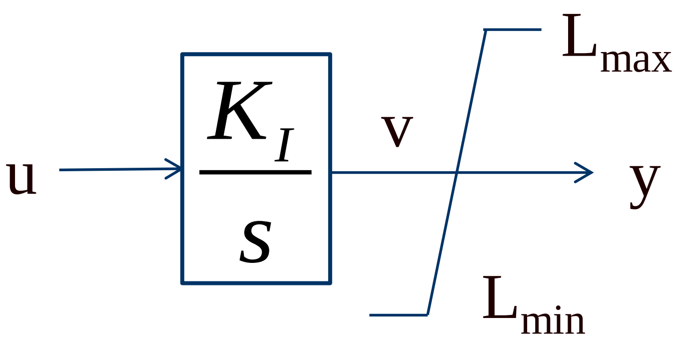
$$y = x + \beta_1 u = x + \frac{T_A}{T_B} u$$

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

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



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

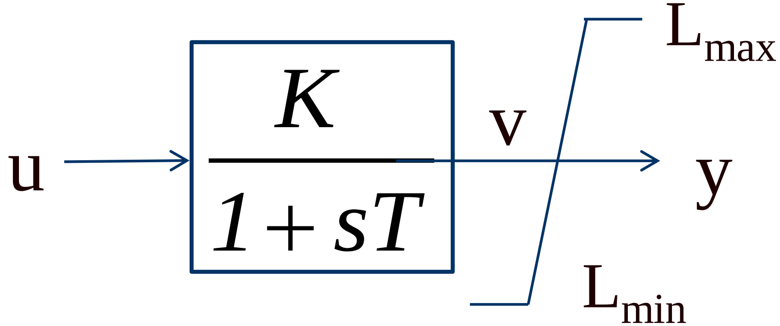
If $L_{min} \le v \le L_{max}$ then $y = v$

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



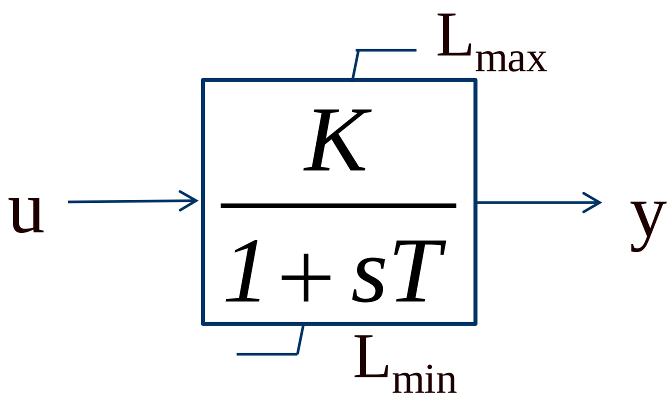
$$\frac{dv}{dt} = \frac{1}{T}(Ku - v)$$

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)

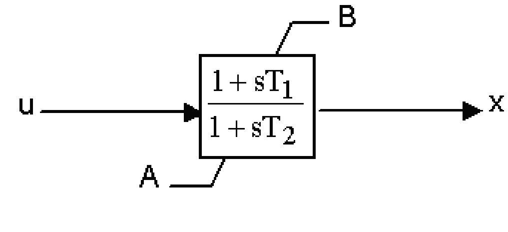
If $L_{min} \le y \le L_{max}$ then normal $\frac{dy}{dt} = \frac{1}{T}\left(Ku - y\right)$

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

If $y \le L_{min}$ 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)



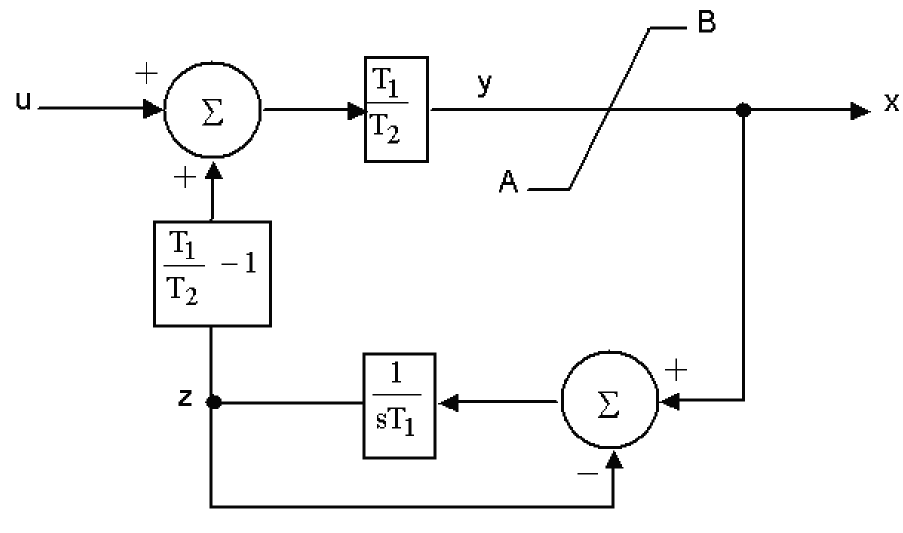
(a) Model

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

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

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

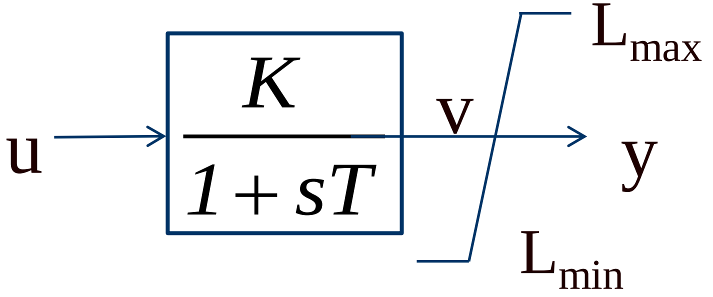
If $B \geq y \geq A$, then $x = y$



(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$\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 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; 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 Gi_f

