ECEN 460
Power System Operation and Control
Spring 2025

Lecture 19: Power System Stability

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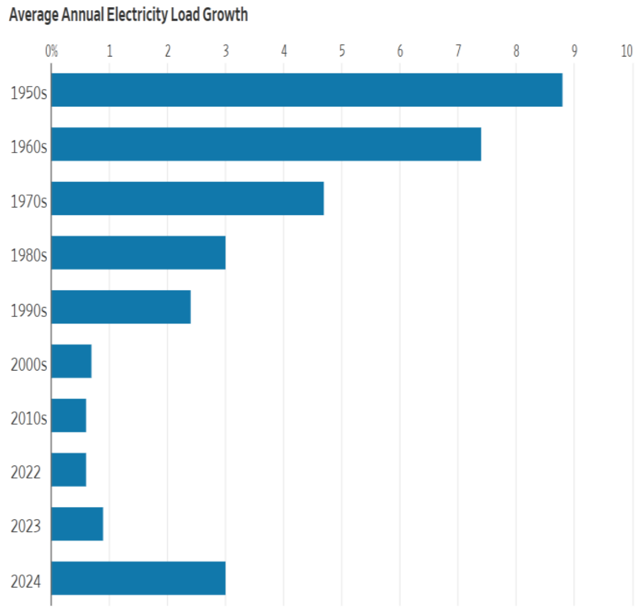
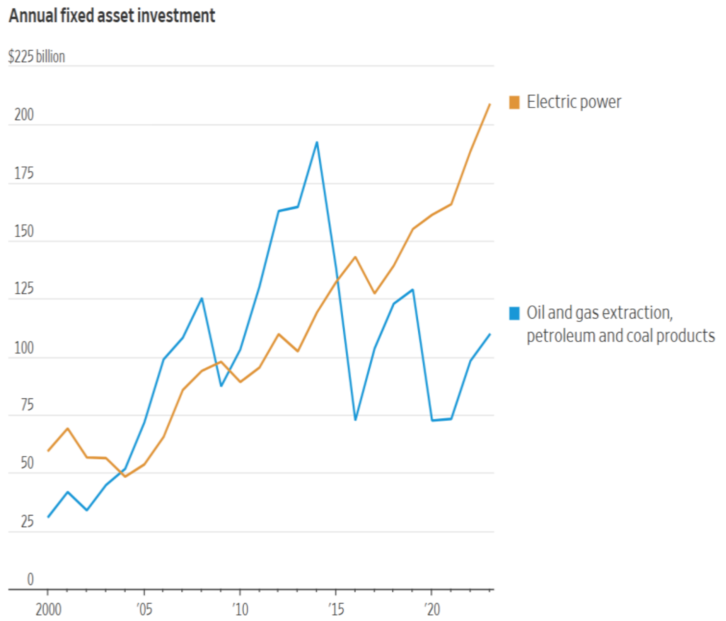
Announcements

- Please read Chapter 13
- By March 31 do problems 12.1, 12.7, 12.10, 12.13, 12.18, 12.19, 12.21
- By April 9 do Problem Set A
- Schedule for the rest of the semester is
  - Lab 9 this week
  - Lab 10 week of April 7
  - Lab 3 week of April 14 (optional, ungraded machine lab)
  - Lab 11 (project presentations) by the individual teams to their TA before the end of classes (on or before April 29)
  - Exam 2 on Wednesday April 23 during class
  - Design project due at 9:30 am on May 1 (i.e., at the end of our final slot; no final)

In the News: WSJ Article Titled, "Economic Growth Now Depends on Electricity Not Oil"

- The beginning of the article is,
  "Americans have long equated energy security with oil. The country wanted as much as possible because of the havoc an interruption to supply—from wars, disasters and political convulsions—can cause. In coming years, though, energy security will mean electricity."
- Electricity growth is back to values from the 1980's
- From a security perspective a key advantage of electricity is its sources are almost 100% domestic
- The article notes that with this growth electricity has become deeply politicized





Source: www.wsj.com/business/energy-oil/economic-growth-now-depends-on-electricity-not-oil-40250941?mod=hp_lead_pos5

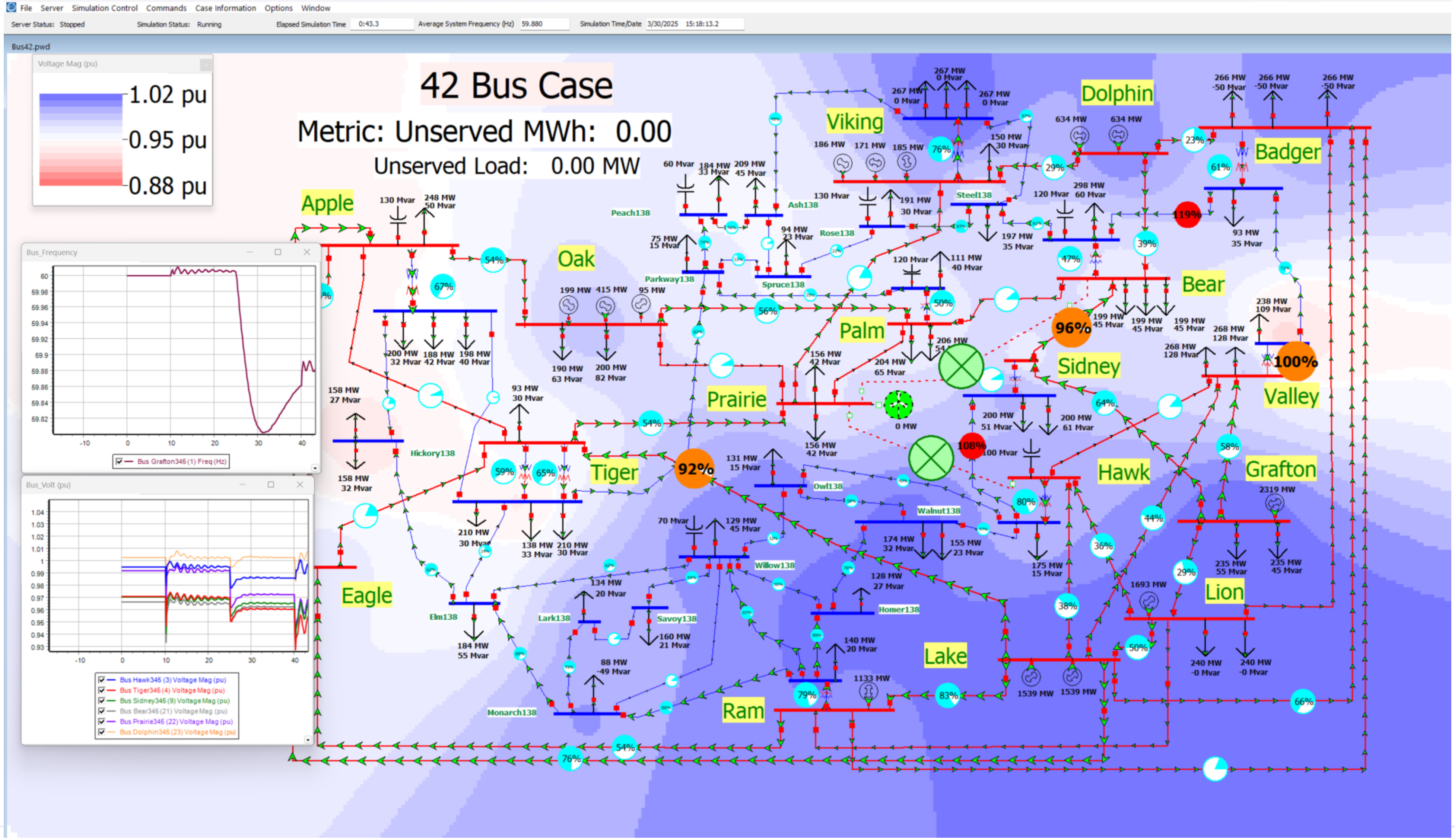
2007 CWLP Dallman Accident

- In 2007 there was an explosion at the CWLP 86 MW Dallman 1 generator. The explosion was eventually determined to be caused by a sticky valve that prevented the cutoff of steam into the turbine when the generator went off line. So the generator turbine continued to accelerate up to over 6000 rpm (3600 normal).
  - High speed caused parts of the generator to shoot out
  - Hydrogen escaped from the cooling system, and eventually escaped causing the explosion
  - Repairs took about 18 months, costing more than $52 million

https://www.dailyregister.com/20080508/news/dallman-explosion-blamed-on-valve-failures/

