THE DYNAMIC STABILITY IMPROVEMENT OF MULTIMACHINE POWER SYSTEMS BY MULTILEVEL OPTIMAL CONTROL

Hardiansyah* • Seizo FURUYA** • Juichi IRISAWA**

The use of supplementary stabilizing signal to improve the dynamic stability of multimachine power system is well known. This paper propose multilevel optimal control scheme (strategies) for interconnected power systems. A large−scale power system may be viewed as an interconnection of several lower−order subsystems, with possible change of interconnection pattern during operation. A multilevel optimal control is proposed for optimization of large−scale systems composed of a number of subsystems. Local controller are used to optimize each subsystem, ignoring the interconnection. Then, a global controller may be applied to minimize the effect of interconnections and improve the performance of the overall system. An optimal state feedback control and robust pole placement are also presented for a comparison. The results for a multimachine power system consisting of two machines show the effectiveness of the control strategies.

Key words : dynamic stability, multilevel optimal control, robust pole placement, multimachine system.

1. Introduction

Power system have been growing in size and com−plexity with increasing interconnections between systems. An increase in the damping of the system response is desirable, not only because it reduces the fluctuations in the controlled variables and hence improving the quality of the electric service, but mainly because this damping is translated into an increase in the power transmission stability limits. Higher stability limits bring significant economic savings as the need for the expansion of the transmission system can be postponed.

Supplementary excitation control, commonly referred to as power system stabilizer (PSS), has become an important means to enhance the damping of low−frequency oscillations in the range 0.5 to 2 Hz, i.e. dynamic or steady−state stability of power systems[1-4]. Rapid attenuation of the transient process in the con−trolled power system can be achieved by determining the best optimal supplementary signal in the excitation control system[1]. It has been widely recognized that excitation control not only effects, but may improve significantly the dynamic stability of the power system. Many papers have been published on the subject but the most of them was either no use of the measurable variable states or they were limited to single machine systems connected to infinite busbars. A multimachine power system could consist of many types of power stations like hydro power station, thermal power station, etc, which have different characteristics. In this paper the power system is decomposed into subsystems. A subsystem could be a generator or group of generators. The advantage of this method is that each subsystem could be optimized with its own criteria.

The control strategy proposed here is applied to three bus, two machine system. The result of the study are presented to demonstrate the effectiveness of the multilevel optimal control. A comparison between the performance of the proposed controller and that optimal state feedback control and robust pole placement is also included.

2. State Space Modeling of Power System Dynamic

Electric power systems are non−linear system and for any large disturbance the techniques of non−linear systems analysis such as simulation and Liapunov based energy methods are needed in order to model large power system disturbances.

For relatively small disturbances well established linear techniques may be used for analysis the dynamic of power system. These techniques are usually applied to a linear state space model of the power

Receives May 21, 1999
*Department of Electrical Engineering, Tanjungpura University, Indonesia.
**Department of Electrical Engineering, Nagaoka University of Technology, Japan.

system as expressed by (1) and (2),

$$\dot{x}=Ax+Bu \quad (1)$$

$$y=Cx \quad (2)$$

where y and u are vectors of outputs and input respectively. x is the system state vector, and the matrices A, B, and C are constant under the assumption of system linearity and stationarity. We shall choose the control signal to be,

$$u=-Kx \quad (3)$$

This means that the control signal is determined by an instantaneous state, such a scheme is called state feedback. The matrix K is called the state feedback gain matrix.

Figure 1, shows the system defined by equation (1), with state feedback. This is closed−loop control system, because the state x is feedback to the control signal u.

Substituting equation (3) into equation (1) gives

$$\dot{x}(t)=(A-BK)x(t)$$

The solution of this equation is given by

$$x(t)=e^{(A-BK)t}x(0) \quad (4)$$

where x(0) is the initial state caused by external disturbances. The stability and transient response characteristics are determined by the eigenvalues of matrix A−BK. If matrix K is chosen properly, the matrix A−BK can be made an asymptotically stable matrix, and for all $x(0)\neq 0$ it is possible to make x(t) approach 0 as t approaches infinity. The eigenvalues of matrix A−BK are called the regulator poles. If these regulator poles are placed in the left−half s plane, then x(t) approaches 0 as t approach infinity.

