ECE 422/522
Power System Operations & Planning/Power Systems Analysis II

5 - Reactive Power and Voltage Control

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References

- Saadat’s Chapters 12.6 ~12.7
- Kundur’s Sections 11.2.1 ~11.2.7
- EPRI Tutorial’s Chapter 5

Objectives of Reactive Power and Voltage 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

Supply or Absorb Q

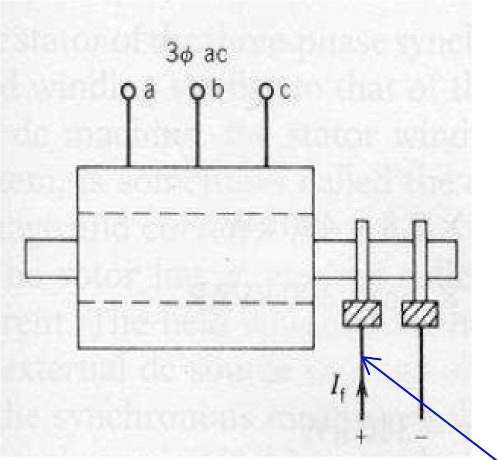
Equipment	Supply Q	Absorb Q
Synchronous generator	Y (when over-excited)	Y (when under-excited)
Overhead lines	Y	Y
Underground cables	Y	
Transformers		Y
Loads		Y
Compensating devices	Y	Y

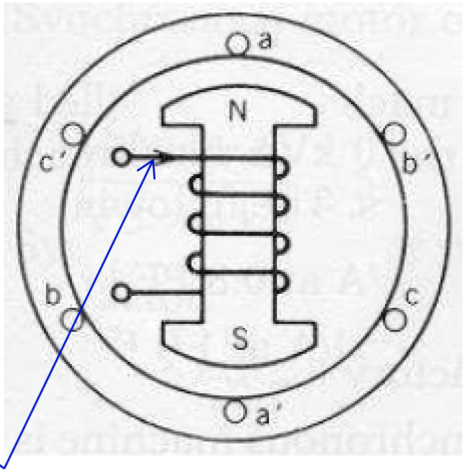
Methods of Reactive Power and Voltage Control

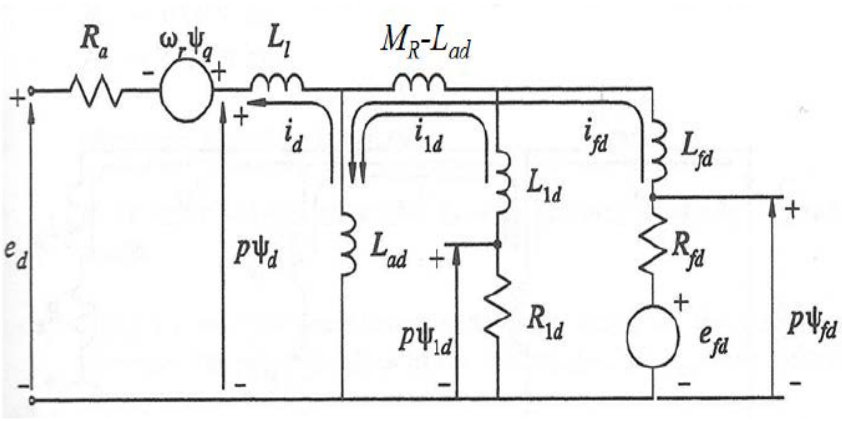
- Generators:
  - Excitation control systems with automatic voltage regulators (AVRs)
- Other control devices
  - Sources or sinks of Q, e.g.
    - shunt capacitors,
    - shunt reactors,
    - synchronous condensers,
    - static var compensators (SVCs)
  - Line reactance compensators, e.g. series capacitors
  - 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

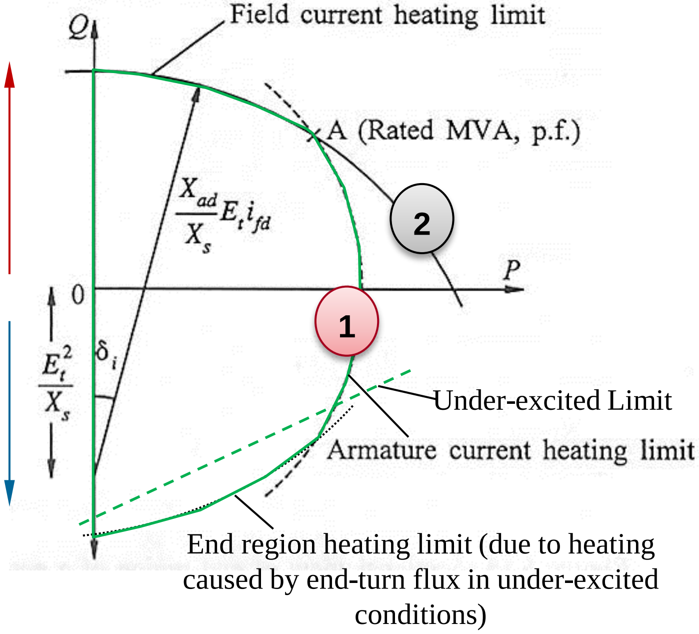
- Generator considerations:
  - Under steady-state conditions, the excitation system should supply and automatically adjust the field current of the synchronous generator to maintain the terminal voltage as the output varies within the continuous capacity of the generator
  - Under disturbances, the 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, thermal limits should be concerned
- Power system considerations
  - The excitation system should contribute to effective control of voltage and enhancement of system stability:
    - Able to respond rapidly to a disturbance so as to enhance transient stability
    - Able to modulate the generator field so as to enhance small-signal stability

Over-excited

(Supplying Q, Lagging p.f.)

Under-excited

(Absorbing Q, Leading p.f.)



End region heating limit (due to heating caused by end-turn flux in under-excited conditions)

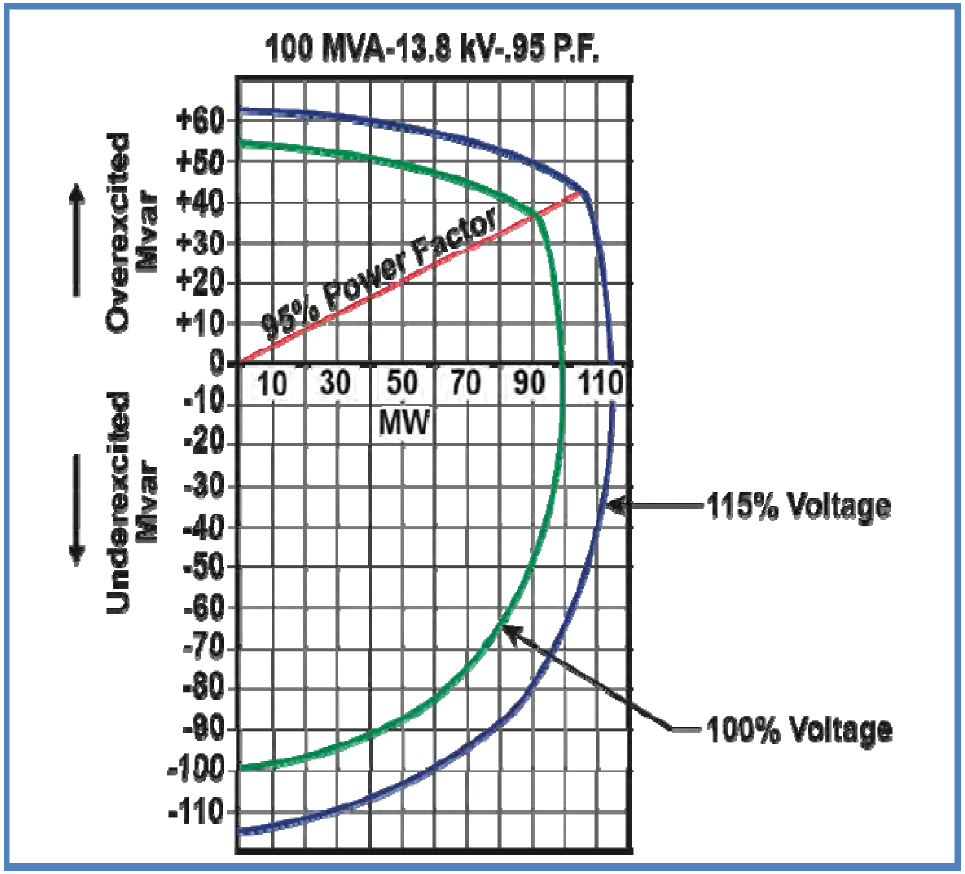


Figure 5-44. Actual Hydro Unit Reactive Capability Curve

① $I_t < I_{t,max}$: Armature current heating limit

② $i_{fd} < i_{fd,\,max}$: Field current heating limit

$$P = E_t I_t \cos\phi = \frac{X_{ad}}{X_s} E_t i_{fd} \sin\delta_i$$

Always >0

$$Q = E_t I_t \sin\phi = \frac{X_{ad}}{X_s} E_t i_{fd} \cos\delta_i - \frac{E_t^2}{X_s}$$

>0 (over-excited)

or <0 (under-excited)

