Analysis of Modal Insensitivity for Generator Using Eigenstructure Assignment

Shu-Chen Wang

***Abstract*—**This paper studies the modal insensitivity design of the synchronous generator in a power system using eigenstructure assignment. Model insensitivity means that the concerned system mode shape is insensitive to small variations in the system. In the proposed design procedure, modal insensitivity is achieved by assigning system eigenstructure and only algebraic computations are involved. Results from the study of a single-machine-infinite-bus system are presented.

***Keywords*—**Power system control, synchronous generator, eigenvalue, eigenstructure assignment, modal insensitivity.

I. Introduction

Eigenstructure assignment refers to the design method for assigning the eigenstructure, i.e. eigenvalues and eigenvectors, of a closed-loop linear system with a constant gain feedback control law [1-22]. Methods of eigenstructure assignment have been proposed and applied to various kinds of control design problems. That includes some applications in power system control [23-44].

The design of linear control system is based on the linearized system model. However, physical system are often subject to operating point drift or plant parameter variations which may cause that the designed controller does not meet the prescribed performance, even result in system instability. Modal insensitivity means that system mode shape is insensitive to small variations [18-23]. Controllers designed with the concept of modal insensitivity will have insensitive closed-loop eigenvalue or eigenvectors.

Based on eigenstructure assignment techniques, the main purpose of this paper is to present a modal insensitivity design for control of synchronous generator in a power system with a view to making the eigenvalues of main system oscillatory modes insensitive to the variation of a certain parameter. The point is to design an output feedback controller for assigning the system eigenvalues as well as for restricting some specified eigenvector components. The design procedure in this paper needs only algebraic computations and thus is easy to apply.

Manuscript received November 4, 2010.

Shu-Chen Wang is with the Department of Computer and Communication Engineering, Taipei College of Maritime Technology, 212, Sec. 9, Yan-Pin N. Rd., Taipei 111, Taiwan (corresponding author to provide phone: 886-2-27376676; fax: 886-2-27376699; e-mail: scwang@ mail.tcmt.edu.tw).

II. Design Methodology

A. Eigenstructure Assignment

Consider a dynamic system described by (1) and (2).

$$\dot{x} = Ax + Bu \tag{1}$$

$$y = Cx \tag{2}$$

Assume that the system has n states, m inputs and r outputs. An output feedback control $u = G\,y = GCx$ will result in the closed-loop system

$$\dot{x} = \left(A + BGC\right)x \tag{3}$$

Denote the corresponding right eigenvectors of the i -th eigenvalue λ_i as V_i and assume the following definitions:

$$S_{\lambda_i} \triangleq [\lambda_i I - A \quad -B] \tag{4}$$

$$\text{Ker}[S_{\lambda_i}] \triangleq \begin{bmatrix} N_{\lambda_i} \\ M_{\lambda_i} \end{bmatrix} \tag{5}$$

$$W_i \triangleq GCV_i \tag{6}$$

The following theorem for eigenstructure assignment has been established [1-22].

Theorem 1 Given a controllable and observable system described by (1) and (2). Let $\{\lambda_i\}_{i=1}^{n}$ and $\{v_i\}_{i=1}^{n}$ be the self-conjugate sets of desired eigenvalues/eigenvectors, respectively. There exists an $m \times r$ real matrix G such that $(A + BGC)V_i = \lambda_i V_i$ if and only if all the following conditions are satisfied:

1) $\{V_i\}_{i=1}^{n}$ is a linearly independent set on C^n;

2) $V_i = V_j^*$ if $\lambda_i = \lambda_j^*$; (7)

3) $\begin{bmatrix} V_i \\ W_i \end{bmatrix} \in \text{span}\begin{bmatrix} N_{\lambda_i} \\ M_{\lambda_i} \end{bmatrix}$; (8)

4) $$\text{rank}\begin{bmatrix} CV_1 & CV_2 & \cdots & CV_n \\ W_1 & W_2 & \cdots & W_n \end{bmatrix} = r \qquad (9)$$

B. Modal Insensitivity

Consider a system with the following dynamic equations

$$\dot{x} = A(\alpha)x + B(\alpha)u \qquad (10)$$

$$y = C(\alpha)x \qquad (11)$$

Note that the matrices $A(\alpha)$, $B(\alpha)$ and $C(\alpha)$ depend on the parameter α whose original value is α_0 .

If we apply an output feedback control law $u = G\,y = GC(\alpha)x$ then the closed-loop system becomes

$$\dot{x} = \left[A(\alpha) + B(\alpha)GC(\alpha)\right]x \equiv \overline{A}(\alpha)x \qquad (12)$$

We are to design an output feedback gain matrix G such that $\overline{A}(\alpha_0)$ has the prescribed eigenvalues that are insensitive to small variation in α around α_0 .