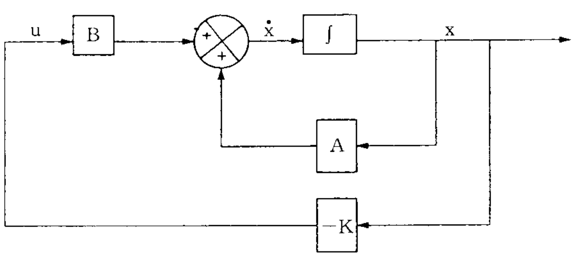

Figure 1 Closed−Loop Control System with u=−Kx

3. Control Strategy

3.1. Multilevel Optimal Control

A multimachine interconnected system S can be described by linear model of the form,

$$S:\dot{x}=Ax+Bu \quad (5)$$

where x is an n−dimensional state vector and u is an m−dimensional control vector. A and B are constant matrices of appropriate dimensions. The system in equation (5) can be considered to be composed of N interconnected subsystems, each subsystem S_i, being described as

Si:

$$\dot{x}_i=A_ix_i+B_iu_i+h_i(x) \qquad i=1,2,\cdots,N \quad (6)$$

such that,

$$h_i(x)=\sum_{\substack{i=1\\ i\neq j}}^{N} A_{ij}\, x_j \quad (7)$$

The total optimal control is given by :

$$u_i=u_i^l+u_i^g \quad (8)$$

Figure 2, show the communication network required for the exchange of information using such a hierarchi−cal technique. The state of individual subsystems are required to be transmitted to the second level controller for computing the global control law. These signal are then sent to the respective subsystems for modifying the locally computed control signal.

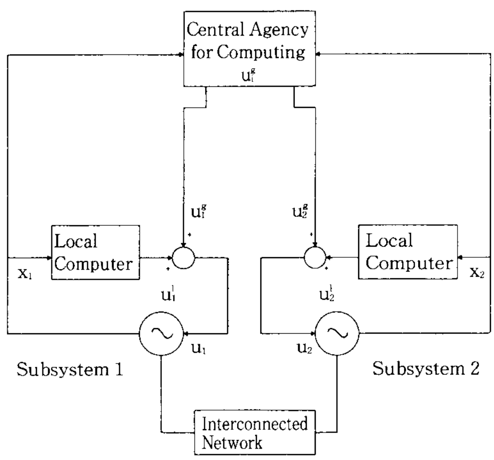

Figure 2 Communication Network for Computing Global Law

U_i^l is a local feedback control vector assuming no interactions between subsystem S, i.e., $h(x)=0$.

U_i^g represent a_i global control signal that compensates for the effect of the presence of coupling.

The performance of each subsystem is measured when the quadratic cost,

$$J_i = \frac{1}{2}\int_0^\infty \{(x_i)^T Q_i x_i + (u_i^l)^T R_i u_i^l\} dt \qquad (9)$$

attains is minimum value when an optimal control U_i^l is applied to each subsystem. Q_i and R_i are symmetric positive semidefinite and positive definite matrices, respectively.

The optimal u_i^l minimizing equation (9) can be determined as,

$$u_i^l = -K_i^l x_i \qquad (10)$$

$$K_i^l = R_i^{-1} B_i^T P_i \qquad (11)$$

where P_i is solution of Riccati equation :

$$(A_i)^T P_i + P_i A_i - P_i B_i R_i^{-1} (B_i)^T P_i + Q_i = 0 \qquad (12)$$

The global signal u^K is determined such that,

$$B.u^K + Cx = 0 \qquad (13)$$

where

$$C_{ij} = A_{ij} \quad ; i \neq j$$
$$= 0 \quad ; i = j \qquad (14)$$

And,

$$u^K = -B' Cx \qquad (15)$$

where B' is the pseudo-inverse of B, defined as

$$B' = [B^T B]^{-1} B^T$$

Thus

$$u^K = [B^T B]^{-1} C_x \qquad (16)$$

where $G = B'C = [B^T B]^{-1} B^T C$ is so called the global gain matrix.

