ECEN 667
Power System Stability

Lecture 12: Exciter Models

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Announcements

- Read Chapter 4
- 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

Lead-Lag Block

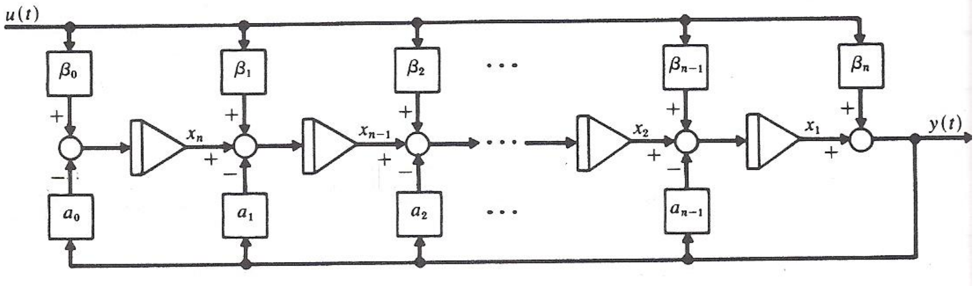
$$u \longrightarrow \boxed{\frac{1+sT_A}{1+sT_B}} \longrightarrow y$$

- 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



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

then

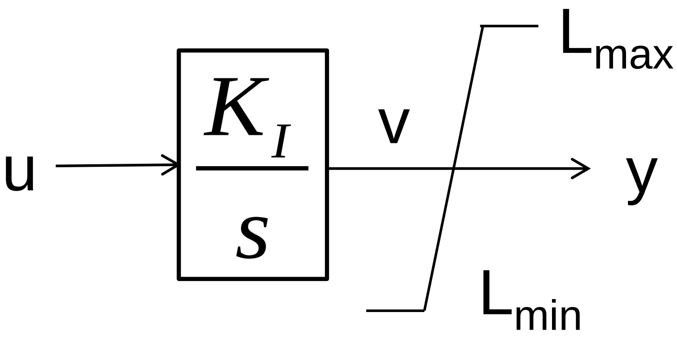
$$\frac{dx}{dt} = \beta_0 u - \alpha_0 y = \frac{1}{T_B}(u - y)$$

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

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

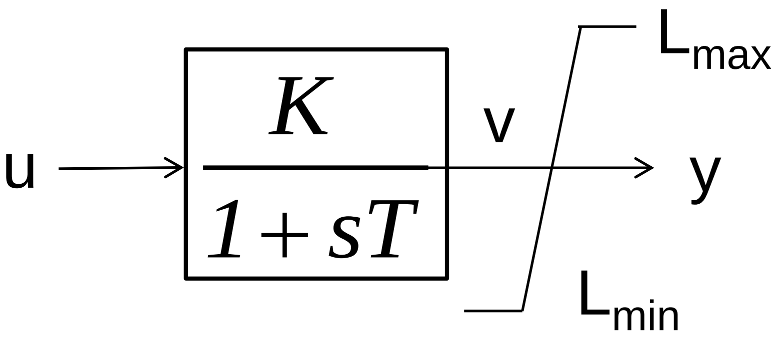
$$\frac{dv}{dt} = K_I u$$

If $L_{min} \leq v \leq L_{max}$ 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

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

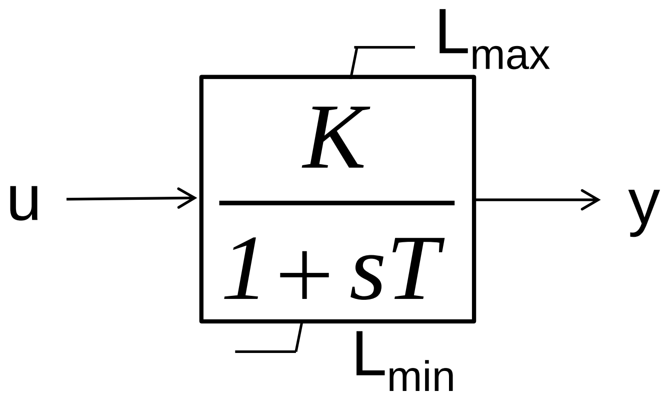


If $L_{min} \le v \le L_{max}$ then $y = v$
else If $v < L_{min}$ then $y = L_{min}$,
else if $v > L_{max}$ then $y = L_{max}$

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)

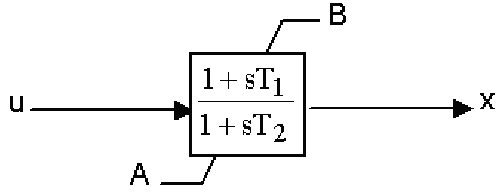
If $L_{min} \le y \le L_{max}$ then normal $\frac{dy}{dt} = \frac{1}{T}\left(Ku - y\right)$

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)



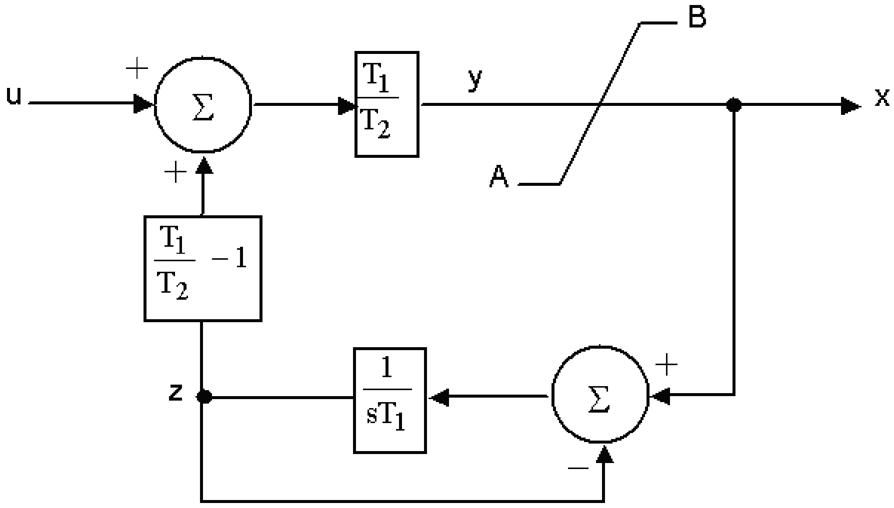
(a) Model

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

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

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

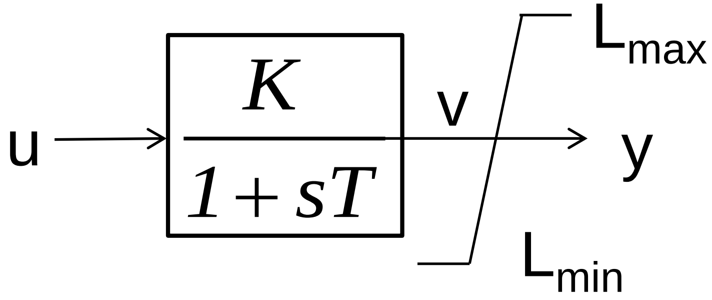
If $B \geq y \geq A$, then $x = y$



(b) Implementation

Ignored States

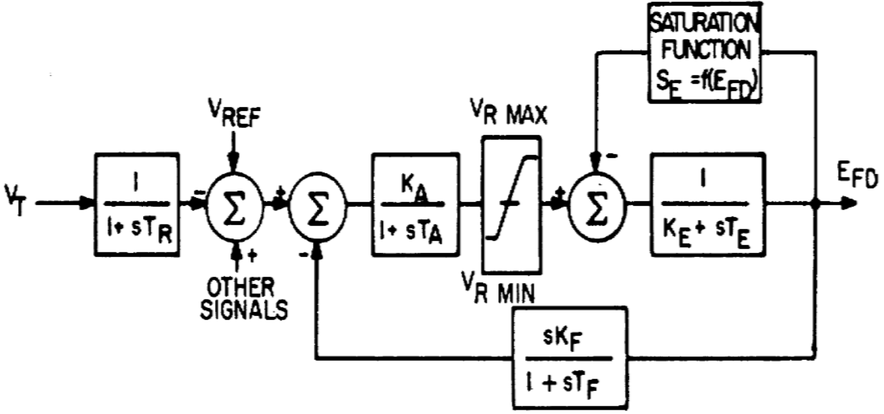
- When integrating block diagrams often states are ignored, such as a measurement delay with $T_R=0$
- In this case the differential equations just become algebraic constraints
- Example: For block at right, as T→0, v=Ku