Denote the corresponding left and right eigenvectors of the i -th eigenvalu λ_i as U_i and V_i , respectively. The variation of closed-loop system matrix, $d\overline{A}$, will be

$$\begin{aligned} d\overline{A} &= \left[\left.\frac{dA}{d\alpha}\right|_{\alpha_0} + \left.\frac{dB}{d\alpha}\right|_{\alpha_0} GC(\alpha_0) + B(\alpha_0)G\left.\frac{dC}{d\alpha}\right|_{\alpha_0} \right] d\alpha \\ &\equiv [\delta A + \delta B\,G\,C + B\,G\,\delta C]d\delta \\ &\equiv [\delta\overline{A}]d\delta \end{aligned} \qquad (13)$$

Then the following theorem can be obtained.

Theorem 2 The necessary and sufficient conditions for λ_i and U_i (or V_i) to be insensitive to a small variation in α are:

$$\begin{bmatrix} U_i^T & U_i^T BK \end{bmatrix} \begin{bmatrix} \delta A & \delta B \\ \delta C & 0 \end{bmatrix} = 0 \qquad (14)$$

$$\begin{bmatrix} \delta A & \delta B \\ \delta C & 0 \end{bmatrix} \begin{bmatrix} V_i \\ KCV_i \end{bmatrix} = 0 \qquad (15)$$

C. Design Procedure

Theorem 1 and Theorem 2 form the basis of the control design approach in this paper. The basic idea is to fully exploit the flexibility offered by feedback beyond closed-loop eigenvalue/eigenvector, i.e. eigenstructure, assignment for restricting certain eigenvector elements in order to achieve modal insensitivity.

The following steps summarize the design procedure for mode-insensitive control:

1) Apply Theorem 1 to deriving algebraic equations with unknowns being the elements in the output feedback gain matrix. The emphasis here is placed on assigning eigenvalues to improve system damping.
2) Utilize Theorem 2 to solve the algebraic equations derived in Step 1 for finding the exact solution of the output feedback gain matrix. The resultant closed-loop eigenvalues will have the property of being insensitive.
3) Verify the control design by calculating the eigenvalue sensitivity and closed-loop system eigenvalues.

Note that the design procedure needs only algebraic manipulations and exact solution can be obtained without any kind of iteration.

III. Study System

The system considered in this work is a synchronous generator connected to a large power system whose linearized model is shown in Fig.1. This linear model has been extensively studied in the literature of power system control. The dynamic characteristics of the system are expressed in terms of the six constants $K_1 - K_6$. The studied system can then be represented by the state space form in (1) and (2).

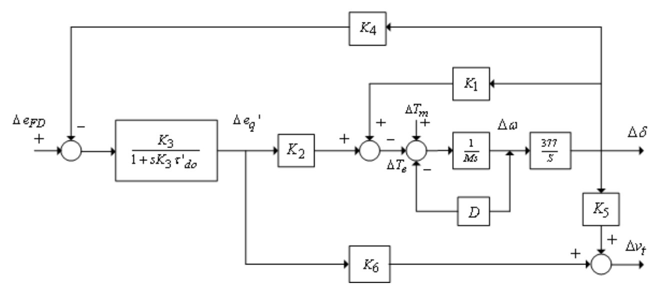


Fig. 1 Linearized model of single-machine-infinite-bus

The definitions for each variable are

e_q'	Voltage proportional to direct axis flux linkage
ω	Rotor speed
δ	Torque angle
e_{FD}	Generator field voltage
T_m	Mechanical torque

where $x = [\Delta e_q{}' \ \Delta\omega \ \Delta\delta]^T$, $u = [\Delta e_{FD} \ \Delta T_m]^T$ and $y = [\Delta\omega \ \Delta\delta]^T$ are the state, control and output vectors, respectively.

The matrices $A, B,$ and C in (1) and (2) are

$$A = \begin{bmatrix} -1/(K_3\tau'_{do}) & 0 & -K_4/\tau'_{do} \\ -K_2/M & -D/M & -K_1/M \\ 0 & \omega_R & 0 \end{bmatrix} \quad (16)$$

$$B = \begin{bmatrix} -1/\tau'_{do} & 0 \\ 0 & 1/M \\ 0 & 0 \end{bmatrix} \quad (17)$$

$$C = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (18)$$

Note that the system parameter K_2 is the change in electrical torque for small change in the d-axis flux linkage at constant rotor angle as described in (19)

$$K_2 = \left.\frac{\Delta T_e}{\Delta e_q{}'}\right|_{\delta=\delta_0} \quad (19)$$

If the field flux linkage is constant, then $e_q{}'$ will be constant and $K_2 = 0$, and the model is reduced to the classical model. The effect of K_2 variation on the electromechanical mode eigenvalues can be investigated by computing the sensitivity of any eigenvalue of interest λ with respect to the parameter K_2, i.e. $\partial \operatorname{Re}(\lambda)/\partial K_2$. The task here is to design a controller to make the electromechanical mode eigenvalues to be insensitive to K_2.

