An Output Feedback Controller for a Synchronous Generator

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A new approach using eigenstructure assignment is developed for the design of excitation controllers for synchronous generators. The computation procedure for the developed method is easy to apply and exact solution can be obtained without any kind of iteration. Controllers designed by the proposed approach can be easily implemented via proportional-integral (PI) controllers. Practical considerations are addressed in reaching an optimum selection of closed-loop eigenvalues. Time domain simulation results are also presented to verify the effectiveness of the proposed design method.

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I. NOMENCLATURE

General

a	Subscript denoting achievable value.
d	Subscript denoting desired value.
A	System matrix.
B	System control matrix.
C	System output matrix.
T	System disturbance matrix.
x	State vector.
u	Control vector.
y	Output vector.
d	Disturbance vector.
λ	Eigenvalue.
v	Eigenvector.

System Variables

ω	Rotor speed.
δ	Torque angle.
e'_q	q axis component of voltage behind transient reactance.
e_{FD}	Equivalent excitation voltage.
v_F	Stabilizing transformer voltage.
v_t	Terminal voltage.
v_0	Infinite bus voltage.
T_e	Energy conversion torque.
T_m	Mechanical input torque.
v_{ref}	Reference input voltage.

System Parameters

Z_e	Transmission line impedance.
K_A	Voltage regulator gain.
T_A	Voltage regulator time constant.
K_F	Stabilizing transformer gain.
T_F	Stabilizing transformer time constant.
$K_1 \sim K_6$	Constants of linearized model of synchronous generators.
T'_{do}	d axis transient open circuit time constant.
M	Inertia coefficient, $M = 2H$.
D	Damping coefficient.
$K_{\Delta\omega}, K_{\Delta\delta}$	Excitation controller feedback gain.
K_P, K_I	PI controller gain.

II. INTRODUCTION

Since the 1970s, supplementary excitation controller, commonly referred to as power system stabilizer (PSS), has been widely employed to enhance the damping of synchronous machine low-frequency oscillations and to improve the stability of power systems [1–4]. Considerable efforts have been placed on the design of PSS, and various types of excitation controllers have been extensively investigated [2–9].

From a practical viewpoint, it is desirable to use system outputs instead of state variables as feedback signals, especially when a large-scale control system is considered. In the excitation controllers proposed in previous works, speed deviation and/or torque angle deviation are often taken to be the output variables and thus the feedback signals. As a matter of fact, these two variables play an important role in the model reduction of power systems [10, 11]. Therefore, we focus on the design of excitation controllers by feeding back the states of speed deviation and torque angle deviation.

A new approach is presented here for the design of excitation controllers using speed deviation and torque angle deviation as feedback signals. This approach which can achieve exact eigenvalue assignment is developed essentially based on output feedback eigenstructure assignment technique [12–15] which has been successfully utilized to design flight control laws for aircraft in the aerospace engineering [16–22]. The proposed method is novel in that the excitation controller designed by such method, as can be shown, is in itself equivalent to a proportional-integral (PI) output feedback controller of which the structure is relatively simple for practical implementation [7, 8]. Another important consideration in the design of an excitation controller using eigenstructure assignment technique is the choice of desired closed-loop eigenvalues. In this study, the effect of alternative assigned closed-loop poles on feedback gains of the excitation controller is examined in detail to obtain an optimal selection of desired eigenvalues. In order to verify the effectiveness of the proposed method, results of time domain simulation for the system under disturbance is demonstrated. It is found that the designed excitation controller is not only simple in structure so that it can be easily implemented but improves system dynamic performance significantly.

III. STUDY SYSTEM

The system considered here is a synchronous generator connected to a large power system as shown in Fig. 1. The synchronous generator is equipped with an IEEE type 1s exciter [2, 4]. The linearized incremental model for this system is shown in Fig. 2. This model, the widely known deMello-Concordia model, has been extensively studied and details can be found in [1, 4]. The following system data [2] are used for the study of power system stabilizer design.