2007 CWLP Dallman Accident

Lab 9 Overview: Stability and PowerWorld DS



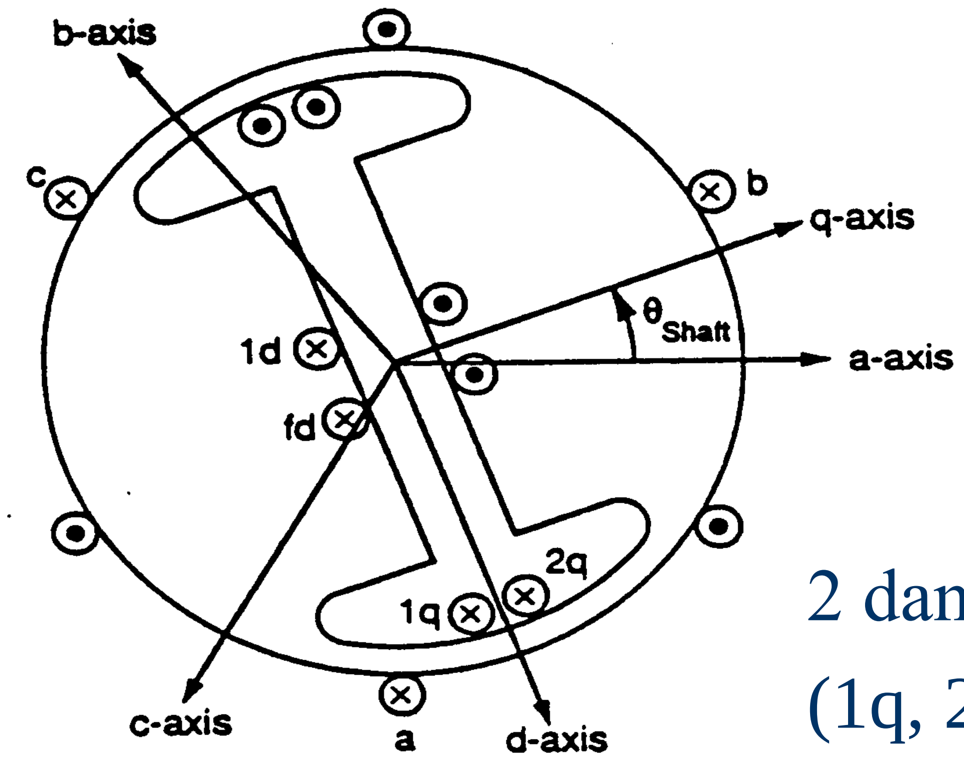
Two-Axis Synchronous Machine Model

- Classical model is appropriate only for the most basic studies; no longer widely used in practice
- More realistic models are required to couple in other devices such as exciters and governors
- A more realistic synchronous machine model requires that the machine be expressed in a reference frame that rotates at rotor speed
- Standard approach is d-q reference frame, in which the major (direct or d-axis) is aligned with the rotor poles and the quadrature (q-axis) leads the direct axis by 90°

Synchronous Machine Modeling

3ϕ bal. windings (a,b,c) – stator

Damper windings are added to help damp out oscillations



Field winding (fd) on rotor

Damper in "d" axis (1d) on rotor

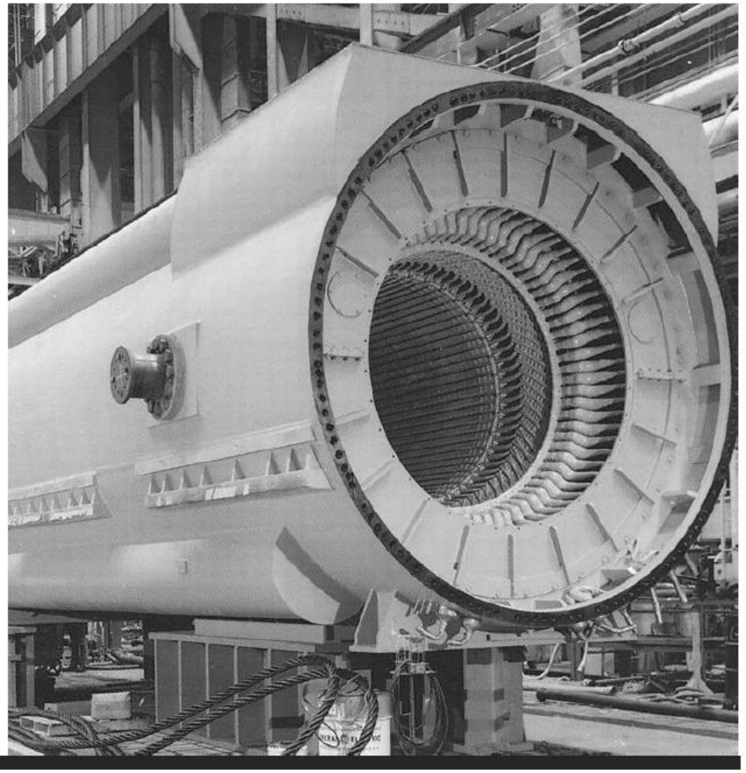
2 dampers in "q" axis (1q, 2q) on rotor

Two Main Types of Synchronous Machines

- Round Rotor
  - Air-gap is constant, used with higher speed machines
- Salient Rotor (often called Salient Pole)
  - Air-gap varies circumferentially
  - Used with many pole, slower machines such as hydro
  - Narrowest part of gap in the d-axis and the widest along the q-axis

Book Chapter 9 Photo

Generator stator showing completed windings for a 757-MVA, 3600-RPM, 60-Hz synchronous generator (Courtesy of General Electric)



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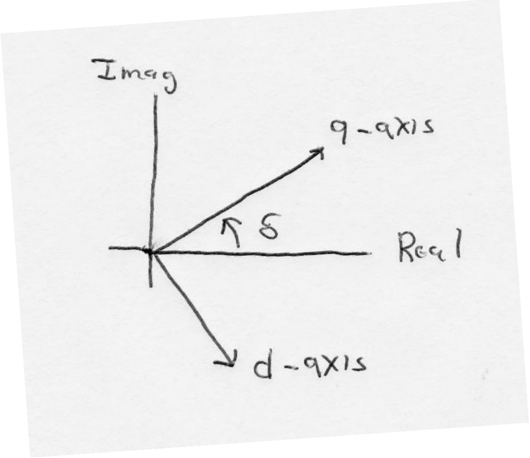
SYMMETRICAL COMPONENTS

D-q Reference Frame

- Analyzing synchronous machines is done using Park's transformation (from 1929) to change the machine differential equations with time-varying components into a set of equations with time invariant components
- That is, the machine voltages and currents are "transformed" into what is known as the d-q reference frame using the rotor angle, δ
  - Terminal voltage in network (power flow) reference frame are $V_T = V_r - V_i$

$$\begin{bmatrix} V_r \\ V_i \end{bmatrix} = \begin{bmatrix} \sin\delta & \cos\delta \\ -\cos\delta & \sin\delta \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \sin\delta & -\cos\delta \\ \cos\delta & \sin\delta \end{bmatrix} \begin{bmatrix} V_{real} \\ V_{imag} \end{bmatrix}$$



Two-Axis Model Equations

- Numerous models exist for synchronous machines. The following is a relatively simple model that represents the field winding and one damper winding; it also includes the generator swing eq.

$$E_q^{'} = V_q + R_a I_q + X_d^{'} I_d \qquad E_d^{'} = V_d + R_a I_d - X_q^{'} I_q$$

$$\frac{dE_q^{'}}{dt} = \frac{1}{T_{do}^{'}}\left(-E_q^{'} - (X_d - X_d^{'})I_d + E_{fd}\right)$$

$$\frac{dE_d^{'}}{dt} = \frac{1}{T_{qo}^{'}}\left(-E_d^{'} + (X_q - X_q^{'})I_q\right)$$

Generator Torque and Initial Conditions

- The generator electrical torque is given by

$$T_e = V_d I_d + V_q I_q + R_a (I_d^2 + I_q^2)$$

- Recall $p_e = T_e \omega_{p.u}$ (sometimes $\omega_{p.u}$ is assumed=1.0)
- Solving the differential equations requires determining δ; it is determined by noting that in steady-state

$$E = V_T + jX_q I$$

Then δ is the angle of *E*

Example 12.10

- Determine the initial conditions for the Example 12.3 case with the classical generator replaced by a two-axis model with H = 3.0 per unit-seconds, D = 0, = 2.1, = 2.0, = 0.3, = 0.5, all per unit using the 100 MVA system base
- First determine the current out of the generator from the initial conditions, then the terminal voltage

$$I = 1.0526\angle -18.20^\circ = 1 - j0.3288$$

$$V_T = 1.0\angle 0^\circ + \left(j0.22\right)\left(1.0526\angle -18.20^\circ\right)$$

$$= 1.0946\angle 11.59^\circ = 1.0723 + j0.220$$

Example 12.10, cont.

- We can then get the initial angle, and initial d and q values

$$\bar{E} = 1.0946\angle 11.59° + (j2.0)(1.052\angle -18.2°) = 2.814\angle 52.1°$$

$$\rightarrow \delta = 52.1°$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 0.7889 & -0.6146 \\ 0.6146 & 0.7889 \end{bmatrix} \begin{bmatrix} 1.0723 \\ 0.220 \end{bmatrix} = \begin{bmatrix} 0.7107 \\ 0.8326 \end{bmatrix}$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} 0.7889 & -0.6146 \\ 0.6146 & 0.7889 \end{bmatrix} \begin{bmatrix} 1.000 \\ -0.3287 \end{bmatrix} = \begin{bmatrix} 0.9909 \\ 0.3553 \end{bmatrix}$$

Example 12.10, cont.

- The initial state variable are determined by solving with the differential equations equal to zero.