3.2 Optimal State Feedback Control

Find $u^*(t) = -G_x(t)$ that minimizes the performance index,

$$J = \frac{1}{2}\int_0^\infty \{(x^T(t).Q.x(t) + u^T(t).R.u(t)\} dt \qquad (17)$$

Subject to the dynamic equality constraint

$$\dot{x}(t) = Ax(t) + Bu(t) \;;\; x(0) = x_0 \qquad (18)$$

where $x(t) \in R^n$ is the state vector; $u(t) \in R^m$ is the control vector; $A \in R^{nxn}$ is the system matrix; $B \in R^{nxm}$ is the input matrix; $Q \in R^{nxn}$ is a positive-semidefinite state weighting matrix; and $R \in R^{nxm}$ is a positive-definite control weighting matrix. It is well known that the optimal control $u^*(t)$, and hence the feedback gain G, exist provided that the pairs (A,B), $(A, Q^{1/2})$ are completely controllable and observable, respectively. The feedback gain matrix is given by

$$G = -R^{-1} B^T P \qquad (19)$$

where K is the (nxn) positive-definite solution of the Riccati equation

$$P.A + A^T.P - P.B.R^{-1}.B^T.P + Q = 0 \qquad (20)$$

where the superscript T denotes the transpose of a matrix. The static Riccati equation given in equation (20) can be solved in closed form.

3.3 Robust Pole Placement

We considered the eigenvalue allocation (pole placement) problem for the controllable system,

$$\dot{x} = Ax + Bu \qquad (21)$$

where $A \in Rnxn$, $B \in Rnxm$ and $x \in Rn$, $u \in Rm$ are the state and the input of the system, respectively. If we use state feedback, that is, if we set $u = -Fx + v$ where $F \in R^{mxn}$, and $v \in R^m$ is a new external input, equation (21) becomes,

$$\dot{x} = (A - BF)x + Bv \qquad (22)$$

and the problem is to allocate any set of eigenvalues to closed-loop matrix A − BF by choosing the gain matrix F. This problem has a solution if and only if (21) is controllable. Many papers[16-19] and tools (e.g. MATLAB) proposed the solution numeric of the problem.

From the eigenvalues of matrix A in open-loop system, it can be effected the following pole placement procedure to achieve a robust pole placement.

1. Unstable poles of A are replaced with their symmetric.

2. Complex pole under damped are removed to a specific damped .
3. Poles too slow (in the right of a imaginary axis chosen) are removed in this vertical.
4. The rest poles remain in their places.
5. A pole could be removed several successive transformations.

4. Simulation Results

To assess the proposed method in the case of multimachine system . The system shown in the Figure 3, taken from[20], is studied.

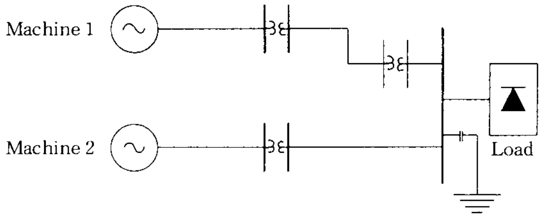

Figure 3 Multimachine System

The model given in[20] is

$$\dot{x} = Ax + Bu$$

where

$$x^T = [\, \Delta\omega_1 \; \Delta\delta_1 \; \Delta e_{q1} \; \Delta e_{FD1} \; \Delta\omega_2 \; \Delta\delta_2 \; \Delta e_{q2} \; \Delta e_{FD2} \,]$$

