ECEN 667
Power System Stability

Lecture 11: Exciters and Governors

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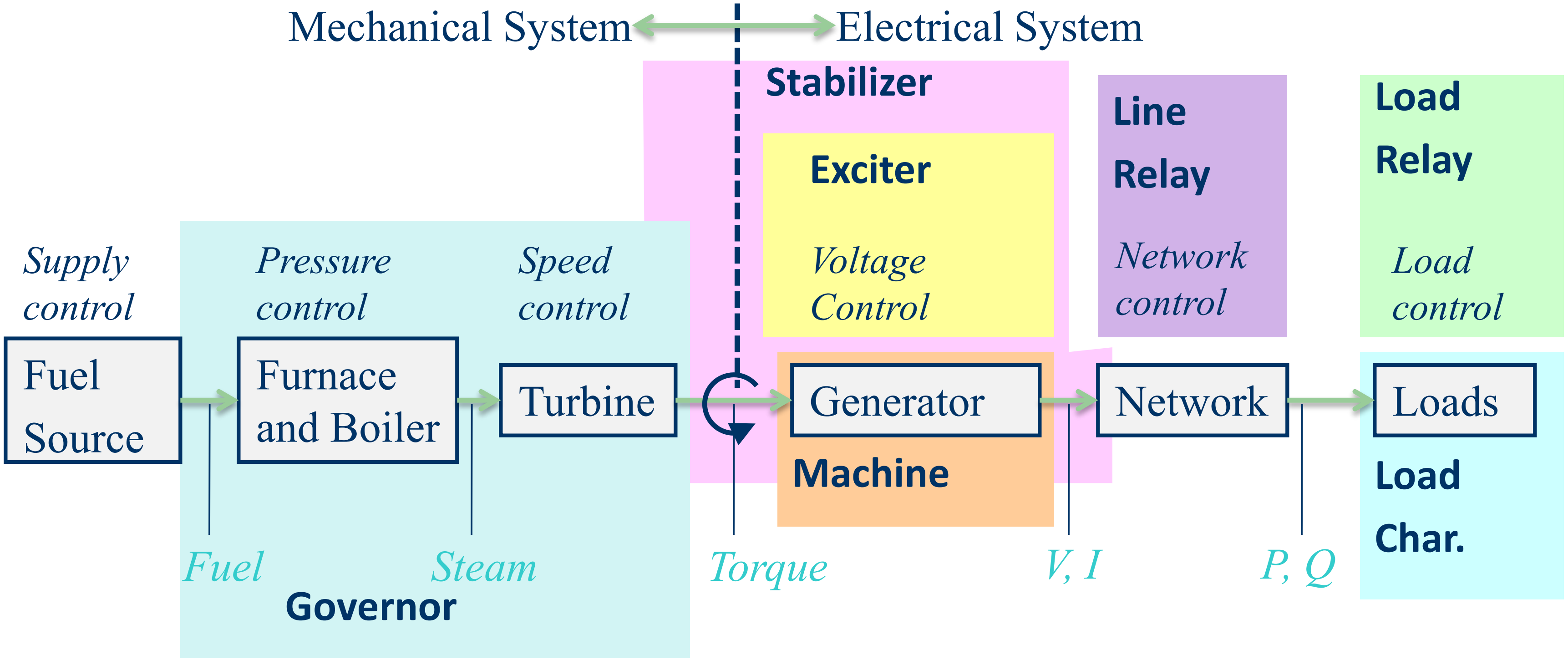
Announcements

- Read Chapter 4
- Homework 3 is due on Thursday Oct 7
- Homework 4 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



Mechanical System

Electrical System

Stabilizer

Exciter

Voltage Control

Line Relay

Network control

Load Relay

Load control

Supply control

Pressure control

Speed control

Fuel Source

Furnace and Boiler

Turbine

Generator

Network

Loads

Machine

Load Char.

Fuel

Steam

Torque

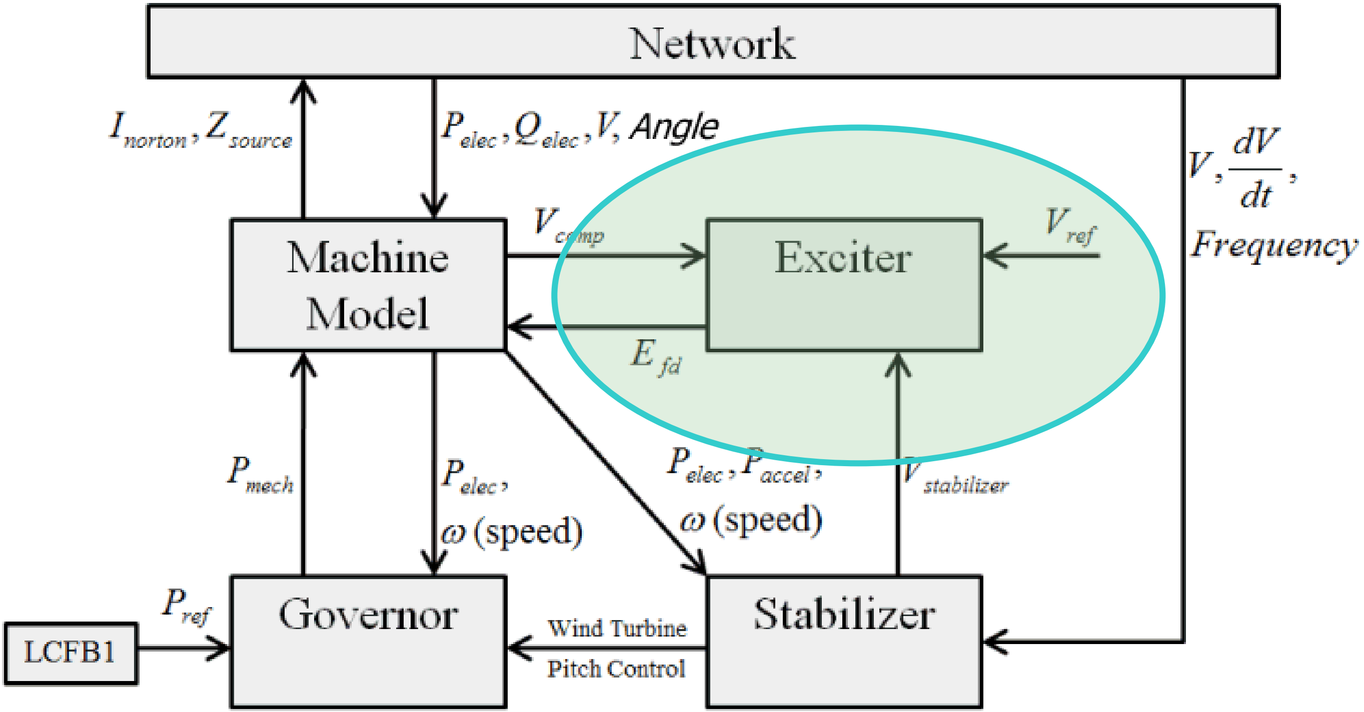
V, I

P, Q

Governor

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)