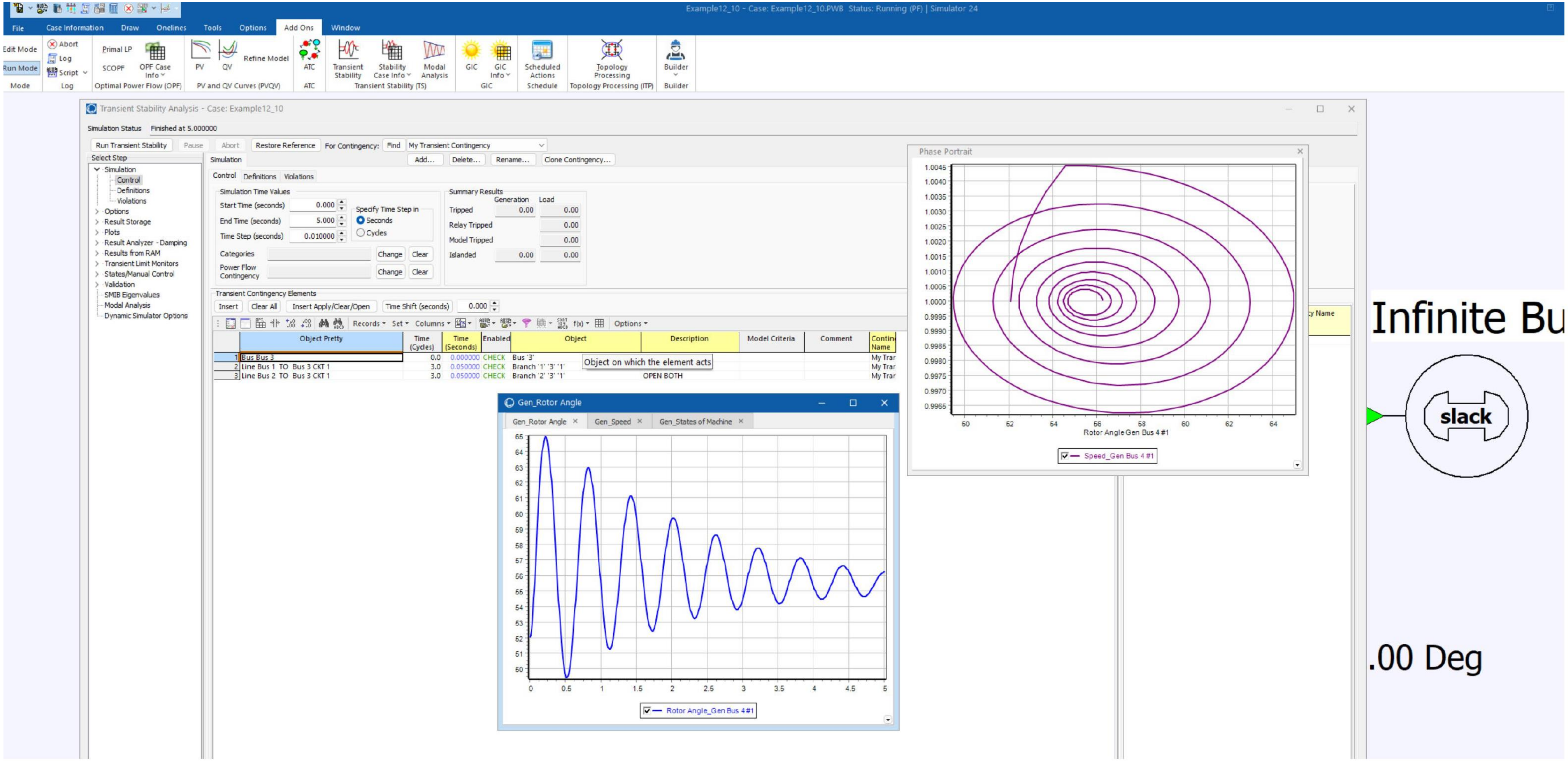
$$E_q^{'} = 0.8326 + (0.3)(0.9909) = 1.1299$$

$$E_d^{'} = 0.7107 - (0.5)(0.3553) = 0.5330$$

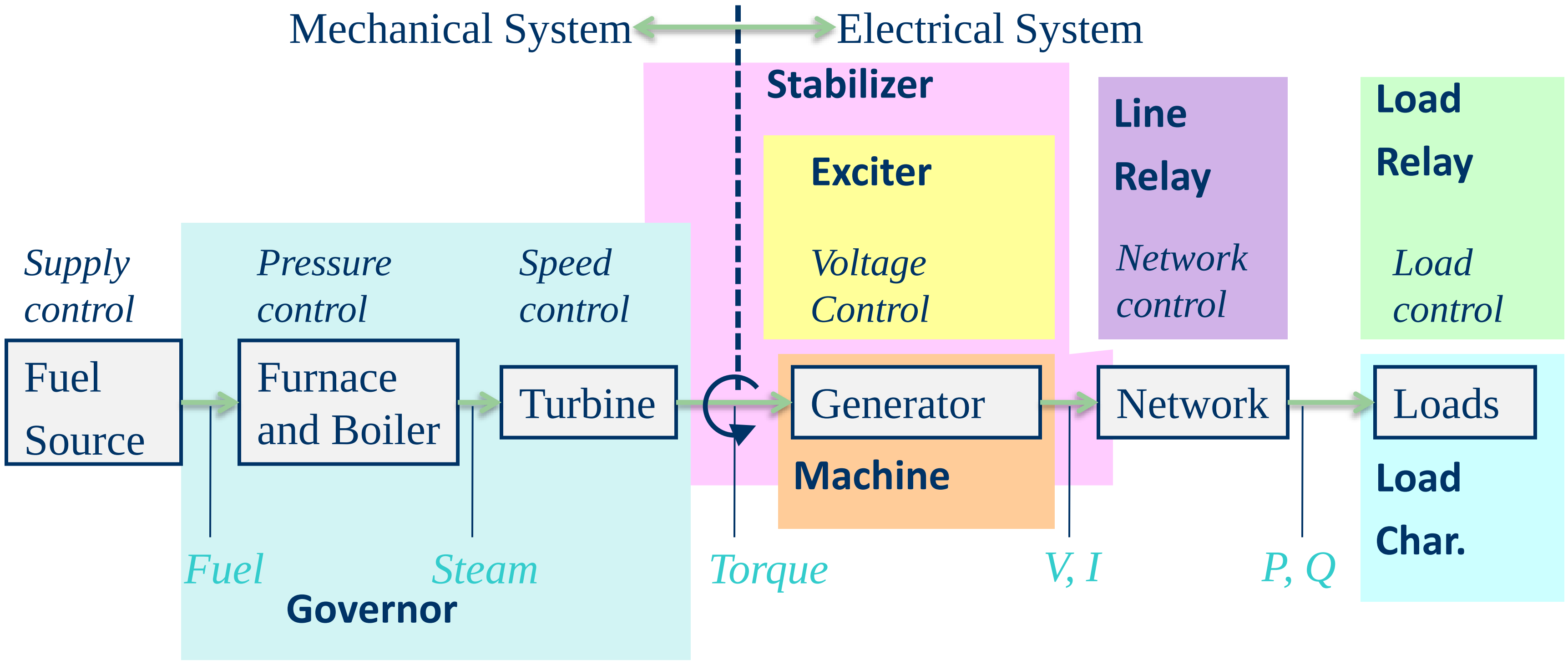
$$E_{fd} = 1.1299 + (2.1 - 0.3)(0.9909) = 2.9135$$

- The transient stability solution is then solved by numerically integrating the differential equations, coupled with solving the algebraic equations

