ECEN 667
Power System Stability

Lecture 11: Exciter Models

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Announcements

- Read Chapter 4
- Homework 3 is due today
- Homework 4 is posted; it should be done before the first exam but need not be turned in
- Midterm exam is on Tuesday Oct 17 in class; closed book, closed notes, one 8.5 by 11 inch hand written notesheet allowed; calculators allowed

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

Brief Review of DC Machines

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

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

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

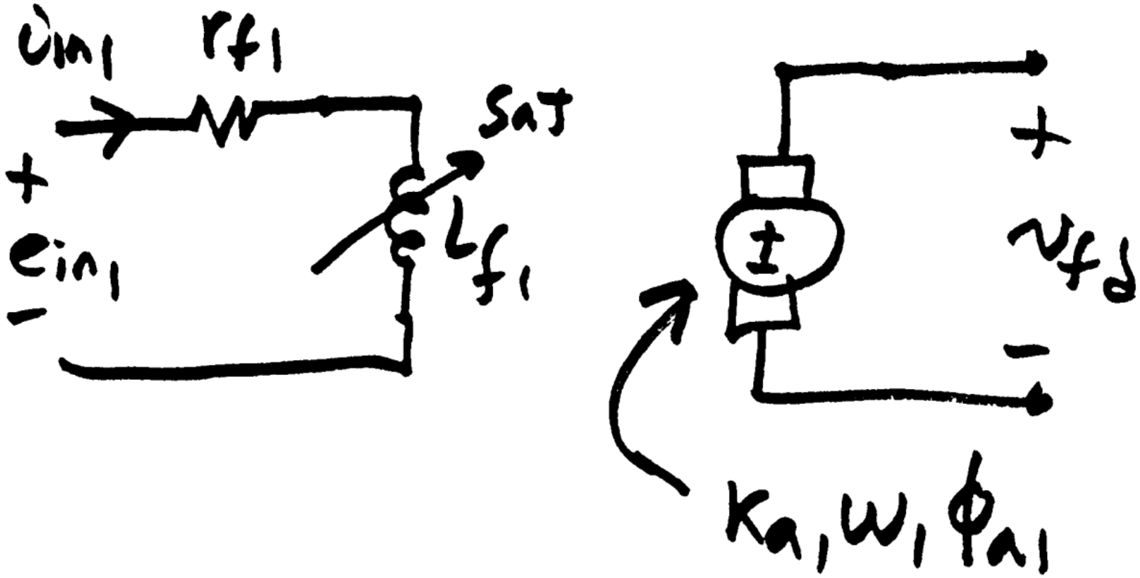
The f subscript refers to the field, the a to the armature; ω is the machine's speed, G is a constant. In a permanent magnet machine the field flux is constant, the field equation goes away, and the field impact is embedded in a equivalent constant to Gi_f

Taken mostly from ECE 330 book, M.A. Pai, *Power Circuits and Electromechanics*

Types of DC Machines

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

Separately Excited DC Exciter



(to sync mach)

