AGC 4

1.0 Problem 11.2

For the isolated generating station with local load shown in Fig. 1 below, it is observed that ΔP_L=0.1pu brings about $\Delta\omega$=-0.2rad/sec in the steady-state.

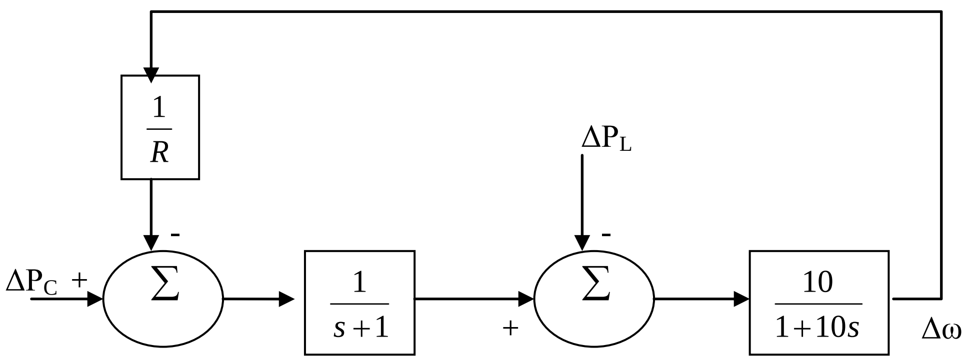

Fig. 1

(a) Find 1/R.

Solution:

We need the transfer function between $\Delta\omega$ and ΔP_L. To get this, write down $\Delta\omega$ as a function of what is coming into it:

$$\Delta\hat{\omega} = \frac{10}{1+10s}\left[\left(\frac{1}{s+1}\right)\left(\Delta\hat{P}_C - \frac{1}{R}\Delta\hat{\omega}\right) + -\Delta\hat{P}_L\right]$$

Now solve for Δω. Expanding:

$$\Delta\hat{\omega} = \frac{10}{1+10s}\left[\left(\frac{1}{s+1}\right)\left(\Delta\hat{P}_C - \frac{1}{R}\Delta\hat{\omega}\right) - \Delta\hat{P}_L\right]$$

$$= \Delta\hat{P}_C \frac{10}{1+10s}\left(\frac{1}{s+1}\right) - \frac{10}{1+10s}\left(\frac{1}{s+1}\right)\left(\frac{1}{R}\Delta\hat{\omega}\right) - \frac{10\Delta\hat{P}_L}{1+10s}$$

Bringing terms in Δω to the left-hand-side:

$$\Delta\hat{\omega} + \frac{10}{1+10s}\left(\frac{1}{s+1}\right)\frac{1}{R}\Delta\hat{\omega} = \Delta\hat{P}_C \frac{10}{1+10s}\left(\frac{1}{s+1}\right) - \frac{10\Delta\hat{P}_L}{1+10s}$$

Factoring Δω:

$$\Delta\hat{\omega}\left[1 + \frac{10}{1+10s}\left(\frac{1}{s+1}\right)\frac{1}{R}\right] = \Delta\hat{P}_C \frac{10}{1+10s}\left(\frac{1}{s+1}\right) - \frac{10\Delta\hat{P}_L}{1+10s}$$

Dividing:

$$\Delta\hat{\omega} = \frac{\Delta\hat{P}_C \frac{10}{1+10s}\left(\frac{1}{s+1}\right) - \frac{10\Delta\hat{P}_L}{1+10s}}{1 + \frac{10}{1+10s}\left(\frac{1}{s+1}\right)\frac{1}{R}}$$

Multiply through by (1+10s)(s+1):

$$\Delta\hat{\omega} = \frac{10\Delta\hat{P}_C - 10\Delta\hat{P}_L(s+1)}{(1+10s)(s+1) + \frac{10}{R}}$$

Rearrange the top and expand the bottom:

$$\Delta\hat{\omega} = \frac{10\Delta\hat{P}_C - 10(s+1)\Delta\hat{P}_L}{10s^2 + 11s + (1 + 10/R)} \qquad (*)$$

Now we consider ΔP_C=0pu, ΔP_L=0.1pu, and assume it is a step change. Therefore:

$$\Delta\hat{P}_L = \frac{\Delta P_L}{s}$$

Substituting into (*), we get:

$$\Delta\hat{\omega} = \frac{-10(s+1)}{10s^2 + 11s + (1 + 10/R)} \frac{\Delta P_L}{s}$$