Functional Block Diagram

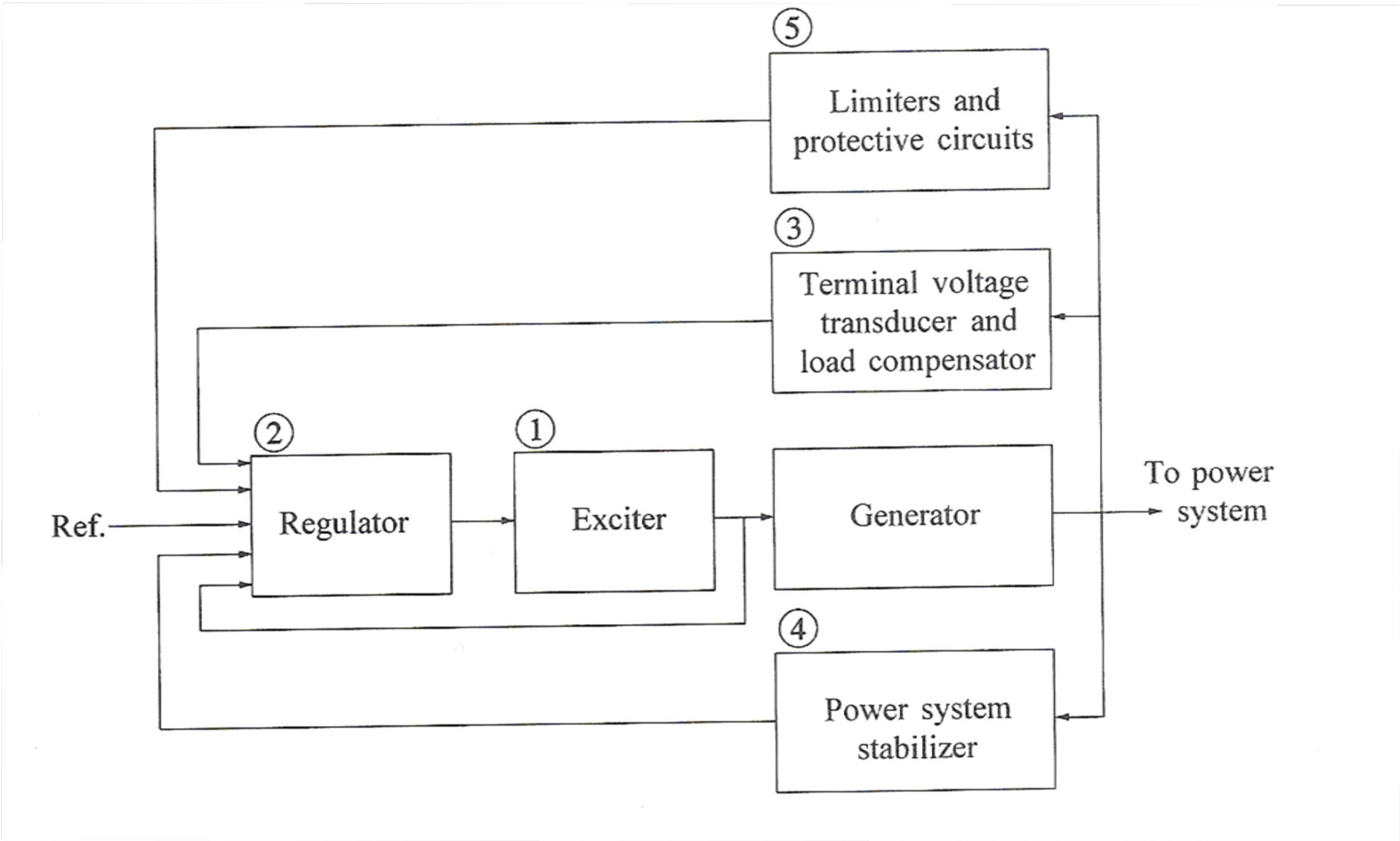
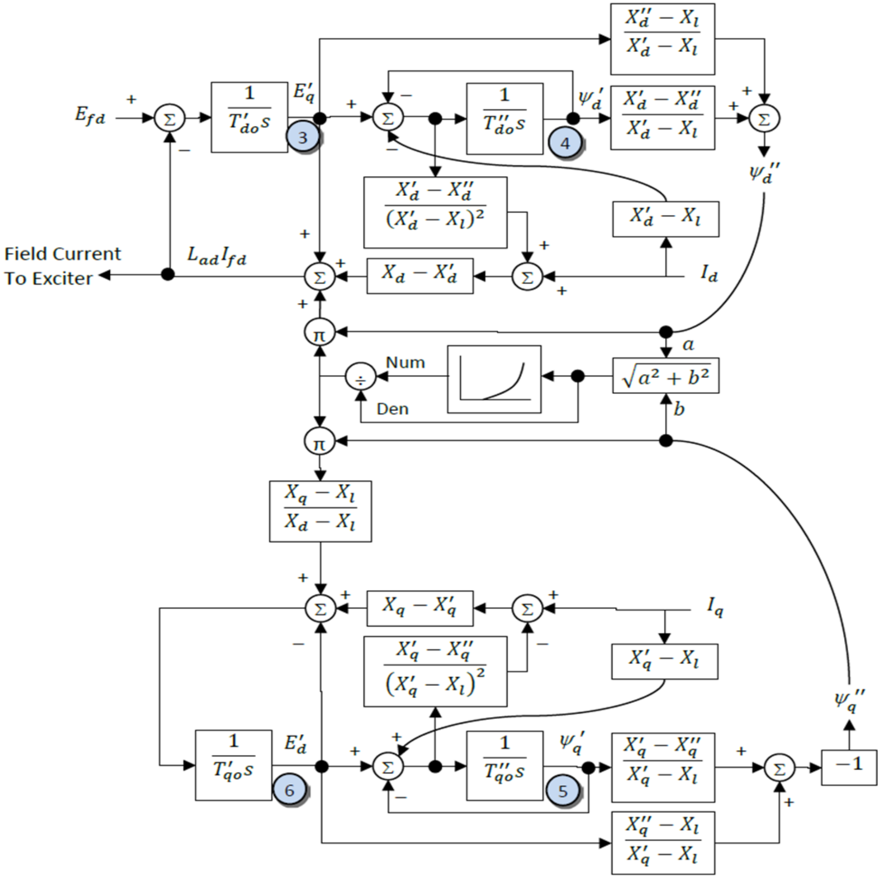


Image source: Fig 8.1 of Kundur, *Power System Stability and Control*

Coupling with the Machine Models

- When initializing the models, the power flow results are used to determine the generator states, including the E_{FD}; E_{FD} along with the terminal voltage is used to initialize the exciter
- During the simulation the exciter changes E_{FD}, which impacts the machine differential equations

GENROU block diagram



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

DC2 Exciters

- Other dc exciters exist, such as the EXDC2, which is quite similar to the EXDC1