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

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

σ_1 is coefficient of dispersion, modeling the flux leakage

Separately Excited DC Exciter

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

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

Assuming a constant speed ω_1

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

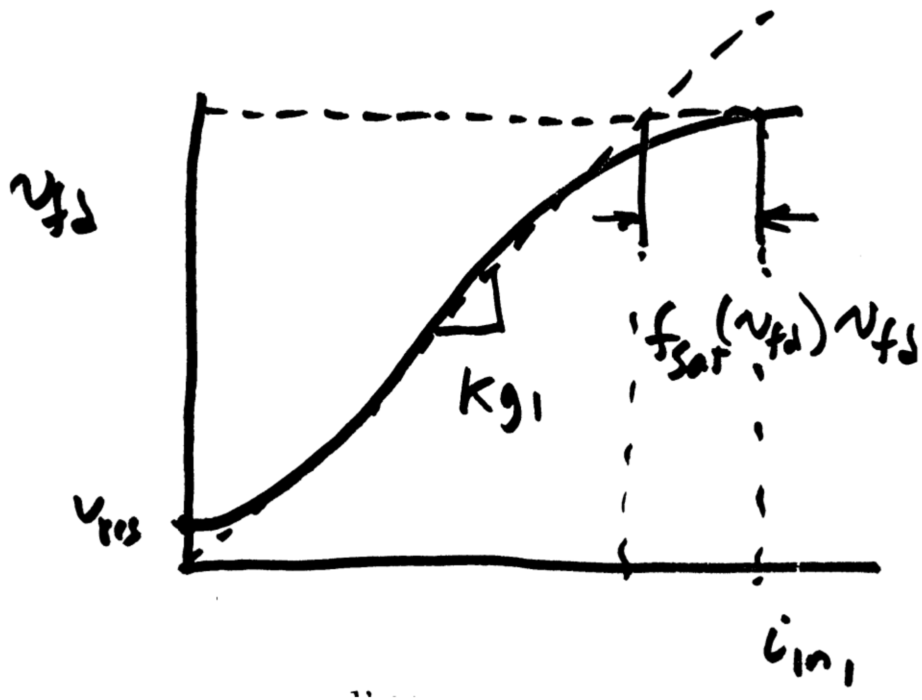
Solve above for ϕ_{f1} which was used in the previous slide

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

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

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

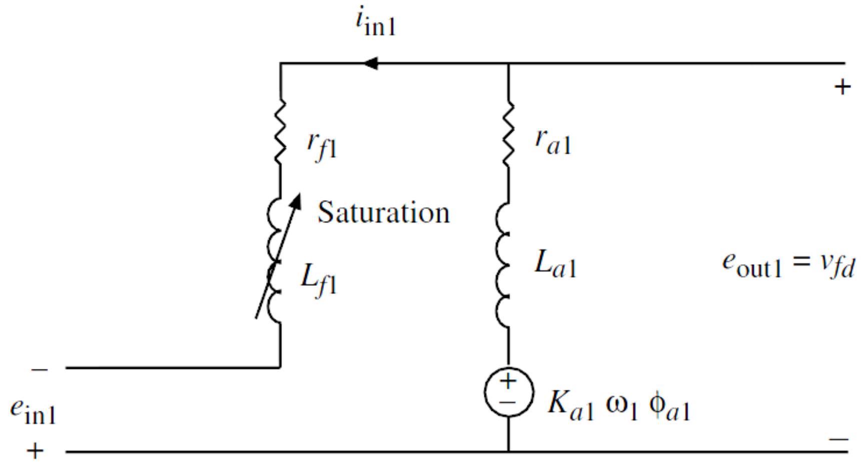


Figure 4.3: *Self-excited dc generator circuit*

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

Note the additional E_{fd} term on the end

Self and Separated Excited Exciters

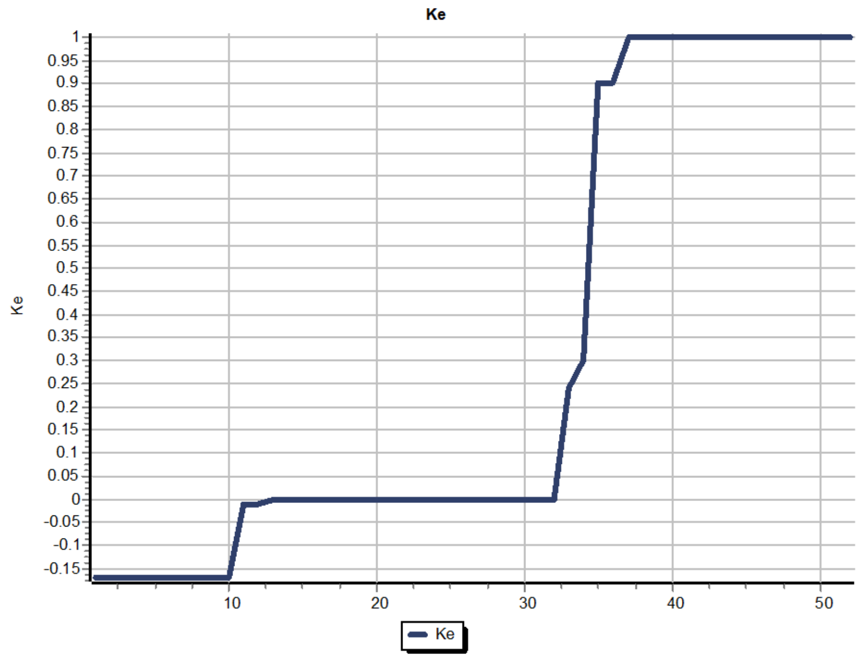
- The same model can be used for both by just modifying the value of K_E

