Decentralised LQI-Type Load-frequency control with controlling delay of one sampling time for interconnected power systems

Decentralised LQI-Type Load-frequency control with controlling delay of one sampling time for interconnected Power systems

Katsumi YAMASHITA* and **Hayao MIYAGI***

Abstract

This paper presents a new method of designing decentralised discrete-type load-frequency regulator with controlling delay of one sampling time for interconnected power systems. In this method, the interconnected multi-area electric energy system is decomposed into several subsystems, each of which is controlled separately by using a local feedback only. An especially attractive feature of the proposed control scheme is that it considers the time delay due to the computation time of the control law and the transmission time of the system data over the telemeter links to the controlling plant. An additional feature is that the construction of the regulator is based on the conventional tie-line bias control. The proposed control scheme is illustrated by digital simulation of a 2-area system provided with reheat steam turbines. The results show that this discrete-type regulator can act satisfactorily for improving dynamic responses of the load-frequency control.

1. Introduction

The load-frequency control (LFC) problem has been one of the major subjects concerning power-system engineers, and the objective of LFC is to minimize the transient errors in the frequency and the scheduled tie-line power and ensure zero steady-state errors of these two quantities[1-3]. For many years, a considerable research effort has been devoted to the development of control strategies for the LFC problem using continuous-time optimization techniques[3-6].

However, further consideration may be required for practical implementation of control strategies designed by using continuous-time optimization techniques, because, in practical power systems, the system data (frequency, tie-line power etc.) are available in the discrete form, i.e. the system data are first sampled and then transferred over telemeter links. Also the use of digital computers has become practically indispensable to electric energy systems, because, with the use of digital computers, it is now possible, through suitable software, to realise a wide range of control strategies. Accordingly, it may be necessary to construct discrete-type regulators for such practical situations. However, until now, few works[7-9] have been done concerning discrete-time load-frequency control, and in most of the past works, they have ignored the time delay due to the computational time of the control law and the transmission time of the system data over the telemeter links to the controlling plant.

Received: Octover 31, 1987.

* Dept. of Electronics & Information Engineering, Fac. of Eng.

Furthermore, it is recognized that the implementation of a centralised load-frequency control possesses certain difficulties, when the size and complexity of the interconnected power systems increses. Specifically, these difficulties can be traced to the need for elaborate instrumentation and telemetery of the required data to the central controller. Also the computational requirements grow very fast with the number of interconnected areas. In recent years, significant efforts have been made to establish suitable decentralised regulator for large interconnected power systems[10-11].

This paper presents a new method of designing decentralised discrete-type load-frequency regulator with controlling delay of one sampling time for interconnected power systems. In this method, the interconnected multi-area electric energy system is decomposed into several subsystems, each of which is controlled separately by using a local feedback only. An especially attractive feature of the proposed control scheme is that it considers the time delay due to the computation time of the control law and the transmission time of the system data over the telemeter links to the controlling plant. An additional feature is that the construction of the regulator is based on the conventional tie-line bias control, which is used by most utilities of the present day.

In this paper, we apply the newly designed regulator to 2-area power system provided with reheat steam turbines. The results show that the proposed discrete-type regulator can act satisfactorily for improving dynamic responses of the load-frequency control.

2. Notation

f^* = nominal system frequency
i = subscript referring to area i
Δf_i = incremental frequency deviation
ΔP_{ti} = incremental generation change
ΔP_{ri} = incremental generation change during steam reheat
ΔP_{gi} = incremental change in governor valve position
ΔP_{tiei} = incremental change in tie-line power
ΔP_{ci} = incremental change in speed changer position
ΔP_{di} = incremental load demand change
H_i = inertia constant
D_i = load frequency constant
k_{hi} = high pressure turbine power fraction
T_{ri} = reheat time constant
T_{ij} = synchronising coefficient
T_{ti} = steam chest time constant
T_{gi} = speed governor time constant
R_i = self regulation parameter for the governor
β_i = frequency bias parameter
T_s = sampling period
Δ = small deviation of state variable
s = Laplace operator

(Other symbols are defined in the text.)

