THE OPTIMAL DECENTRALIZED MODAL LOAD-FREQUENCY CONTROL OF INTERCONNECTED POWER SYSTEMS

Mahmoud A. El-Gammal
Department of Electrical Engineering,
Alexandria University, Egypt

ABSTRACT

A simple and computationally efficient optimal decentralized control design is introduced for load-frequency control in interconnected power systems. The design procedure of the 'decoupled' system is based on Solheim's sequentially optimal pole placement technique [9] which minimizes a quadratic cost function. The eigenvalues selected to shift into the desired region are determined using the concept of dominant energy modes. The weighting matrix elements and the feedback gains of the local controllers that correspond to the selected dominant eigenvalues are sequentially computed within each subsystem. The weighting matrices can be furthery tuned sequentially in order to satisfy the condition of Yang et al. [13] which ensures the global optimality of the interconnected system. The proposed method is applied to the two-area Egyptian power network. The results demonstrate the usefulness of the proposed design mode.

1. INTRODUCTION

In the dynamical operation of interconnected power systems, it is usually important to aim for decentralization of control action to individual areas. This aim should coincide with the requirements for keeping the system frequency and inter-area tie-line power as near to the scheduled values as possible through the control action. The advantages of this operating technique are apparent in providing cost savings in data communication and in reducing the scope of the monitoring network.

Recently, the problem of decentralized load-frequency control (LFC) for multi-area interconnected power systems has received considerable attention [1-7]. These methods use either suboptimal control strategies or decentralized pole placement technique. Though most of the suboptimal decentralized LFC design techniques meet the requirements of load-frequency scheduling, they do not guarantee closed-loop stability for a general case. On the other hand the decentralized pole placement technique will ensure closed-loop stability if the design is successful.

In this paper, an optimal decentralized controller with prescribed dominant eigenvalues is introduced. The eigenvalues selected to shift into the desired region are determined using the dominant mode energy analysis [9,11]. Since the poles to be shifted can be determined and the effect of the transfer function zeros has been considered in the dominant mode energy analysis, very good control performance can be obtained [10]. The weighting matrix can be sequentially tuned to ensure global optimality of the interconnected system.

The rest of the paper is divided into four sections. In Section 2, the general dynamical model of the decentralized LFC problem, taking into consideration the speed governor backlash nonlinearity, is first stated. The design procedure of the optimal decentralized controllers is given in section 3. Then, in section 4, the proposed design control mode is applied to the two area Egyptian power system. Finally, some conclusions are given in section 5.

2. STATEMENT OF PROBLEM

The multi-area model used here and developed previously by Bahnasawi et al. [5] is summarized in Appendix. In this model the speed governor backlash nonlinearity has been considered and the linearized system is obtained by using the generalized describing function approach [8].

Following [5], the decentralized optimization problem of N-linear dynamical multi-area interconnected power system can be written in the compact form :

$$Min\ J = \sum_{i=1}^{N} \frac{1}{2} \int_0^\infty \left(\| X_i \|_{Q_i}^2 + \| u_i \|_{R_i}^2 \right) dt \qquad (1)$$

subject to

$$\dot{X}_i = A_i X_i + B_i u_i + \Gamma_i d_i + \sum_{j=1, j\neq i}^{N} A_{ij} X_j \qquad (2)$$

$$y_i = C_i X_i \qquad (3)$$

where $X_i \in R^{n_i}$ is the state vector of the ith control area, $u_i \in R^{m_i}$ is the control vector, $d_i \in R^{v_i}$ is the disturbance vector, $y_i \in R^{r_i}$ is the output vector, and A_i, B_i, Γ_i, C_i are constant matrices of appropriate dimensions. The determination of the optimal control law u_i^* which minimizes the quadratic performance index **J**, requires that R_i to be positive definite and Q_i to be at least positive semidefinite.

