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INDEPENDENT DECENTRALISED ROBUST LOAD FREQUENCY CONTROLLER DESIGN

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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 inter action margin.

It is demonstrated by computer simulation that within this general framework, each local area controller can be designed to achieve satisfactory performances for a sample two-area power system even each design method is different.

Key Words: Robust, Decentralised, Load Frequency, Power System

BAĞIMSIZ, YEREL KONTROLÖR DİZAYNI

ÖZET

Yerel yük-frekans kontrolör dizayn problemi çok-giriş ve çok-çıkışlı çok bölgeli sistemler için eşdeğer yerel kontrolör dizayn problemine dönüştürüldü.

Yapılandırılmış tekil değerlerle ilgili bir şarta bağlı olarak bağımsız yerel kontrolörlerin dizayn edilebileceği gösterildi. Bu şart tüm sistemin stabilite şartı için belirli bir karşılıklı etkileme sınırı olarak belirlendi.

Bilgisayar simulasyonları da gösterdi ki, bu genel yaklaşım içinde , her bir yerel bölge kontrolörü yeterli bir performans sağlamak için her lokal kontrolör dizayn metodu değişik olsa bile dizayn edilebilir.

Anahtar Kelimeler: Sağlam, Yerel, Yük frekans, Güç sistemi

1. INTRODUCTION

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 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 [1-3] applied the concept of variable-structure system (VSS) to the design of load-frequency controllers. Various adaptive control techniques [4-6] were proposed for dealing with parameter variations. Recently, there are also publications in applying a Riccati equation approach to the stabilisation of uncertain linear system [4, 8] to 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 [8].

In this paper, structured singular values are used in a different way from those commonly used in the robust literature [9-13]. 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 [8, 14], 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 each local area controller with different design method to achieve satisfactory system performances.

2. SAMPLE SYSTEM

A state-space model for the system of sample two-area system can be constructed as [8, 18]

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

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

$x = [\Delta f_1 \; \Delta P_{T1} \; \Delta P_{G1} \; \Delta P_{c1} \; \Delta P_{tie} \; \Delta f_2 \; \Delta P_{T2} \; \Delta P_{G2} \; \Delta P_{c2} \;]^T$;

The system matrices and parameters are given in references [8, 14,16]
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 ΔP_{tie} is caused by Δf_1-Δf_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 2, 3 and 4 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

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

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 mXm transfer function matrix $\mathbf{G(s)}$ linking $\mathbf{U}$(s)=[u_1(s),...., u_m(s)]^T and $\mathbf{Y}$(s)=[y_1(s),..., y_m(s)]^T :

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

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 $\mathbf{K(s)}$=diag[k_i(s)]$_{i=1,\ldots,m}$ [8, 13, 15].

If all $g_{ij}(s)(i{\neq}j)$ in G(s) were equal zero, each controller could be designed independently just as if it were in a SISO system . However, since $g_{ij}(s)(i{\neq}j)$ are not zeros, 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, what are the additional conditions which can guarantee what the global system is stable?

In [15], a transfer function $G(s)=[g_{ij}(s)]_{i,j=1,2,\ldots m}$ for a $m{\times}m$ MIMO plant is composed into

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

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

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

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

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

where $\mathbf{K}(s) = diag[k_i(s)]_{i=1,2,\ldots m}$ is a diagonal transfer function for a decentralised controller; $\tilde{\mathbf{H}}\mathbf{(s)}$ or $\mathbf{H(s)}$ is a closed loop transfer function matrix for a feedback system consisting of $\mathbf{K(s)}$ and $\tilde{\mathbf{G}}\mathbf{(s)}$, or $\mathbf{K(s)}$ and $\mathbf{G}(s)$, respectively. The following theorem is proved in [15]:

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

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

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

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

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

.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 $\tilde{\mathbf{G}}(\mathbf{s})$, 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 $\mu^{-1}(\mathbf{E}(jw))$.

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 $\mu^{-1}(E(jw))$ 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 $k_i(jw)g_{ii}(jw)$.

The interaction margin is therefore checked by the frequency responses of $\mu^{-1}(E(jw))$ and $|h_i(jw)|$. A plot of $\mu^{-1}(E(jw))$ for plant $\mathbf{G(s)}$ is given in Figure 1 as a solid line.

4. LOCAL CONTROLLER DESIGN

Within the general framework of the independent design subject to some conditions given in Section 2, different controller design methods may be applied to the local area load-frequency controller design. It is assumed that first area local controller is a state-space based controller, second one is a simple phase-lead compensator.

State-space controller design is based on Aldeen and Crusca's approach [17]. This proposes a systematic way to choose weighting functions. This approach adopted here and the feedback gains are obtained are;

$$k_1 = [2.051 \quad 2.455 \quad 2.189 \quad -10.549]$$

The closed-loop transfer function $h_1(s)$ can be obtained by first connecting the above state feedback k to the state-space model used to calculate $g_{11}(s)$, (the A matrix, the first column of the B matrix and first row of the C matrix in equation (1)), then finding the resulted closed-loop system transfer function. The frequency response of $|h_1(jw)|$ is plotted in Figure as a dashed line. The interaction margin obtained is 5.26 db at a frequency of $w \approx$ 3.39 rad./sec.

