ECEN 667
Power System Stability

Lecture 9: Exciters

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Special Guest Lecture by TA Hanyue Li!

TEXAS A&M UNIVERSITY

Announcements

- Read Chapter 4
- Homework 3 is due on Tuesday October 1
- Exam 1 is Thursday October 10 during class

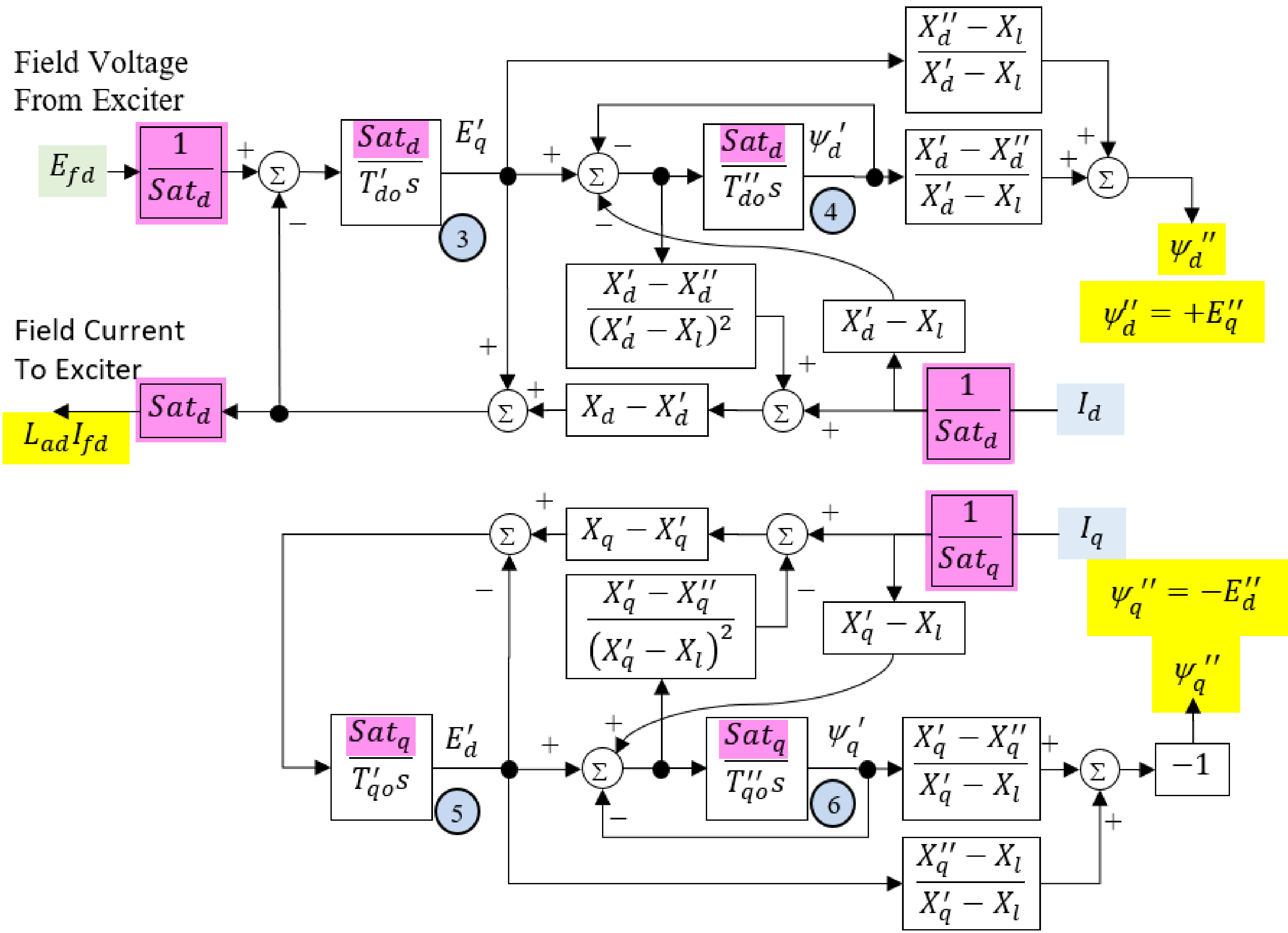
Why does this even matter?

- GENROU and GENSAL models date from 1970, and their purpose was to replicate the dynamic response the synchronous machine
  - They have done a great job doing that
- Weaknesses of the GENROU and GENSAL model has been found to be with matching the field current and field voltage measurements
  - Field Voltage/Current may have been off a little bit, but that didn't effect *dynamic* response
  - It just *shifted* the values and gave them an offset
- Shifted/Offset field voltage/current didn't matter too much in the past

GENTPW, GENQEC

- New models are under development that address several issues
  - Saturation function should be applied to all input parameters by multiplication
    - This also ensures a conservative coupling field assumption of Peter W. Sauer paper from 1992
  - Same multiplication should be applied to both d-axis and q-axis terms (assume same amount of saturation on both)
- Results in differential equations that are nearly the same as GENROU
  - Scales the inputs and outputs, and effects time constants
- Network Interface Equation is same as GENTPF/J