Area state-vector is $X_i=[\Delta p_{tie,i}\ ,\ \Delta f_i\ ,\ \Delta P_{gi}\ ,\ \Delta X_{vi}\ ,\ \int ACE_i\ dt]^T$

where $\Delta X_{vi} \triangleq \Delta X_{gvi} - \frac{b_i}{T_{gvi}} \Delta P_{ci} + \frac{b_i}{T_{gvi} R_i} \Delta f_i$

Global state vector is $X=[\Delta p_{tie},\Delta f_1,\Delta P_{g1},\Delta X_{v1},\int ACE_1\ dt,\ \Delta f_2,\Delta P_{g2},\Delta X_{v2},\int ACE_2 dt]^T$

where $\Delta p_{tie}\ =\ \Delta p_{tie,1}\ =\ -\Delta p_{tie,2}$

Global control vector is $\quad u\ =\ [\Delta p_{c1}\ ,\ \Delta p_{c2}]^T$

Global disturbance vector is $\ d\ =\ [\Delta P_{d1}\ ,\ \Delta P_{d2}]^T$

Global output vector is $\quad y\ =\ [\Delta f_1\ ,\ \Delta f_2]^T$

Now, the objective is to design N decentralized controllers, one for each area which will meet the following requirements:

(a) The closed-loop system should have good dynamic response.

(b) The steady-state Area Control Error (ACE) should be zero.

(c) The design of linear optimal controllers with bounded control signals to only local areas.

3. OPTIMAL DECENTRALIZED CONTROL DESIGN

3.1 *Decentralized LFC scheme:*

The actuating signal u_i is formed in accordance with the feedback control law

$$u_i=-K_i X_i+r_i \triangleq -\left(\sum_{j=1}^{s_i} K_i^{(j)}\right)X_i+r_i \tag{4}$$

where $K_i \in R^{m_i \times n_i}$ and r_i is m_ix1 reference input. With a given R_i matrix, the feedback gain $K_i^{(j)}$ and the weighting matrix $Q_i^{(j)}$,j=1,2,...,s_i, are found by assigning s_i dominant eigenvalues using an optimal sequential pole placement technique [9]. The poles to be shifted are determined using the dominant energy mode analysis [10,11]. The dominant energy mode analysis and the sequentially optimal pole assignment techniques will be briefly introduced.

3.1.1 *Dominant energy mode analysis :*

The transfer function of the output to the control input the ith control area

$$H_{P_i}(s) \triangleq \frac{Y_i(s)}{U_i(s)} = C_i(sI-A_i)^{-1}B_i \tag{5}$$

can be expressed by

$$H_{P_i}(s)=\sum_{k=1}^{n_i} \frac{h_k}{s-\mu_k} \tag{6}$$

The energy contribution of the kth dynamical mode μ_k can be measured by the dynamical dispersion coefficient

$$D_k \triangleq d_k / \sum_{j=1}^{n_i} d_j \tag{7}$$

where $d_j=\sum_{l=1}^{n_i} \frac{h_l h_j}{-(\mu_l+\mu_j)}$, j=1,2,..,n_i, are coefficients of variance of output normalized to the variance of white noise input. The importance of the dynamic mode μ_k to the control-area output y_i can be determined by how the absolute value of D_k is large compared with the other dynamical dispersions. However, the importance of poles of long time constant may be underestimated for LFC dynamical system dominated by poles of short time constant. In such a case the h_k's coefficients in eqn.6 is divided by a weighting factor equals the eigenvalue μ_k [10].

For the optimal regulator problem (reference input; $r_i=0$), the dynamic modes located too close to the imaginary axis and dominated in both transfer functions of the output to the control input $H_p(s)$ and the output to the disturbance input $H_d(s)$ will be shifted.

3.1.2 *Sequential optimal pole assignment :*

Given an open-loop system or an already optimal feedback system, a weighting matrix Q_i, i=1,2,..,N, can be sequentially build up, based on the following procedure, so that s_i dominant energy closed-loop eigenvalues can be located in a specified region.