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

IEEE T1 Example

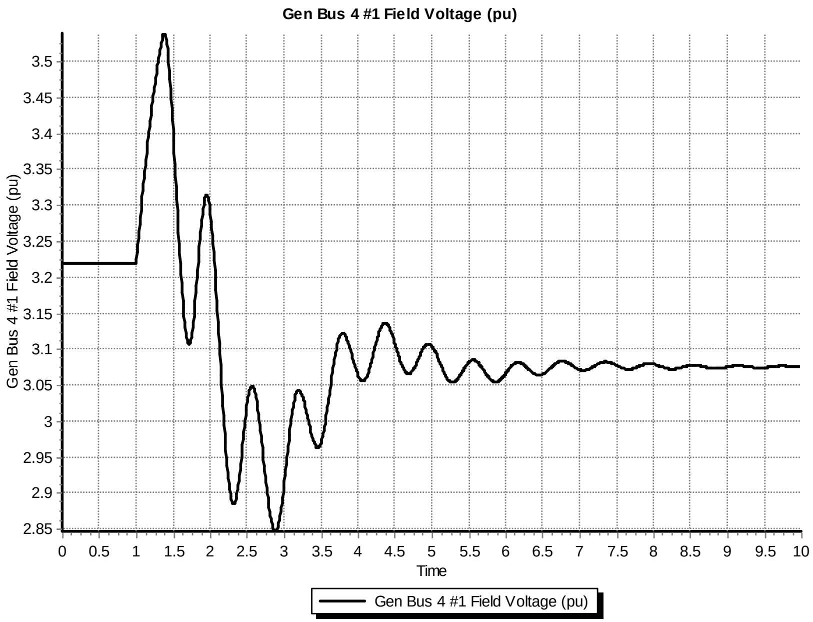
- Assume previous GENROU case with saturation. Then add a IEEE T1 exciter with Ka=50, Ta=0.04, Ke=-0.06, Te=0.6, Vr_{max}=1.0, Vr_{min}= -1.0 For saturation assume Se(2.8) = 0.04, Se(3.73)=0.33
- Saturation function is $0.1621(Efd-2.303)^2$ (for Efd > 2.303); otherwise zero
- Efd is initially 3.22
-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

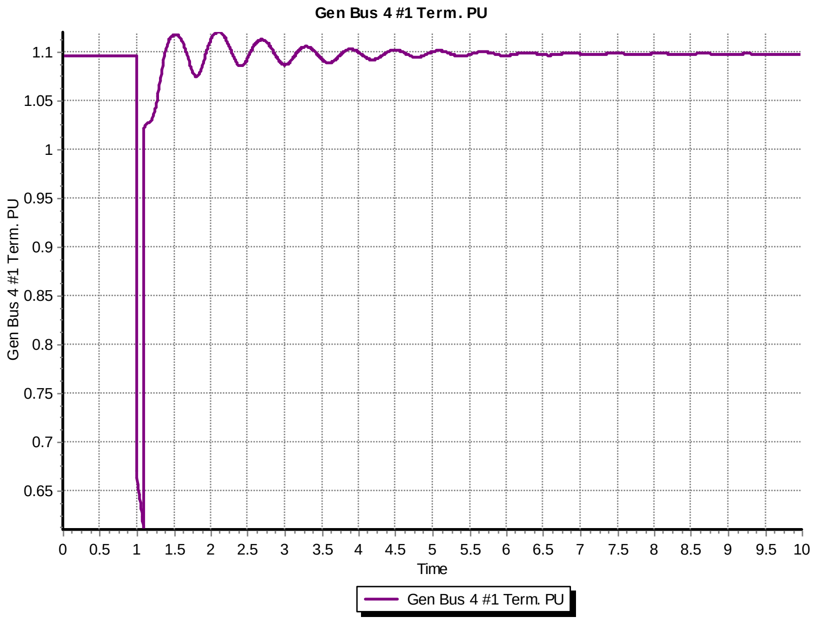


B4_GENROU_Sat_IEEET1

IEEE T1 Example

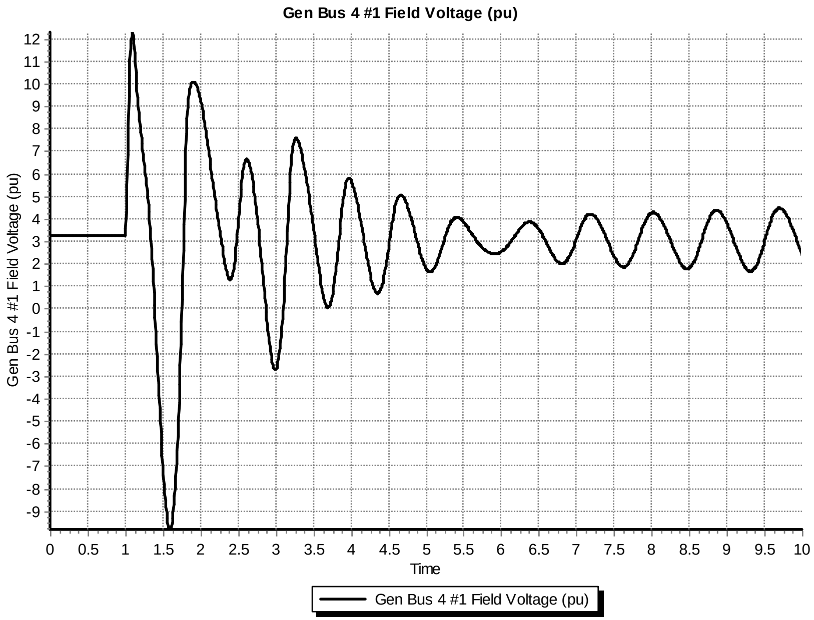
- For 0.1 second fault (from before), plot of Efd and the terminal voltage is given below
- Initial V_4=1.0946, final V_4=1.0973
  - Steady-state error depends on the value of Ka

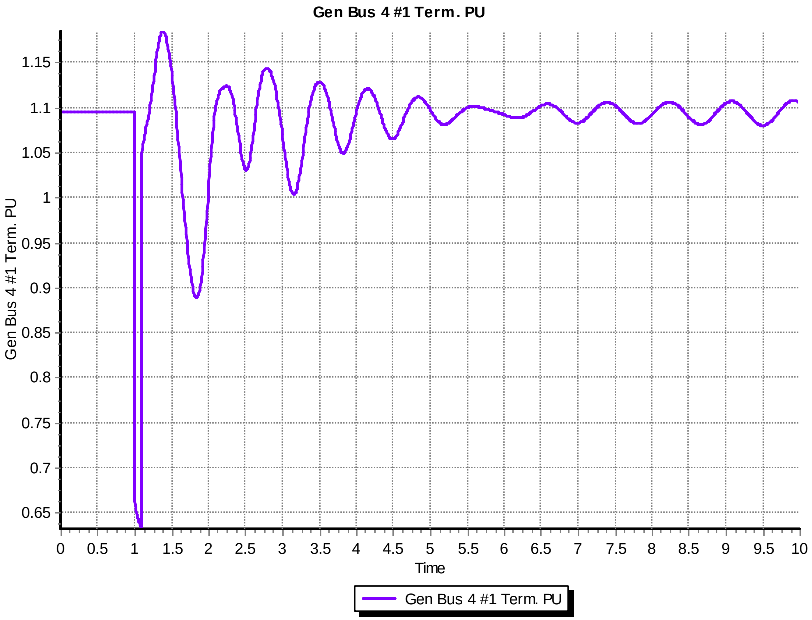




IEEE T1 Example

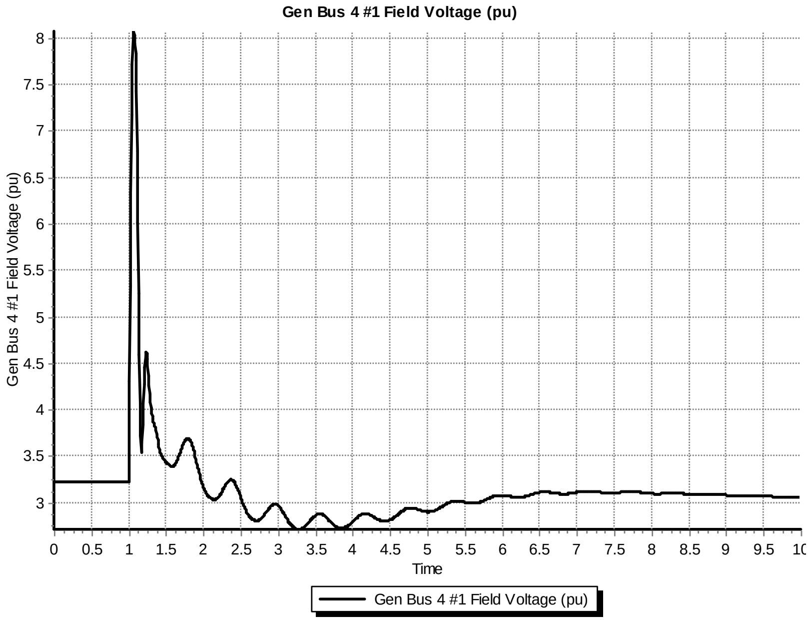
- Same case, except with Ka=500 to decrease steady-state error, no Vr limits; this case is actually unstable