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

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

IEEE T1 K1 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	

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

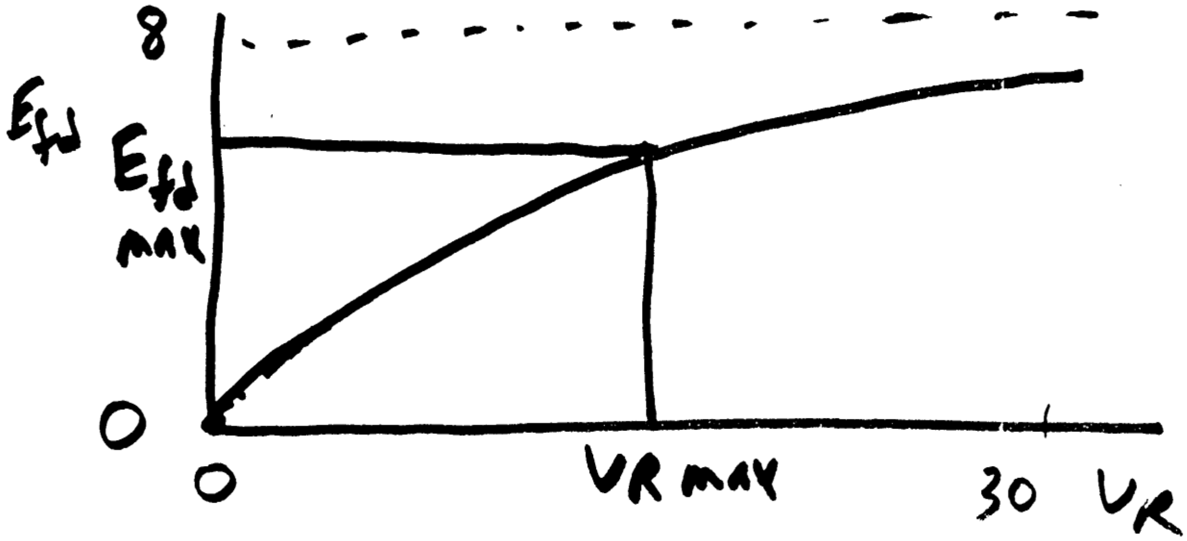
- Exponential function could also be used