3. Problem formulation

A typical 2-area power system with reheat steam turbines is shown in Figure 1 for LFC. In state variable form, the continuous-time dynamics of the i-th controlling plant in an n-interconnected system is described by a set of linear differential equations with input delays:

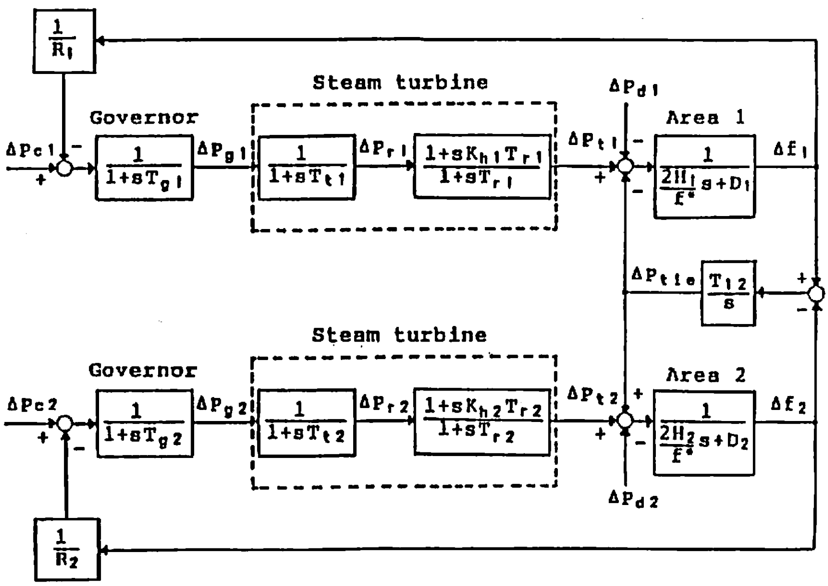

Fig. 1 Block diagram of 2-area reheat thermal system

$$\dot{x}_i(t)=A_i x_i(t)+\sum_j A_{ij} x_j(t)+B_i u_i(t-T_s)+\Gamma_i v_i(t) \qquad x_i(0)=0 \tag{1}$$

where

$$x_i=[\triangle f_i \ \triangle P_{ti} \ \triangle P_{ri} \ \triangle P_{gi} \ \triangle P_{tiei}]^T \qquad u_i=[\triangle P_{ci}] \qquad v_i=[\triangle P_{di}]$$

and T_s is the sampling period. In this case, $u_i(t-T_s)$ with controlling delay of one sampling time is sufficient to consider the effect of the time delay due to the computation time of the control law and the transmission time of the system data over the telemeter links to the controlling plant for practical sampling periods ($1.5 \leqq T_s \leqq 2.5$) used for LFC. The matrices in equation (1) are given by:

$$A_i = \begin{bmatrix} -\frac{f^*D_i}{2H_i} & \frac{f^*}{2H_i} & 0 & 0 & -\frac{f^*}{2H_i} \\ 0 & -\frac{1}{T_{ri}} & \frac{1}{T_{ri}}-\frac{k_{hi}}{T_{ti}} & \frac{k_{hi}}{T_{ti}} & 0 \\ 0 & 0 & -\frac{1}{T_{ti}} & \frac{1}{T_{ti}} & 0 \\ -\frac{1}{T_{gi}R_i} & 0 & 0 & -\frac{1}{T_{gi}} & 0 \\ \sum_j T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix} \quad B_i = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{T_{gi}} \\ 0 \end{bmatrix}$$

$$A_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix} \quad \Gamma_i = \begin{bmatrix} -\frac{f^*}{2H_i} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

However, if it is assumed that $v_i(t)$ represents known disturbances, equation (1) can be rewritten in the standard state form as

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t - T_s) \qquad x_i(0) = -x_{is} \tag{3}$$

where x_i and u_i are the new state and control vectors which equal the old vectors minus these steady state values x_{is} and u_{is}. In equation (3), the coupling terms between the areas are set equal to zero to simplify the problem formulation (non-zero coupling is considered in the example).