Elements of an Excitation Control System

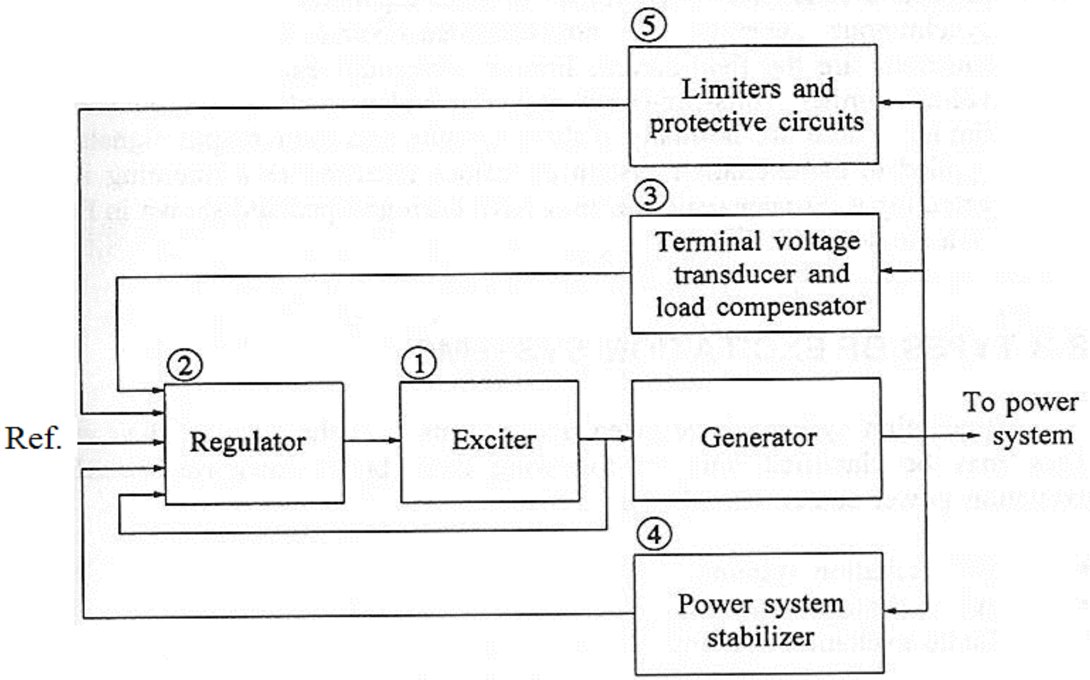
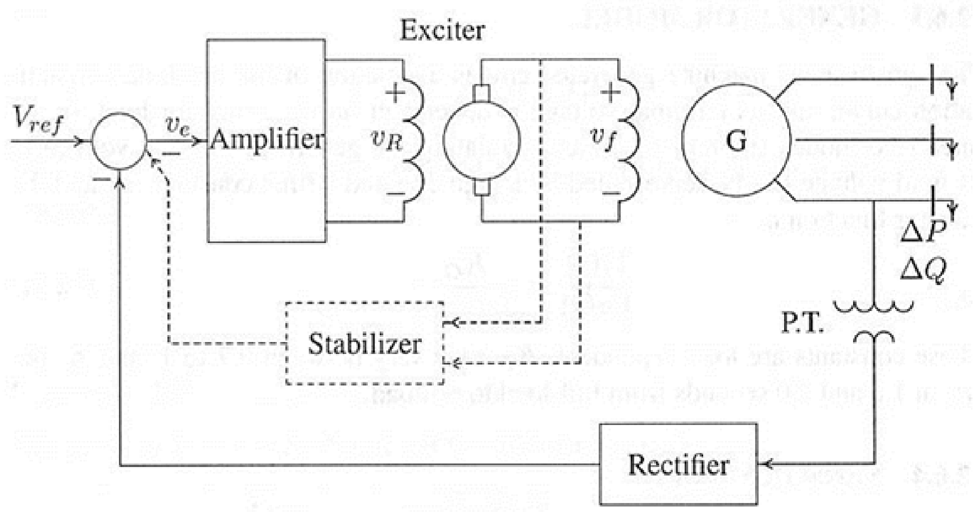
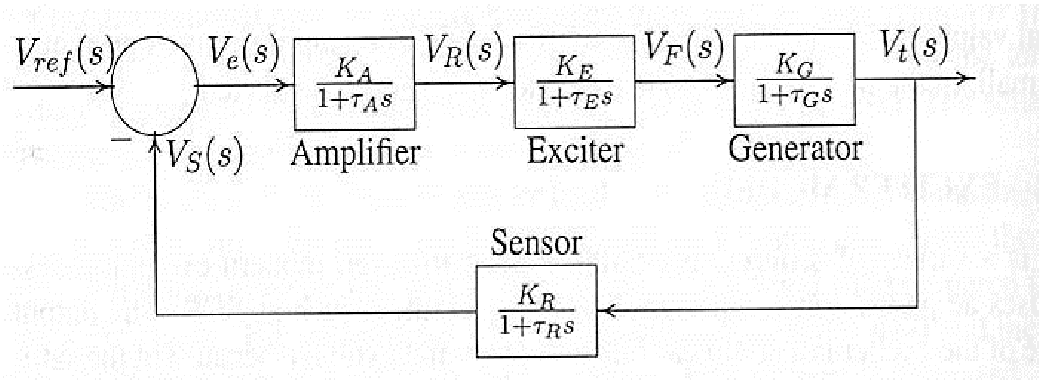


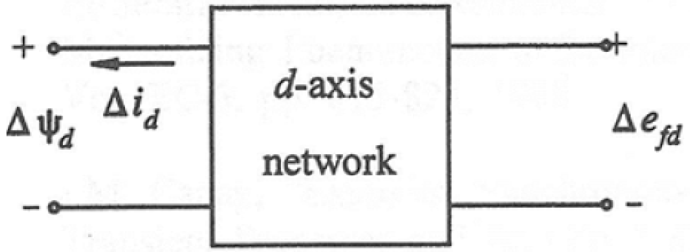
Figure 8.1 Functional block diagram of a synchronous generator excitation control system

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







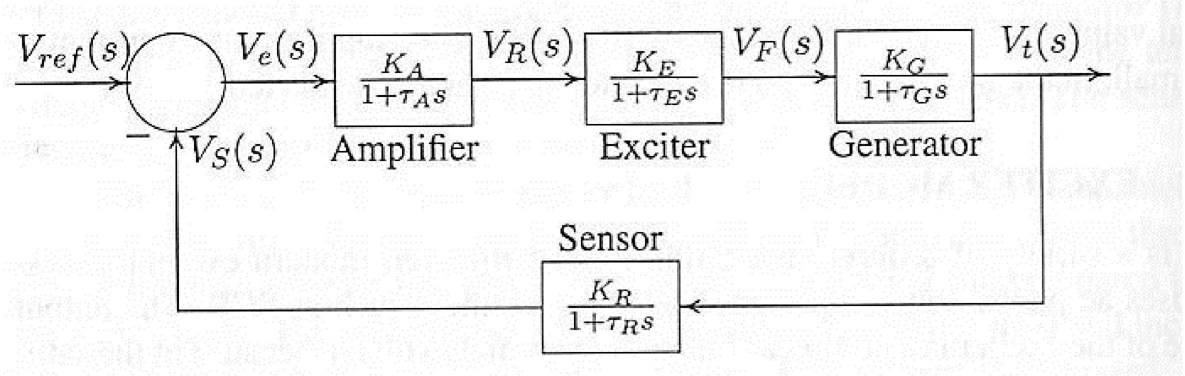
Simplified linear model (ignoring saturations with the amplifier and exciter and other nonlinearities

- Rectifier/Sensor model:
  - τ_R is very small, e.g. 0.01~0.06s
- Amplifier model:
  - K_A=10~400, τ_A=0.02~0.1s
- Exciter model:
  - τ_E is very small for modern exciters
- Generator model:
  - K_G=0.7~1, τ_G=1.0~2.0s from full load to no-load

What is τ_G?

$$G(s) = G_0 \frac{(1+sT_{kd})}{(1+sT'_{d0})(1+sT''_{d0})}$$

Simplified Linear Model



- Open- and closed-loop transfer functions:

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

$$\frac{V_t(s)}{V_{ref}(s)}=\frac{K_A K_E K_G(1+\tau_R s)}{(1+\tau_A s)(1+\tau_E s)(1+\tau_G s)(1+\tau_R s)+K_A K_E K_G K_R} \qquad (K_E K_G K_R \approx 1)$$

For a step input $V_{ref}(s)=\frac{1}{s}$, using the final value theorem, the steady-state response is

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

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.

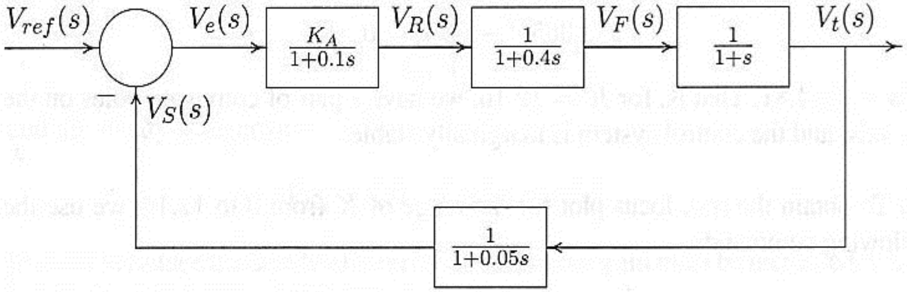


FIGURE 12.31
AVR block diagram for Example 12.6.

