4 – Frequency Control

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Instructor: Kai Sun
Generator Control Loops

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

• The frequency of a system depends on real power balance.
  – Changes in real power affect mainly the system frequency,
  – reactive power is less sensitive to changes in frequency and mainly depends on changes in voltage magnitude.

• As frequency is a common factor throughout the system, a change in real power at one point is reflected through the system by a change in frequency.

• In an interconnected system with two or more independently controlled areas, in addition to control of frequency, the generation within each area has to be controlled so as to maintain scheduled power interchange.

• The control of generation and frequency is commonly referred to as Load Frequency Control (LFC), which involves
  – Speed governing system with each generator
  – Automatic Generation Control (AGC) for interconnected systems
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.
**Speed Governing System (LFC Loop)**

\[ P = \omega_r T \]

- Under the rated condition:
  \[ \omega_r = \omega_0 = 1 \text{ pu}, \quad P_m = P_e = P_0 = \omega_0 T_0 = T_0 = T_m = T_e \]

- Under a small change (\( \Delta \omega_r \ll \omega_0 \)) around the rated condition:
  \[ \omega_r = 1 + \Delta \omega_r \text{ pu}, \quad P_m - P_e = \Delta P_m - \Delta P_e = (1 + \Delta \omega_r)(T_m - T_e) \approx T_m - T_e = \Delta T_m - \Delta T_e \]
Generator and Load Models

**Generator:**

\[
2H \frac{d(\Delta \omega_r)}{dt} = T_m - T_e = P_m - P_e = \Delta P_m - \Delta P_e
\]

\[
\frac{1}{\omega_0} \frac{d \delta}{dt} = \Delta \omega_r
\]

**Load:**

\[
\Delta P_e = \Delta P_L + D \Delta \omega_r
\]

- \(\Delta P_L\) Frequency-insensitive load change (due to ZIP load)
- \(D \Delta \omega_r\) Frequency-sensitive load change (due to the total effect of external frequency-dependent load and the damping coefficient of the generator)

Damping constant \(D\) (pu) = % change in load per 1% frequency change

\[
2Hs \Delta \omega_r = \Delta P_m - \Delta P_e = \Delta P_m - \Delta P_L - D \Delta \omega_r.
\]

\[
(2Hs + D) \Delta \omega_r = \Delta P_m - \Delta P_L
\]
## Frequency Deviation with LFC Loop Open

<table>
<thead>
<tr>
<th>M=2H</th>
<th>D</th>
<th>( \Delta P_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 sec</td>
<td>0.75 pu</td>
<td>-0.01 pu</td>
</tr>
<tr>
<td>(load varies by 0.75% by 1 % change in of frequency)</td>
<td>(10MW decrease on 1GW)</td>
<td></td>
</tr>
</tbody>
</table>

For a step change of load by -0.01pu:

\[
\Delta P_L(s) = \frac{-0.01}{s}
\]

Speed (or frequency) deviation:

\[
\Delta \omega_r(s) = -\left(\frac{-0.01}{s}\right)\left(\frac{K}{1+sT}\right) = \frac{-0.01K}{s+1/T} + \frac{0.01K}{s}
\]

\[
\Delta \omega_r(t) = -0.01Ke^{-\frac{t}{T}} + 0.01K
\]

\[
= -0.01 \times 1.33 e^{-\frac{t}{13.33}} + 0.01 \times 1.33
\]

\[
= -0.0133 e^{-0.075t} + 0.0133
\]

\[
K = \frac{1}{D} = \frac{1}{0.75} = 1.33
\]

\[
T = \frac{M}{D} = \frac{10}{0.75} = 13.33 \text{ s}
\]

\[
0.0133 \times 60 = 0.8 \text{ Hz}
\]
Governor Model

**Classic Watt Centrifugal Governing System**

Speed changer (setting the reference power/speed)

**Linkage mechanism**

![Diagram of a classic Watt centrifugal governing system](image)

**Speed governor**

![Diagram showing components of the speed governor](image)

**Hydraulic Amplifier**

**Figure 11.1** Servo-assisted speed governor.
Governor Model

• Without a governor, the generator speed drops significantly when load increases

• The speed governor closes the loop of negative feedback control
  – For stable operation, the governor reduces (but does not eliminate) the speed drop due to load increase.
  – Usually, speed regulation $R$ is 5-6% from zero to full load
  – Governor output $\Delta \omega_f/R$ is compared to the change in the reference power $\Delta P_{ref}$
    $$\Delta P_g = \Delta P_{ref} - \Delta \omega_f/R$$
  – The difference $\Delta P_g$ is then transformed through the hydraulic amplifier to the steam valve/gate position command $\Delta P_v$ with time constant $\tau_g$
Governor Speed characteristic

**Governor Speed characteristic**

**Slope = -R**

**Total Load Characteristic**

**Slope = 1/D**

**Frequency-sensitive Load Characteristic**

**Frequency-insensitive Load Characteristic**

If $D \uparrow$ (more frequency-dependent load), then $\Delta f \downarrow$

If $R \downarrow$ (stronger LFC feedback), then $\Delta f \downarrow$

$$-\Delta P_L = \Delta \omega_{ss} (D + 1/R)$$
Turbine Model

The prime mover, i.e. the source of mechanical power, may be a hydraulic turbine at water falls, a steam turbine burning coal and nuclear fuel, or a gas turbine.