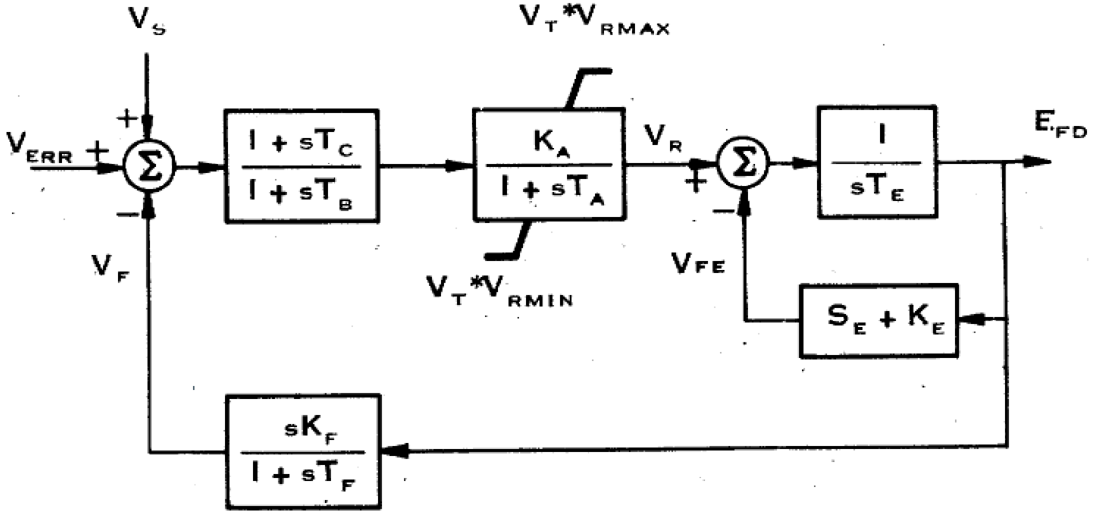


Fig. 4. Type DC2 - DC Commutator Exciter

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

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

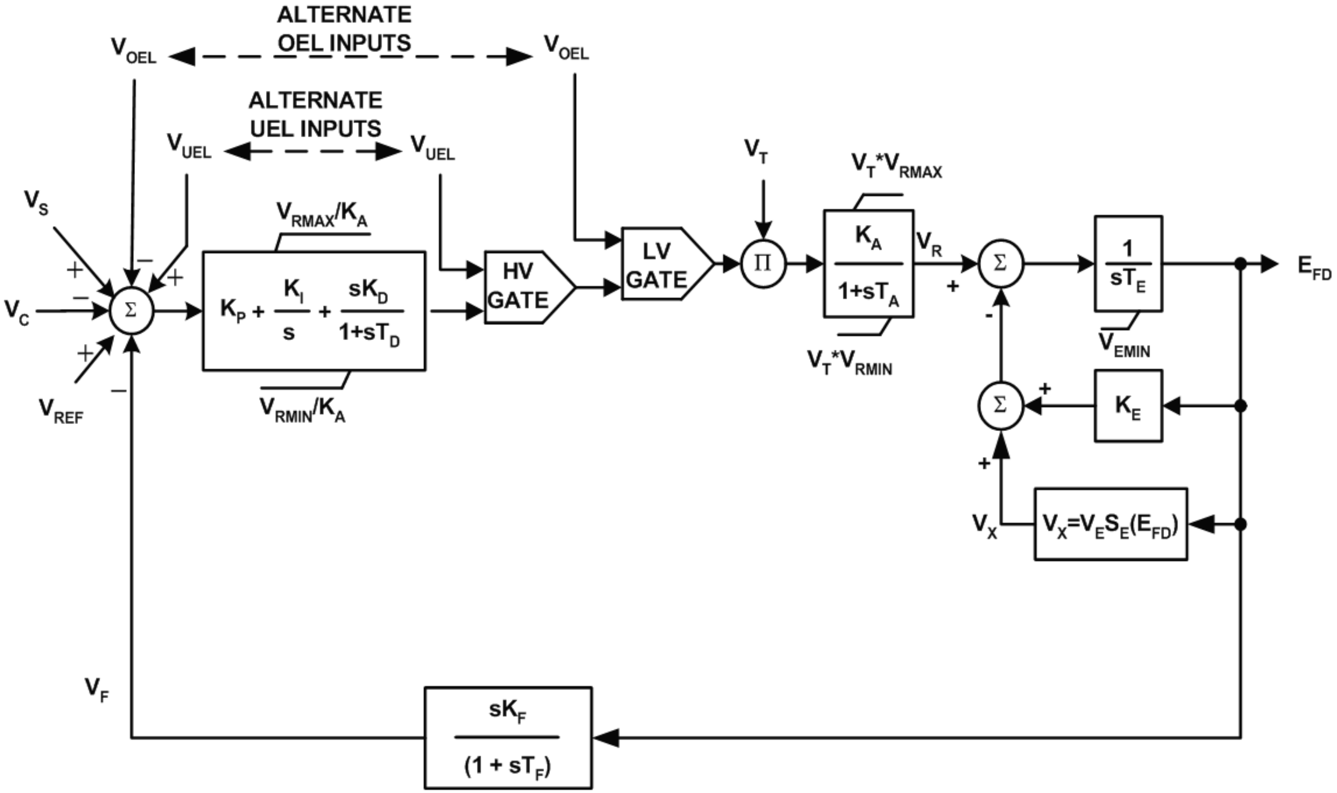


Image Source: Fig 5-4 of IEEE Std 421.5-2005

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

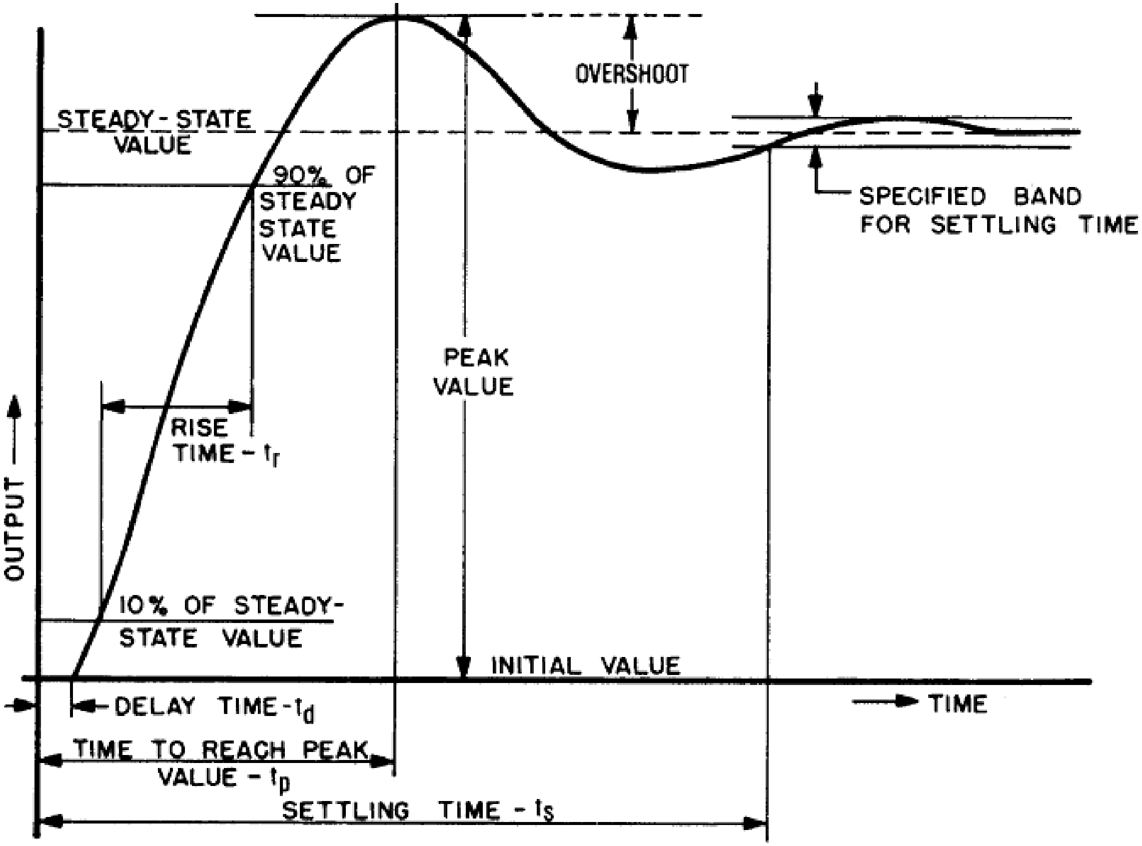


Image Source: IEEE Std 421.2-1990, Figure 3

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

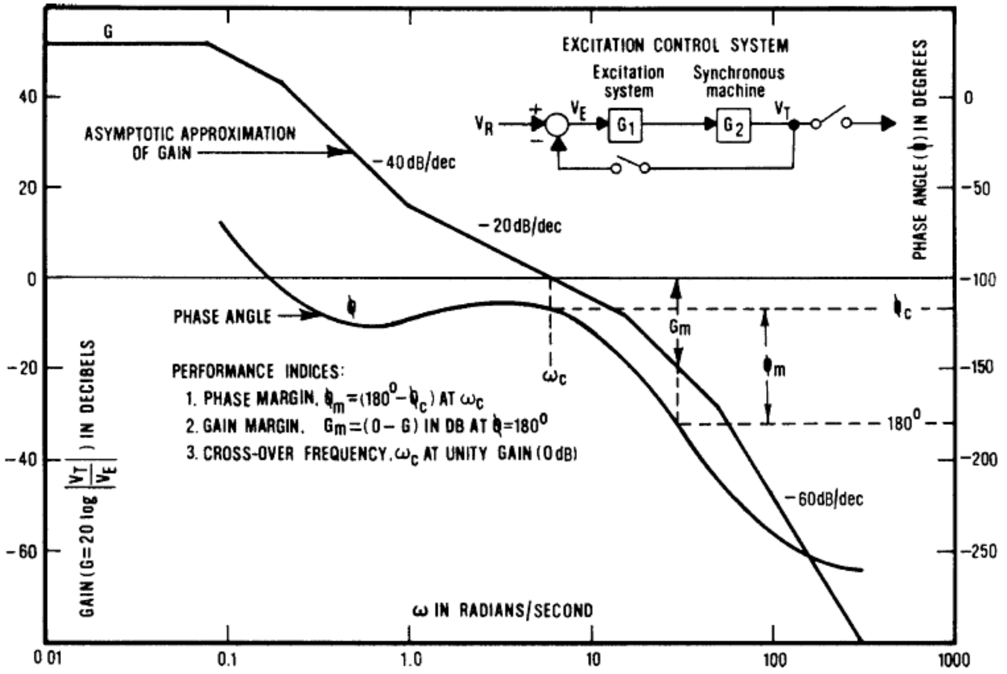


Figure 4—Typical Open-Loop Frequency Response of an Excitation Control System with the Synchronous Machine Open-Circuited

Image Source: IEEE Std 421.2-1990, Figure 4

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

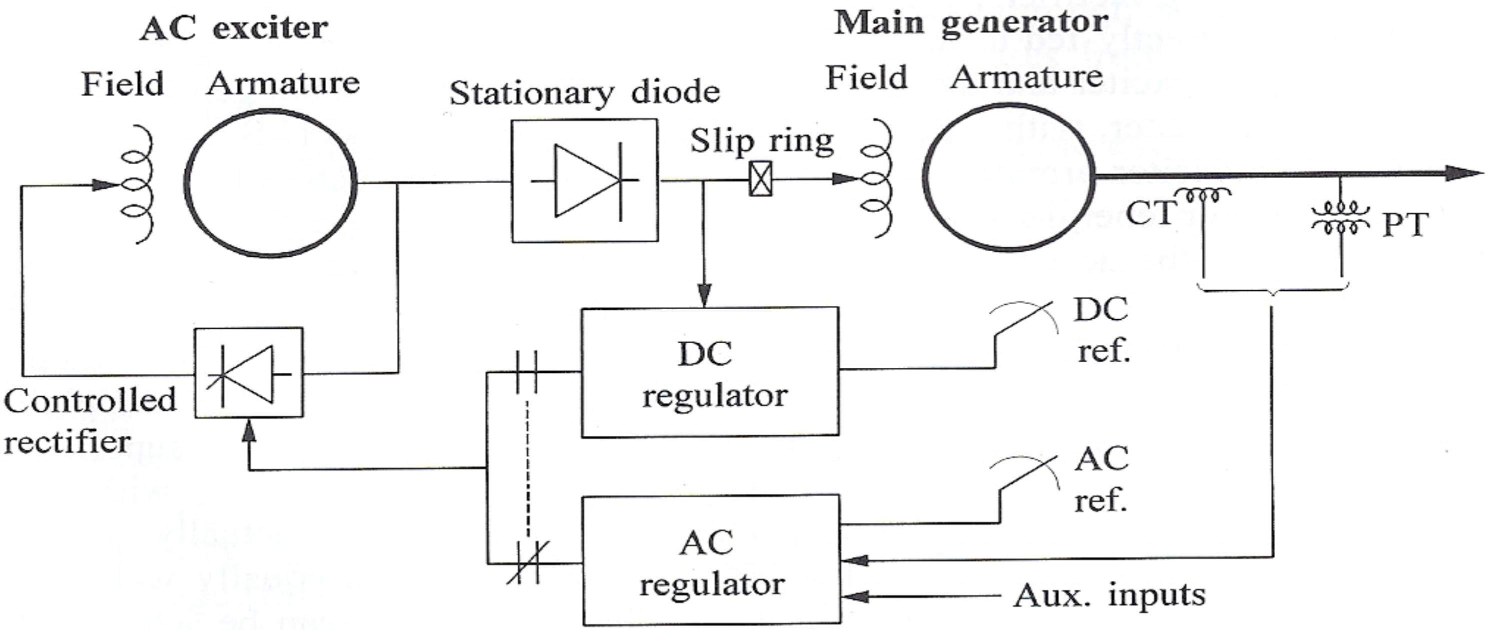
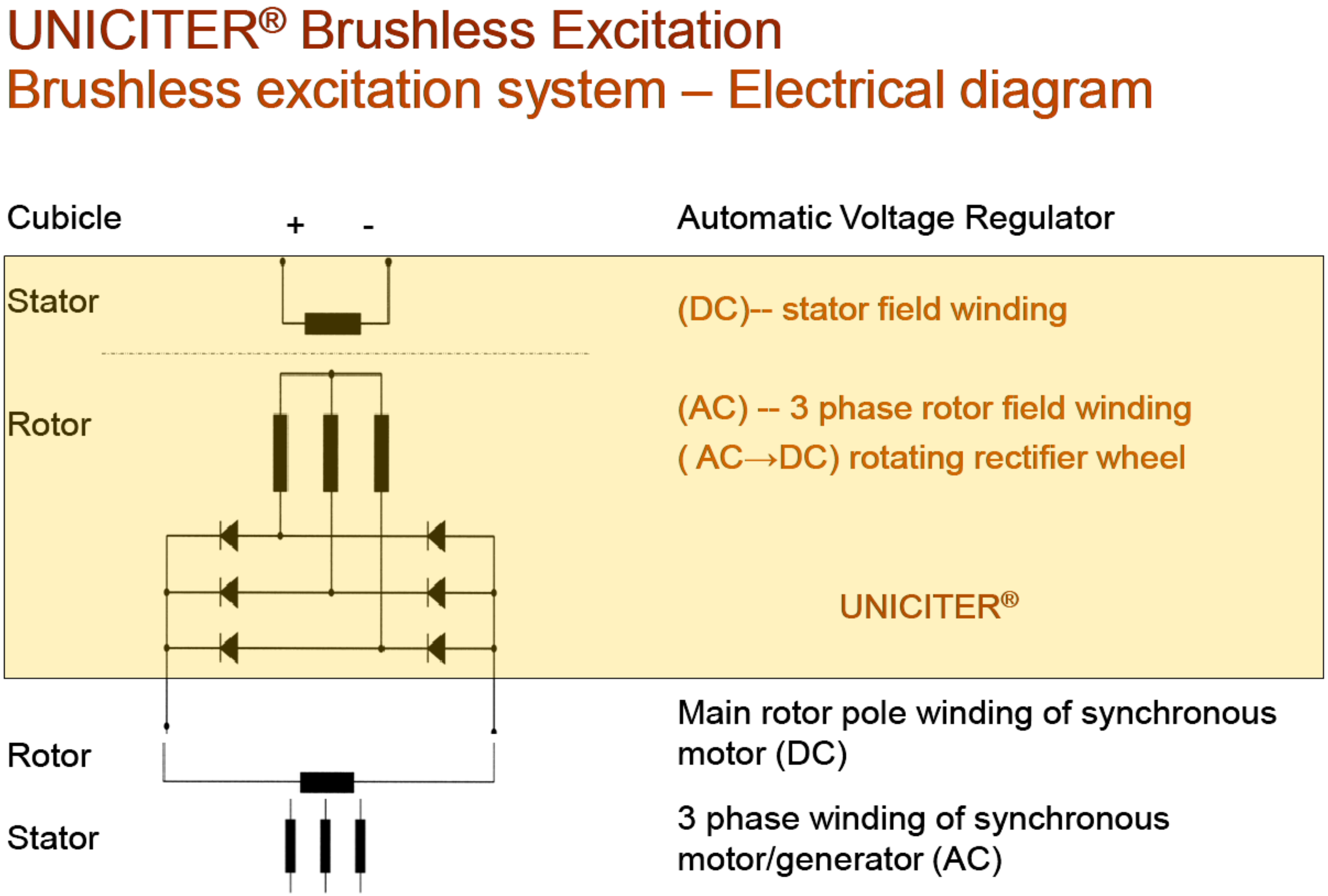


