ECE 522 - Power Systems Analysis II
Spring 2021

Voltage Regulation and Control

Spring 2021

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Content

- Modeling the excitation control system (AVR) of a generator
- Influence on angular stability and power system stabilizer (PSS)
- Reactive power compensation and control

- References:
  - Saadat's Chapters 12.6-12.7
  - Kundur's Chapters 5.4, 8 and 11.2
  - EPRI Tutorial's Chapter 5

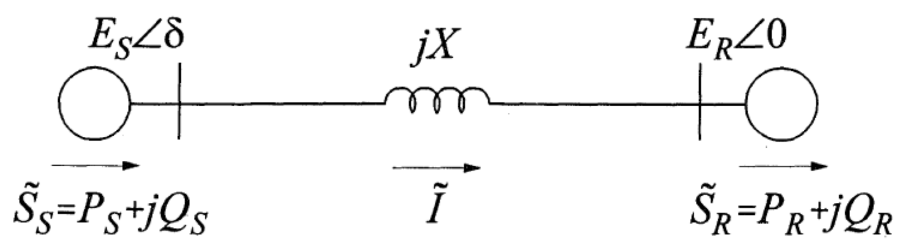
Objectives of Voltage and Reactive Power Control

- Equipment security:
  - Voltages at terminals of all equipment (of either utility and customers) in the system are within acceptable limits to avoid damage

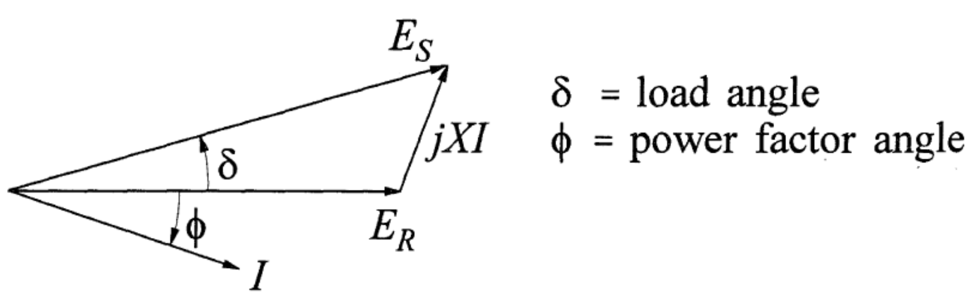
- System stability:
  - System stability is enhanced to maximize utilization of the transmission system. (Voltage and reactive power control have a significant impact on system stability.)

- Transmission efficiency:
  - The reactive power flow is minimized so as to reduce RI^2 and XI^2 losses to improve transmission system efficiency, i.e. leaving the room mainly for real power transfer

Reactive Power Transfers



(a) Equivalent system diagram



(b) Phasor diagram

Figure 6.21 Power transfer between two sources

$$P_R = P_S = \frac{E_S E_R}{X}\sin\delta$$

$$Q_R = \frac{E_S E_R \cos\delta - E_R^2}{X} \doteq \frac{E_R(E_S - E_R)}{X}$$

$$Q_S = \frac{E_S^2 - E_S E_R \cos\delta}{X} \doteq \frac{E_S(E_S - E_R)}{X}$$

$$Q_{loss} = XI^2 = X\frac{P_R^2 + Q_R^2}{E_R^2}$$

$$P_{loss} = RI^2 = R\frac{P_R^2 + Q_R^2}{E_R^2}$$

- Reactive power flows from the high voltage side to the low voltage side.
- But reactive power cannot be transmitted over long distances because
  - it would require a large voltage gradient to do so, and
  - an increase in reactive power transfer causes an increase in Q_{loss} as well as P_{loss}.

- The unit of reactive power is var (volt-ampere reactive) although Var, VAR and Var are also used.

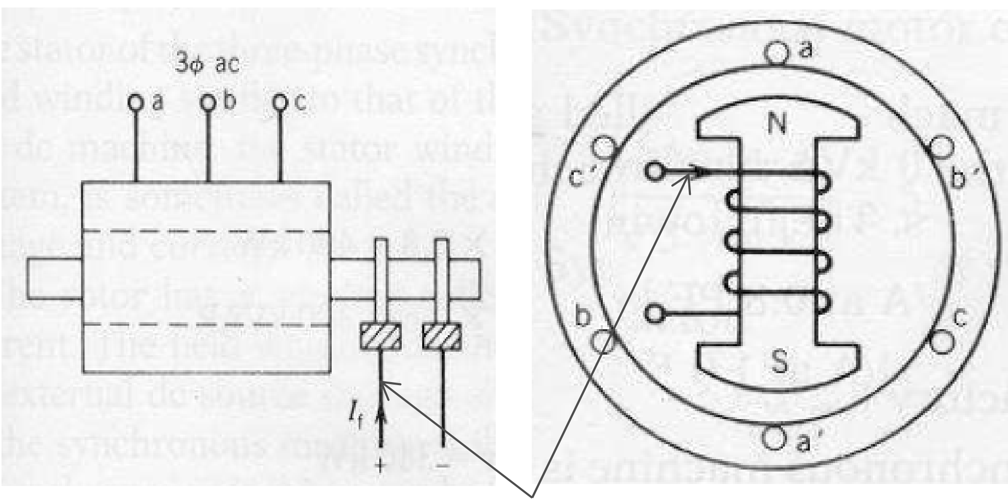
Methods of Reactive Power and Voltage Control

Equipment	Supply Q	Absorb Q
Synchronous generator	Y (Over-excited)	Y (Under-excited)
Overhead lines	Y	Y
Underground cables	Mostly	
Transformers		Y
Loads		Mostly
Compensating devices	Y	Y

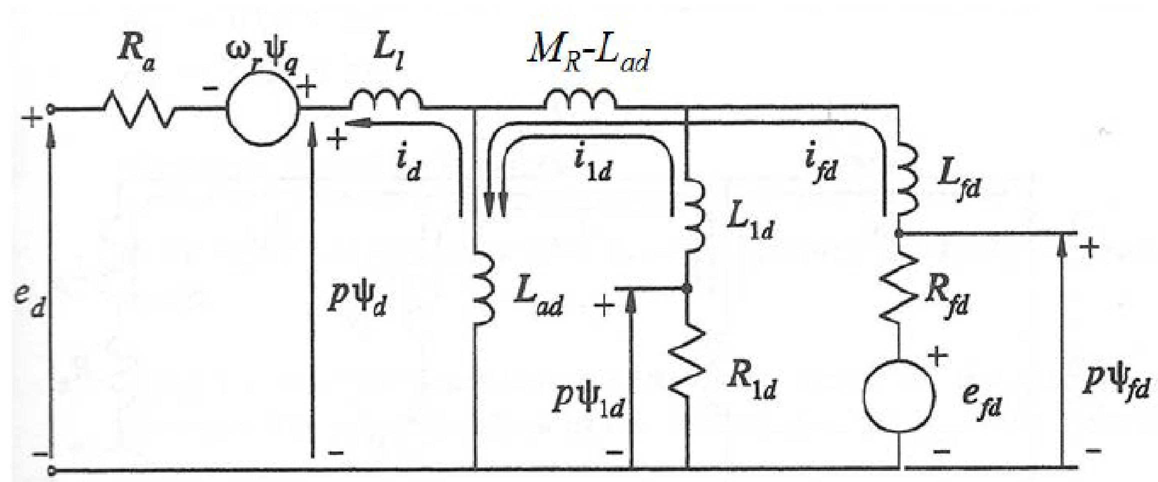
- Generators:
  - Excitation control systems with automatic voltage regulators (AVRs)
- Other control devices
  - Sources or sinks of var, e.g.
    - shunt capacitors,
    - shunt reactors,
    - synchronous condensers,
    - static var compensators (SVC)
  - Line reactance compensators, e.g. series capacitors
  - Regulating transformers, e.g. tap-changing transformers and boosters.

Excitation Systems of Generators

- The basic function of an excitation system is to provide direct current to the synchronous machine field winding.
- In addition, the automatic voltage regulator (AVR) with an excitation system performs control and protective functions essential to the satisfactory performance of the power system by controlling the field voltage and thereby the field current.



Field current

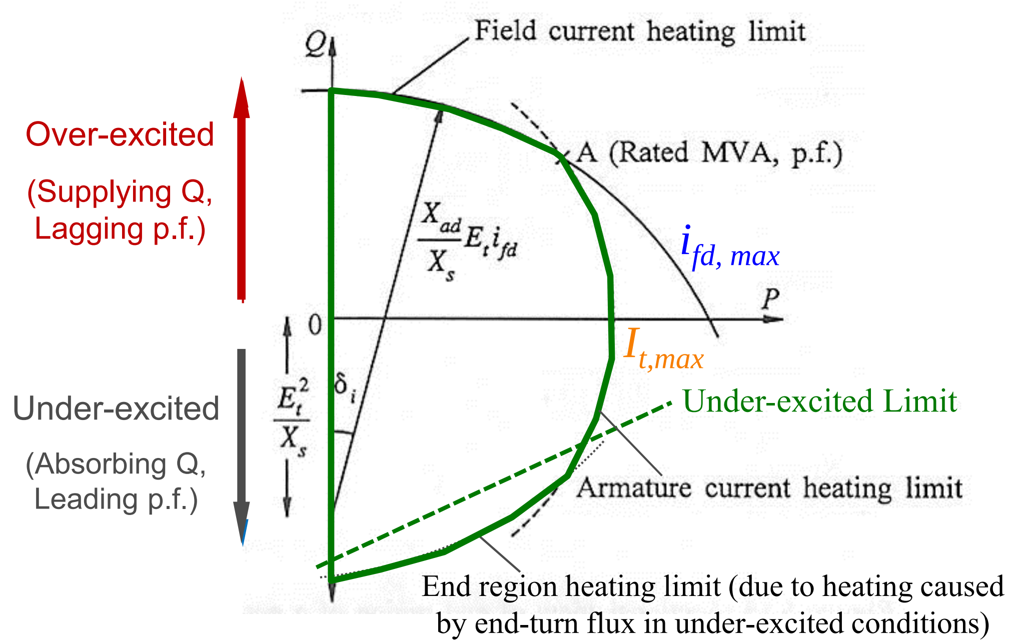


Performance Requirements of Excitation Systems

- On the generator:
  - Under steady-state conditions, the excitation system should supply and automatically adjust the field current of the synchronous generator to maintain the terminal voltage as the output varies continuously within the capacity of the generator.
  - Under disturbances, the excitation system must be able to respond to transient disturbances with field forcing consistent with the generator instantaneous and short-term capacities
  - In either case, heating limits (e.g. due to resistances that carry I_t or i_{fd}) should be concerned.

- On the power system
  - The excitation system should contribute to effective control of voltage and enhancement of system stability under both large and small disturbances.

Reactive Power Capacity of a Generator



D-curve

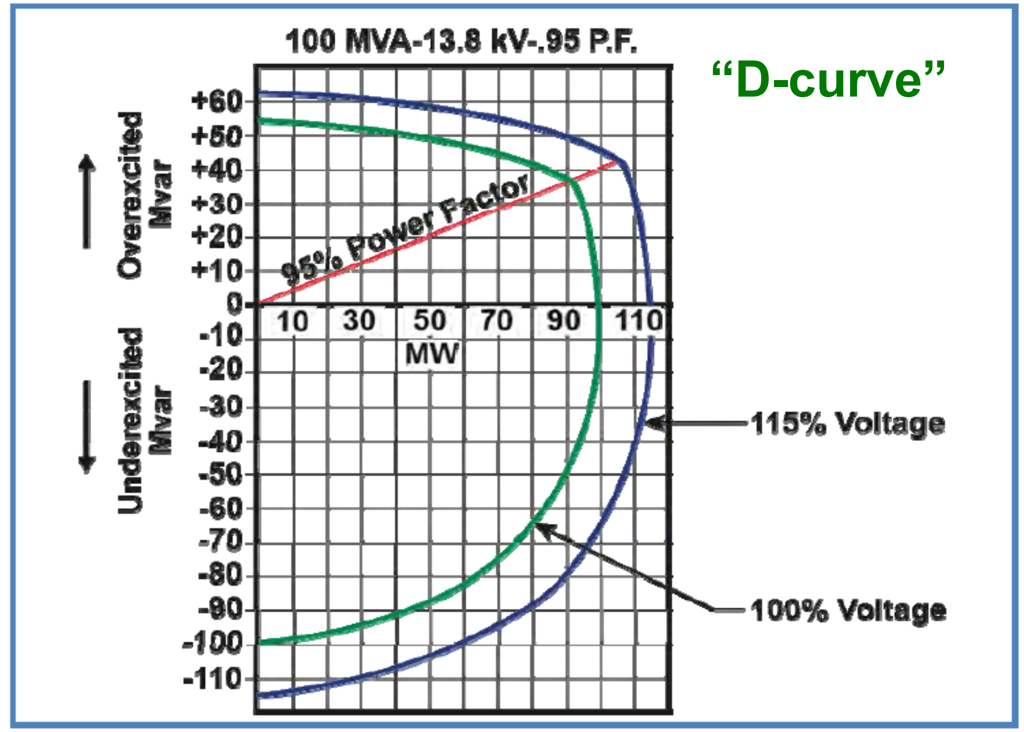
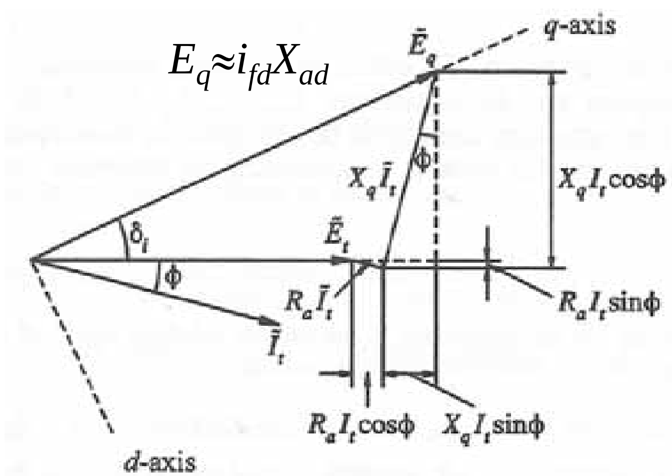
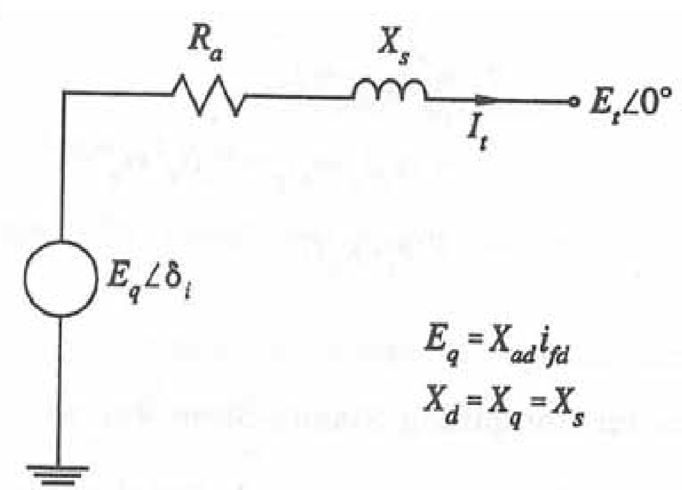


Figure 5-44. Actual Hydro Unit Reactive Capability Curve

$I_t < I_{t,max}$: Armature current heating limit

$i_{fd} < i_{fd,\ max}$: Field current heating limit





$$P = E_t I_t \cos\phi \approx E_t i_{fd} \frac{X_{ad}}{X_s} \sin\delta_i \quad \text{Always} > 0$$

$$Q = E_t I_t \sin\phi \approx E_t i_{fd} \frac{X_{ad}}{X_s} \cos\delta_i - \frac{E_t^2}{X_s} \begin{cases} >0 \text{ (over-excited)} \\ <0 \text{ (under-excited)} \end{cases}$$

Ignore R_a

Elements of an Excitation Control System

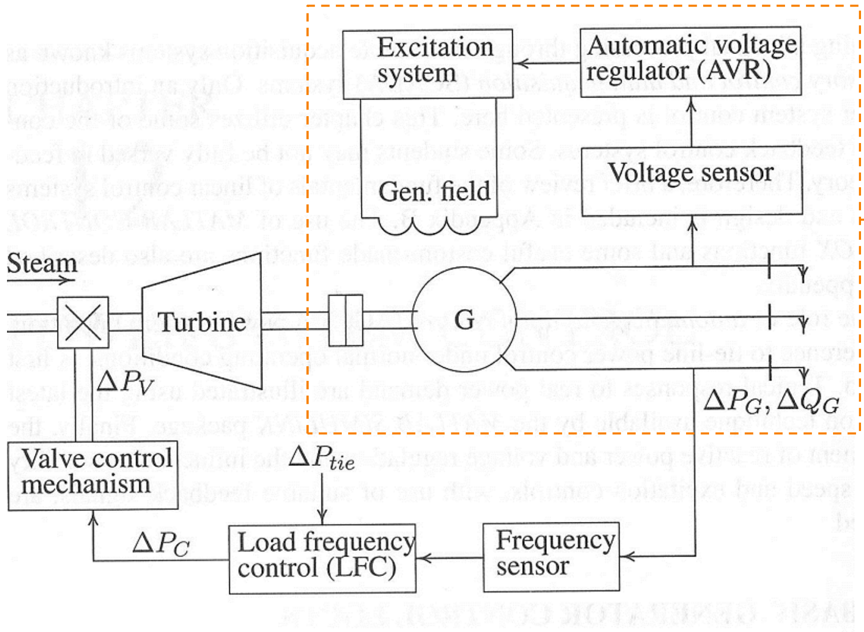


FIGURE 12.1
Schematic diagram of LFC and AVR of a synchronous generator.