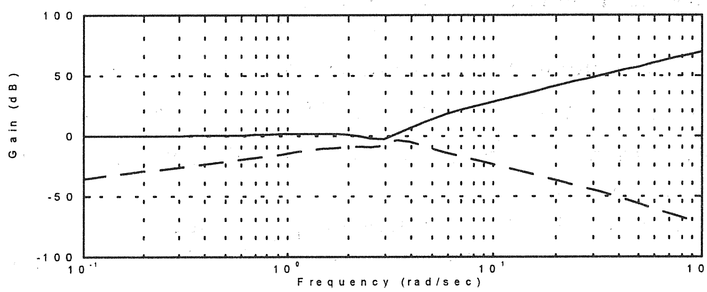

Figure 1. Bode plot of $\mu^{-1}(E(jw))$(-) and h_1(--)

Within the general framework of the independent design subject to some conditions given in Section 2 ,different controller design methods may be applied to each local area load frequency controller design. For the open-loop frequency response of $g_{11}(s)$, a phase-lead compansetor can be designed to increase the gain and phase margins. From the classical feedback control point view, such increase means an improvement in the system robustness [9]. The principles and techniques for the phase-lead compensator design are well established [13]. Applying these with some trial and error to our system $g_{11}(s)$, a phase-lead compensator with the transfer function

$$k_2 = \frac{0.7s + 0.7}{s + 8.5} \quad (i = 1,2)$$

is designed. The gain margin is increased from 2.88 to 17.8 *db* and the phase margin is increased from 32 to 89°. The interaction margin defined before is 6.34 db at a frequency of $w \approx 2.95$ rad./sec.

6. SIMULATION RESULTS

To test system performance, a step load disturbance of ΔP_{D1}=0.01*pu* 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:

$$J_{fre} = 1000 \int_0^{20} |\Delta f(t)| t dt \qquad (19)$$

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 with δ=0.015 [8, 14]. 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 publication [18, 19].

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

(1) Case A: two different controller designed in section 6 based on LQR and phase-lead design which are added to first area and second area respectively,
(2) Case B: no additional controller is connected to the system.

Some selected time response plots are given in Figures 2, 3, and 4; solid lines are for Case A and dashed lines are for Case B. 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
0	0	3.5	11.6
1	+5	3.8	16.3
2	-5	3.1	8.4
3	+10	4.0	23.4
4	-10	3.3	6.5
5	+15	4.3	32.8
6	-15	3.3	4.9
7	+20	4.7	45.7
8	-20	3.3	4.4
9	+25	5.5	64.9
10	-25	3.4	4.9
11	+30	6.2	89.1
12	-30	3.6	5.4

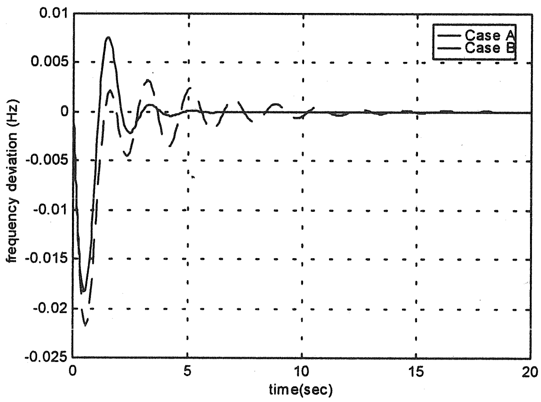

Figure 2. Δf_1 response for Test No. 0

An IAET criteria of the following form is used:

$$J_{tie} = 1000\int_{0}^{20} \left|\Delta P_{tie1}(t)\right| t dt \qquad (20)$$

The results for the two cases are given in Table 2.