The model for the turbine relates changes in mechanical power output $\Delta P_m$ to changes in gate or valve position $\Delta P_V$.

\[ G_T(t) = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1+\tau_T s} \]

$\tau_T$ is in 0.2-2.0 seconds.
Load Frequency Control block Diagram

\[
\begin{align*}
\Delta \omega_r(s) &= \frac{(1 + \tau_T s)(1 + \tau_g s)}{(2Hs + D)(1 + \tau_T s)(1 + \tau_g s) + 1/R} \\
-\Delta P_L(s) &= \frac{(1 + \tau_T s)(1 + \tau_g s)}{(2Hs + D)(1 + \tau_T s)(1 + \tau_g s) + 1/R}
\end{align*}
\]

- 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:

\[
\Delta \omega_{ss} = \frac{-\Delta P_L}{D + 1/R} \quad \Rightarrow \quad \Delta \omega_{ss} = \frac{-\Delta P_L}{D + 1/R}
\]

\[
R_\Sigma = \frac{1}{1/R_1 + 1/R_2 + \cdots + 1/R_n} = R_1 / R_2 / \cdots / R_n
\]

The smaller \(R\) the better?

**Figure 11.12** Response of a generating unit with a governor having speed-droop characteristic
Saadat’s Example 12.1

Example 12.1  (chp12ex1)

An isolated power station has the following parameters

- Turbine time constant $\tau_T = 0.5$ sec
- Governor time constant $\tau_g = 0.2$ sec
- Generator inertia constant $H = 5$ sec
- Governor speed regulation $= R$ per unit

The load varies by 0.8 percent for a 1 percent change in frequency, i.e., $D = 0.8$

(a) Use the Routh-Hurwitz array (Appendix B.2.1) to find the range of $R$ for control system stability.

(b) Use MATLAB `rlocus` function to obtain the root locus plot.

(c) The governor speed regulation of Example 12.1 is set to $R = 0.05$ per unit. The turbine rated output is 250 MW at nominal frequency of 60 Hz. A sudden load change of 50 MW ($\Delta P_L = 0.2$ per unit) occurs.

(i) Find the steady-state frequency deviation in Hz.

(ii) Use MATLAB to obtain the time-domain performance specifications and the frequency deviation step response.

(d) Construct the SIMULINK block diagram (see Appendix A.17) and obtain the frequency deviation response for the condition in part (c).
Substituting the system parameters in the LFC block diagram of Figure 12.10 results in the block diagram shown in Figure 12.11.

![Block Diagram](image)

**FIGURE 12.11**
LFC block diagram for Example 12.1.

The open-loop transfer function is

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

where \( K = \frac{1}{R} \)

(a) The characteristic equation is given by

\[ 1 + KG(s)H(s) = 1 + \frac{K}{s^3 + 7.08s^2 + 10.56s + 0.8} = 0 \]

which results in the characteristic polynomial equation

\[ s^3 + 7.08s^2 + 10.56s + 0.8 + K = 0 \]
Routh-Hurwitz Stability Criterion

• **Characteristic equation**
  \[ a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0 = 0 \quad (a_n > 0) \]

• **Routh table:**
  For \( i > 2 \),
  \[ x_{ij} = \frac{x_{i-2,j+1} x_{i-1,1} - x_{i-2,1} x_{i-1,j+1}}{x_{i-1,1}} \]
  where \( x_{ij} \) is the element in the \( i \)-th row and \( j \)-th column

\[
\begin{array}{c|cccc}
  s^n & a_n & a_{n-2} & a_{n-4} & \ldots \\
  \hline
  s^{n-1} & a_{n-1} & a_{n-3} & a_{n-5} & \ldots \\
  s^{n-2} & b_1 & b_2 & b_3 & \ldots \\
  s^{n-3} & c_1 & c_2 & c_3 & \ldots \\
  \vdots & \vdots & \vdots & \vdots & \vdots \\
  b_1 &=& \frac{a_{n-1} a_{n-2} - a_n a_{n-3}}{a_{n-1}} \quad \text{etc.} \\
  b_2 &=& \frac{a_{n-1} a_{n-4} - a_n a_{n-5}}{a_{n-1}} \\
  c_1 &=& \frac{b_1 a_{n-3} - a_{n-1} b_2}{b_1} \quad \text{etc.} \\
  \end{array}
\]

• **Routh-Hurwitz criterion:** No. of roots of the equation with positive real parts = No. of changes in sign of the 1st column of the Routh table

• **Necessary and sufficient condition for a linear system to be stable:** The 1st column only has positive numbers

\[
\begin{array}{c|cc}
  s^3 & 1 & 10.56 \\
  s^2 & 7.08 & 0.8 + K \\
  s^1 & 73.965 - K & 0 \\
  s^0 & 7.08 & 0.8 + K \\
  \end{array}
\]

• \( s^1 \) row > 0 if \( K < 73.965 \)
• \( s^0 \) row > 0 since \( K > 0 \)
• So \( R = 1/K > 1/73.965 = 0.0135 \)