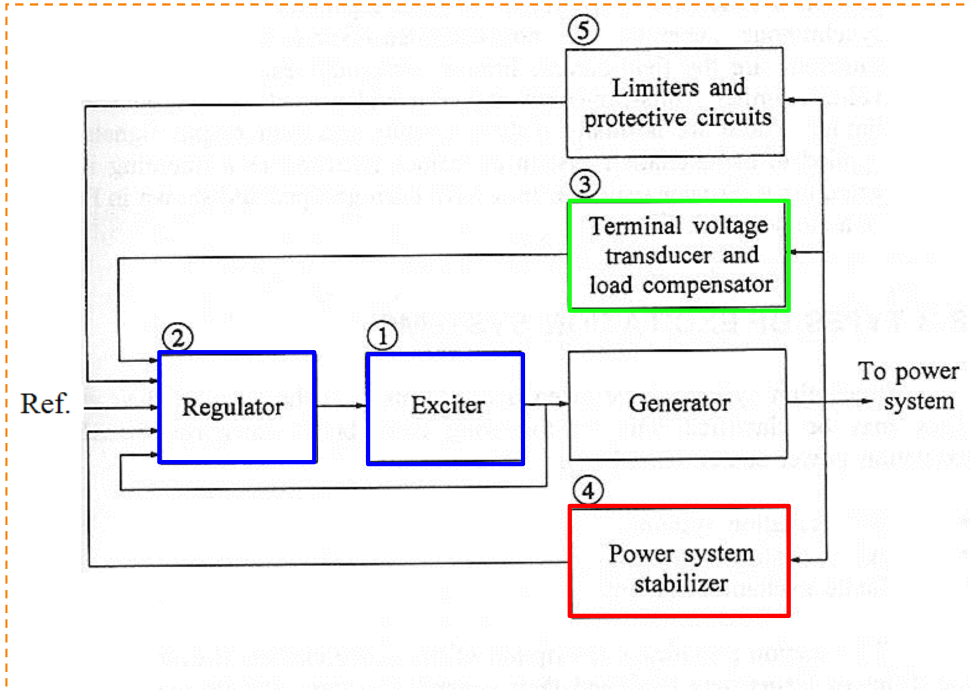
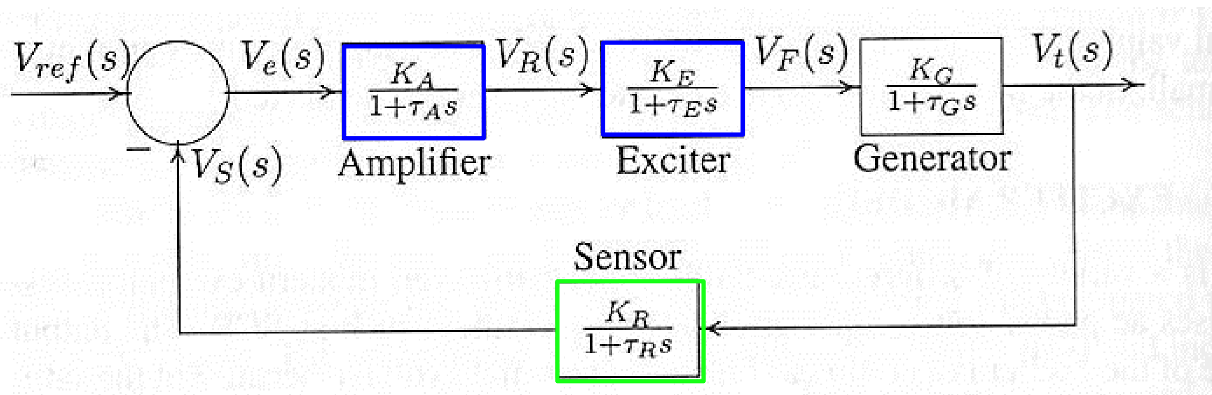


Figure 8.1 Functional block diagram of a synchronous generator excitation control system

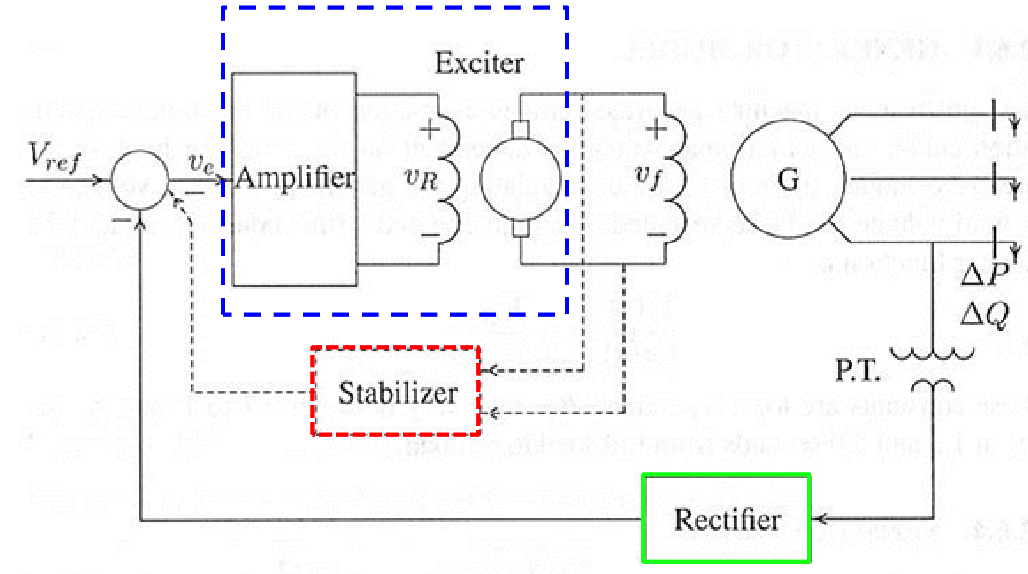
1. Exciter provides dc power to the generator field winding
2. Regulator (AVR) processes and amplifies input control signals for control of the exciter
3. Terminal voltage transducer and load compensator helps maintain the terminal voltage and the voltage at a remote point at desired levels
4. Power system stabilizer (PSS) provides an additional input signal to the regulator to damp system oscillations
5. Limiters and protective circuits ensure that the capability limits of the exciter and generator are not exceeded.

Excitation Control System/AVR Model

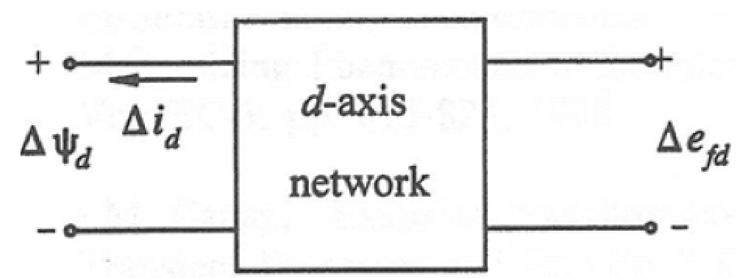
- Simplified linear model (ignoring saturations with the amplifier and exciter and other nonlinearities:



  - Rectifier/Sensor model:
    - τ_R is very small, e.g. 0.01 to 0.06s
  - Amplifier model:
    - K_A=10 to 400, τ_A=0.02 to 0.1s
  - Exciter model:
    - τ_E is very small for modern exciters
  - Generator model:
    - K_G=0.7 to 1.0, τ_G=1.0 to a few seconds from full load to no-load

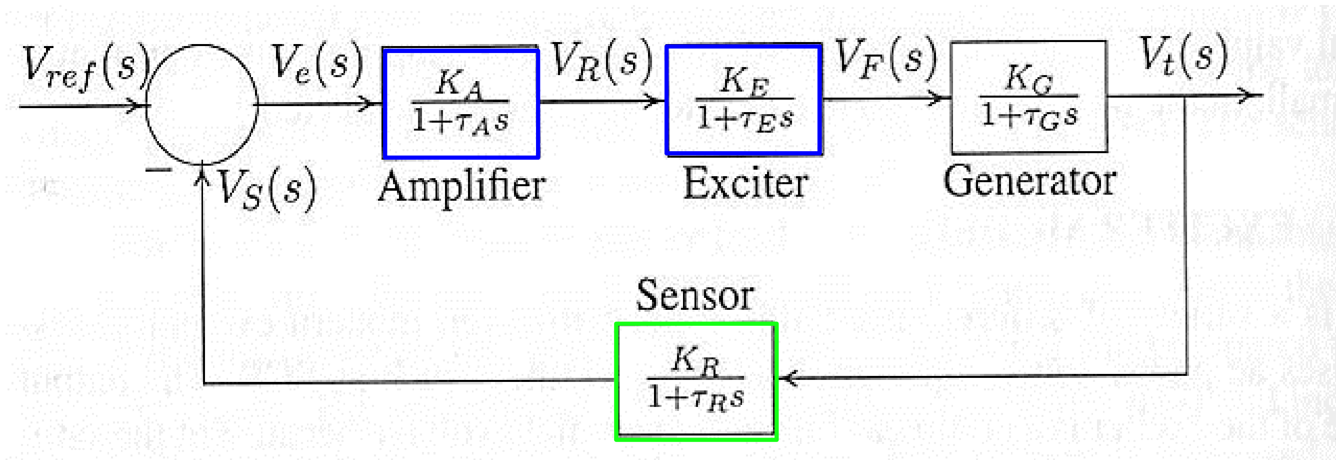


What is τ_G?



$$\frac{\Delta V_t(s)}{\Delta V_F(s)} \sim \frac{s\Delta\psi_d(s)}{\Delta e_{fd}(s)} = G_0 \frac{s(1+sT_{kd})}{(1+sT'_{d0})(1+sT''_{d0})}$$

Simplified Linear Model



- Open-loop transfer functions: $$KG(s)H(s) = \frac{K_A K_E K_G K_R}{(1+\tau_A s)(1+\tau_E s)(1+\tau_G s)(1+\tau_R s)}$$
- Closed-loop transfer functions: $$\frac{V_t(s)}{V_{ref}(s)} = \frac{K_A K_E K_G (1+\tau_R s)}{(1+\tau_A s)(1+\tau_E s)(1+\tau_G s)(1+\tau_R s)+K_A K_E K_G K_R} \qquad (K_E K_G K_R \approx 1)$$
- For a step input $V_{ref}(s) = \frac{1}{s}$, using the final value theorem, the steady-state response is

$$V_{tss} = \lim_{s\to 0} sV_t(s) = \frac{K_A K_E K_G}{1+K_A K_E K_G K_R} \approx \frac{K_A}{1+K_A} \qquad \text{If } K_A \to \infty, \quad V_{tss} = V_{ref}$$

Saadat's Example 12.6

Example 12.6 (chp12ex6), (sim12ex6.mdl)

The AVR system of a generator has the following parameters

	Gain	Time constant
Amplifier	K_A	$\tau_A = 0.1$
Exciter	$K_E = 1$	$\tau_E = 0.4$
Generator	$K_G = 1$	$\tau_G = 1.0$
Sensor	$K_R = 1$	$\tau_R = 0.05$

(a) Use the Routh-Hurwitz array (Appendix B.2.1) to find the range of K_A for control system stability.
(b) Use *MATLAB* **rlocus** function to obtain the root locus plot.
(c) The amplifier gain is set to $K_A = 10$
 (i) Find the steady-state step response.
 (ii) Use *MATLAB* to obtain the step response and the time-domain performance specifications.
(d) Construct the *SIMULINK* block diagram and obtain the step response.

Substituting the system parameters in the AVR block diagram of Figure 12.30 results in the block diagram shown in Figure 12.31.

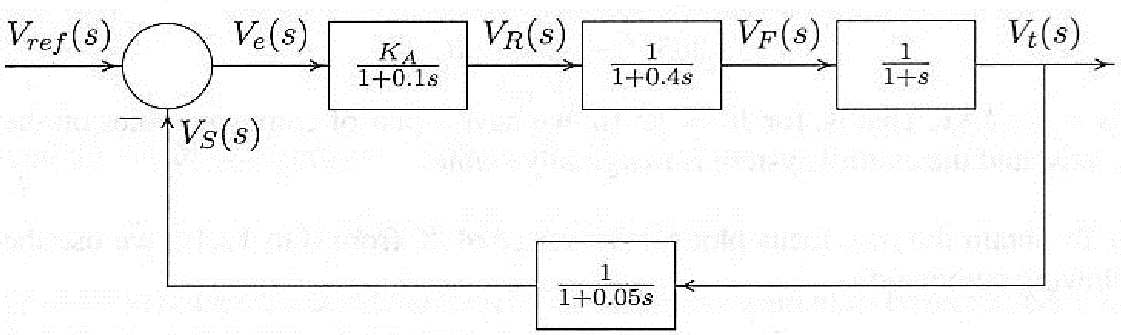


FIGURE 12.31
AVR block diagram for Example 12.6.

The open-loop transfer function of the AVR system shown in Figure 12.31 is

$$KG(s)H(s) = \frac{K_A}{(1+0.1s)(1+0.4s)(1+s)(1+0.05s)}$$
$$= \frac{500K_A}{(s+10)(s+2.5)(s+1)(s+20)}$$
$$= \frac{500K_A}{s^4 + 33.5s^3 + 307.5s^2 + 775s + 500}$$

(a) The characteristic equation is given by

$$1 + KG(s)H(s) = 1 + \frac{500K_A}{s^4 + 33.5s^3 + 307.5s^2 + 775ss + 500} = 0$$

which results in the characteristic polynomial equation

$$s^4 + 33.5s^3 + 307.5s^2 + 775s + 500 + 500K_A = 0$$

The Routh-Hurwitz array for this polynomial is then (see Appendix B.2.1)

s^4	1	307.5	$500 + 500K_A$
s^3	33.5	775	0
s^2	284.365	$500 + 500K_A$	0
s^1	$58.9K_A - 716.1$	0	0
s^0	$500 + 500K_A$		

From the s^1 row we see that, for control system stability, K_A must be less than 12.16, also from the s^0 row, K_A must be greater than -1. Thus, with positive values of K_A, for control system stability, the amplifier gain must be

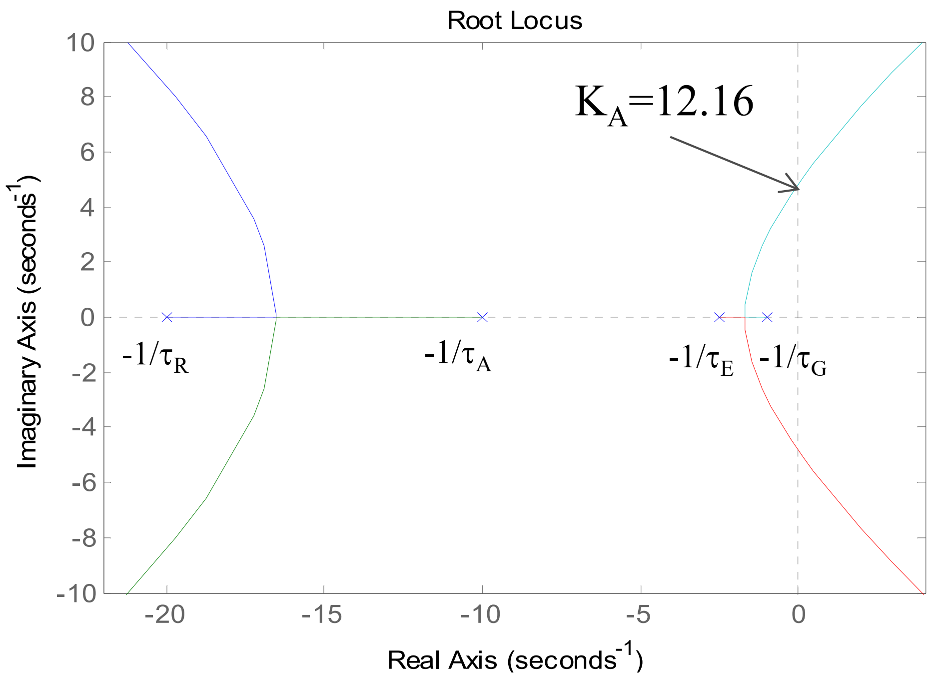
$$K_A < 12.16$$

For $K = 12.16$, the auxiliary equation from the s^2 row is

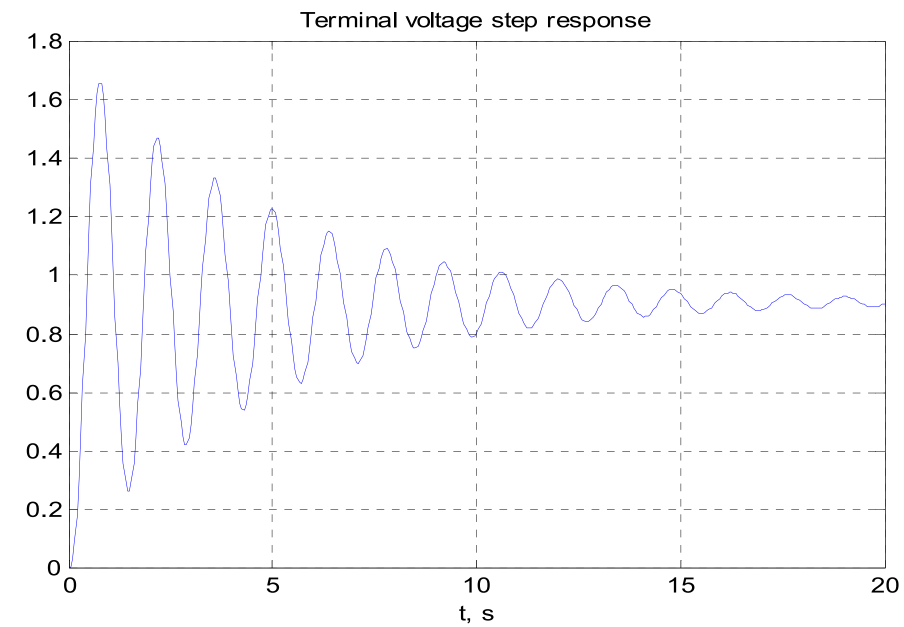
$$284.365s^2 + 6580 = 0$$

or $s = \pm j4.81$. That is, for $K = 12.16$, we have a pair of conjugate poles on the $j\omega$ axis, and the control system is marginally stable.

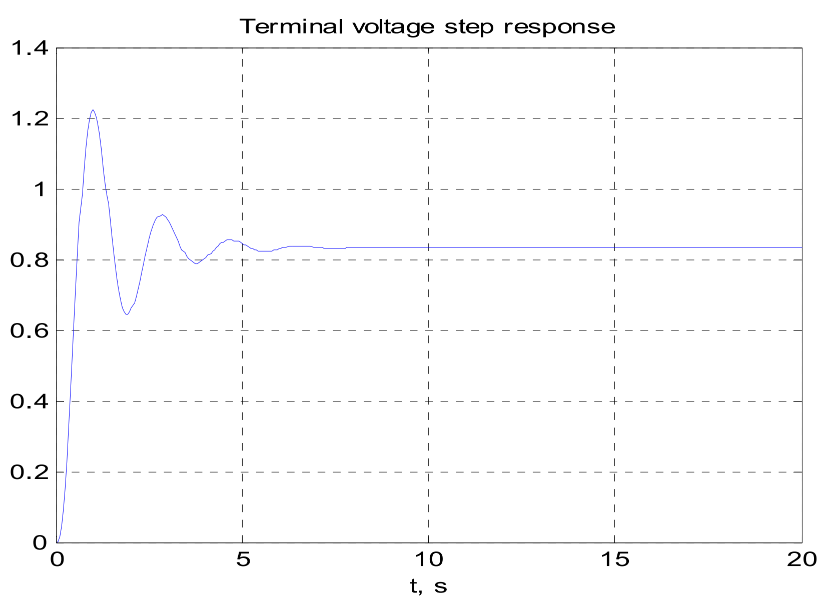
$$KG(s)H(s) = \frac{K_A K_E K_G K_R}{(1+\tau_R s)(1+\tau_A s)(1+\tau_E s)(1+\tau_G s)} = \frac{500K_A}{(s+20)(s+10)(s+2.5)(s+1)}$$



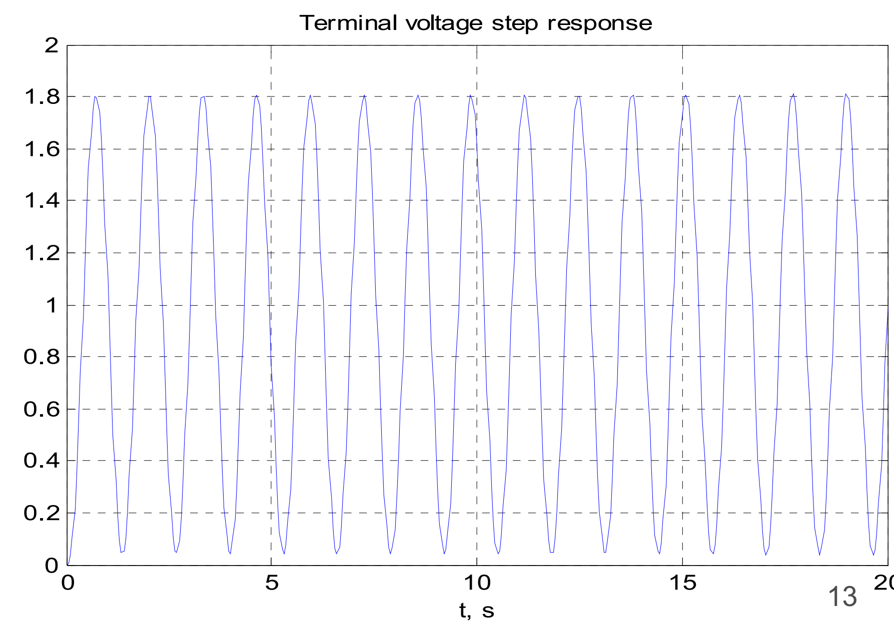
- K_A=10, V_{tss}=0.909V_{ref}



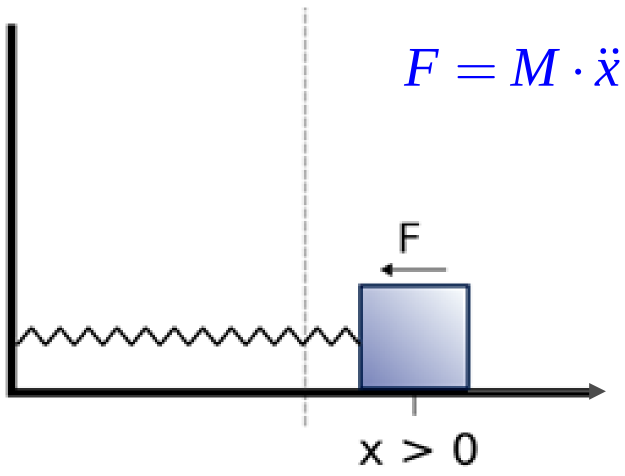
- K_A=5, V_{tss}=0.833V_{ref}



- K_A=12.16, V_{tss}=0.924V_{ref}



Harmonic oscillator



$$F = M \cdot \ddot{x} = -K \cdot x - D \cdot \dot{x}$$

$$s^2 + \frac{D}{M}s + \frac{K}{M} = 0$$

$$\boxed{s^2 + 2\zeta\omega_n s + \omega_n^2 = (s - s_1)(s - s_2) = 0}$$

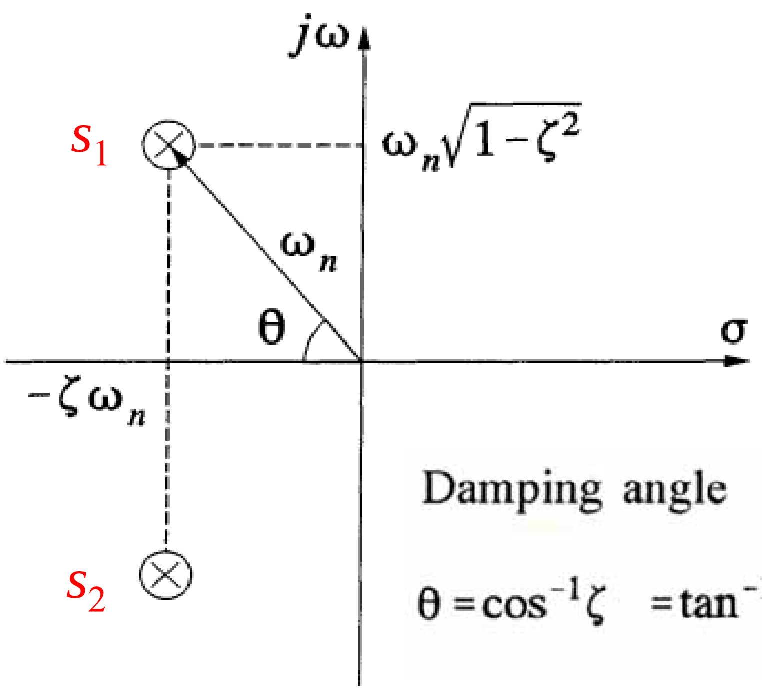
ζ – Damping ratio

ω_n – Natural frequency

- It has two conjugate complex roots and its zero-input response is a damped sinusoidal oscillation:

$$s_1, s_2 = \sigma \pm j\omega = -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2}$$

$$x(t) = Ae^{\sigma t}\sin(\omega t + \varphi)$$
$$= Ae^{-\zeta\omega_n t}\sin(\omega_n t\sqrt{1-\zeta^2} + \varphi)$$



