2.3 Modeling of frequency and voltage regulation
Generator Control Loops

• For each generator,
  – **LFC** (Load Frequency Control) loop controls the frequency (or real power output)
  – **AVR** (Automatic Voltage Regulator) loop controls the voltage (or reactive power output)

• The LFC and AVR controllers are set for a particular steady-state operating condition to maintain frequency and voltage against small changes in load demand.

• Cross-coupling between the LFC and AVR loops is negligible because the excitation-system time constant is much smaller than the prime mover/governor time constants.

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

• Under normal conditions, frequency in a large Interconnected power system (e.g. the Eastern Interconnection) varies approximately ±0.03Hz from the scheduled value.

• Under abnormal events, e.g. loss of a large generator unit, frequency experiences larger deviations.
Impact of Abnormal Frequency Deviations

- Prolonged operation at frequencies above or below 60Hz can damage power system equipment.
- Turbine blades of steam turbine generators can be exposed to only a certain amount of off-frequency operation over their entire lifetime.
- Steam turbine generators often have under- and over-frequency relays installed to trip the unit if operated at off-frequencies for a period

A typical steam turbine can be operated, under load, for 10 minutes over the lifetime at 58Hz before damage is likely to occur to the turbine blades.
Governor Model

Classic Watt Centrifugal Governing System

Speed changer

Linkage mechanism

Speed governor

Hydraulic Amplifier

Figure 11.1 Servo-assisted speed governor.
Governor Model

- Without a governor, the generator speed drops when load increases
- The speed governor closes the loop for negative feedback control
  - For stable operation, the governor reduces (does not eliminate) the speed drop due to load increase.
  - Usually, speed regulation $R$ is 5-6% from zero to full load
  - Governor output $\Delta \omega / R$ is compared to the change in the reference power $\Delta P_{ref}$
    \[
    \Delta P_g = \Delta P_{ref} - \Delta \omega / R
    \]
  - The difference $\Delta P_g$ is transformed through the hydraulic amplifier to the steam valve/gate position command $\Delta P_v$ with time constant $\tau_g$

Governor steady-state speed characteristics (i.e. how the speed drops as load increases)
Load Frequency Control block Diagram

- For a step load change, i.e. $-\Delta P_L(s) = -\Delta P_L/s$

$$\Delta \omega_{ss} = \lim_{s \to 0} s\Delta \omega_r(s) \quad \Rightarrow \quad \Delta \omega_{ss} = \frac{-\Delta P_L}{D + 1/R}$$

- For $n$ generators supporting the load:

$$\Delta \omega_{ss} = \frac{-\Delta P_L}{D + 1/R_{eq}}$$

$R_{eq}$

$$\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} = R_1 / \cdots / R_n$$

$t_g$ is very small
$t_T$ is in 0.2~2.0 s
$R$ is around 0.05 pu
Relationships between Load, Speed Regulation and Frequency

Governor Speed characteristic

\[ \Delta \omega_{ss} = \frac{-\Delta P_L}{D + 1/ R_{eq}} \]

D ↑ (more frequency-dependent load), R ↓ (stronger LFC feedback) → Δf ↓
Stability Analysis on LFC

Substituting the system parameters in the LFC block diagram of Figure 12.10 results in the block diagram shown in Figure 12.11.

Open-loop transfer function:

\[ KG(s)H(s) = \frac{K}{(10s + 0.8)(1 + 0.2s)(1 + 0.5s)} \]

Characteristic polynomial:

\[ s^3 + 7.08s^2 + 10.56s + 0.8 + K = 0 \]

When \( s = \pm j3.25 \), \( K_{\text{max}} = 73.965 \)

so, \( R > 0.0135 \)
IEEE Type 1 Speed-Governor Model: IEEEG1/IEESEG1_GE

**States**
1. Governor Output
2. Lead-Lag
3. Turbine Bowl
4. Reheater
5. Crossover
6. Double Reheat

IEEEG1_GE is supported by PSLF. PowerWorld ignores the db2 term. All values are specified on the turbine rating which is a parameter in PowerWorld and PSLF. If the turbine rating is omitted or zero, then the generator MVABase is used. If there are two generators, then the SUM of the two MVABases is used.

IEEEG1 is supported by PSSE. PSSE does not include the db2, db1, non-linear gain term, or turbine rating. For the IEEEG1 model, if the turbine rating is omitted then the MVABase of only the high-pressure generator is used.