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

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

(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)

$$\begin{array}{c|lll} s^4 & 1 & 307.5 & 500+500K_A \\ s^3 & 33.5 & 775 & 0 \\ s^2 & 284.365 & 500+500K_A & 0 \\ s^1 & 58.9K_A - 716.1 & 0 & 0 \\ s^0 & 500+500K_A & & \end{array}$$

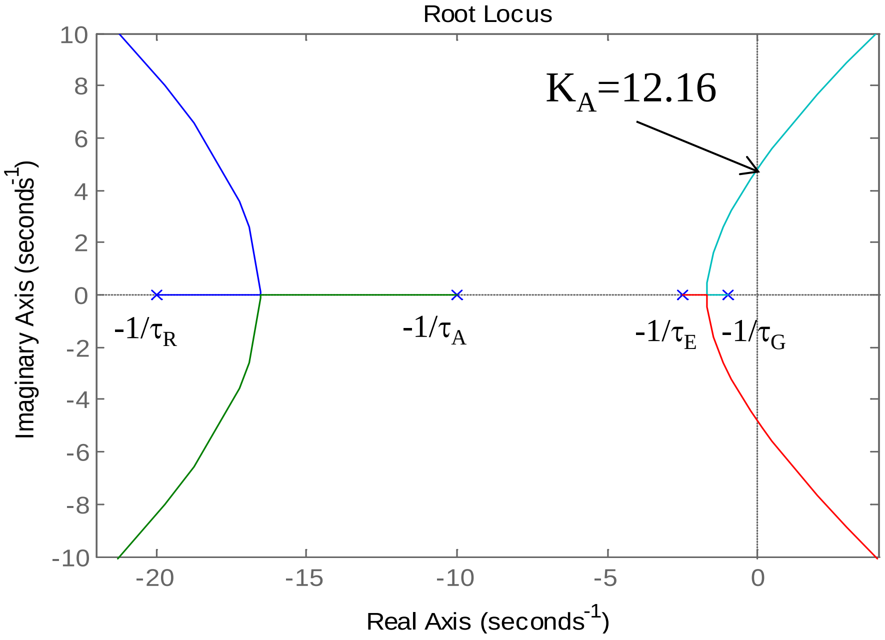
From the s^1 row we see that, for control system stability, K_A must be less than 12.16, also from the s^0 row, K_A must be greater than -1. Thus, with positive values of K_A, for control system stability, the amplifier gain must be

$$K_A < 12.16$$

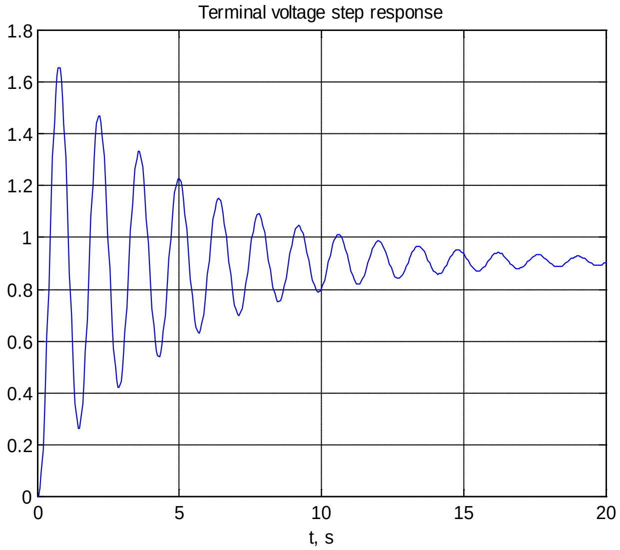
For $K = 12.16$, the auxiliary equation from the s^2 row is

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

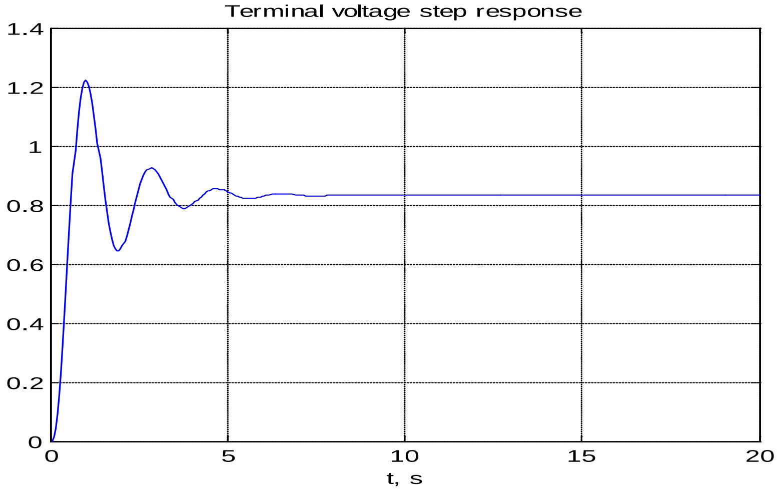
or $s = \pm j4.81$. That is, for $K = 12.16$, we have a pair of conjugate poles on the $j\omega$ axis, and the control system is marginally stable.



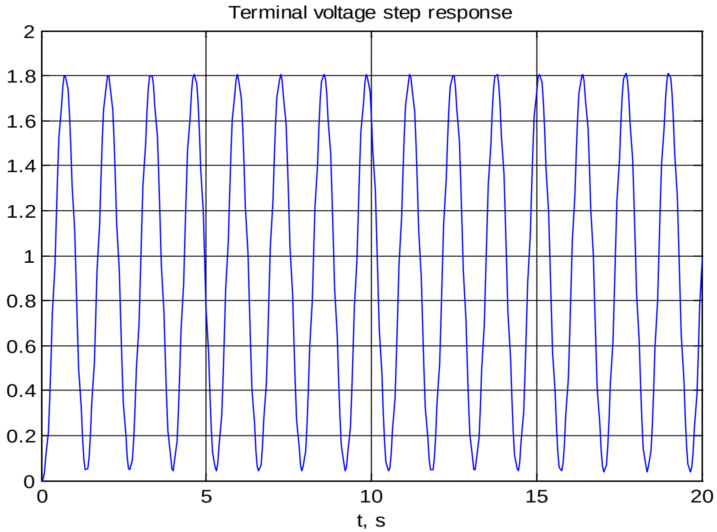
- $K_A=10$, $V_{tss}=0.909V_{ref}$



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



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



Excitation System Stabilizer

- Rate feedback (sim12ex7.mdl)

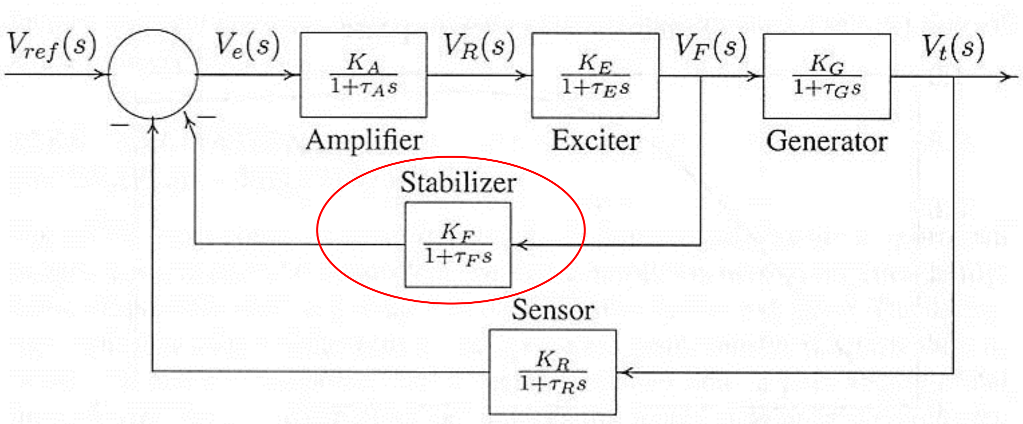
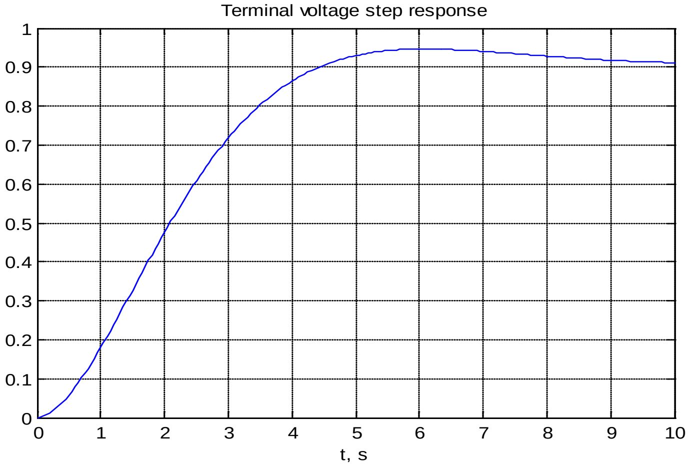


FIGURE 12.35
Block diagram of the compensated AVR system.