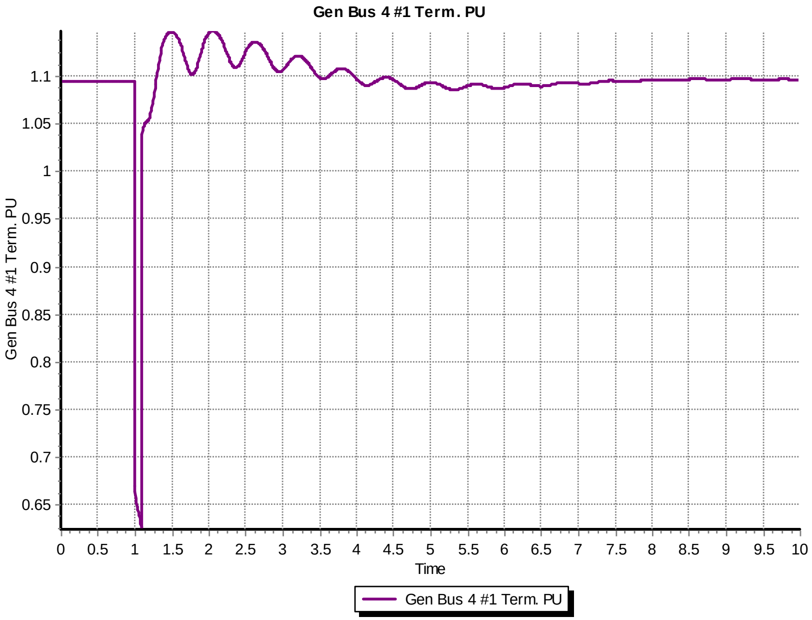




IEEE T1 Example

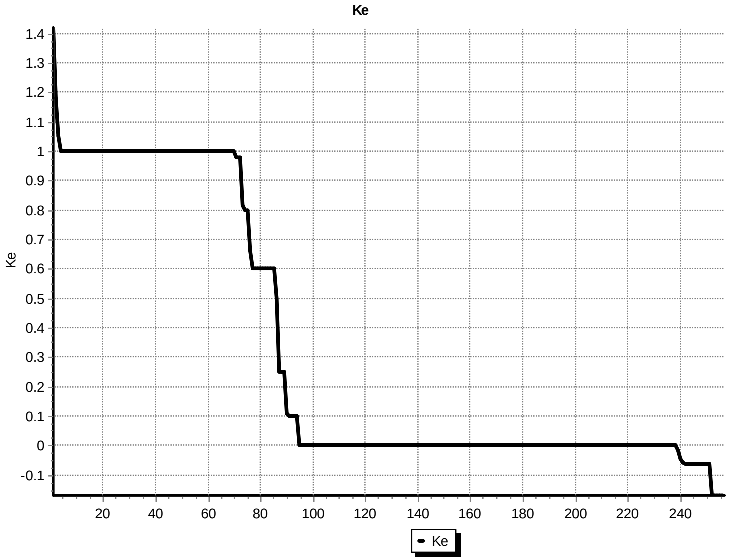
- With Ka=500 and rate feedback, Kf=0.05, Tf=0.5
- Initial V_4=1.0946, final V_4=1.0957





WECC Case Type 1 Exciters

- In a recent WECC case with 2782 exciters, 58 are modeled with the IEEE T1, 257 with the EXDC1 and none with the ESDC1A
- Graph shows K_E value for the EXDC1 exciters in case; about 1/3 are separately excited, and the rest self excited
  - 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; about 41 WECC exciters are of this type

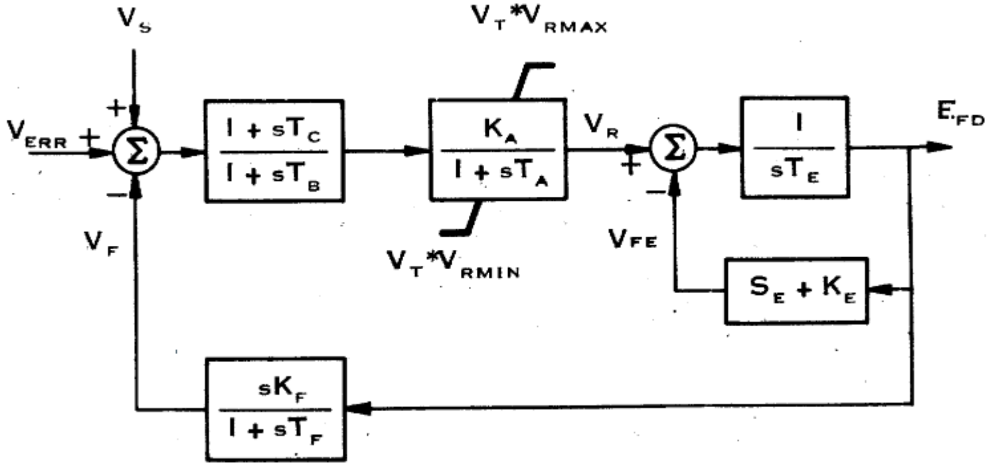


Fig. 4. Type DC2 - DC Commutator Exciter

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

- Newer dc model introduced in 421.5-2005 in which a PID controller is added; might represent a retrofit