$$A = \begin{bmatrix} -0.244 & -0.0747 & -0.1431 & 0 & 0 & 0.0747 & 0.0041 & 0 \\ 377 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.046 & -0.455 & 0.244 & 0 & 0.046 & 0.13 & 0 \\ 0 & -398.56 & -19498.9 & -50 & 0 & 398.58 & -3967 & 0 \\ 0 & 0.178 & -0.0433 & 0 & -0.2473 & -0.178 & -0.146 & 0 \\ 0 & 0 & 0 & 0 & 376.99 & 0 & 0 & 0 \\ 0 & 0.056 & 0.1234 & 0 & 0 & -0.0565 & -0.3061 & 0.149 \\ 0 & -677.39 & -10234.22 & 0 & 0 & 677.78 & -13364.16 & -50 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 25000 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 25000 \end{bmatrix}^T$$

In the robust pole placement simulations, it is desired to remove the original eigenvalues in the sets, of eigenvalues K1 and K2, as shown in Table 1. Here it is desired to improve the dynamic performances of the power system of the form as shown in Figure 4.

The dynamic responses of the angular frequencies with and without global control to a 5% change in

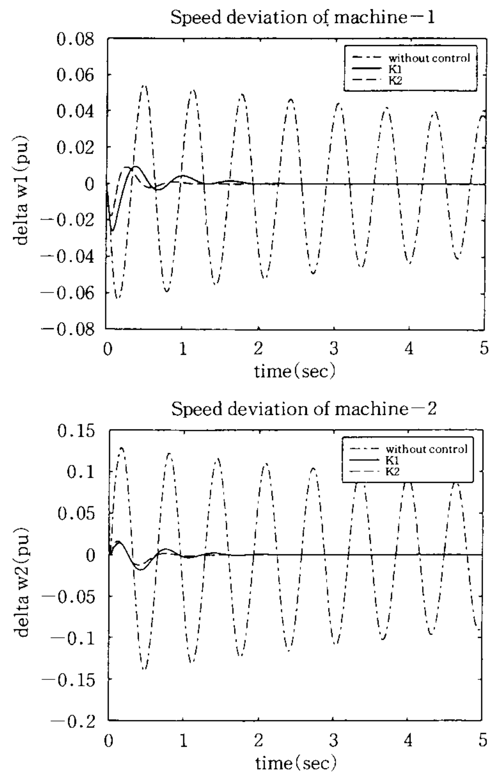

Figure 4 Dynamic Response of Angular Frequency Deviation

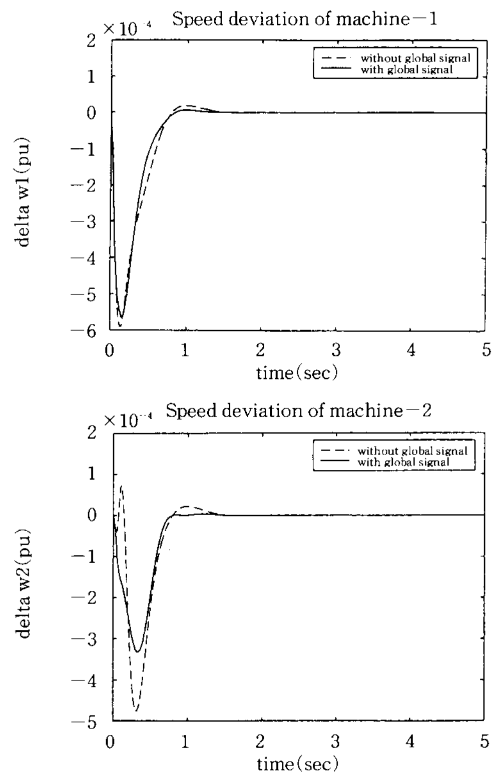

Figure 5 Dynamic Response of the Angular Frequencies with and without Global Control to a 5%Change in the Mechanical Torque of Machine 1.