The algorithm for shifting s_i distinct eigenvalues $(\lambda_1,\ldots,\lambda_{si})$ may be described as follows [9] (lower suffix i for ith area will be omitted for simplicity) :

1 initialize $Q=0$, $K=0$, $j=1$, for an open-loop system, or $Q=Q_o$, $K=K_o$,$j=1$, for an already optimal feedback system

2 set $A^j = A + BK$

3 compute the left eigenvector v_j of A^j corresponding to real λ_j (or $v_j = v_j^r + v_j^c$ corresponding to complex conjugate eigenvalues λ_j , λ_{j+1})

4(a) <u>shift real eigenvalue to</u> ρ_j

compute $h_j = v_j^T B R^{-1} B^T v_j$, $q_j=(\rho_j^2-\lambda_j^2)/h_j$, $k_j=(\lambda_j-\rho_j)/h_j$ and $Q_j = q_j v_j v_j^T$,

$K_j = -k_j R^{-1} B^T v_j v_j^T$

4(b) <u>shift real part of complex conjugate eigenvalues to</u> ρ_j

compute $H_j = \begin{vmatrix} v_j^{(r)T} BR^{-1}B^T v_j^{(r)} & v_j^{(r)T} BR^{-1}B^T v_j^c \\ v_j^{(r)T} BR^{-1}B^T v_j^c & v_j^{(c)T} BR^{-1}B^T v_j^c \end{vmatrix}$ and

$\hat{Q} = \begin{vmatrix} q_j & 0 \\ 0 & q_j \end{vmatrix}$ as follows :

1 compute positive real root q_o of $(aq^2 + bq + c = 0)$, where

$a=\frac{(h_{11}+h_{22})^2}{4} - |H|$, $b=2(h_{11}+h_{22})\beta^2$, $c=4\alpha^2\beta^2$, $\lambda_j=\alpha$ +

2 select the left real shift ρ_j

3 compute q_j by the formula given in [9]

4 if $q_j < q_o$ compute damping of assigned complex conjugate eigenvalue by the formula given in [9] and proceed forward, otherwise decrease the left real shift ρ_j and go back to **3**.

5 compute $\hat{K}_j=W_{21}W_{11}^{-1}$, $\begin{vmatrix} W_{11} \\ W_{21} \end{vmatrix}$ is the matrix of eigenvectors of the canonical matrix $N=\begin{vmatrix} \Lambda_j & -H_j \\ -\hat{Q}_j & -\Lambda_j^T \end{vmatrix}$, $\Lambda_j=\begin{vmatrix} \alpha & \beta \\ -\beta & \alpha \end{vmatrix}$ corresponding to the assigned complex conjugate eigenvalues. Now,

$$Q_j=\begin{vmatrix} v_j^r & v_j^c \end{vmatrix} \hat{Q}_j \begin{vmatrix} v_j^{(r)T} \\ v_j^{(c)T} \end{vmatrix} , \quad K_j=-R^{-1}\begin{vmatrix} v_j^r & v_j^c \end{vmatrix} \hat{K}_j \begin{vmatrix} v_j^{(r)T} \\ v_j^{(c)T} \end{vmatrix}$$

3.2 *Global optimality of the decentralized control law :*

M.Ikeda and D.D.Siljak [12] have proposed a condition that ensures the global optimality of the decentralized optimal control law eqn.4. Yang et al. [13] has improved the condition of global optimality of [12] to a more simplified equivalent form.

The local decentralized optimal control law of eqn.4 is globally optimal for the interconnected system, with respect to a modified cost function to include the additional terms arising from the subsystem interactions (as defined in [12]), as long as [13]

$$\frac{\lambda_m(Q_i)}{\lambda_M(P_i)} \succ V \quad ,i=1,2,..,N \tag{8}$$

for each control area, and the global detectbility condition [12] is satisfied. Where $\lambda_m(.)$, $\lambda_M(.)$ denote the minimum and maximum eigenvalues of the indicated matrices, and **V** is a positive number calculated in the following steps :

Step 1 : Form a normal matrix $T=\{t_{ij}\},i,j=1,2,..,N$, with all diagonal elements $t_{ii}=1$ and off-diagonal elements $t_{ij}=\|A_{ij}\|$. Let $Z = \max\|A_{ii}\|$ and $\alpha_i = Z - \|A_{ii}\| + \delta$, where $\delta > 0$ and the initial value of δ can be chosen as 1.