Taken mostly from M.A. Pai, *Power Circuits and Electromechanics*

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

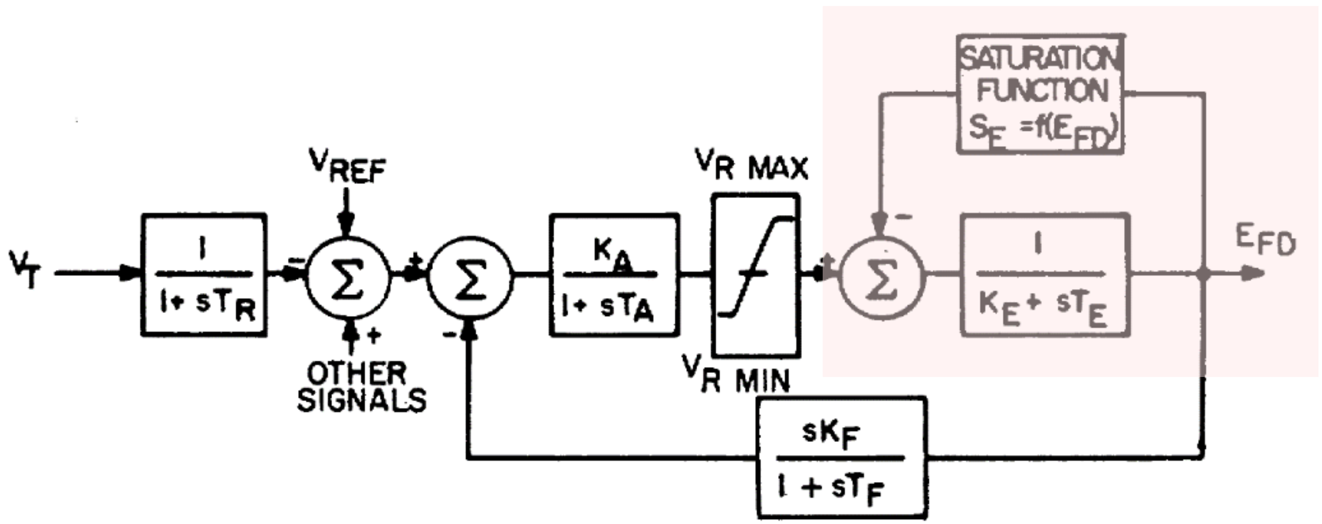
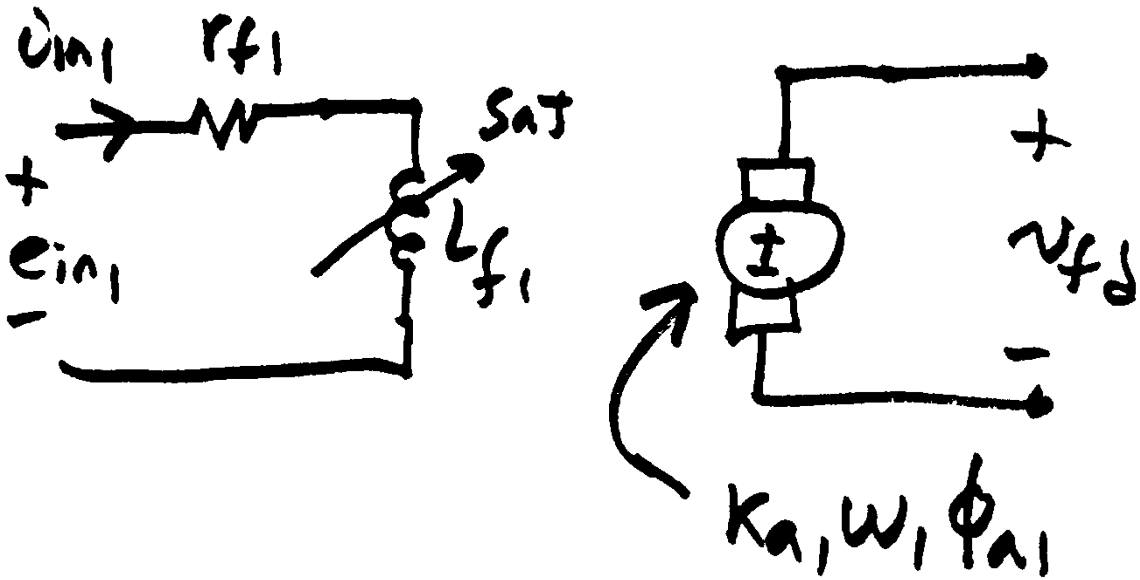


Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

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 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}