IV. Example

Consider the linearized model of a synchronous generator connected to a large power system as shown in Fig.1. The parameters tabulated in Table 1 are taken for this study.

TABLE I
PARAMETERS FOR STUDY SYSTEM

$K_1 = 1.0755$	$K_2 = 1.2578$	$K_3 = 0.3072$
$K_4 = 1.7124$	$K_5 = -0.0409$	$K_6 = 0.4971$
$\tau'_{do} = 5.9$	$M = 4.74$	$D = 0$

Then the numerical values for matrices A and B of the system model in (16) and (17) are obtained as

$$A = \begin{bmatrix} -0.5517 & 0 & -0.2909 \\ -0.2654 & 0 & -0.2269 \\ 0 & 377 & 0 \end{bmatrix} \quad (20)$$

$$B = \begin{bmatrix} 0.1695 & 0 \\ 0 & 0.211 \\ 0 & 0 \end{bmatrix} \quad (21)$$

The open-loop eigenvalues and left/right eigenvectors for the study system are calculated as (22) and (23), respectively.

$$\begin{aligned} \lambda_1 &= -0.2124, \\ \lambda_2 &= -0.1696 + j9.2434, \\ \lambda_3 &= -0.1696 - j9.2434 \end{aligned} \quad (22)$$

$$U_1 = \begin{bmatrix} 1.5410 \\ -1.9699 \\ 0.0011 \end{bmatrix}, \quad U_2 = \begin{bmatrix} 0.2893 + j0.5096 \\ 17.3325 - j10.8083 \\ 0.2572 + j0.4298 \end{bmatrix}, \quad U_3 = \begin{bmatrix} 0.2893 - j0.5096 \\ 17.3325 + j10.8083 \\ 0.2572 - j0.4298 \end{bmatrix}, \quad (23)$$

$$V_1 = \begin{bmatrix} 0.6500 \\ 0.0004 \\ -0.7599 \end{bmatrix}, \quad V_2 = \begin{bmatrix} 0.0265 + j0.0167 \\ 0.0210 + j0.0126 \\ 0.4973 - j0.8667 \end{bmatrix}, \quad V_3 = \begin{bmatrix} 0.0265 - j0.0167 \\ 0.0210 - j0.0126 \\ 0.4973 + j0.8667 \end{bmatrix}.$$

The pair of eigenvalues λ_2, λ_3, often referred to as the electromechanical mode, is the eigenvalues associated with generator rotor oscillation. It is the primary objective of this study to design an output feedback controller to enhance the damping of the electromechanical mode. We can analyze the effect of K_2 variation on the electromechanical mode eigenvalues by computing the following sensitivity:

$$\begin{aligned} \frac{\partial \lambda_1}{\partial K_2} &= 0.269, \\ \frac{\partial \operatorname{Re}(\lambda_2)}{\partial K_2} &= \frac{\partial \operatorname{Re}(\lambda_3)}{\partial K_2} = -0.134, \\ \frac{\partial \operatorname{Im}(\lambda_2)}{\partial K_2} &= \frac{\partial \operatorname{Im}(\lambda_3)}{\partial K_2} = \pm 6.3\times 10^{-4} \end{aligned} \quad (24)$$

From (24), it is obvious that the electromechanical mode eigenvalues are much affected by K_2. It is desirable that the assigned closed-loop eigenvalues be insensitive to K_2.

Now the closed-loop eigenvalues are chosen to be

$$\begin{aligned} \lambda_1 &= -0.5517, \\ \lambda_2 &= -1.0 + j9.2434, \\ \lambda_3 &= -1.0 - j9.2434 \end{aligned} \tag{25}$$

and the open-loop left and right eigenvectors are calculated as (26), respectively.

$$U^T = \begin{bmatrix} 1.5378 & 0 & 0 \\ 0.4741 - j0.3428 & -11.1387 - j17.0896 & 0.3895 - j0.3184 \\ 0.4741 + j0.3428 & -11.1387 + j17.0896 & 0.3895 + j0.3184 \end{bmatrix},$$
$$V = \begin{bmatrix} 0.6503 & 0 & 0 \\ 0.0011 & -0.0156 + j0.0191 & -0.0156 - j0.0191 \\ -0.7597 & 0.8375 + j0.5459 & 0.8375 - j0.5459 \end{bmatrix} \tag{26}$$

Note that a real part of –1.0 for electromechanical mode eigenvalues will give satisfactory dynamic behavior and the oscillation frequency is kept to remain unaltered. It is required that the assigned closed-loop eigenvalues be insensitive to parameter K_2.

