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Decentralised H$_\infty$ Load Frequency Controller Design Based on SSVs

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Abstract

The decentralised load-frequency controller design problem concerned is translated into an equivalent problem of decentralised controller design for a multi-area multi-input multi-output (MIMO) control system. It is shown that subject to a condition based on the structured singular values (SSVs), each local area load-frequency controller can be designed independently. The stability condition for the overall system can be stated as to achieve a sufficient interaction margin. It is demonstrated by computer simulation that within this general framework, local H_∞ controllers can be designed to achieve satisfactory performances for a sample two-area power system.

1. Introduction

In the load-frequency control function it is necessary to keep the system frequency and the interarea tie-line power as near to the scheduled values as possible through control action. The important requirement for system stability may be conveniently met by adopting a global policy for design, based, for example, on well-established principles of pole placement or optimal control by state feedback. Where such an approach is to be used with decentralised control, the state vector for the entire system should be made available for the generation of local feedback control signals in all areas. This requirement may be met if a reconstruction of the whole system state vector is made within each area only, i.e., if the system state vector is observable from area measurements. However, even if the observability condition is satisfied, the resulting controllers with appropriately designed observers are normally quite complicated and this approach is not suitable for a large power system where the total number of the state variables is large.

In the dynamical operation of power systems it is usually important to aim for decentralisation of control action to individual areas. This aim should coincide with the requirements for stability and load-frequency scheduling within the overall system. In a completely decentralised control scheme, the feedback controls in each area are computed on the basis of measurements taken in that area only. This implies that no interchange of information among areas is necessary for the purpose of load-frequency control (LFC). The advantages of this operating philosophy are apparent in providing cost savings in data communications and in reducing the scope of the monitoring network.

Another important issue in the load-frequency controller design is robustness. An industrial plant such as a power system always contains some uncertainties. Several authors [1-4] applied the concept of a variable-structure system (VSS) to the design of load-frequency controllers. Various adaptive control techniques [5-7] were proposed for dealing with parameter variations. Recently, there are also publications in which a Riccati equation approach is applied to the stabilisation of an uncertain linear system [5, 8] in the LFC design. All the proposed methods with consideration of robustness are based on the state-space approach. It is known that although the load frequency control for multi-area power systems can be naturally formulated as a large-scale system decentralised control problem, it can be translated into an equivalent problem of decentralised controller design for a multi-input multi-output (MIMO) control system [9]. The frequency response based robust controller design methods, for example H_∞ or other design techniques, may be applied to such a MIMO system. However, applying these methods in general leads to a centralised controller.

In this paper, structured singular values are used in a different way from those commonly used in the literature [10-14]. It is shown that subject to a condition based on structured singular values, each local area controller can be designed independently. The stability condition for power systems with local area controllers can be stated as to achieve a sufficient interaction margin proposed in [9, 15], and sufficient gain and phase margins defined in classical feedback theory during each independent design. It is shown that within this framework it is possible to design H_∞ local area controllers to achieve satisfactory system performances.

2. Sample System

Figure 1 is a block diagram for the load-frequency control of a two-area power system. The nomenclature used and the nominal parameter values, in per unit (pu), are given in the Appendix.

A state-space model for the system of Figure 1 can be constructed as

$$\begin{aligned} \mathbf{x} &= \mathbf{Ax} + \mathbf{Bu} \\ \mathbf{y} &= \mathbf{Cx} \end{aligned} \tag{1}$$

where ;

$$\mathbf{u} = [u_1\ u_2]^T; \mathbf{y} = [y_1\ y_2]^T = [\Delta f_1\ \ \Delta f_2]^T$$

$$x = [\Delta f_1\ \Delta P_{T1}\ \Delta P_{G1}\ \Delta P_{cl}\ \Delta P_{tie}\ \Delta f_2\ \Delta P_{T2}\ \Delta P_{G2}\ \Delta P_{c2}]^T$$