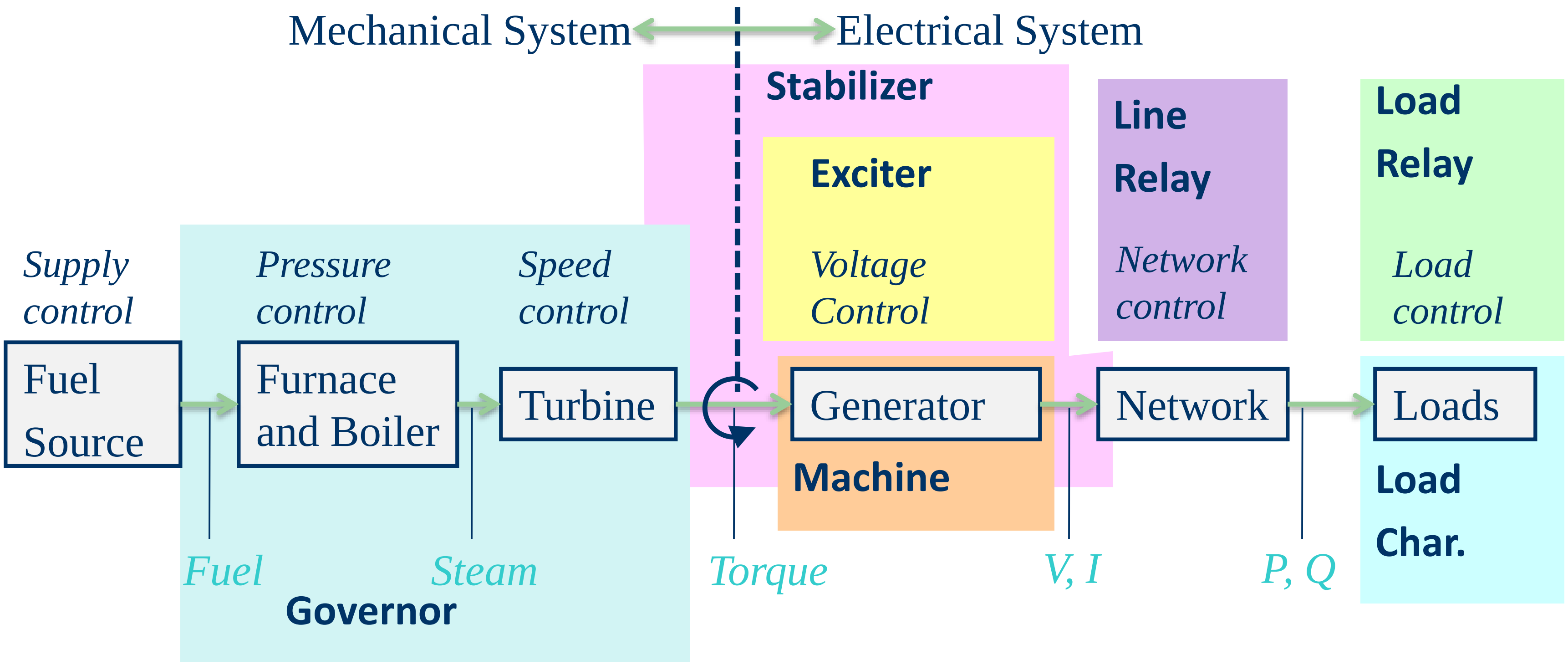
GENTPW and GENQEC Basic Diagram



Comment about all these Synchronous Machine Models

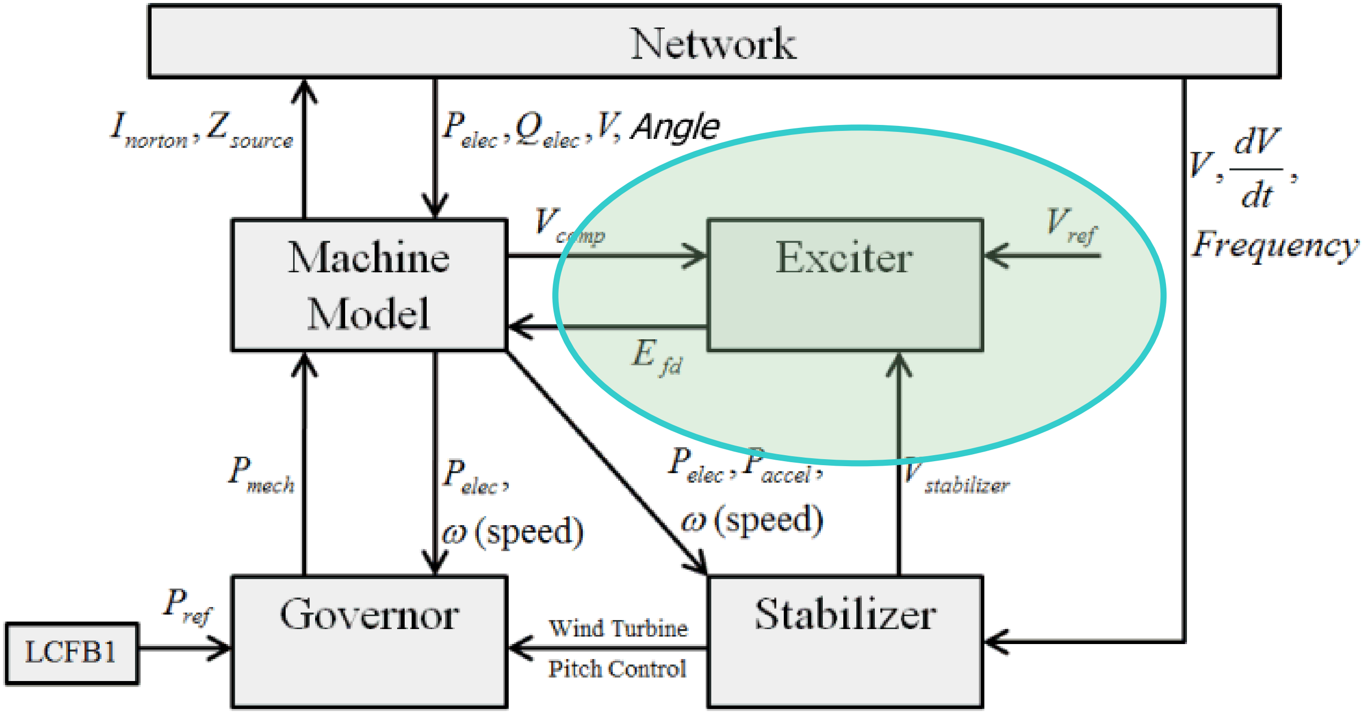
- The models are improving. However, this does not mean the old models were useless
- All these models have the same input parameter names, but that does not mean they are exactly the same
  - Input parameters are tuned for a particular model
  - It is NOT appropriate to take the all the parameters for GENROU and just copy them over to a GENTPJ model and call that your new model
  - When performing a new generator testing study, that is the time to update the parameters