PowerWorld Solution of 12.10

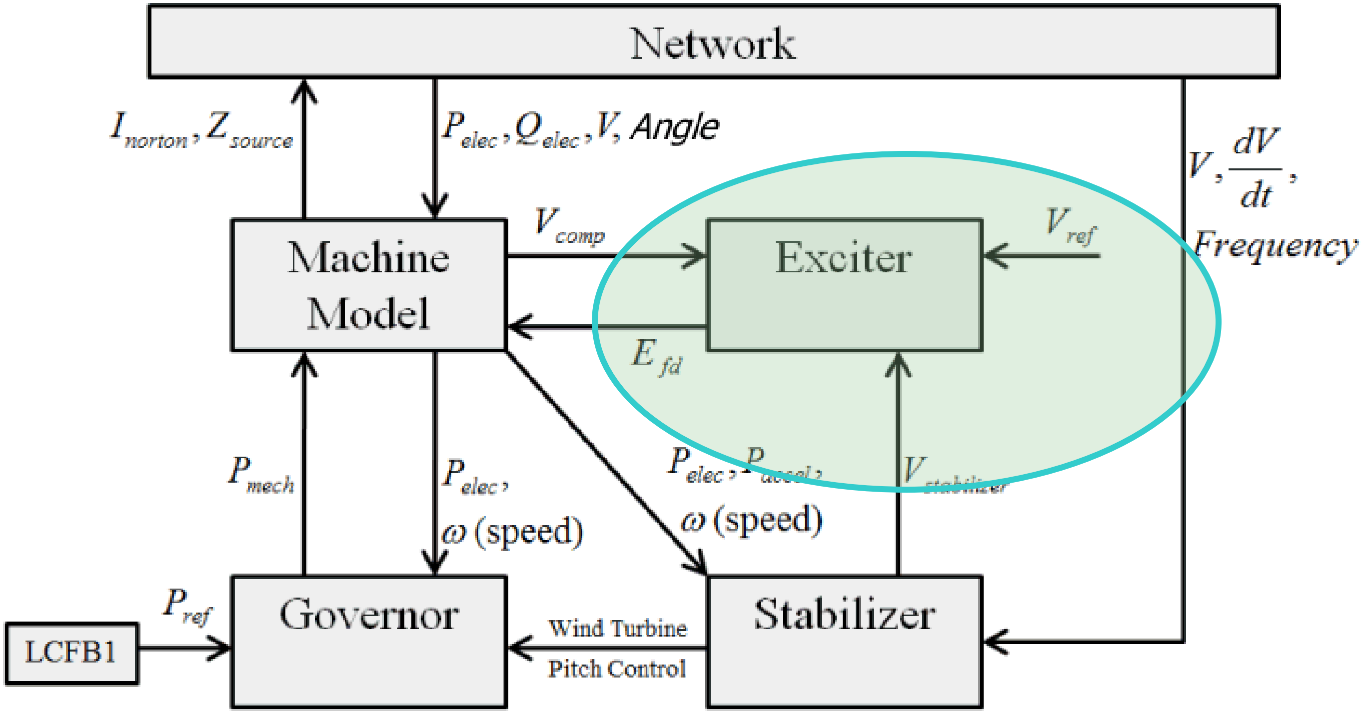


Dynamic Models in the Physical Structure: Exciters



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

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

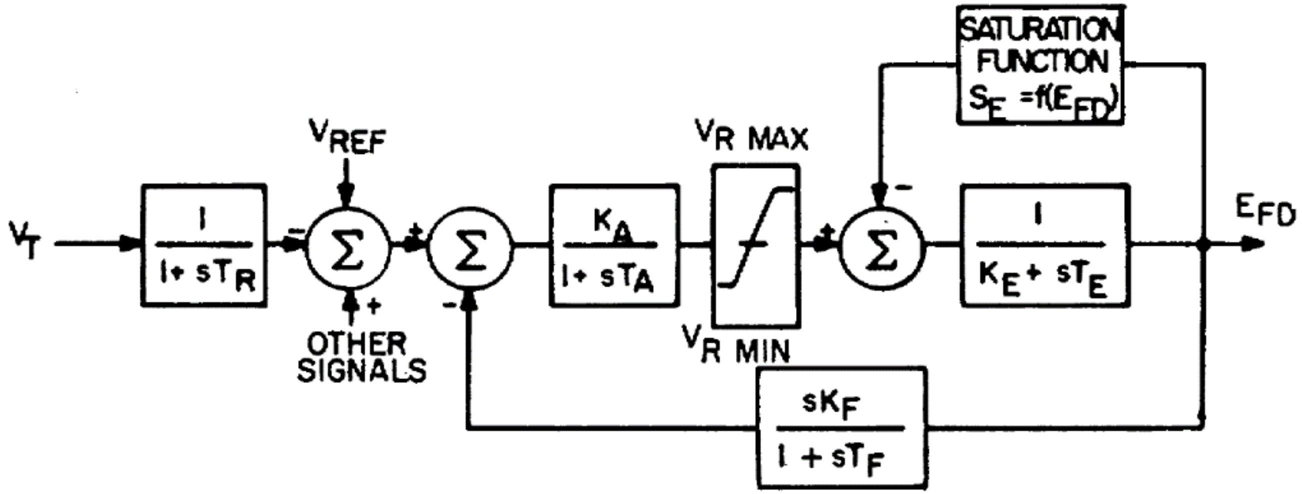
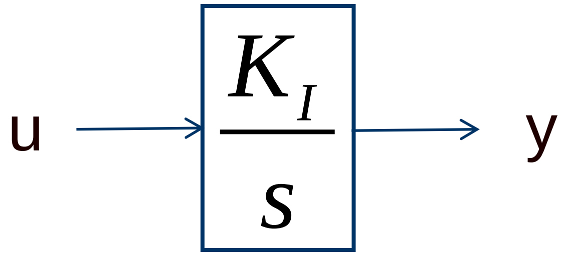


Fig. 1. Type 1 excitation system representation, continuously acting regulator and exciter.

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

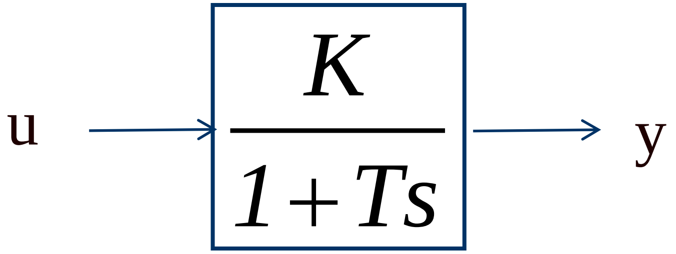


- Equation for an integrator with u as an input and y as an output is

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

- 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

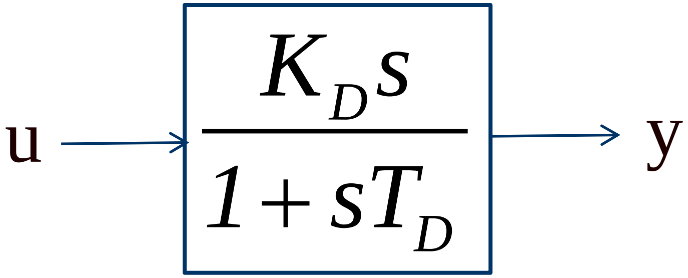


- Equation with u as an input and y as an output is

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

- 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



- 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

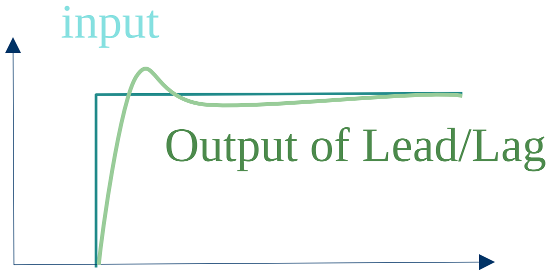
$$\beta_0 u + \beta_1 \frac{du}{dt} + \cdots + \beta_m \frac{d^m u}{dt^m} =$$

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

- To be physically realizable we need n >= m

Lead-Lag Block

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



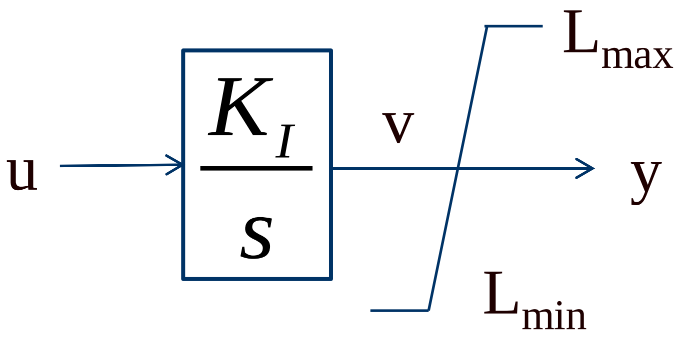
The steady-state requirement that u = y is readily apparent

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

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

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



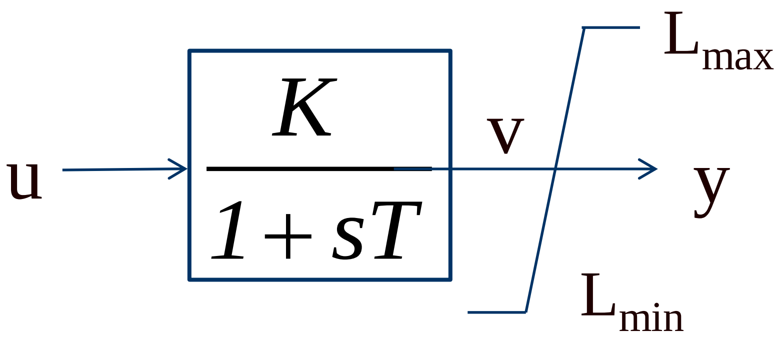
The value of v is NOT limited, so its value can "windup" beyond the limits, delaying backing off of the limit

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

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



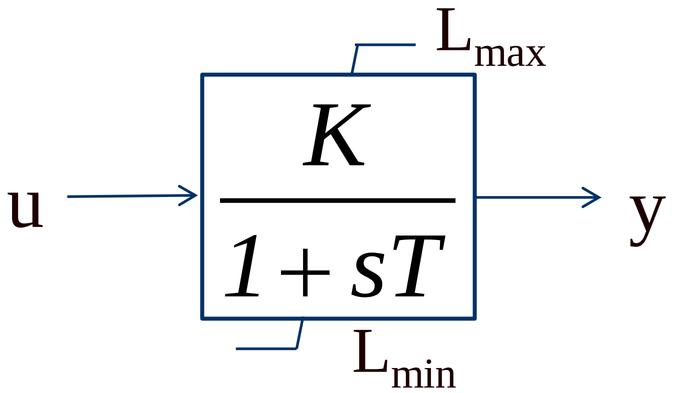
$$\frac{dv}{dt} = \frac{1}{T}(Ku - v)$$

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)

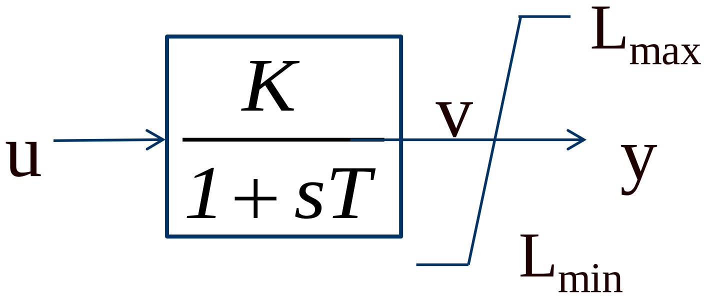
If $L_{min} \leq y \leq L_{max}$ then normal $\frac{dy}{dt} = \frac{1}{T}\left(Ku - y\right)$

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 $\frac{dy}{dt} = 0$

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

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

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

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

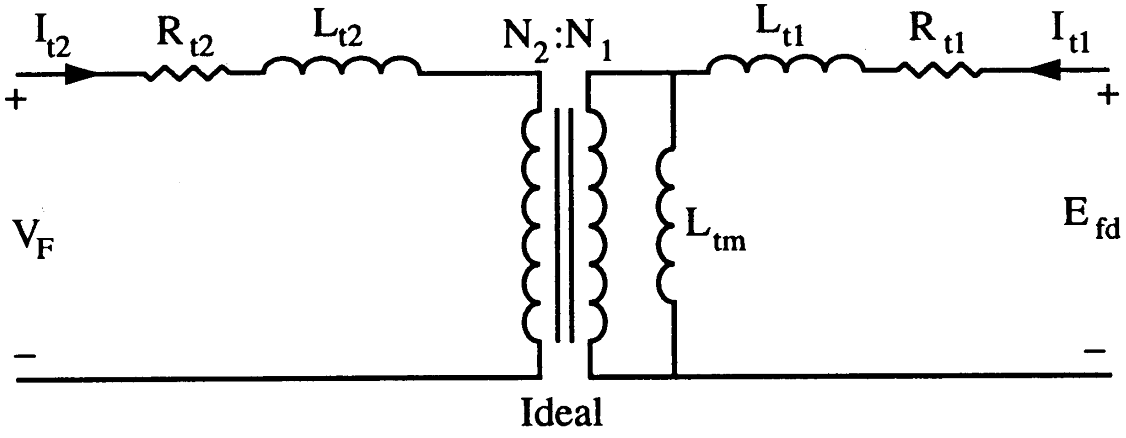
In steady state $$V_{ref} - V_t = V_{in} = \frac{V_R}{K_A}$$