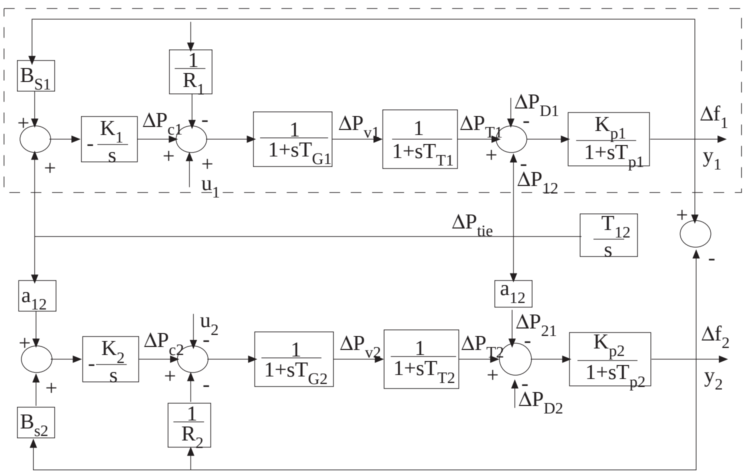

Figure 1. Block diagram of two-area system

$$\mathbf{A} = \begin{bmatrix} \frac{-1}{T_{p1}} & \frac{K_{p1}}{T_{pl}} & 0 & 0 & \frac{-K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{T_{t1}} & \frac{1}{T_{t1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{R_1 * T_{G1}} & 0 & \frac{-1}{T_{G1}} & \frac{1}{T_{G1}} & 0 & 0 & 0 & 0 & 0 \\ -K_1 * B_1 & 0 & 0 & 0 & -K_1 & 0 & 0 & 0 & 0 \\ T_{12} & 0 & 0 & 0 & 0 & -T_{12} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{K_{p2}}{T_{p2}} & \frac{-1}{T_{p2}} & \frac{K_{p2}}{T_{p2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{-1}{T_{T2}} & \frac{1}{T_{T2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{R_2 * T_{G2}} & 0 & \frac{-1}{T_{G2}} & \frac{1}{T_{G2}} \\ 0 & 0 & 0 & 0 & K_2 & -K_2 * B_2 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & \frac{1}{T_{G1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{T_{G2}} & 0 \end{bmatrix}^T$$

$$\mathbf{B} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}^T$$

The system is stable and the control task is to minimise the system frequency deviation Δf_1 in area 1, Δf_2 in area 2 and the deviation in the tie-line power flow ΔP_{tie} between the two areas under the load disturbances ΔP_{D1} and ΔP_{D2} in the two areas. Since the system parameters for the two areas are identical and the Δ $Ptie$ is caused by $\Delta f_1 - \Delta f_2$, the system performance can be mainly tested by applying a disturbance ΔP_{D1} to the system and observing the time response of Δf_1. Some simulation results for Δf_1 when a step disturbance of ΔP_{D1}=0.01pu is applied to the system are plotted in Figures 7, 8 and 9 as dashed lines.

3. Transform into equivalent design problem

In general, an m-area power system load-frequency control problem can be modelled as a large-scale system consisting of m subsystems

$$\begin{aligned} \mathbf{x} &= \mathbf{A}_m x + \mathbf{B}_m u \\ \mathbf{y} &= \mathbf{C}_m \end{aligned} \tag{2}$$

where $\mathbf{u}=[u_1, \ldots, u_m]^T, \mathbf{y}=[y_1, \ldots y_m]^T = [\Delta f_1, \ldots, \Delta f_m]^T \mathbf{x}=[x_1, \ldots, x_m]^T$ and x_i are the state variables for i th area (i th subsystem). The sample system used here is a special case of m=2. An $m$xm transfer function matrix $\mathbf{G(s)}$ linking $\mathbf{U(s)}$=[u$_1$(s),..., u$_m$(s)]^T and $\mathbf{Y(s)}$= [y1(s),, y$_m$(s)]^T:

$$\mathbf{Y}(s) = \mathbf{G}(s)\mathbf{U}(s)\mathbf{G}(s) = [g_{ij}(s)_{i,j=1,\ldots,m}] \tag{3}$$

can be calculated as

$$\mathbf{G}(s) = \mathbf{C}_m(s\mathbf{I} - \mathbf{A}_m)^{-1}\mathbf{B}_m \tag{4}$$