Since the system output variables are $\Delta\omega$ and $\Delta\delta$ we can express the output feedback control law as

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \tag{27}$$

For the system specification mentioned above, the output feedback gain matrix G are obtained as

$$G = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} = \begin{bmatrix} 0 & 1.7121 \\ -9.4787 & -0.0113 \end{bmatrix} \tag{28}$$

and the closed-loop system matrix $\bar{A}$ is

$$\bar{A} = \left(A + BGC\right) = \begin{bmatrix} -0.5517 & 0 & 0 \\ -0.2654 & -2 & -0.2293 \\ 0 & 377 & 0 \end{bmatrix} \tag{29}$$

For the purpose of verification, the eigenvalues of the closed-loop system matrix $\bar{A}$ are calculated and found to be exactly as those in (25). Moreover, the sensitivity for each of the closed-loop system eigenvalues with respect to K_2 is computed as (30)

$$\frac{\partial \lambda_1}{\partial K_2} = \frac{\partial \lambda_2}{\partial K_2} = \frac{\partial \lambda_3}{\partial K_2} = 0 \tag{30}$$

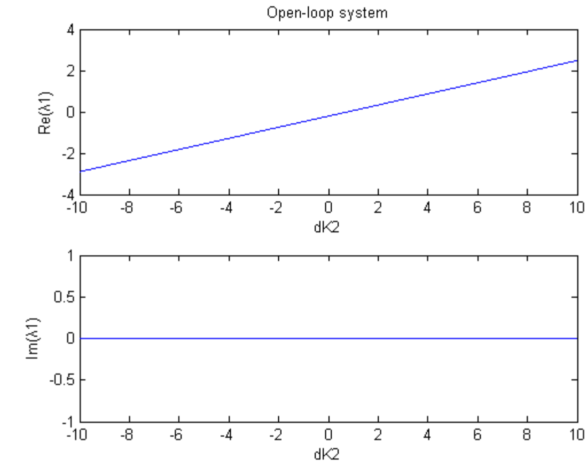
The eigenvalues in (25) with the values of sensitivity in (30) reveal that, with the designed output feedback controller, system damping has been greatly improved and the closed-loop system eigenvalues remain unaffected under the variations in parameter K_2.

Simulation results are shown from Fig 2 to Fig 6. The control of the synchronous generator in a power system using modal insensitivity design is thus verified. Fig 2 and Fig 3 show the sensitivity of the open-loop system and closed-loop system eigenvalues under the variations in parameter K_2, respectively. As compared to those in Fig 2 and Fig 3, the results in Fig 4 show that the proposed controller has improved on the sensitivity.

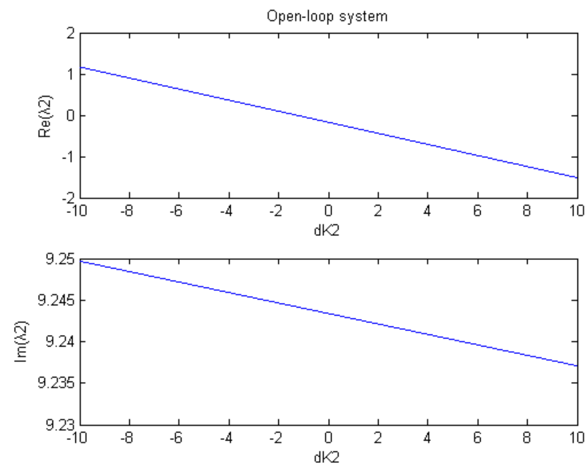
Dynamic responses of generator angle and speed for the open-loop system and closed-loop system under the variations in parameter K_2 are shown in Fig 5 and Fig 6, respectively.

V. Conclusion

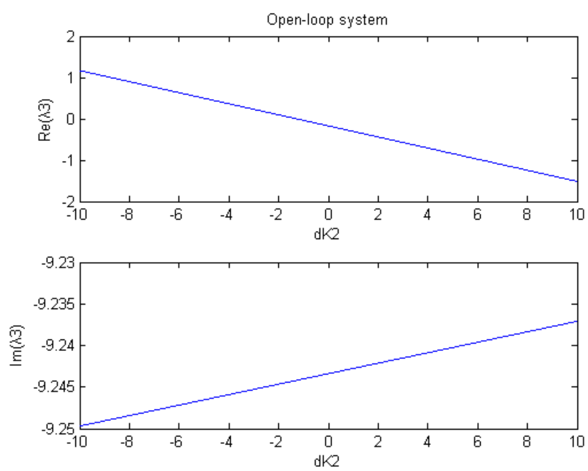
The use of modal insensitivity design for synchronous generator stabilization control in a power system has been presented in this paper. The design method is based on the concepts of eigenstructure assignment and sensitivity analysis. Only algebraic computations are needed and exact solution can be obtained without iteration. From the presented simulation results, it is found that the system damping has been greatly improved with the assigned eigenvalues, which are also made insensitive to the variations of the investigated parameter.