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



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

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

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

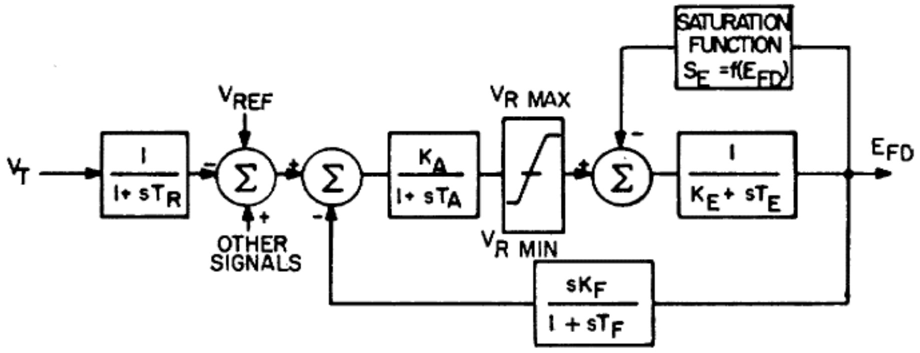
$$\frac{1}{T_F} \qquad\qquad K_F$$

Designed with a large L_{t2} so $I_{t2} \approx 0$

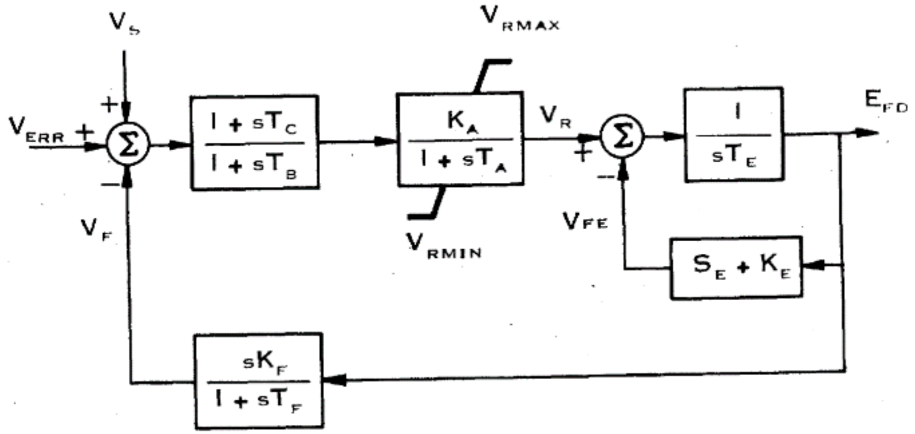
$$V_F = \frac{N_2}{N_1}L_{tm}\frac{dI_{t1}}{dt}$$

IEEET1 Model Evolution

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



1968



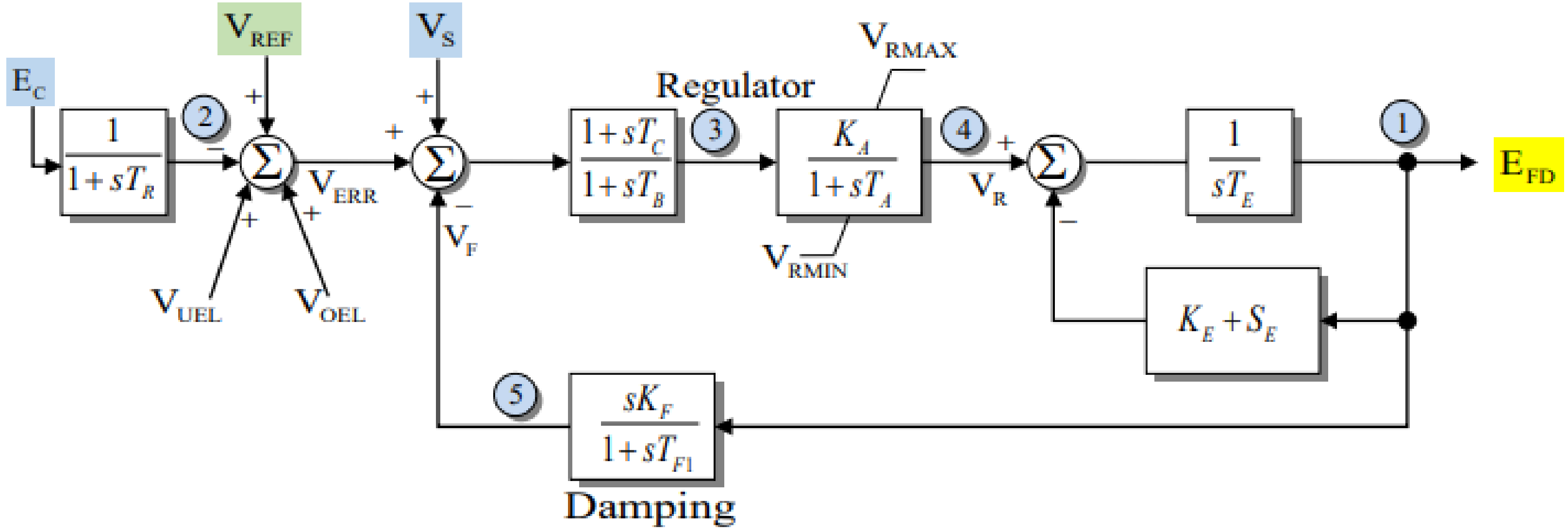
1981

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)

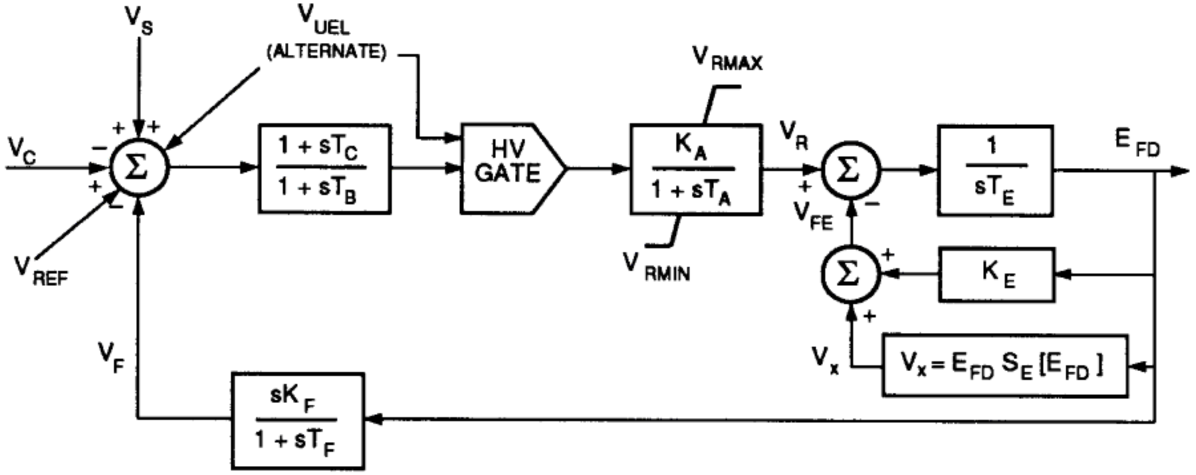


Figure 3—Type DC1A — DC Commutator Exciter

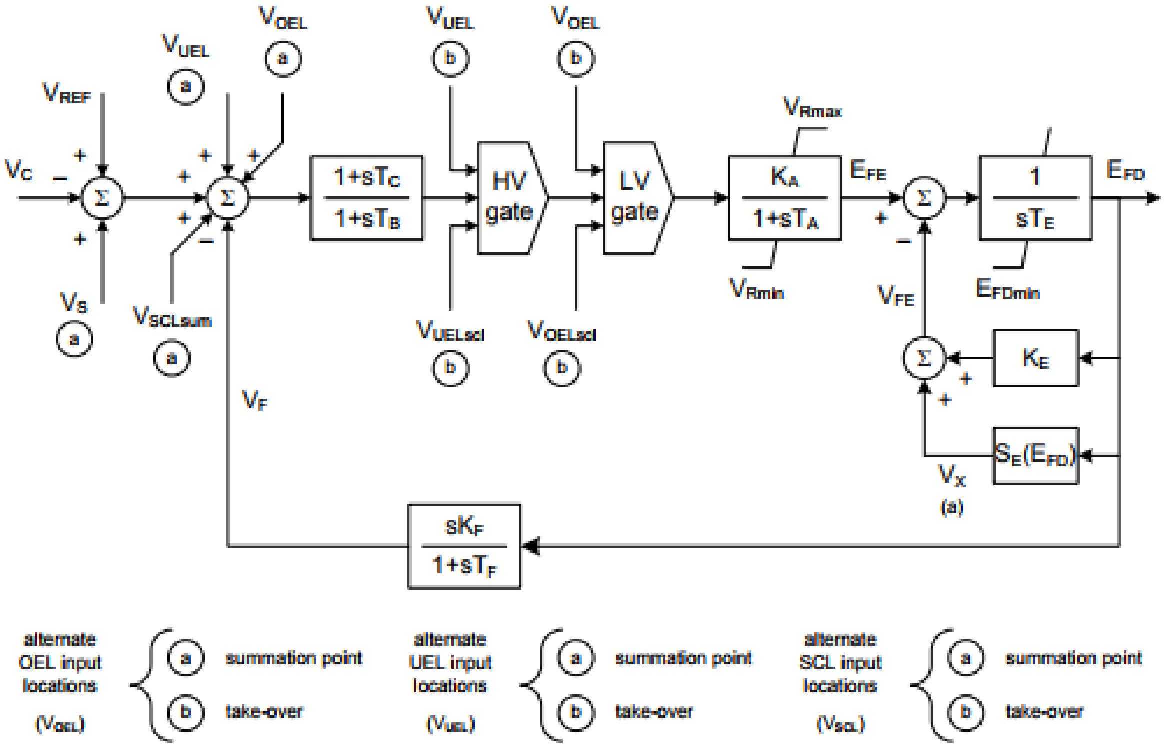
V_{UEL} is a signal from an under-excitation limiter, which we'll briefly cover later