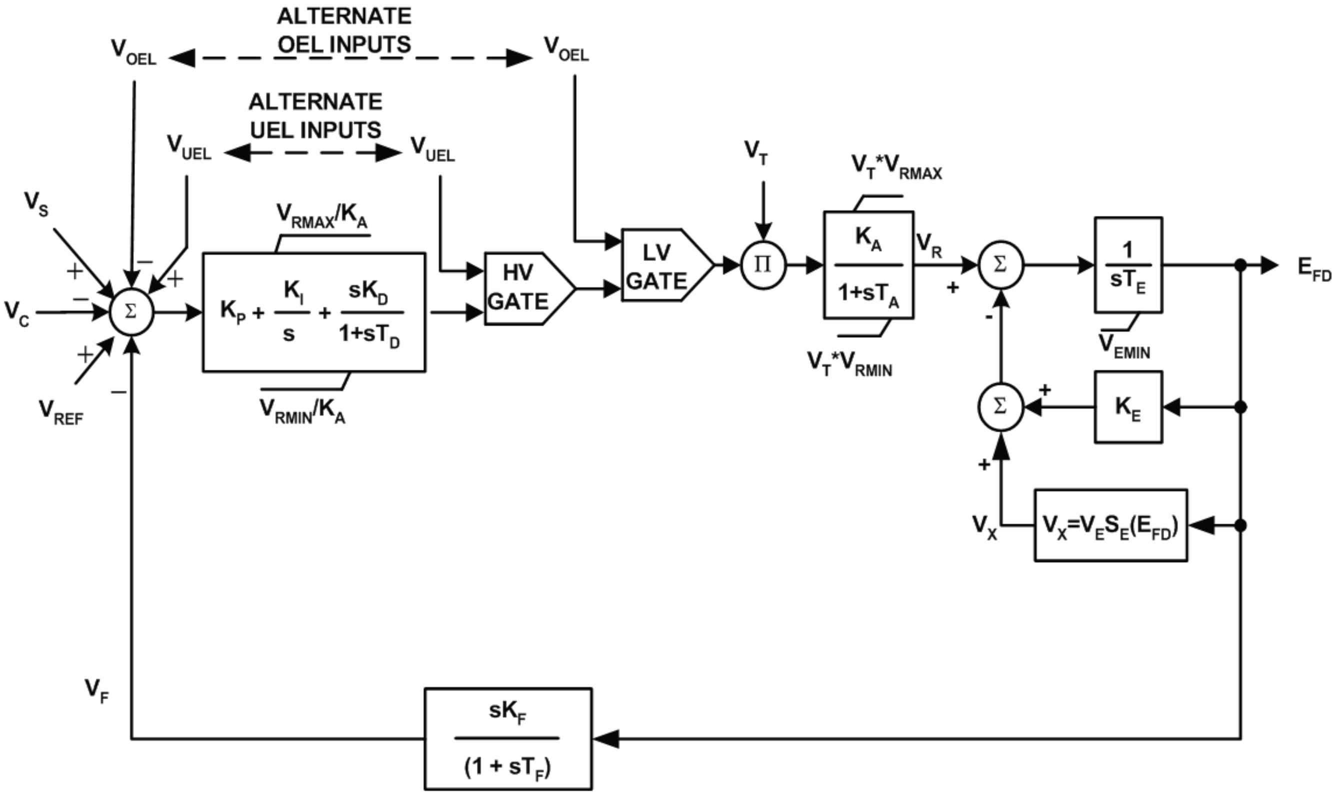


Image Source: Fig 5-4 of IEEE Std 421.5-2005

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

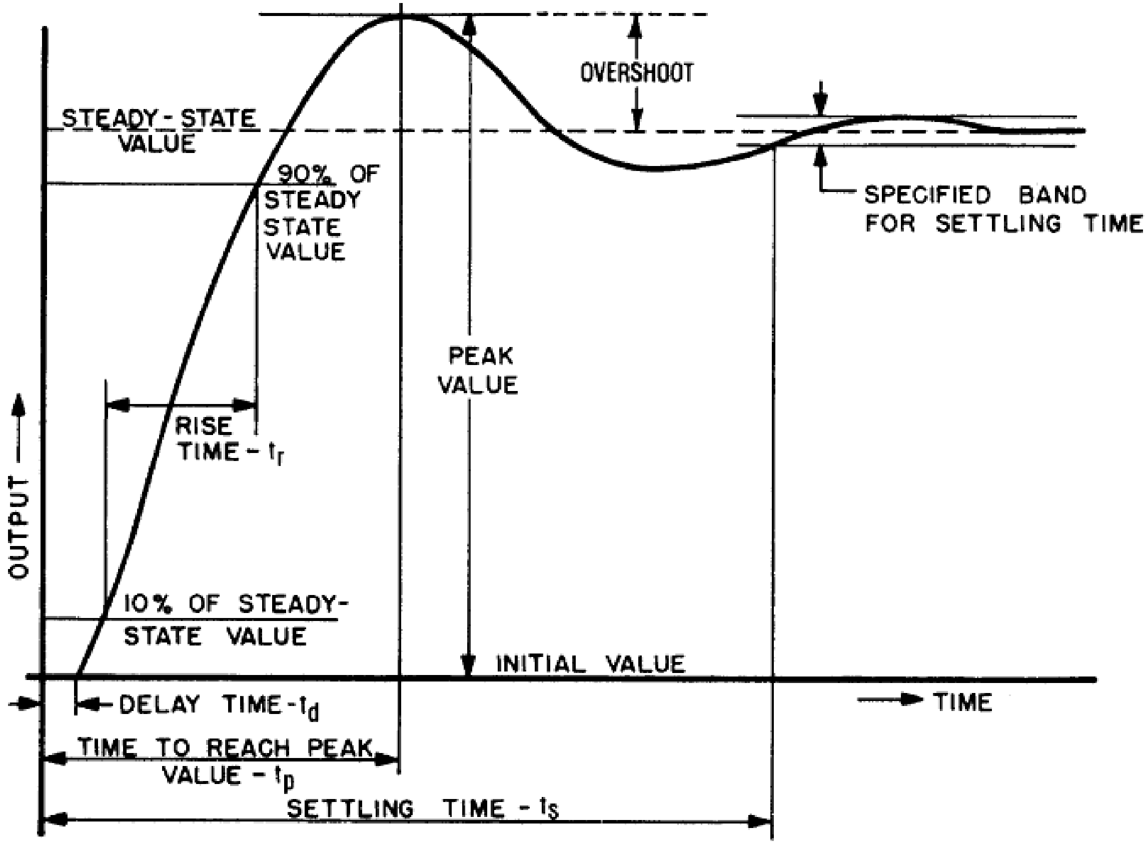


Image Source: IEEE Std 421.2-1990, Figure 3

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

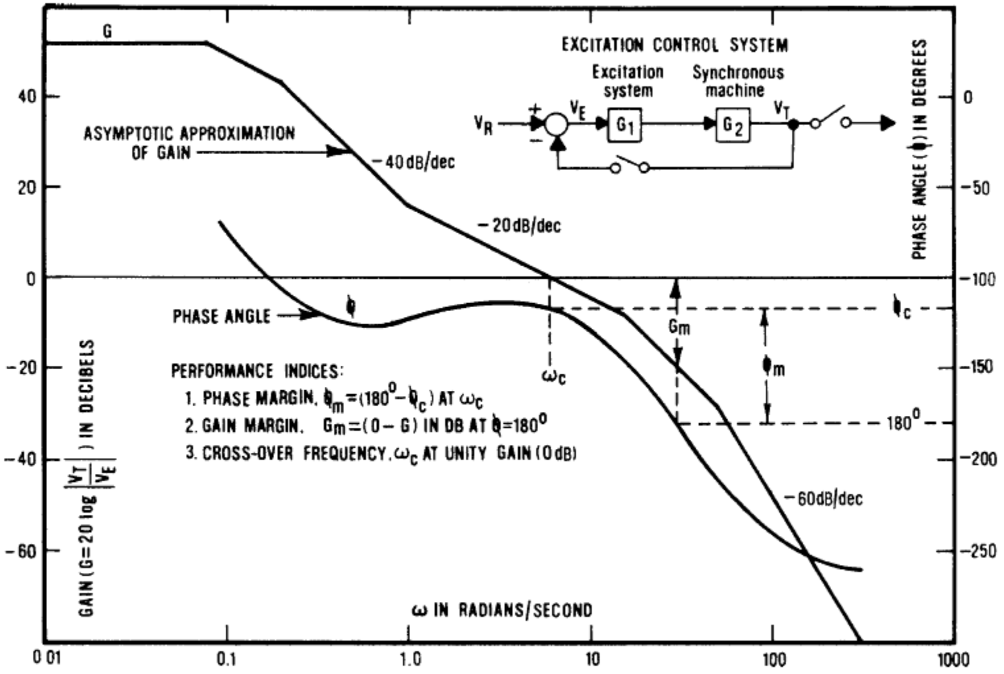
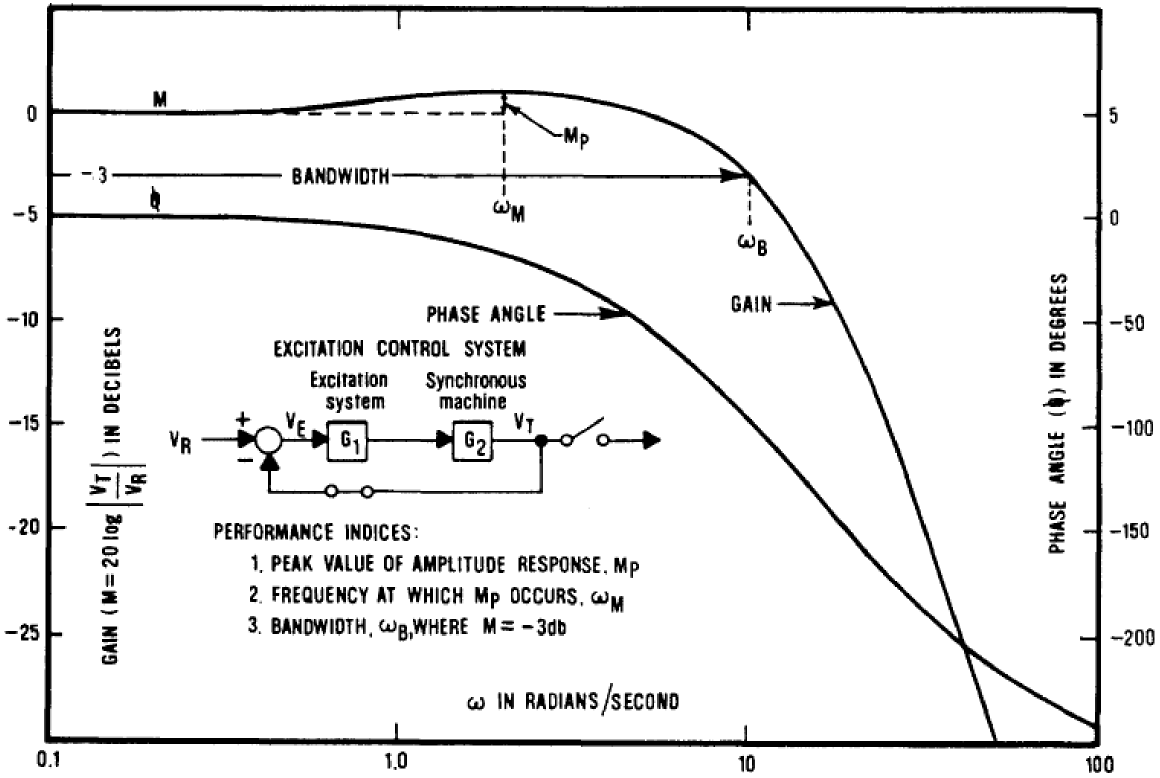


