MODULE 3: AGC and Automatic Generation Control in Interconnected Power system

Structure

3.1 **Automatic Generation Control in interconnected Power system:** Introductions
3.2 Tie – Line Control with Primary Speed Control
3.3 Frequency Bias Tie - Line Control
3.4 State-Space Models **10 Hours**

Revised Bloom's Taxonomy Level: L4-Analysing

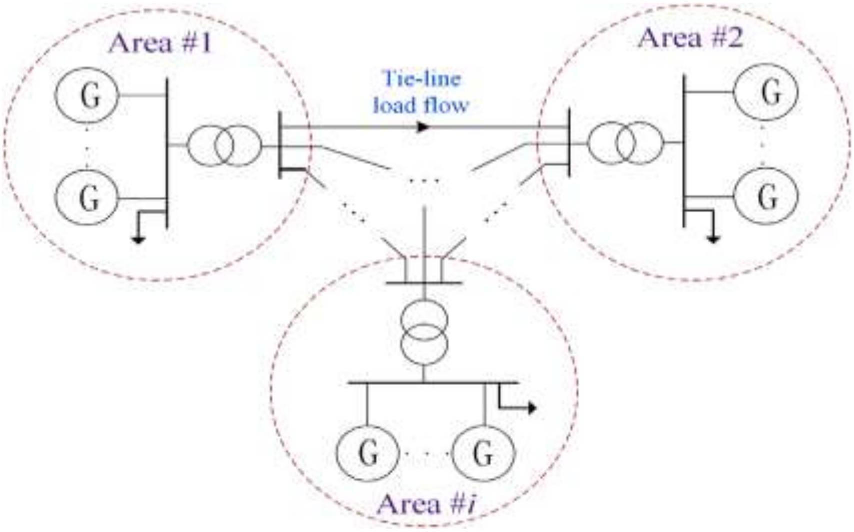
Objectives

To explain Tie – Line Control, Frequency Bias Tie - Line Control, State-Space Models

3.1 **Automatic Generation Control in interconnected Power system:** Introductions

- **To restore the frequency to the nominal value, we need supplementary control which changes the load reference set point.**
- **With different control areas connected, Role of AGC:**
- **Hold the system frequency to the nominal value of <u>50Hz</u>**
- **Maintain correct value of <u>power interchange</u> between the control areas**
- **Maintain generation of each unit at an <u>economical value</u>**

MULTI AREA SYSTEM: TIE LINE CONTROL

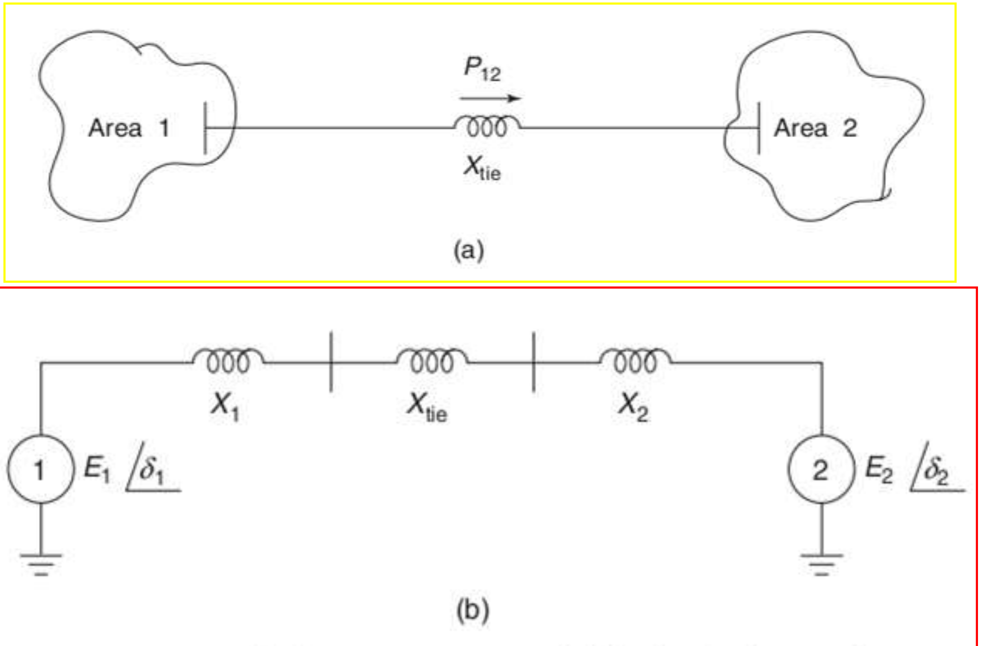


3.2 Tie – Line Control with Primary Speed Control

Consider Two area system:

1. **Let Positive Power Flow from Area 1 to Area 2 be P_{12}**
2. **Power Flow from Area 1 to Area 2 is:**

$$P_{12} = \frac{E_1 E_2}{X_{12}} \sin(\delta_1 - \delta_2)$$



(a) Two-area system and (b) Electrical equivalent.