The design of m decentralised local controllers now becomes the design of a mXm diagonal matrix $\mathbf{K}(\mathbf{s})$ = diag $[k_i(s)]_{i=1,\ldots,m}$ as shown in Figure 2. If all $g_{ij}(s)(i \neq j)$ in $\mathbf{G}$(s) were equal to zero, each controller could be designed independently just as if it were in a SISO system as shown in Figure 3. However, since $g_{ij}(s)(i \neq j)$ are not zero, the following question must be resolved, i.e., if each $k_i(s)(i = 1, \ldots, m)$ is designed to form a stable closed-loop system as shown in Figure 3, what are the additional conditions which can guarantee that the global system of Figure 2 is stable? The answer to this question is discussed in the following section based on the theorem given in [16].

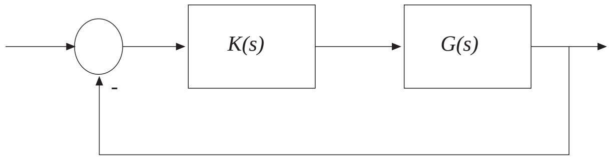

Figure 2. Equivalent MIMO system

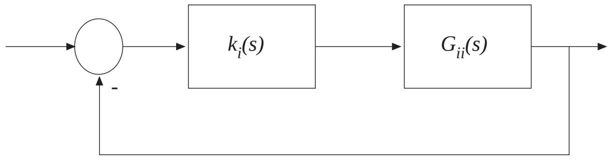

Figure 3. Independent SISO system design

4. Decentralised Controller Design for MIMO systems

In [16], a transfer function $G(s) = [g_{ij}(s)]_{i,j=1,2,\ldots m}$ for a mxm MIMO plant is composed into

$$\mathbf{G(s)} = \mathbf{\tilde{G}(s)} + \mathbf{\hat{G}(s)} \tag{5}$$

where $\mathbf{G(s)} = \text{diag}[g_{ii}(s)]_{i=1,2,\ldots m}$ is a diagonal matrix; all diagonal elements in $\mathbf{\hat{G}(s)}$ are zero and off-diagonal elements in are equal to those in G(s). Using the notations

$$\mathbf{E(s)} = \mathbf{\hat{G}(s)\tilde{G}^{-1}(s)} \tag{6}$$

$$\mathbf{\tilde{H}}(s) = \mathbf{\tilde{G}}(s)(\mathbf{I} + \mathbf{\tilde{G}}(s)\mathbf{K}(s))^{-1} = \text{diag}[h_1(s)] \tag{7}$$

$$\mathbf{H}(s) = \mathbf{G}(s)\mathbf{K}(s)(\mathbf{I} + \mathbf{G}(s)\mathbf{K}(s))^{-1} \tag{8}$$

where $\mathbf{K}(s) = diag[k_i(s)]_{i=1,2,\ldots m}$ is a diagonal transfer function for a decentralised controller in Figure 2; $\mathbf{\tilde{H}(s)}$ or $\mathbf{H}$ $\mathbf{(s)}$ is a closed-loop transfer function matrix for a feedback system consisting of $\mathbf{K(s)}$ and $\mathbf{\tilde{G}(s)}$, or $\mathbf{K(s)}$ and $\mathbf{G(s)}$, respectively. The following theorem is proved in [16]:

Theorem: The closed-loop system $\mathbf{H(s)}$ is stable if

(c-1) $\mathbf{G(s)}$ and $\mathbf{\tilde{H}(s)}$ have the same number of right half plane poles

(c-2) $\mathbf{\tilde{H}(s)}$ is stable, and

(c-3) $|h_i(jw)| < \mu^{-1}(\mathbf{E}(jw))\forall w(i = 1, 2, \ldots m)$

where || denotes magnitude and μ denotes Doyle's structured singular value with respect to the decentralised controller structure of $\mathbf{K(s)}$.