$K_1 = 1.0755$	$K_A = 400$	$D = 0$
$K_2 = 1.2578$	$T_A = 0.05$	$u_{max} = 0.12$
$K_3 = 0.3072$	$K_F = 0.025$	$u_{min} = -0.12.$
$K_4 = 1.7124$	$T_F = 1.0$	
$K_5 = -0.0409$	$T'_{do} = 5.9$	
$K_6 = 0.4971$	$M = 4.74$	

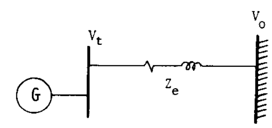

Fig. 1. System configuration for single machine connected to large power system through external impedance.

TABLE I
System Open-Loop Eigenvalues

Open-loop Eigenvalues
$-0.0138 \pm j9.2216$
$-1.8523 \pm j0.0320$
-217.8194

Then the study system can be represented by the following state space form:

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

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

where $x = [\Delta\omega \;\; \Delta\delta \;\; \Delta e'_q \;\; \Delta e_{FD} \;\; \Delta V_F]^{\mathrm{T}}$ is the state vector, u is the supplementary excitation control signal, and

$$d = [\Delta T_m \quad \Delta v_{\mathrm{ref}}]^{\mathrm{T}} \tag{3}$$

and

$$y = [\Delta\omega \quad \Delta\delta]^{\mathrm{T}} \tag{4}$$

are the disturbance vector and output vector, respectively. The numerical values for the matrices A, B, C, and T are derived as follows:

$$A = \begin{bmatrix} 0 & -0.2269 & -0.2654 & 0 & 0 \\ 377 & 0 & 0 & 0 & 0 \\ 0 & -0.2902 & -0.5517 & 0.1695 & 0 \\ 0 & 327.2 & -3976.8 & -20 & -8000 \\ 0 & 8.18 & -99.42 & -0.5 & -201 \end{bmatrix} \tag{5}$$

$$B = [0 \quad 0 \quad 0 \quad 8000 \quad 200]^{\mathrm{T}} \tag{6}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

$$T = \begin{bmatrix} 0.2110 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 8000 & 200 \end{bmatrix}^{\mathrm{T}}. \tag{8}$$

Equations (5), (6), (7), and (8) form the mathematical model of the study system. Then eigenvalues of this system can be figured out. The results are listed in Table I.

From the eigenvalues listed in Table I, it is found that there exist one pair of critical eigenvalues, i.e., $-0.0138 \pm j9.2216$, which are likely to cause oscillation problem. This pair of eigenvalues, often referred to as the electromechanical mode, are the eigenvalues associated with rotor oscillation. The poor damping

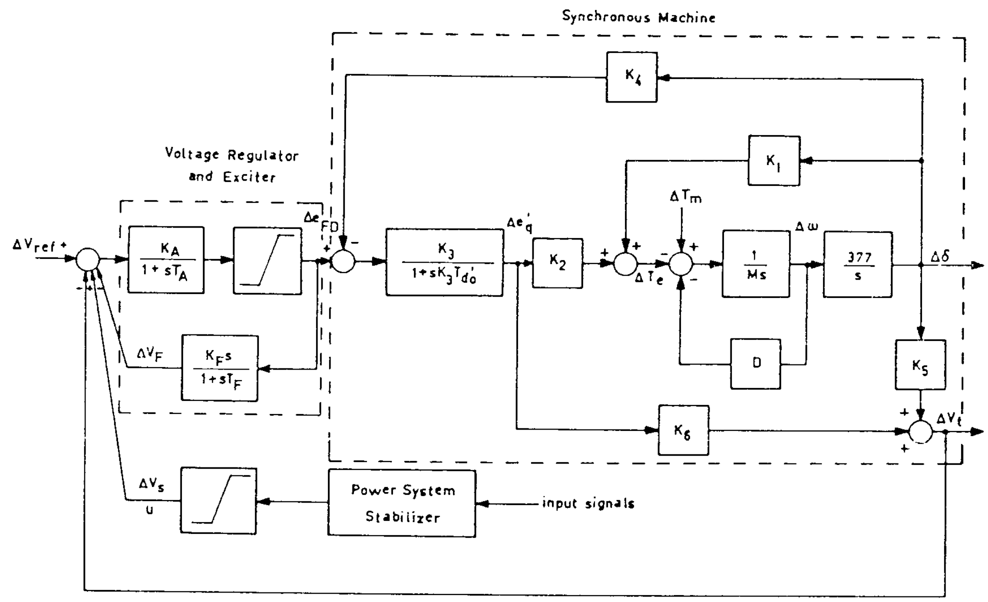

Fig. 2. Linearized incremental model of synchronous machine with exciter and stabilizer.