(For details on choosing K_F and τ_F, see Anderson's Page 280)

- PID control (sim12ex8.mdl)

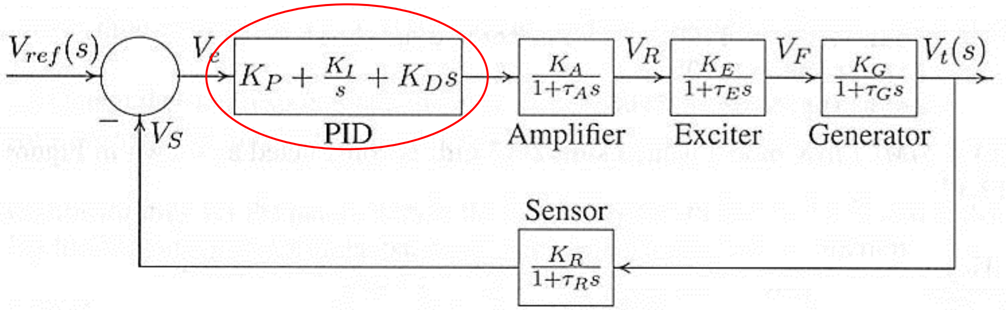
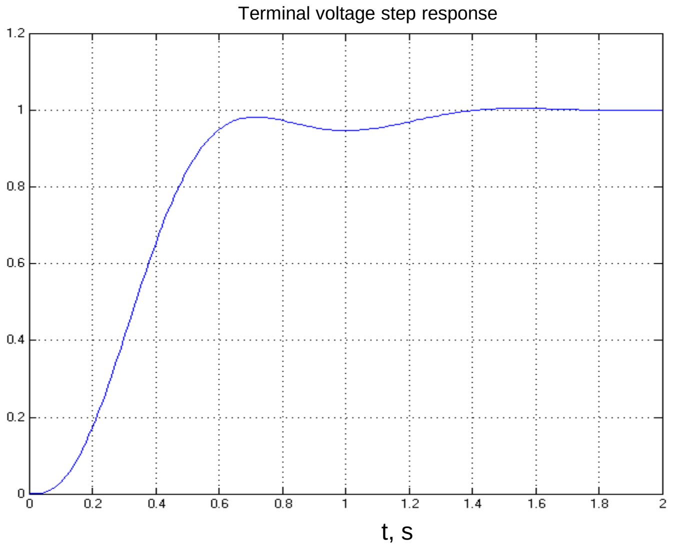


FIGURE 12.38
AVR system with PID controller.



Power System Stabilizer (PSS)

- PSS adds damping to rotor oscillations by controlling its excitation using auxiliary stabilizing signal(s), e.g. frequency
- Figure 12.13 from Kundur's book

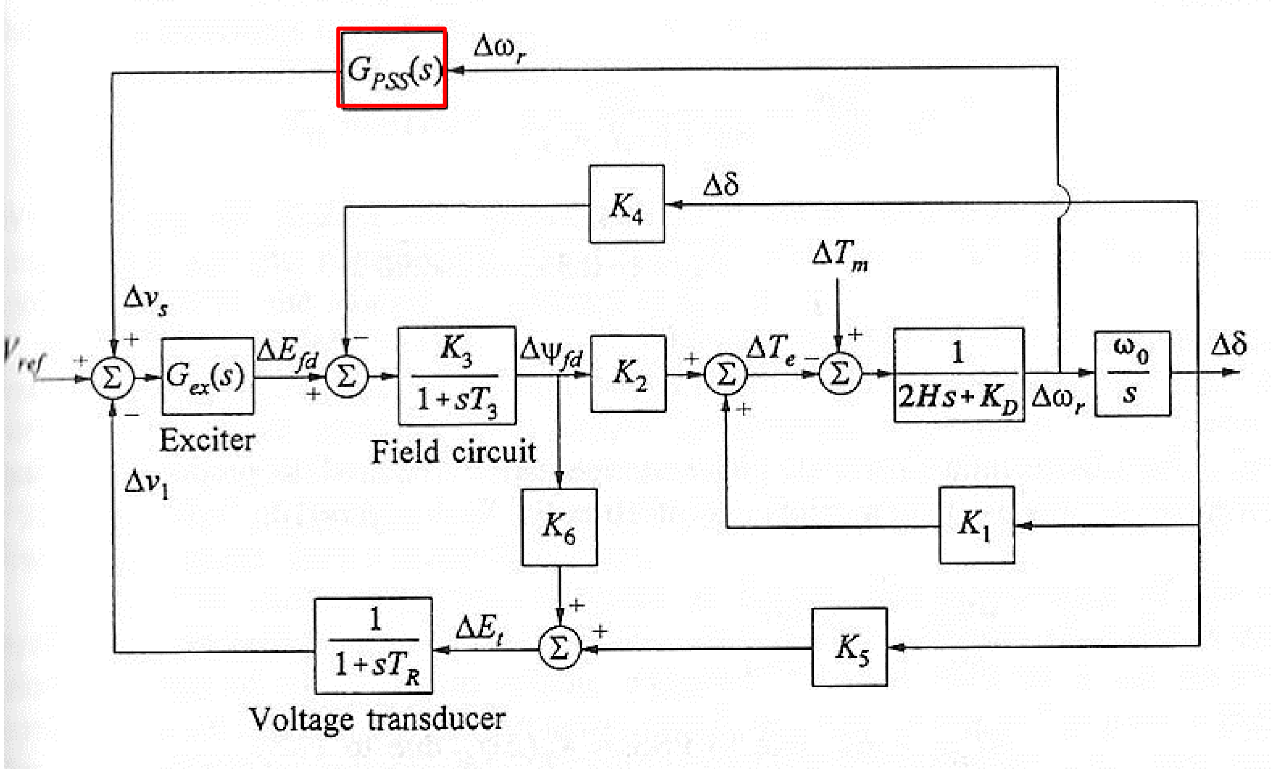


Figure 12.13 Block diagram representation with AVR and PSS

Use of Other Voltage Control Equipment

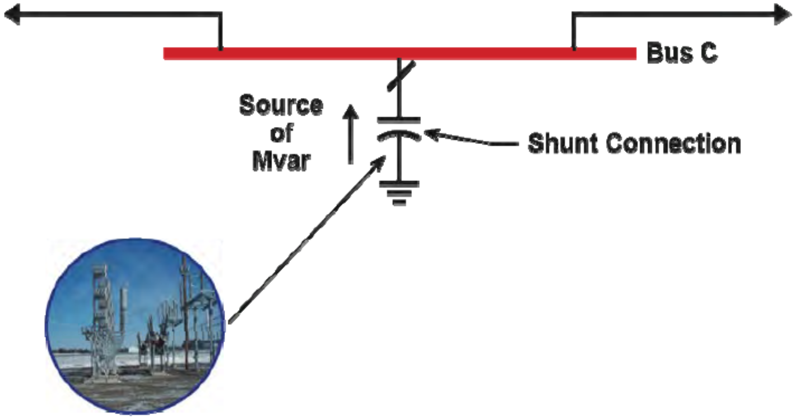
- Passive (modifying the network characteristics)
  - Capacitors and reactors

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

Use of Capacitors and Reactors

- Can be 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 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.
  - Series reactors: increase the impedance of the path by adding inductive reactance.

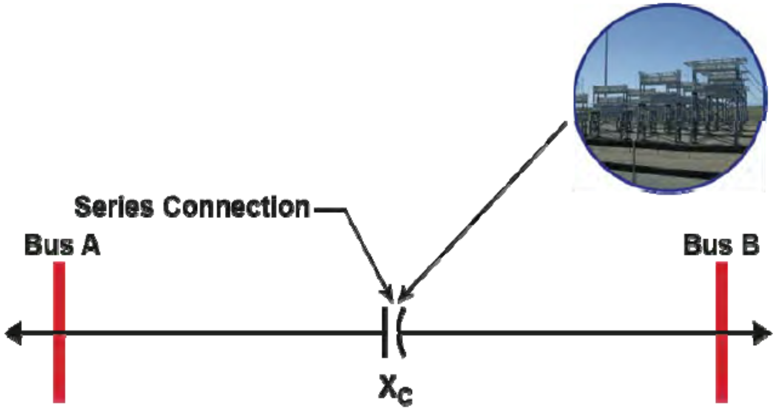
Shunt Capacitors



- 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: The Mvar output Q is proportional to V^2, and is hence reduced at low voltages when it is likely to be needed most. E.g., if a 25 Mvar shunt capacitor normally rated at 115 kV is operated at 109 kV (V=0.95pu) the output of the capacitor is 22.5 Mvar or 90% of the rated value ($Q=0.95^2=0.90$pu).