Figure 8.3 Field-controlled alternator rectifier excitation system

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

ABB UNICITER



UNICITER® Brushless Excitation
Brushless excitation system – Electrical diagram

Automatic Voltage Regulator

(DC)-- stator field winding

(AC) -- 3 phase rotor field winding

(AC→DC) rotating rectifier wheel

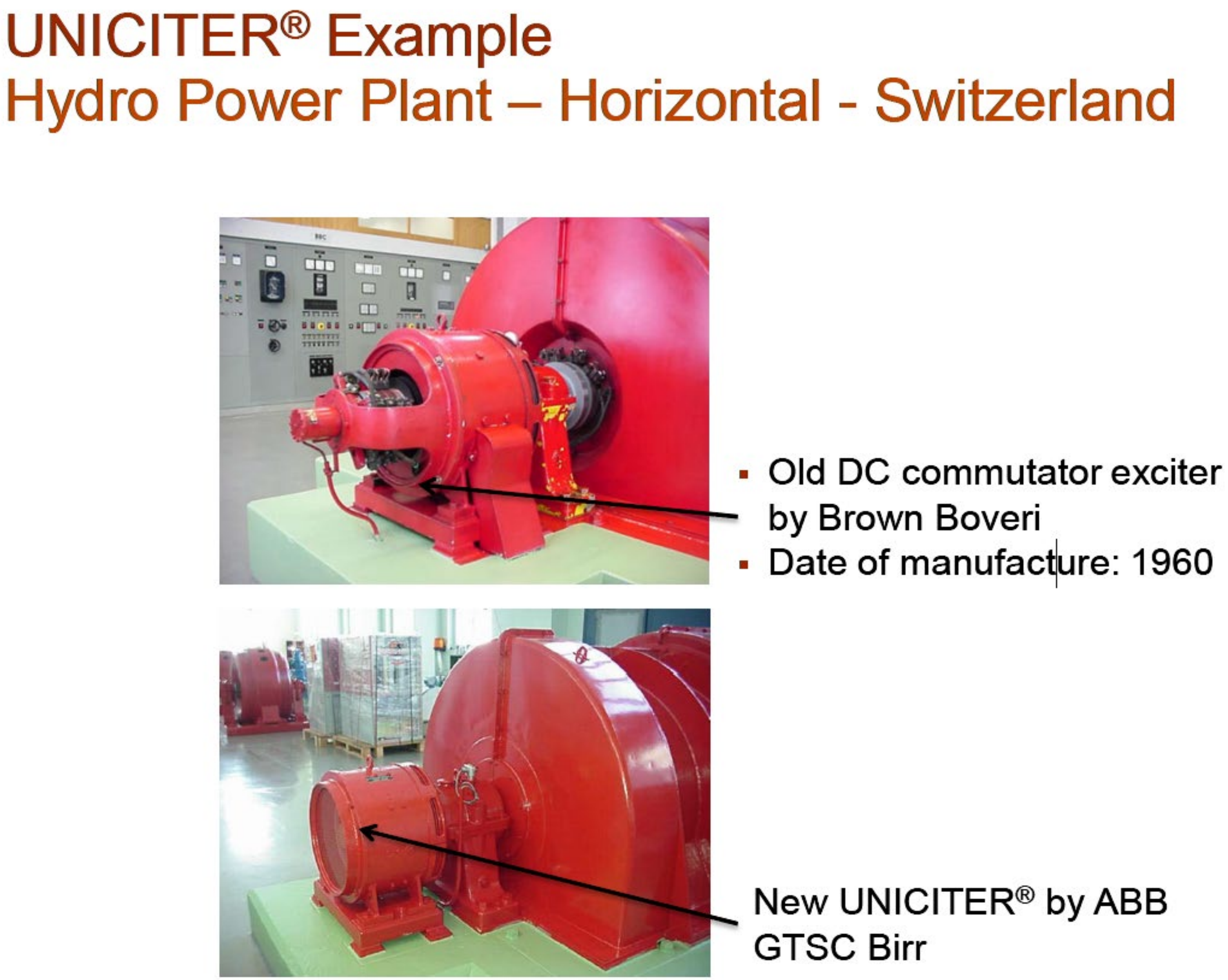
UNICITER®

Main rotor pole winding of synchronous motor (DC)

3 phase winding of synchronous motor/generator (AC)

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

ABB UNICITER Example



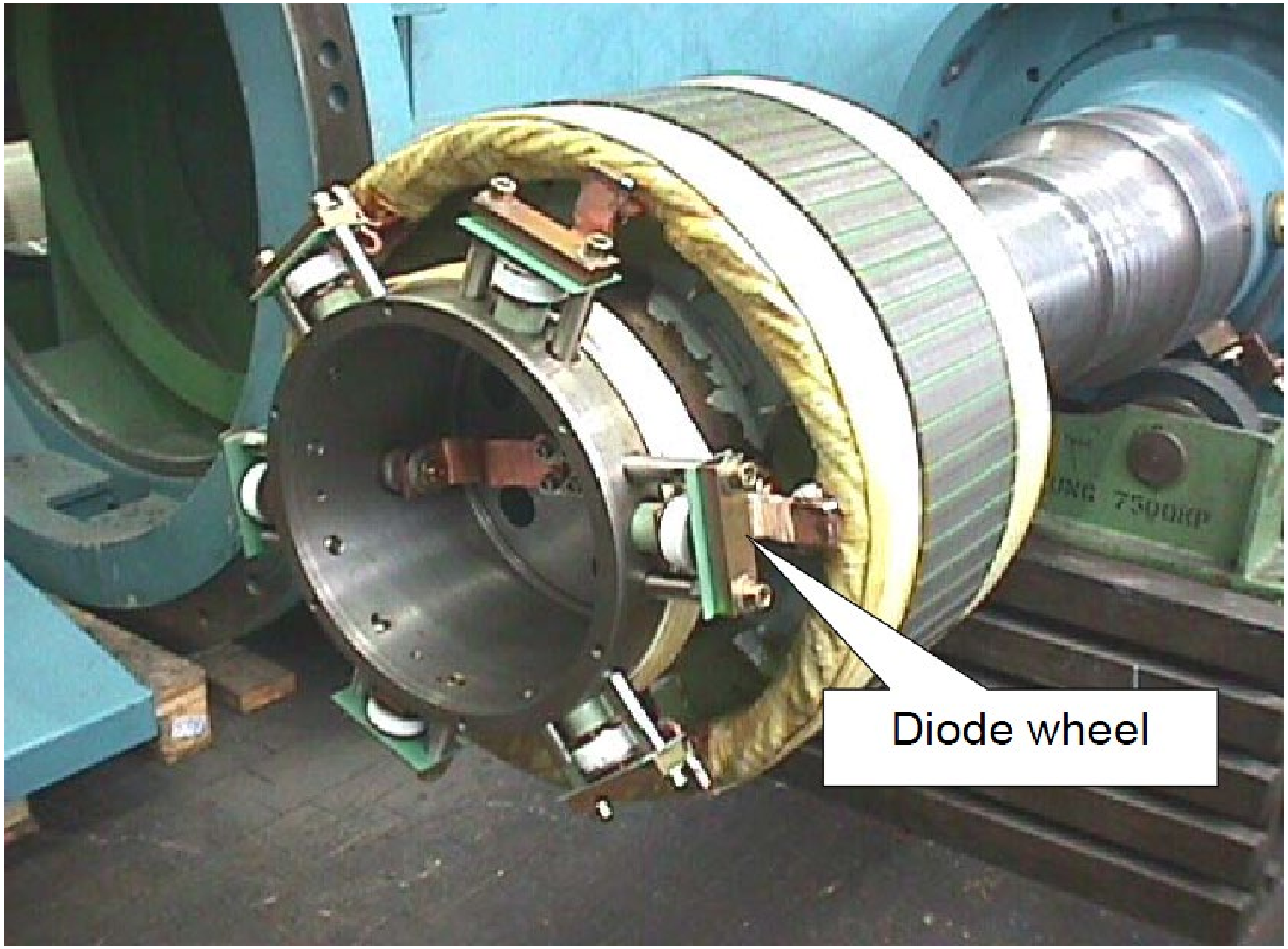
UNICITER® Example
Hydro Power Plant – Horizontal - Switzerland

