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 $Rl^2$ and $Xl^2$ losses to improve transmission system efficiency, i.e. leaving the room mainly for real power transfer
Active and Reactive Power Transfers

- $Q$ flows from the high voltage side to the low voltage side.
- But $Q$ cannot be transmitted over long distances because
  - It would require a large voltage gradient to do so.
  - An increase in $Q$ transfer causes an increase in $Q_{loss}$ as well as $P_{loss}$.

**Figure 6.21** Power transfer between two sources

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

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

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

\[
Q_{loss} = X I^2 = X \frac{P_R^2 + Q_R^2}{E_R^2}
\]

\[
P_{loss} = R I^2 = R \frac{P_R^2 + Q_R^2}{E_R^2}
\]

(a) Equivalent system diagram

(b) Phasor diagram
## Methods of Reactive Power and Voltage Control

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Supply Q</th>
<th>Absorb Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous generator</td>
<td>Y (Over-excited)</td>
<td>Y (Under-excited)</td>
</tr>
<tr>
<td>Overhead lines</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Underground cables</td>
<td>Mostly</td>
<td></td>
</tr>
<tr>
<td>Transformers</td>
<td></td>
<td>Y</td>
</tr>
<tr>
<td>Loads</td>
<td></td>
<td>Mostly</td>
</tr>
<tr>
<td>Compensating devices</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

- **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.
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 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.

• Power system considerations
  – The excitation system should contribute to effective control of voltage and enhancement of system stability under both large and small disturbances.
Reactive Capacity of a Generator

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)

\[ I_t < I_{t,\text{max}} : \text{Armature current heating limit} \]

\[ i_{fd} < i_{fd,\text{max}} : \text{Field current heating limit} \]

Always >0
>0 (over-excited)
or <0 (under-excited)

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

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

Ignore \( R_a \)
Elements of an 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.
Simplified linear model (ignoring saturations with the amplifier and exciter and other nonlinearities)

- **Rectifier/Sensor model:**
  - \( \tau_R \) is very small, e.g. 0.01 to 0.06s

- **Amplifier model:**
  - \( K_A = 10 \) to 400, \( \tau_A = 0.02 \) to 0.1s

- **Exciter model:**
  - \( \tau_E \) is very small for modern exciters

- **Generator model:**
  - \( K_G = 0.7 \) to 1.0, \( \tau_G = 1.0 \) to 2.0s from full load to no-load

What is \( \tau_G \)?

\[
\frac{\Delta V_t(s)}{\Delta V_F(s)} \approx \frac{\Delta \psi_d(s)}{\Delta e_{fd}(s)} = G_0 \frac{(1+sT_{kd})}{(1+sT_{d0}')(1+sT_{d0}'')}
\]
Open- and closed-loop transfer functions:

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

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

(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

\[ V_{tss} = \lim_{s \to 0} sV_t(s) = \frac{K_A K_E K_G}{1 + K_A K_E K_G K_R} \approx \frac{K_A}{1 + K_A} \]

If \( K_A \to \infty \), \( V_{tss} = V_{ref} \)
Saadat’s Example 12.6

The AVR system of a generator has the following parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Gain $K$</th>
<th>Time Constant $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifier</td>
<td>$K_A$</td>
<td>$\tau_A = 0.1$</td>
</tr>
<tr>
<td>Exciter</td>
<td>$K_E = 1$</td>
<td>$\tau_E = 0.4$</td>
</tr>
<tr>
<td>Generator</td>
<td>$K_G = 1$</td>
<td>$\tau_G = 1.0$</td>
</tr>
<tr>
<td>Sensor</td>
<td>$K_R = 1$</td>
<td>$\tau_R = 0.05$</td>
</tr>
</tbody>
</table>

(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.

![AVR block diagram for Example 12.6.](image)

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

$\frac{K_G(s)H(s)}{1 + KG(s)H(s)} = \frac{\frac{K_A}{(1 + 0.1s)(1 + 0.4s)(1 + s)(1 + 0.05s)}}{500K_A(s + 10)(s + 2.5)(s + 1)(s + 20)}$

\[= \frac{500K_A}{s^4 + 33.55s^3 + 307.5s^2 + 775s + 500}\]

(a) The characteristic equation is given by

\[1 + KG(s)H(s) = 1 + \frac{500K_A}{s^4 + 33.55s^3 + 307.5s^2 + 775s + 500} = 0\]

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)

<table>
<thead>
<tr>
<th>$s^4$</th>
<th>1</th>
<th>307.5</th>
<th>500 + 500$K_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s^3$</td>
<td>33.5</td>
<td>775</td>
<td>0</td>
</tr>
<tr>
<td>$s^2$</td>
<td>284.365</td>
<td>500 + 500$K_A$</td>
<td>0</td>
</tr>
<tr>
<td>$s^1$</td>
<td>58.9$K_A$ - 716.1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$s^0$</td>
<td>500 + 500$K_A$</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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.
• $K_A = 10, \quad V_{tss} = 0.909 V_{\text{ref}}$

• $K_A = 12.16, \quad V_{tss} = 0.924 V_{\text{ref}}$

• $K_A = 5, \quad V_{tss} = 0.833 V_{\text{ref}}$
Excitation System Stabilizers

- Rate feedback

\[
\begin{align*}
V_{ref}(s) &\rightarrow V_e(s) & V_R(s) &\rightarrow V_F(s) & V_I(s) \\
&\text{Amplifier} & &\text{Exciter} & \text{Generator} \\
&\frac{K_A}{1+\tau_A s} & &\frac{K_E}{1+\tau_E s} & \frac{K_G}{1+\tau_G s} \\
&\text{Stabilizer} & &\frac{K_F}{1+\tau_F s} & \frac{K_R}{1+\tau_R s} \\
&\text{Sensor} & & & \text{Sensor}
\end{align*}
\]

**FIGURE 12.35**
Block diagram of the compensated AVR system.

- PID control (sim12ex8.mdl)

\[
\begin{align*}
V_{ref}(s) &\rightarrow V_e(s) & V_R(s) &\rightarrow V_F(s) & V_I(s) \\
&\text{PID} & &\text{Exciter} & \text{Generator} \\
&\frac{K_P}{1+\tau_A s} + \frac{K_I}{s} + \frac{K_D s}{1} & &\frac{K_E}{1+\tau_E s} & \frac{K_G}{1+\tau_G s} \\
&\text{Amplifier} & & & \text{Sensor} \\
&\frac{K_P}{1+\tau_A s} & & & \frac{K_R}{1+\tau_R s}
\end{align*}
\]

**FIGURE 12.38**
AVR system with PID controller.
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 \( Q = \frac{V^2}{X_C} \), 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 \((V=0.95\text{pu})\), its actual output is 22.5 Mvar, i.e. 90% of the rated value \((Q=0.95^2=0.90\text{pu})\).
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 (output $Q=XCI^2$) under heavier power flows

• Disadvantage:
  – Sub-synchronous resonance (SSR) is often caused by the series-resonant circuit

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