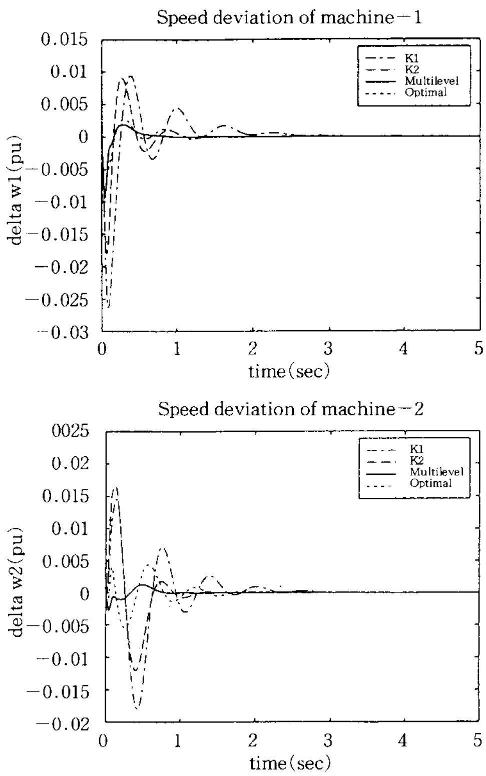

Figure 6 Dynamic Response of the Angular Frequencies to a 5% Change in the Mechanical Torque of Machine 1.

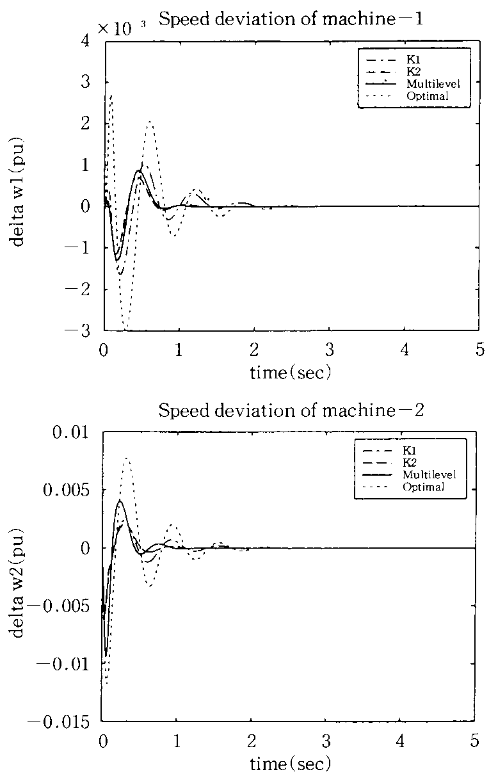

Figure 7 Dynamic Response of the Angular Frequencies to a 5% Change in the Mechanical Torque of Machine 2.

the mechanical torque of machine 1 are shown in Figure 5.

The overall system eigenvalues are given in Table 2. It is shown, that the relative stability of the proposed method is much better than others.

The dynamic responses of the angular frequencies to a 5% change in the mechanic torque of machine 1 and machine 2 are shown in Figure 6 and 7, respectively.

Table 1 System Eigenvalues and Desired Eigenvalues

Open-Loop	K1	K2
−25.1741±j67.8187	−25.1741±j67.8187	−25.1741±j67.8187
−25.2329±j30.3073	−25.2329±j30.3073	−25.2329±j30.3073
−0.0904 ±j9.8430	−2.0904±j9.8430	−4.0904±j9.8430
−0.0006	−2.0006	−4.0006
−0.2443	−2.2443	−4.2443

K1 & K2 : Desired Eigenvalues

Table 2 System Eigenvalues.