Power Flow from Area 1 to Area 2 is:

$$P_{12} = \frac{E_1 E_2}{X_{12}} \sin(\delta_1 - \delta_2)$$

$$X_{12} = X_1 + X_{\text{tie}} + X_2$$

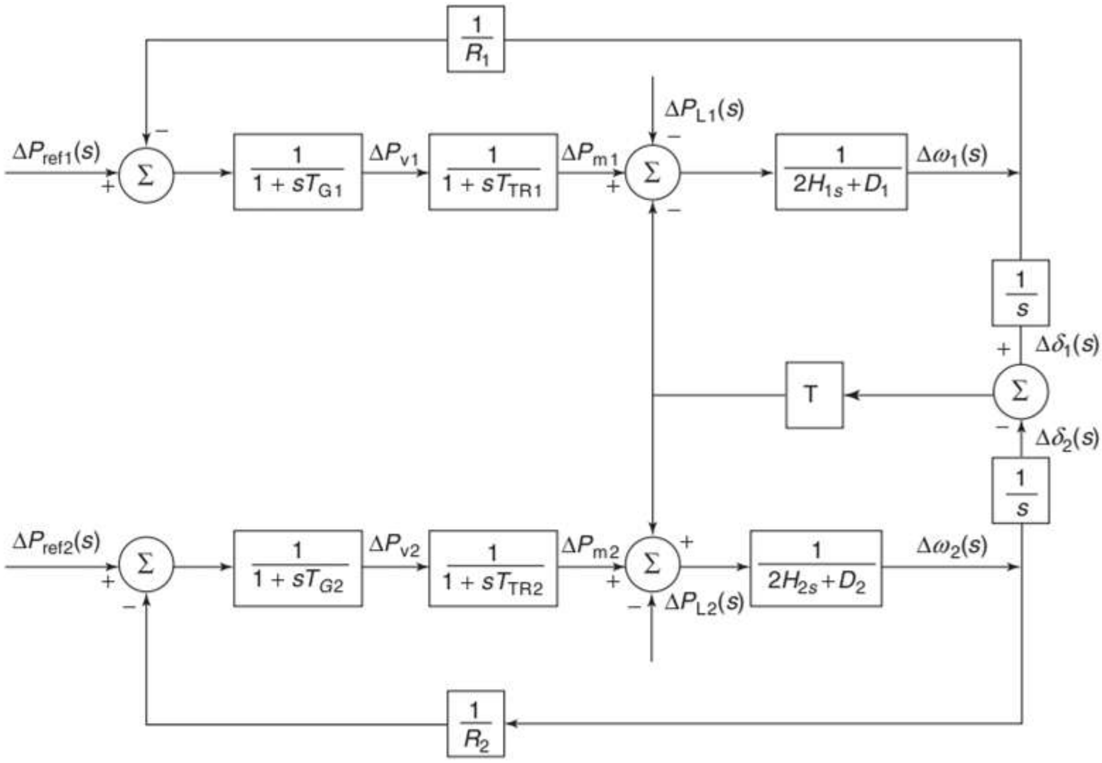
initial operating point $\delta_1 = \delta_{10}$ and $\delta_2 = \delta_{20}$ as

$$\Delta P_{12} = \frac{E_1 E_2}{X_{12}} \cos(\delta_{10} - \delta_{20}) \Delta\delta_{12}$$

$$\Delta\delta_{12} = \Delta\delta_1 - \Delta\delta_2$$

T is called Synchronizing torque coefficient

$$\text{Let } T = \frac{E_1 E_2}{X_{12}} \cos(\delta_{10} - \delta_{20}) = P_{\max} \cos(\delta_{10} - \delta_{20})$$



Two-area system with primary loop.