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

Exponential Saturation

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

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

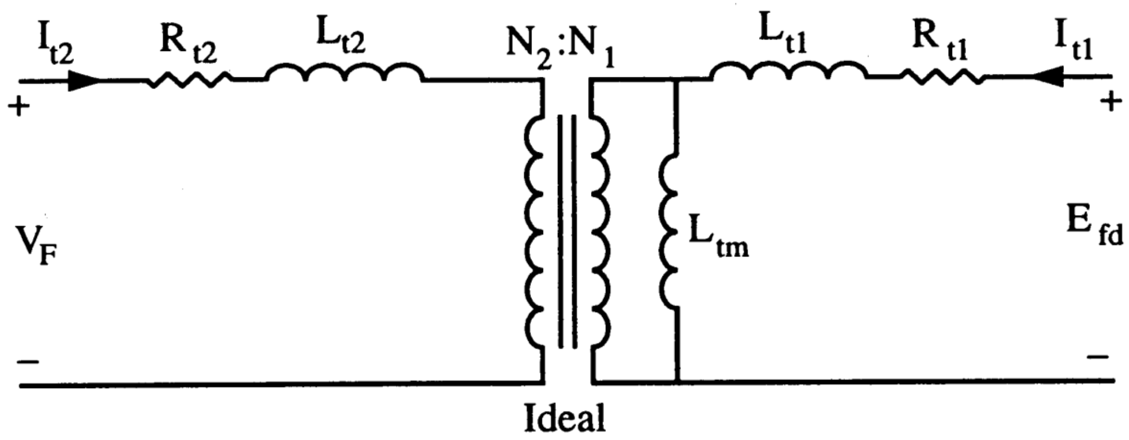
In steady state $$V_{ref} - V_t = V_{in} = \frac{V_R}{K_A}$$

Big $$K_A \to V_t \approx V_{ref}$$

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