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

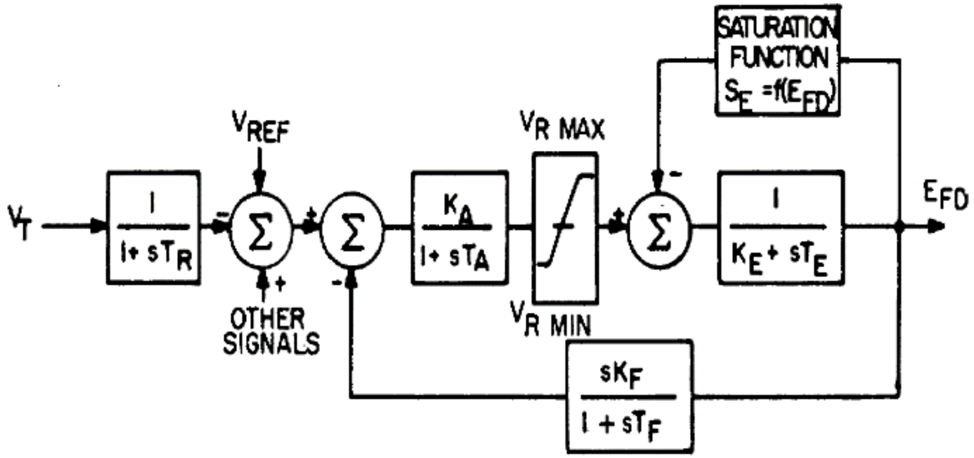
Figure 4—Type DC1C dc commutator exciter

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

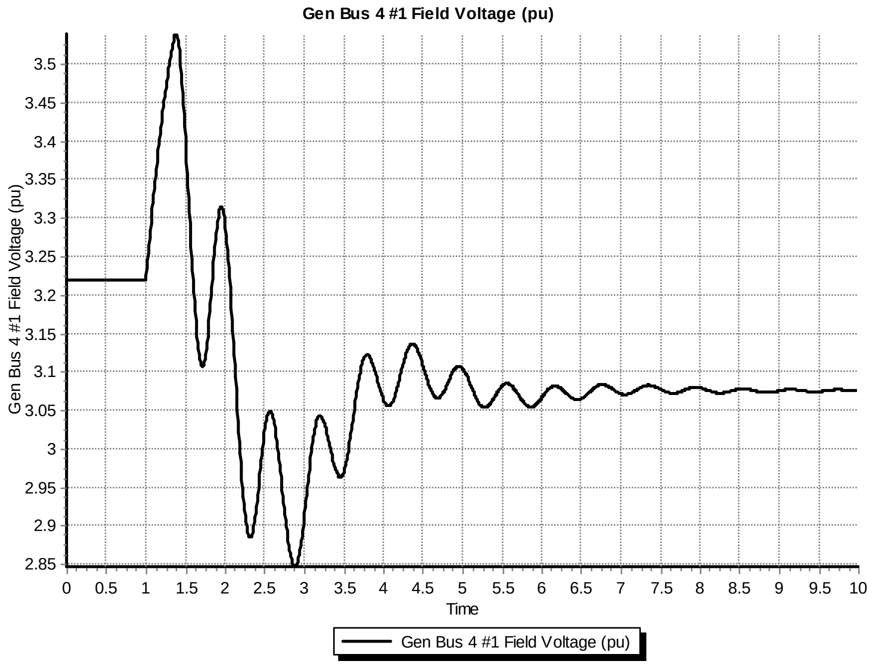
- Assume previous GENROU case with saturation. Then add a IEEE T1 exciter with K_A=50, T_A=0.04, K_E=-0.06, T_E=0.6, $V_{R,max}$=1.0, $V_{R,min}$= -1.0 For saturation assume $S_E(2.8) = 0.04$, $S_E(3.73)=0.33$
- Saturation function is $0.1621(E_{FD}-2.303)^2$ (for $E_{FD} > 2.303$); otherwise zero
- 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
- $V_{REF} = 0.244/Ka + V_T = 0.0488 + 1.0946 = 1.09948$

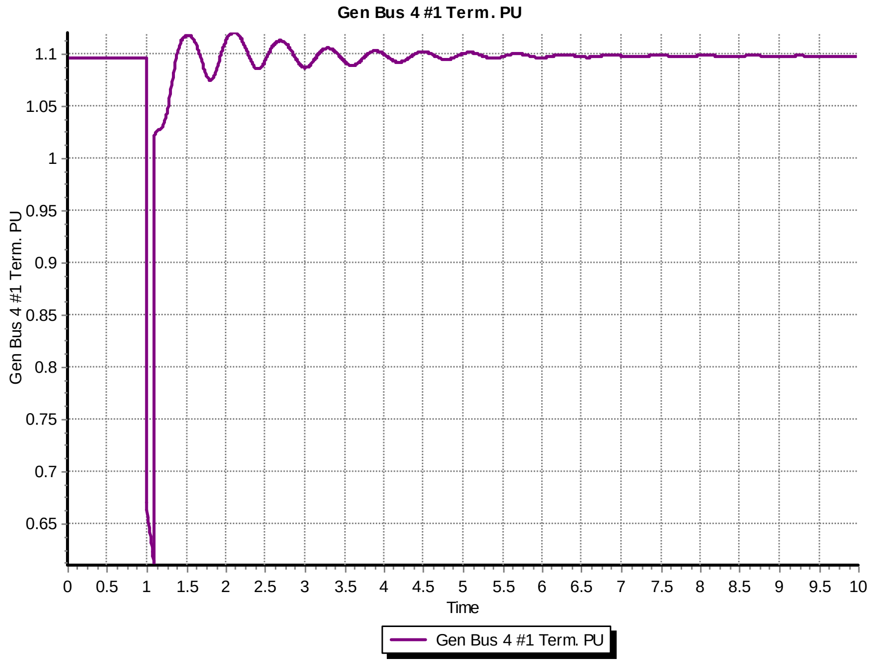


Case **B4_GENROU_Sat_IEEET1**

IEEE T1 Example

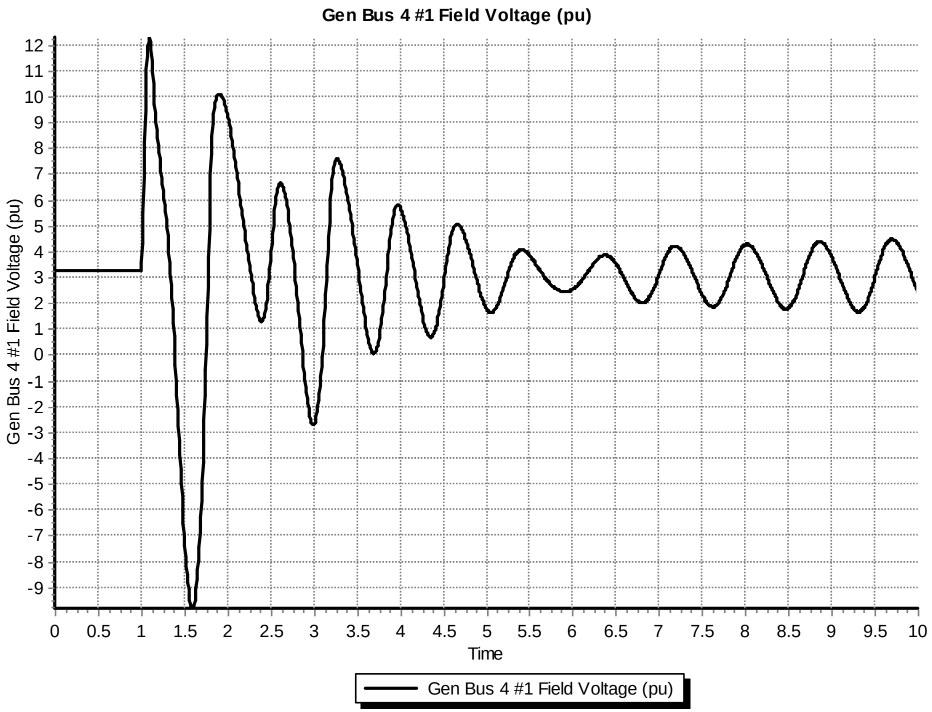
- For 0.1 second fault (from before), plot of E_{FD} and the terminal voltage is given below
- Initial V_4=1.0946, final V_4=1.0973
  - Steady-state error depends on the value of K_A