Remark: In [16], the more general block-diagonal structure is considered, condition (c-3) is in the more general form of (c-3)*, $\sigma_{\max}(\mathbf{\tilde{H}}(jw)) < \mu^{-1}(\mathbf{E}(jw))\forall w$, where $\sigma_{\max}$ denotes the maximum singular value.

This theorem gives sufficient conditions for the system $\mathbf{H(s)}$ to be stable if the controller design is based on the fully non-interactive model $\mathbf{\tilde{G}(s)}$, i.e., each $k_i(s)$ is designed independently, based on an SISO model $g_{ii}(s)$. In particular, condition (c-3) states that the magnitude of the frequency response of SISO closed-loop transfer function $h_i(s) = k_i(s)g_{ii}(s)/(1 + k_i(s)g_{ii}(s)$ must be less than the value of a scalar frequency-dependent function $\mu^{-1}(\mathbf{E}(\text{jw}))$. It is also proved [16] that, although (c-3) is a sufficient condition and therefore may have some conservativeness, compared with the other conditions developed for the independent decoupled design, for example, the diagonal dominant condition and the generalised diagonal dominant condition, (c-3) gives the tightest restrictive band and is the least conservative. However, since the same restriction $\mu^{-1}(\mathbf{E}(jw))$ is applied to all $h_i(s)$ in condition (c-3), a modification to this condition [16] can be made to provide more flexibility and to reduce further the possible conservativeness caused by the inflexibility in condition (c-3):

(c-4) $|h_i(jw)w_i^{-1}(jw)| < \mu^{-1}(\mathbf{E}(jw)(\mathbf{W}(jw))\forall w(i = 1, 2 \ldots m)$

where $\mathbf{W}$(s) = diag$[w_i(s)]_{i=1,2,\ldots m}$ is a properly chosen diagonal weighting function matrix. Due to $w_i^{-1}(jw)$ in (c-4), although $\mu^{-1}(\mathbf{E}(jw)(\mathbf{W}(jw))$ is still the same for all SISO loops, the restrictions on $|h_i(jw)$ are different. In fact, (c-3) is a special case of (c-4). For this reason, we specify the stability conditions [17] as:

(r-1) Condition (c-4) is satisfied with a sufficient margin. This can be checked by plotting $|h_i(jw)|$ and $\mu^{-1}E(jw)(W(jw)w_i(jw)|$ on the same graph and an interaction margin for loop i can be defined as the shortest vertical distance between the two curves.

(r-2) There are sufficient gain and phase margins in each SISO loop for the stability. This can also be checked by a Bode or Nyquist plot of $k_i(jw)g_{ii}(jw)$.

Remark: For most systems, a satisfactory disturbance-rejection performance can be achieved if there are sufficient stability margins.

For the given sample system, m=2 and the equivalent MIMO system can be represented by Figure 4. Since the plant parameters in the two subsystems are identical, $\mathbf{W}$ can be chosen as $\mathbf{I}$ and neglected. The interaction margin is therefore checked by the frequency responses of $\mu^{-1}(\mathbf{E}(jw))$ and $|h_i(jw)|$. A plot of $\mu^{-1}(\mathbf{E}(jw))$ for plant $\mathbf{G}(\mathbf{s})$ is given in Figure 5 as a solid line.

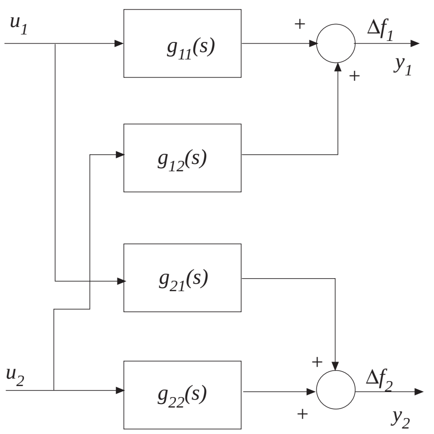

Figure 4. A two-input two-output system

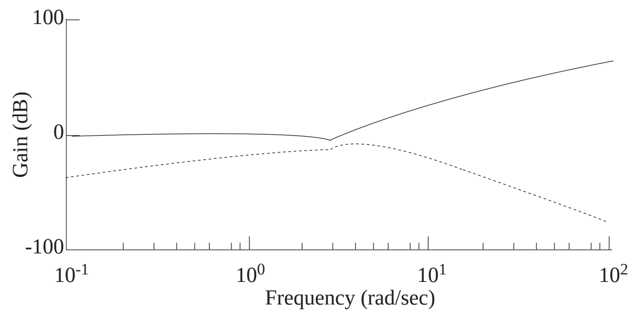

Figure 5. Bode plot of $\mu^{-1}(E(jw))$ (-) and h_1 (–)