of the electromechanical mode can be further verified through time domain simulations by applying a 0.05 per unit step change in the mechanical torque input ΔT_m or reference voltage input Δv_{ref}. The resultant response curves of rotor speed deviation ($\Delta\omega$) are shown in Fig. 3. These simulation results indicate that system responses are highly oscillatory and poorly damped. Therefore, an excitation controller is utilized to enhance system damping.

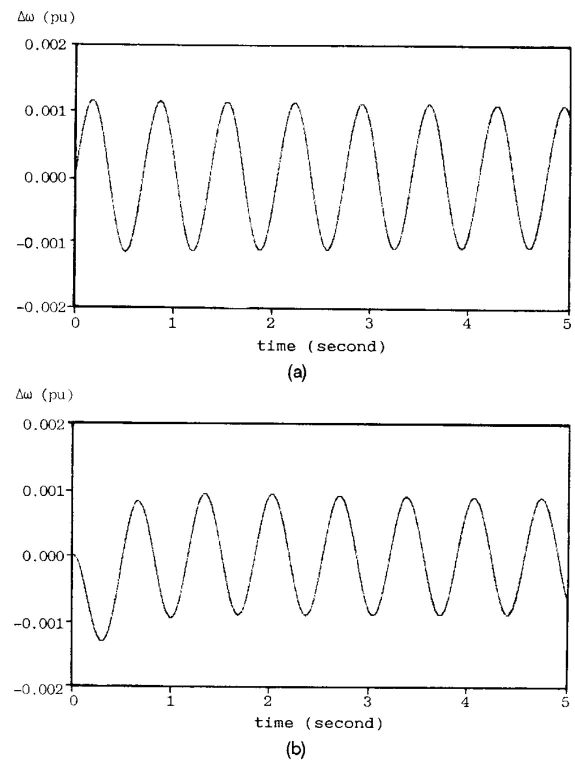

Fig. 3. Dynamic responses of open-loop system subject to step change disturbance. (a) $\Delta T_m = 0.05$ per unit. (b) $\Delta v_{\text{ref}} = 0.05$ per unit.

IV. OUTPUT FEEDBACK EIGENSTRUCTURE ASSIGNMENT

In this section the eigenstructure assignment technique using output feedback is reviewed. References [16] and [17] have provided nice presentations and expositions to this topic. The materials discussed here are primarily based on [16] and [17].

Consider a linear time invariant system described by the following state equation:

$$\dot{x} = Ax + Bu \tag{9}$$

$$y = Cx \tag{10}$$

where x, u, and y are called state, control, and output and are of dimensions $n \times 1$, $m \times 1$, and $r \times 1$, respectively. Matrices A, B, and C are of appropriate dimensions. This system is of nth order and has m inputs and r outputs. Formally, both m and r are not equal to zero. Given this system, we have the following problem statements.

Given a self-conjugate set of scalars $\{\lambda_i\}$ and a corresponding self-conjugate set of $n \times 1$ vectors $\{V_i\}$, $i = 1,\ldots,k$, find control laws of the form $u = Fy$, where matrix F is of appropriate dimension such that k of the eigenvalues of closed-loop matrix $A + BFC$ are precisely those of the self-conjugate set $\{\lambda_i\}$, with corresponding eigenvectors the self-conjugate set $\{V_i\}$.

Note that the set $\{\lambda_i\}$ and $\{V_i\}$ correspond to the desired closed-loop eigenvalues and eigenvectors, respectively, and the matrix F is the output constant feedback gain matrix. Then, according to [13], we have the following.

THEOREM. *Given the controllable and observable system described by (9) and (10), then* $\max(m,r)$ *closed-loop eigenvalues can be assigned and* $\max(m,r)$ *eigenvectors can be partially assigned with* $\min(m,r)$ *entries in each vector arbitrarily chosen using gain output feedback.*

With this Theorem, we can determine the number of eigenvalue/eigenvector pairs, i.e., the "k" in the problem statements, as well as the number of eigenvector elements which can be assigned by constant gain output feedback.