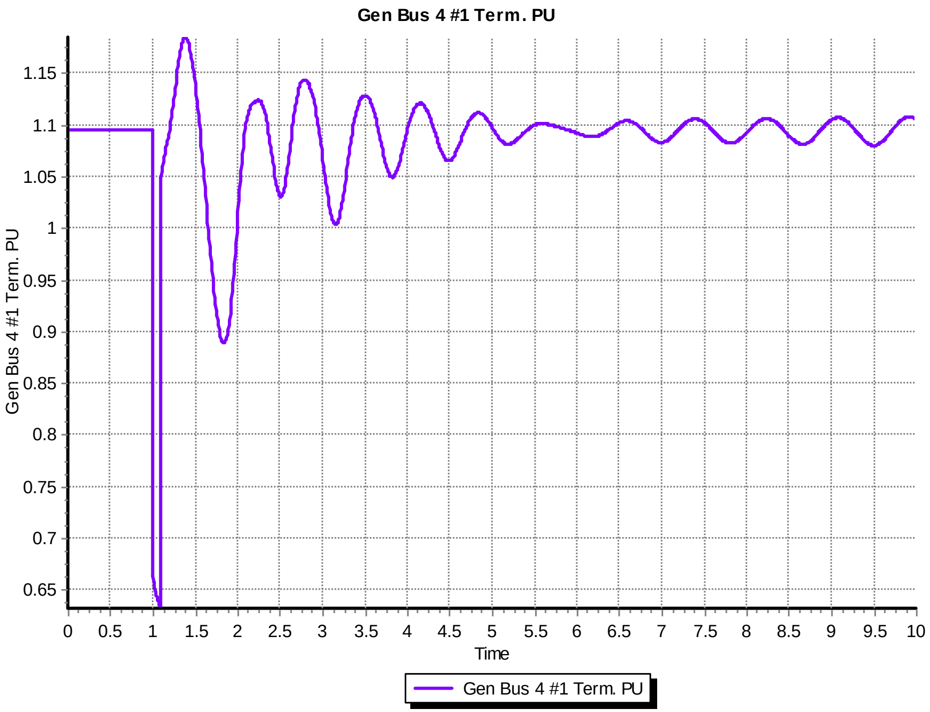




IEEET1 Example

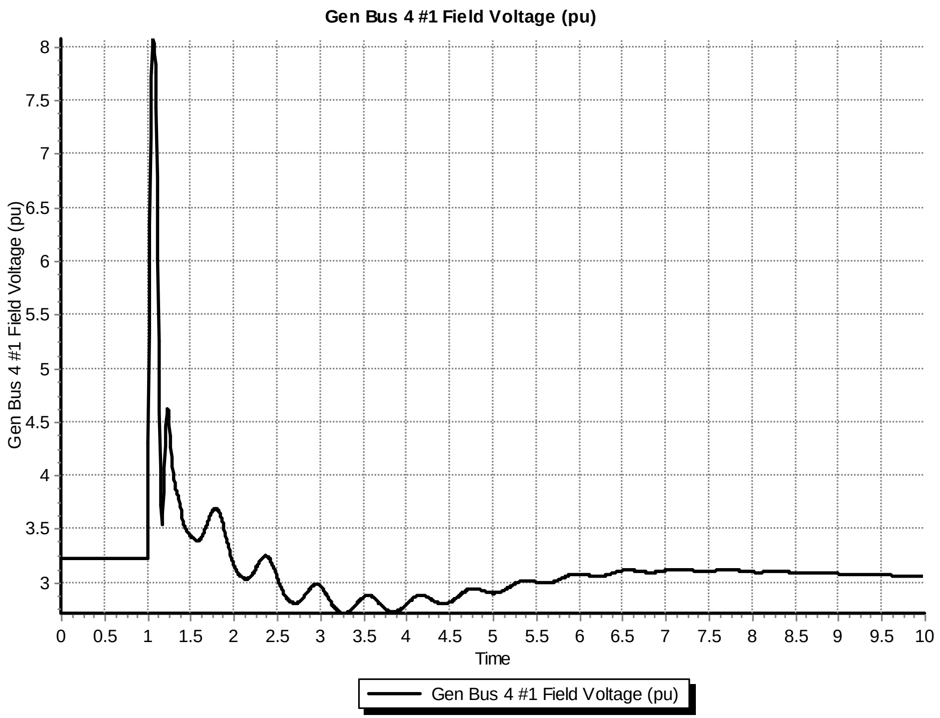
- Same case, except with K_A=500 to decrease steady-state error, no V_R limits; this case is actually unstable