Damping angle

$$\theta = \cos^{-1}\zeta \quad = \tan^{-1}\left(\frac{\sqrt{1-\zeta^2}}{\zeta}\right)$$

The time of decaying to $1/e$=36.8%:

$$\tau = -1/\sigma = \frac{1}{\zeta\omega_n}$$

Excitation System Stabilizers

- Rate feedback

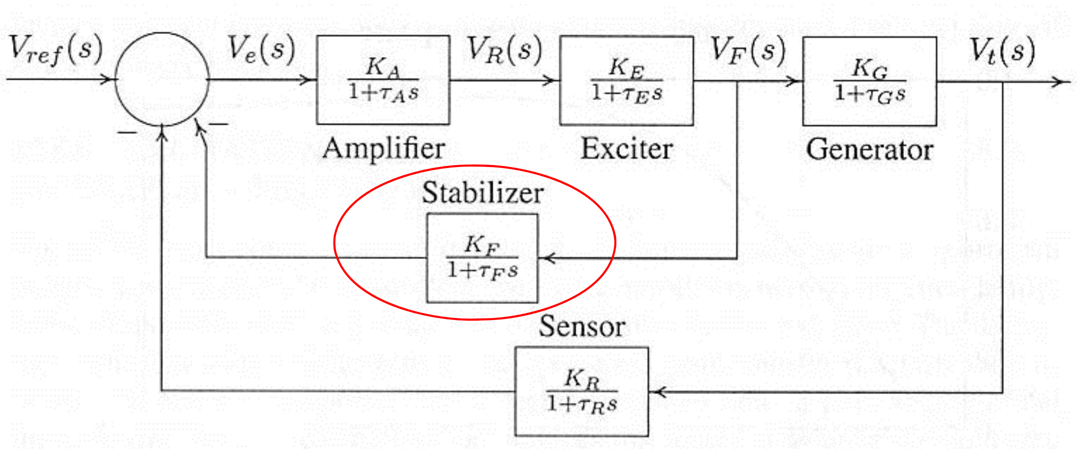


FIGURE 12.35
Block diagram of the compensated AVR system.

- PID control (sim12ex8.mdl)

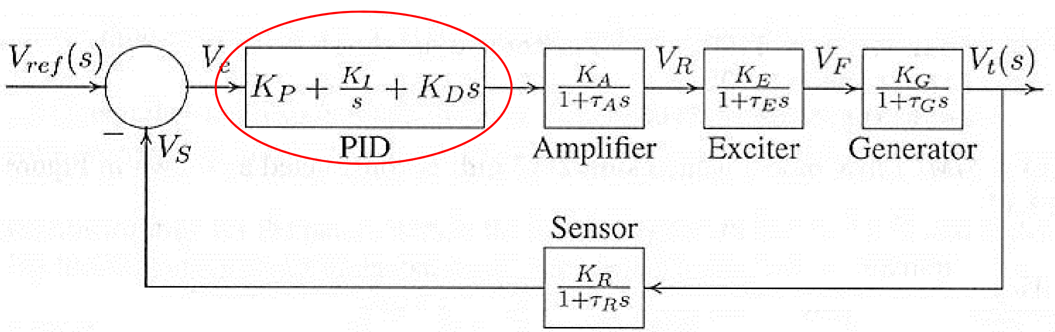
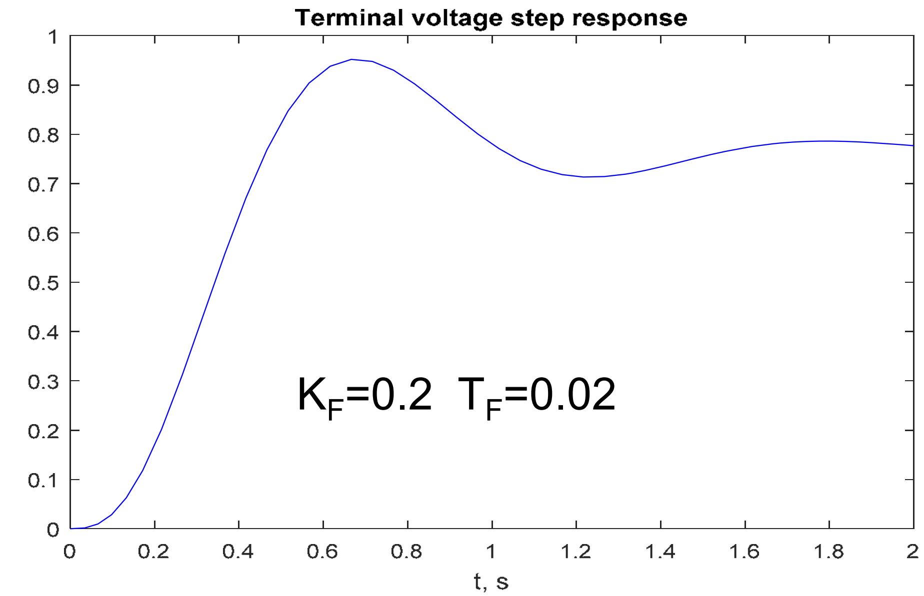
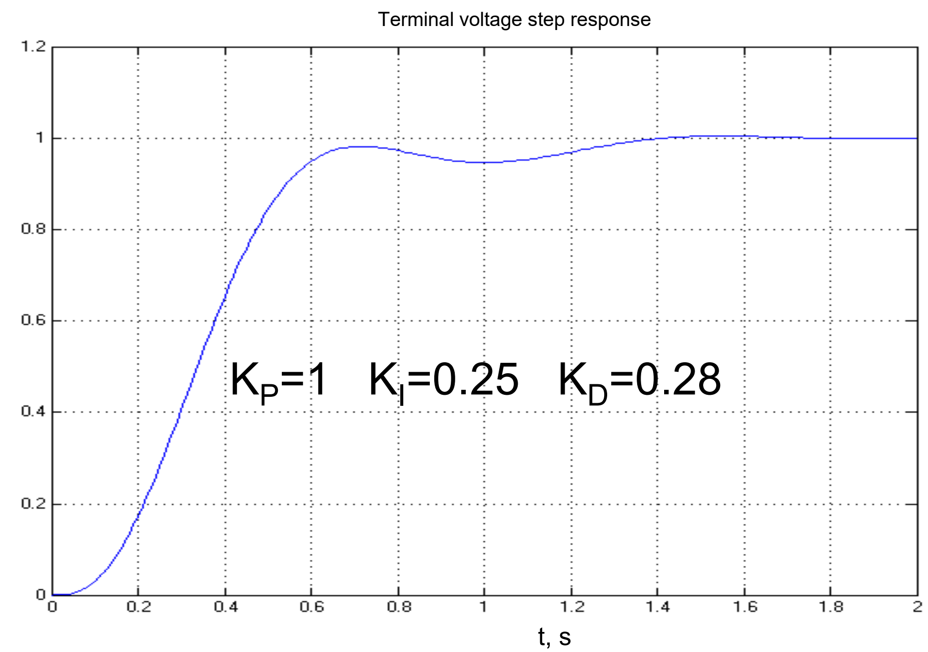


FIGURE 12.38
AVR system with PID controller.

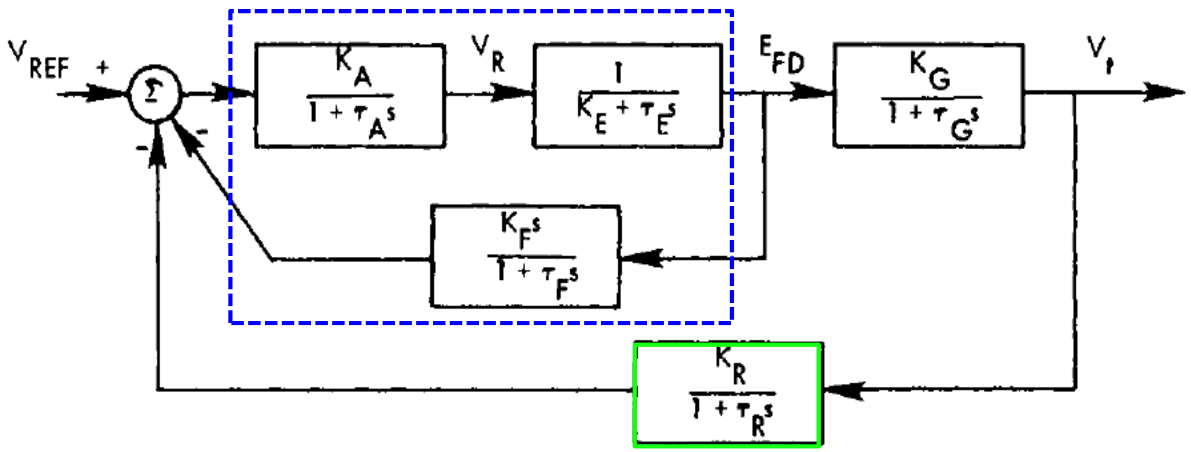
K_A=10





Stabilizer Design for AVR

- See Example 7.8 in Anderson's "Power System Control and Stability" for details on choosing K_F and τ_F



$$KGH = \frac{K_A K_F}{\tau_A \tau_E \tau_F} \frac{s(s + 1/\tau_G)(s + 1/\tau_R) + (K_R K_G \tau_F/\tau_R \tau_G K_F)(s + 1/\tau_F)}{(s + 1/\tau_A)(s + K_E/\tau_E)(s + 1/\tau_G)(s + 1/\tau_F)(s + 1/\tau_R)}$$

Substituting the values $\tau_A = 0.1$, $\tau_E = 0.5$, $\tau_R = 0.05$, $\tau_G = 1.0$ $K_E = -0.05$, $K_G = 1.0$, and $K_R = 1.0$,

$$KGH = 20 K_A \frac{K_F}{\tau_F} \frac{s(s + 1)(s + 20) + 20(\tau_F/K_F)(s + 1/\tau_F)}{(s + 10)(s - 0.1)(s + 1)(s + 1/\tau_F)(s + 20)} \qquad (7.61)$$

The stabilizer adds a new pole at $-1/\tau_F$

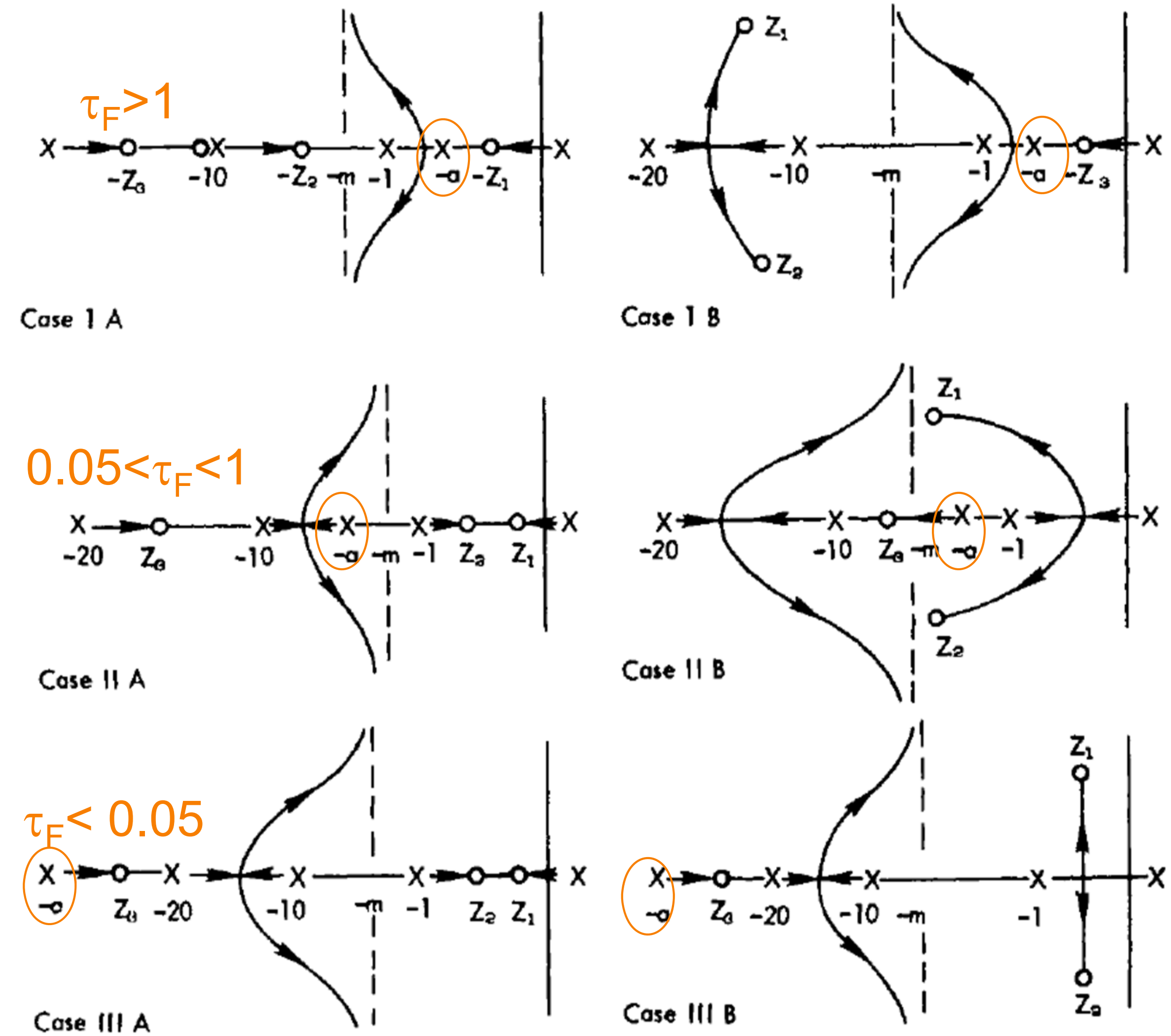


Fig. 7.57 Root loci of $KGH = 20K_A \dfrac{(K_F/\tau_F)[s(s + 1)(s + 20) + 20(s + a)]}{(s + 20)(s + 10)(s + 1)(s - 0.1)(s + a)}$

Non-reciprocal per unit system

- **L_{ad}-base Reciprocal per unit system**: armature terminal voltage E_t is around 1.0 pu under normal operating conditions, but exciter output voltage e_{fd} (i.e. field voltage) in pu is very small (~0.001 pu)
- **Non-reciprocal per unit system**, as an alternative:
  - 1 pu field voltage E_{fd} produces rated armature terminal voltage E_t on the air-gap line
  - 1 pu field current I_{fd} corresponds to rated field current i_{fd}

$$i_{fd} \sim \frac{1}{L_{adu}} \quad \text{pu} \qquad \boxed{I_{fd} = L_{adu} i_{fd}}$$

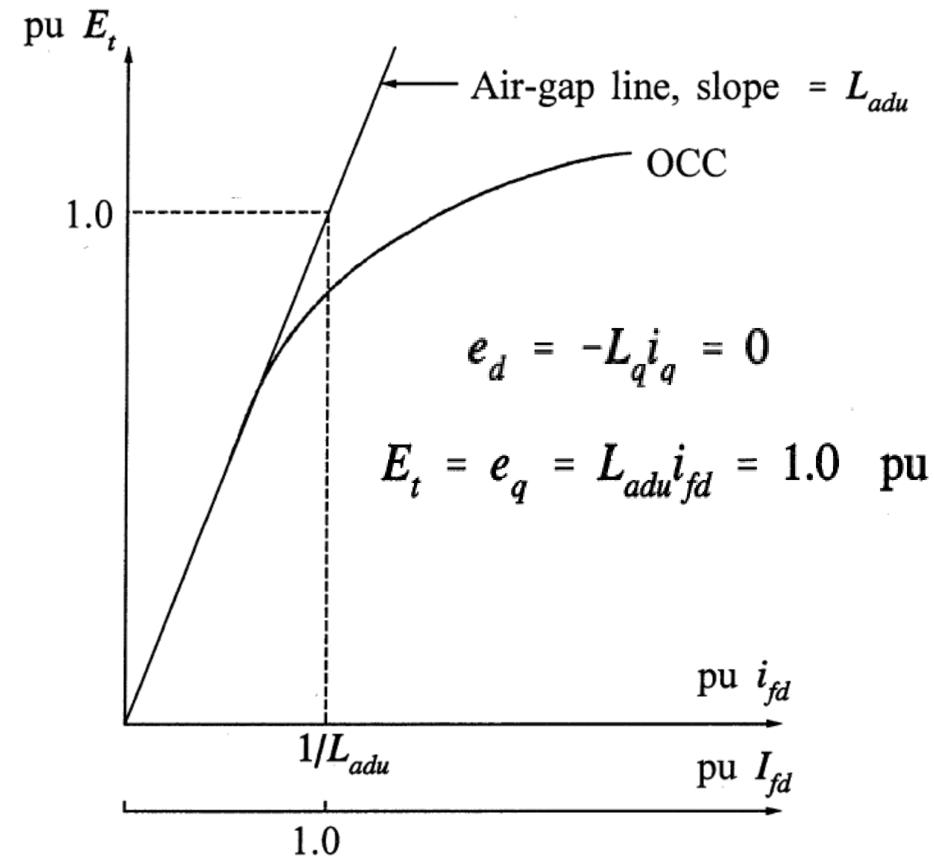
$$e_{fd} = R_{fd} i_{fd} \sim \frac{R_{fd}}{L_{adu}} \quad \text{pu} \qquad \boxed{E_{fd} = \frac{L_{adu}}{R_{fd}} e_{fd}}$$

See **Example 8.1**:

R_{fd}=0.0006 pu, L_{adu}=1.66 pu

i_{fd}=1.565 pu, $\mathbf{e_{fd}}$ **= 0.000939** pu

I_{fd}=2.598 pu, E_{fd}=2.598 pu



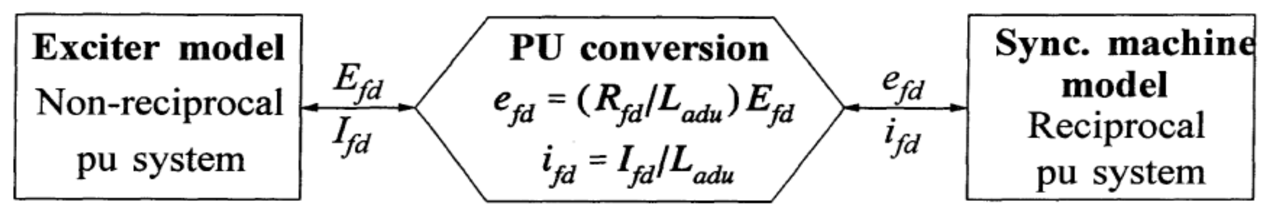
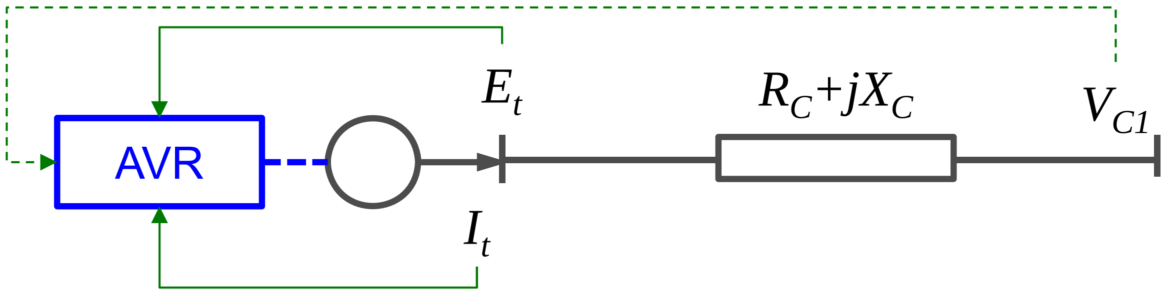


Figure 8.22 Per unit conversion at the interface between excitation system and synchronous machine field circuit

Detailed excitation system model with load compensation



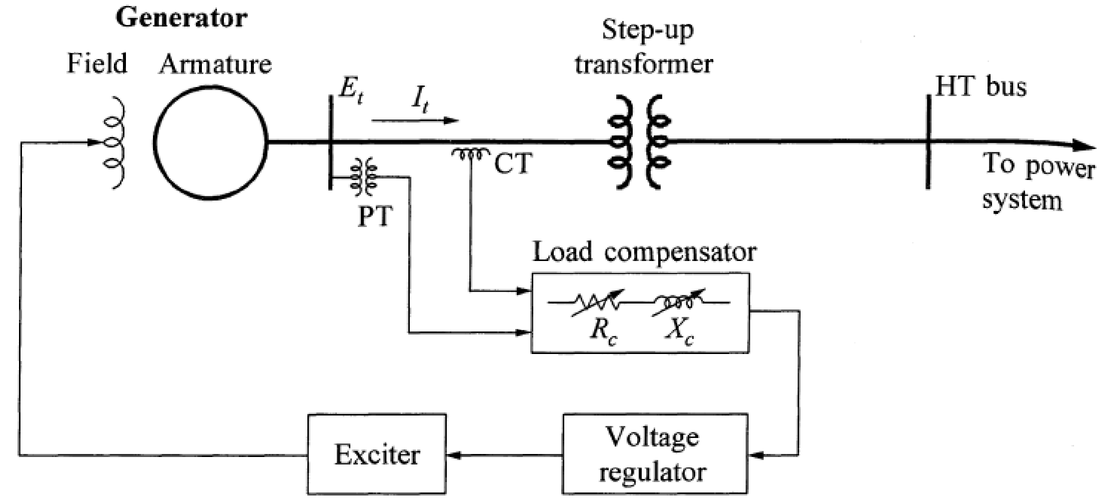


Figure 8.16 Schematic diagram of a load compensator

With positive (or negative) R_C and X_C, the voltage at a point within (or outside) the generator is regulated.

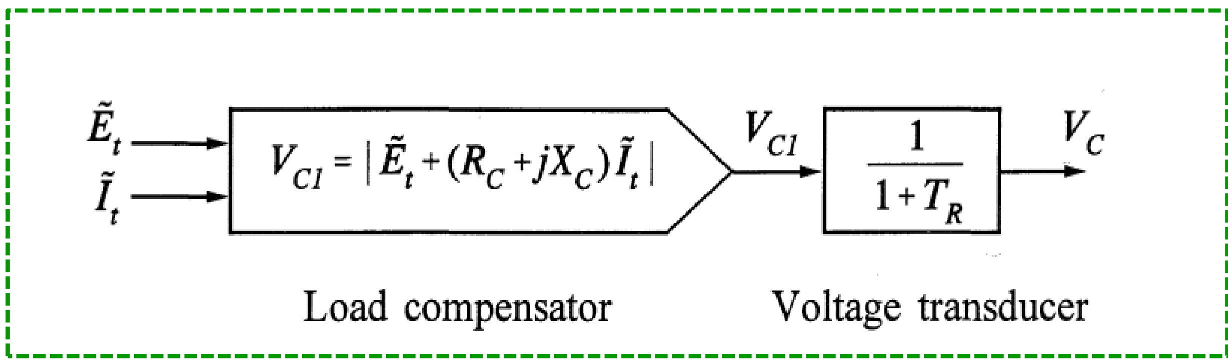


Figure 8.38 Terminal voltage transducer and load compensator model

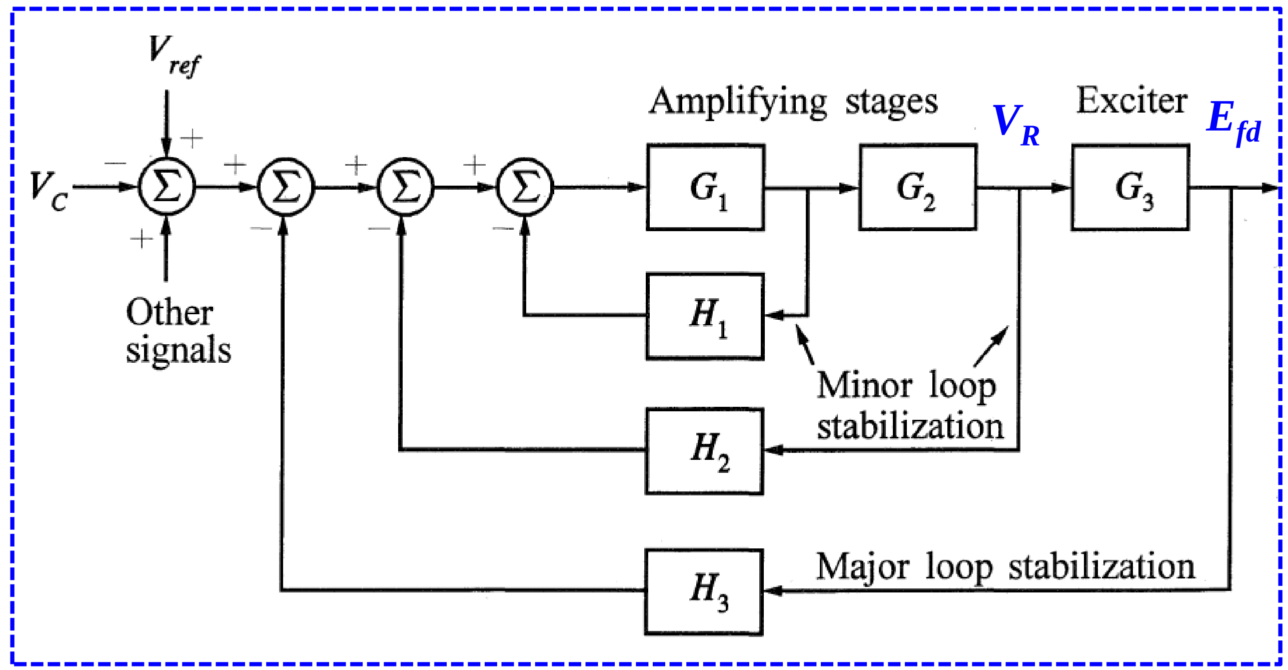
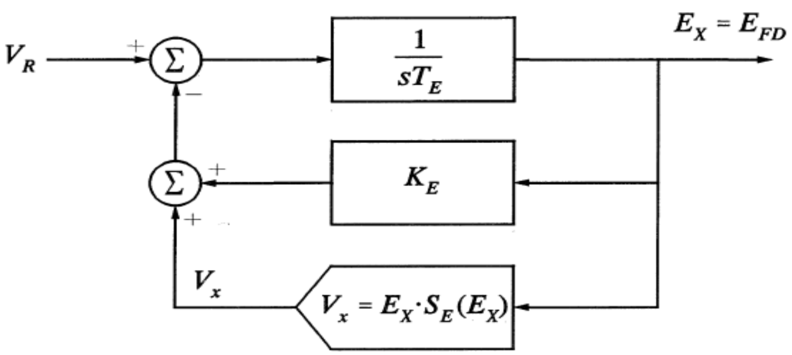


Figure 8.39 Structure of a detailed excitation system model

DC Exciter

$$E_{ef} = R_{ef} I_{ef} + \frac{d(L_{ef} I_{ef})}{dt} = R_{ef}\left(\frac{E_X}{R_g} + E_X S_e(E_X)\right) + \frac{L_{ef}}{R_g}\frac{dE_X}{dt} + L_{ef}\frac{d\Delta I_{ef}}{dt}$$

$$\bar{E}_{ef} \doteq K_E \bar{E}_X + \bar{E}_X S_e(\bar{E}_X) + T_E \frac{d\bar{E}_X}{dt}$$

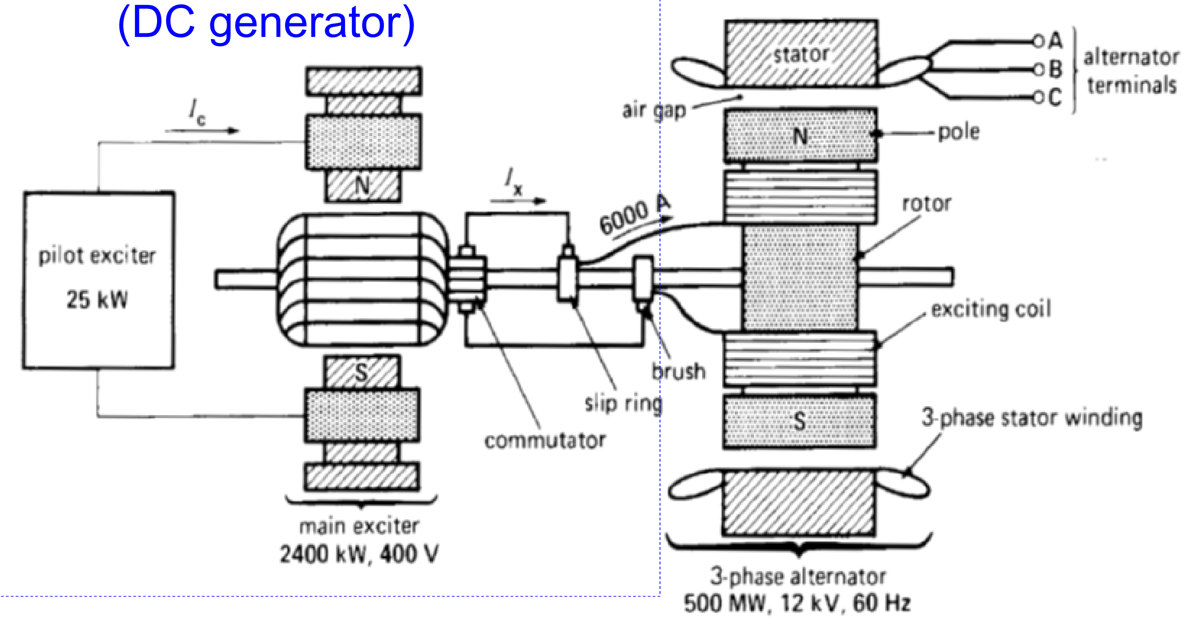


Commonly used representation: $V_X = A_{EX} e^{B_{EX} E_X}$

Figure 8.26 Block diagram of a dc exciter

Separately excited DC Exciter (DC generator)

Main generator



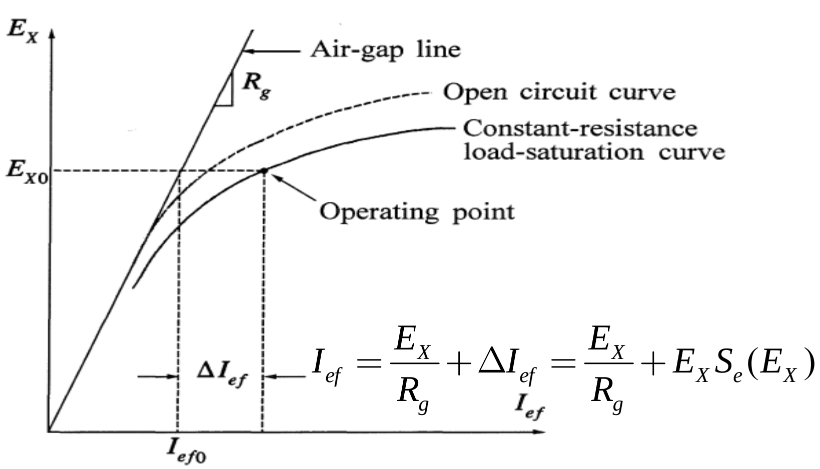


Figure 8.24 Exciter load-saturation curve

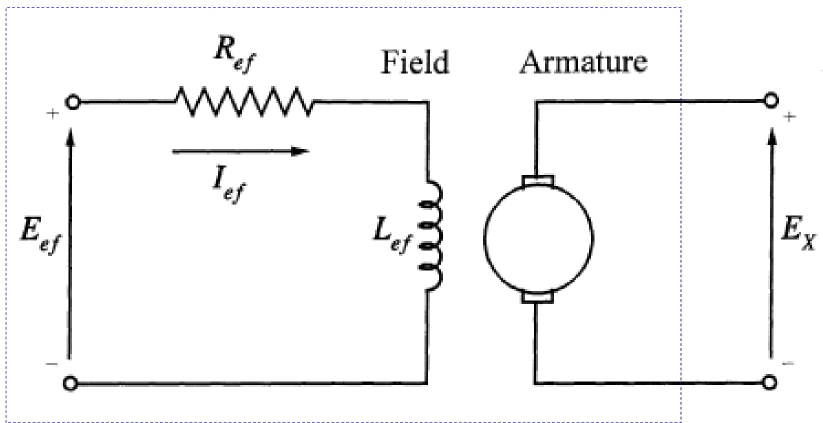


Figure 8.23 Separately excited dc exciter

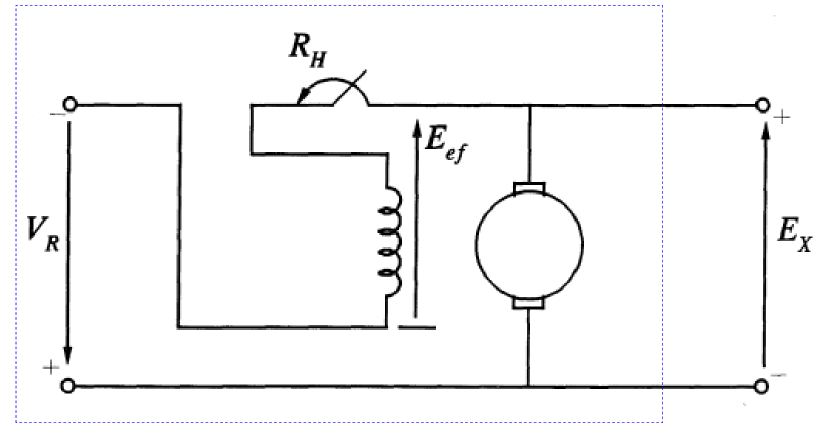


Figure 8.27 Self-excited dc exciter

$V_R = E_{ef}$ $\quad K_E = \frac{R_{ef}}{R_g}$

$V_R = E_{ef} - E_X$ $\quad K_E = \frac{R_{ef}}{R_g} - 1$

IEEE Type DC2A Excitation System Model: ESDC2A

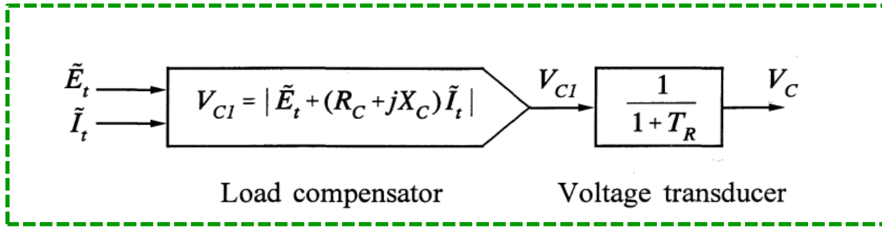


Figure 8.38 Terminal voltage transducer and load compensator model

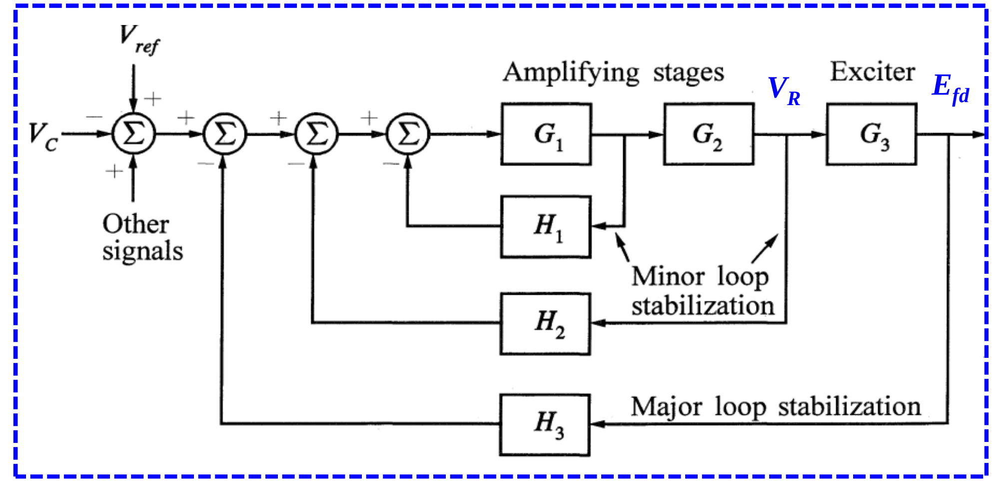
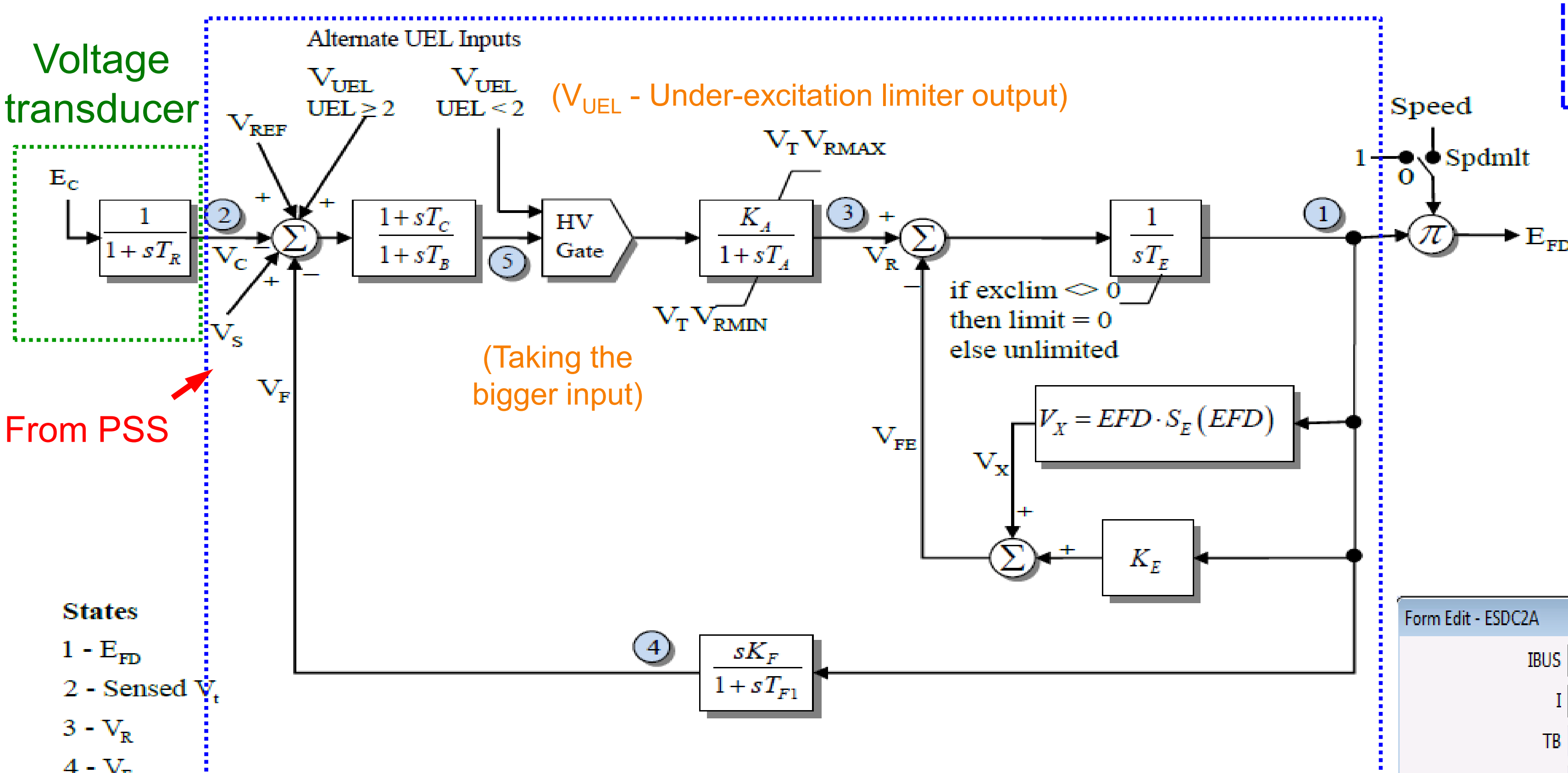