Assuming a constant speed ω_1

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

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

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

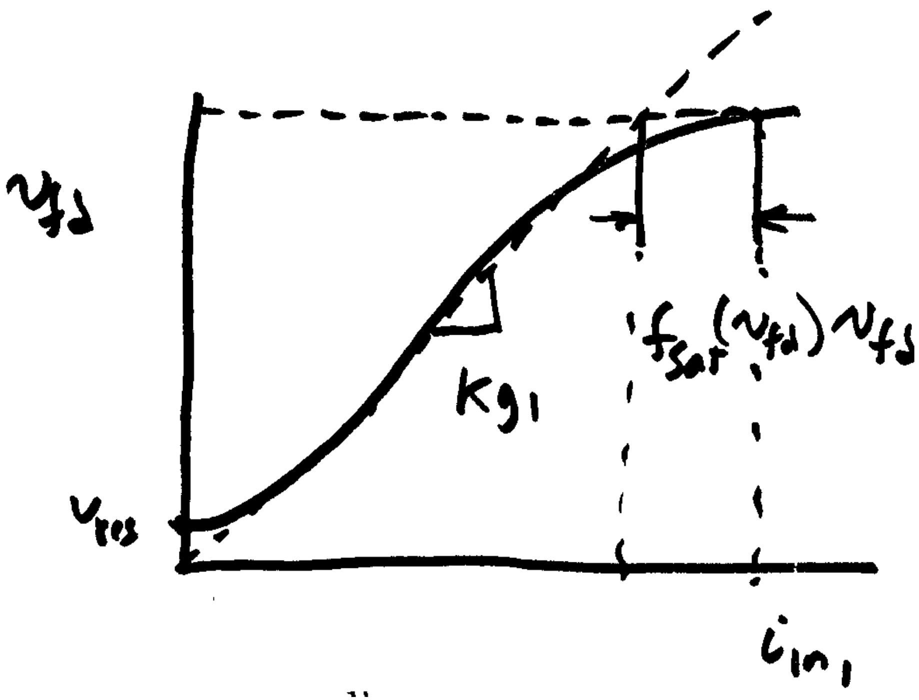
$$\frac{d\phi_{f1}}{dt} = \frac{\sigma_1}{K_{a1}\omega_1}\frac{dv_{fd}}{dt}$$

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

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

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

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

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

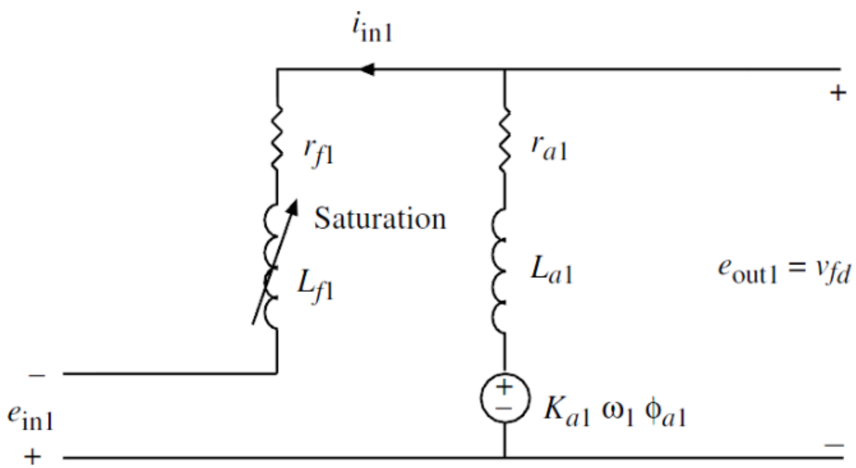
V_R is the scaled output of the voltage regulator amplifier

Thus we have

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

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

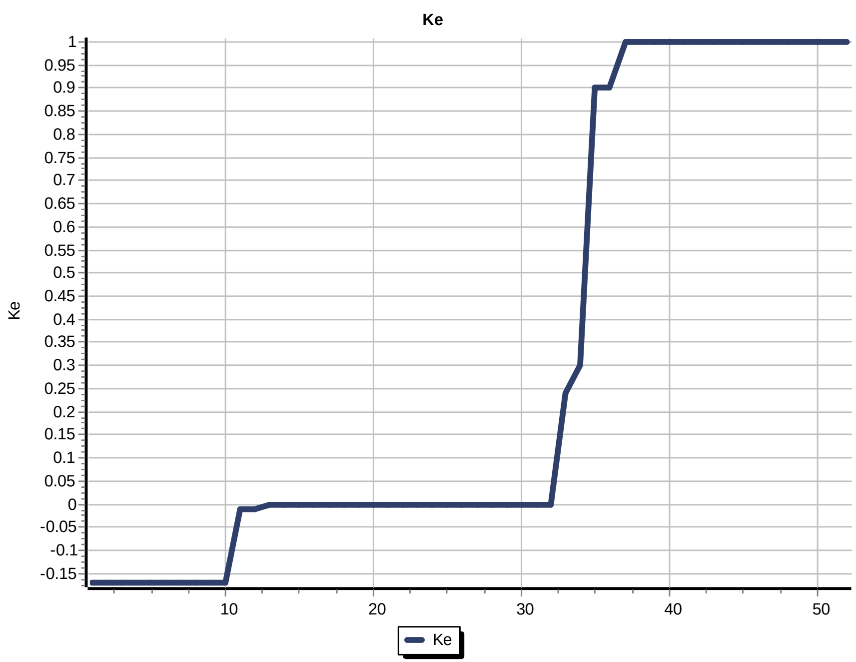
- The same model can be used for both by just modifying the value of K_E

