Relationships between Load, Speed Regulation and Frequency

Governor Speed characteristic

Slope = \(-R\)

Total Load Characteristic

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 $\Delta f \downarrow$
Governor Model

Classic Watt Centrifugal Governing System

Speed changer

Linkage mechanism

Speed governor

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 (does not eliminate) the speed drop due to load increase.
  - Usually, speed regulation $R$ is 5-6% from zero to full load.
  - Governor output $\Delta \omega_r/R$ is compared to the change in the reference power $\Delta P_{ref}$.
  \[ \Delta P_g = \Delta P_{ref} - \Delta \omega_r/R \]
  - 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 $\tau_g$.
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

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

- 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:

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

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

**The smaller \(R\) the better?**

**Figure 11.12** Response of a generating unit with a governor having speed-droop characteristic
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).
The open-loop transfer function is

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

\[ = \frac{K}{s^3 + 7.08s^2 + 10.56s + 0.8} \]

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**
  \[ a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0 = 0 \quad (a_n > 0) \]
  \[ s^3 + 7.08 s^2 + 10.56 s + 0.8 + K = 0 \]

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

\[
\begin{array}{cccccc}
  s^n & | & a_n & a_{n-2} & a_{n-4} & \ldots \\
  s^{n-1} & | & a_{n-1} & a_{n-3} & a_{n-5} & \ldots \\
  s^{n-2} & | & b_1 & b_2 & b_3 & \ldots \\
  s^{n-3} & | & c_1 & c_2 & c_3 & \ldots \\
  \vdots & | & \vdots & \vdots & \vdots & \ddots \\
  b_1 &=& \frac{a_{n-1} a_{n-2} - a_n a_{n-3}}{a_{n-1}} \\
  b_2 &=& \frac{a_{n-1} a_{n-4} - a_n a_{n-5}}{a_{n-1}} \\
  c_1 &=& \frac{b_1 a_{n-3} - a_n b_2}{b_1} \\
  c_2 &=& \frac{b_1 a_{n-5} - a_n b_3}{b_1} \\
\end{array}
\]

- **Routh-Hurwitz criterion:** No. of roots of the equation with positive real parts = No. of changes in sign of the 1\(^{st} \) column of the Routh table

- **Necessary and sufficient condition for a linear system to be stable:** The 1\(^{st} \) column only has positive numbers

- \( s^1 \) row > 0 if \( K < 73.965 \)
- \( s^0 \) row > 0 since \( K > 0 \)
- So \( R = 1/K > 1/73.965 = 0.0135 \)
Root-Locus Method

\[ KG(s)H(s) = \frac{K(s + z_1)(s + z_2) \cdots (s + z_m)}{(s + p_1)(s + p_2) \cdots (s + p_n)} \quad (B.5) \]

- \( z_i \) is the \( i \)-th zero and \( -p_j \) is \( j \)-th pole

Conclusions (see Saadat’s B2.22 for details):

- The loci of roots of \( 1+KG(s)H(s) \) begins at \( KG(s)H(s) \)'s poles and ends at its zeros as \( K=0 \rightarrow \infty \)
- No. of separate loci = No. of poles; root loci must be symmetrical with respect to the real axis
- The root locus on the real axis always lies in a section of the real axis to the left of an odd number of poles and zeros
- Linear asymptotes of loci are centered at a point \((x, 0)\) on the real axis with angle \( \phi \) with respect to the real axis

\[
x = \left[ \sum_{j=1}^{n} (-p_j) - \sum_{i=1}^{m} (-z_i) \right] / (n-m)
\]

\[
\phi = \pi \times (2k+1) / (n-m) \quad k = 0, 1, \ldots, (n-m-1)
\]

When \( s = \pm 3.25 \),

\( R_{\text{min}} = 1/K = 0.0135 \quad (R > 0.0135) \)
• Closed-loop transfer function with R=0.05pu (>0.0135):

\[
\frac{\Delta \omega_r(s)}{-\Delta P_L(s)} = \frac{(1 + 0.2s)(1 + 0.5s)}{(10s + 0.8)(1 + 0.2s)(1 + 0.5s) + 1/0.05} = \frac{0.1s^2 + 0.7s + 1}{s^3 + 7.08s^2 + 10.56s + 20.8}
\]

• Steady-state frequency deviation due to a step input:

\[
\Delta \omega_{ss} = \lim_{s \to 0} s \Delta \omega_r(s) = -\Delta P_L \frac{1}{D + 1/R} = -0.2 \times \frac{1}{20.8} = -0.0096 \text{ p.u.}
\]

\[
\Delta f = -0.0096 \times 60 = 0.576 \text{ Hz}
\]
Compare different values of $R$

Without LFC (Open-loop)

- $R = 0.0135$
- $R = 0.05$
- $R = 0.135$
- $R = 0.0135$
FIGURE 1.2
Simplified diagram of a conventional coal-fired steam generator.
IEEE Type 1 Speed-Governor Model: IEEEG1/IEEEG1_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.