Figure 8.39 Structure of a detailed excitation system model



States

1 - E_{FD}
2 - Sensed V_t
3 - V_R
4 - V_F
5 - Lead-Lag

Model supported by PSSE but always assumes values of spdmlt = 0, UELin = 0, and exclim = 1

Model supported by PSLF

Form Edit - ESDC2A

IBUS	82485	Bus	MAN FG12	Area	703	Zone	786
I	1	TR	0.0200	KA	50.0000	TA	0.0200
TB	0.0500	TC	0.5000	VRMAX	2.9100	VRMIN	-2.7500
KE	0.1670	TE	0.9430	KF	0.0200	TF1	0.1500
E1	2.7429	SE(E1)	0.1987	E2	3.6572	SE(E2)	0.9843
MVA Base	100.0000	Status	0				

AC Exciter (Brushless Excitation)

- Electronic rectifiers replace the commutator, slip-rings and brushes

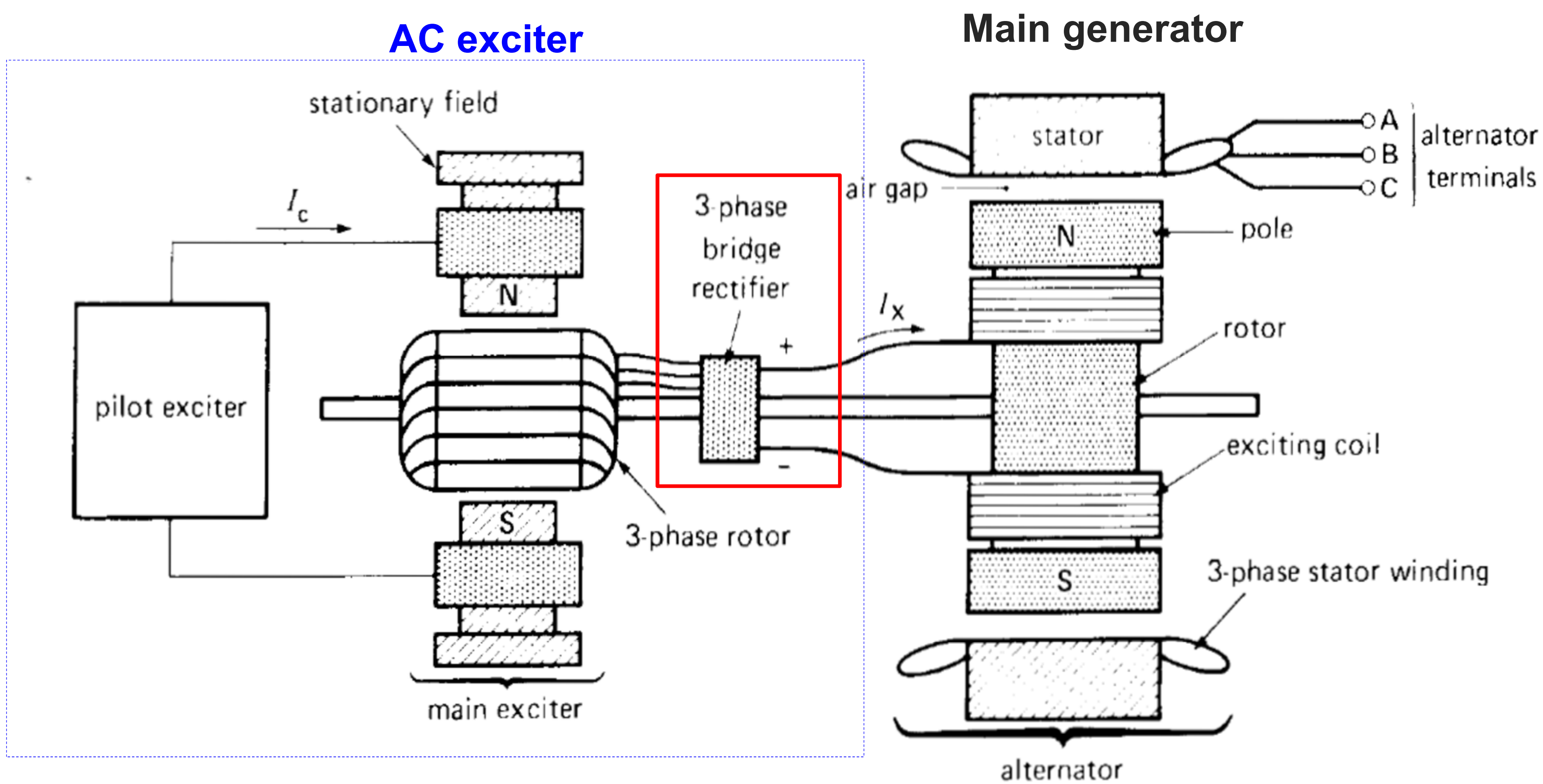
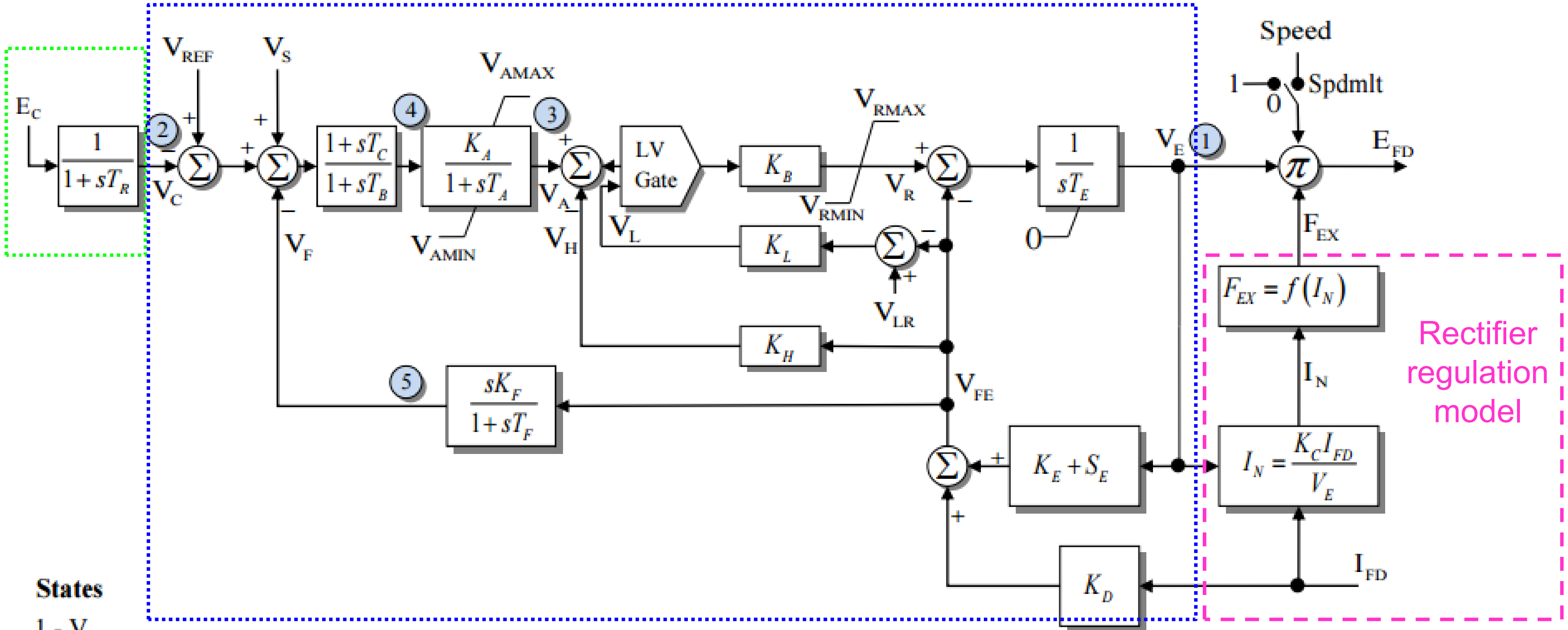


Figure 16.8
Typical brushless exciter system.

IEEE Type AC2A Excitation System Model: ESAC2A



States

1 - V_E

2 - Sensed V_t

3 - V_A

4 - V_{LL}

5 - V_F

Model supported by PSSE but always assumes value of spdmlt = 0

Model supported by PSLF but always assumes value of spdmlt = 1

Form Edit - ESAC2A

IBUS	74870	Bus	B 27721	Area	34	Zone	339
I	4	TR	0.0000	TB	0.0000	TC	0.0000
KA	400.0000	TA	0.0200	VAMAX	115.0000	VAMIN	-115.0000
KB	1.0000	VRMAX	47.9000	VRMIN	-38.3000	TE	0.8000
VFEMAX	18.5000	KH	0.0000	KF	0.0300	TF	1.0000
KC	0.6400	KD	0.3500	KE	1.0000	E1	4.5300
SE(E1)	0.0700	E2	6.0400	SE(E2)	0.2200	MVA Base	100.0000
Status	0						

Influence of excitation control on angular stability

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = T_m - T_e(\delta, \omega_r) = \Delta T_m - \Delta T_e$$

$$\Delta T_e = \Delta T_S + \Delta T_D \approx K_S \Delta\delta + K_D \Delta\omega_r$$

- $K_S = K_{S(\Delta\psi_{fd})} + K_{S(\text{gen \& network})}$

  $K_D = K_{D(\Delta\psi_{fd})} + K_{D(\text{gen \& network})}$

  Usually, $K_{S\,(\text{gen \& network})} > 0$, $K_{D\,(\text{gen \& network})} > 0$

- Constant field voltage E_{fd} (K_A=0):

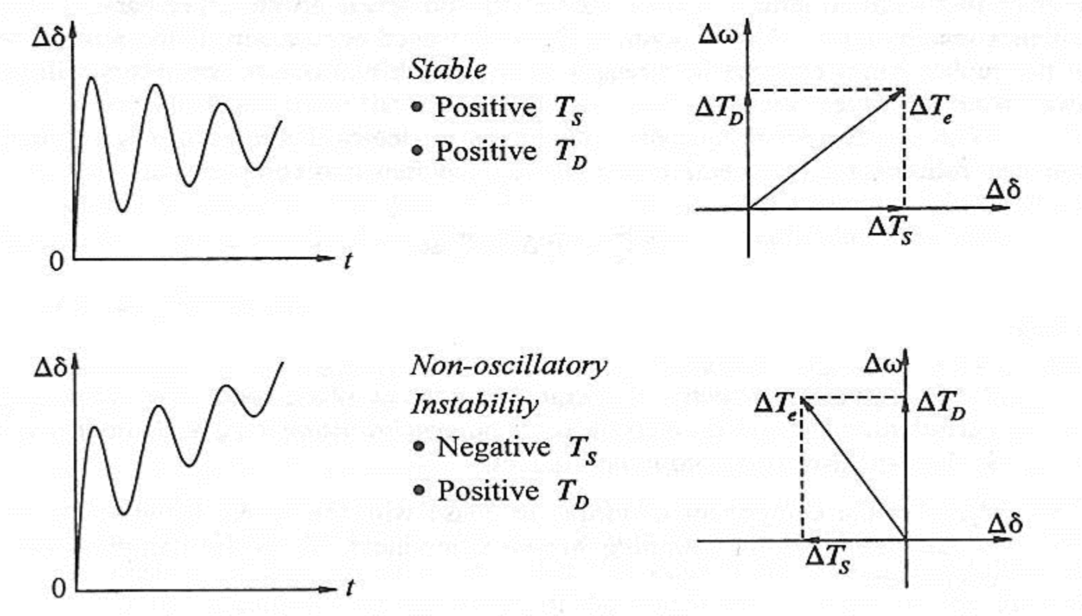
  $K_D > 0$

  $K_S = K_{S(\text{gen \& network})} + K_{S\,(\Delta\psi_{fd})} > 0$ or < 0

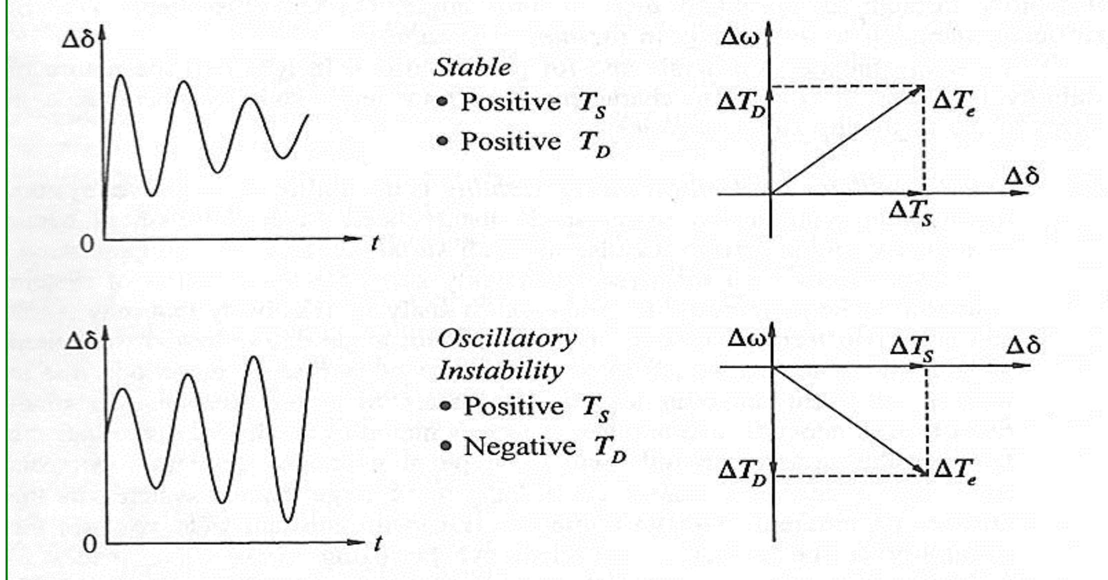
- With excitation control (large K_A)

  $K_S > 0$

  $K_D = K_{D(\text{gen \& network})} + K_{D\,(\Delta\psi_{fd})} > 0$ or < 0



(a) With constant field voltage



(b) With excitation control

Figure 2.2 Nature of small-disturbance response

Find $K_{D\,(\Delta\psi_{fd})}$

$$\Delta T_e = \Delta T_e|_{\Delta\psi_{fd}} + \Delta T_e|_{\text{gen \& network}}$$

$$\Delta T_e|_{\Delta\psi_{fd}} = K_2\Delta\psi_{fd} = \frac{-K_2K_3[K_4(1+sT_R)+K_5G_{ex}(s)]}{s^2T_3T_R+s(T_3+T_R)+1+K_3K_6G_{ex}(s)}\Delta\delta$$

- The effect of the AVR on damping and synchronizing torque components is primarily influenced by K_5 and $G_{ex}(s)\approx K_A$. Usually, $\mathbf{K_5<0}$ can introduce a positive synchronizing torque.
- Steady-state ($s\to 0$):

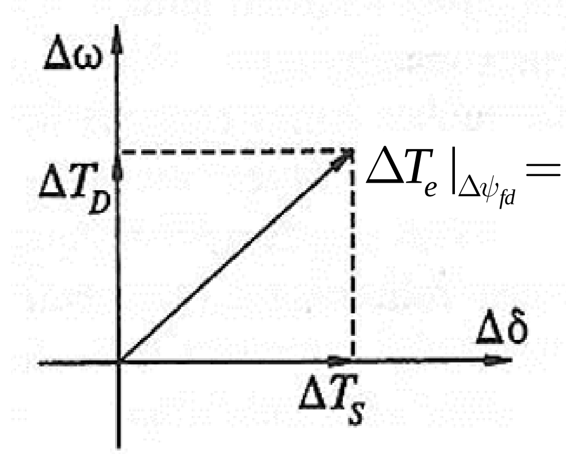
$$\Delta T_e|_{\Delta\psi_{fd}} = \frac{-K_2K_3(K_4+K_5K_A)}{1+K_3K_6K_A}\Delta\delta \;=\; K_R\Delta\delta + K_I\, j\Delta\delta$$

- For a given oscillation frequency $s=j\omega_{osc}$:

$$j\Delta\delta = \frac{j\omega_{osc}\Delta\delta}{\omega_{osc}} = \frac{s\Delta\delta}{\omega_{osc}} = \frac{\Delta\dot{\delta}}{\omega_{osc}} = \frac{\omega_0}{\omega_{osc}}\Delta\omega_r$$

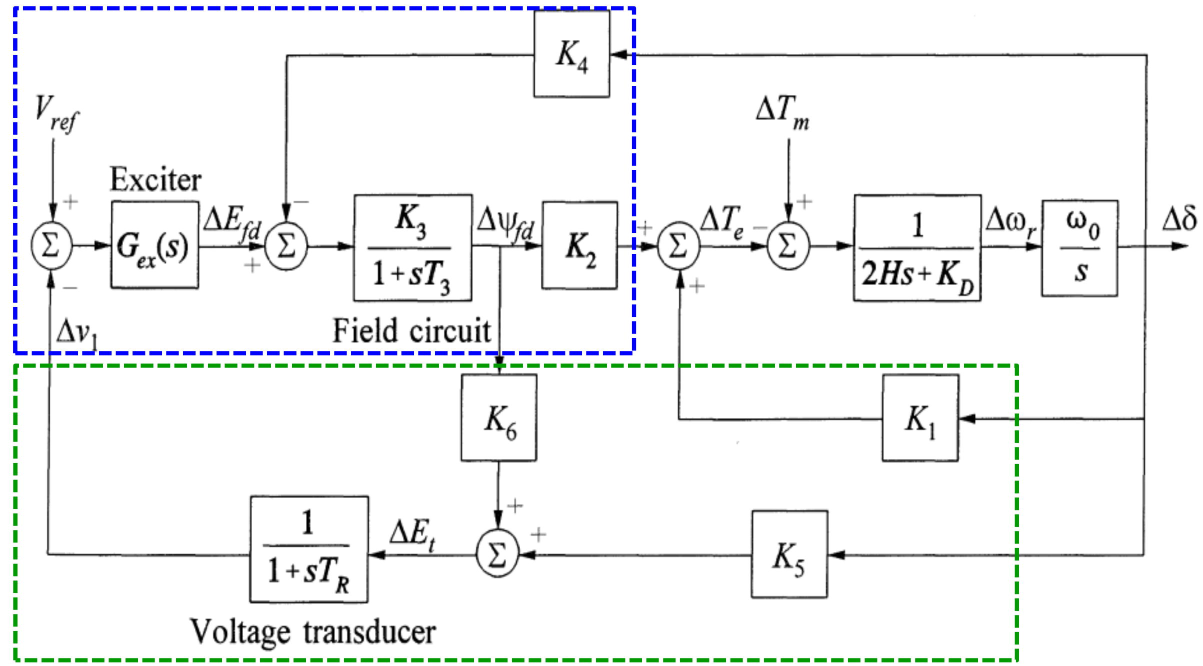
$$\Delta T_e|_{\Delta\psi_{fd}} = K_R\Delta\delta + \frac{K_I\omega_0}{\omega_{osc}}\Delta\omega_r = K_{S(\Delta\psi_{fd})}\Delta\delta + K_{D(\Delta\psi_{fd})}\Delta\omega_r$$