Figure 4—Typical Open-Loop Frequency Response of an Excitation Control System with the Synchronous Machine Open-Circuited

Image Source: IEEE Std 421.2-1990, Figure 4

Small Signal Performance

- Figure shows typical closed-loop performance



Peak value of M_p indicates relative stability; too large a value indicates overshoot

Note system connection is open

A larger bandwidth indicates a faster response

Image Source: IEEE Std 421.2-1990, Figure 5

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

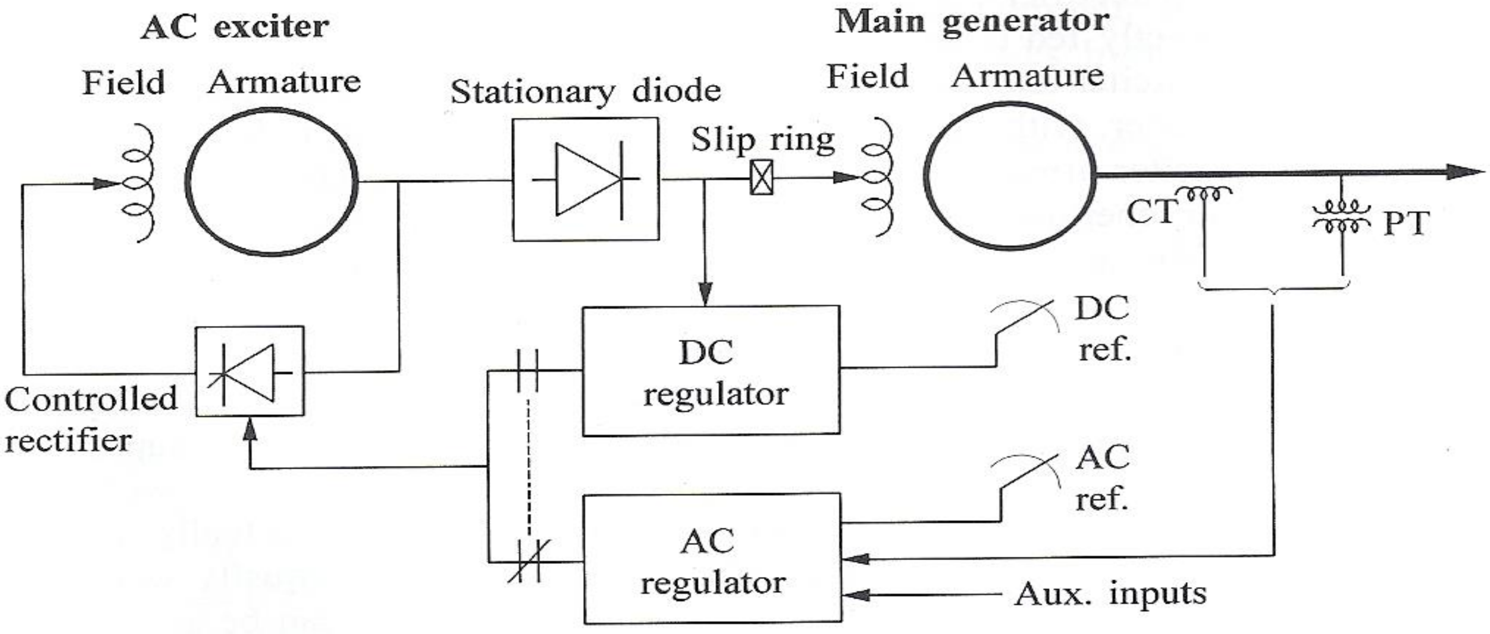


Figure 8.3 Field-controlled alternator rectifier excitation system

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

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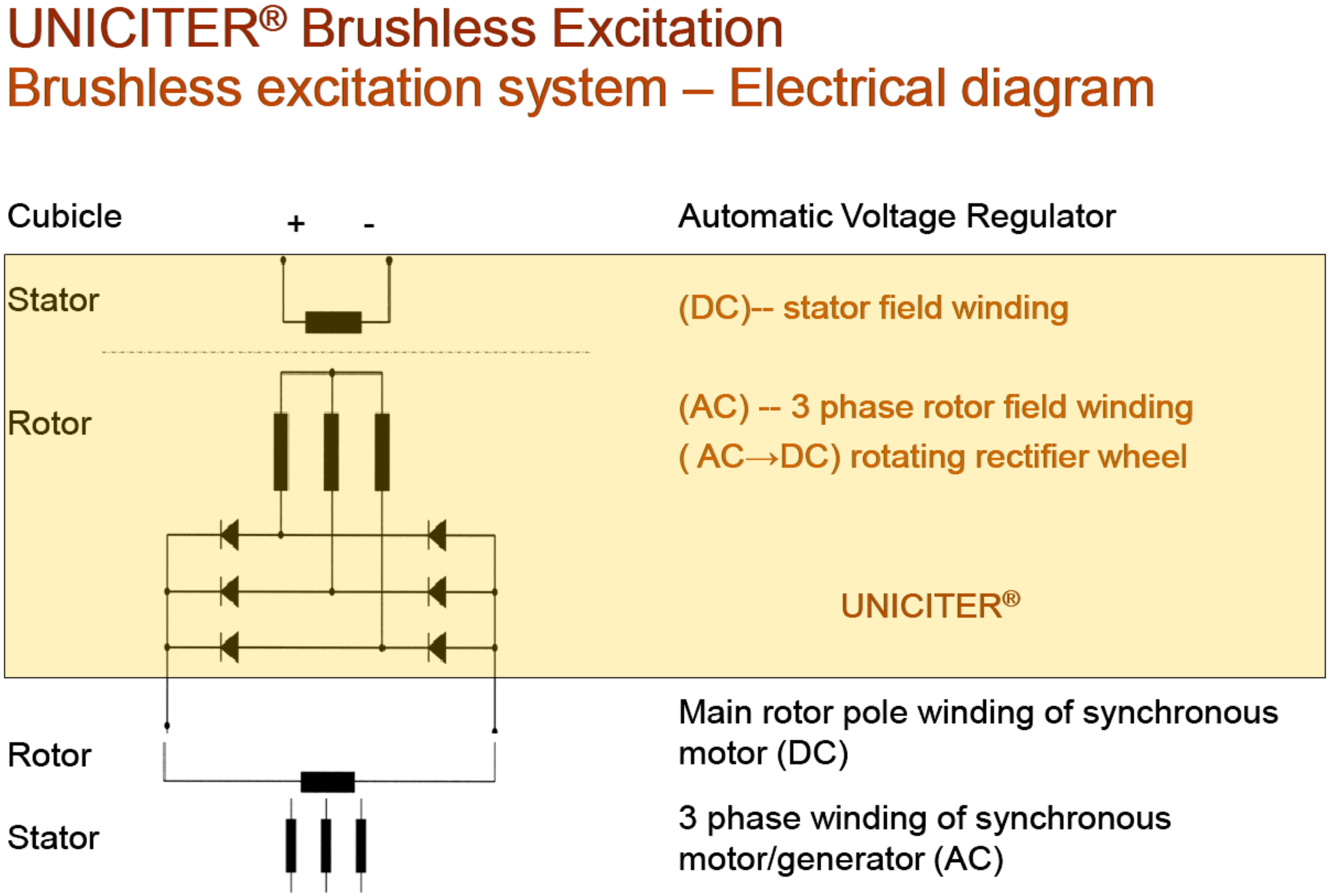