(a) eigenvalue λ_1

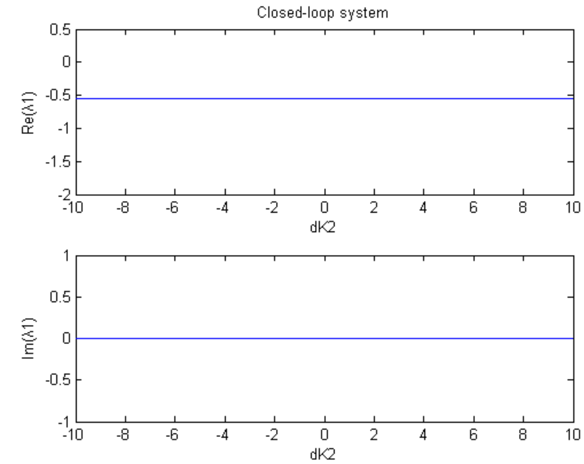


(b) eigenvalue λ_2

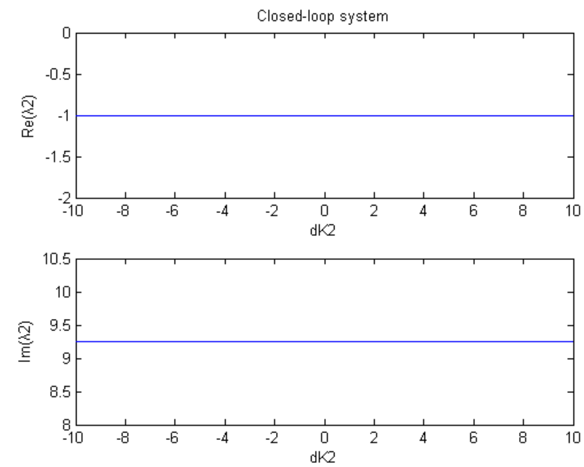


(c) eigenvalue λ_3

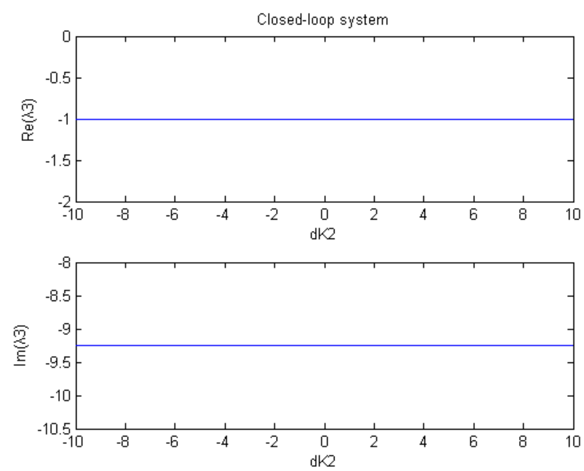
Fig. 2 The sensitivity of the open-loop system eigenvalues under the variations in parameter K_2



(a) eigenvalue λ_1

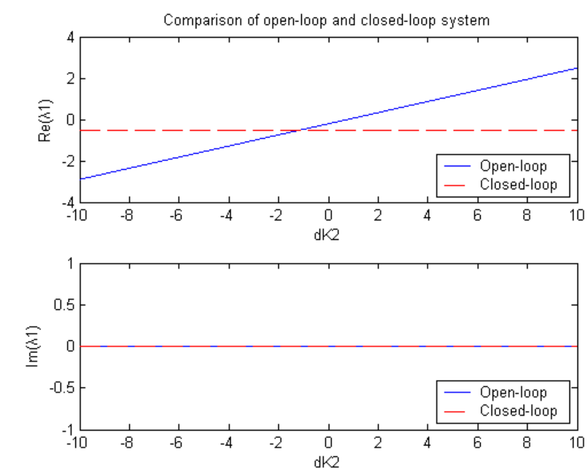


(b) eigenvalue λ_2

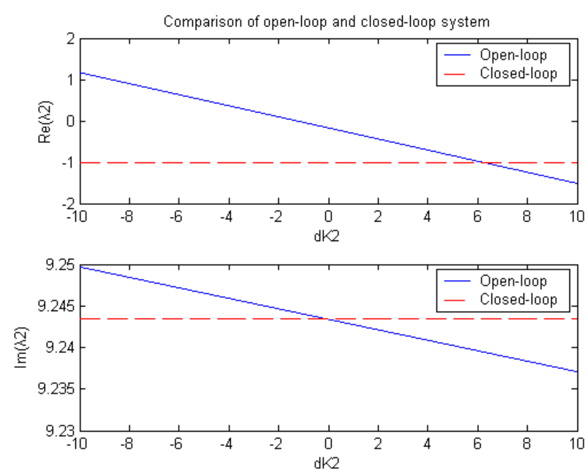


(c) eigenvalue λ_3

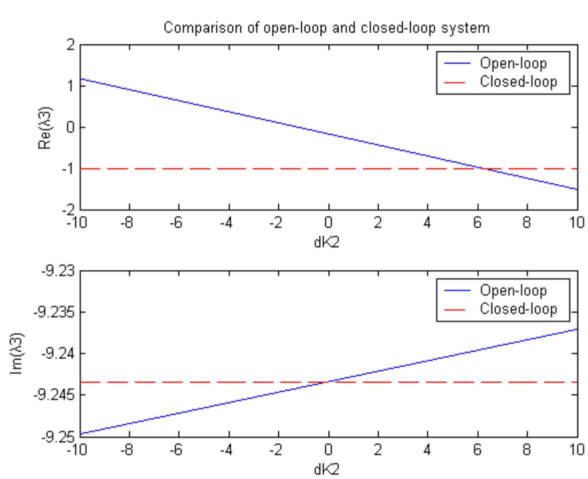
Fig. 3 The sensitivity of the closed-loop system eigenvalues under the variations in parameter K_2