Synchronizing and damping torque coefficients due to $\Delta\psi_{fd}$ at oscillation frequency ω_{osc}



$$\Delta T_e|_{\Delta\psi_{fd}} = K_{S(\Delta\psi_{fd})}\Delta\delta + K_{D(\Delta\psi_{fd})}\Delta\omega_r$$

$$\Delta\psi_{fd} = \frac{K_3}{1+sT_3}\left[-K_4\Delta\delta - \frac{G_{ex}(s)}{1+sT_R}(K_5\Delta\delta + K_6\Delta\psi_{fd})\right]$$



(See Kundur's Ch. 12.4 "Effects of Excitation System" for more details)

Example on effects of different AVR settings

$K_1 = 1.591$ $K_2 = 1.5$ $K_3 = 0.333$ $K_4 = 1.8$ $T_3 = 1.91$
$\underline{K_5 = -0.12}$ $K_6 = 0.3$ $T_R = 0.02$ $\underline{G_{ex}(s) = K_A}$
$H = 3.0$ $K_D = 0.0$

- Steady-state synchronizing torque coefficient:

$$\Delta T_e\big|_{\Delta\psi_{fd}} = \frac{-K_2K_3(K_4+K_5K_A)}{1+K_3K_6K_A}\Delta\delta = \frac{0.06K_A-0.9}{1+0.1K_A}\Delta\delta$$

The effect of the AVR is to increase the synchronizing torque component at the steady state

- Damping and synchronizing torque components at rotor oscillation frequency 10 rad/s (f_{osc}=1.59Hz, s=jω_{osc}=j10)

K_A	$K_{S(\Delta\psi_{fd})}$	$K_S = K_1 + K_{S(\Delta\psi_{fd})}$	$K_{D(\Delta\psi_{fd})}$
0.0	−0.0025	1.5885	1.772
10.0	−0.0079	1.5831	0.614
15.0	−0.0093	1.5817	0.024
25.0	−0.0098	1.5812	−1.166
50.0	0.0029	1.5939	−4.090
100.0	0.0782	1.6692	−8.866
200.0	0.2804	1.8714	−12.272
400.0	0.4874	2.0784	−9.722
1000.0	0.5847	2.1757	−4.448
Infinity	0.6000	2.1910	0.000

Power System Stabilizer (PSS)

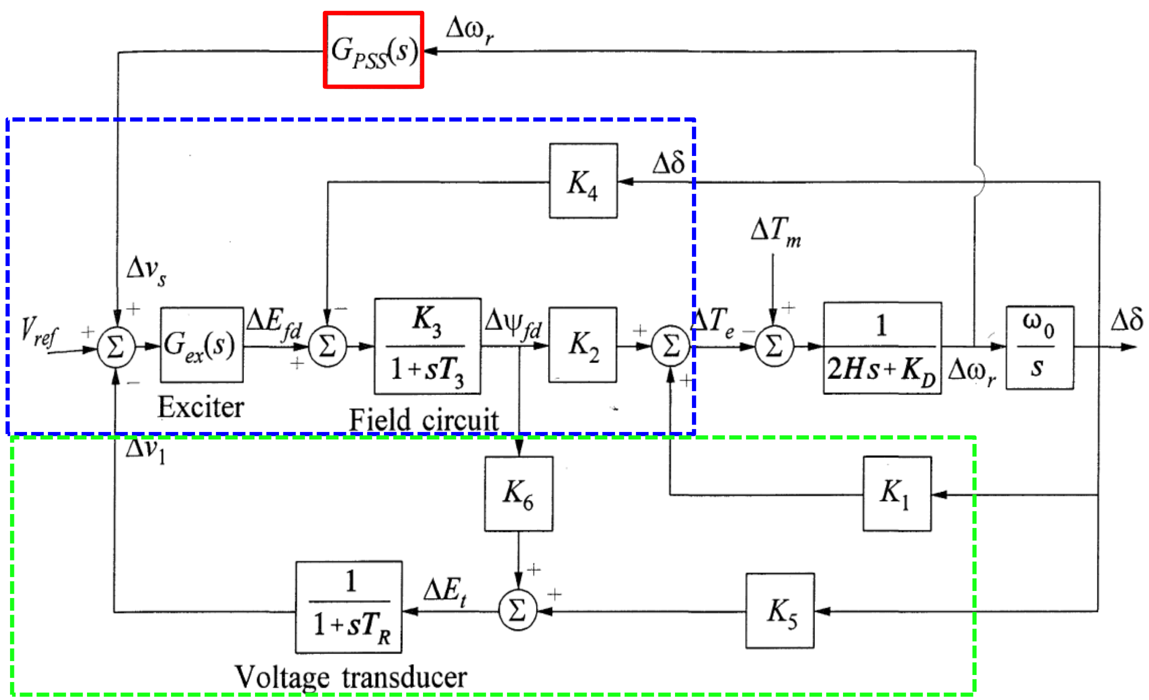


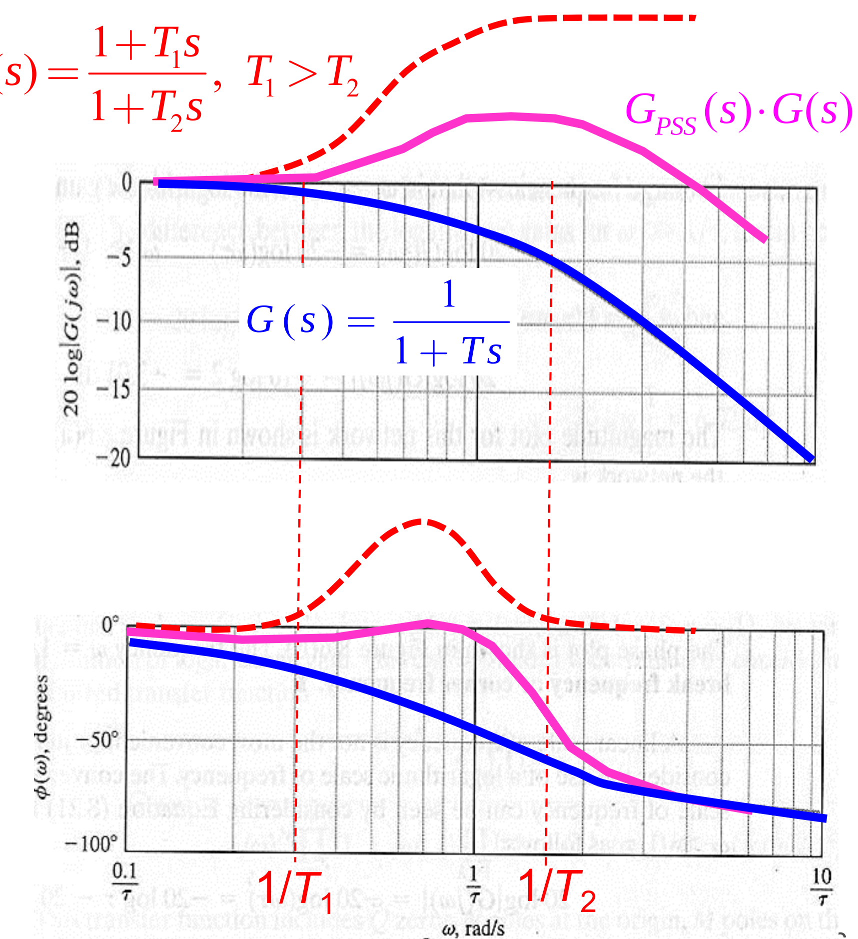
Figure 12.13 Block diagram representation with AVR and PSS

$$\Delta T_e|_{PSS} = G_{PSS}(j\omega_{osc})G_{\Delta v_S \to \Delta T_e}(j\omega_{osc})\Delta\omega_r \doteq \frac{K}{1+T_\Sigma j\omega_{osc}}\Delta\omega_r$$

$$= \frac{K(1-jT_\Sigma\omega_{osc})}{1+(T_\Sigma\omega_{osc})^2}\Delta\omega_r$$

$$= \underbrace{\frac{K}{1+(T_\Sigma\omega_{osc})^2}}_{>0}\Delta\omega_r + \underbrace{\frac{KT_\Sigma\omega_{osc}}{1+(T_\Sigma\omega_{osc})^2}\cdot\frac{\omega_{osc}}{\omega_0}}_{\text{small}}\cdot\Delta\delta$$

$$G_{PSS}(s) = \frac{1+T_1 s}{1+T_2 s}, \quad T_1 > T_2$$



- The basic function is to add damping to generator oscillation by controlling its exciter using non-voltage auxiliary signal(s):
  - If $G_{PSS}(s)$ is a pure gain (i.e. a direct feedback of $\Delta\omega_r$), then the transfer function of $\Delta T_e/\Delta v_s$ has to be a pure gain to create a positive damping torque (i.e. a torque component in phase with $\Delta\omega_r$).
  - However, $\Delta T_e/\Delta v_s$ for the actual generator and exciter exhibits a frequency dependent gain and phase-lag characteristics, so $G_{PSS}(s)$ needs to provide phase-lead compensation to create a torque in phase with $\Delta\omega_r$.

PSS Model

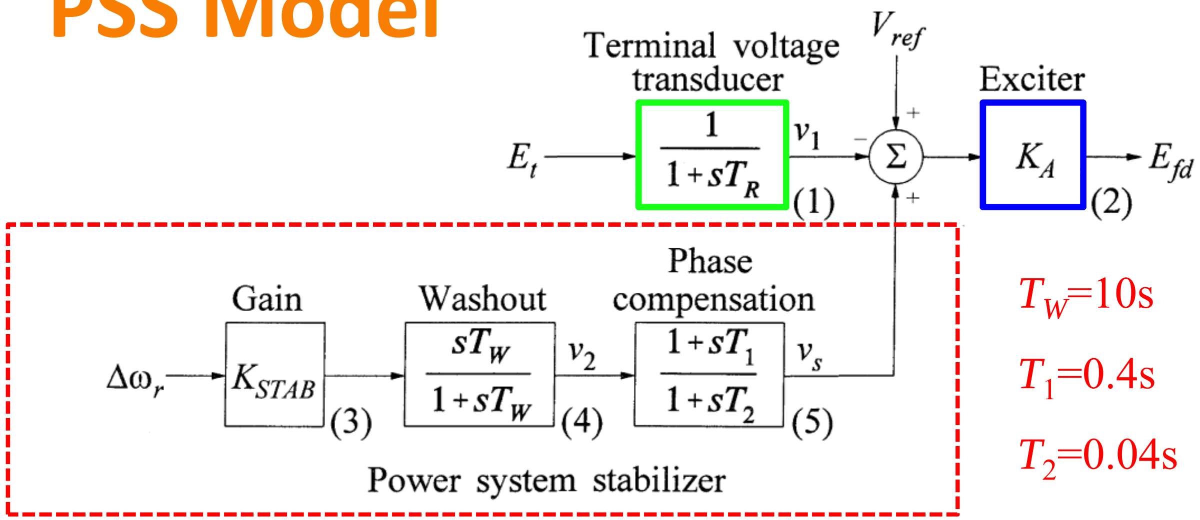
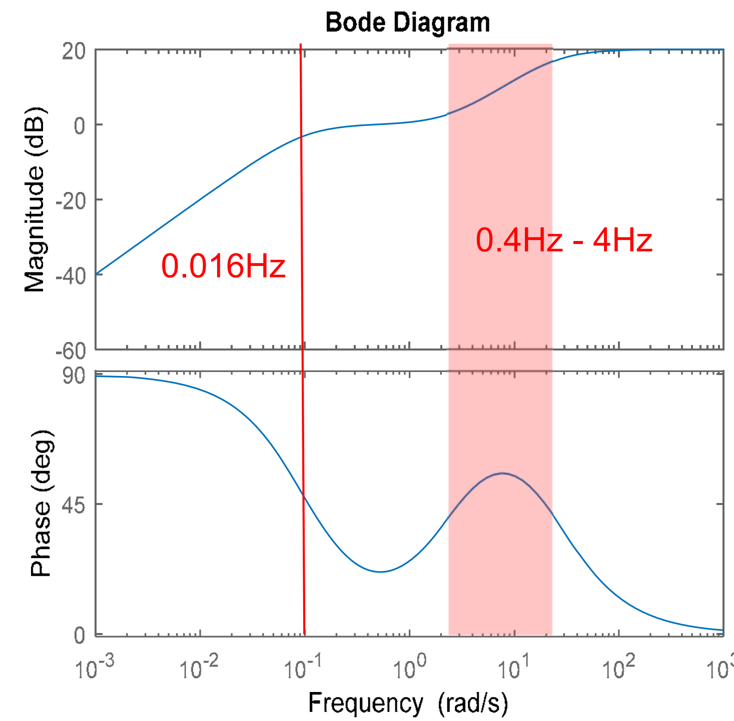


Figure 12.14 Thyristor excitation system with AVR and PSS

T_W=10s (ω_W=0.1rad/s → 0.016Hz)

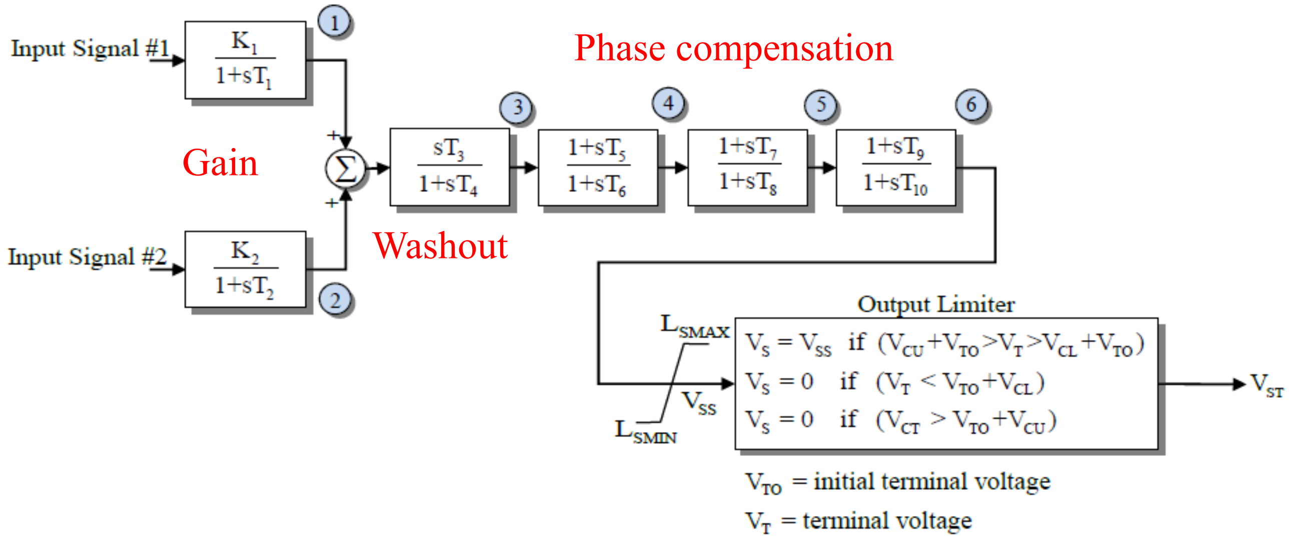
T_1=0.4s (ω_{osc1}=2.5rad/s → 0.4Hz)

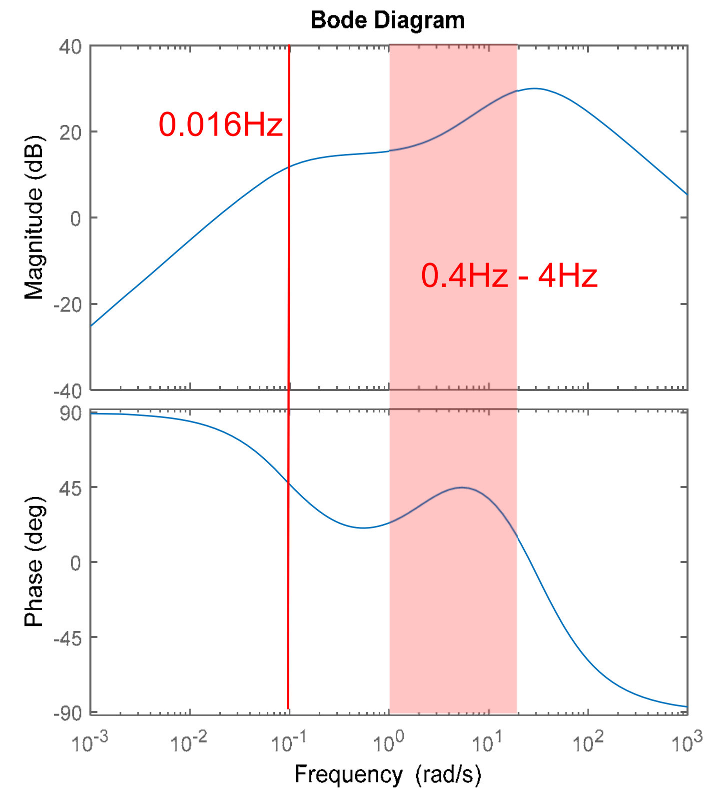
T_2=0.04s (ω_{osc2}=25rad/s → 4.0Hz)



- Stabilizer gain K_{STAB}
  - determines the amount of damping introduced by PSS
- Signal washout block:
  - High-pass filter with T_W long enough (typically 1 to 20s) to allow signals associated with oscillations in ω_r to pass unchanged. However, if it is too long, steady changes in speed would cause generator voltage excursions
- Phase compensation block:
  - Provides phase-lead compensation over the frequency range of interest (typically, f=0.1 Hz to 2.0 Hz, i.e. ω=0.6 to 12.6 rad/s)
  - Two or more first-order blocks, or even second-order blocks may be used.
  - Generally, some under-compensation is desirable so that the PSS results in a slight increase of the synchronizing torque (a positive projection on $\Delta\delta$ axis) as well

PSS/E ST2CUT stabilizer





States
1 - Transducer1
2 - Transducer2
3 - Washout
4 - LL1
5 - LL2
6 - Unlimited Signal
Model supported by PSSE

Ic1 and Ic2:
1 - Shaft speed deviation in per unit
2 - Bus voltage frequency deviation in per unit
3 - Generator electrical power in per unit on the machine MVA Base
4 - Generator accelerating power in per unit on the machine MVA Base
5 - Magnitude of bus voltage in per unit

Form Edit - ST2CUT

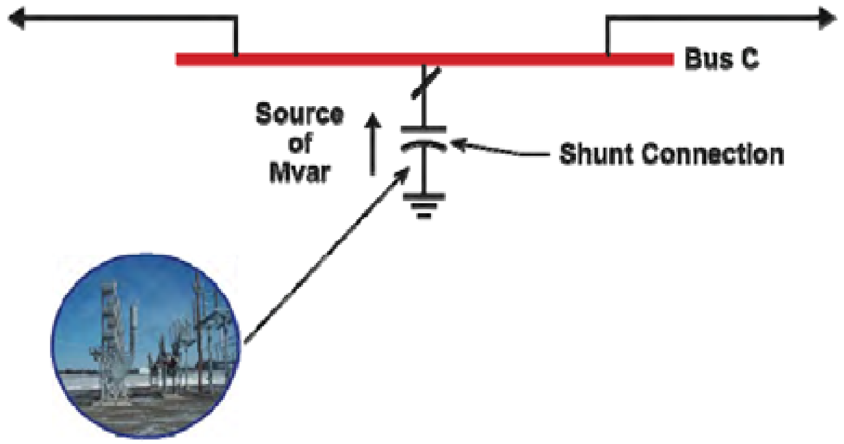
IBUS	6	Bus	CRAIG	Area	60	Zone	70
I	1	IC1	2	IB1	0	IC2	0
IB2	0	K1	5.5000	K2	0.0000	T1	0.0300
T2	0.0000	T3*	10.0000 T_w	T4	10.0000 T_w	T5	0.4000 T_1
T6	0.0400 T_2	T7	0.0000	T8	0.0000	T9	0.0000
T10	0.0000	LSMAX	0.0500	LSMIN	-0.0500	VCU	0.0000
VCL	0.0000	MVA Base	1488.0000	Status	1		

Use of Other Voltage Control Equipment

- **Passive**: designed to be a permanent part of the system (fixed) or be switched in and out of service via circuit breakers or switchers
  - Shunt capacitors: supply Mvar (proportional to V^2) to the system at a location and increase voltages near that location.
  - Shunt reactors: absorb excessive Mvar from the system at a location and reduce voltages near that location.
  - Series capacitors: reduce the impedance of the path by adding capacitive reactance (pro: self-regulating; con: causing sub-synchronous resonance)
  - Series reactors: increase the impedance of the path by adding inductive reactance.