Since the control signals $u_i(t)$, $(i=1, 2, \cdots\cdots, n)$ are now outputs of sample-and-hold devices, they are constant during the sampling period T_s and described by

$$u_i(\overline{k-1}T_s) \qquad \text{for } kT_s \leqq t < \overline{k+1}T_s \tag{4}$$

Thus the solution of equation (3) is found to be

$$\begin{aligned} x_i(t) &= e^{A_i(t-kT_s)} x_i(kT_s) + \int_{kT_s}^{t} e^{A_i(t-\tau)} B_i d\tau u_i(\overline{k-1}T_s) \\ &= e^{A_i(t-kT_s)} x_i(kT_s) + [e^{A_i(t-kT_s)} - I] A_i^{-1} B_i u_i(\overline{k-1}T_s) \end{aligned} \tag{5}$$

The equation can be further modified to describe the transition of the states of the digital system at the sampling instants only. By letting $t = \overline{k+1}T_s$, equation (5) becomes

$$x_i(\overline{k+1}T_s) = \Phi_i x_i(kT_s) + \Psi_i u_i(\overline{k-1}T_s) \tag{6}$$

where

$$\Phi_i = e^{A_iT_s} \qquad \Psi_i = [e^{A_iT_s} - I] A_i^{-1} B_i$$

I = identity matrix

Since the steady-state errors of frequency and tie-line power deviations should be driven to zero by LFC, we suggest as feedback signals accumulative quantities of the area control error on the basis of linear quadratic integrating technique[12]. They can be defined as follows:

$$\tilde{x}_i(\overline{k+1T_s})=\sum_{m=0}^{\overline{k+1T_s}}\{\beta_i\triangle f_i(m)+\triangle P_{tiei}(m)\} \tag{7}$$

Using equation (6), equation (7) can be rewritten as

$$\begin{aligned}\tilde{x}_i(\overline{k+1T_s})&=\tilde{x}_i(kT_s)+C_i x_i(\overline{k+1}T_s)\\&=\tilde{x}_i(kT_s)+C_i\Phi_i x_i(kT_s)+C_i\Psi_i u_i(\overline{k-1}T_s)\end{aligned} \tag{8}$$

where

$$C_i=[\beta_i \quad 0 \quad 0 \quad 0 \quad 1]$$

Now, define the augumented state vector as

$$\hat{x}_i(k)^T=[x_i(k)^T \quad \tilde{x}_i(k) \quad u_i(k-1)] \tag{9}$$

where $x_i(k)$, $\tilde{x}_i(k)$ and $u_i(k-1)$ imply $x_i(kT_s)$, $\tilde{x}_i(kT_s)$ and $u_i(k-1T_s)$, respectively.

The augumented set of difference equations for LFC system are

$$\hat{x}_i(k+1)=\hat{\Phi}_i\hat{x}_i(k)+\hat{\Psi}_i u_i(k) \tag{10}$$

where

$$\hat{\Phi}_i=\begin{bmatrix}\Phi_i & 0 & \Psi_i\\ C_i\Phi_i & 1 & C_i\Psi_i\\ 0 & 0 & 0\end{bmatrix} \qquad \hat{\Psi}_i=\begin{bmatrix}0\\0\\1\end{bmatrix}$$

An optimal control can be achived by minimizing a quadratic cost function of the form

$$J_i=E\left[\sum_{k=0}^{\infty}\{\hat{x}_i(k)^T Q_i\hat{x}_i(k)+u_i(k)^T R_i u_i(k)\}\right] \tag{11}$$

subject to the system control constraint of equation (10), where E is the expectation operator over the random initial state, Q_i is 7×7 symmetric positive-semi-definite constant matrix and R_i is positive scalar value.

Now, define the output vector $y_i(k)$ as

$$y_i(k)=[\triangle f_i(k) \quad \triangle P_{tiei}(k)]^T \tag{12}$$

These variables are easily measurable variables and used as the feedback signals of the conventional tie-line bias control. Additional, $\tilde{x}_i(k)$ constructed by the elements of equation (12) and $u_i(k-1)$ are measurable variables. Therefore, suppose that control variable $u_i(k)$ is represented by a linear combination of measurable variables $y_i(k)$, $\tilde{x}_i(k)$ and $u_i(k-1)$ as follows:

$$u_i(k) = -F_i\hat{D}_i\hat{x}_i(k) \tag{13}$$

where

$$F_i^T = \begin{bmatrix} F_{i1}^T \\ F_{i2} \\ F_{i3} \end{bmatrix} \quad D_i = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \hat{D}_i = \begin{bmatrix} D_i & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and F_i is undefined feedback gain vector.