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

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

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

This is the same function used with the machine models

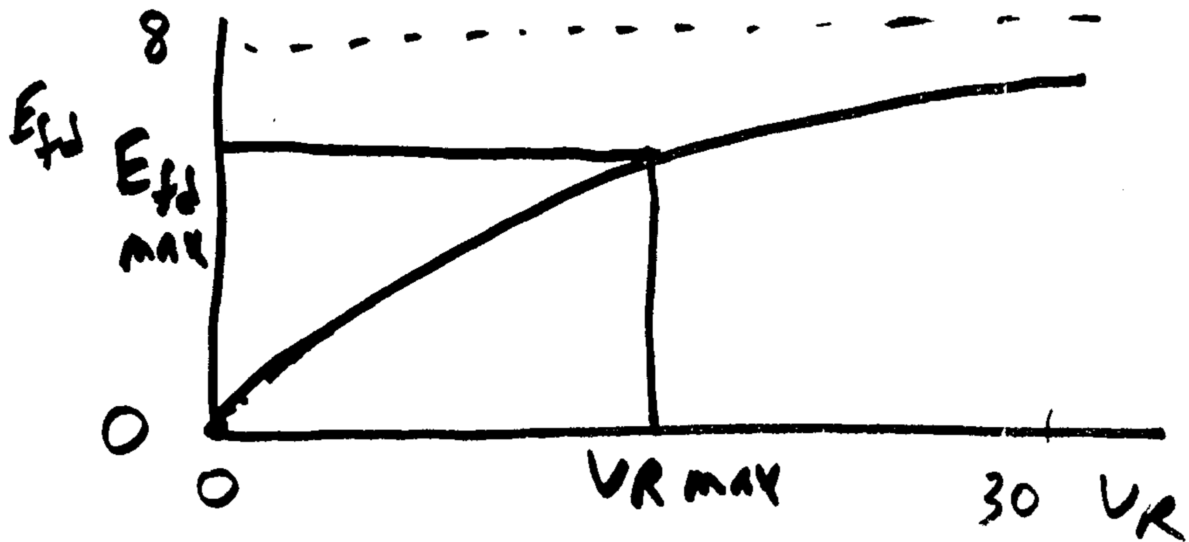
- Exponential function could also be used

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

Exponential Saturation

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

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



Exponential Saturation Example

Given: $K_E = -.05$

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

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

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

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

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

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

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

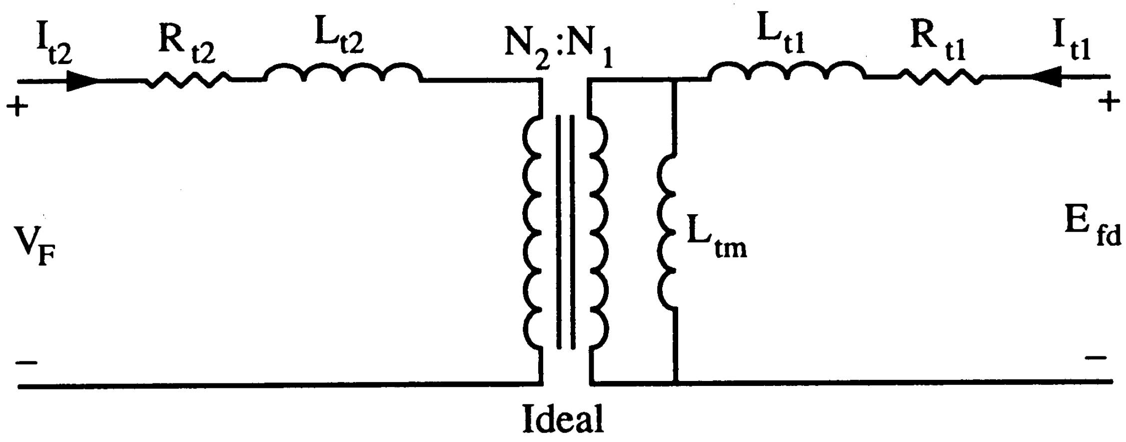
In steady state $$V_{ref} - V_t = V_{in} = \frac{V_R}{K_A}$$