(a) eigenvalue λ_1

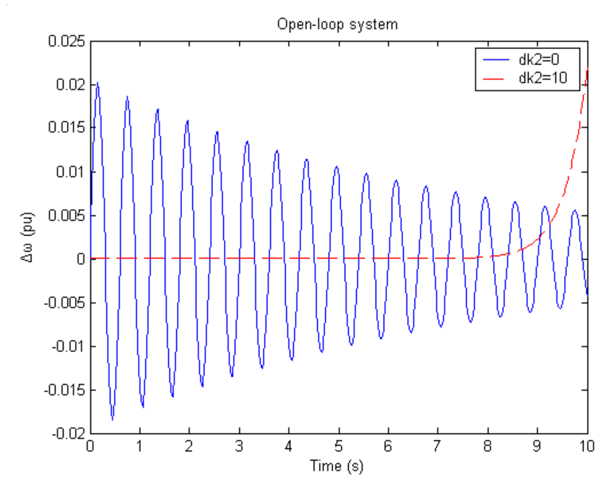


(b) eigenvalue λ_2

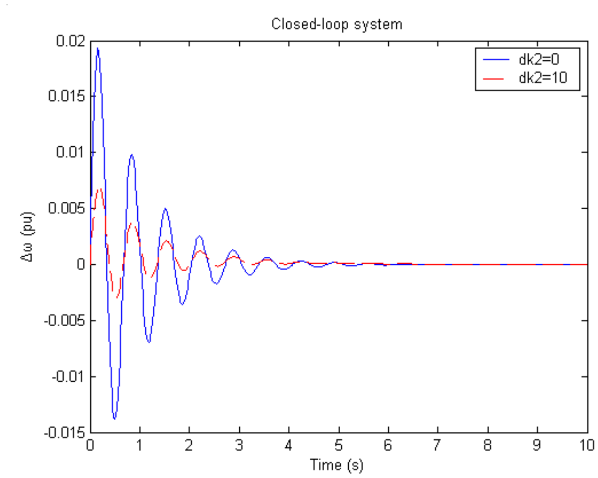


(c) eigenvalue λ_3

Fig. 4 Comparison of the sensitivity for the open-loop system and closed-loop system eigenvalues under the variations in parameter K_2

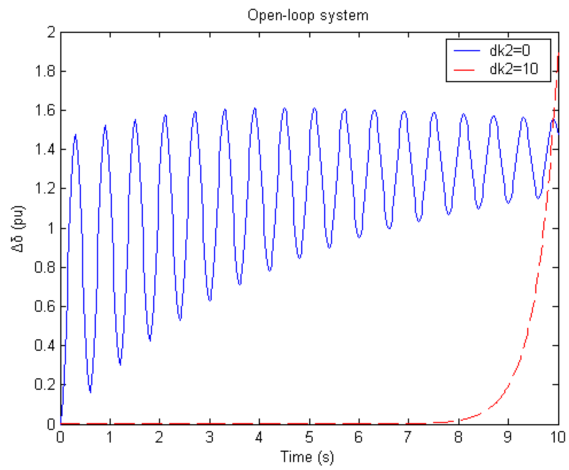


(a) Open-loop

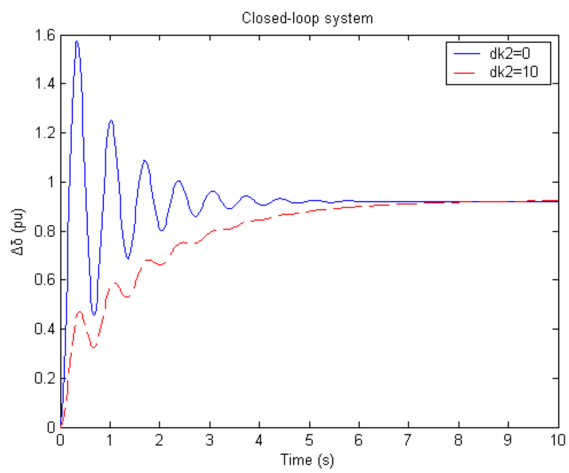


(b) Closed-loop

Fig. 5 Dynamic responses of generator speed for the open-loop system and closed-loop system under the variations in parameter K_2



(a) Open-loop



(b) Closed-loop

Fig. 6 Dynamic responses of generator angle for the open-loop system and closed-loop system under the variations in parameter K_2

ACKNOWLEDGMENT

The paper is partly supported by the Taipei College of Maritime Technology and the National Science Council of Taiwan, project number, NSC 98-2622-E-229-001-CC3.