UNICITER® Brushless Excitation

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

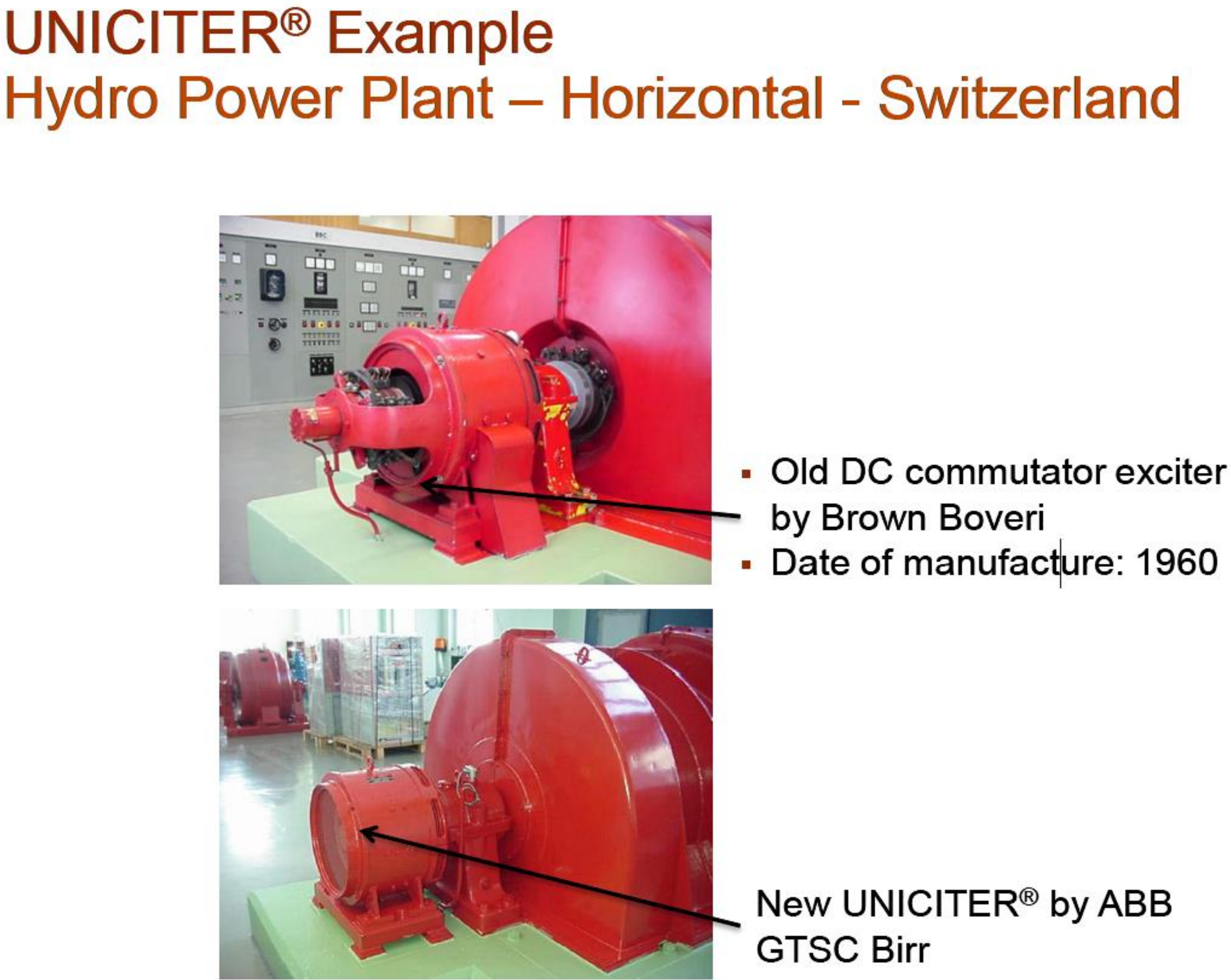
Main rotor pole winding of synchronous motor (DC)

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

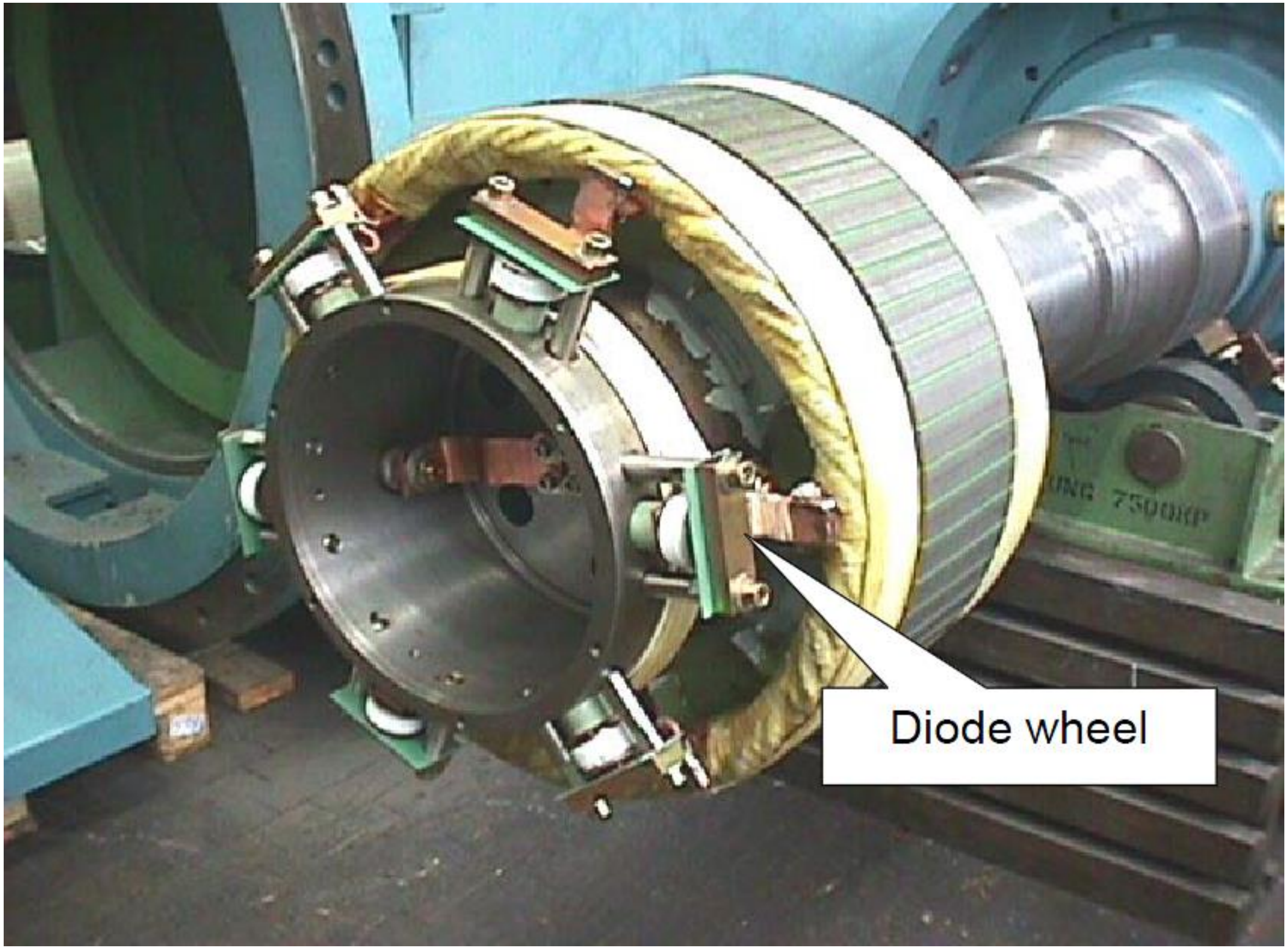
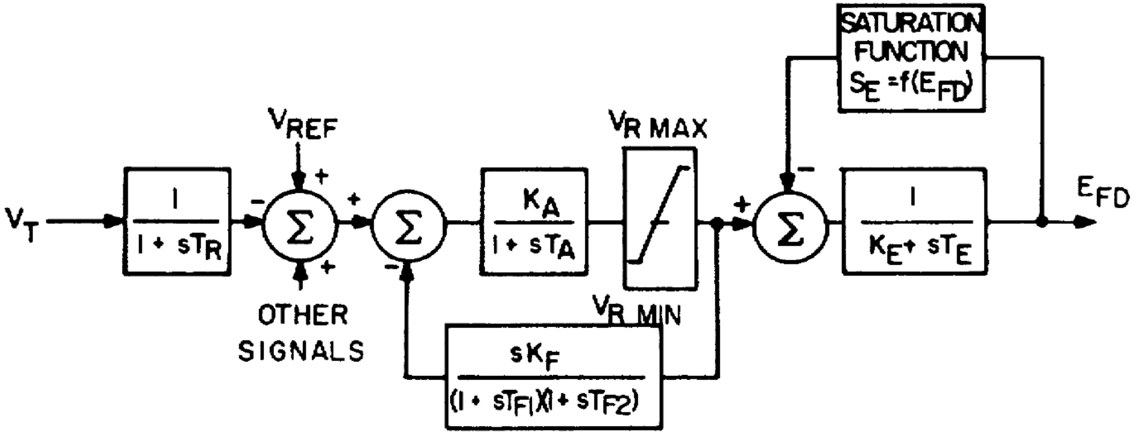


