**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 \(E_{fd} (K_A=0)\):**
- \(K_D > 0\)
- Perhaps, \(K_S = K_S(\text{gen & network}) + K_S(\Delta \psi_{fd}) < 0\)

**• With excitation control (large \(K_A\))**
- \(K_S > 0\)
- Perhaps, \(K_D = K_D(\text{gen & network}) + K_D(\Delta \psi_{fd}) < 0\)

![Figure 2.2 Nature of small-disturbance response](image-url)
For a given oscillation frequency $s=j\omega_{osc}$:

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

$$\rightarrow -\frac{K_2K_3(K_4+K_5K_A)}{K_3K_6K_A} \Delta \delta \text{ when } s \to 0$$

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

$$\Delta T_e|_{\Delta \psi_{fd}} = K_R \Delta \delta + K_I j \Delta \delta = K_R \Delta \delta + \frac{K_I\omega_0}{\omega_{osc}} \Delta \omega_r$$

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

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, $K_5<0$ to introduce a positive synchronizing torque.

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

(See Kundur’s Ch. 12.4 “Effects of Excitation System” for more details)
Example on effects of different AVR settings

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

- Steady-state synchronizing torque coefficient:

\[ \Delta T_e \bigg|_{\Delta \psi_{fd}} = \frac{-K_2 K_3 (K_4 + K_5 K_A)}{1 + K_3 K_6 K_A} \Delta \delta = \frac{0.06 K_A - 0.9}{1 + 0.1 K_A} \Delta \delta \]

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 \((f_{osc} = 1.59\text{Hz}, \ s = j\omega_{osc} = j10)\)

<table>
<thead>
<tr>
<th>(K_A)</th>
<th>(K_S(\Delta \psi_{fd}))</th>
<th>(K_S = K_1 + K_S(\Delta \psi_{fd}))</th>
<th>(K_D(\Delta \psi_{fd}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>-0.0025</td>
<td>1.5885</td>
<td>1.772</td>
</tr>
<tr>
<td>10.0</td>
<td>-0.0079</td>
<td>1.5831</td>
<td>0.614</td>
</tr>
<tr>
<td>15.0</td>
<td>-0.0093</td>
<td>1.5817</td>
<td>0.024</td>
</tr>
<tr>
<td>25.0</td>
<td>-0.0098</td>
<td>1.5812</td>
<td>-1.166</td>
</tr>
<tr>
<td>50.0</td>
<td>0.0029</td>
<td>1.5939</td>
<td>-4.090</td>
</tr>
<tr>
<td>100.0</td>
<td>0.0782</td>
<td>1.6692</td>
<td>-8.866</td>
</tr>
<tr>
<td>200.0</td>
<td>0.2804</td>
<td>1.8714</td>
<td>-12.272</td>
</tr>
<tr>
<td>400.0</td>
<td>0.4874</td>
<td>2.0784</td>
<td>-9.722</td>
</tr>
<tr>
<td>1000.0</td>
<td>0.5847</td>
<td>2.1757</td>
<td>-4.448</td>
</tr>
<tr>
<td>Infinity</td>
<td>0.6000</td>
<td>2.1910</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Power System Stabilizer (PSS) (See Kundur’s Ch. 12.5)

- The basic function is to add damping to generator oscillations by controlling its exciter using non-voltage auxiliary signal(s)
  - If the transfer function from \( G_{PSS}(s) \)’s output to \( \Delta T_e \) was a pure gain, \( G_{PSS}(s) \) could be a pure gain (i.e. a direct feedback of \( \Delta \omega_r \)) to create a positive damping torque.
  - However, the actual generator and exciter exhibit a frequency dependent gain and phase-lag characteristics. Therefore, \( G_{PSS}(s) \) should provide phase-lead compensation to create a torque in phase with \( \Delta \omega_r \)

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

![Block diagram representation with AVR and PSS](image-url)

**Figure 12.13**  Block diagram representation with AVR and PSS
PSS Model

Figure 12.14 Thyristor excitation system with AVR and PSS

- **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 $\omega_r$ 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. $\omega=0.6$ 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

$T_W=10s \ (\omega_w=0.1\text{rad/s} \ \rightarrow \ 0.016\text{Hz})$

$T_1=0.4s \ (\omega_{osc1}=2.5\text{rad/s} \ \rightarrow \ 0.4\text{Hz})$

$T_2=0.04s \ (\omega_{osc2}=25\text{rad/s} \ \rightarrow \ 4.0\text{Hz})$
PSS/E ST2CUT stabilizer

States
1 - Transducer1
2 - Transducer2
3 - Washout
4 - LL1
5 - LL2
6 - Unlimited Signal