Change of Load in Area 1

Consider a load change of ΔP_{L1} in area 1. When the system has reached a steady state, both areas will have same steady-state frequency deviations. Therefore,

$$\Delta\omega = \Delta\omega_1 = \Delta\omega_2$$

(or $\Delta f = \Delta f_1 = \Delta f_2$. Remember that *in pu both Δf and $\Delta\omega$ are the same*)

For area 1, we can write

Assume Mechanical Powers (ΔPref) Constant

$$\Delta P_{m1} - \Delta P_{12} - \Delta P_{L1} = \Delta\omega D_1$$

For area 2, we have

$$\Delta P_{m2} + \Delta P_{12} = \Delta\omega D_2$$

$$\Delta P_{m1} = \frac{-\Delta\omega}{R_1} \qquad \Delta P_{m2} = \frac{-\Delta\omega}{R_2}$$

$$\boxed{-\Delta P_{12} - \Delta P_{L1} = \Delta\omega\left(\frac{1}{R_1} + D_1\right)} \qquad \boxed{\Delta P_{12} = \Delta\omega\left(\frac{1}{R_2} + D_2\right)}$$

$$\Delta P_{12} = \Delta\omega\left(\frac{1}{R_2} + D_2\right)$$

$$\Delta\omega = \frac{-\Delta P_{L1}}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right) + (D_1 + D_2)}$$

$$\Delta P_{12} = \Delta\omega\left(\frac{1}{R_2} + D_2\right) = \frac{-\Delta P_{L1}\left(\frac{1}{R_2} + D_2\right)}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right) + (D_1 + D_2)}$$

$$\Delta\omega = \frac{-\Delta P_{L1}}{\left(\frac{1}{R_1} + D_1\right) + \left(\frac{1}{R_2} + D_2\right)} = \frac{-\Delta P_{L1}}{\beta_1 + \beta_2}$$

β_1 and β_2 are the *composite frequency response characteristics* of area 1 and area 2,

$$\Delta P_{12} = \frac{-\Delta P_{L1}\left(\frac{1}{R_2} + D_2\right)}{\left(\frac{1}{R_1} + D_1\right) + \left(\frac{1}{R_2} + D_2\right)} = \frac{-\Delta P_{L1}\,\beta_2}{\beta_1 + \beta_2}$$

CHANGE OF LOAD IN AREA 2

$$\Delta P_{m1} - \Delta P_{12} = \Delta\omega D_1 \qquad \text{-----------------(1)}$$

$$\Delta P_{m2} + \Delta P_{12} - \underline{\Delta P_{L2}} = \Delta\omega D_2 \qquad \text{-----------------(2)}$$

$$\Delta P_{m1} = \frac{-\Delta\omega}{R_1} \qquad \text{-----------------(3)}$$

$$\Delta P_{m2} = \frac{-\Delta\omega}{R_2} \qquad \text{-----------------(4)}$$

From (1) and (3)

$$-\Delta P_{12} = \Delta\omega\left(D_1 + \frac{1}{R_1}\right)$$

From (2) and (4)

$$\Delta P_{12} - \Delta P_{L2} = \Delta\omega\left(D_2 + \frac{1}{R_2}\right)$$

$$-\Delta P_{12} = \Delta\omega\left(D_1 + \frac{1}{R_1}\right)$$

$$\Delta P_{12} - \Delta P_{L2} = \Delta\omega\left(D_2 + \frac{1}{R_2}\right)$$

$$\Delta\omega = \frac{-\Delta P_{L2}}{\beta_1 + \beta_2}$$

$$\Delta P_{12} = \frac{\Delta P_{L2}\,\beta_1}{\beta_1 + \beta_2} = -\Delta P_{21}$$

CHANGE OF LOAD IN BOTH AREAS

If we have simultaneous change of Load in both the areas:

$$\Delta P_{m1} - \Delta P_{12} - \Delta P_{L1} = \Delta\omega D_1 \quad \text{------------------(1)}$$

$$\Delta P_{m2} + \Delta P_{12} - \Delta P_{L2} = \Delta\omega D_2 \quad \text{------------------(2)}$$

Adding (1) and (2)

$$-\Delta P_{L1} - \Delta P_{L2} = (\Delta\omega D_1 - \Delta P_{m1}) + (\Delta\omega D_2 - \Delta P_{m2})$$

$$= \Delta\omega\left(D_1 + \frac{1}{R_1}\right) + \Delta\omega\left(D_2 + \frac{1}{R_2}\right)$$

$$= \Delta\omega(\beta_1 + \beta_2)$$

$$\therefore \Delta\omega = \frac{-(\Delta P_{L1} + \Delta P_{L2})}{\beta_1 + \beta_2}$$

$$\Delta P_{12} = \frac{-\Delta P_{L1}\,\beta_2}{\beta_1 + \beta_2} + \frac{\Delta P_{L2}\,\beta_1}{\beta_1 + \beta_2}$$

$$= \frac{1}{\beta_1 + \beta_2}[-\Delta P_{L1}\,\beta_2 + \Delta P_{L2}\,\beta_1]$$

We can observe from the above: With only primary governor control, load change in <u>both areas</u> will lead to a <u>steady state deviation in frequency of both areas.</u>

NUMERICALS

Example 7.1 Two control areas are connected via a tie-line with the following characteristics:

Area 1: $R_1 = 1\%$, $D_1 = 0.8$, base MVA = 500
Area 2: $R_2 = 2\%$, $D_2 = 1.0$, base MVA = 500

A load increase of 100 MW occurs in area 1. What is the new steady-state frequency and the change in tie flow if the nominal frequency is 50 Hz? Repeat if the load change occurs in area 2.