Substituting for $u_i(k)$ from equation (13) in equation (10), the closed-loop system matrix becomes $\Gamma_i = \hat{\Phi}_i - \hat{\Psi}_i F_i \hat{D}_i$,equation (10) reduces to

$$\hat{x}_i(k+1) = \Gamma_i \hat{x}_i(k) \tag{14}$$

and the performance index J_i is also expressed as

$$J_i = E\ [\hat{x}_i(0)^T P_i \hat{x}_i(0)] \tag{15}$$

where P_i is the solution of the Lyapunov Matrix equation

$$P_i - \Gamma_i^T P_i \Gamma_i = Q_i + \hat{D}_i^T F_i^T R_i F_i \hat{D}_i \tag{16}$$

On assuming now that $\hat{x}_i(0)$ is uniformly distributed over the surface of a hypersphere[13], the performance index becomes

$$J_i = \mathrm{tr}P_i \tag{17}$$

where $\mathrm{tr}P_i$ is the sum of the diagonal terms of P_i.

Therefore F_i for the optimal controller must be determined in such a manner that J_i can be minimized subject to the constraint given by equation (16). For minimizing J_i, the Hamiltonian

$$H_i = \mathrm{tr}P_i + \mathrm{tr}L_i(Q_i + \hat{D}_i^T F_i^T R_i F_i \hat{D}_i + \Gamma_i^T P_i \Gamma_i - P_i) \tag{18}$$

is chosen and the necessary conditions for minimization of H_i

$$\frac{\partial H_i}{\partial F_i} = 0, \quad \frac{\partial H_i}{\partial L_i} = 0, \quad \frac{\partial H_i}{\partial P_i} = 0, \tag{19}$$

yield the following solutions:

$$F_i = (R_i + \hat{\Psi}_i^T P_i \hat{\Psi}_i)^{-1} \hat{\Psi}_i^T P_i \hat{\Phi}_i L_i \hat{D}_i^T (\hat{D}_i L_i \hat{D}_i^T)^{-1} \tag{20}$$

$$(\hat{\Phi}_i - \hat{\Psi}_i F_i \hat{D}_i)^T P_i (\hat{\Phi}_i - \hat{\Psi}_i F_i \hat{D}_i) - P_i + Q_i + \hat{D}_i F_i^T R_i F_i \hat{D}_i = 0 \tag{21}$$

$$(\hat{\Phi}_i - \hat{\Psi}_i F_i \hat{D}_i) L_i (\hat{\Phi}_i - \hat{\Psi}_i F_i \hat{D}_i)^T - L_i + I = 0 \tag{22}$$

The equations (20),(21) and (22) are solved iteratively in the following steps:

Step 1: Assume an initial value of $F_i\hat{D}_i$ such that all eigenvalues of $(\hat{\Phi}_i - \hat{\Psi}_i F_i \hat{D}_i)$ lie inside of the unite circle in the z-plane.

Step 2: Use this value of $F_i\hat{D}_i$ to solve equations (21) and (22) for P_i and L_i.

Step 3: Find a new value of F_i by substituting these values of P_i and L_i in equation (20).

Step 4: Obtain a new value of $F_i\hat{D}_i$ by using the value of F_i from Step 3, and then return to Step 2.

By executing the above steps, we can uniquely determine the optimal feedback gain vector F_i.

4. Application

A 2-area power system with reheat steam turbines as shown in Figure 1 is used to evaluate the effectiveness of the proposed load-frequency controller. The values of the system parameters are given in Table 1. The weighting matrices in equation (11) are shown as $Q_i = I$ and $R_i = 1$, $(i = 1, 2)$, respectively. The optimal feedback gain vectors F_i,$(i = 1, 2)$ are obtained as the solution of equations (20),(21) and (22). The results are indicated in Table 2 ($\triangle ACE_i(m)$ implies $\beta_i \triangle f_i(m) + \triangle P_{tiei}(m)$). Figures 2-5 indicate the control effects achived by the proposed load-frequency regulators under a step-load change $\triangle P_{d1} = 0.01$ pu MW in area 1. Curves in Figures 2-5 show the performance of $\triangle f_1$,$\triangle f_2$,$\triangle P_{tie}$ and $\triangle P_c$ for the optimal system and the uncontrolled system (here set $\triangle P_{tie} = \triangle P_{tie1} = -\triangle P_{tie2}$). The solid curves show the performance of the optimal system, whereas the dotted curves show the performance of the uncontrolled system. It can be seen from these figures that the transient errors in the frequency and the scheduled tie-line power are much reduced and zero steady-state errors of these quantities are ensured, by the regulator with the optimal

Table 1 System Parameters.