REFERENCES

[1] B. C. Moore, "On the flexibility offered by state feedback in multivariable systems beyond closed loop eigenvalue assignment, "*IEEE Trans. on Automatic Control*," Vol. AC-21, pp. 689-692, 1976.

[2] S. L. Shah, D. G. Fisher, and D. E. Seborg, "Eigenvalue invariance to system parameter variations by eigenvector assignment," *Int. J. Control*, Vol. 26, No. 6, pp. 871-881, 1977.

[3] A. Sambandan and P. C. Chandrasekharan, "Design of output feedback controller with eigenvalue and eigenvector insensitivity," *International Journal of Control*, Vol. 33, No. 5, pp. 935-943, 1981.

[4] M. M. Fahmy and J. O'Reilly, "On eigenstructure assignment in linear multivariable systems," *IEEE Trans. Automatic Control*, Vol. AC-27, No. 3, pp. 690-693, 1982.

[5] A. N. Andry, E. Y. Shapiro, and J. C. Chung, "Eigenstructure assignment for linear system," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. AES-19, pp. 711-729, 1983.

[6] M. M. Fahmy and J. O'Reilly, "Eigenstructure assignment in linear multivariable systems-A parametric solution," *IEEE Trans. Automatic Control*, Vol. AC-28, No. 10, pp. 990-994, 1983.

[7] R. F. Wilson, J. R. Cloutier, and R. K. Yedavalli, "Control design for robust eigenstructure assignment in linear uncertain systems," *IEEE Control Systems Magazine*, pp. 29-34, 1992.

[8] A. T. Alexandridis and P. N. Paraskevopoulos, "A new approach to eigenstructure assignment by output feedback," *IEEE Trans. on Automatic Control*, Vol. 41, No. 7, pp. 1046-1050, 1996.

[9] S. Askarpour and T. J. Owens, "Integrated approach to eigenstructure assignment by output feedback," *IEE Proc.-Control Theory Appl.*, Vol. 144, No. 5, pp. 435-438, 1997.

[10] G. P. Liu and R. J. Patton, *Eigenstructure Assignment for Control System Design*, John Wiley & Sons, 1998.

[11] S. Askarpour and T. J. Owens, "Integrated approach to eigenstructure assignment by state feedback," *IEE Proc.-Control Theory Appl.*, Vol. 146, No. 2, pp. 113-118, 1999.

[12] P. Subrahmanyan and D. Trumper, "Eigenvector assignment," *Proc. of the 1999 American Control Conference*, Vol. 4, pp. 2238-2243, 1999.

[13] J. W. Choi, "A simultaneous assignment methodology of right/left eigenstructures," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 34, No. 2, pp. 625-634, 1998.

[14] H. S. Kim and Y. Kim, "Partial eigenstructure assignment algorithm in flight control system design," *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 35, No. 4, pp. 1403-1409, 1999.

[15] P. H. Huang and Y. Y. Hsu, "Eigenstructure assignment in a longitudinal power system via excitation control," *IEEE Trans. on Power Systems*, Vol. 5, No. 1, pp. 96-102, 1990.

[16] T. L. Huang, S. C. Chen, T. Y. Hwang, and W. T. Yang, "Power system output feedback stabilizer design via optimal subeigenstructure assignment," *IEEE Trans. on Power Systems*, Vol. 6, No. 3, pp. 1035-1041, 1991.

[17] J. Lu, H. D. Chiang, and J. S. Thorp, "Eigenstructure assignment by decentralized feedback controller," *IEEE Trans. on Automatic Control*, Vol. 38, No. 4, pp. 587-594, 1993.

[18] J. W. Howze and R. K. Cavin, "Regulator Design with Modal insensitivity," *IEEE Trans. On Automatic Control*, Vol. AC-24, pp. 466-469, 1979.