Dynamic Models in the Physical Structure: Exciters



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

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

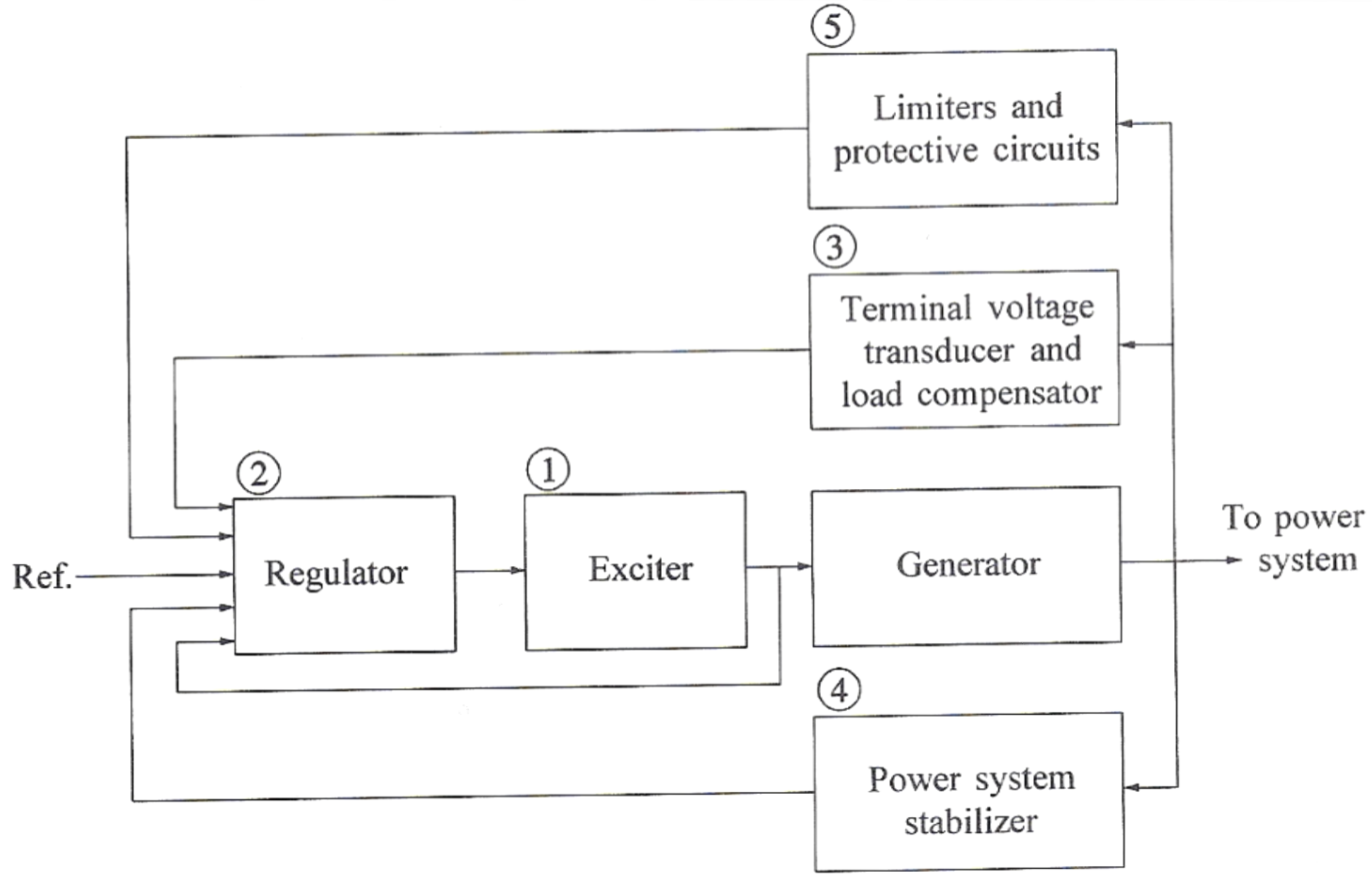