Image source: www02.abb.com, Brushless Excitation Systems Upgrade,

AC Exciter Modeling

- Originally represented by IEEE T2 shown below

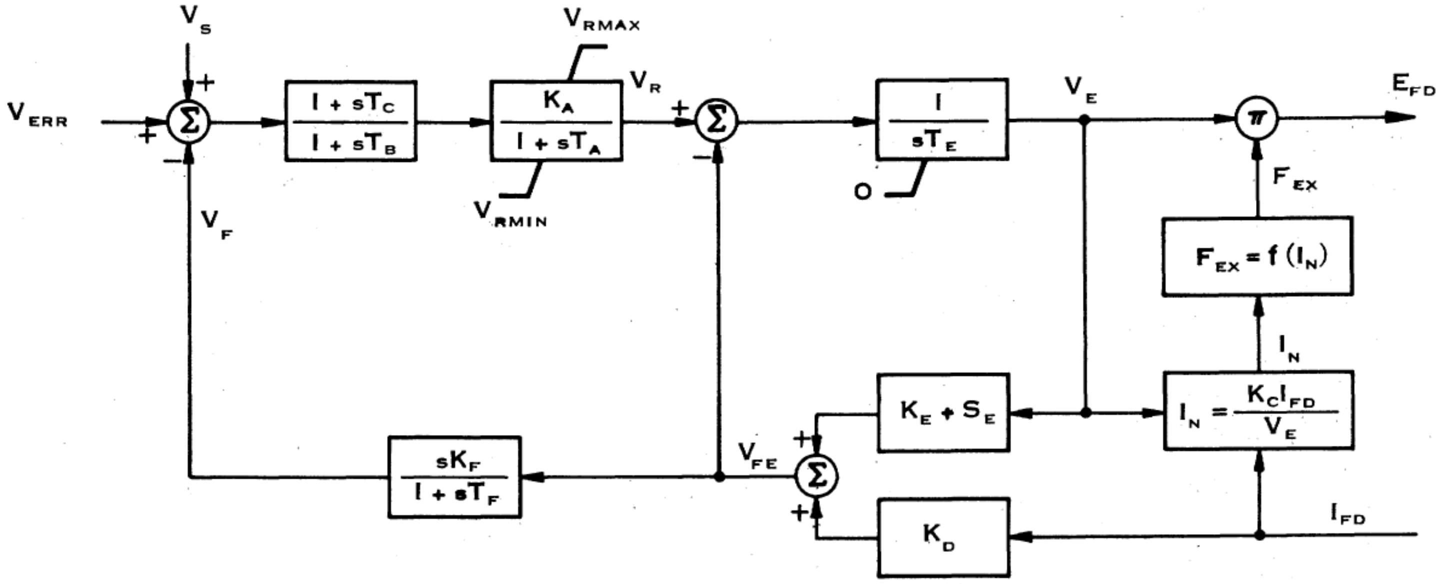


Exciter model is quite similar to IEEE T1

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

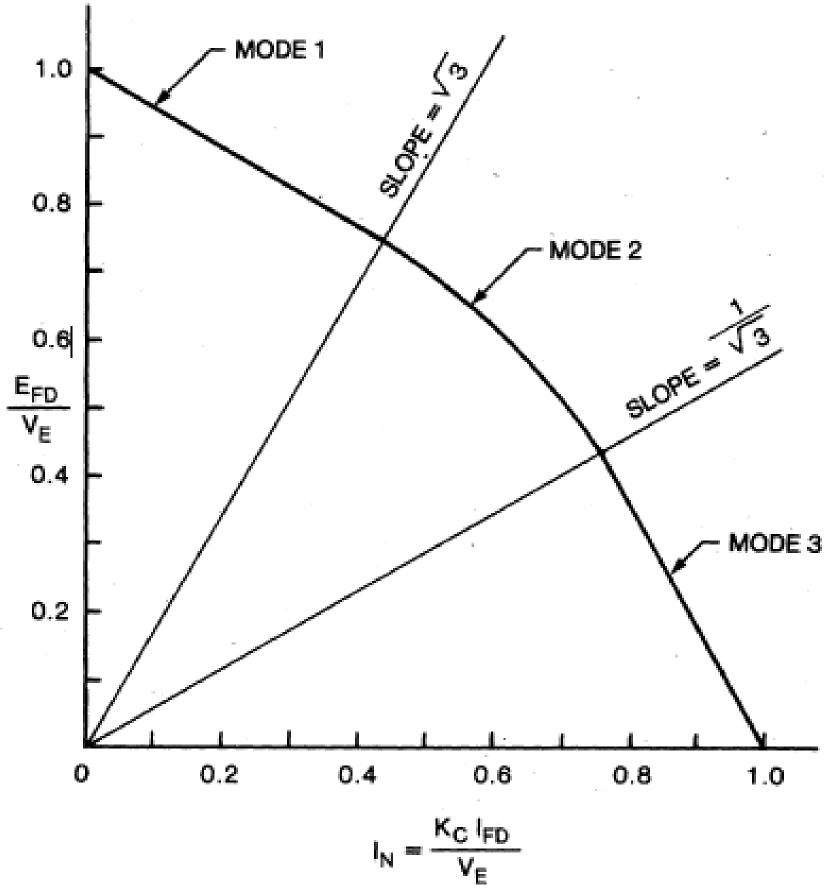


About 5% of WECC exciters are EXAC1

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



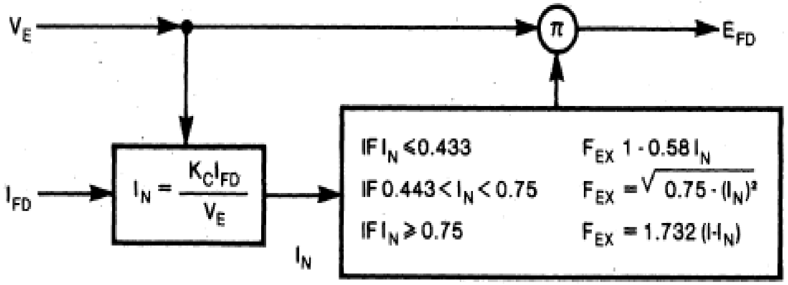


Fig. E.2. Rectifier Regulation Equations

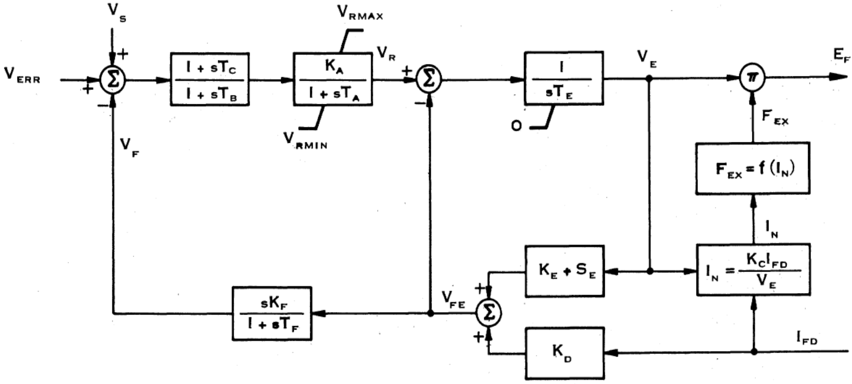
Kc represents the commuting reactance

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 $\frac{\mathrm{E}_{\mathrm{fd}}}{1.732} = V_e - K_c I_{fd} \rightarrow \frac{\mathrm{E}_{\mathrm{fd}}}{1.732} + K_c I_{fd}$

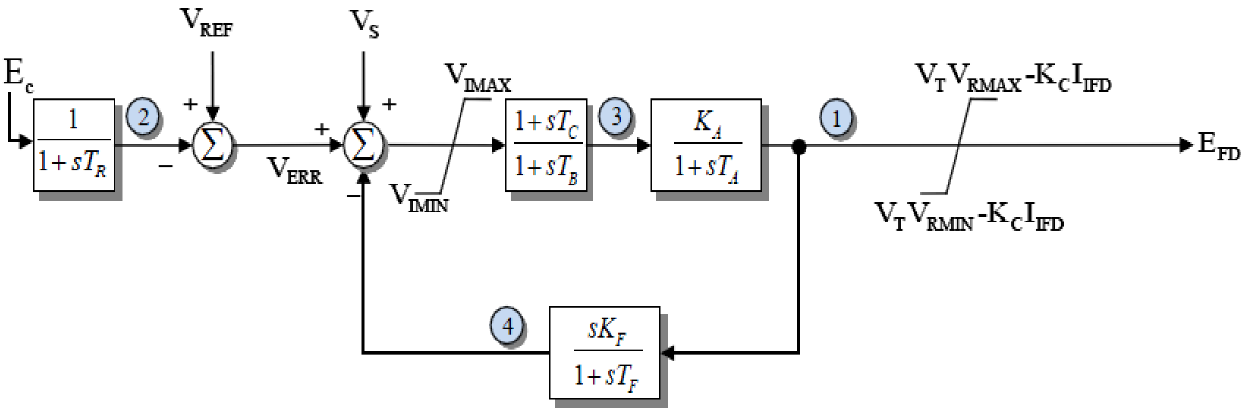
Need to check to make sure we are on this segment