Solution

When load change occurs in area 1:

$$\Delta\omega = \frac{-\Delta P_{L2}}{\beta_1 + \beta_2}$$

$$\Delta P_{L1} = \frac{100}{500} = 0.2\,\text{pu.}$$

$$\beta_1 = \frac{1}{R_1} + D_1 = \frac{1}{0.01} + 0.8 = 100.8$$

$$\beta_2 = \frac{1}{R_2} + D_2 = \frac{1}{0.02} + 1.0 = 51$$

$$\Delta\omega = \frac{-0.2}{100.8+51} = -1.3175\times10^{-3}\,\text{pu}$$

$$\Delta f = -1.3175\times10^{-3}\times 50 = -0.065875\ \text{Hz}$$

New frequency = 50 − 0.065875 = 49.934125 Hz

= 49.93 Hz

$$\Delta P_{12} = \frac{-\Delta P_{L1}\,\beta_2}{\beta_1+\beta_2} = \frac{-0.2\times51}{100.8+51} = -0.0671936\,\text{pu} = -33.597\,\text{MW}$$

(There is a drop in tie-line flow)

We balance the changes as follows:

(i) Change in generation of area 1, $\Delta P_{m1} = \frac{-\Delta\omega}{R_1}$

$$= \frac{-(-1.3175\times10^{-3})}{0.01} = 0.13175\ \text{pu}$$

= 65.875 MW (Increase in generation since it is a positive value)

(ii) Change in generation of area 2, $\Delta P_{m2} = \frac{-\Delta\omega}{R_2}$

$$= \frac{-(-1.3175\times10^{-3})}{0.02} = 0.065875\ \text{pu}$$

= 32.9375 MW

(iii) Increase in load in area 1 = 100 MW.

(iv) Change in load in area 1 due to drop in frequency = $\Delta\omega D_1 = -1.054\times10^{-3}$
= −0.527 MW.

(v) Change in load in area 2 due to drop in frequency = $\Delta\omega D_2 = -1.3175\times10^{-3}$
= −0.65875 MW

Change in generation = (i) + (ii) = 98.8125 MW
Change in load = (iii) + (iv) + (v) = 98.81 MW
Change in generation = change in load.

ΔP_{12} being negative means there is a flow of 33.597 MW from area 2 to area 1. Out of this, 32.9375 MW comes from increased generation in area 2 and 0.65875 MW from drop in load in area 2.

When load change occurs in area 2:

$$\Delta\omega = \frac{-\Delta P_{L2}}{\beta_1 + \beta_2} = \frac{-0.2}{100.8+51} = -1.3175 \times 10^{-3}\,\text{pu}$$

$$\Delta f = -0.06875\ \text{Hz}$$

$$f = 49.93\ \text{Hz (same as before)}$$

$$\Delta P_{12} = \frac{\Delta P_{L2}\,\beta_1}{\beta_1 + \beta_2} = \frac{0.2 \times 100.8}{100.8+51} = 0.1328\,\text{pu} = 66.4\,\text{MW}$$

(There is an increase in tie-line from area 1 to 2, to meet the increased load in area 2). The increase in tie-line is met by increase in generation in area 1 by 65.875 MW and decrease in load of area 1 by 0.527 MW.

3.3 Frequency Bias Control

Three Modes in which interconnected operation works:

1. **<u>Flat frequency where control is to obtain a constant frequency</u>:**

In an interconnected systems, when one of the system responds to frequency change only: It cannot have control over the power flow in the interconnected lines

2.When a system responds to Tie-Line changes and changes its generation to maintain the scheduled tie line interchanges: It cannot respond to frequency changes. This is called FLAT TIE LINE MODE

3. Both the methods specified has disadvantages.

Hence a combined control called <u>Frequency Bias Control</u> is used.