Large L_{t2} so $I_{t2} \approx 0$ $\quad V_F = \frac{N_2}{N_1} L_{tm} \frac{dI_{t1}}{dt}$

Feedback

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

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

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

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

IEEE T1 Exciter

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

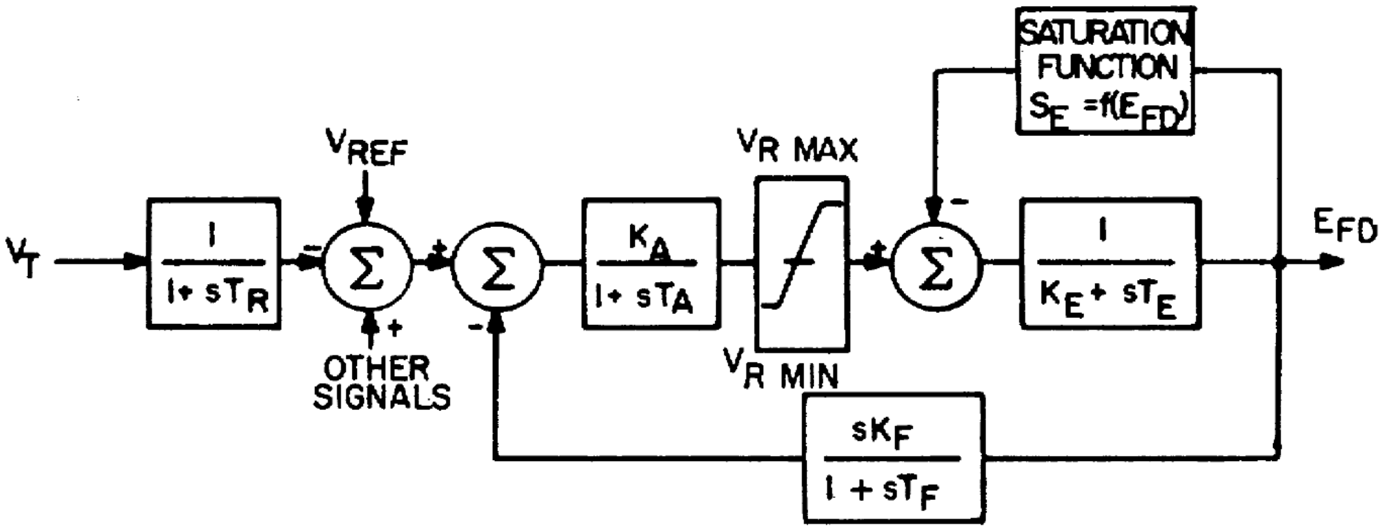
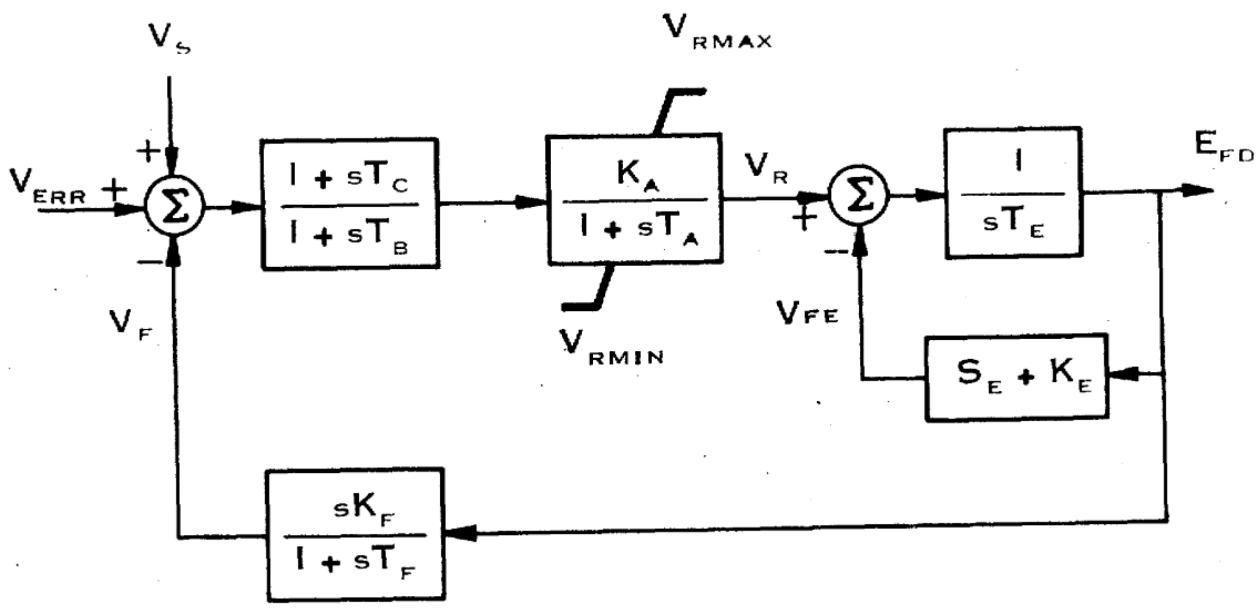


Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

IEEE T1 Evolution

- This model has been subsequently modified over the years, called the DC1 in a 1981 IEEE paper (modeled as the EXDC1 in stability packages)



Note, K_E in the feedback is the same as the 1968 approach

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

IEEE T1 Evolution

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

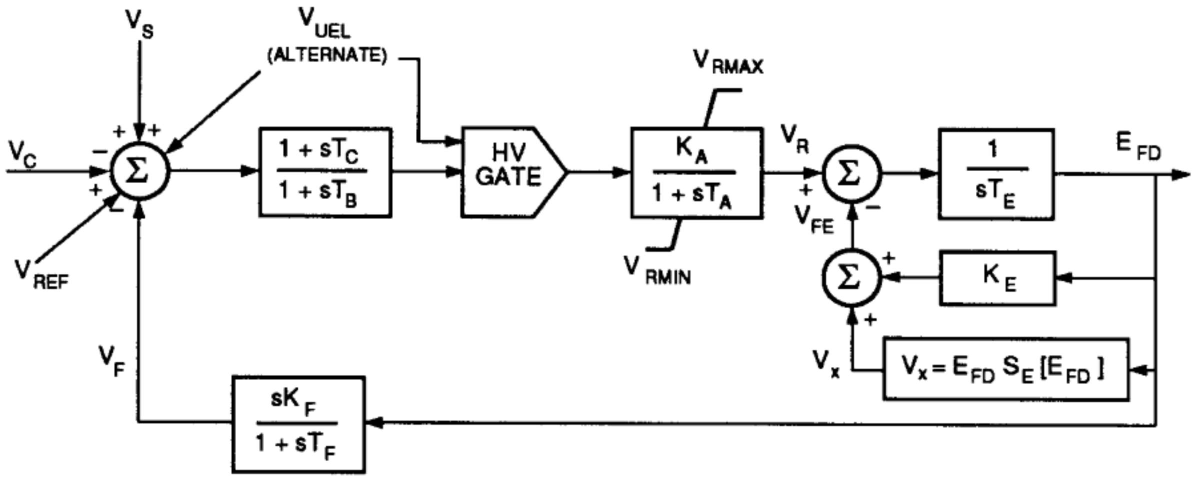


Figure 3—Type DC1A — DC Commutator Exciter

Same model is in 421.5-2005

Image Source: Fig 3 of IEEE Std 421.5-1992

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

IEEE T1 Evolution

- Slightly modified in Std 421.5-2016

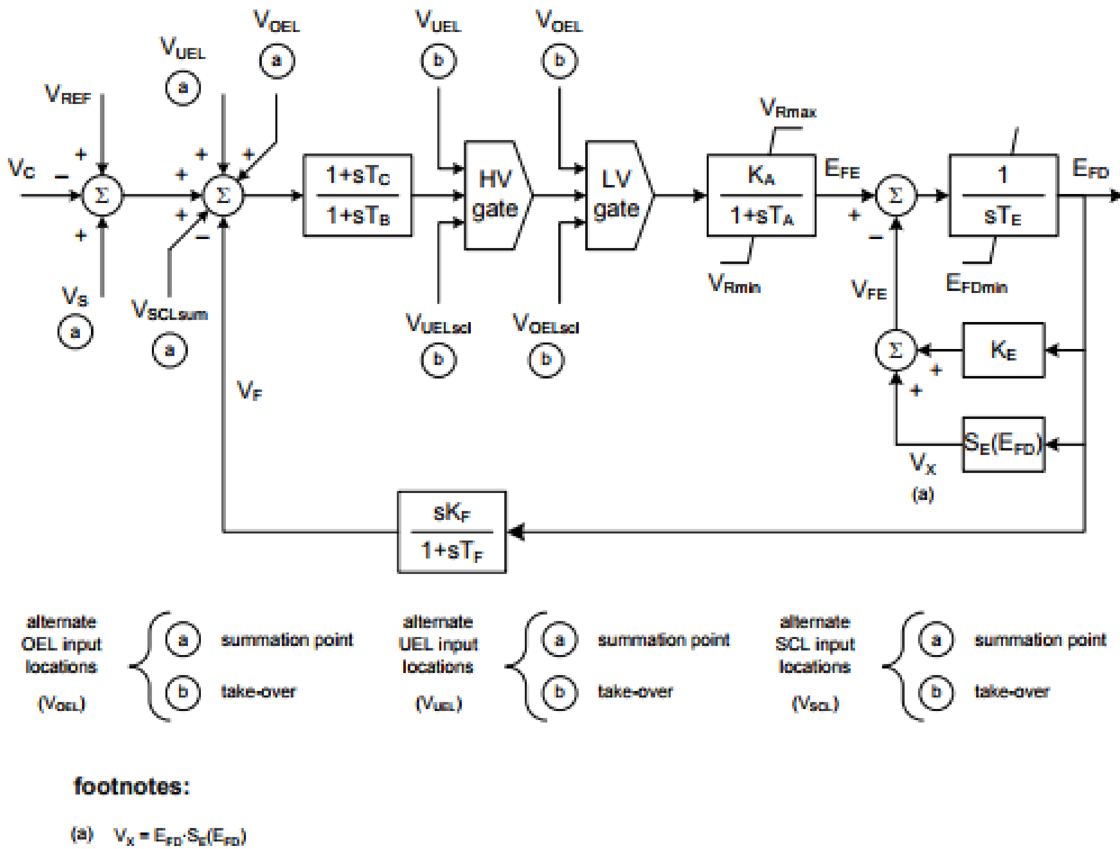


Figure 4—Type DC1C dc commutator exciter

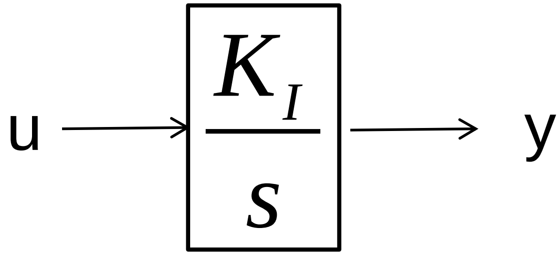