GVI, PGV1...GV6, PGV6 are the x,y coordinates of \( P_{Gy} \) vs. GV block

Form Edit - IEEEG1

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=1/R
Composite Governor and Load Characteristic

Under steady-state conditions ($s=0$):

$$\Delta f (pu) = \Delta \omega_{ss} (pu) = \frac{-\Delta P_L (pu)}{D + 1/R}$$

Figure 11.17 Composite governor and load characteristic
Saadat’s Example 12.2

Example 12.2  (chp12ex2)

A single area consists of two generating units with the following characteristics.

<table>
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<tr>
<th>Unit</th>
<th>Rating</th>
<th>Speed regulation R (pu on unit MVA base)</th>
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<tr>
<td>1</td>
<td>600 MVA</td>
<td>6%</td>
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<tr>
<td>2</td>
<td>500 MVA</td>
<td>4%</td>
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The units are operating in parallel, sharing 900 MW at the nominal frequency. Unit 1 supplies 500 MW and unit 2 supplies 400 MW at 60 Hz. The load is increased by 90 MW.

(a) Assume there is no frequency-dependent load, i.e., \( D = 0 \). Find the steady-state frequency deviation and the new generation on each unit.

(b) The load varies 1.5 percent for every 1 percent change in frequency, i.e., \( D = 1.5 \). Find the steady-state frequency deviation and the new generation on each unit.

Note: two generators use different MVA bases. Select 1000MVA as the common MVA base.

\[
\Delta \omega_{ss} \text{ (pu)} = \frac{-\Delta P_L \text{ (pu)}}{D + \sum_i \frac{1}{R_i}}
\]

\[
R^{B1} = \frac{\Delta \omega_{ss}}{-\Delta P_{m}} = \frac{\Delta \omega_{ss}}{-\Delta P_{m}} \times \frac{S_{B1}}{S_{B2}} = \frac{S_{B1}}{S_{B2}} \times R^{B2}
\]

\[
R_1 = \frac{1000}{600} (0.06) = 0.1 \text{ pu} \quad R_2 = \frac{1000}{500} (0.04) = 0.08 \text{ pu} \quad \Delta P_L = \frac{90}{1000} = 0.09 \text{ pu}
\]
(a) \( D=0 \)  

\[
\Delta \omega_{ss} = \frac{-\Delta P_L}{\frac{1}{R_1} + \frac{1}{R_2}} = \frac{-0.09}{10+12.5} = -0.004 \text{ pu}
\]

\[
\Delta f = -0.004 \times 60 = -0.24 \text{ Hz}
\]

\[
f = f_0 + \Delta f = 60 - 0.24 = 59.76 \text{ Hz}
\]

\[
\Delta P_{m1} = -\frac{\Delta \omega_{ss}}{R_1} = -\frac{-0.004}{0.1} = 0.04 \text{ pu} = 40 \text{ MW}
\]

\[
\Delta P_{m2} = -\frac{\Delta \omega_{ss}}{R_2} = -\frac{-0.004}{0.08} = 0.05 \text{ pu} = 50 \text{ MW}
\]

Unit 1 supplies 540MW and unit 2 supplies 450MW at the new operating frequency of 59.76Hz.

(b) \( D=1.5 \) (ignoring its change due to load increase)  

\[
\Delta \omega_{ss} = \frac{-\Delta P_L}{\frac{1}{R_1} + \frac{1}{R_2} + D} = \frac{-0.09}{10+12.5+1.5} = -0.00375 \text{ pu}
\]

\[
\Delta f = -0.00375 \times 60 = -0.225 \text{ Hz}
\]

\[
f = f_0 + \Delta f = 60 - 0.225 = 59.775 \text{ Hz}
\]

\[
\Delta P_{m1} = -\frac{\Delta \omega_{ss}}{R_1} = -\frac{-0.00375}{0.1} = 0.0375 \text{ pu}=37.5\text{MW}
\]

\[
\Delta P_{m2} = -\frac{\Delta \omega_{ss}}{R_2} = -\frac{-0.00375}{0.08} = 0.0469 \text{ pu}=46.9\text{MW}
\]

Unit supplies 537.5MW and unit 2 supplies 446.9MW at the new operating frequency of 59.775Hz. The total change in generation is 84.4MW, i.e. 5.6MW less than 90MW load change, because of the change in load due to frequency drop.

\[
\Delta \omega_{ss} \cdot D = -0.00375 \times 1.5 = -0.005625 \text{ pu} = -5.625\text{MW}
\]