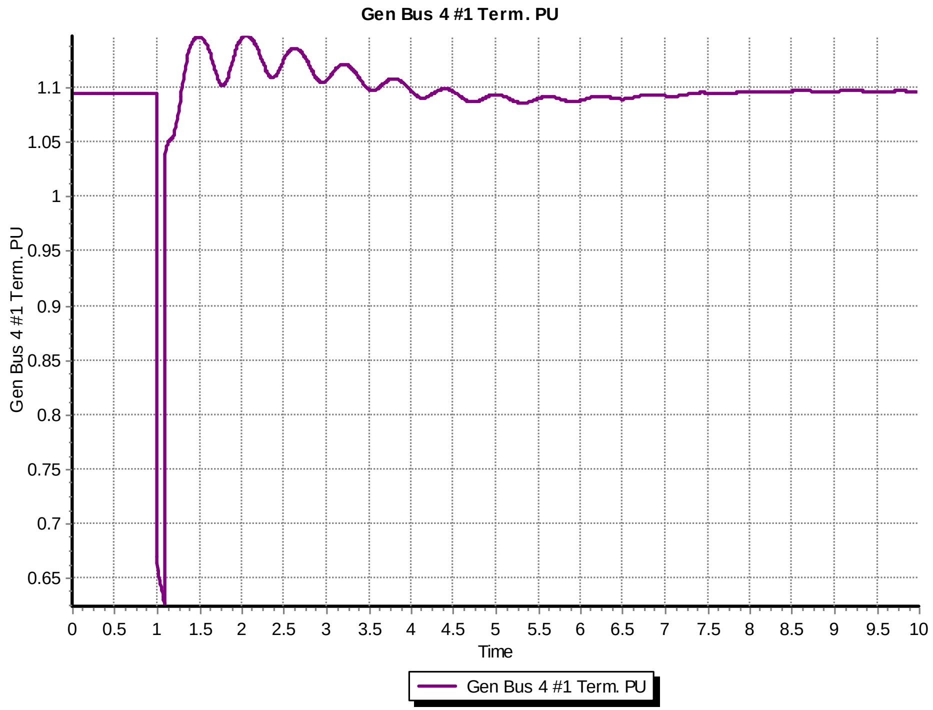




IEEET1 Example

- 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



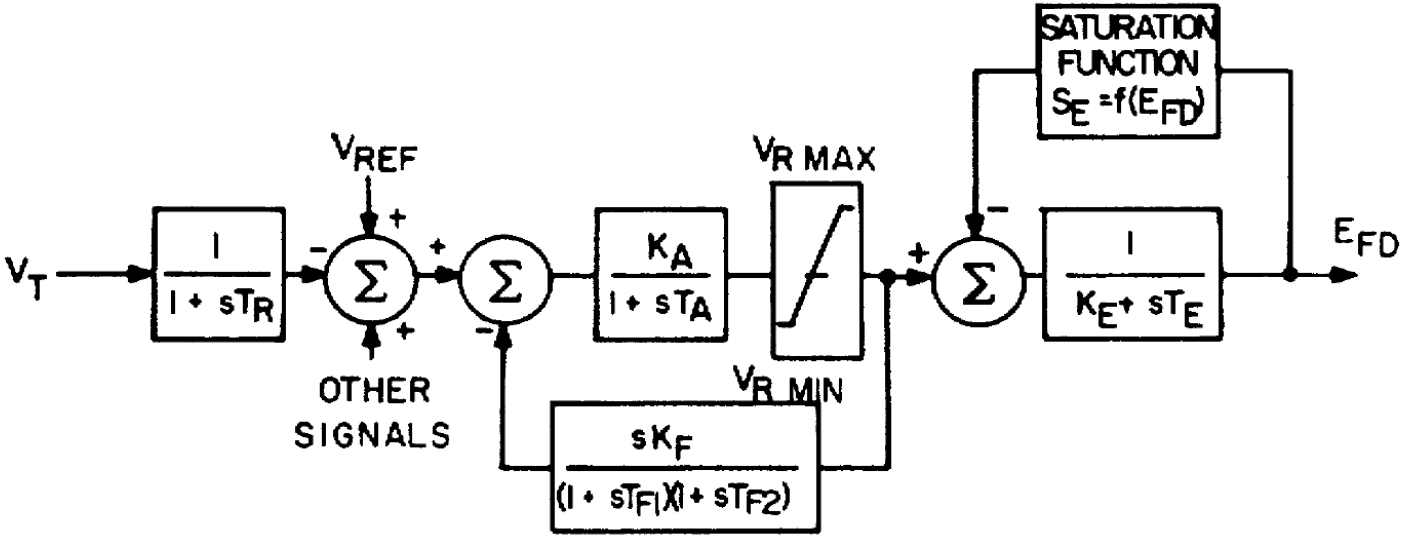


AC Exciters

- 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

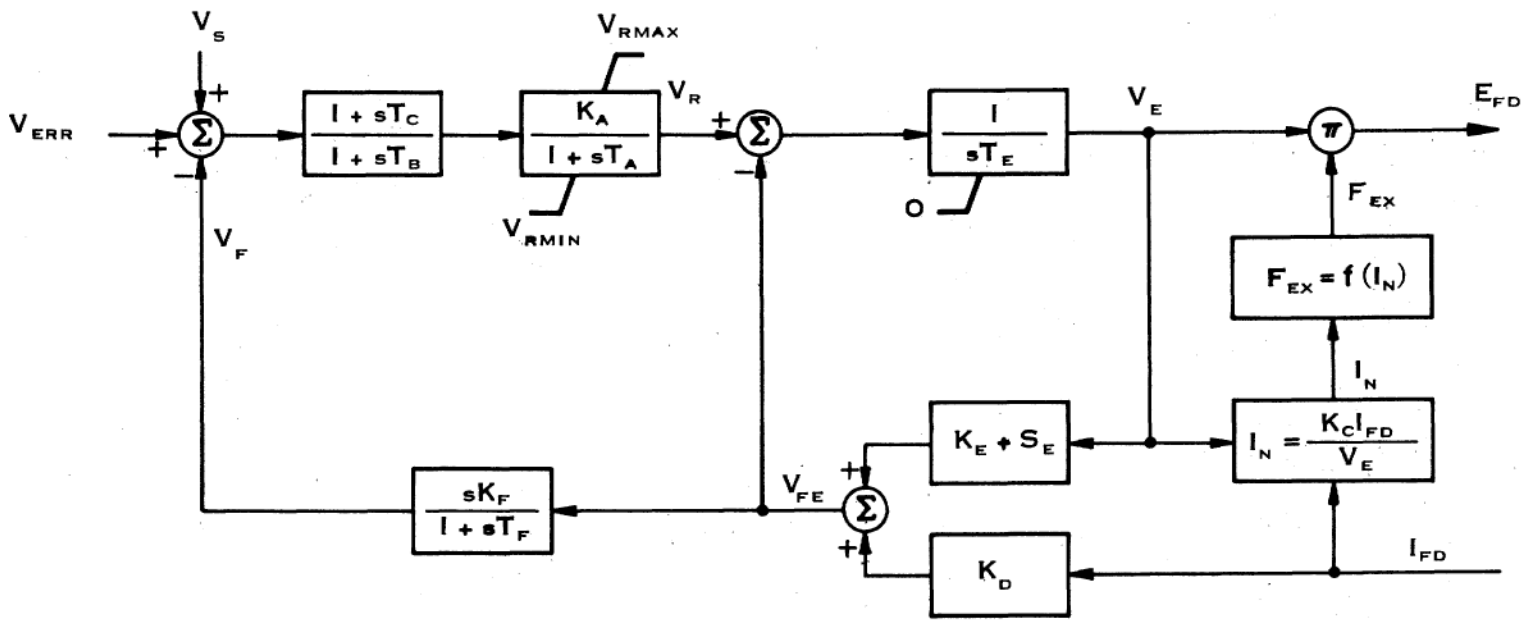


Exciter model is quite similar to IEEE T1; in the EI/WECC case there are 105 IEEE T2 exciters (about 1%)

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

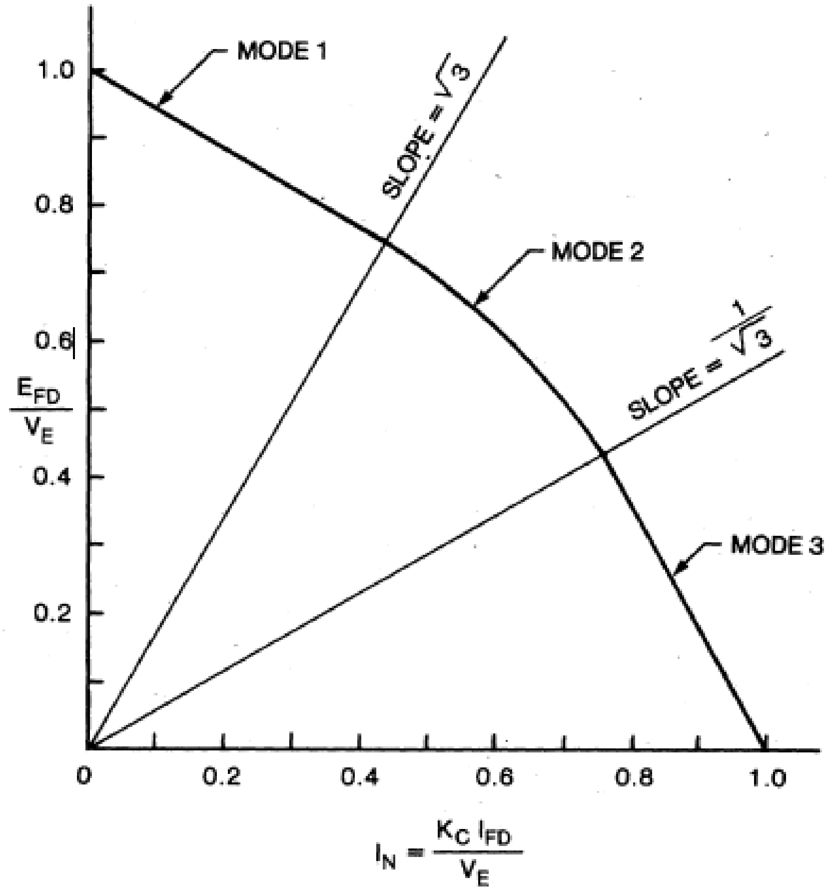


About 1% of the EI/WECC exciters are EXAC1

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



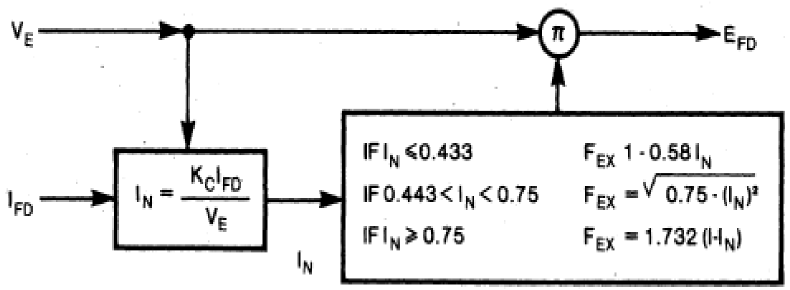


Fig. E.2. Rectifier Regulation Equations

Kc represents the commuting reactance

There are about 6 or 7 main types of ac exciter models

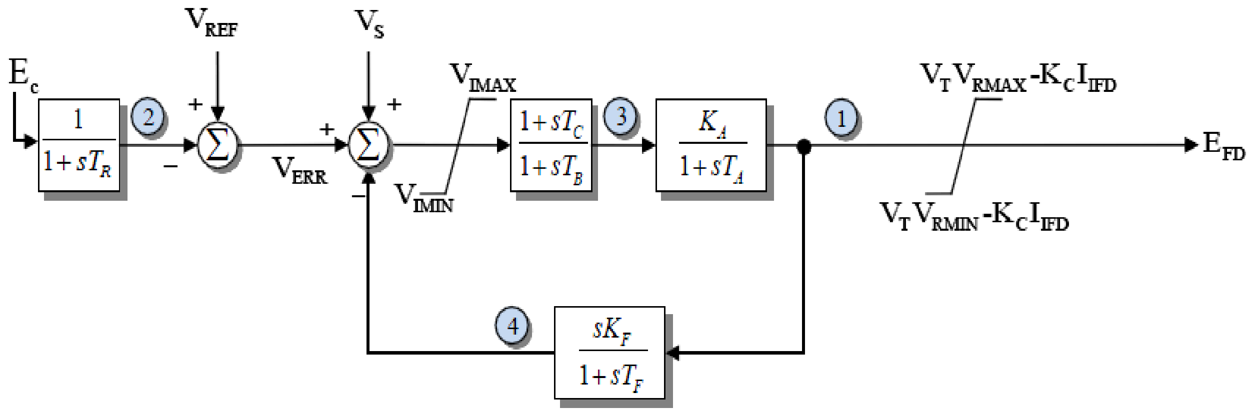
Image Source: Figures E.1 and E.2 of "Excitation System Models for Power Stability Studies," *IEEE Trans. Power App. and Syst.*, vol. PAS-100, pp. 494-509, February 1981

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)

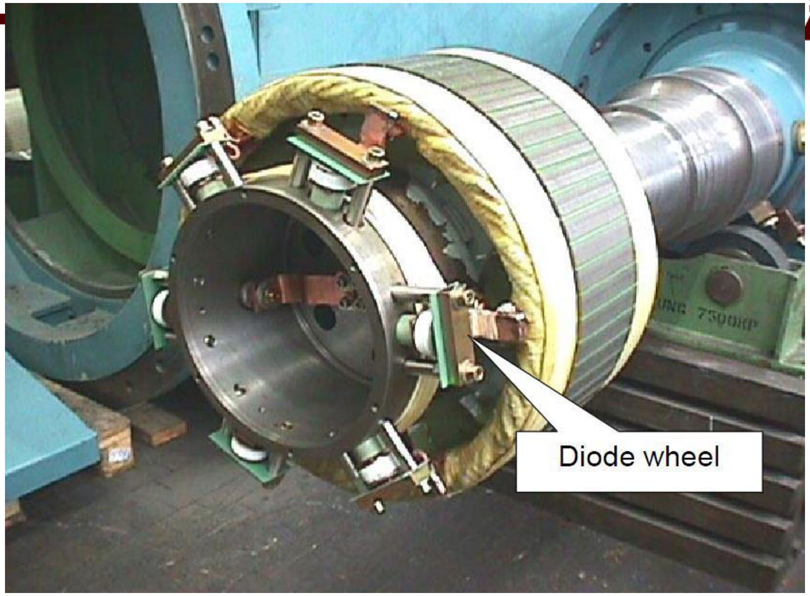
Kc represents the commuting reactance

Exciter Upgrade Example: ABB UNICITER

UNICITER® Example
Hydro Power Plant – Horizontal - Switzerland

- Old DC commutator exciter by Brown Boveri
- Date of manufacture: 1960

New UNICITER® by ABB GTSC Birr



Exciter Stator Field

Image Source: qdoc.tips/brushlessexcitationsystemsupgrade-pdf-free.html

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 (negative convention)
  - Specified on the machine base
- PSSE requires a separate model with their COMP model also using a negative sign

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

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

Initial Limit Violations

- Since many models have limits and the initial state variables are dependent on power flow values, there is certainly no guarantee that there will not be initial limit violations
- If limits are not changed, this does not result in an equilibrium point solution
- PowerWorld has several options for dealing with this, with the default value to just modify the limits to match the initial operating point
  - If the steady-state power flow case is correct, then the limit must be different than what is modeled