Note the minimum limit on E_{FD}

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

Initialization and Coding: 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
- Next several slides quickly cover the standard block diagram elements

Integrator Block

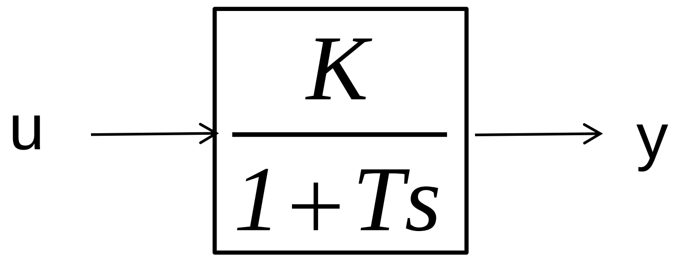


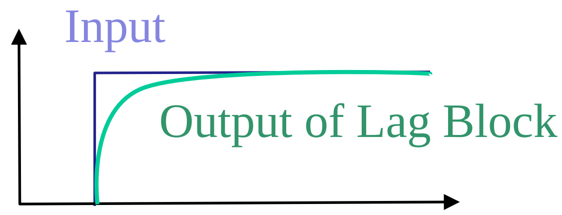
- Equation for an integrator with u as an input and y as an output is

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

- 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



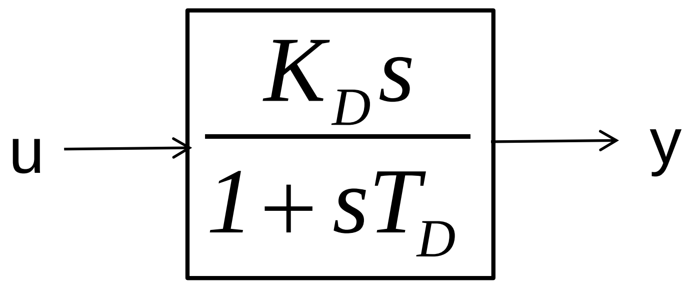


- Equation with u as an input and y as an output is

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

- 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
- 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