Step 2 : Calculate the P-F (Perron-Forbenius) eigenvalue of **T**

Step 3 : Change the **T** matrix by increasing δ with a positive increment if P-F eigenvalue of **T** is greater than 2, then multiply the off-diagonal elements in the ith row by $1/\alpha_i$,$i=1,..,N$, until the P-F eigenvalue of **T** is ≤ 2 and update α_i^*, δ^*, T^*.

Step 4 : Set $V = 2(Z + \delta^*)$

3.3 *Design procedure:*

The recursive design procedure is proposed as follows :

(a) $i=1$

(b) If $i > N$ then go to step (f), otherwise set $Q_i=0$, $K_i=0$ for the open-loop system A_i.

(c) Perform the dispersion analysis for the closed-loop system $(A_i + B_iK_i)$ and select the s_i eigenvalues to be shifted. If all dominant energy modes are located in the desired region then go to step (e).

(d) Assign the selected eigenvalues sequentially in the desired region. Update Q_i and K_i and then go to step (c).

(e) $i=i+1$ and then go to step (a).

(f) Check for global optimality. If the condition in eqn.8 is satisfied then stop, otherwise the weighting matrices Q_i, $i=1,2,..,N$, are tuned sequentially as explained previously in section 3.1.2.

4. APPLICATION TO A TWO-AREA INTERCONNECTED SYSTEM

The proposed decentralized optimal **LFC** design procedure is applied to the two-area Egyptian power system. Data for the system are taken from [5] and are given in the Appendix.

Initially, the unstable zero eigenvalues of the open-loop systems A_1 and A_2 are assigned to -0.1 and -0.15; respectively, and the dispersion analysis are tabulated in Tables 1 and 2.

Table 1. Eigenvalues of initial system A_1.

Dynamic Modes	Dynamic Dispersion	
	$H_p(s)$	$H_d(s)$
λ_1=-13.5327	0.0%	-0.02%
λ_2=-1.2963	44.76%	29.6%
$\lambda_3+\lambda_4$=-0.5229 ± j 2.4897	60.556	74.52%
λ_5=-0.1	-5.32	-4.07

Table 2. Eigenvalues of initial system A_2.

Dynamic Modes	Dynamic Dispersion	
	$H_p(s)$	$H_d(s)$
λ_1=-13.5463	0.0%	-0.002%
$\lambda_2+\lambda_3$=-1.1643 ± j1.9745	-0.15%	2.44%
λ_4=-0.15	100.15%	97.56%

Starting from the initial systems (Tables 1,2), the results of the design procedures to compute the optimal decentralized controllers are tabulated in Tables (3) and (4).

Table 3. Eigenvalues of closed-loop system A_1.

Dynamic Modes		Dynamic Dispersion	
Initial Eigenvalues	Closed-loop Eigenvalues	$H_p(s)$	$H_d(s)$
λ_1=-13.5327	-13.5327	-0.08%	-0.7%
λ_2=-1.2963	-3	127.4%	107.8%
$\lambda_3+\lambda_4$=-0.5229 ± j2.4897	-2 ± j 1.5024	-18.1%	1.08%
λ_5=-0.1	-0.1	-9.1%	-8.8%

Table 4. Eigenvalues of closed-loop system A2.