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

New UNICITER® by ABB
GTSC Birr

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

ABB UNICITER Rotor Field



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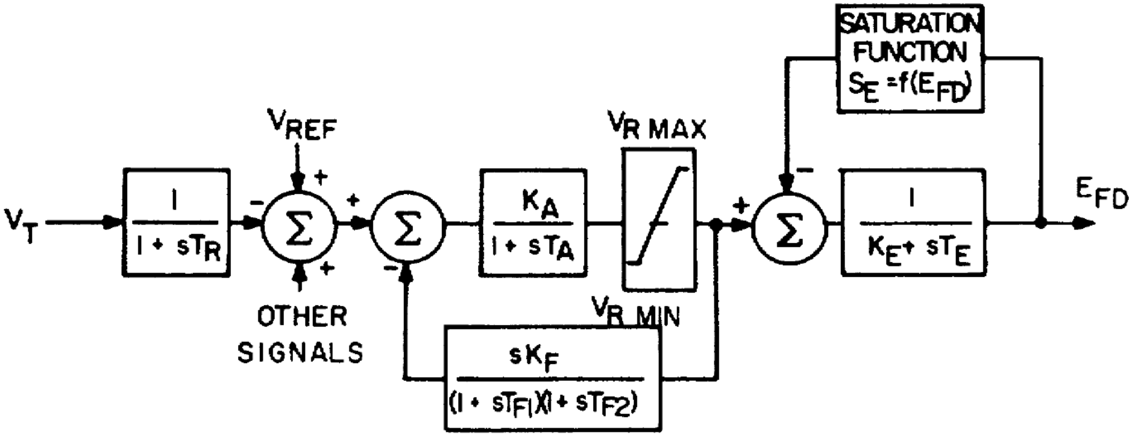
AC Exciter Modeling

- Originally represented by IEEET2 shown below

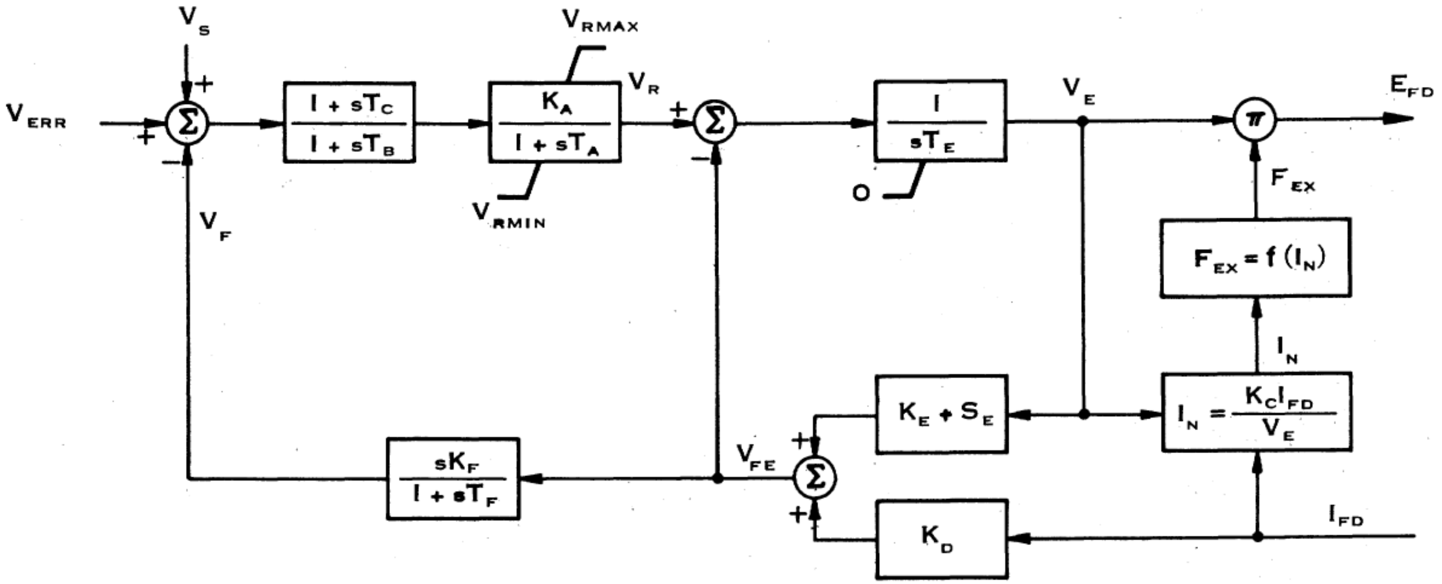


Exciter model is quite similar to IEEE T1

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

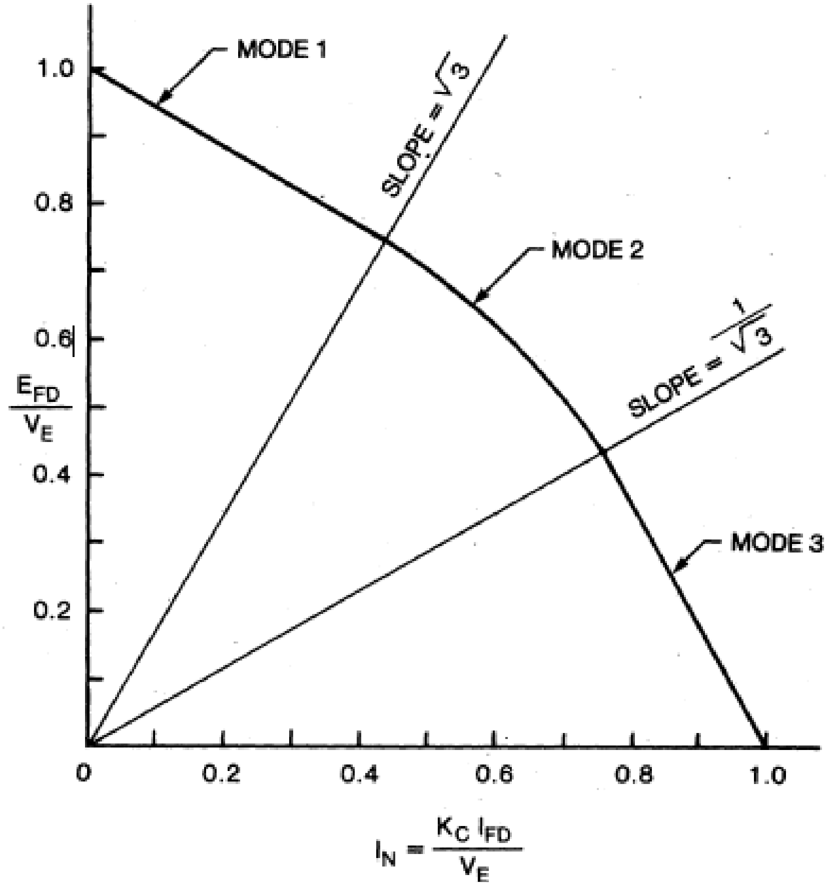


About 5% of WECC exciters are EXAC1

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



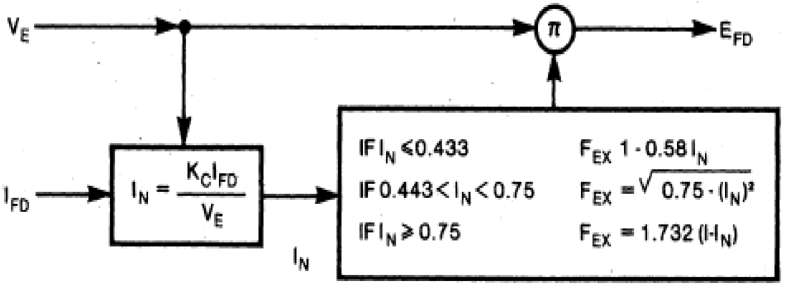


Fig. E.2. Rectifier Regulation Equations

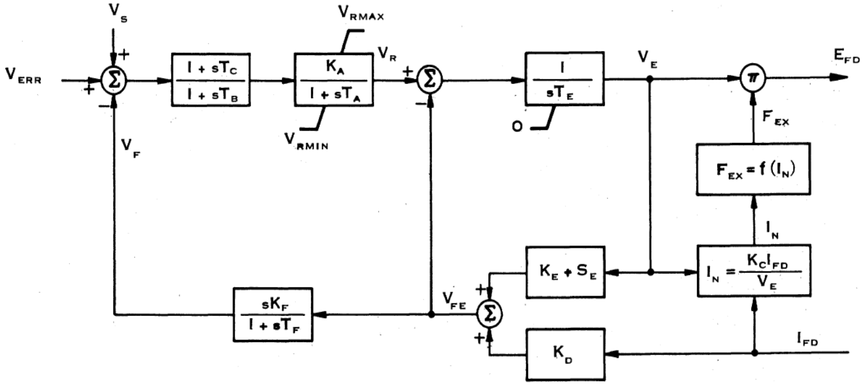
Kc represents the commuting reactance

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

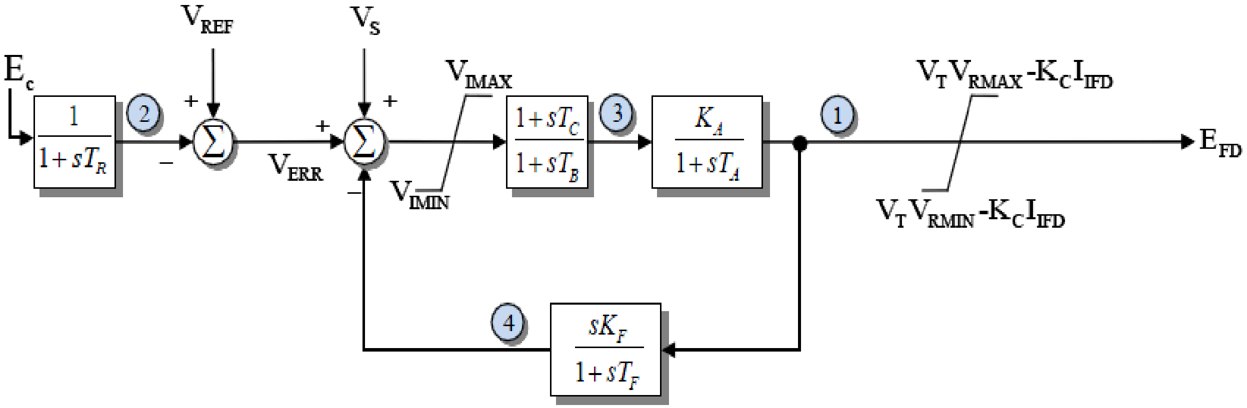
Need to check to make sure we are on this segment