$H_i = 5s$	$D_i = 8.33 \times 10^{-3}$puMW/Hz
$R_i = 2.4$Hz/puMW	$T_{ti} = 0.3s$
$T_{gi} = 0.08s$	$T_{ri} = 10.0s$
$K_{hi} = 0.5$	$\beta_i = D_i + 1/R_i = 0.425$puMW/Hz
$(i = 1,2)$	
$f^* = 60$Hz	$T_{12} = 0.545$puMW/Hz · s
$T_s = 2.0s$	

Table 2 Optimal feedback gain vector F_i

Ourput feedback	F_1	Output feedback	F_2
$\triangle f_1(k)$	-0.1776	$\triangle f_2(k)$	-0.1776
$\triangle P_{tie1}(k)$	0.3594	$\triangle P_{tie2}(k)$	0.3594
$\sum_{m=0}^{k} \triangle ACE_1(m)$	0.5320	$\sum_{m=0}^{k} \triangle ACE_2(m)$	0.5320
$\triangle P_{c1}(k-1)$	0.1052	$\triangle P_{c2}(k-1)$	0.1052

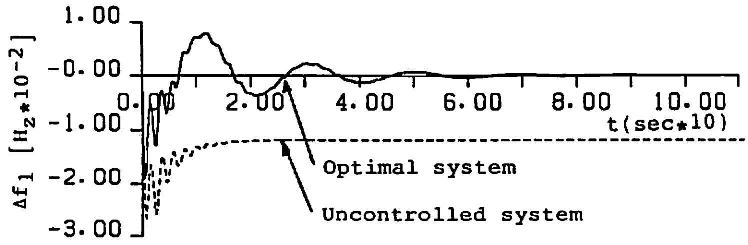

Fig. 2 Responses of △ f_1

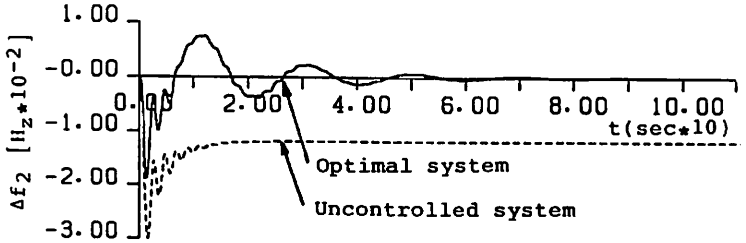

Fig. 3 Responses of △ f_2

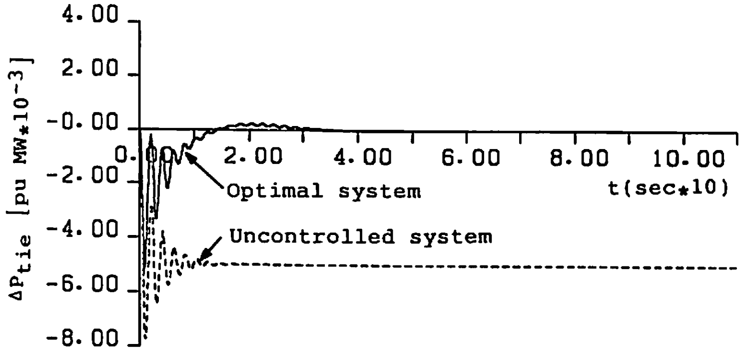

Fig. 4 Responses of △ P_{tie}

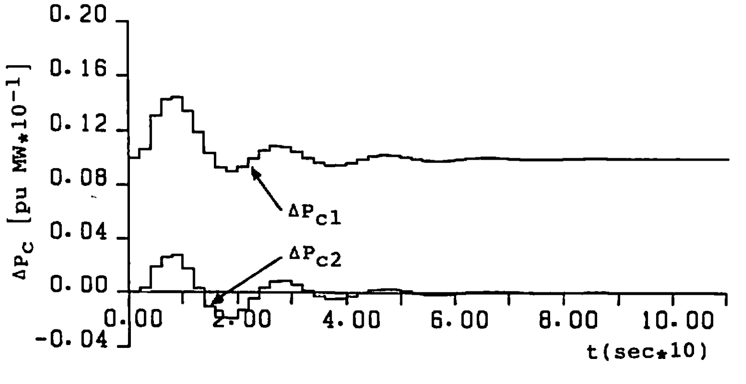

Fig. 5 Responses of △ P_{c1} and △ P_{c2}

gains. It may thus inferred that the proposed control scheme can be acceptable for LFC of interconnected power systems.

5. Conclusions

In this paper, a new method of designing a decentralised discrete-type load-frequency regulator with controlling delay of one sampling time has been proposed, and the effectiveness of the proposed regulator has been shown in 2-area power system with reheat steam turbines. The major contributions of this paper are as follows:

(a) The proposed control scheme is very realistic, because the regulator is designed to consider the effect of the time delay due to the computation time of the control law and the transmission time of the system data over the telemeter links to the controlling plant.

(b) The realisation of this regulator is very easy, because the feedback data, required to form the control signals are only sampled frequency and tie-line power, which are used by most of the utilities of the present day.

6. Acknowledgement

The authors wish to thank Dr. T. Taniguchi, University of Osaka Prefecture, for his valuable advice. The authors are favored to have had the assistance of R. Imabeppu, S. Ikemura and K. Oyadomari, who contributed their experimental skill and sustained effort in the execution of the experiment. This work was supported by the Grant in Aid for Scientific Research from the Ministry of Education of Japan.