Inference :

Supplementary control in a given area should <u>change the generation only for change in load in same area</u>

TIE LINE BIAS CONTROL(FREQUENCY BIAS TIE LINE CONTROL)

$$\Delta P_{12} = P_{12} - P_{12,\,\text{sch}}$$

where P_{12} = actual power flow from area 1 to 2

$P_{12,\,\text{sch}}$ = scheduled interchange power from area 1 to area 2

Tie-line control actions for two-area system

$\Delta\omega$	ΔP_{12}	Load Change	Control Action
−	−	ΔP_{L1} + ΔP_{L2} 0	Increase P_{G1}
−	+	ΔP_{L1} 0 ΔP_{L2} +	Increase P_{G2}
+	−	ΔP_{L1} 0 ΔP_{L2} −	Decrease P_{G2}
+	+	ΔP_{L1} − ΔP_{L2} 0	Decrease P_{G1}

Control Signal : Area Control Error

$$\text{ACE}_1 = \Delta P_{12} + B_1 \Delta\omega$$

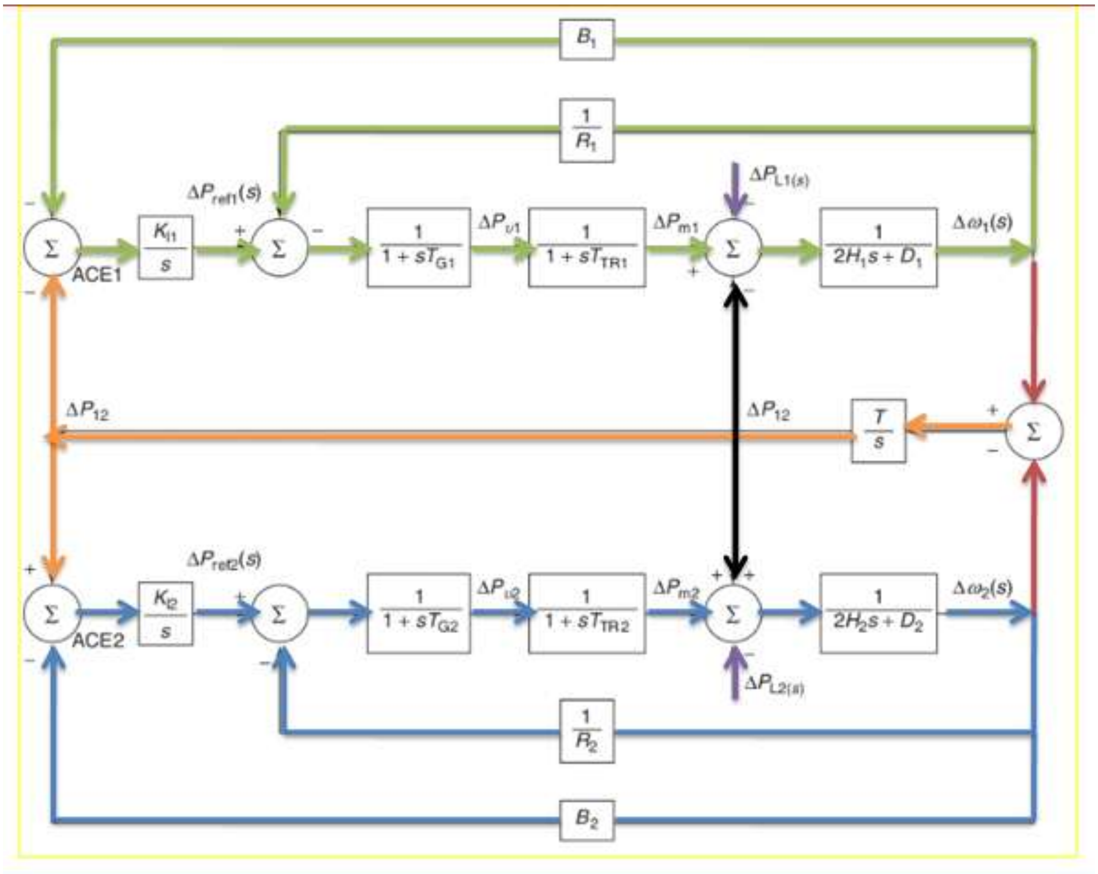
$$\text{ACE}_2 = \Delta P_{21} + B_2 \Delta\omega$$

B_1, B_2 are the bias factors and determine the amount of interaction during a disturbance in the other area

most suitable bias factor for an area is its frequency response characteristic β

$$\text{ACE}_1 = \Delta P_{12} + \beta_1 \Delta\omega$$
$$\text{ACE}_2 = \Delta P_{21} + \beta_2 \Delta\omega$$

$$\beta_1 = D_1 + \frac{1}{R_1} \text{ and } \beta_2 = D_2 + \frac{1}{R_2}$$



ACE Expression

ACE Signal in General Form

$$\mathrm{ACE}_1 = K_1 \Delta P_{12} + B_1 \Delta\omega = 0$$
$$\mathrm{ACE}_2 = K_2 \Delta P_{21} + B_2 \Delta\omega = 0$$