- **Active** (maintaining voltage levels at specific buses)
  - Tap Changing Transformers
  - Synchronous condensers
  - Static Var Systems, e.g. SVC and STATCOM, often referred to as FACTS (Flexible AC Transmission Systems)

Shunt Capacitors



- When a switchable shunt capacitor is switched in, the local voltage rises
- Shunt capacitor switching is often used to control normal daily fluctuations in system voltage levels due to load changes

- Locations:
  - **Distribution systems**: typically close to large customers to supply Mvar needs (so called *power-factor correction*); placed at appropriate locations along the length of a feeder to ensure that voltages at all points remain within the allowable limits as the loads vary (so called *feeder voltage control*)
  - **Transmission systems**: at transmission substations to support the Mvar needs of the bulk power system and maintain voltage levels during heavy loading conditions
- Advantage: Low cost and flexibility of installation and operation
- Disadvantage: Mvar output $Q = V^2/X_C$, and is hence reduced at low voltages when it is likely to be needed most.
  - e.g., if a 25 Mvar shunt capacitor rated at 115 kV is operated at 109 kV (V=0.95pu), its actual output is 22.5 Mvar, i.e. 90% of the rated value (Q=0.95^2=0.90pu).

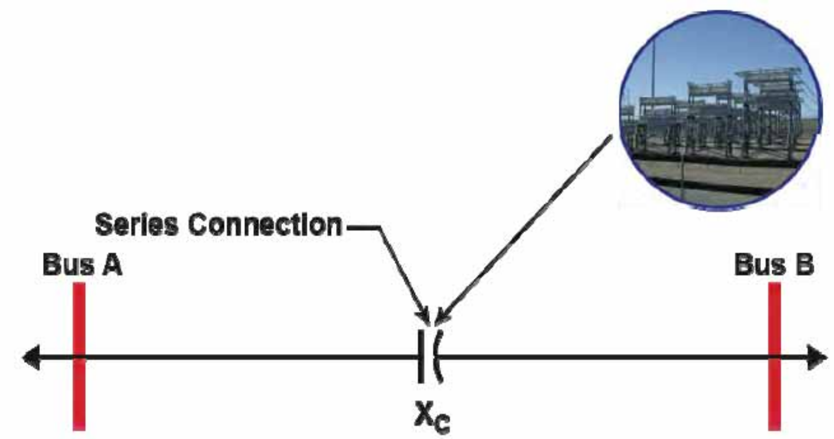
Series Capacitors

- Connected in series with the line conductors to compensate for the inductive reactance of the line.
- Increasing the transmitted maximum power and reduce the effective reactive power loss (XI^2), while contributing to improved voltage control

- Advantage:
  - "Self-regulating" nature: unlike a shunt capacitor, series capacitors produce more reactive power (output $Q=X_CI^2$) under heavier power flows
- Disadvantage:
  - Sub-synchronous resonance (SSR) is often caused by the series-resonant circuit

$$f_{SSR} = \frac{1}{2\pi\sqrt{LC}} = f_0\sqrt{\frac{X_C}{X_L}}$$

e.g. f_{SSR}=19Hz if X_C=0.1X_L (i.e. 10% series compensation)



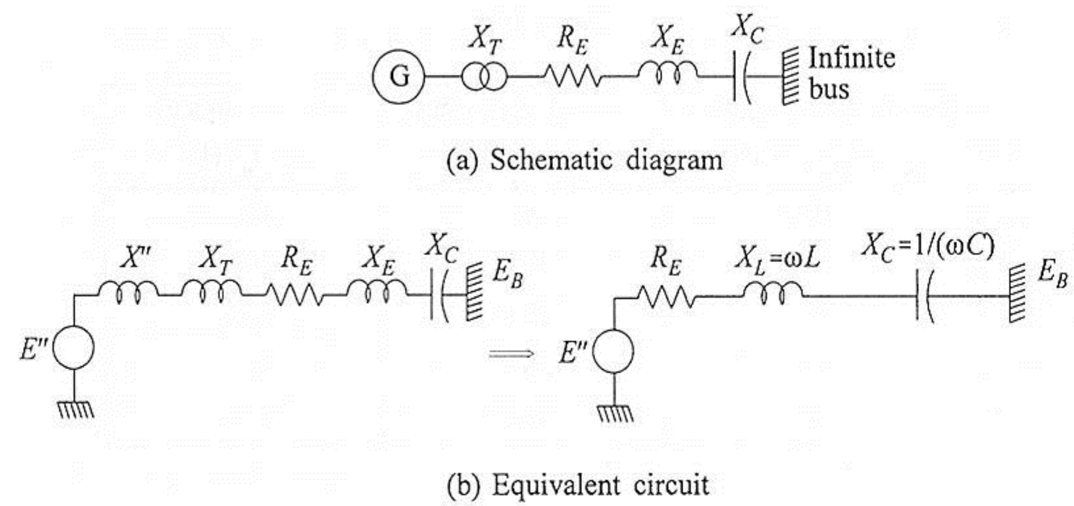
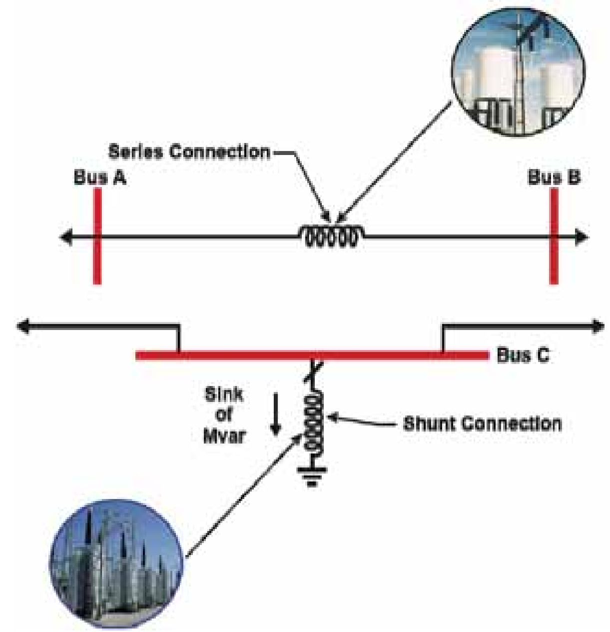


Figure 15.9 Radial series compensated system

Use of Reactors



- Series reactors: the primary use is to limit fault current
- Shunt reactors
  - Used to compensate for the overvoltage effects of line capacitance to limit voltage rise on open circuit or light load (see EPRI's Ch-5.3 or Kundur's 6.1 for causes of high voltage)
  - Usually required for long EHV lines
  - Connected either to the tertiary windings of transformers or to EHV buses
  - During heavy loading conditions, some of shunt reactors may have to be disconnected.

Surge impedance (real number): $Z_C = \sqrt{\frac{L}{C}}\ (\Omega)$

If a power line supports its Surge Impedance Load (SIL), i.e. with load impedance equal to Z_C, then PF=1 everywhere along the line.

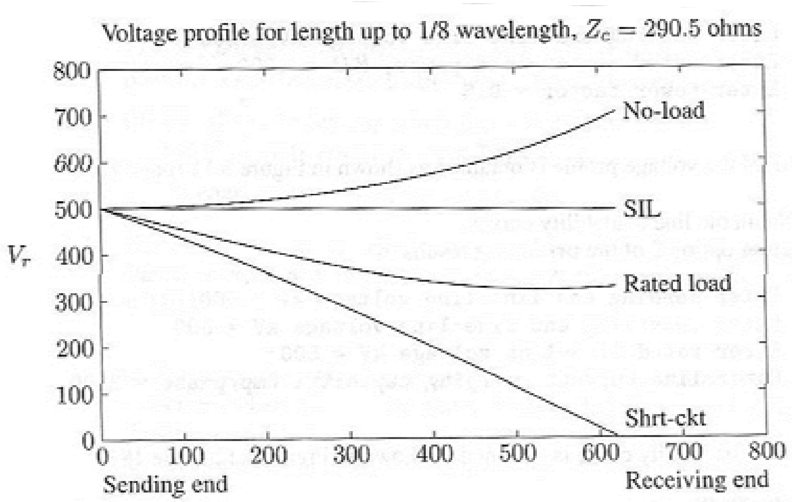


FIGURE 5.11
Voltage profile for length up to 1/8 wavelength.

- Load >>SIL: a shunt capacitor is often needed at the receiving end to reduce voltage drop.
- Load <<SIL: a shunt reactor is often needed at the receiving end to avoid over voltage.

Table 6.1 Typical overhead transmission line parameters

Nominal Voltage	230 kV	345 kV	500 kV	765 kV	1,100 kV
R (Ω/km)	*0.050*	*0.037*	*0.028*	*0.012*	*0.005*
$x_L=\omega L$ (Ω/km)	0.488	0.367	0.325	0.329	0.292
$b_C=\omega C$ (μs/km)	3.371	4.518	5.200	4.978	5.544
α (nepers/km)	0.000067	0.000066	0.000057	0.000025	0.000012
β (rad/km)	0.00128	0.00129	0.00130	0.00128	0.00127
Z_C (Ω)	380	285	250	257	230
SIL (MW)	140	420	1000	2280	5260
Charging MVA/km $= V_0^2 b_C$	0.18	0.54	1.30	2.92	6.71

Notes: 1. Rated frequency is assumed to be 60 Hz.
2. Bundled conductors used for all lines listed, except for the 230 kV line.
3. R, x_L, and b_C are per-phase values.
4. SIL and charging MVA are three-phase values.

Use of Tap Changing Transformers

- A tap changer control the voltage of a transformer's winding by adjusting the number of turns in the winding.
- **Off-load tap changer (OLTC)**: mechanical linkages within the primary or secondary windings; can only be adjusted when the transformer current flow has been completely interrupted.
- **Under-load tap changer (ULTC)**: designed to change tap positions while the transformer is carrying load current.
- ULTCs can be operated in either a manual or an automatic mode. When in an automatic mode, the ULTCs automatically respond to system conditions and adjust tap positions.
- ULTCs may control a remote secondary voltage (no at its physical location)

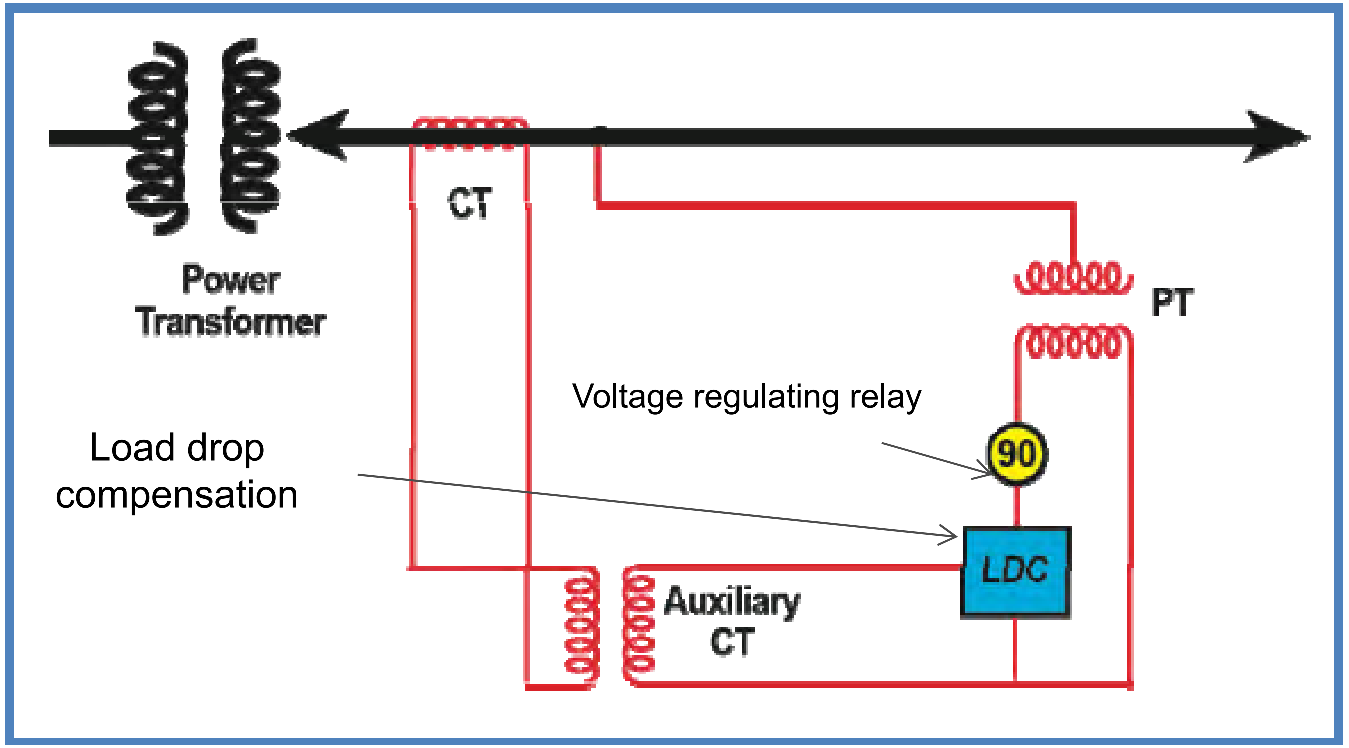


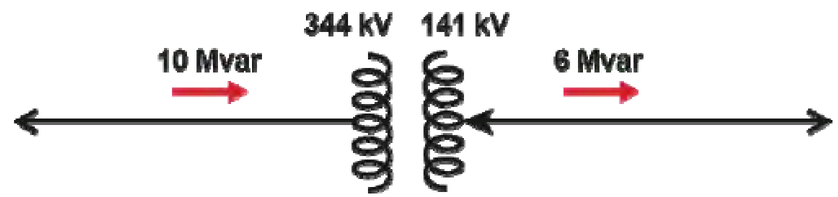
Figure 5-38. A ULTC Control Scheme

Concerns of Using Tap Changing Transformers

- Normally, when the turns ratio is adjusted, the Mvar flow across the transformer is also adjusted
- However since a transformer absorbs Mvar to build its internal magnetic field, when its secondary voltage is raised via a tap change, its Mvar usage increases and its primary voltage often drops. The greater the tap change and the weaker the primary side, the greater the primary voltage drop.
- If the primary side is weak, the tap change may not necessarily increase the secondary voltage. Therefore, spare Mvar must be available for a tap change to be successful.

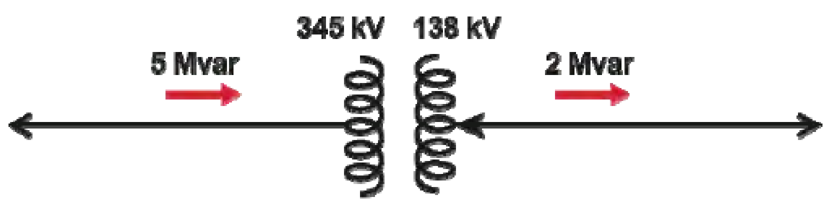
An example:

±10% / 33-position ULTC



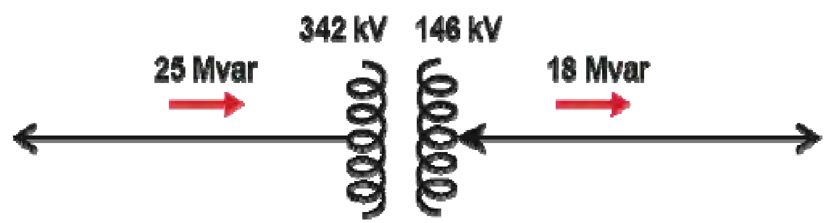
(b) Raise Five Positions

(5/16x10%= +3.125% ~ 142.3kV)



(a) Flat Taps

(Neutral point: 0% ~ 138kV)



(c) Raise 16 Positions

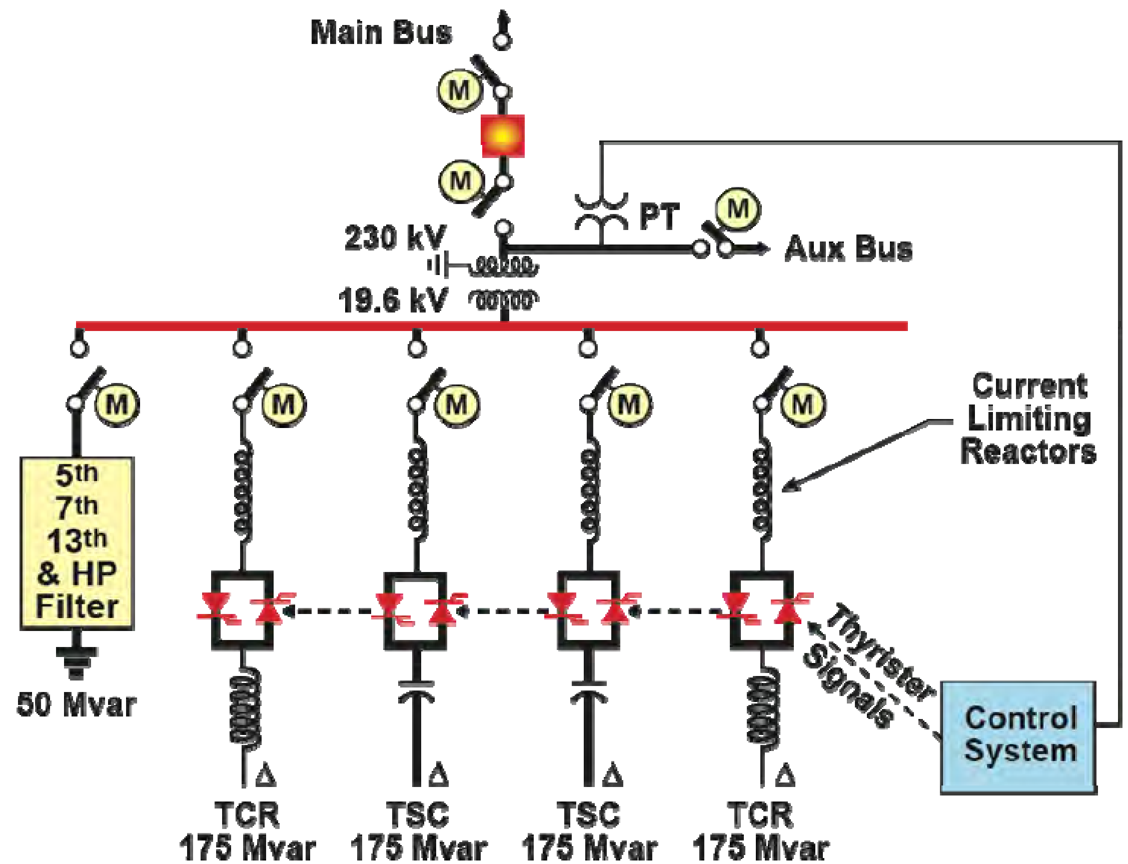
(+10% ~ 151.8kV)

Use of Synchronous Condensers

- Synchronous machines running as synchronous motors without a prime mover. The power system supplies MW to turn the rotor.
- By controlling the field excitation, it can be made to either generate or absorb Mvar.
- Often connected to the tertiary windings of transformers.
- Expensive Mvar source, seldom used in modern power systems.
- However, some companies use them to support Mvar and increase inertia by their spinning mass.
- Some synchronous generators can be operated in a motoring mode when MW is not required from the generators, such as
  - Some hydro units in light load conditions,
  - Some combustion turbine peaking units (by disconnecting the turbine from the generator).