Open-Loop	Optimal Control	Multilevel Control
−25.1741±j67.8187	−25.4947±j67.9481	−25.2335±j64.4124
−25.2329±j30.3073	−25.7861±j30.7483	−25.1817±j37.0836
−0.0904±j9.8430	−2.1329±j10.1152	−4.8862±j11.4038
−0.0006	−3.3733±j3.1807	−5.4999±j3.7619
−0.2443		

5. Conclusions

The Multilevel optimal control for a multimachine power systems as well as optimal state feedback control and robust pole placement have been presented The control configurations consist two levels, where optimization is carried out on both the subsystem and overall system level. On the subsystem level, local controllers are chosen to optimize subsystem performance indices, totally disregarding the interconnections among the subsystems. On the overall system level, a global controllers is implemented to minimize the effects of interconnections.

The simulation results showed that dynamic responses of multimachine have been improved with multilevel control as well as optimal control. The robust pole placement required a large signal control to obtain a similar performance with optimal control.

Acknowledgment

The authors would like to thank the JICA (Japan International Cooperation Agency) for its valuable support.

References

1. De Mello, F.P., and Concordia C., IEEE Trans. of Power Appar Sys., 88, pp. 316-329, (1969).
2. Lim C. M., and Elangovan S., IEE Proc. C, 132(3), (1985).
3. Dorpiswami R., Sharaf A. M., and Castro J.C., IEEE Trans. of Power Appar Sys., 103(5), (1984).
4. Ray P. S., Duttagupta P. B., and Bhakta P., IEE Proc. Gener. Transm. Distrib., 142(5), (1995).
5. Jamshidi M., North-Holland, 9, 1983.
6. Anderson P. M., and Fouad A. A., Power System Control and Stability, Iowa State University Press, Ames, Iowa, (1977).
7. Ogata K., Modern Control Engineering, Prentice-Hall Inc, 3rd ed, (1997).
8. Chen G. P., Malik O. P., Qin Y. H., and Xu G. Y., IEEE Trans. of Energy Conversion, 7(3), (1992).
9. Hanmandlu M., and Suryanarayana., IEE Proc. D, 140 (4), pp. 293-297, (1993).
10. Premakumaran N., Parthasarathy K., Kincha H. P., and Chidambara M. R., IEE Proc. C, 129(6), pp. 290-294, (1982).
11. Huang T.L., Chen S.C., Hwang T.Y., and Yang W.T., IEEE Trans. of Power Appar Sys., 6(3), pp. 1035-1041, (1991).
12. Y.L, Abdel-Magid., and G.M, Aly., J. of Electric Power System Research, 6, pp. 33-41, (1983).
13. Xinogalas C. T., Mahmoud M. S., and singh M. G., Automatica, 18(4), pp. 473-478, (1982).
14. Bourles H., Colledani F., and Houry M. P., IEEE Trans. of Power Appar Sys., 12(1), (1997).
15. Arnautovic D., and Medanic J., IEEE Trans. of Energy Conversion, 2(4), (1987).
16. Kautsky J., Nichols N. K., and Van Doorens P., Int. J. Control, 41(5), pp.1129-1155, (1985).
17. Miminis G. S., and Paige C. C., Automatica, 24(3), pp. 343-356, (1988).
18. Kawasaki N., and Shimemura E., Automatica, 19(5), pp. 557-560, (1983).
19. Shieh L. S., H. M. Dib., and Ganesan S., Automatica, 24(6), pp. 819-823, (1988).
20. Feliachi A., Zhang X., and Siams C. S., IEEE Trans. of Power Sys, 3(4), pp. 1676-1684, (1988).

Appendix

List of Symbols

A	:	System matrix
B	:	Control matrix
C	:	Output matrix
x	:	state vector
y	:	Output vector
u	:	Control vector
J	:	Performance index
Q	:	Weighting matrix for state variable
R	:	Weighting matrix for controls signal
G,K,F	:	Feedback gain matrix
P	:	Solution of the linear matrix Riccati equation
Δ	:	Linearized incremental quantity
ω	:	Angular frequency (velocity)
δ	:	Torque angle
e'_q	:	q-axis component voltage behind transient reactance
e_{FD}	:	Equivalent excitation voltage