5. H_∞ Controller Design Based on Normalised Coprime Factorisation

Glover et al proposed normalised coprime factors as a tool for obtaining robust stability using H_∞ theory [18]. This is a particularly nice problem because it does not require λ-iteration for its solution, and explicit formulas for the corresponding controllers are available.

The problem was stated as [18]:

Let (M_l, N_l) be a normalised left coprime factorisation of G, then

1- Find a largest positive number $\varepsilon_{\max}$, called the maximum stability margin, such that $(M_l, N_l, \varepsilon_{max})$ is robustly stabilizable.

2- For a particular value $\varepsilon \leq \varepsilon_{\max}$, synthesise a feedback controller, K, such that $(N_l, M_l, K, \varepsilon)$ is robustly stable.

The main results will now be stated for a system, G, with normalised left coprime factor (M_l, N_l). We need to find the controller K which stabilises the nominal closed-loop system and which minimises γ where

$$\gamma = \left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} M_l^{-1} \right\|_\alpha \leq \frac{1}{\varepsilon} \tag{9}$$

This is the problem of robust stabilisation of normalised coprime factor plant descriptions. The lowest achievable value of γ and the corresponding maximum stability margin ϵ are given as [18],

$$\gamma_{min} = (1 + \lambda_{\max}(ZX))^{1/2} \tag{10}$$

where $\lambda_{\max}$ (.) represents the maximum eigenvalue, and for state-space realisation (A,B,C,D) of G, the matrix Z $\geq$ 0 is the unique stabilising solution to the Riccati equation.

$$(A - BS^{-1}D^TC)Z + Z(A - BS^{-1}D^TC)^T - ZC^TR^{-1}CZ + BS^{-1}B^T = 0 \tag{11}$$

where $R = I + DD^T, S = I + D^TD$, and X is the unique stabilising solution of the following Riccati equation

$$(A - BS^{-1}D^TC)^TX + X(A - BS^{-1}D^TC) - XBS^{-1}B^TX + C^TR^{-1}C = 0 \tag{12}$$

A controller which guarantees that

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} M_l^{-1} \right\|_\infty \leq \gamma \tag{13}$$

for a specified $\gamma > \gamma_{\min}$, is given by

$$K = \begin{bmatrix} A + BF + T(C + DF) & T \\ B^TX & -D^T \end{bmatrix} \tag{14}$$

where

$$T = \gamma^2 (L^T)^{-1} ZC^T \tag{15}$$

$$F = S^{-1}(D^TC + B^TX) \tag{16}$$

$$L = (1 - \gamma^2)I + XZ \tag{17}$$

The controller K(s) has the same number of poles (states) as G, and its minimal state-space realisation is given (14).

6. Local Controller Design

Now consider a system enclosed by a block with broken lines in Figure 1, the system has an input u_1 and output y_1. As before, since the plant parameters in the two areas are identical, we only need to consider a decentralised local controller for area 1. To design a local controller based on the assumed nominal model of $g_{11}^0(s)$ it is necessary to obtain sufficient stability margins as stated in (r-1) and (r-2) given in section 4, in order to have a robust performance for the global system represented by Figure 1. This is also because the $g_{11}^0(s)$ is an approximation of the plant model $g_{11}(s)$ given in Figure 4.