GV1, PGV1...GV6, PGV6 are the x,y coordinates of $P_{GV}$ vs. $GV$ block

---

**Form Edit - IEEEG1**

<table>
<thead>
<tr>
<th>IBUS</th>
<th>IBUS</th>
<th>BUS</th>
<th>CORONADO</th>
<th>Area</th>
<th>Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>T1</td>
<td>0.1000</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>T2</td>
<td>0.0000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-1.0000</td>
<td>PMAX</td>
<td>0.9500</td>
<td></td>
<td>0.2000</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>K1</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>T6</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>T7</td>
<td>8.7200</td>
<td>0.7000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>K7</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>Pgen (Powerflow)</td>
<td>541.4351</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pmax (Powerflow)</td>
<td>9999.0000</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Underfrequency Load Shedding (UFLS)

- In many situations, the frequency decline may lead to tripping of steam turbine generators by underfrequency protective relays, thus aggravating the situation further.
- UFLS is a protection program that automatically trips selected customer loads once frequency falls below a specific value.
- The intent of UFLS is not to recover the frequency to 60 Hz but rather to arrest or stop the frequency decline. Once UFLS has operated, manual intervention by the system operators is likely required to restore the system frequency to a healthy state.

- A typical UFLS setting for a North American utility may include three steps conducted by under-frequency relays, e.g.,
  - shedding 10% load at 59.3 Hz
  - shedding 10% additional load at 59.0 Hz, and
  - shedding 10% more at 58.7 Hz
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)

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

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

Always >0

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

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

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

\[ E_q = X_{ad} i_{fd} \]

\[ R_a I_t \sin \phi \]

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. 0.01~0.06s

- **Amplifier model:**
  - $K_A=10$~400, $\tau_A=0.02$~0.1s

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

- **Generator model:**
  - $K_G=0.7$~1, $\tau_G=1.0$~2.0s from full load to no-load

What is $\tau_G$?

$$\frac{\Delta V_t(s)}{s \Delta V_F(s)} = \frac{\Delta \psi_d(s)}{\Delta e_{fd}(s)} = \frac{G_o}{(1+sT_{kd})(1+sT_{d0}')(1+sT_{d0}''')}$$
Simplified Linear Model

- Open- and closed-loop transfer functions:

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

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

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

\[
V_{tss} = \lim_{s \to 0} sV_t(s) = \frac{K_A K_E K_G}{1 + K_A K_E K_G K_R} \approx \frac{K_A}{1 + K_A} \quad \text{If } K_A \to \infty, \quad V_{tss} = V_{ref}
\]
Detailed excitation system model

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

Figure 8.38 Terminal voltage transducer and load compensator model

Figure 8.39 Structure of a detailed excitation system model
IEEE Type DC2A Excitation System Model: ESDC2A

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

<table>
<thead>
<tr>
<th>Form Edit - ESDC2A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IBUS</strong></td>
</tr>
<tr>
<td><strong>1</strong></td>
</tr>
<tr>
<td><strong>TB</strong></td>
</tr>
<tr>
<td><strong>KE</strong></td>
</tr>
<tr>
<td><strong>E1</strong></td>
</tr>
<tr>
<td><strong>MVA Base</strong></td>
</tr>
<tr>
<td><strong>Bus</strong></td>
</tr>
<tr>
<td><strong>TR</strong></td>
</tr>
<tr>
<td><strong>TC</strong></td>
</tr>
<tr>
<td><strong>TE</strong></td>
</tr>
<tr>
<td><strong>SE(E1)</strong></td>
</tr>
<tr>
<td><strong>Area</strong></td>
</tr>
<tr>
<td><strong>KA</strong></td>
</tr>
<tr>
<td><strong>VRMAX</strong></td>
</tr>
<tr>
<td><strong>VRMIN</strong></td>
</tr>
<tr>
<td><strong>Zone</strong></td>
</tr>
<tr>
<td><strong>TA</strong></td>
</tr>
<tr>
<td><strong>KF</strong></td>
</tr>
<tr>
<td><strong>TF1</strong></td>
</tr>
<tr>
<td><strong>E2</strong></td>
</tr>
<tr>
<td><strong>SE(E2)</strong></td>
</tr>
<tr>
<td><strong>Status</strong></td>
</tr>
</tbody>
</table>
Stability Analysis on AVR