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 $I_{t2} \approx 0$

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

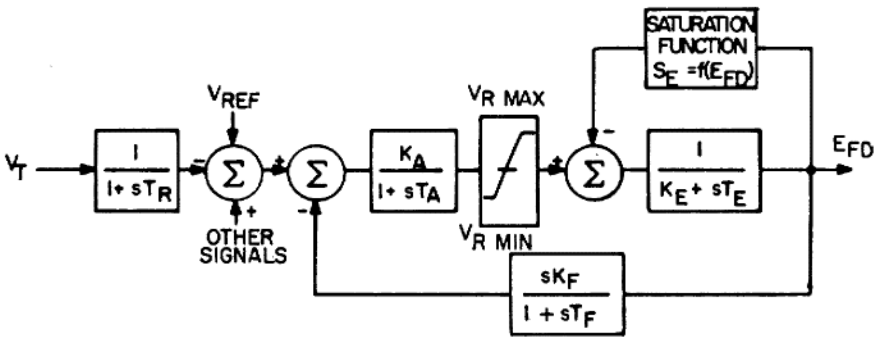
Feedback

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

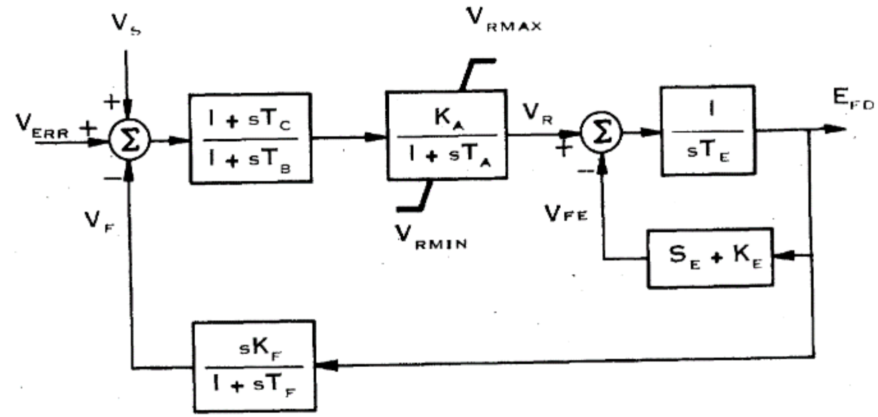
$$\frac{dV_F}{dt} = \underbrace{\frac{R_{t1}}{\left(L_{t1} + L_{tm}\right)}}_{\frac{1}{T_F}} \left(-V_F + \underbrace{\frac{N_2}{N_1} \frac{L_{tm}}{R_{t1}}}_{K_F} \frac{dE_{fd}}{dt} \right)$$

IEEET1 Model Evolution

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



1968



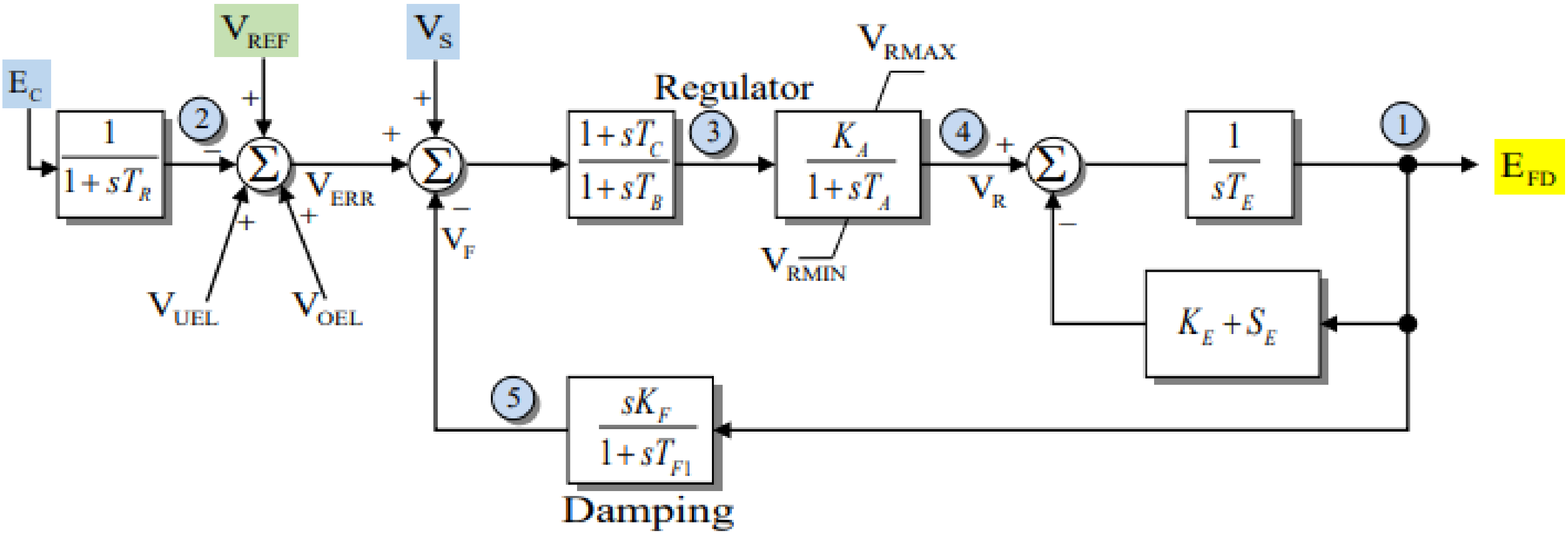
1981

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)