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

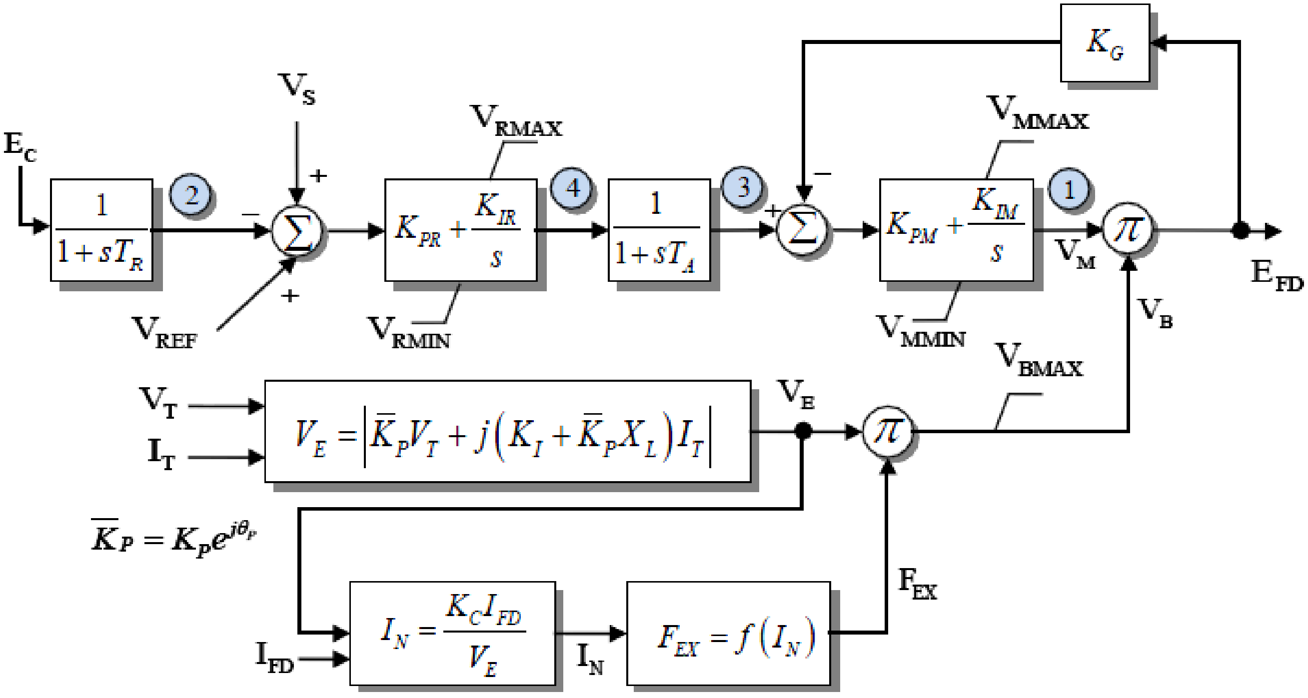


Most common exciter in WECC with about 14% modeled with this type

Kc represents the commuting reactance

EXST4B

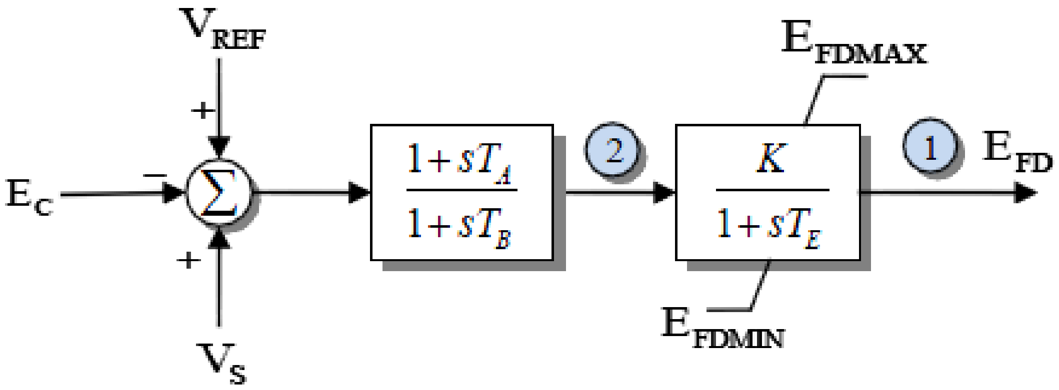
- EXST4B models a controlled rectifier design; field voltage loop is used to make output independent of supply voltage



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 (negative convention)
  - Specified on the machine base

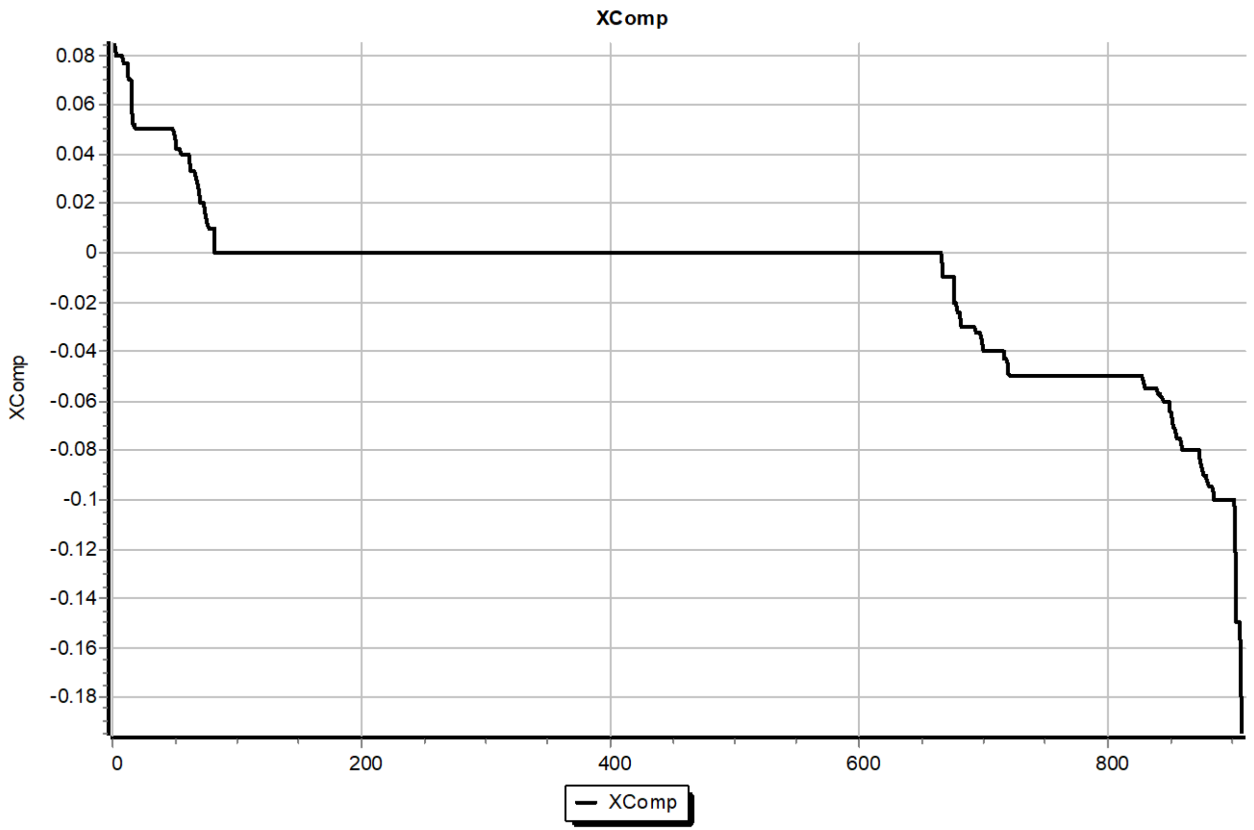
$$E_c = \left| \bar{V}_t - \left(R_c + jX_c \right) I_T \right|$$

- 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

Compensation Example 1

- Added EXST1 model to 4 bus GENROU case with compensation of 0.05 pu (on gen's 100 MVA base) (using negative sign convention)
  - This is looking into step-up transformer
  - Initial voltage value is