In advance of further analysis, the concept of eigenvector assignability should be addressed since in general, arbitrary eigenvector assignment is not always possible. An assignable eigenvector must reside in the subspace spanned by the columns of $(\lambda I - A)^{-1}B$ which is of dimension m. We can obtain a "best assignable" eigenvector by orthogonal projection of a desired eigenvector onto the subspace spanned by $(\lambda I - A)^{-1}B$. Refer to this best assignable eigenvector as achievable eigenvector. Then for a pair of desired eigenvalue λ_d and eigenvector v_d, the achievable eigenvector v_a can be computed as [16, 17, 23]:

$$v_a = L(L^{\mathrm{T}}L)^{-1}L^{\mathrm{T}}v_d \tag{11}$$

where

$$L = (\lambda_d I - A)^{-1}B. \tag{12}$$

In many practical situations, the designer is interested only in certain elements of the eigenvector and thus will attempt to assign only the concerned elements but not the whole column of the eigenvector. As an example, which is the case in this study, system control engineers are often concerned with the rotor speed deviation state, $\Delta\omega$. In such case of partial specification of v_d, v_a can also be computed in the same manner [16, 17]:

$$v_a = L(D^{\mathrm{T}}D)^{-1}D^{\mathrm{T}}z_d \tag{13}$$

where z_d is the vector consisting of desired elements which have been reordered to the leading position of v_d, and D is the submatrix obtained by reordering the rows of L to conform with the reordering performed on v_d.

Note that the v_a computed from (13) is of dimension $n \times 1$. In other words, though we only give partial specification of the eigenvector, even in the extreme case of only one specified element (z_d is of dimension 1×1), the computed achievable eigenvector is of full dimension $n \times 1$.

Then, as shown in [16, 17], by a similarity transformation and some manipulations, we can obtain the following equation which holds for each λ_d/v_a pair:

$$\lambda_d z_a - A_1 v_a = FCv_a \tag{14}$$

where z_a is the specified part of v_a, and A_1 is the submatrix of A conforming with z_a. Equation (14) can be put into a more concise form by defining

$$q = Cv_a \tag{15}$$

and

$$p = \lambda_d z_a - A_1 v_a \tag{16}$$

and then we have

$$Fq = p. \tag{17}$$

Equation (17) forms the basis of F computation and is used in Section V to establish the design algorithm. It is noticed that for each pair of λ_d and v_a, there exist a pair of p and q, where both p and q are vectors of appropriate dimensions.

V. DESIGN OF EXCITATION CONTROLLER

In this section, based on the materials of the previous section, we develop a new approach to the design of excitation controllers. This approach takes advantage of the eigenvalue assignment capability of the output feedback eigenstructure technique.

Recall the study system as described in Section III. It is a single-input two-output system. Then from the Theorem in Section IV, we can assign two closed-loop eigenvalues, and their associated eigenvectors can be partially assigned with one element in each vector arbitrarily specified. Therefore, in view of the open-loop eigenvalues of the study system, we wish to assign the electromechanical mode eigenvalues (two eigenvalues of complex-conjugate pair). As for the desired element of the eigenvector, we choose the speed deviation state $\Delta\omega$ as the element to be specified since the electromechanical mode is associated with rotor speed deviation, and this element can always be set to be 1.0. Note that once a choice of desired eigenvalue is made and the desired element of the associated eigenvector is specified, an achievable eigenvector, which is of full dimension, can be obtained from (13).

It is our purpose to apply the controller as shown in Fig. 4 to generate the supplementary signal for excitation control. Obviously, feedback gain matrix F has the following structure:

$$F = [K_{\Delta\omega} \quad K_{\Delta\delta}] \tag{18}$$

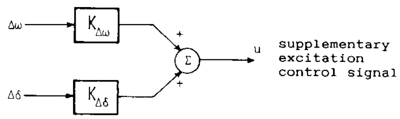

Fig. 4. Excitation controller configuration.

where $K_{\Delta\omega}$ and $K_{\Delta\delta}$ are the feedback gains for $\Delta\omega$ and $\Delta\delta$, respectively.