$$\Delta\omega = \frac{-\Delta P_{L1}}{\beta_1 + \beta_2}$$

$$\Delta P_{12} = \frac{-\Delta P_{L1}\,\beta_2}{\beta_1 + \beta_2}$$

$K_1 = K_2 = 1,\ B_1 = \beta_1$ and $B_2 = \beta_2$, we get

$$\mathrm{ACE}_1 = -\Delta P_{L1}\left[\frac{\beta_1+\beta_2}{\beta_1+\beta_2}\right] = -\Delta P_{L1}$$

$$\mathrm{ACE}_2 = -\Delta P_{L1}\left[\frac{-\beta_2+\beta_2}{\beta_1+\beta_2}\right] = 0$$

Thus, only the supplementary control in area 1 will change the load reference point to meet load change in area 1. *The supplementary control of area 2 will not be affected.*

An alternative expression commonly used for ACE is

$$\mathrm{ACE}_i = (T_i - T_{si}) - 10B_i\,(F_i - F_{si})$$

T_i is net actual tie-line interchange from area i.

T_{si} is the scheduled tie-line interchange of area i.

F_i is actual frequency of area i in Hz.
F_{si} is scheduled frequency of area i in Hz.

B_i is the area frequency bias in MW/0.1 Hz. Multiplying by 10 gives it in MW/Hz.

Example 7.5 The data of a two-area system are as follows:

Area 1: $P_{G1} = P_{L1} = 1000\,\mathrm{MW}$, $R_1 = 0.015$, $D_1 = 0$

Area 2: $P_{G2} = P_{L2} = 10000\,\mathrm{MW}$, $R_2 = 0.0015$, $D_2 = 0$

An increase of 10 MW takes place in area 1. Determine the change in frequency, ACE and the appropriate control action.

Solution

$$\Delta P_{m1} = D_1\Delta\omega_1 + \Delta P_{L1} + \Delta P_{12} = \Delta P_{L1} + \Delta P_{12}$$
$$\Delta P_{m2} = D_2\Delta\omega_2 + \Delta P_{L2} + \Delta P_{21} = \Delta P_{21} = \Delta P_{12}$$

$$\Delta\omega = \Delta\omega_1 = \Delta\omega_2$$

$$\Delta P_{m1} = -\frac{1}{R_1}\Delta\omega_1 \text{ and } \Delta P_{m2} = -\frac{1}{R_2}\Delta\omega_2$$

$$\Delta\omega = \frac{-\Delta P_{L1}}{\left(\frac{1}{R_1}+\frac{1}{R_2}\right)} = \frac{-10}{\left(\frac{1}{0.015}+\frac{1}{0.0015}\right)} = -0.0136 \text{ rad/s}$$

or

$$\Delta P_{m1} = \frac{-(-0.0136)}{0.015} = 0.9091 \text{ MW}$$

$$\Delta P_{12} = \Delta P_{m1} - \Delta P_{L1} = 0.9091 - 10 = -9.091 \text{ MW}$$

$$\Delta P_{21} = -\Delta P_{12} = 9.091 \text{ MW}$$

$$\text{ACE}_1 = \Delta P_{12} + \frac{1}{R_1}\Delta\omega = -9.091 + \frac{1}{0.015}(-0.0136) = -10 \text{ MW}$$

$$\text{ACE}_2 = \Delta P_{21} + \frac{1}{R_2}\Delta\omega = 9.091 + \frac{1}{0.015}(-0.0136) = 0 \text{ MW}$$

The ACEs indicate the action to be taken in each area. $\text{ACE}_2 = 0$ means that area 2 need not take any action.

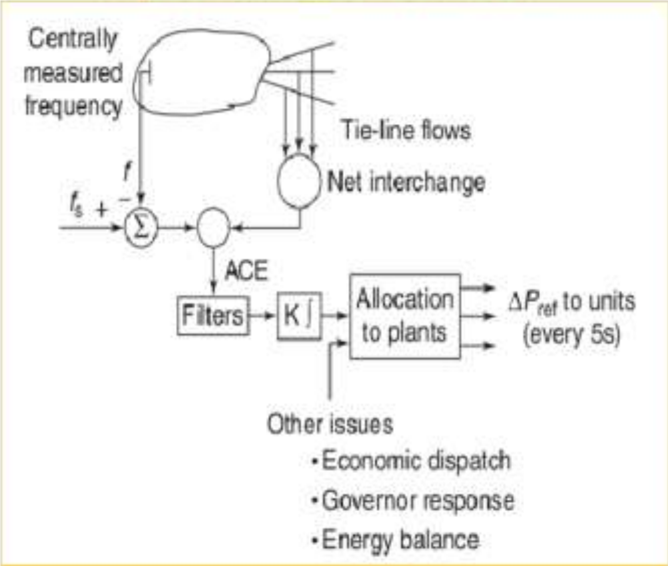
$\text{ACE}_1 = -10$ means that area 1 should increase its load power reference point to $-(-10) = 10$ MW and increase generation to meet the increased load.