Use of Static Var Compensators (SVC)

- "Static" (no rotating parts); supply or absorb Mvar
- Typically, a SVC is composed of
  - shunt reactors and capacitors
  - high speed thyristor switches used to adjust the amount of reactors or capacitors in-service at any one time
  - a control system (similar to AVR) to maintain a target voltage level
- If the bus voltage dips below the target value, the control system can control thyristors to reduce reactor current flow or to switch more capacitors in service, such as to raise the bus voltage



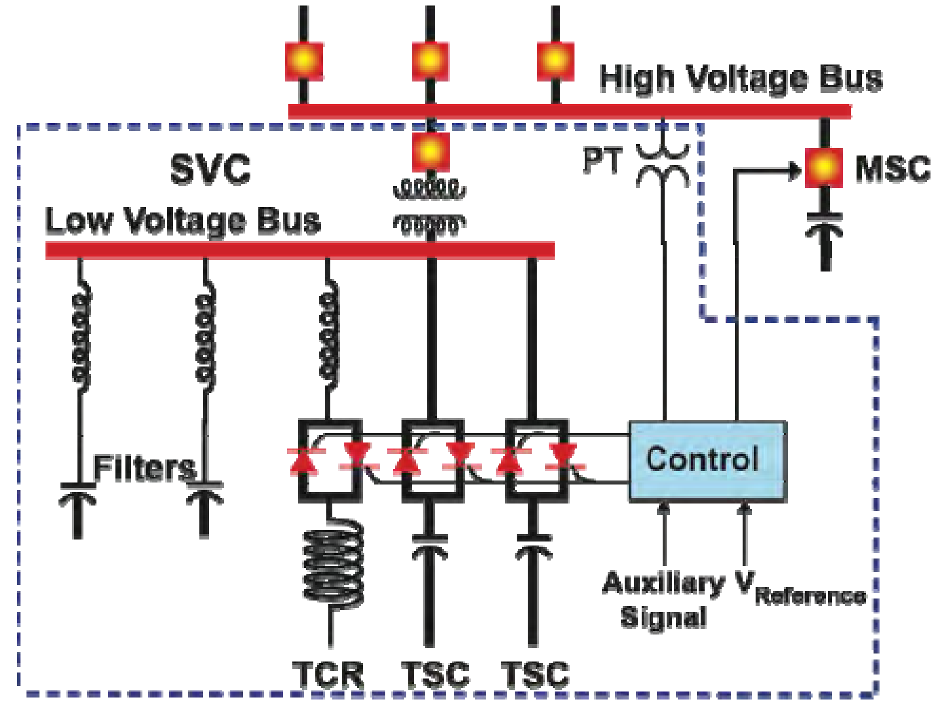
TCR - Thyristor-controlled reactor

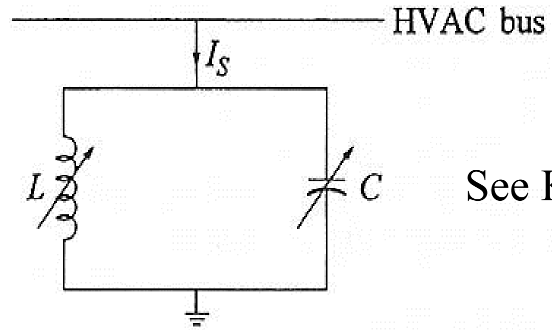
TSC - Thyristor-switched capacitor

HP filer - High-pass filter to absorb high frequency harmonics caused by thyristor switches

Static Var Systems (SVS)

- A SVS is an aggregation of SVCs and mechanically switched capacitors (MSCs) or reactors (MSRs) whose outputs are coordinated.
- A simple example of an SVS is one SVC combined with local ULTCs.





See Kundur's Pages 640-645

Figure 11.39 Idealized static var system

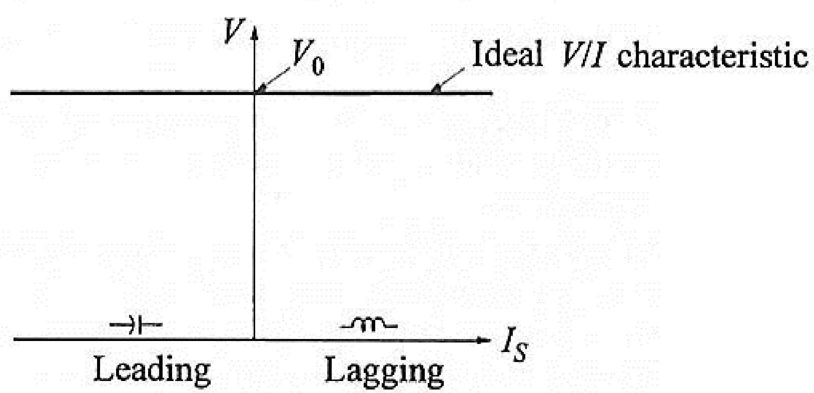


Figure 11.40 V/I characteristic of ideal compensator

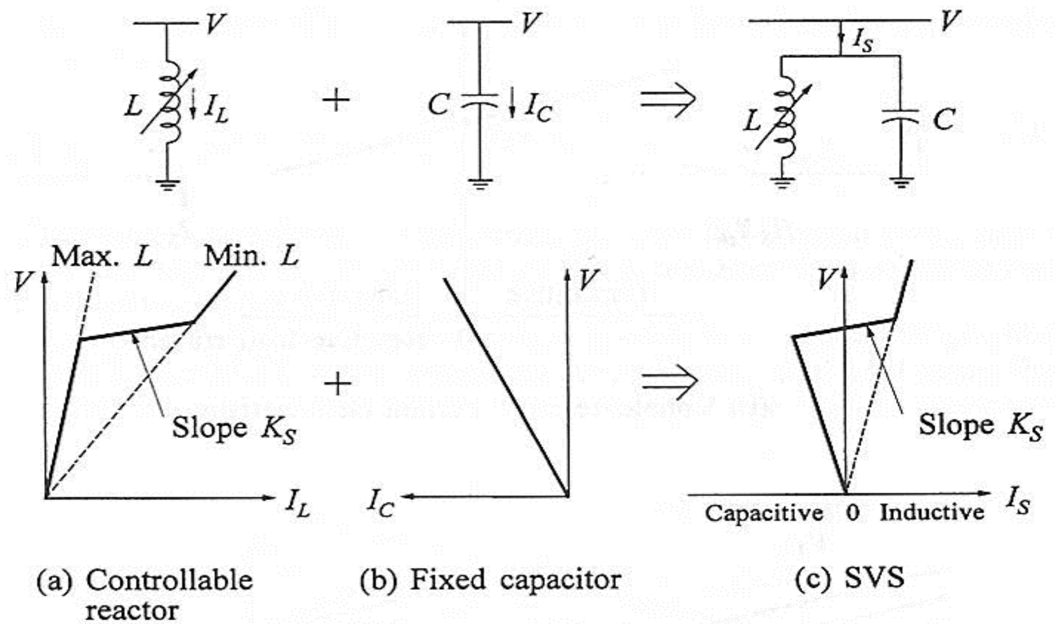
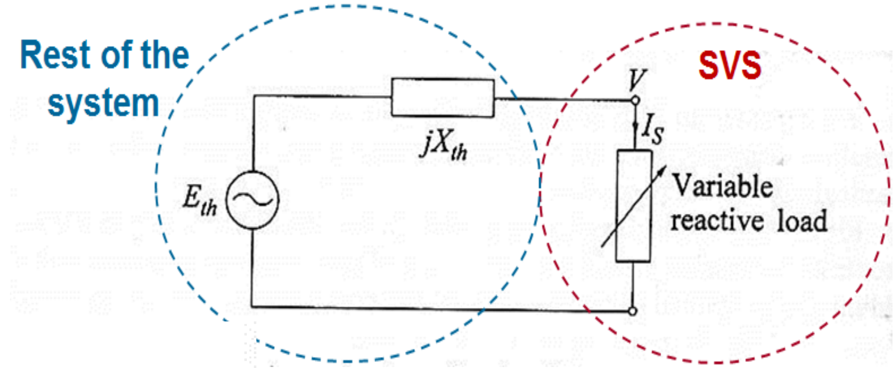


Figure 11.41 Composite characteristics of an SVS

Disadvantage of a practical SVC/SVS

- At the maximum output, an SVC/SVS downgrades to a regular shunt capacitor and the Mvar produced is proportional to $|V|^2$.



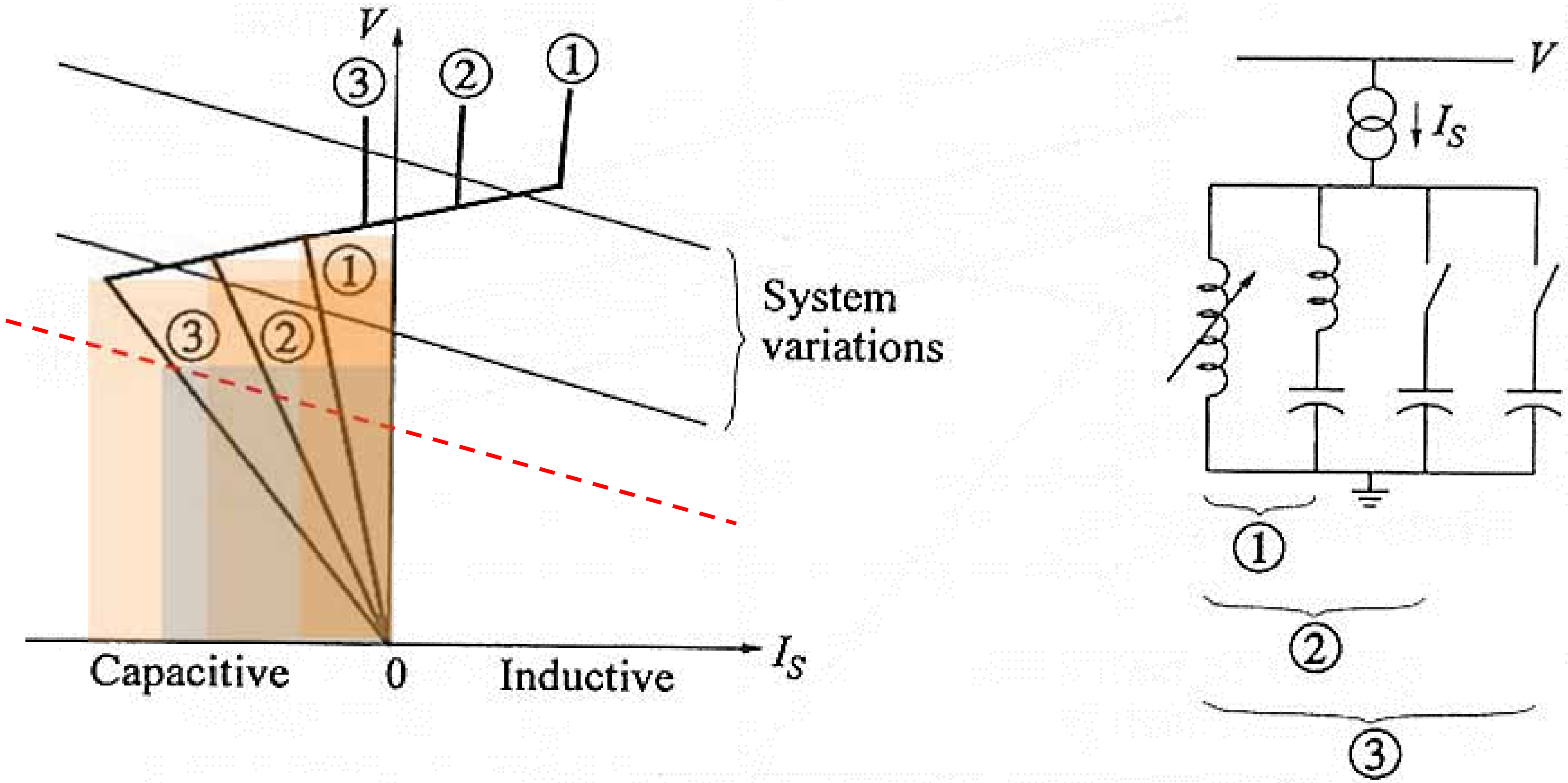
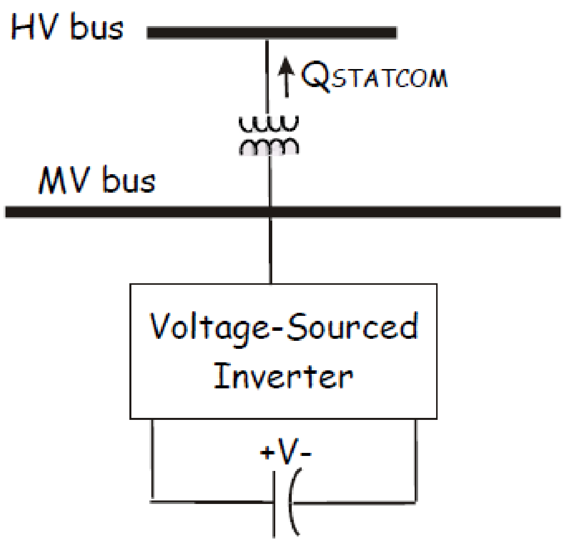
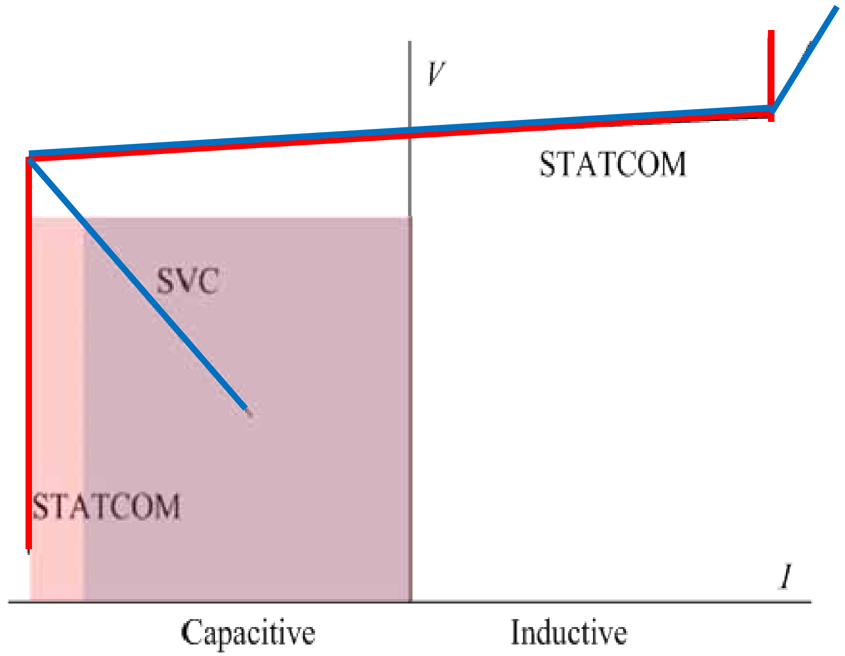


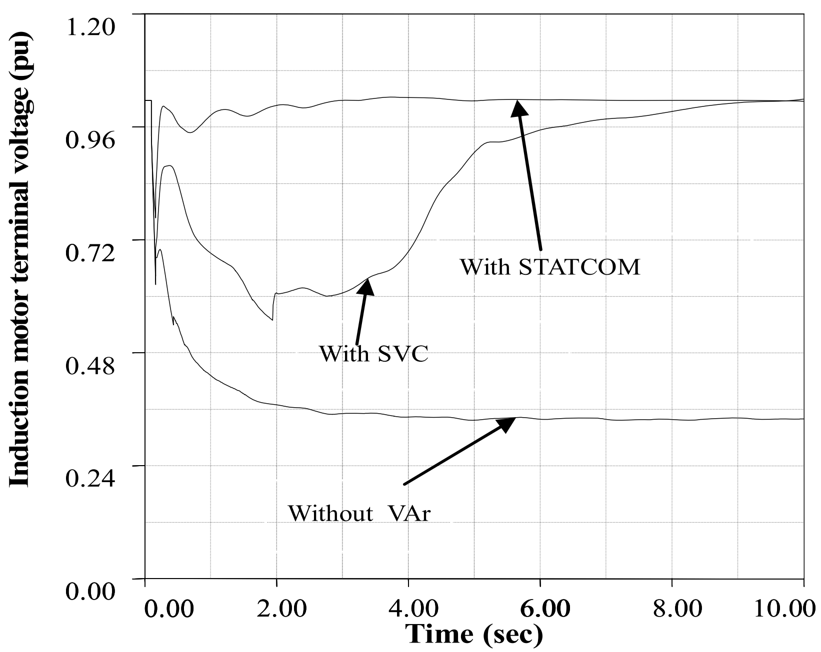
Figure 11.44 Use of switched capacitors to extend continuous control range

Use of STATCOM

- Similar to synchronous condenser, STATCOM (static synchronous compensator) has an internal voltage source which provides constant output current even at very low voltages. Therefore, its Mvar output is linearly proportional to |V|.
- The voltage-sourced converter (VSC) converts the dc voltage into a three-phase set of output voltages with desired amplitude, frequency, and phase.



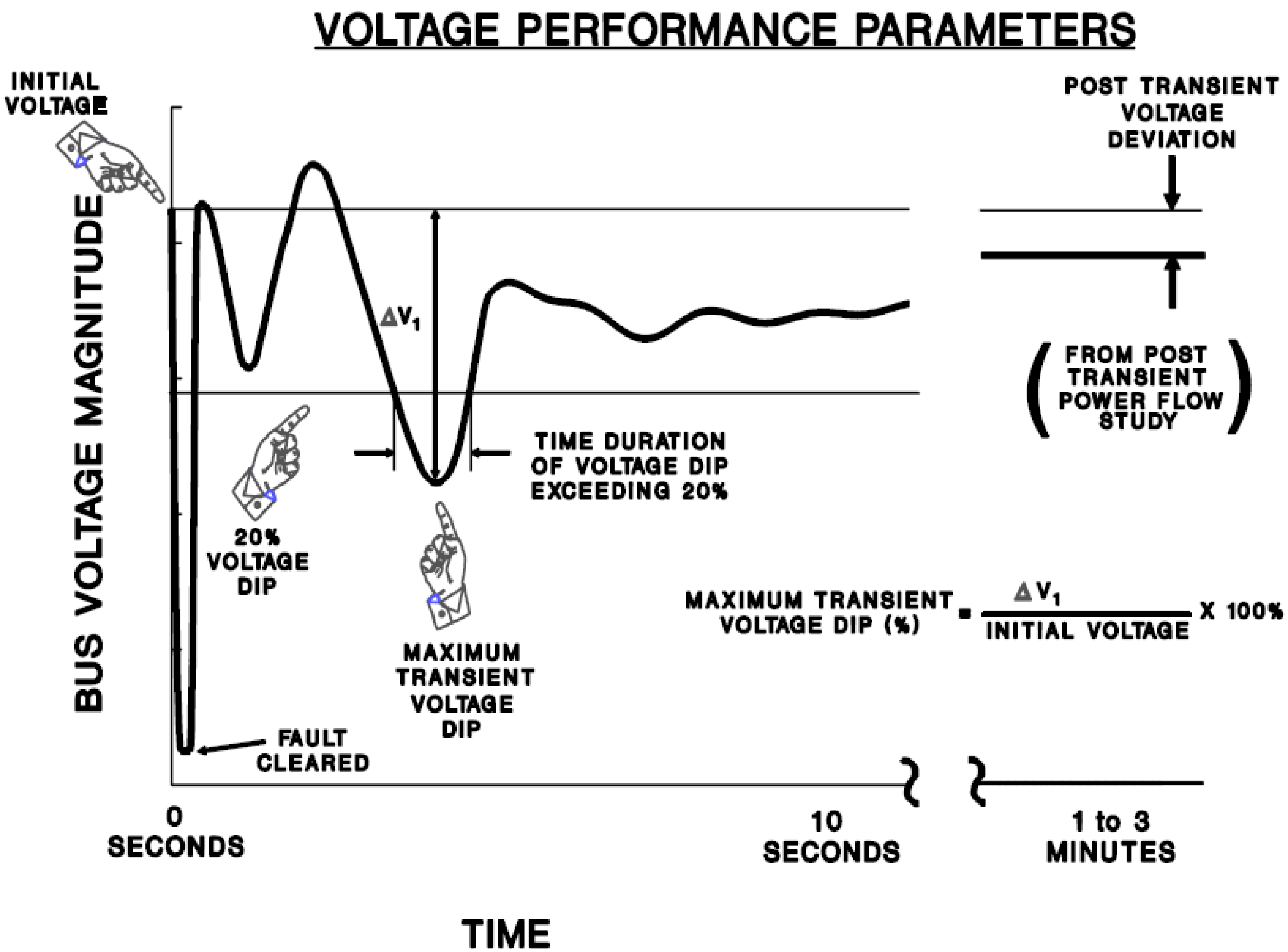




B. Sapkota, et al, "Dynamic VAR planning in a large power system using trajectory sensitivities," IEEE Trans. Power Systems, 2010.

FIDVR (Fault-Induced Delayed Voltage Recovery)

In some literature, FIDVR is also called "transient voltage stability" (an old term discouraged by IEEE PES from 2021)



NERC/WECC Planning standards require that following a single contingency,

- Voltage dip should not exceed 25% at load buses or 30% at non-load buses
- Voltage dip should not exceed 20% for more than 20 cycles at load buses
- Post-transient voltage deviation not exceed 5% at any bus