Dynamic Modes		Dynamic Dispersion	
Initial Eigenvalues	Closed-loop Eigenvalues	$H_p(s)$	$H_d(s)$
λ_1=-13.5463	-13.5463	-10.81%	-7.96%
λ_2=-0.15	-12	20.27%	14.96%
$\lambda_3+\lambda_4$=-1.1643 ± j1.9745	-3 ± j1.2073	90.54%	93%

The computed weighting control matrices $\mathbf{Q_1}$ and $\mathbf{Q_2}$ are then tuned by shifting dynamical modes (-13.5327,-0.1) of $\mathbf{A_1}$ to (-20,-8) and (-13.5463) of $\mathbf{A_2}$ to (-19) to ensure global optimality.

The global optimality procedue are evaluated on diagonalized systems of eqns.2 by using the transformati ($X_i=U_iZ_i$; U_i is the modal matrix of A_i). The compu results are as follows :

$$\hat{Q}_1 = U_1^T Q_1 U_1 = \text{diag}(889.2, 280, 280, 118.4, 100.002)$$

$$\hat{Q}_2 = U_2^T Q_2 U_2 = \text{diag}(1016.2, 1016.2, 140.6, 145.4)$$

$$\lambda_m(\hat{Q}_1) \simeq 100, \lambda_M(\hat{P}_1) = 1.96$$

and

$$T = \left\| \begin{matrix} 1 & 0.2971 \\ .9576 & 1 \end{matrix} \right\| = 50.1$$

The decentralized state feedback gains are :

$$\mathbf{K_1} = [\ 0.4092, -9.8857, -9.5152, -2.2241, -33.066]$$

$$\mathbf{K_2} = [-9.9660, -10.5774, -2.4655, -25.2602]$$

The two-area Egyptian power system with decentralized controllers has been simulated for a step lo disturbance $\Delta P_{d1}=0.01$ P.U. M.W and the responses frequency and tie-line power deviations are plotted Figures (1) to (3). For the purpose of comparison, responses of Δf_1 , Δf_2 and ΔP_{tie} of the system w decentralized controller of K.Ramar et al.[7] and optir centralized controller have been plotted on the same grap

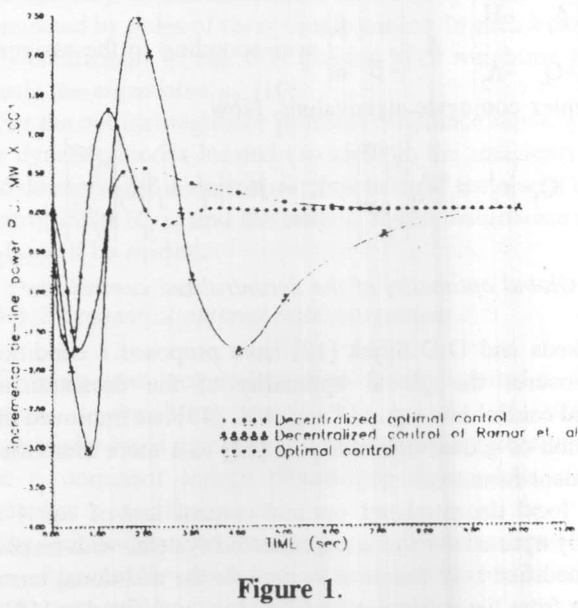

Figure 1.

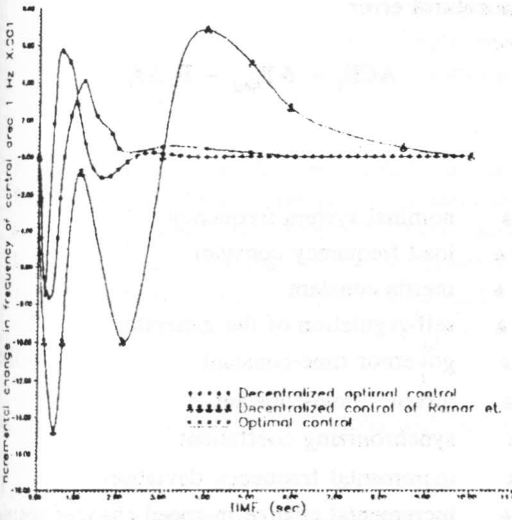

Figure 2.