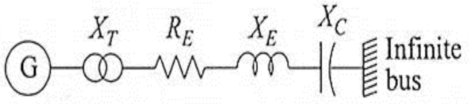
Series Capacitors

- 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

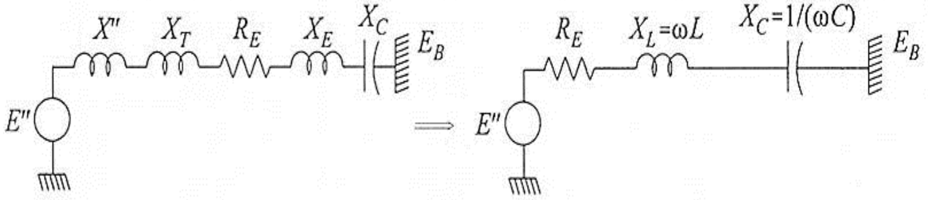


- Advantage:
  - “Self-regulating” nature: unlike a shunt capacitor, series capacitors produce more reactive power with heavier power current flows
- Disadvantage:
  - Sub-synchronous resonance (SSR) is often caused by the series-resonant circuit

$f_n = f_0\sqrt{X_C/X_L}$ (f_n= 19Hz for 10% series compensation, i.e. $X_C=0.1X_L$)



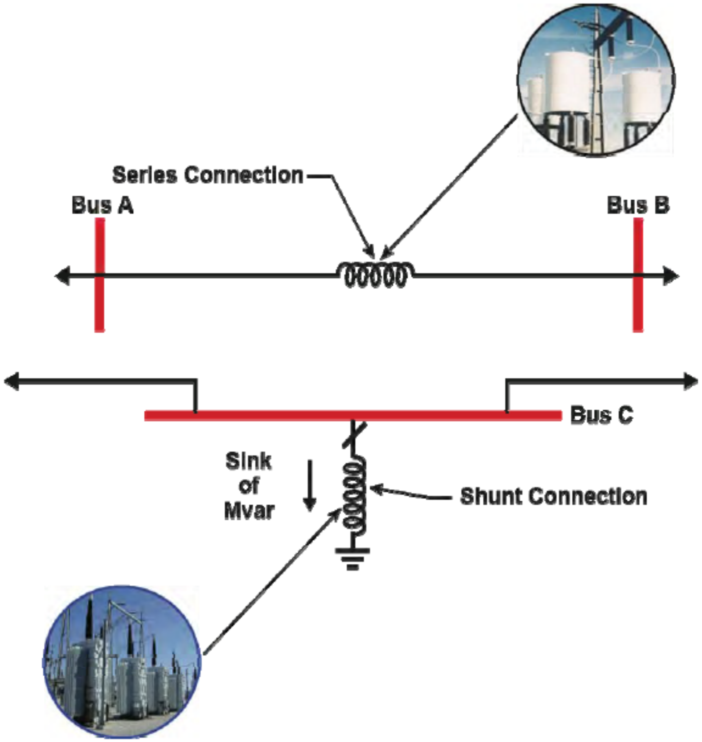
(a) Schematic diagram



(b) Equivalent circuit

Figure 15.9 Radial series compensated system

Use of Reactors



- 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.

- Series reactors
  - The primary use is to limit fault current
  - Also help reduce power oscillations between generators

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

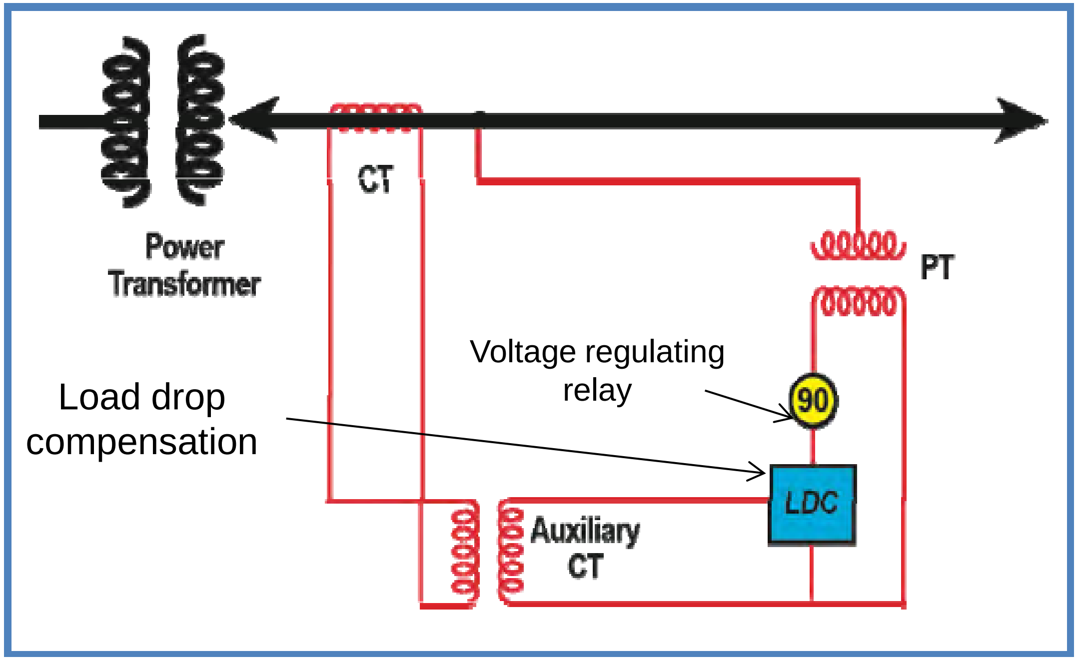


Figure 5-38. A ULTC Control Scheme

- 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.

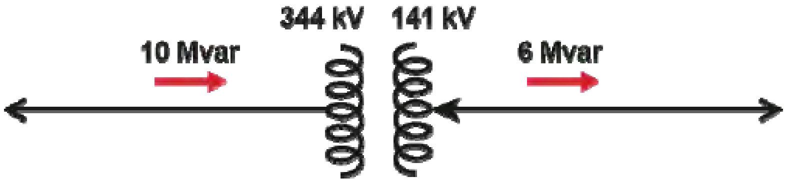
- A ULTC may control a remote secondary voltage (no at its physical location)

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.

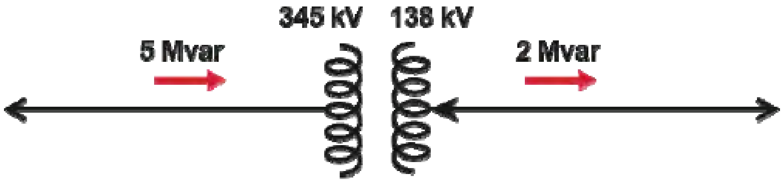
An example:

±10% / 33-position ULTC



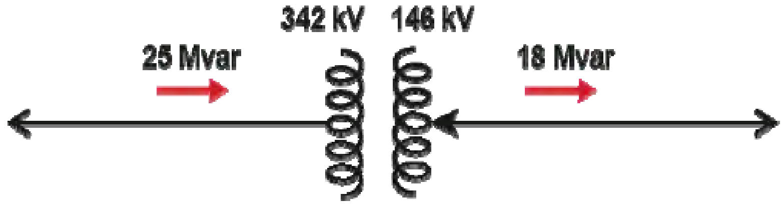
(b) Raise Five Positions

(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)

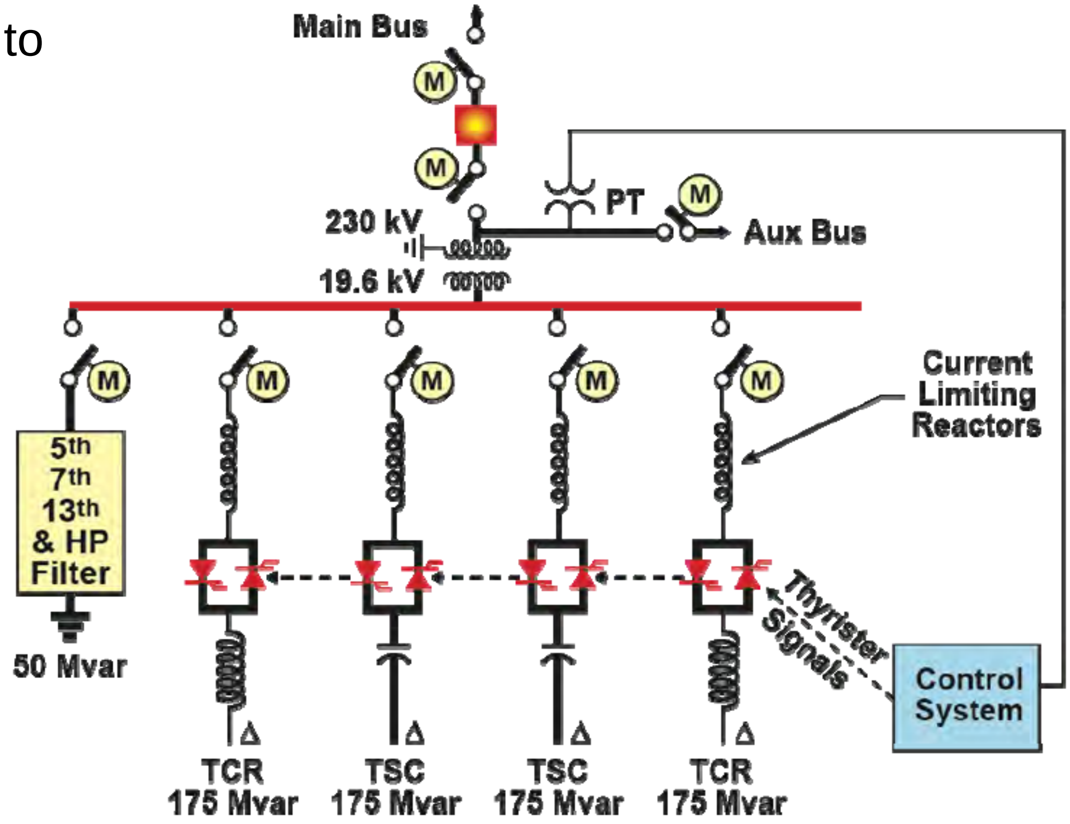
- "Static" (no rotating parts); supply or absorb Mvar
- Typically, a SVC is composed of
  - shunt reactors and capacitors
  - high speed thyristor switches used to adjust the amount of reactors or capacitors in-service at any one time
  - a control system (similar to AVR) to maintain a target voltage 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