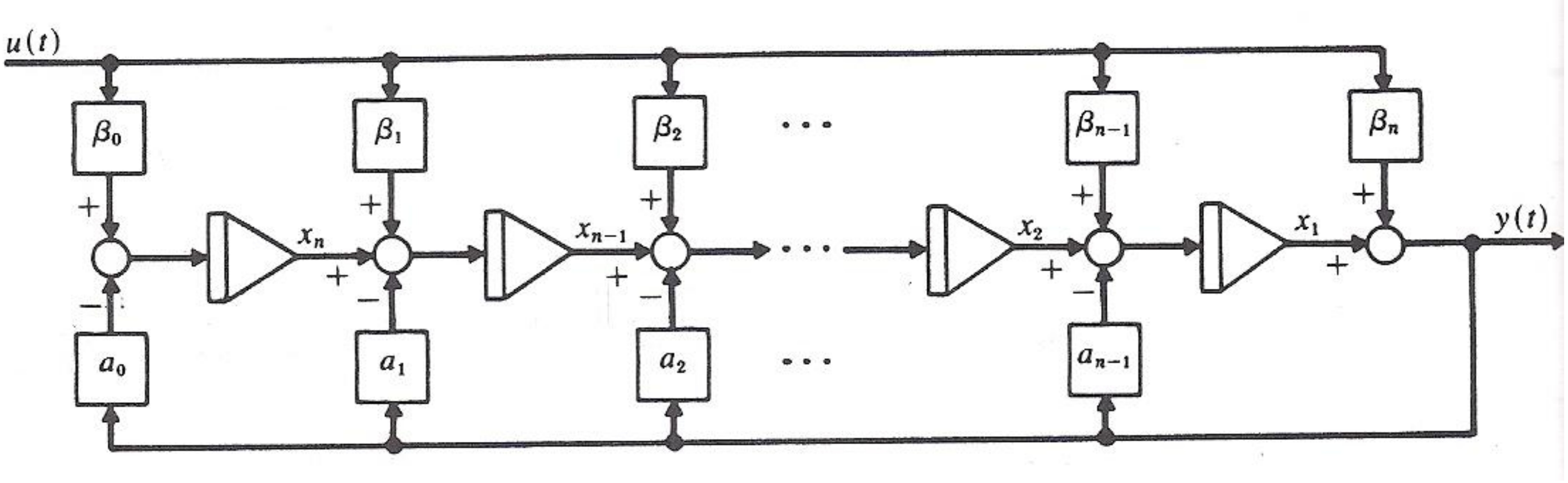
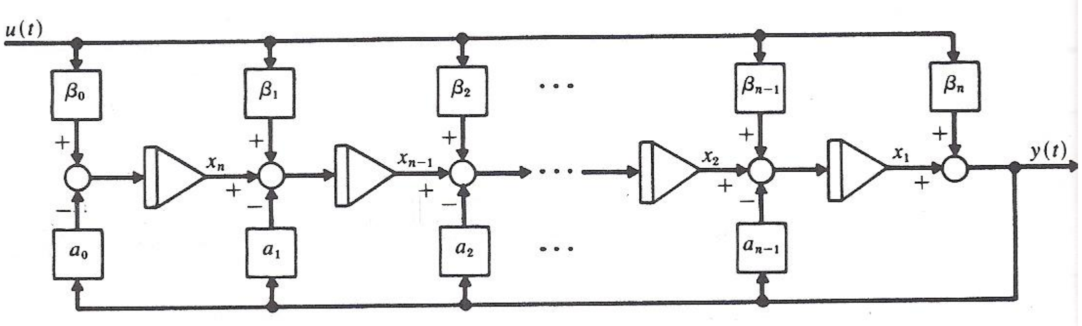


Image source: W.L. Brogan, *Modern Control Theory*, Prentice Hall, 1991, Figure 3.7

Derivative Example

- Write in form

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



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

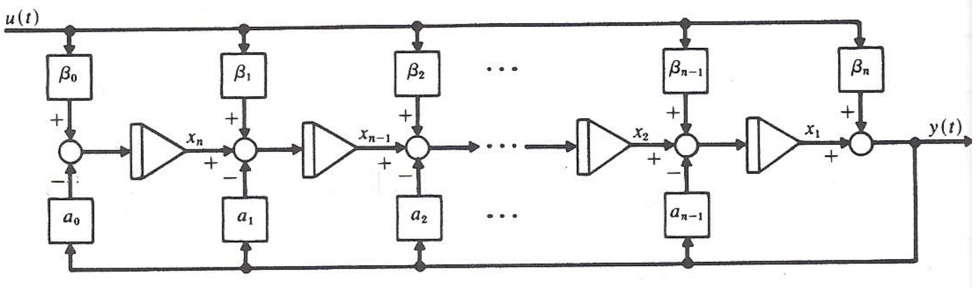
$$\boxed{\frac{1+sT_A}{1+sT_B} = \frac{\dfrac{1}{T_B}+s\dfrac{T_A}{T_B}}{1/T_B+s}}$$

Lead-Lag Block

- The equations are with

  β_0=1/T_B, β_1=T_A/T_B,
  α_0=1/T_B

  then



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

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

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