Model supported by PSSE

Form Edit - ST2CUT

<table>
<thead>
<tr>
<th>IBUS</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>IB2</td>
<td>0</td>
</tr>
<tr>
<td>T2</td>
<td>0.0000</td>
</tr>
<tr>
<td>T6</td>
<td>0.0400</td>
</tr>
<tr>
<td>T10</td>
<td>0.0000</td>
</tr>
<tr>
<td>VCL</td>
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<table>
<thead>
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<tbody>
<tr>
<td>Zone</td>
<td>70</td>
</tr>
<tr>
<td>IC1</td>
<td>2</td>
</tr>
<tr>
<td>K1</td>
<td>5.5000</td>
</tr>
<tr>
<td>K2</td>
<td>0.0000</td>
</tr>
<tr>
<td>T3*</td>
<td>10.0000</td>
</tr>
<tr>
<td>T7</td>
<td>0.0000</td>
</tr>
<tr>
<td>LS MAX</td>
<td>0.0500</td>
</tr>
<tr>
<td>LS MIN</td>
<td>-0.0500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bus</th>
<th>CRAIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC2</td>
<td>0</td>
</tr>
<tr>
<td>IB1</td>
<td>0</td>
</tr>
<tr>
<td>T4</td>
<td>10.0000</td>
</tr>
<tr>
<td>T8</td>
<td>0.0000</td>
</tr>
<tr>
<td>T9</td>
<td>0.0000</td>
</tr>
<tr>
<td>VCU</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T_w</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_w</td>
</tr>
</tbody>
</table>

Washout
Phase compensation

Gain

Output Limiter

\[
\begin{align*}
V_s &= V_{ss} \text{ if } (V_{cu} + V_{to} > V_T + V_{cl} + V_{to}) \\
V_s &= 0 \text{ if } (V_T < V_{to} + V_{cl}) \\
V_s &= 0 \text{ if } (V_{ct} > V_{to} + V_{cu}) \\
V_{20} &= \text{initial terminal voltage} \\
V_2 &= \text{terminal voltage}
\end{align*}
\]
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 ($X^2$), while contributing to improved voltage control

• Advantage:
  – “Self-regulating” nature: unlike a shunt capacitor, series capacitors produce more reactive power (output $Q=XC^2$) under heavier power flows

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

\[ f_n = f_0 \sqrt{XC/X_L} \quad (f_n = 19\text{Hz for 10% series compensation, i.e. } XC=0.1X_L) \]
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
Table 6.1 Typical overhead transmission line parameters

<table>
<thead>
<tr>
<th>Nominal Voltage</th>
<th>230 kV</th>
<th>345 kV</th>
<th>500 kV</th>
<th>765 kV</th>
<th>1,100 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R \ (\Omega/\text{km})$</td>
<td>0.050</td>
<td>0.037</td>
<td>0.028</td>
<td>0.012</td>
<td>0.005</td>
</tr>
<tr>
<td>$x_L = \omega L \ (\Omega/\text{km})$</td>
<td>0.488</td>
<td>0.367</td>
<td>0.325</td>
<td>0.329</td>
<td>0.292</td>
</tr>
<tr>
<td>$b_C = \omega C \ (\mu\text{s}/\text{km})$</td>
<td>3.371</td>
<td>4.518</td>
<td>5.200</td>
<td>4.978</td>
<td>5.544</td>
</tr>
<tr>
<td>$\alpha \ (\text{nepers/\text{km}})$</td>
<td>0.000067</td>
<td>0.000066</td>
<td>0.000057</td>
<td>0.000025</td>
<td>0.000012</td>
</tr>
<tr>
<td>$\beta \ (\text{rad/\text{km}})$</td>
<td>0.00128</td>
<td>0.00129</td>
<td>0.00130</td>
<td>0.00128</td>
<td>0.00127</td>
</tr>
<tr>
<td>$Z_C \ (\Omega)$</td>
<td>380</td>
<td>285</td>
<td>250</td>
<td>257</td>
<td>230</td>
</tr>
<tr>
<td>SIL (MW)</td>
<td>140</td>
<td>420</td>
<td>1000</td>
<td>2280</td>
<td>5260</td>
</tr>
<tr>
<td>Charging MVA/km = $V_0^2 b_C$</td>
<td>0.18</td>
<td>0.54</td>
<td>1.30</td>
<td>2.92</td>
<td>6.71</td>
</tr>
</tbody>
</table>

Notes:
1. Rated frequency is assumed to be 60 Hz.
2. Bundled conductors are 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.

(Source: Kundur’s book)
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.

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
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 filter - 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

• From Kundur’s Pages 640-645

![Diagram of HVAC bus with ideal static var system](image1)

**Figure 11.39** Idealized static var system

![Ideal V/I characteristic](image2)

**Figure 11.40** V/I characteristic of ideal compensator

![Composite characteristics of an SVS](image3)

**Figure 11.41** Composite characteristics of an SVS
Disadvantage of SVCs

- At their maximum outputs, SVCs downgrade to regular shunt capacitors and the Mvar produced is proportional to $|V|^2$. 
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.

FIDVR (Fault-Induced Delayed Voltage Recovery)

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