Recall (17). Once the desired eigenvalue λ_d has been chosen and then the achievable eigenvector v_a is figured out, the vectors q and p can be determined. Note that for the study system, q is of dimension 2×1 and p is of dimension 1×1. Denote the desired 2 eigenvalues as λ and $\overline{\lambda}$($\overline{\lambda}$ is the complex conjugate of λ) and the associated achievable eigenvector pair v and $\overline{v}$($\overline{v}$ is the complex conjugate of v). Then there will be vector pairs p, p and q, q such that

$$Fq = p \quad \text{and} \quad F\overline{q} = \overline{p}. \tag{19}$$

Because both feedback gains $K_{\Delta\omega}$ and $K_{\Delta\delta}$ are real numbers, only one equation of (19) is needed to solve the unknowns, $K_{\Delta\omega}$ and $K_{\Delta\delta}$. Picking out the former one, we have

$$[K_{\Delta\omega} \quad K_{\Delta\delta}]\begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = [p_1] \tag{20}$$

where $q = [q_1 q_2]^{\mathrm{T}}$ and $p = [p_1]$. Multiplying through yields

$$K_{\Delta\omega} q_1 + K_{\Delta\delta} q_2 = p_1. \tag{21}$$

Note again that $K_{\Delta\omega}$ and $K_{\Delta\delta}$, which are the unknowns of (21), are real numbers, and q_1, q_2, and p_1 are of complex values. By equating the real parts and imaginary parts of the two sides of (21), respectively, we can calculate $K_{\Delta\omega}$ and $K_{\Delta\delta}$. This completes the parameter computation of the output feedback excitation controller.

Fig. 5 summarizes the computation procedure of the proposed method for the design of excitation controller. It is found that the computing algorithm is simple and easy to apply. The solution to the problem is unique and can be obtained directly without any iteration. This implies the efficiency inherent in the proposed design approach.

A relevant comment on the implementation of the proposed excitation controller whose configuration is shown in Fig. 4 is that such controller can be implemented as an output feedback PI controller using rotor speed deviation ($\Delta\omega$) as the input signal [7, 8], as shown in Fig. 6. This is due to the fact that the rotor angle deviation $\Delta\delta$ is the time integral of speed deviation $\Delta\omega$. Comparing Fig. 4 with Fig. 6 yields

$$K_P = K_{\Delta\omega} \tag{22}$$

$$K_I = K_{\Delta\delta}. \tag{23}$$

Equations (22) and (23) set up the equivalence of the proposed controller to a PI controller. Meanwhile, it is worth noting that, from the mathematical viewpoint, the addition of a PI controller using $\Delta\omega$ as the input signal to the study system does not alter system order. A characteristic feature of the PI controller is that it is very simple for practical implementation as commercial PI controllers have been widely employed by the industry for years.

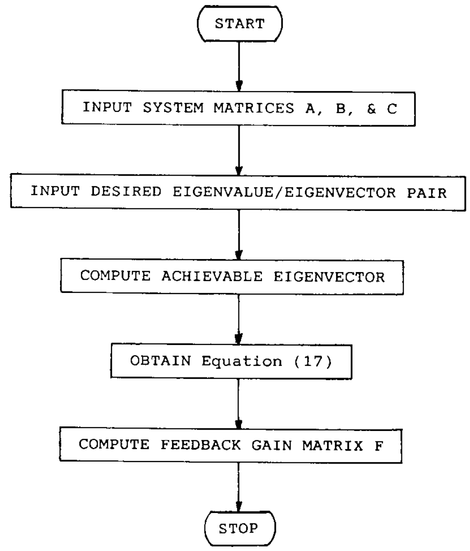

Fig. 5. Flow chart of design algorithm.

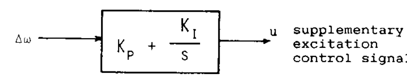

Fig. 6. PI excitation controller.