3.4 State-Space Models

A **state** variable is one of the set of variables that are used to describe the mathematical "**state**" of a dynamical **system**.

Intuitively, the **state** of a **system** describes enough about the **system** to determine its future behaviour in the absence of any external forces affecting the **system**.

Implementation of AGC



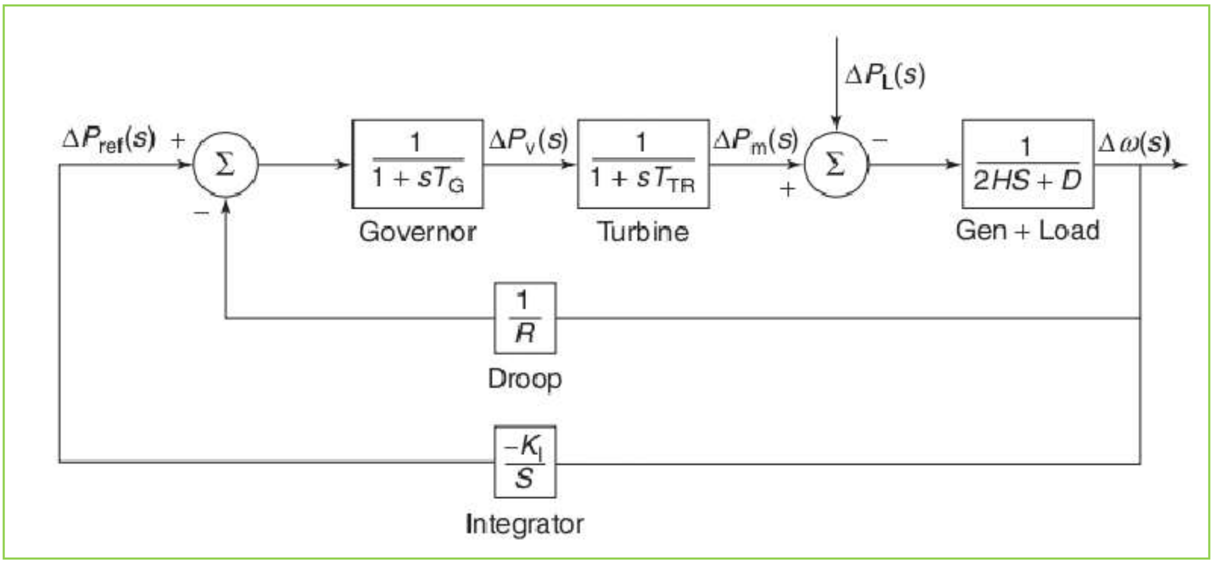
The s-domain equations are as follows:

$$\left[\frac{1}{2Hs+D}\right](\Delta P_m(s) - \Delta P_L(s)) = \Delta\omega(s)$$

$$\Delta\omega(s)\,(2Hs + D) = \Delta P_m(s) - \Delta P_L(s)$$

For the turbine we have: $\Delta P_v(s)\left[\frac{1}{1+sT_{TR}}\right] = \Delta P_m(s)$

ISOLATED SYSTEM WITH AGC



$$\Delta P_v(s)\left[\frac{1}{1+sT_{TR}}\right]=\Delta P_m(s)$$

$$(1+sT_{TR})\,\Delta P_m(s)=\Delta P_v(s)$$

$$s\Delta P_m(s)=\frac{-1}{T_{TR}}\Delta P_m(s)+\frac{1}{T_{TR}}\Delta P_v(s)$$

For the Governors we have

$$\left[\Delta P_{ref}(s)-\frac{1}{R}\Delta\omega(s)\right]\left[\frac{1}{1+sT_G}\right]=\Delta P_v(s)$$

$$\Delta P_v(s)\,(1+sT_G)=\Delta P_{ref}(s)-\frac{1}{R}\Delta\omega(s)$$

$$s\Delta P_v(s)=\frac{-1}{T_G}\Delta P_v(s)+\frac{1}{T_G}\Delta P_{ref}(s)-\frac{1}{RT_G}\Delta\omega(s)$$