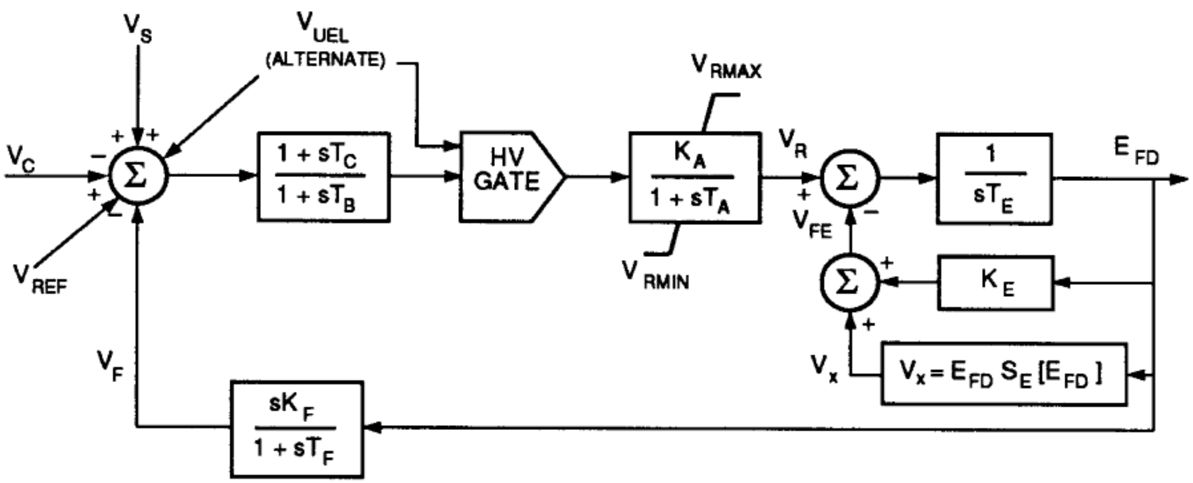


Figure 3—Type DC1A — DC Commutator Exciter

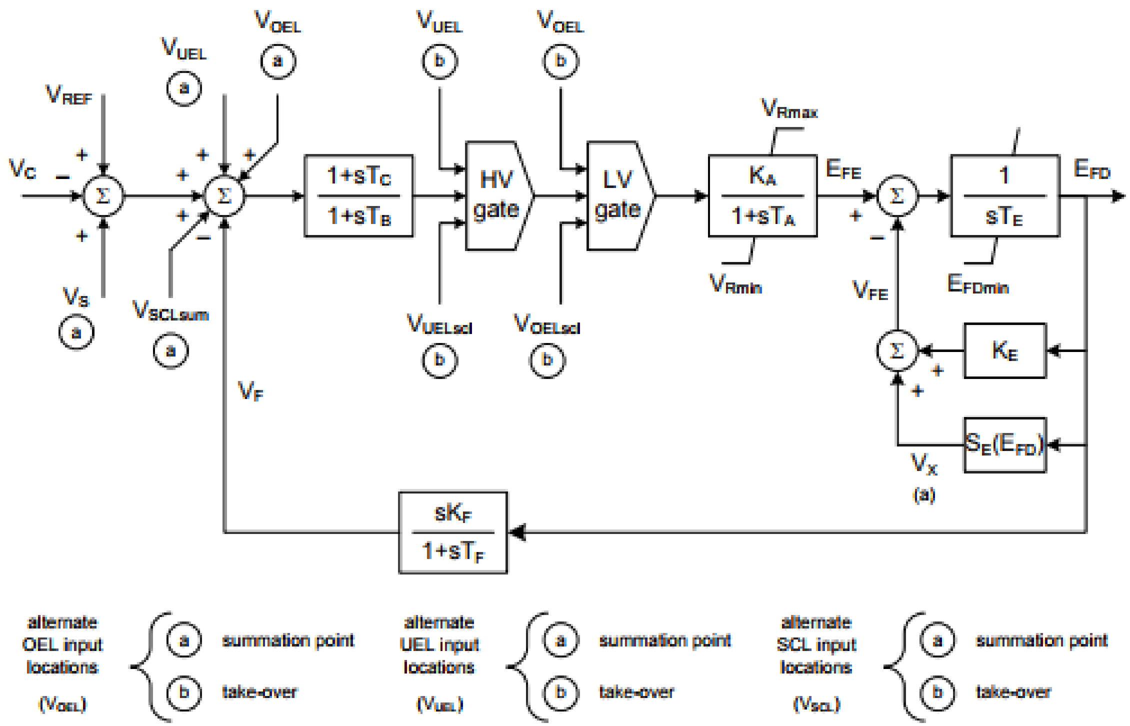
V_{UEL} is a signal from an under-excitation limiter, which we'll cover later

Same model is in 421.5-2005

Image Source: Fig 3 of IEEE Std 421.5-1992

IEEET1 Evolution

- Slightly modified in Std 421.5-2016



footnotes:

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

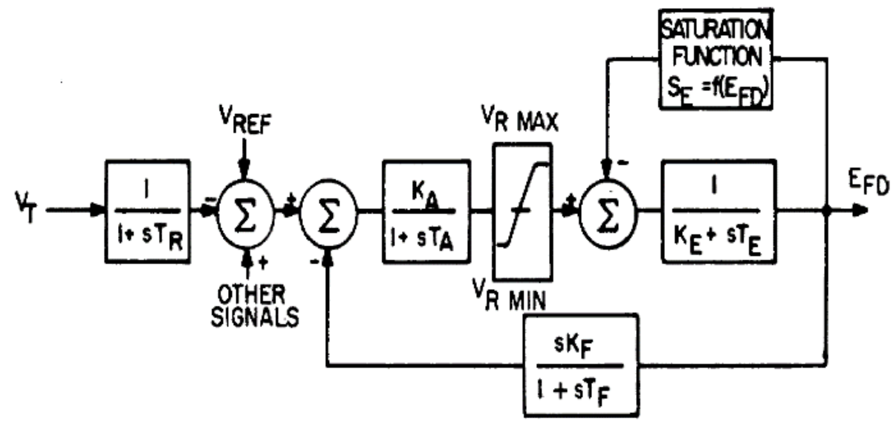
Figure 4—Type DC1C dc commutator exciter