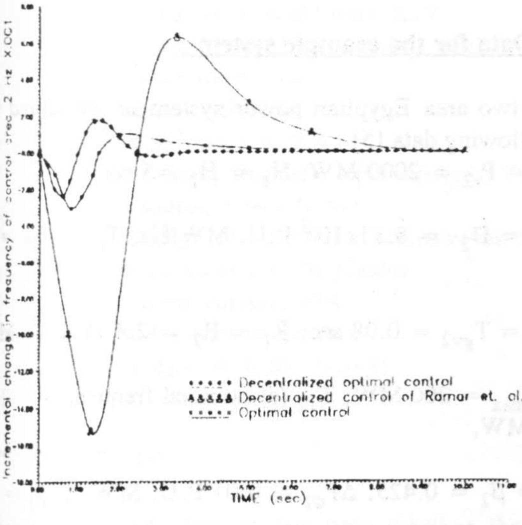

Figure 3.

From the simulation results shown in Figures (1)- (3) we can conclude that :

(a) The transient performance of the closed-loop system with the proposed decentralized controller is much superior than with the controller of K.Ramar et al. [7].

(b) The control technique adopted in this paper succeeded in stabilizing the system in a very small period (about 5 sec) and the control trajectories are very close to the optimal ones.

5. CONCLUSION

A fully decentralized optimal feedback control scheme has been introduced for use with multi-area interconnected power systems. The design procedure of local controllers is based on a sequentially optimal pole placement method of Solheim [9]. The eigenvalues to be shifted are determined properly by using the concept of dominant energy modes. Since the left shift of dominant poles are selected and the effect of transfer function zeros has been considered in the dominant energy mode analysis, very good control performance can be obtained. The computed weighting control matrices of local control areas can be sequentially tuned so as to satisfy the condition of Yang et al. [13] which ensures the global optimalityofthe interconnected system. The design procedure is computationally quite attractive and the simulation results of the two-area Egyptian power network demonstrate the efficiency of the proposed design mode.

6. REFERENCES

[1] *M.M.Elmetwally and N.D.Rao*, "Decentralized optimal control of multi-area Power Systems", IEEE Power Engineering Society Winter Meeting, New York, USA, P.A 76146-1/1-6, 1976.

[2] *Y.Mizutani*, "Suboptimal control for load-frequency control system using an area-decomposition method", electrical engineering in Japan, Vol.98, pp.86-92, 1978.

[3] *M.Ikeda, D.D.Siljack and D.E.White*, "Decentralized control with overlapping information sets", JOTA, Vol.34, pp.279-310, June 1981.

[4] *J.C.Geromel and P.L.D.peres*, "Decentraliaed load-frequency control", IEE Proc., Vol.132D, pp.225-230, September 1985.

[5] *A.Bahnasawi, M.Hassan and S.Eid*,"A new decdntralized controller for the interconnected Egyption power network",Large Scale Syst Vol.11,pp.217-232, 1986.

[6] *A.Feliachi*,"Optimal decentralized load-frequency control", IEEE Trans. on power system, Vol.PWRS-2, pp.379-386, 1987.

[7] *K.Ramar and S.Velusami*, "Design of decentralized load-frequency controllers using pole placement technique", Electric Machines and Power Systems, Vol.16, pp.193-207, 1989.

[8] *S.C.Tripathy, G.S.Hope and O.P.Malik*, "Optimization of load frequency control parameters for power system with reheat steam turbines and governor deadband nonlinearity", IEE Proc. 129, pt. C (1982) 10-16.

[9] *O.A.Solheim*,"Design of optimal control systems with prescribed eigenvalues", Int. J. Control, Vol.15,

pp. 143-160, 1972.

[10] *M. Ouyang, C.M. Liaw, and C.T. Pan*, "Model reduction by power decomposition and frequency response matching", IEEE Trans., AC-32, (1), pp. 59-62, 1987.