[19] K. V. Raman and A. J. Calise, “Modal decoupling Insensitivity,” *IEEE Trans. on Automatic Control*, Vol. AC-32, No 6, pp. 524-526, 1987.
[20] T. J. Owens, “Parametric output feedback control with response insensitivity,” *International Journal of Control*, Vol. 48, No. 3, pp. 1213-1239, 1988.
[21] T. J. Owens, “Parametric output feedback control with left eigenstructure insensitivity,” *International Journal of Control*, Vol. 21, No. 8, pp. 1603-1630, 1990.
[22] Shu-Chen Wang and Chi-Jui Wu, “Design of Modal Insensitivity for Generator via Eigenstructure Assignment,” *Proceedings of the 10th WSEAS International Conference on electric power systems, high voltages, electric machines (POWER '10),* pp.124-128, Oct. 4-6, 2010.
[23] T. J. Owens, and J. O’Reilly, “Parametric state-feedback control with response insensitivity,” *Int. J. Control*, Vol. 45, No. 3, pp. 791-809, 1987.
[24] C. C. Tsui, *Robust Control System Design: Advanced State Space Techniques*, Second Edition, Chapter 8, Marcel Dekker, 2004.
[25] P. H. Huang and Y. Y. Hsu, “An output feedback controller for a synchronous generator,” *IEEE Trans. on Aerospace and Electronic Systems*, Vol. AES-26, No. 2, pp. 337-343, 1990.
[26] P. H. Huang, “Analysis of power system dynamic stability via fuzzy concepts,” *Proc. of the 1992 IEEE International Conference on Systems, Man and Cybernetics*, Vol.2, pp. 1584-1588, 1992.
[27] S. Lee and C. C. Liu, “Damping torsional oscillations using a SIMO static VAR controller,” *IEE Proc., Pt. C*, Vol. 140, No. 6, pp. 462-468, 1993.
[28] S. Lee and C. C. Liu, “Damping subsynchronous resonance using a SIMO shunt reactor controller,” *IEEE Trans. on Power Systems*, Vol. 9, No. 3, pp. 1253-1260, 1994.
[29] C. L. DeMarco, “Eigenvector assignment in power system controller design: illustration through predatory control,” *Conference Record of the 2000 IEEE PES Summer Meeting*, Vol. 2, pp. 830-834, 2000.
[30] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*, IEEE Press, 1994.
[31] P. Kundur, *Power System Stability and Control*, McGraw-Hill, 1994.
[32] L. Bao, X. Duan, and Y. He, “Analysis of voltage collapse mechanisms in state space,” *IEE Proceedings- Generation, Transmission and Distribution*, Vol. 147, No. 6, pp. 395-400, 2000.
[33] T.K.A. Rahman and G.B. Jasmon, “A new technique for voltage stability analysis in a power system and improved loadflow algorithm for distribution network,” *Proc. of the Energy Management and Power Delivery Conference*, Vol. 2, pp. 714-719, 1995.
[34] R. A. Schlueter, “A voltage stability security assessment method,” *IEEE Trans. on Power Systems*, Vol. 13, No. 4, pp. 1423-1438, 1998.
[35] B. Bezdek, “Fuzzy models-What are they, and why,” *IEEE Trans. on Fuzzy Systems*, Vol. 1, pp. 1-6, 1993.
[36] R. Yager and D. Filev, *Essentials of Fuzzy Modeling and Control*, John Wiley & Sons, 1994.
[37] M. Sugeno and T. Yasukawa, “A fuzzy-logic-based approach to qualitative modeling,” *IEEE Trans. on Fuzzy Systems*, Vol. 1, No. 1, pp. 7-31, 1993.
[38] M. Sugeno and G. Kang, “Structure identification of fuzzy model, *Fuzzy Sets and Systems*,” Vol. 28, pp. 15-23, 1988.
[39] J. S. R. Jang, “ANFIS: adaptive-network-based fuzzy inference system,” *IEEE Trans. on Systems, Man and Cybernetics*, Vol. 23, No. 3, pp. 665-685, 1993.
[40] F.W. Mohn and A.C.Z. de Souza, “Tracing PV and QV curves with the help of a CRIC continuation method,” *IEEE Trans. on Power Systems*, Vol. 21, No. 3, pp. 1115-1122, 2006.
[41] J. Jang and C. Sun, “Neuro-fuzzy modeling and control,” *Proceedings of the IEEE*, Vol. 83, pp. 378-406, 1995.
[42] S. C. Wang and P. H. Huang, “Power system output feedback controller design using fuzzy c-means clustering reduced model,” *WSEAS Trans. on Systems*, Vol. 6, No. 3, pp. 475-480, 2007.
[43] Y. S Chuang, S. C Wang, and C. J Wu, “Novel Decentralized Pole Placement Design of Power System Stabilizers Using Hybrid Differential Evolution,” *WSEAS Trans. on Power Systems*, Vol. 3, No. 3, pp. 47-55, 2008.
[44] Shu-Chen Wang, Yu-Jen Chen, Chi-Jui Wu, “Design and Implementation of Three-Phase Voltage Flicker Calculation Based on an FPGA,” *International Journal of Circuits, Systems and Signal Processing*, Vol. 1, No. 2, pp. 211-216, 2007.

Shu-Chen Wang was born in Taiwan, 1969. She received the B. Sc., M. Sc., and Ph.D. degree from the Department of Electrical Engineering, National Taiwan Ocean University in 1992, 1994, and 2007, respectively. Currently she is an associate professor in the Department of Computer and Communication Engineering, Taipei College of Maritime Technology. Her current research interests include fuzzy theory, control system, and power system dynamics.