For the Integrator we have

$$\Delta P_{ref}(s)=\frac{-K_1}{s}\Delta\omega(s)$$

$$s\Delta P_{ref}(s)=-K_1\Delta\omega(s)$$

The following are called State Equations

$$\Delta P_v(s)\left[\frac{1}{1+sT_{TR}}\right]=\Delta P_m(s)$$

$$s\Delta P_v(s)=\frac{-1}{T_G}\Delta P_v(s)+\frac{1}{T_G}\Delta P_{ref}(s)-\frac{1}{RT_G}\Delta\omega(s)$$

$$s\Delta P_{ref}(s)=-K_1\Delta\omega(s)$$

State Vector in Time domain

$$X=[\Delta\omega\ \Delta P_m\ \Delta P_v\ \Delta P_{ref}]^T$$

State Equations can be transformed into time domain and written in matrix form as:

$$\begin{bmatrix}\dot{\Delta\omega}\\ \dot{\Delta P_m}\\ \dot{\Delta P_v}\\ \dot{\Delta P_{ref}}\end{bmatrix}=\begin{bmatrix}\frac{-D}{2H} & \frac{1}{2H} & 0 & 0\\ 0 & \frac{-1}{T_{TR}} & \frac{1}{T_{TR}} & 0\\ -\frac{1}{RT_G} & 0 & \frac{-1}{T_G} & \frac{1}{T_G}\\ -K_1 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \Delta P_m\\ \Delta P_v\\ \Delta P_{ref}\end{bmatrix}+\begin{bmatrix}-\frac{1}{2H}\\ 0\\ 0\\ 0\end{bmatrix}\Delta P_L$$

Standard Form of State Space Model

$$\dot{X}(t) = AX(t) + Bu(t)$$
$$y(t) = CX(t) + Du(t)$$

where $X(t)$ – state vector
$u(t)$ – input vector
$y(t)$ – output vector

$$A = \begin{bmatrix} \frac{-D}{2H} & \frac{1}{2H} & 0 & 0 \\ 0 & \frac{-1}{T_{TR}} & \frac{1}{T_{TR}} & 0 \\ \frac{-1}{RT_G} & 0 & \frac{-1}{T_G} & \frac{1}{T_G} \\ -K_1 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -\frac{1}{2H} \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad C = [\,1\;0\;0\;0\,] \quad D = 0$$

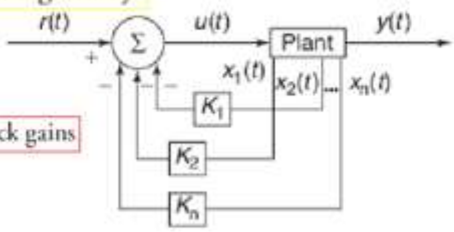
Pole Placement Design

- The Co-efficient matrix A determines the stability of the system
- For the system to be stable co-efficients of the **Eigen Matrix should be on the LHS of the s-plane.**

The state feedback control used is given by

$$u(t) = -KX(t)$$

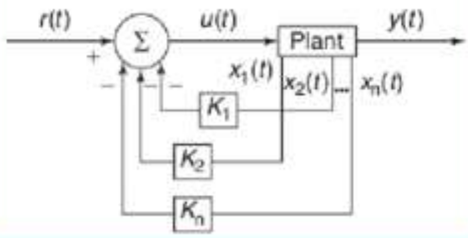
where K is a $1 \times n$ vector of feedback gains



The state feedback control used is given by

$$u(t) = -KX(t)$$

We can now substitute in the state equation to get



$$\dot{X}(t) = A\,X(t) + B\,(-K\,X(t))$$
$$= (A - BK)X(t) = A_{fb}\,X(t)$$

where A_{fb} is the coefficient matrix with feedback

The characteristic equation for the above state model

$$|sI - A_{fb}| = |sI - A + BK| = 0$$

At the end of the Module students will be able to:

CO-3: Develop mathematical model of Automatic Generation Control in Interconnected Power system [L4]

List of Text Books
1. Power System Operation and Control, K. Uma Rao, Wiley, 1st Edition, 2012. 2. Modern Power System Analysis, D. P. Kothari, McGraw Hill, 4th Edition, 2011. 3. Power Generation Operation and Control, Allen J Wood et al, Wiley, 2nd Edition, 2003. 4. Electric Power Systems, B M Weedy, B J Cory, Wiley. 4th Edition, 2012.
List of Reference Books
1. Computer-Aided Power System Analysis, G. L. Kusic, CRC Press, 2nd Edition.2010. 2. Power System SCADA and Smart Grid, Mini S Thom and John D. McDonald, CRC Press 2015. 3. Power System Stability and Control, Kundur, McGraw Hill, 8th Reprint, 2009.
List of URLs, Text Books, Notes, Multimedia Content, etc
https://archive.nptel.ac.in/courses/108/104/108104052/