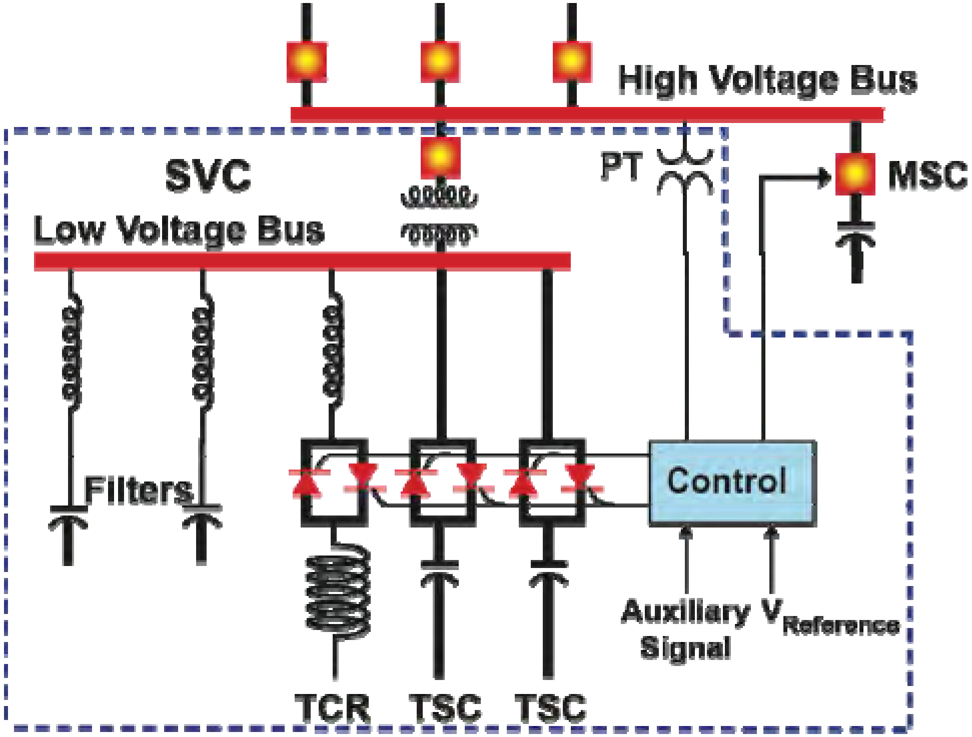
__TSC__ - Thyristor-switched capacitor

__HP filer__ - High-pass filter to absorb high frequency harmonics caused by thyristor switches



Use of 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 a SVC combined with local ULTCs.



Characteristic of Ideal and Realistic SVS's

- Kundur's Pages 640-645

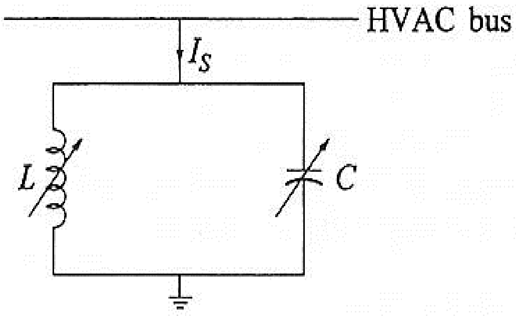


Figure 11.39 Idealized static var system

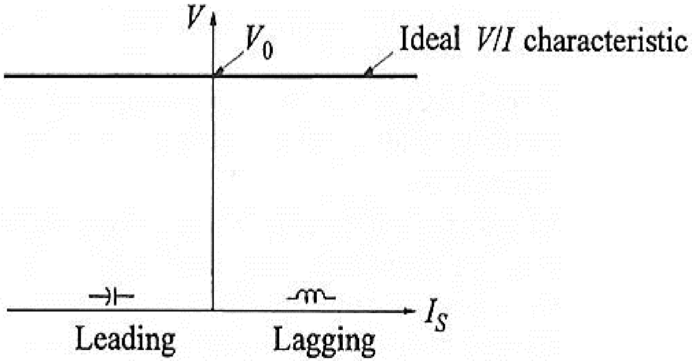
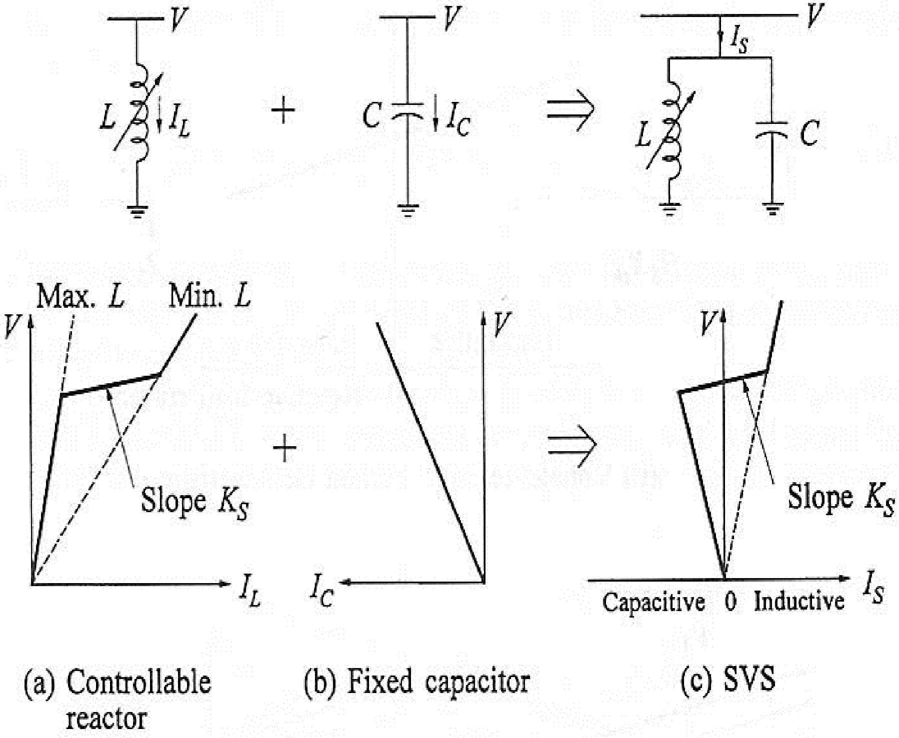


Figure 11.40 V/I characteristic of ideal compensator



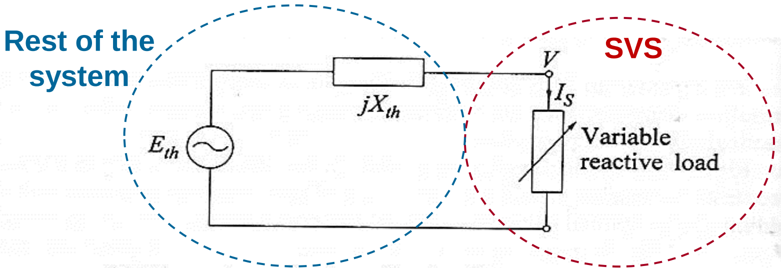
(a) Controllable reactor

(b) Fixed capacitor

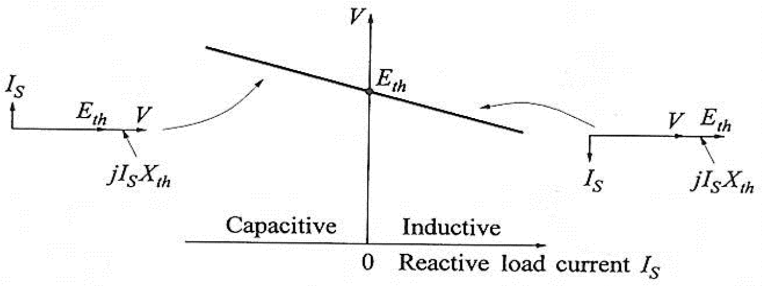
(c) SVS

Figure 11.41 Composite characteristics of an SVS

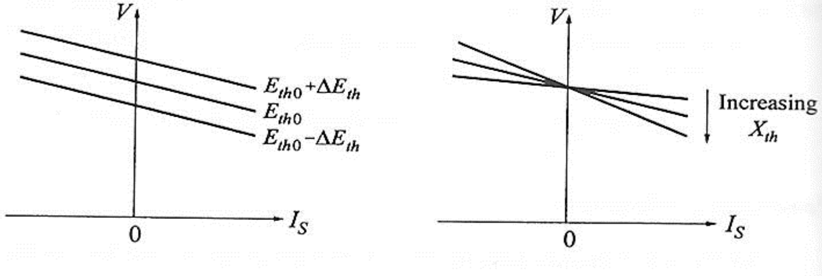
Considering Power System Characteristic



(a) Thevenin equivalent circuit of HVAC network



(b) Voltage-reactive current characteristic



(c) Effect of varying source voltage E_{th}

(d) Effect of varying system reactance X_{th}

Figure 11.42 Power system voltage versus reactive current characteristic [38]