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

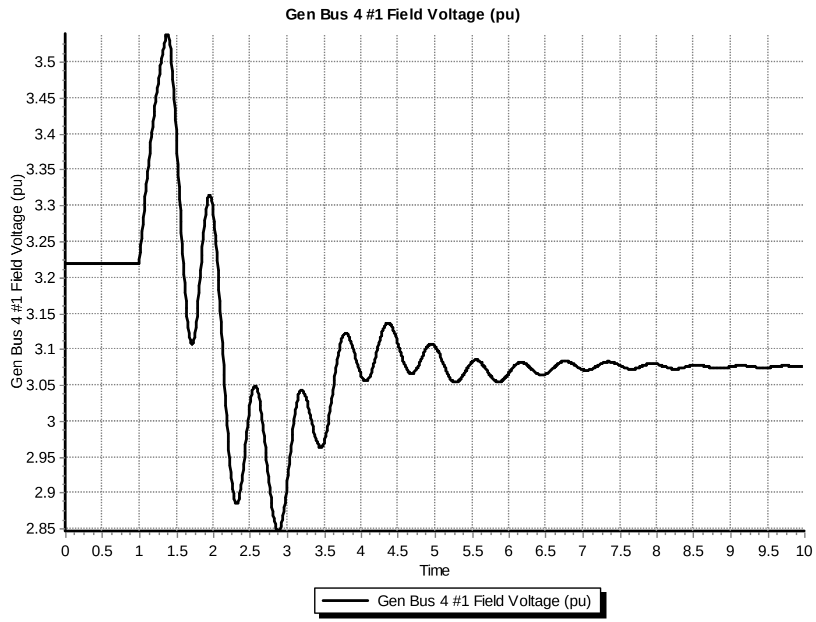
- Assume previous GENROU case with saturation. Then add a IEEE T1 exciter with K_A=50, T_A=0.04, K_E=-0.06, T_E=0.6, $V_{R,max}$=1.0, $V_{R,min}$= -1.0 For saturation assume $S_E(2.8) = 0.04$, $S_E(3.73)=0.33$
- Saturation function is $0.1621(E_{FD}-2.303)^2$ (for $E_{FD} > 2.303$); otherwise zero
- 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 +1.0946=1.09948

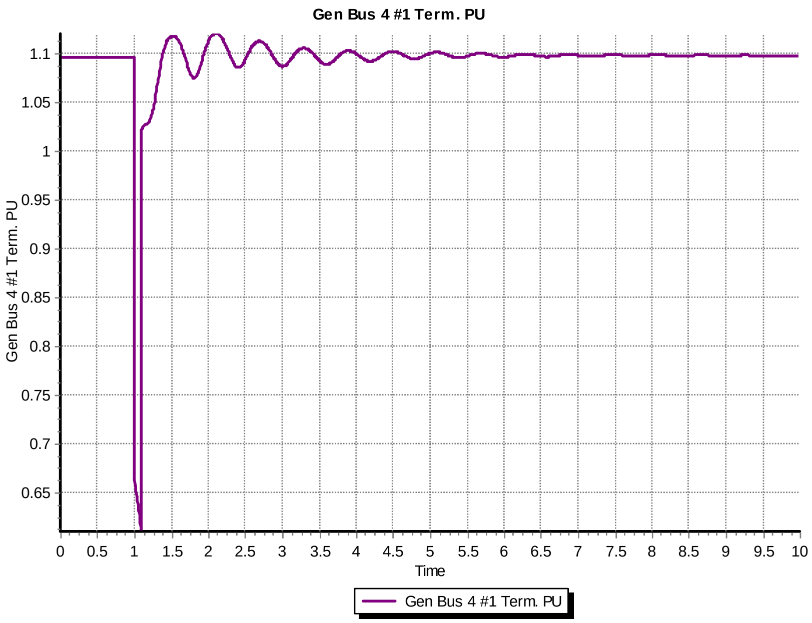


Case **B4_GENROU_Sat_IEEET1**

IEEE T1 Example

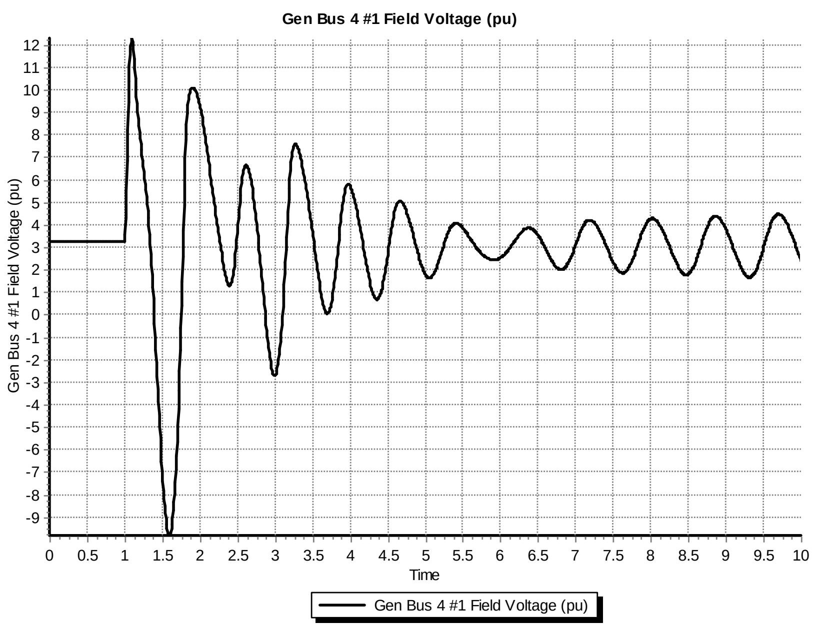
- For 0.1 second fault (from before), plot of E_{FD} and the terminal voltage is given below
- Initial V_4=1.0946, final V_4=1.0973
  - Steady-state error depends on the value of K_A