Image source: Fig 8.1 of Kundur, *Power System Stability and Control*

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

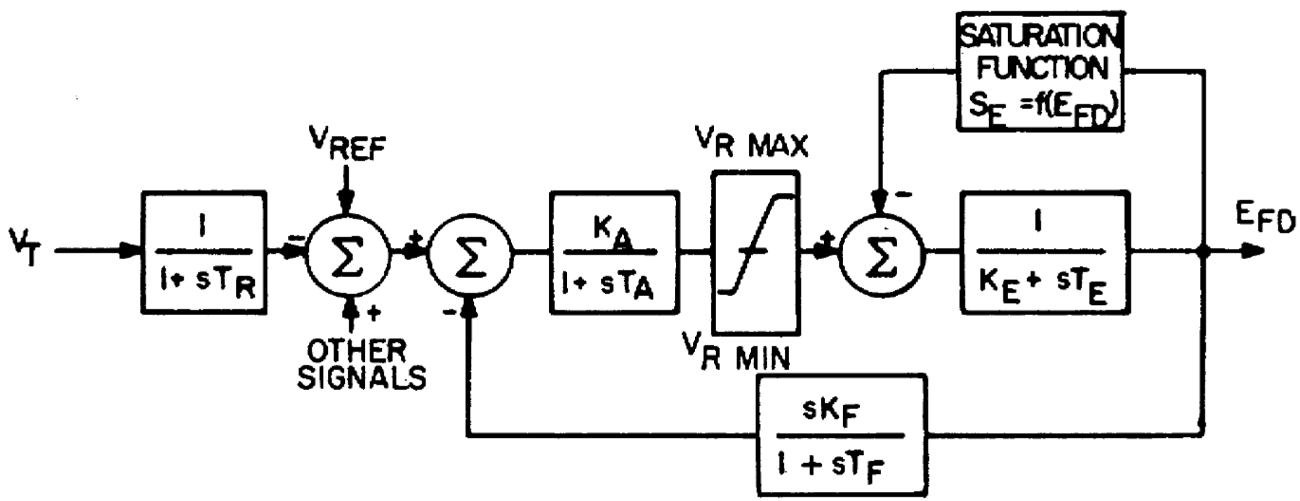
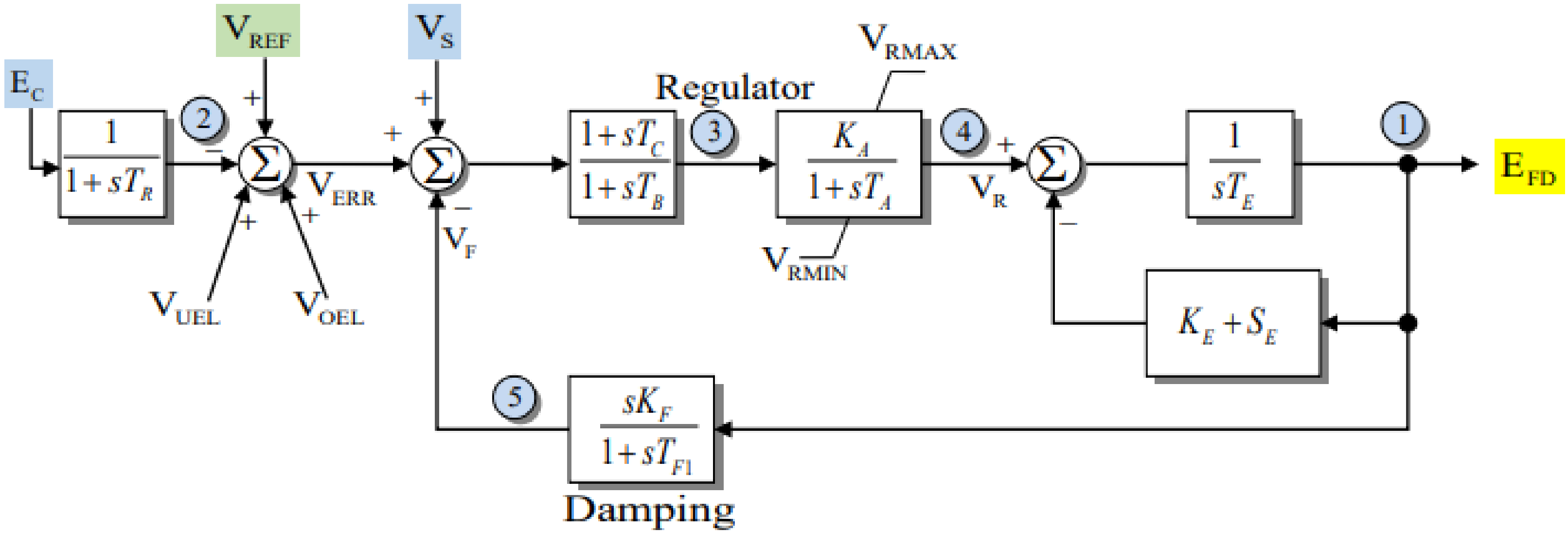


Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

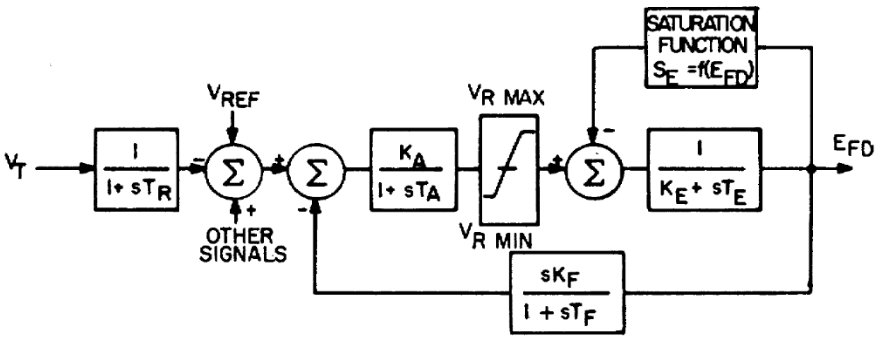
IEEEX1

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

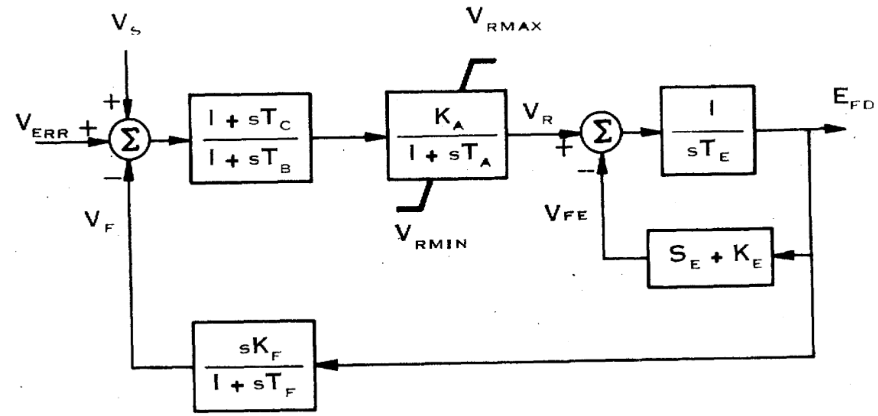


IEEET1 Model Evolution

- 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

IEEET1 Evolution

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

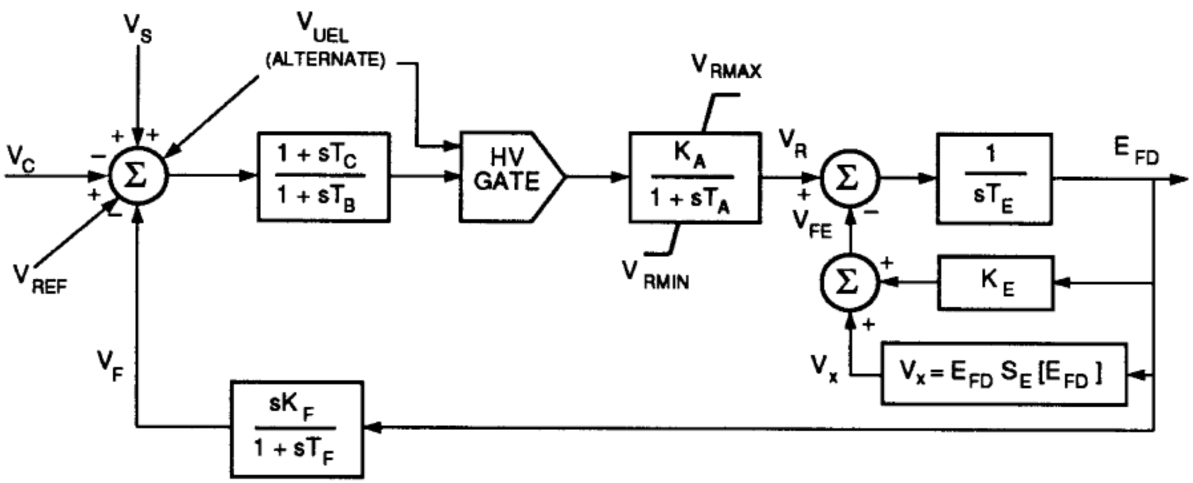


Figure 3—Type DC1A — DC Commutator Exciter

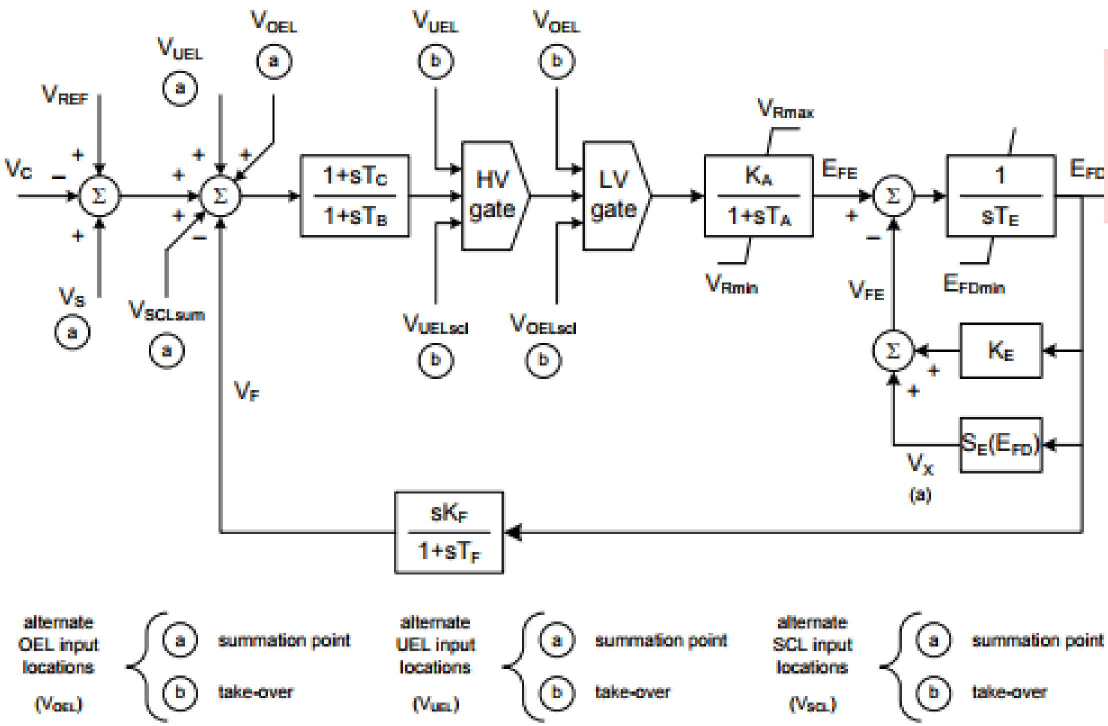
Same model is in 421.5-2005

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