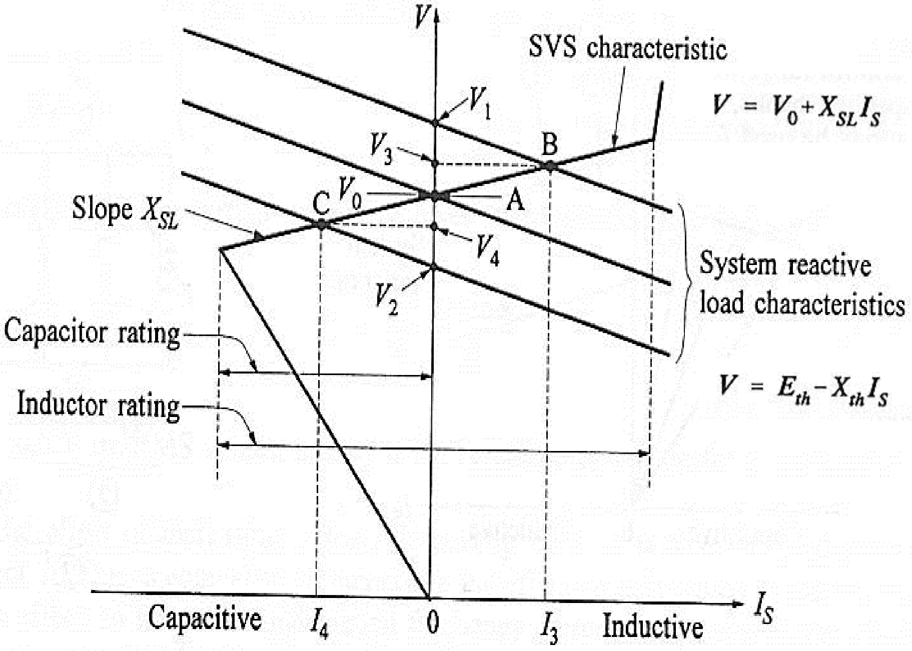


Figure 11.43 Graphical solution of SVS operating point for given system conditions

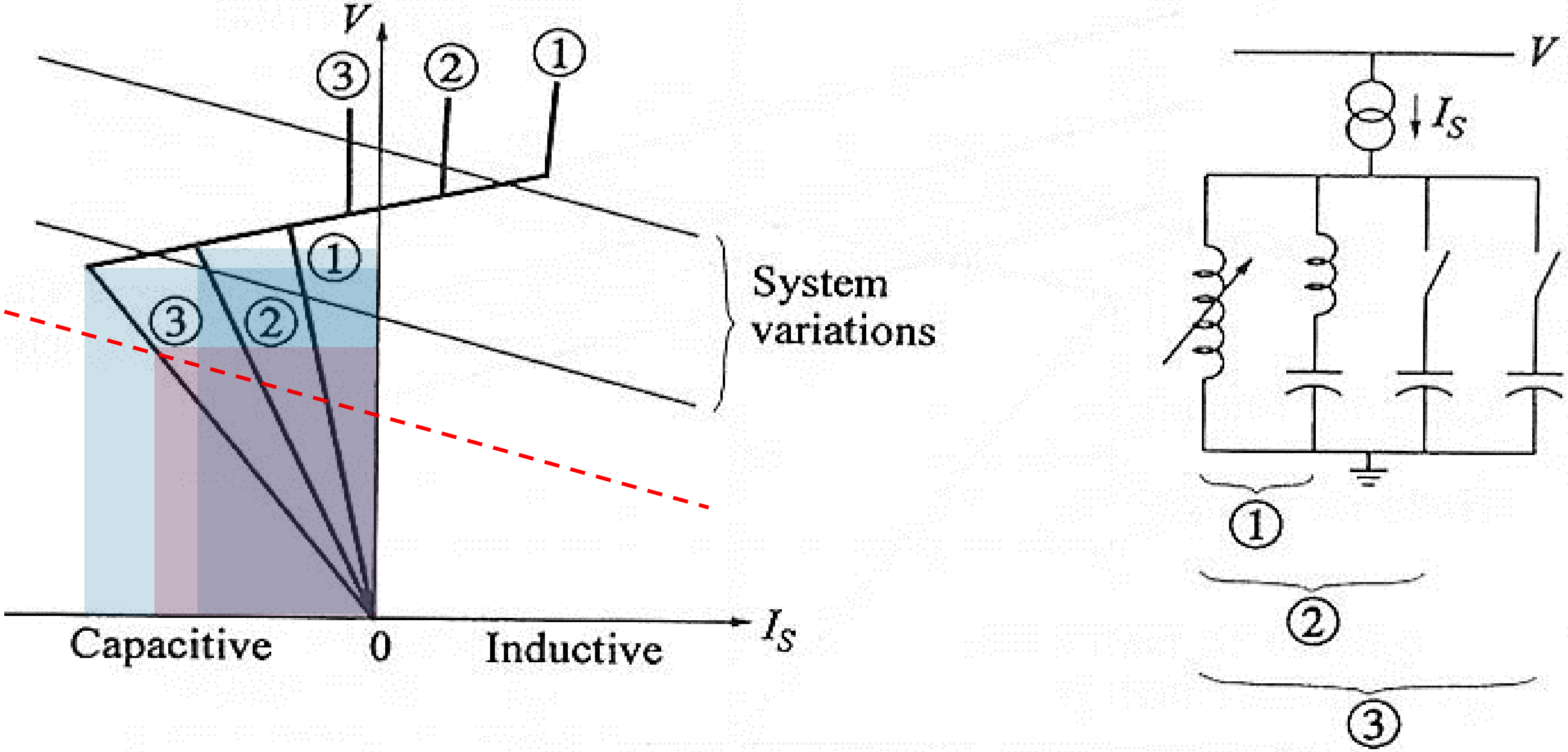


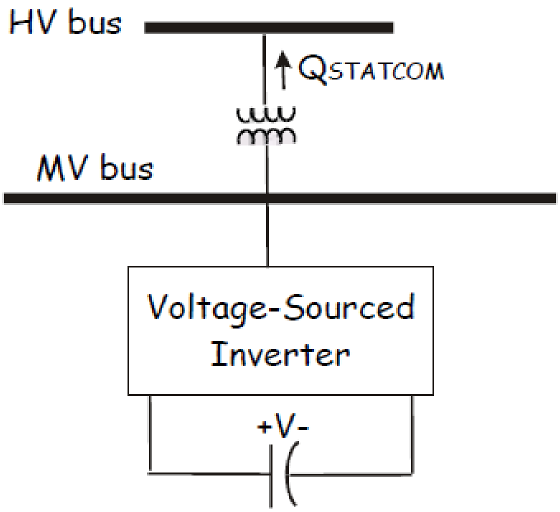
Figure 11.44 Use of switched capacitors to extend continuous control range

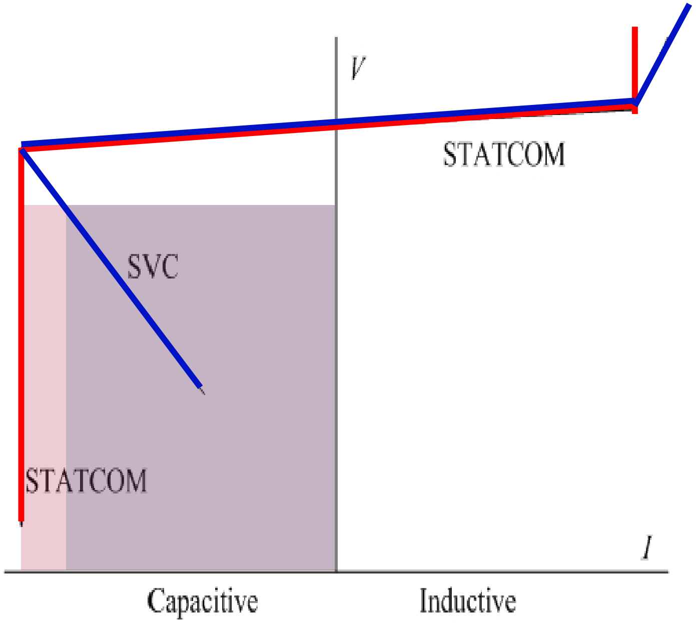
A major disadvantage of SVCs is that at their maximum output they behave as regular shunt capacitors and the Mvar produced is proportional to $|V|^2$.