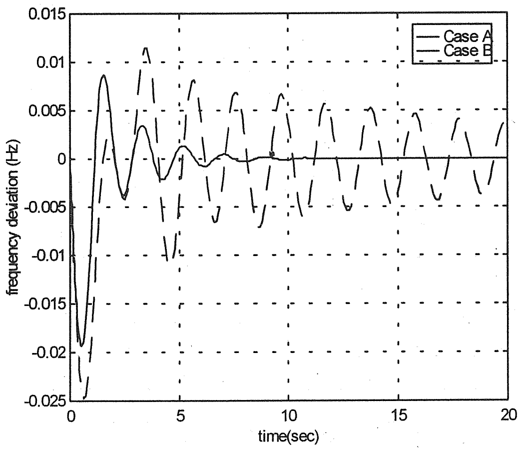

Figure 3. Δf_1 response for Test No. 11

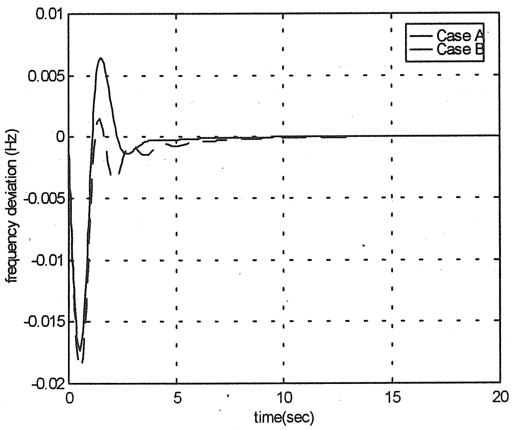

Figure 4. Δf_1 response for Test No. 12

The results in Tables 1 and 2 show that, in comparison with no additional controller and with the controllers designed by the methods, 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
0	0	1.1	4.2
1	+5	1.2	5.5
2	-5	1.1	3.3
3	+10	1.4	7.7
4	-10	1.1	2.8
5	+15	1.4	11.1
6	-15	1.1	2.5
7	+20	1.5	15.8
8	-20	1.1	2.3
9	+25	1.7	22.4
10	-25	1.2	2.3
11	+30	1.9	30.6
12	-30	1.3	2.4

7. CONCLUSION

A robust decentralised power system load-frequency controller design approach has been proposed in this paper. In addition to the local controller design methods presented in this paper and previous papers [8, 14] , other design methods may also be applied. Other possible designs are currently under investigation. Due to the nature of independent design subject to some conditions, the proposed design approach and the other methods can be applied to a general *m*-area power system. It is shown that proposed approach can be used to design local controllers independently even they are designed with different methods.

8. REFERENCES

1. Sivaramakrishnan A.Y., Hariharan M.V. and Srisailam M.C., "Design of variable structure load-frequency controller using pole assignment technique", Int. J. Control, Vol. 40, pp. 487-498, 1984.

2. Bengiamin N.N., Chon, W.C. "Variable structure control of electric power generation", IEEE Trans., PAS-101, pp. 376-380, 1982.

3. Al-Hamouz A.Z., Abdel Magid Y.L, "Variable structure load frequency

controllers for multiarea power systems", Int. J. Electr. Power Energy Syst., Vol. 15, pp. 293-300, 1993.

4. Wang Y., Zhou R. and Wen C., "New Robust adaptive load-frequency control with system parametric uncertainties", IEE Proc.-Gener. Transm. Distrib., Vol. 141, pp. 184-190, 1994.

5. Pan C.T., Liaw C.M., " An adaptive controller for power system load frequency control", IEEE Trans., PWRS-4, pp. 122-127, 1989.

6. Liaw C.M., "Design of a reduced-order adaptive load-frequency controller for an interconnected hydrothermal power system", Int. J. Control, Vol. 60, pp. 1051-1068, 1994.

7. Wang Y., Zhou R. and Wen C., " Robust load-frequency controller design for power systems", IEE Proc. C, Vol. 140, pp. 11-16, 1993.

8. Çimen H., Yang T.C. , " Applying structured singular values to decentralised load frequency control", UPEC'96, 31st Universities Conference Iraklio, Vol. 3, pp. 880-884.

9. Hammond P.H., Robust Control System Design Using H_∞ and Related Methods, Institute of measurement and control, LONDON, 1991.

10. Grimble M.J., Robust Industrial Control, Prentice Hall, 1994.

11. Doyle J.C., "Analysis of feedback systems with structured uncertainty" IEE, D, 129, pp. 242-250.

12. Balas G.J, et al., μ-Analysis and Synthesis Toolbox User's Guide, The math Works Inc., 1991.

13. Skogestad S. and Postlethwaite I., Multivariable Feedback Control Analysis and Design, Jhon Wiley & Sons, 1996.

14. Yang T.C., Çimen H. and Zhu Q.M., "Decentralised load frequency controller design based on structured singular values", IEE Proc. Gener. Transm. And Distrib., Vol. 145, pp. 7-14, 1998.

15. Grosdidier P., Morari M., "Interaction measures for system under decentralised control", Automatica, Vol.22, pp. 309-319, 1986.

16. Yang T.C., Çimen H. "Applying structured singular values and a new LQR design to robust decentralised power system load frequency control", Proceedings of IEEE international conference on Industrial technology, pp. 880-884, 1996.

17. Aldeen M. and Crusca M., Multimachine power system stabiliser design based on new LQR approach, IEE Proc.-Gener. Transm. Distrib., 142(5), 494-502 (1999)

18. Fosha C. E., Elgerd O.I., " The megawatt-frequency control problem: a new approach via optimal control theory", IEEE Trans., PAS-89, pp. 563-573, 1970.

19. Geromel J.C. and Peres P.L.D., "Decentralised load-frequency control", IEE Proc. D, Vol. 132, pp. 225-230, 1985.