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

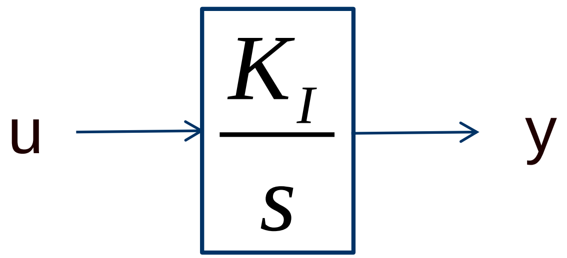
Note the minimum limit on E_{FD}

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

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

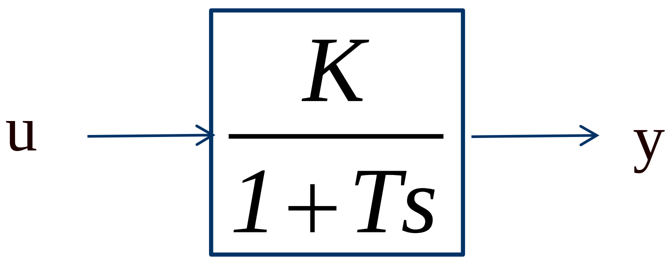


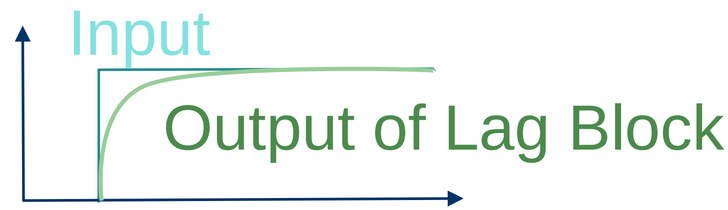
- Equation for an integrator with u as an input and y as an output is

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

- 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
- 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