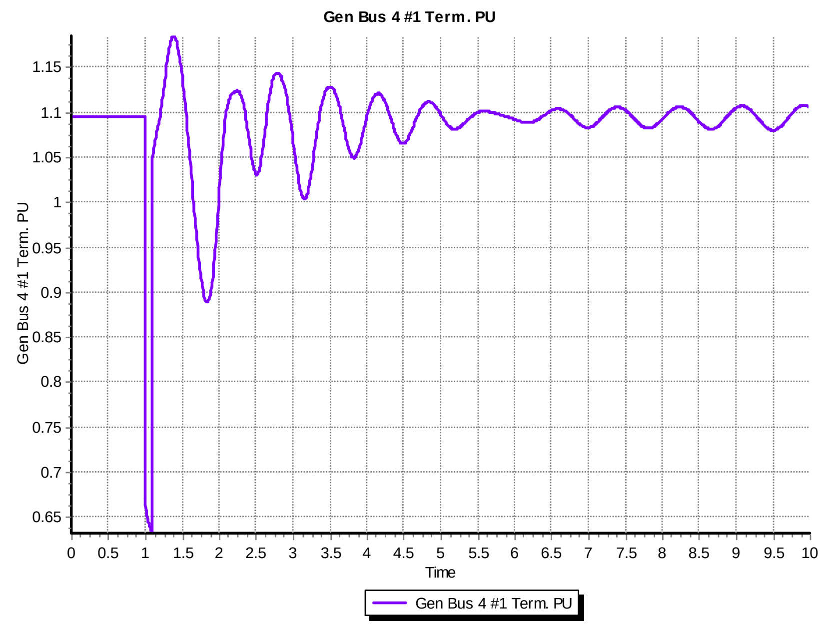




IEEET1 Example

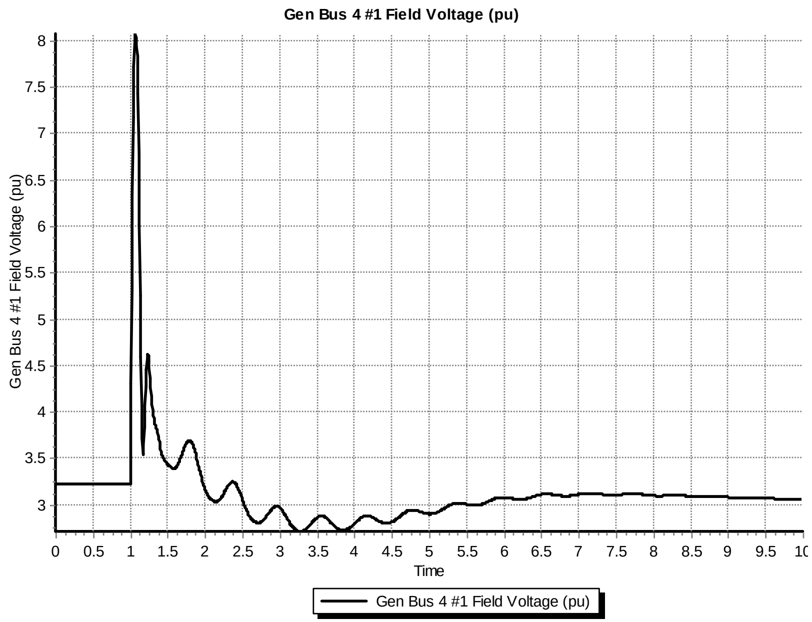
- Same case, except with K_A=500 to decrease steady-state error, no V_R limits; this case is actually unstable

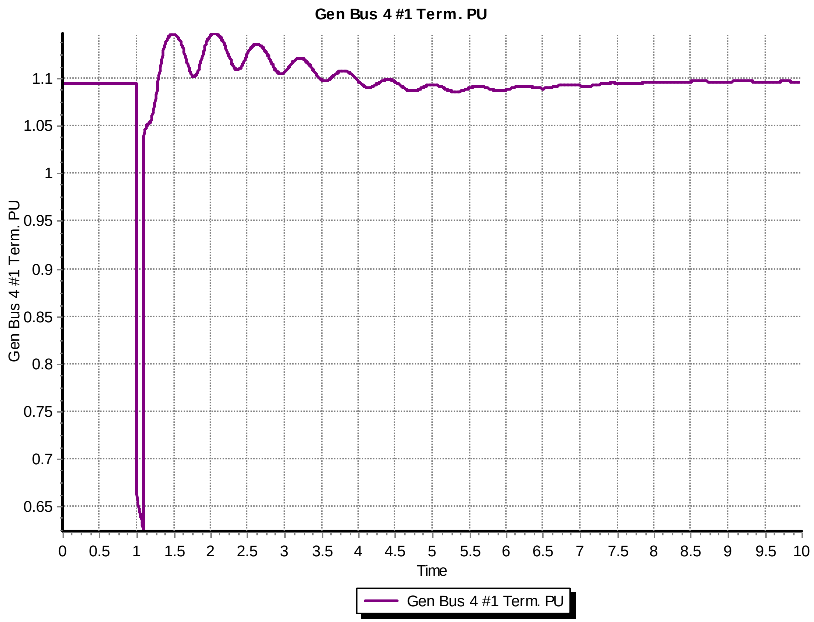




IEEET1 Example

- 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





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