See Example 7.8 in Anderson’s “Power System Control and Stability” for details on choosing $K_F$ and $\tau_F$

$$KGH = \frac{K_A K_F}{\tau_A \tau_E \tau_F} \frac{s(s + 1/\tau_G)(s + 1/\tau_R) + (K_R K_G \tau_F/\tau_R \tau_G K_F)(s + 1/\tau_F)}{(s + 1/\tau_A)(s + K_E/\tau_E)(s + 1/\tau_G)(s + 1/\tau_F)(s + 1/\tau_R)}$$
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 $K_R = 1.0$,

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

### $\tau_F > 1$

**Case 1 A**

### $0.05 < \tau_F < 1$

**Case II A**

### $\tau_F < 0.05$

**Case III A**
Influence of excitation control on angular stability

\[ \Delta T_e = \Delta T_S + \Delta T_D = K_S \Delta \delta + K_D \Delta \omega \]

- \( K_S = K_{S(\Delta \psi fd)} + K_{S(\text{gen & network})} \)
- \( K_D = K_{D(\Delta \psi fd)} + K_{D(\text{gen & network})} \)

Usually, \( K_S(\text{gen & network}) > 0 \)
\( K_D(\text{gen & network}) > 0 \)

- Constant field voltage (\( K_A = 0 \)):
  - \( K_D > 0 \)
  - 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*
For a given oscillation frequency $s=j\omega$:

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

$$= K_S(\Delta \psi_{fd}) \Delta \delta + K_D(\Delta \psi_{fd}) \Delta \omega_r$$

Synchronizing and damping torque coefficients due to $\Delta \psi_{fd}$

- The effect of the AVR on damping and synchronizing torque components is primarily influenced by $G_{ex}(s)$ and $K_5$

- Usually, $K_5 < 0$ to introduce a positive synchronizing torque

$K_R$ and $K_I$ are respectively the real and imaginary parts of the coefficient of $\Delta \delta$

$$j\Delta \delta = j\omega \Delta \delta / \omega = s \Delta \delta / \omega = \Delta \omega_r \omega_0 / \omega$$
Example on effects of different AVR settings

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

- Steady-state synchronizing torque coefficient:

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

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=1.59Hz, s=jω=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)

- 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 $\Delta \omega_r$

\[
G_{PSS}(s) = \frac{1 + \tau_1 s}{1 + \tau_2 s}, \quad \tau_1 > \tau_2
\]

Figure 12.13 Block diagram representation with AVR and PSS
PSS Model

- **Stabilizer gain** $K_{STAB}$
  - determines the amount of damping introduced by PSS

- **Signal washout block:**
  - High-pass filter with $T_W$ long enough (typically 1~20s) 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, $f=0.1$~2.0 Hz, i.e. $\omega=0.6$~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 as well
PSS/E ST2CUT stabilizer

Input Signal #1: \( \frac{K_1}{1+sT_1} \)

Input Signal #2: \( \frac{K_2}{1+sT_2} \)

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>IC1</th>
<th>K1</th>
<th>T2</th>
<th>T6</th>
<th>T10</th>
<th>VCL</th>
<th>Bus</th>
<th>Area</th>
<th>Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5.5</td>
<td>0.0000</td>
<td>0.0400</td>
<td>0.0000</td>
<td>0.0000</td>
<td>CRAIG</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>IC2</td>
<td>K2</td>
<td>T3*</td>
<td>T7</td>
<td>LSMax</td>
<td>MVA Base</td>
<td></td>
<td>1488.0000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.0000</td>
<td>0.0000</td>
<td>0.0500</td>
<td>Status</td>
<td>0.0000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Output Limiter:
- \( V_S = V_{ss} \) if \((V_{cu} + V_{to} > V_T > V_{ct} + V_{to})\)
- \( V_S = 0 \) if \((V_T < V_{to} + V_{ct})\)
- \( V_S = 0 \) if \((V_{ct} > V_{to} + V_{cu})\)

\( V_{to} \) = initial terminal voltage
\( V_T \) = terminal voltage

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
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

![Figure 11.39 Idealized static var system](image)

![Figure 11.40 V/I characteristic of ideal compensator](image)

![Figure 11.41 Composite characteristics of an SVS](image)
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.

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