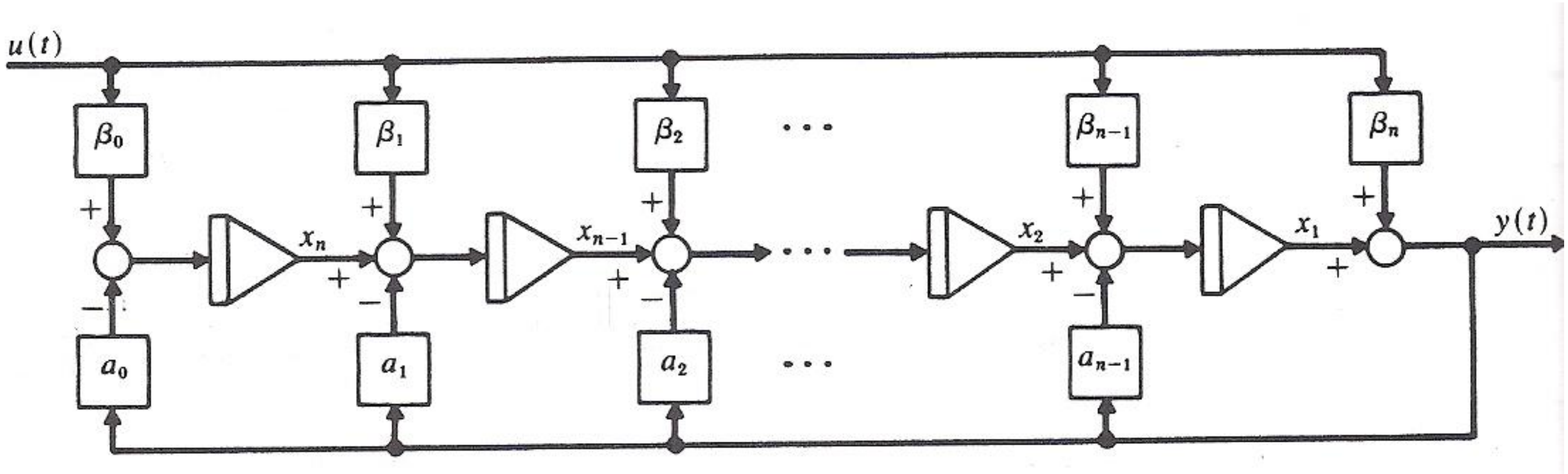
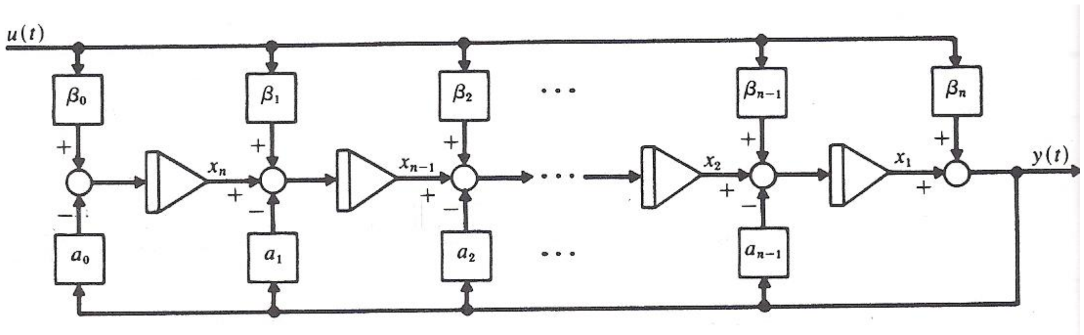


Image source: W.L. Brogan, *Modern Control Theory*, Prentice Hall, 1991, Figure 3.7

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

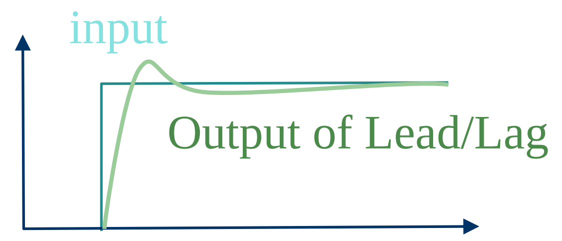
$$\frac{dx}{dt} = \beta_0 u - \alpha_0 y = -\frac{y}{T_D}$$

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

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

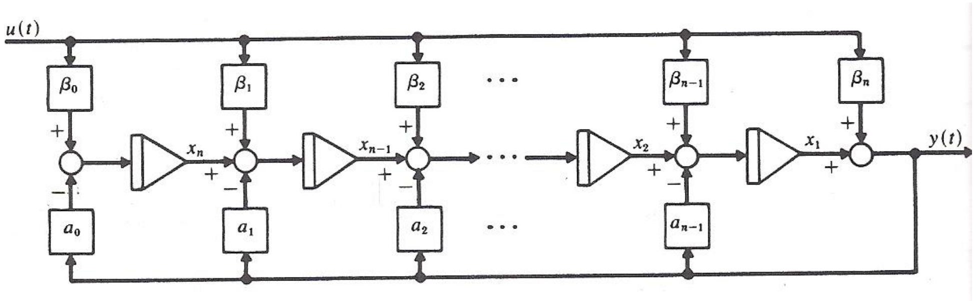
$$\boxed{\frac{1+sT_A}{1+sT_B} = \frac{\frac{1}{T_B}+s\frac{T_A}{T_B}}{1/T_B+s}}$$

Lead-Lag Block

- The equations are with

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

  then



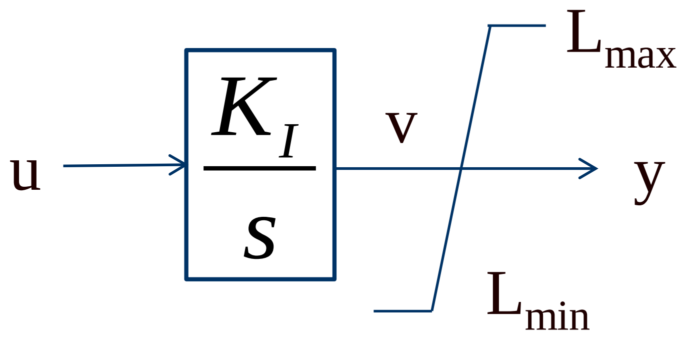
$$\frac{dx}{dt} = \beta_0 u - \alpha_0 y = \frac{1}{T_B}(u - y)$$