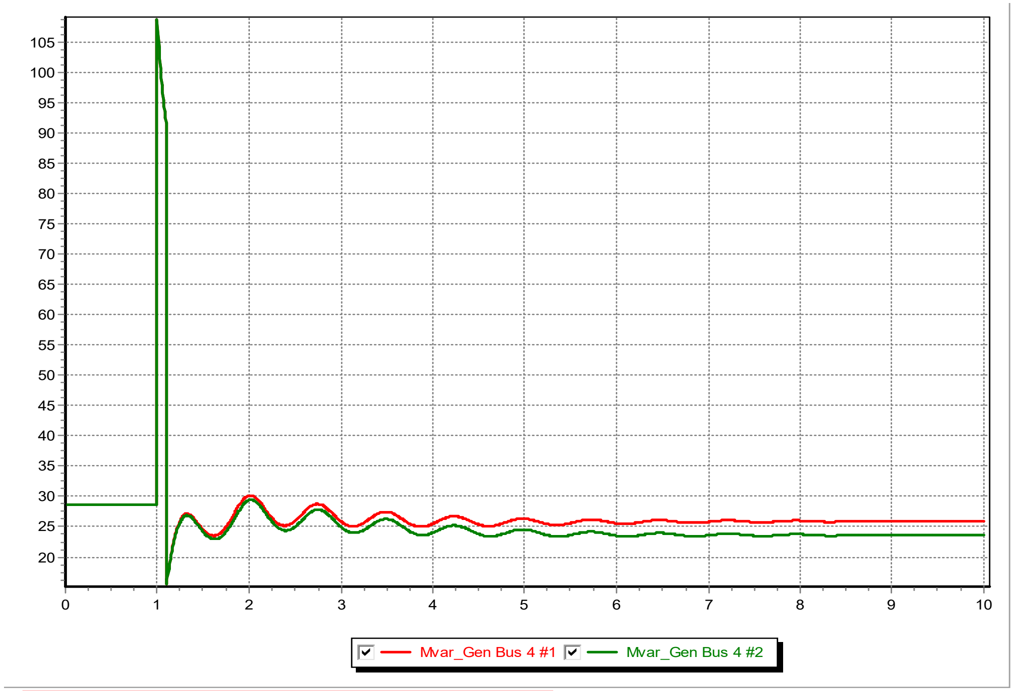
$$V_t = 1.072 + j0.22, \quad I_t = 1.0 - j0.3286$$

$$E_c = \left|1.072 + j0.22 - (j0.05)(1.0 - j0.3286)\right| = \left|1.0557 + j0.17\right| = 1.069$$

Case is **B4_comp1**

Compensation Example 2

- B4 case with two identical generators, except one in Xc = -0.1, one with Xc=-0.05; in the power flow the Mvars are shared equally (i.e., the initial value)



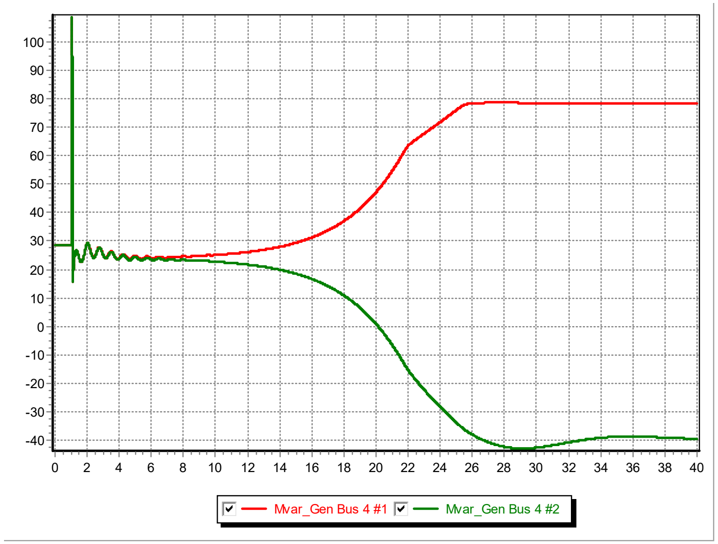
Plot shows the reactive power output of the two units, which start out equal, but diverage because of the difference values for X_c

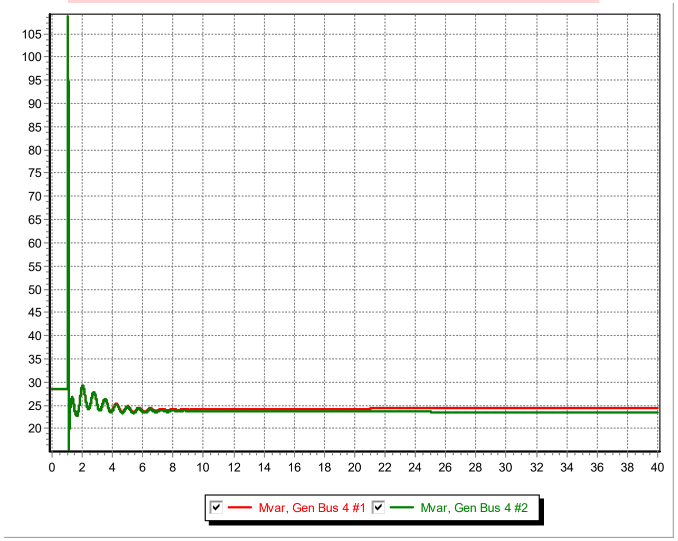
Case is **B4_comp2**

Compensation Example 3

- B4 case with two identical generators except with slightly different Xc values (into net) (0.05 and 0.048)
- Below graphs show reactive power output if the currents from the generators not coordinated (left) or are coordinated (right); PowerWorld always does the coordinated approach

Case is **B4_comp3**

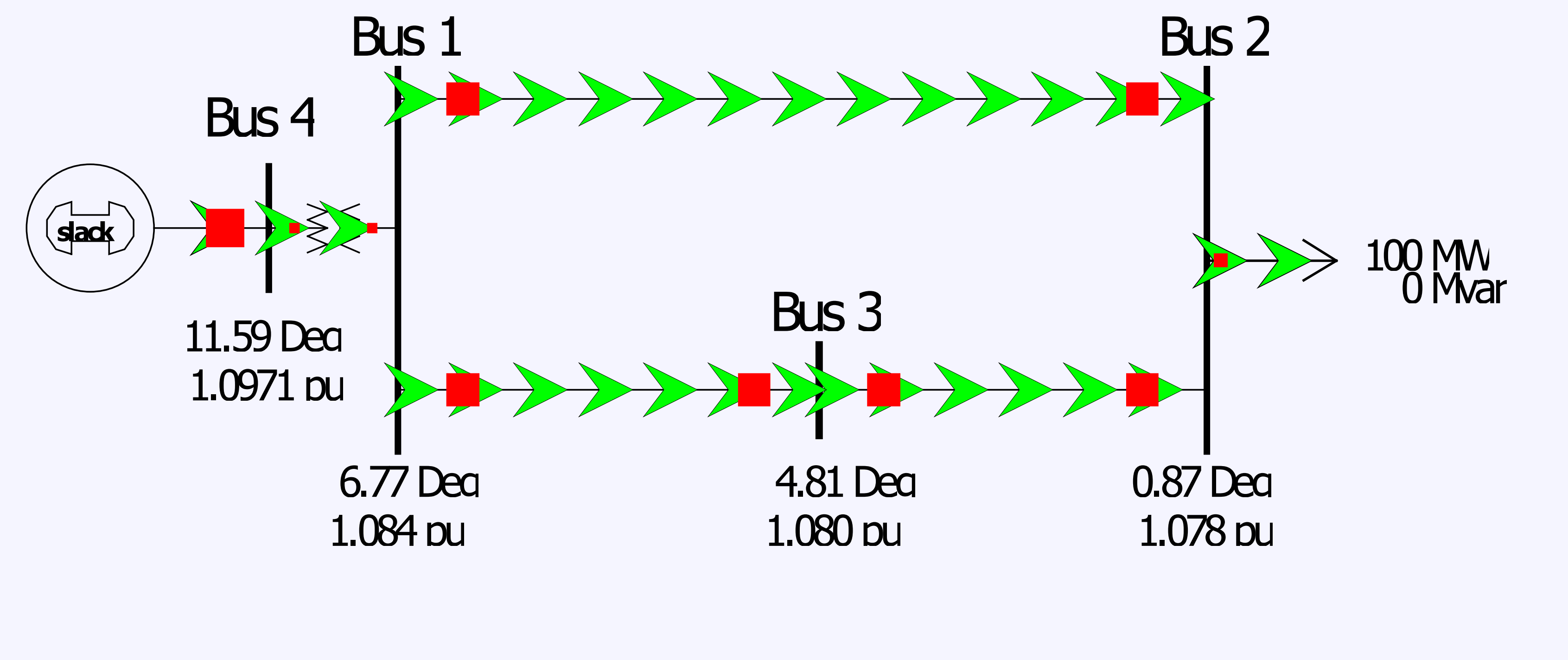




Compensation Benefits

- A reason for using compensation to control voltages in the transmission system is to move the source of voltage support closer to the load