Use of STATCOM

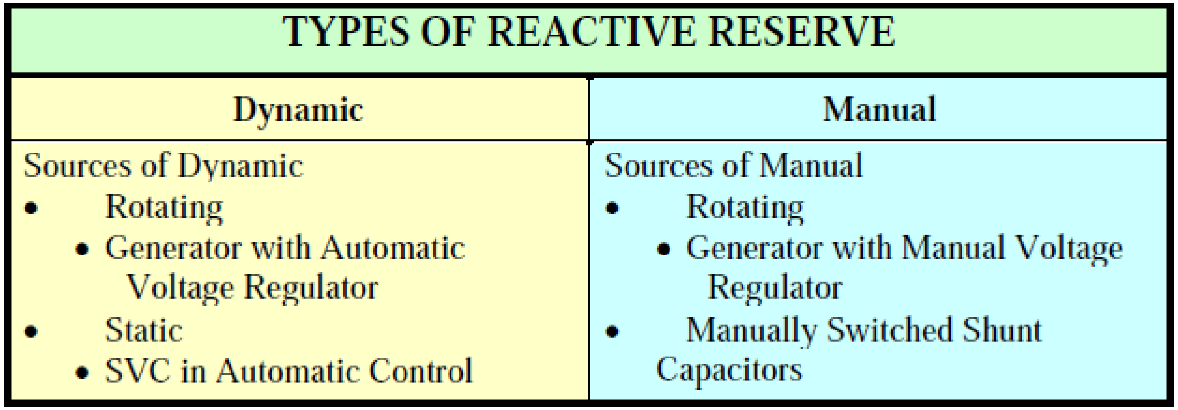
- Similar to synchronous condenser, STATCOM has an internal voltage source which provides constant output current even at very low voltages. Therefore, its Mvar output is linearly proportional to |V|.
- The voltage-sourced converter (VSC) converts the dc voltage into a three-phase set of output voltages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

M. Noroozian, C.W. Taylor, Benefits of SVC and STATCOM for Electric Utility Application, 2003 IEEE PES Transmission and Distribution Conference and Exposition, 7-12 Sept. 2003, vol. 3, pp. 1192-1199





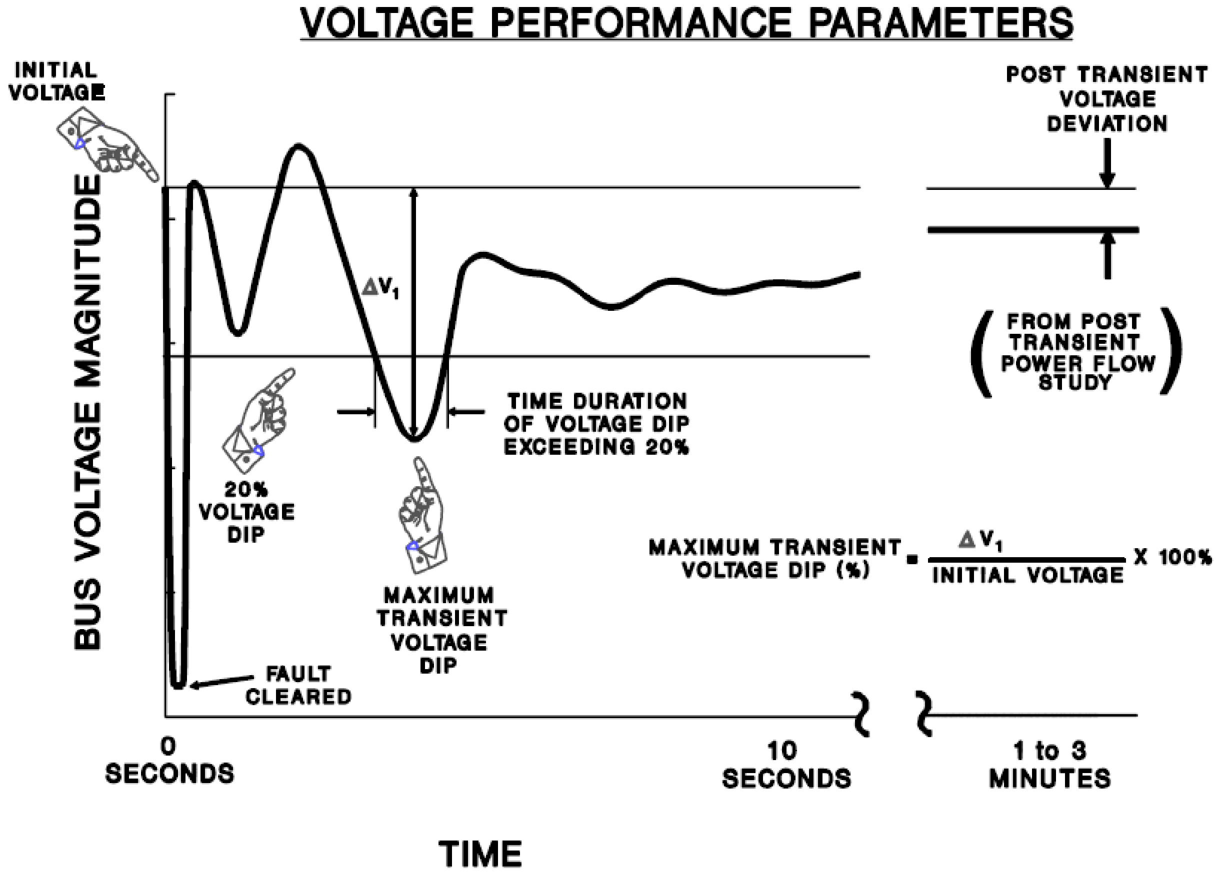
Reactive Reserves



TYPES OF REACTIVE RESERVE

Dynamic	Manual
Sources of Dynamic • Rotating • Generator with Automatic Voltage Regulator • Static • SVC in Automatic Control	Sources of Manual • Rotating • Generator with Manual Voltage Regulator • Manually Switched Shunt Capacitors

- Characteristics
  - Rotating (e.g. generators and synchronous condensers)
  - Static (e.g. shunt capacitors, SVC and STATCOM)
- Operations
  - Manual (requiring operator actions)
  - Dynamic (rapidly responding to voltage deviations within a few cycles to a few seconds)
- To respond to rapid unexpected system voltage deviations, a utility needs to carry sufficient dynamic reactive reserves in the better responding reactive resources (both Mvar production and absorption)



About motor Stalling

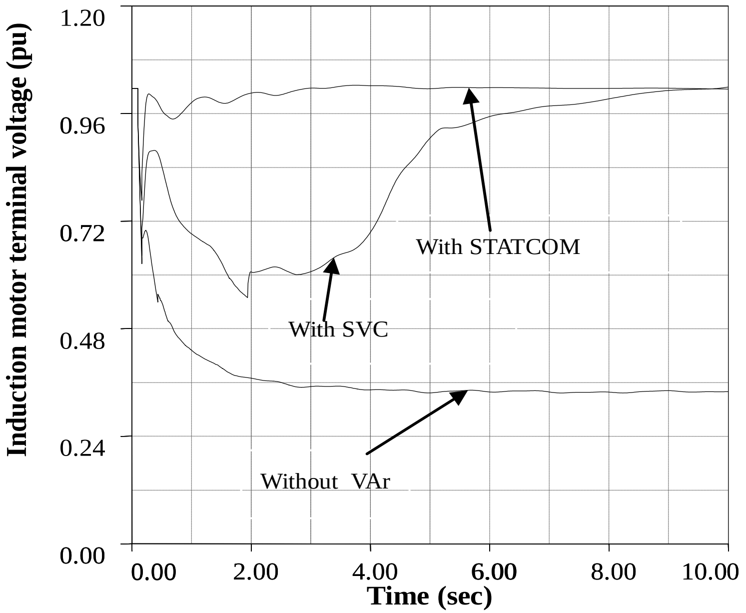
- Induction motors are designed to operate roughly at 90-110% of their rated voltage. If the system voltage declines to values below 70-80% of rated, motors may slow down or stall.
- Stalled motors may naturally try to regain speed as the system voltage attempts to recover. If enough motors have stalled, their combined reactive power draw could prevent a system voltage recovery.

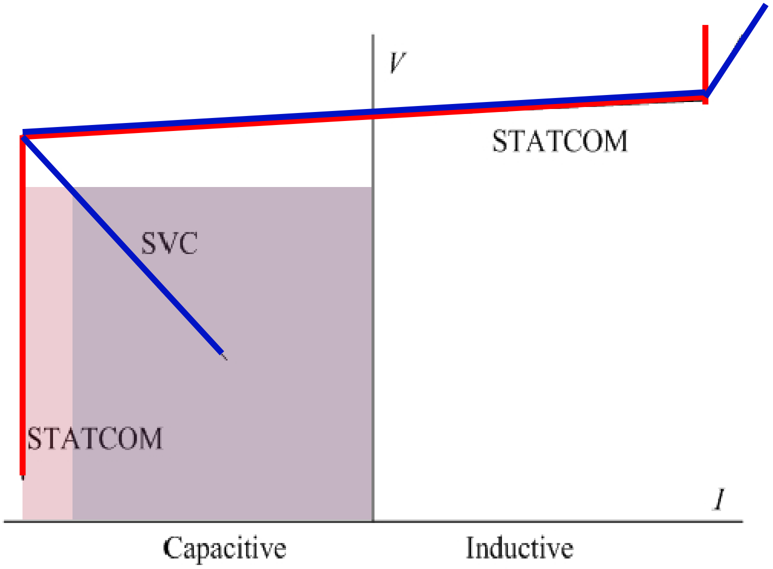
For example, NERC/WECC Planning standards require that following a Category B contingency,

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

Dynamic Reactive Reserves

- Generators are major resources of dynamic reactive reserves
  - For example, a utility may specify that all generators must have at least 50% Mvar capability (both lagging and leading) available to respond to unforeseen events.
  - If load is rising and generators are moving well up into their lagging region, the system operator may switch in shunt capacitors to supply Mvar in order to release Mvar reserves of generators.
- SVCs and STATCOMs can also provide dynamic reactive reserves





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