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

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

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

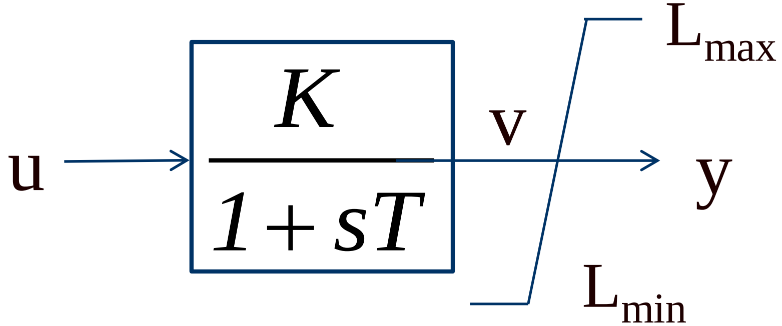
If $L_{min} \le v \le L_{max}$ then $y = v$

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



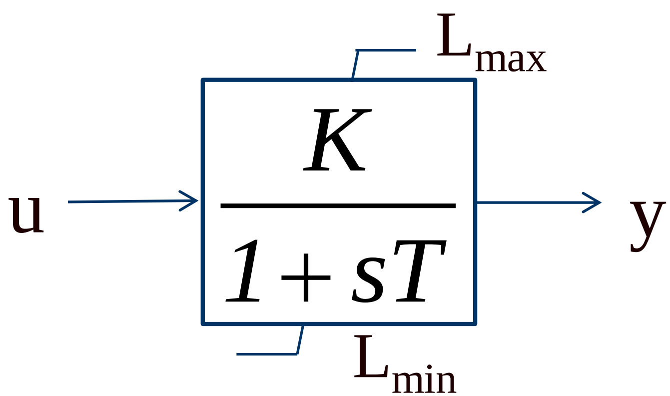
$$\frac{dv}{dt} = \frac{1}{T}(Ku - v)$$

If $L_{min} \le v \le L_{max}$ then $y = v$
else If $v < L_{min}$ then $y = L_{min}$,
else if $v > L_{max}$ then $y = L_{max}$

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)

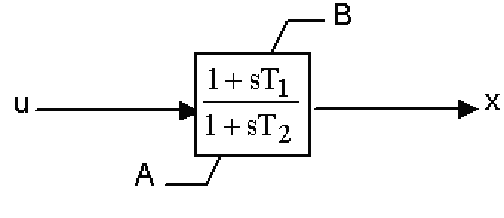
If $L_{min} \le y \le L_{max}$ then normal $\frac{dy}{dt} = \frac{1}{T}\left(Ku - y\right)$

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)



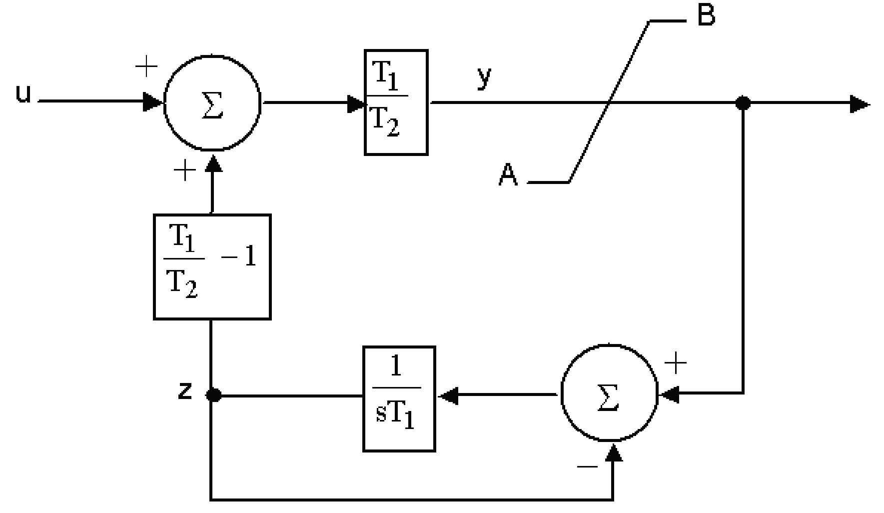
(a) Model

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

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

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

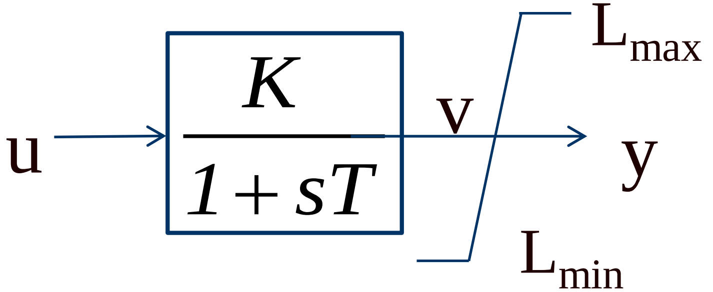
If $B \geq y \geq A$, then $x = y$



(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→0, v=Ku



- With lead-lag it is quite common for T_A=T_B, resulting in the block being ignored

Over and Under Excitation Limiters

- Traditionally our industry has not modeled over excitation limiters (OEL) and under excitation limiters (UEL) in transient stability simulation
  - The Mvar outputs of synchronous machines during transients likely do go outside these bounds in our existing simulations
  - Our Simulation haven't been modeling limits being hit anyway, so the overall dynamic response isn't impacted
- If the industry wants to start modeling OEL and UEL, then we need to better match the field voltage and currents
  - Otherwise we're going to be hitting these limits when in real life we are not