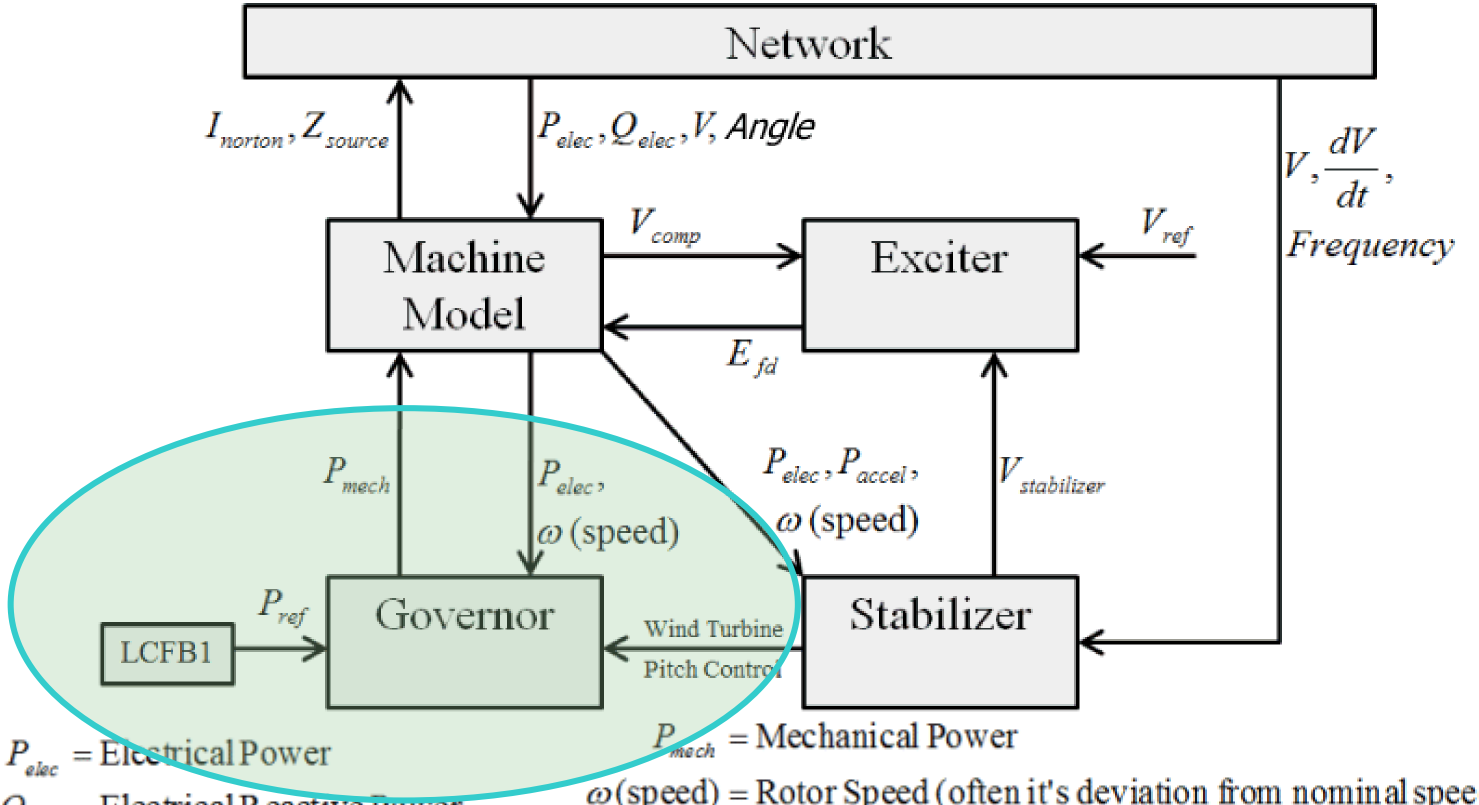
Case is **B4_comp_voltagestability**



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

Governor Models



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Prime Movers and Governors

- Synchronous generator is used to convert mechanical energy from a rotating shaft into electrical energy
- The "prime mover" is what converts the orginal energy source into the mechanical energy in the rotating shaft
- Possible sources: 1) steam (nuclear, coal, combined cycle, solar thermal), 2) gas turbines, 3) water wheel (hydro turbines), 4) diesel/ gasoline, 5) wind (which we'll cover separately)
- The governor is used to control the speed

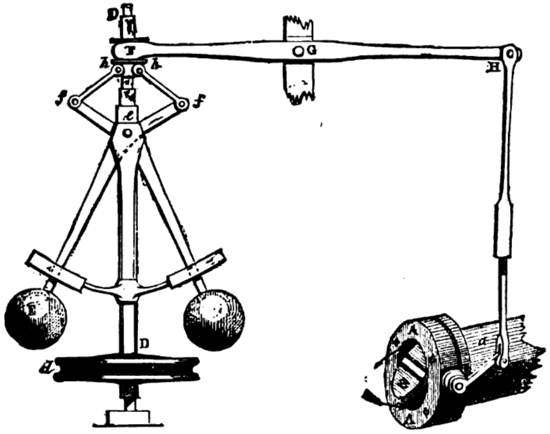


FIG. 4.—*Governor and Throttle-Valve.*

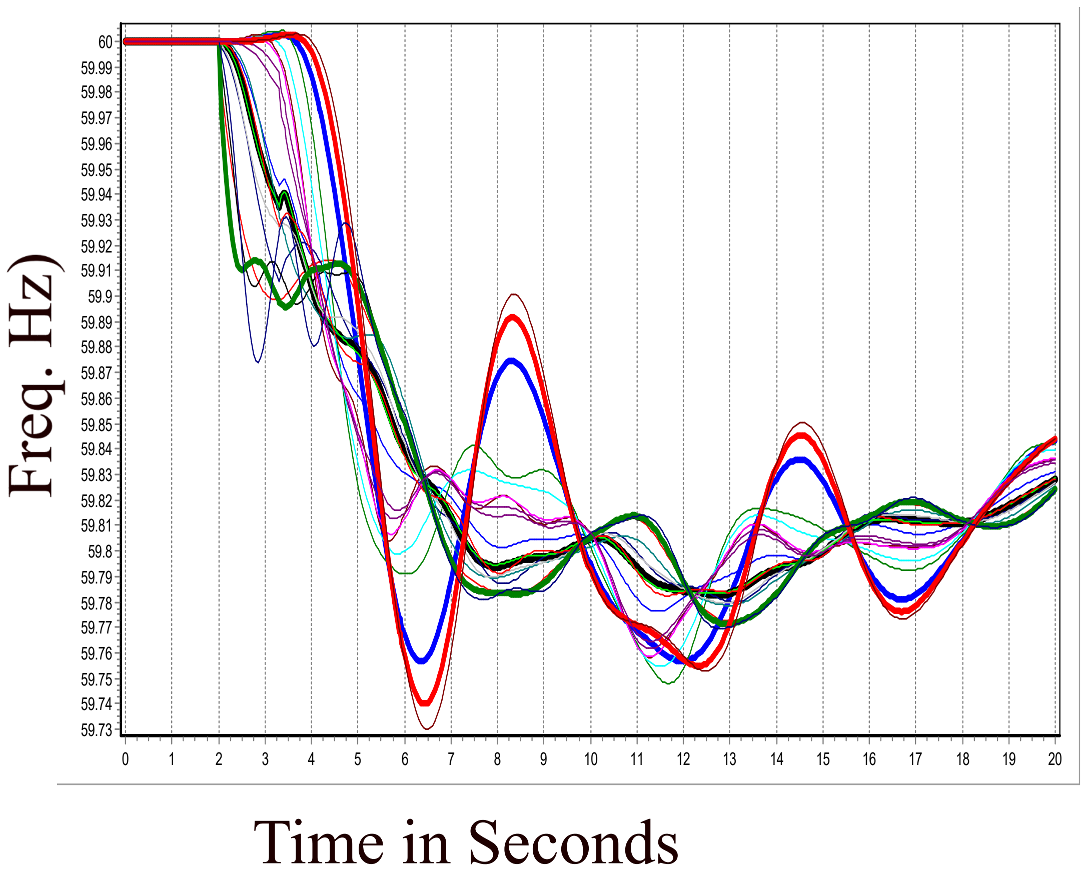
Image source: http://upload.wikimedia.org/wikipedia/commons/1/1e/Centrifugal_governor.png

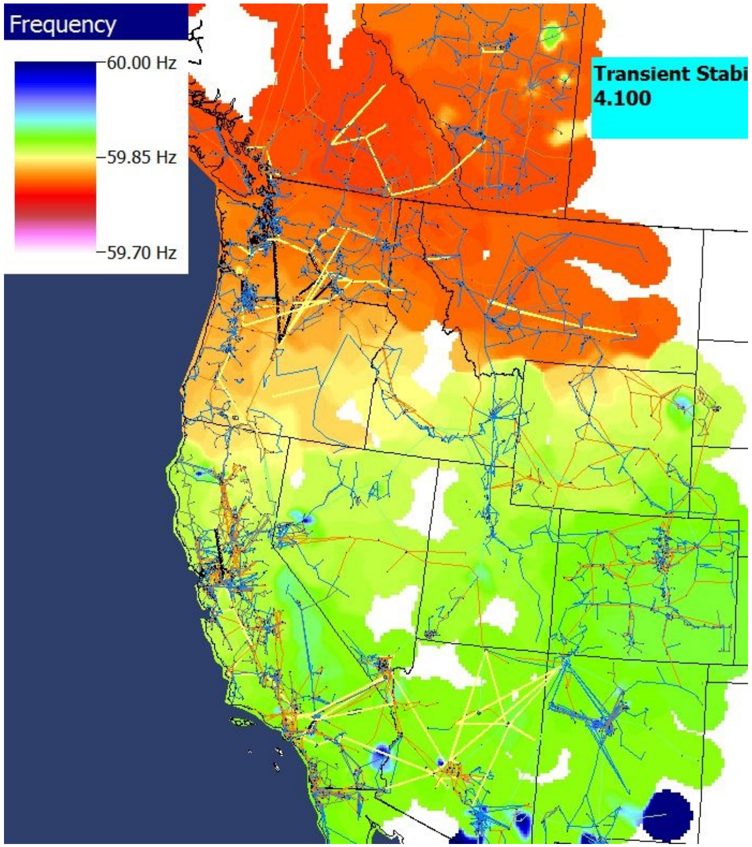
Prime Movers and Governors

- In transient stability collectively the prime mover and the governor are called the "governor"
- As has been previously discussed, models need to be appropriate for the application
- In transient stability the response of the system for seconds to perhaps minutes is considered
- Long-term dynamics, such as those of the boiler and automatic generation control (AGC), are usually not considered
- These dynamics would need to be considered in longer simulations (e.g. dispatcher training simulator (DTS)

Power Grid Disturbance Example

Figures show the frequency change as a result of the sudden loss of a large amount of generation in the Southern WECC





Frequency Contour