The above expression is a LaPlace function (i.e., in s). The problem gives data for the steady-state (in time). We may apply the final-value theorem to the above expression to obtain:

$$\Delta\omega = \lim_{t\to\infty} \Delta\omega(t)$$

$$= \lim_{s\to 0} s\Delta\hat{\omega} = \lim_{s\to 0} s \frac{-10(s+1)}{10s^2 + 11s + (1 + 10/R)} \frac{\Delta P_L}{s}$$

$$= \lim_{s\to 0} \frac{-10(s+1)\Delta P_L}{10s^2 + 11s + (1 + 10/R)} = \frac{-10\Delta P_L}{1 + 10/R}$$

that is,

$$\Delta\omega = \frac{-10\Delta P_L}{1 + 10/R}$$

Solving for R, we obtain:

$$10/R = \frac{-10\Delta P_L}{\Delta\omega} - 1 = \frac{-10\Delta P_L - \Delta\omega}{\Delta\omega}$$

$$R = \frac{-10\Delta\omega}{10\Delta P_L + \Delta\omega}$$

Substituting ΔP_L=0.1pu and $\Delta\omega$=-0.2rad/sec, we obtain:

$$R = \frac{-10\Delta\omega}{10\Delta P_L + \Delta\omega} = \frac{-10(-0.2)}{10(0.1)+(-0.2)} = 2.5$$

The problem was specified with power in per-unit and $\Delta\omega$ in rad/sec. Reference to the block diagram indicates that the left-hand-side summing junction outputs ΔP_C-$\Delta\omega$/R. To make this sum have commensurate units, it must be the case that R has units of (rad/sec)/pu power. So R=2.5 (rad/sec)/pu power.

The problem asks for 1/R, which would be 1/2.5=0.4 pu power/(rad/sec).

One might also express R and 1/R in units of pu frequency/pu power. This would be:

R_{pu}=2.5/60=0.0417

1/R_{pu}=24

Recalling the NERC specification that all units should have R=0.05, then this R should be adjusted upwards.

Question: What does an R=0.0417 mean relative to an R=0.05?

Answer: Recalling that $R_{pu}=-\Delta\omega_{pu}/\Delta P_{m,pu}$, we can say that R_{pu} expresses the steady-state frequency deviation, as a percentage of 60 Hz, for which the machine will move by an amount equal to its full rating. So:

- if R_{pu}=0.05, then the steady-state frequency deviation for which the machine will move by an amount equal to its full rating is 0.05*60=3hz.
- if R_{pu}=0.0417, then the steady-state frequency deviation for which the machine will move by an amount equal to its full rating is 0.0417*60=2.502hz.

(b) Specify ΔP_C to bring $\Delta\omega$ back to zero (i.e., back to the steady-state frequency $\omega=\omega_0$).

Solution:

Recalling eq. (*):

$$\Delta\hat{\omega} = \frac{10\Delta\hat{P}_C - 10(s+1)\Delta\hat{P}_L}{10s^2 + 11s + (1+10/R)} \qquad (*)$$

Now we have that

$$\Delta\hat{P}_C = \frac{\Delta P_C}{s}$$

and $\Delta P_L=0$. In this case, eq. (*) becomes:

$$\Delta\hat{\omega} = \frac{10\Delta P_C / s}{10s^2 + 11s + (1+10/R)}$$

Applying the final value theorem again:

$$\Delta\omega = \lim_{t\to\infty} \Delta\omega(t)$$

$$= \lim_{s\to 0} s\Delta\hat{\omega} = \lim_{s\to 0} s$$

$$\Delta\omega = \lim_{t\to\infty} \Delta\omega(t)$$

$$= \lim_{s\to 0} s\Delta\hat{\omega} = \lim_{s\to 0} s \frac{10\Delta P_C / s}{10s^2 + 11s + (1+10/R)}$$

$$= \lim_{s\to 0} \frac{10\Delta P_C}{10s^2 + 11s + (1+10/R)} = \frac{10\Delta P_C}{1+10/R}$$

that is,

$$\Delta\omega = \frac{10\Delta P_C}{1+10/R}$$

Solving for ΔP_C, we get:

$$\Delta P_C = \frac{\Delta\omega(1+10/R)}{10}$$

Having already computed 1/R=0.4 in part (a), and with Δω=-0.2, we have

$$\Delta P_C = \frac{-0.2(1+10/2.5)}{10} = -0.1$$

which indicates that for this load increase of 0.1 which results (from primary speed control) in a frequency deviation of -0.2 rad/sec, we need to adjust the speed-changer motor to increase plant output by 0.1 pu in order to correct the steady-state frequency deviation back to 0.

The change to the speed-changer motor would be accomplished by the supplementary control.

2.0 Last comments on AGC

Someone asked me about applying the root locus method as in Example 11.3 of text. Root locus is a procedure for analysis of stability, that you would not have learned unless you took EE 475, and so I choose not to cover this.

Hint on Problem 11.3: At the bottom of page 390, the text says: "The reader is invited to check that with $K_{Pi} = 1/\tilde{D}_i$ and $T_{Pi} = M_i/\tilde{D}_i$, Figure 11.10 represents (11.22) in block diagram form. In Figure 11.10 we have $\Delta\omega_i$ as an output and ΔP_{Mi} as an input and can close the power control loop by introducing the turbine-governor block diagram shown in Figure 11.4."

This will result in the following block diagram.