$g_{11}^0(s)$ here is the plant model G. A state-space realisation A, B, C, D for G can be easily obtained. By solving the Riccati equations (11), and (12), Z and X are obtained as:

$$Z = \begin{bmatrix} 3.0654 & 0.8086 & -0.5363 & 0.0 \\ 0.8086 & 1.1670 & 1.2651 & 0.1303 \\ -0.5363 & 1.2651 & 6.6541 & 0.1921 \\ 0.0 & 0.1303 & 0.1921 & 0.1821 \end{bmatrix}$$

$$X = \begin{bmatrix} 0.3542 & 0.2930 & 0.0560 & -0.2129 \\ 0.2930 & 0.3675 & 0.0826 & -0.0736 \\ 0.056 & 0.0826 & 0.0196 & 0.0 \\ -0.2129 & -0.0736 & 0.0 & 2.7866 \end{bmatrix}$$

From (10), $\gamma_{\min} = 1.2$, we choose $\gamma = 1.75$; substituting this value and other known matrices into (15), (16) and (17) gives:

$$F = \begin{bmatrix} -0.6999 & -1.0324 & -0.2452 & 0.00] \end{bmatrix}$$

$$L = \begin{bmatrix} -2.1274 & 0.6714 & 0.5123 & 0.0103 \\ 1.1509 & -2.6594 & 0.8432 & 0.0504 \\ 0.2279 & 0.1665 & -3.2151 & 0.0145 \\ -0.7122 & 0.105 & 0.5565 & -2.9275 \end{bmatrix}$$

$$T = \begin{bmatrix} -8.4374 & -3.5758 & -1.5622 & -0.0992]^T \end{bmatrix}$$

From (14), the transfer function for the local output feedback controller can be obtained as:

$$\hat{k}_1 = \frac{9.9803s^3 + 151.0511s^2 + 242.436s - 113.6777}{s^4 + 27.4s^3 + 276.8s^2 + 1449.8s + 88.6}$$

This $k_1(s)$ is normally of high order. A low order $k_1(s)$

$$k_1(s) = \frac{b_2 s^2 + b_1 s + b_0}{s^2 + a_1 s + a_0}$$

can be used to approximate $k_1(s)$ based on the minimisation of the frequency response errors between $\hat{k}_1(jw)$ and $k_1(jw)$. This is carried out as follows:

(1) obtain the frequency of $k_1(jw)$ over the relevant frequency range, in our case from $w = 0.01\, rad/sec$ to $w = 100\, rad/sec$.

(2) using the *Matlab* function *invfreqs* in the Signal Processing toolbox to find the values b_2, b_1, b_0 and a_0 in $k_1(s)$ which can give the best fit between the frequency response of $k_1(jw)$ (from $w = 0.01\,rad/sec$ to $w = 100\,rad/sec$) and that obtained in the first step.

The result is

$$k_1(s) = \frac{9.9687s^2 + 6.7076s + 0.2316}{s^3 + 12.7752s^2 + 81.832s - 0.1569}$$

$h_1(s)$ can be obtained by first connecting the above transfer function $k_1(s)$ to the state-space model used to calculate g_{11}(s), (the A matrix, the first column of the B matrix and the first row of the C matrix in equation (1)), then finding the resulting closed-loop system transfer function. The frequency response of $|h_1(jw)|$ is plotted in Figure 5 as a dotted-dashed line. The interaction margin obtained is 4.264 *db* at a frequency of $w \approx 2.95$ rad/sec.

7. Simulation Results

To test system performance, a step load disturbance of ΔP_{D1}=0.01pu is applied to area 1 and the system output of Δf_1 is observed. An integration-absolute-error-time (IAET) criteria of the following form is also used:

$$J_{fre} = 1000 \int_0^{20} |\Delta f(t)| t dt \tag{18}$$

In the simulation study, the linear model of a nonreheating turbine $\Delta P_T / \Delta P_G$ in Figure 1 is replaced by a nonlinear model of Figure 6 with $\delta = 0.015$. This is to take into account the generating rate constrain, i.e., the practical limit on the response speed of a turbine, which was not considered in some early publications [19, 20].