7. References

[1] Elgerd, O.I., Fosha, C.E., "Optimum Megawatt-Frequency Control of Multiarea Electric Energy Systems", IEEE Transactions on PAS-89, 1970, pp.556-562.

[2] Elgerd, O.I., Electric Energy Systems Theory: An Introduction, McGraw-Hill INTERNATIONAL, 1983.

[3] Fosha, C.E., Elgerd, O.I., "The Megawatt-Frequency Control Problem: A New Approach Via Optimal Control Theory", IEEE Transactions on PAS-89, 1970, pp.563-577.

[4] Nanda, J., Kaul, B.L., "Automatic Generation Control of an Interconnected Power System", Proc. IEE, vol.125, 1978, pp.385-390.

[5] Hsu, Y.Y., Chan, W.C., "Optimal Variable Structure Controller for the Load-Frequency Control of Interconnected Hydrothermal Power Systems", Int. J. of Electrical Power & Energy Systems, 1984, pp.221-229.

[6] Yamashita, K., Taniguchi, T., "Optimal Observer Design for Load-Frequency Control", Int. J. of Electrical Power & Energy Systems, 1986, pp.93-100.

[7] Bohn, E.V., Miniesy, S.M., "Optimum Load-Frequency Sampled-Data Control with Randomly Varying System Disturbances", IEEE Transactions on PAS-91, 1972, pp. 1916-1923.

[8] Glover, J.D., Schweppe, F.C., "Advanced Load Frequency Control", IEEE Transactions on PAS-91, 1972, pp.2095-2103.

[9] Tripathy, S.C., Bhatti, T.S., Jha. C.S., Malik, O.P., Hope, G.S., "Sampled Data Automatic Generation Control Analysis with Reheat Steam Turbines and Governor Dead-Band Effects", IEEE Transactions on PAS-103, 1984, pp.1045-1051.

[10] Hiyama, T., "Design of Decentralised Load-Frequency Regulators for Interconnected Power Systems", Proc. IEE, vol.129, 1982, pp.17-23.

[11] Geromal, J.C., Peres, P.L.D., "Decentralised Load-Frequency Control", Proc. IEE, vol.132, 1985, pp.225-229.

[12] Narita, S., Digital Control Systems: Theory and Application, Syoukoudo, 1980.

[13] Levine, W.S., Athans, M., "On the Determination of the Optimal Constant Output Feedback Gains for Linear Multivariable Systems", IEEE Transactions on AC-15, 1970, pp.44-48.