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

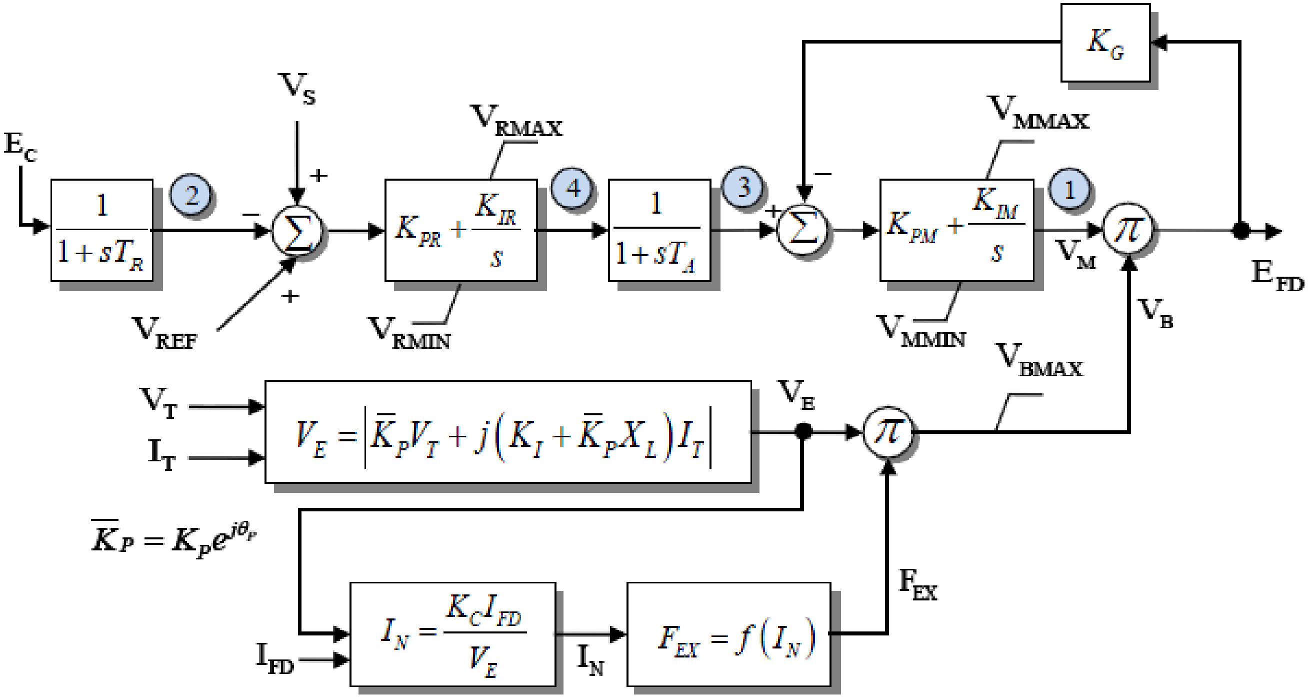


Most common exciter in WECC with about 29% modeled with this type

Kc represents the commuting reactance

EXST4B

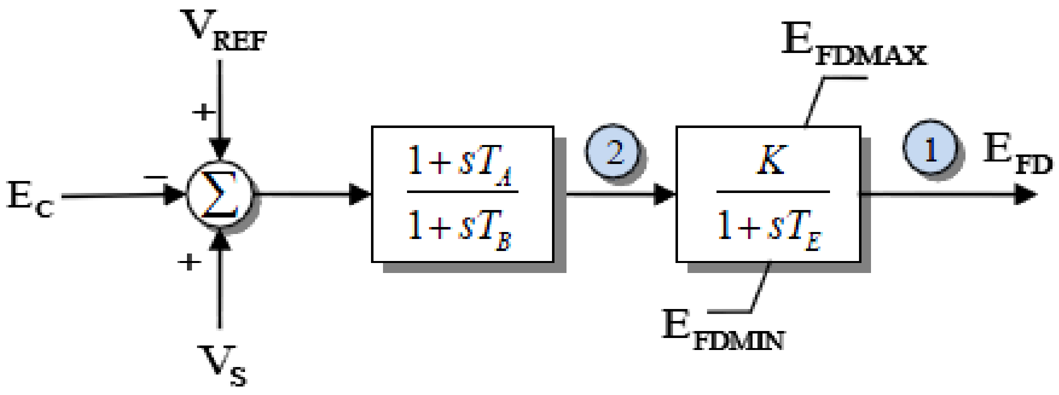
- EXST4B models a controlled rectifier design; field voltage loop is used to make output independent of supply voltage



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

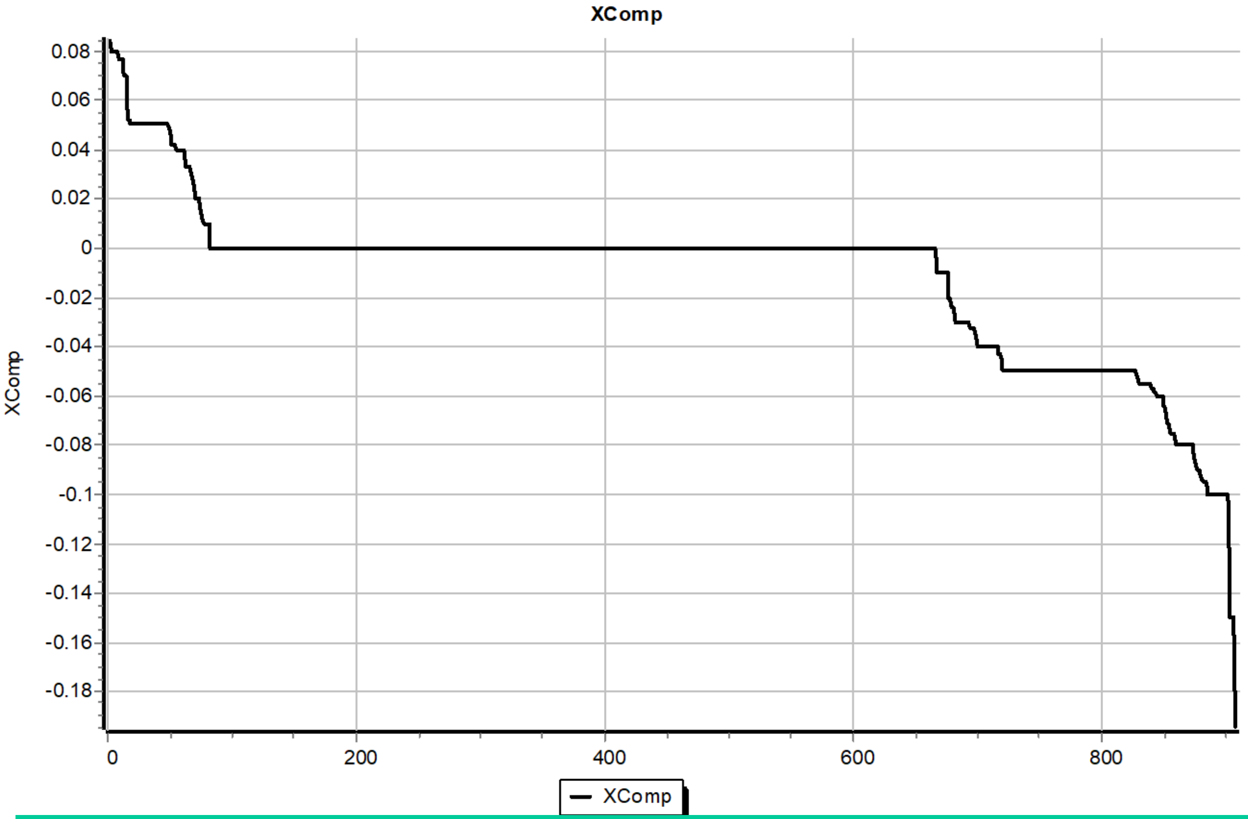
$$E_c = \left|\bar{V}_t - \left(R_c + jX_c\right) I_T\right|$$

- 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