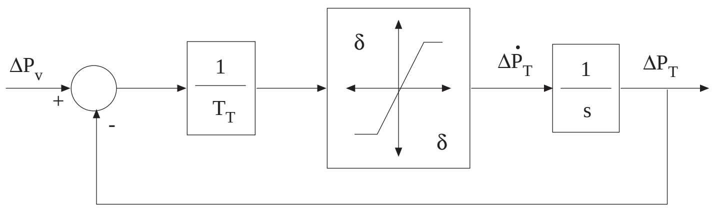

Figure 6. Nonlinear turbine model with GRC

A number of simulations, using the nominal plant parameters and those with all plant parameters changed by some percentage, were carried out for three different cases. The J_{fre} values obtained are listed in Table 1, where

(1) Case A: two identical compensators designed in section 4 based on the H_∞ design are added to the system of Figure 1,

(2) Case B: two identical controllers designed with the Riccati equation approach given in [8] applied for comparison, are added to the system of Figure 1,

(3) Case C: no additional controller is connected to the system represented by Figure 1.

Some selected time response plots are given in Figures 7, 8 and 9; solid lines are for Case A and dotted-dashed lines are for Case B and dashed lines are for Case C.

Similarly, deviation in the tie-line power flow ΔP_{tie} between the two areas under the load disturbances ΔP_{D1}=0.01pu is also checked.

Table 1. J_{fre} values

Test	Parameter Changes %	Case A	Case B	Case C
0	0	3.5	15.9	11.6
1	+5	3.1	15.2	16.3
2	-5	3.6	16.8	8.4
3	+10	3.1	14.6	23.4
4	-10	3.5	17.6	6.5
5	+15	2.9	14.0	32.8
6	-15	3.9	18.5	4.9
7	+20	3.3	13.5	45.7
8	-20	4.1	19.7	4.4
9	+25	3.3	13.1	64.9
10	-25	4.5	21.1	4.9
11	+30	3.5	12.7	89.1
12	-30	4.7	22.8	5.4

An IAET criteria of the following form is used:

$$J_{tie} = 1000 \int_0^{20} |\Delta P_{tie1}(t)| t dt \qquad (19)$$

The results for the two cases are given in Table 2. The results in Tables 1 and 2 show that, in comparison with both no additional controller and with the controllers designed by the method given in [8], the system performance significantly improved and that this performance is robust against the plant parameter changes.

Table 2. J_{tie} values

Test	Parameter Changes %	Case A	Case B	Case C
0	0	2.0	6.6	4.2
1	+5	1.8	6.3	5.5
2	-5	2.0	6.9	3.3
3	+10	1.8	6.1	7.7
4	-10	1.9	7.2	2.8
5	+15	1.7	5.9	11.1
6	-15	2.1	7.6	2.5
7	+20	1.8	5.7	15.8
8	-20	2.1	8.0	2.3
9	+25	1.8	5.5	22.4
10	-25	2.3	8.5	2.3
11	+30	1.7	5.4	30.6
12	-30	2.2	9.1	2.4

8. Conclusion

A robust decentralised power system load-frequency controller design approach has been proposed in this paper. An output feedback local area H_{∞} controller design technique based on general framework proposed in section 4 is applied to the problem of decentralised load frequency controller design. Most researchers use a two-area power system for the study of a multi-area system load frequency control problem and assume that the results can be extended to power systems consisting of more than two areas. The same approach is adopted in this study. Extention to four-area power system for phase-lead compensator is also shown in [21]. Due to the nature of the independent design, subject to some conditions, the proposed design approach can be applied to a general m-area power system. These and other possible designs are currently under investigation.

9. Appendix

System Parameters [19]

T_T turbine time constant, $T_{T1} = T_{T2} = 0.3$ s; T_G governor time constant, $T_{G1} = T_{G2} = 0.08$s.; T_P power system time constant $T_{P1} = T_{P2} = 20$s; R regulation parameter, $R_1 = R_2$=2.4Hz/puMW; K_p power system gain, $K_{p1} = K_{p2} =$ 120Hz/puMW; T_{12} synchronising coefficient, T_{12} = 0.545puMW; B frequency bias parameter, $B_1 = B_2 =$ 0.425puMW/Hz; P_D load disturbance; K integration gain, $K_1 = K_2$ =0.6; a_{12} ratio between the base values of two area, a_{12}=-1

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