[11] *C.M. Liaw*, "Optimal controller with prescribed dominant energy eigenvalues", IEE Proc. D, Vol. 138, (4), pp. 405-409, 1991.

[12] *M. Ikeda and D.D. Silijak*, "When a linear decentralized control is optimal ?", Proc. 5th Int. Conf. Anal & Optimization and Systems, Versaillers, France, 1982.

[13] *T. Yang, N. Munro and A. Brameller*, "Improved condition of optimality of decentralized control for large-scale systems", IEE Proc., Vol. 136 (1), pt. D, pp. 44-46, 1989.

7. APPENDIX:

7.1 System dynamic model

The dynamical model for a single-machine area equivalent model, taking into consideration the speed governor backlash nonlinearity, is summarized below. However, more details can be found in [5].

speed governor

$$\Delta \dot{X}_{gvi}(t) = -\frac{1}{T_{gvi}}\Delta X_{gvi}(t) + \frac{a_i}{T_{gvi}}\left(\Delta P_{ci}(t) - \frac{1}{R_i}\Delta f_i(t)\right) + \frac{b_i}{T_{gvi}}\left(\Delta \dot{P}_{ci} - \frac{1}{R_i}\Delta \dot{f}\right.$$

turbine-generator

$$\Delta \dot{P}_{gi}(t) = -\frac{1}{T_{ti}}\Delta P_{gi}(t) + \frac{1}{T_{ti}}\Delta X_{gvi}(t)$$

power system

$$\Delta \dot{f}_i(t) = -\frac{D_i f^o}{2H_i}\Delta f_i(t) - \frac{f^o}{2H_i}\left(\Delta p_{tie,i}(t) - \Delta P_{gi}(t) + \Delta P_{di}(t)\right)$$

tie-line power

$$\Delta \dot{p}_{tie,i} = \sum_{j=1}^{N} T_{ij}\left(\Delta f_i(t) - \Delta f_j(t)\right) \qquad i = 1,2,\ldots,N$$

and area control error

$$ACE_i = \Delta P_{tie,i} + B_i \Delta f_i$$

where

$f^o \triangleq$ nominal system frequency
$D \triangleq$ load-frequency constant
$H \triangleq$ inertia constant
$R \triangleq$ self-regulation of the generator
$T_{gv} \triangleq$ governor time-constant
$T_t \triangleq$ turbine time-constant
$T_{ij} \triangleq$ synchronizing coefficient
$\Delta f \triangleq$ incremental frequency deviation
$\Delta P_c \triangleq$ incremental change in speed changer position
$\Delta P_d \triangleq$ incremental change in load demand
$\Delta P_g \triangleq$ incremental power generation level
$\Delta P_{tie} \triangleq$ incremental tie-line power
$\Delta X_{gv} \triangleq$ incremental change in valve position

7.2 <u>Data for the example system :</u>

The two area Egyptian power system is considered with the following data [5] :

$P_{r1} = P_{r2} = 2000$ MW; $H_1 = H_2 = 5$ sec,

$D_1 = D_2 = 8.33\times10^{-3}$ P.U. MW/Hz; $T_{t1} = T_{t2} = 0.3$ sec,

$T_{gv1} = T_{gv2} = 0.08$ sec; $R_1 = R_2 = 2.4$ Hz/P.U. MW,

$P_{tie,max} = 200$ MW; T_{12} (at nominal frequency) $= 0.545$ P.U. MW,

$\beta_1 = \beta_2 = 0.425$; $\Delta P_{d1} = 0.01$ P.U. MW; $\Delta P_{d2} = 0.0$

Furthermore, the speed governor backlash coefficients are calculated and are given by
$a_1 = a_2 = 0.8$; $b_1 = b_2 = -0.2/\pi$.
The control weighting matrices $\mathbf{R}_1$ and $\mathbf{R}_2$ are selected to be unity.