TABLE II
Sample Results Of Computed Controller Parameters And Closed-Loop Eigenvalues

$K_{\Delta\omega} = -20.381$	$K_{\Delta\omega} = -1.429$	$K_{\Delta\omega} = 22.486$
$K_{\Delta\delta} = -0.295$	$K_{\Delta\delta} = -0.270$	$K_{\Delta\delta} = -0.258$
$-1.0 \pm j7.0$*	$-1.0 \pm j9.0$*	$-1.0 \pm j11.0$*
$-0.9424 \pm j1.1290$	$-0.8698 \pm j0.8692$	$-0.7781 \pm j0.6838$
-217.669	-217.8120	-217.9950

Note: * denotes exact assignment of eigenvalues.

VI. NUMERICAL RESULTS

Consider the study system. We are to design excitation controllers using the approach developed in Section V. Several desired closed-loop electromechanical mode eigenvalue pairs have been chosen, and then the corresponding feedback gains are computed. Sample results, including controller parameters and closed-loop eigenvalues, are given in Table II.

In using the pole assignment technique, the choice of desired closed-loop eigenvalue(s) deserves deliberate

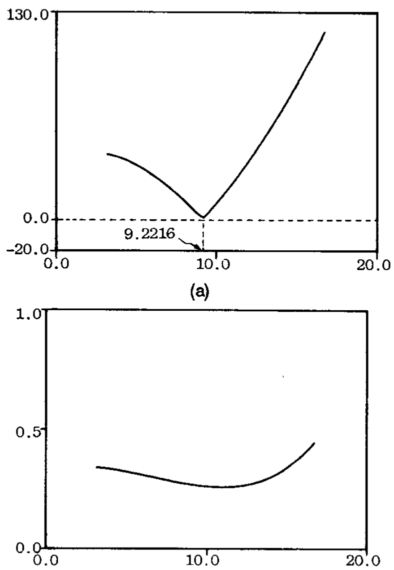

Fig. 7. Effect of imaginary part of desired eigenvalues on controller parameters. (a) $\mathrm{Im}(\lambda_d)$ versus $K_{\Delta\omega}$. (b) $\mathrm{Im}(\lambda_d)$ versus $K_{\Delta\delta}$.

TABLE III
Feedback Gains And Closed-Loop System Eigenvalues

$K_{\Delta\omega} = 0.978$ $K_{\Delta\delta} = -0.270$
$-1.0 \pm j9.2216$*
$-0.8606 \pm j0.8464$
-217.8305

Note: * denotes exact assignment of eigenvalues.

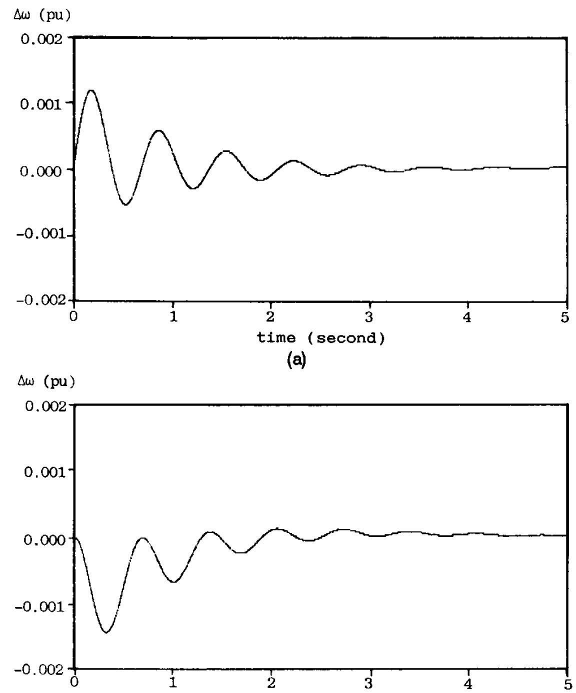

Fig. 8. Dynamic responses of closed-loop system subject to step change disturbance. (a) $\Delta T_m = 0.05$ per unit. (b) $\Delta v_{\mathrm{ref}} = 0.05$ per unit.

consideration. For power system engineering practice, a real part of -1.0 for electromechanical mode eigenvalues will give satisfactory dynamic behavior [3, 9]. On the other hand, the selection of imaginary part of the desired eigenvalue requires detailed analyses to reach a final decision.

In order to obtain a suitable choice of closed-loop electromechanical mode eigenvalues, the effect of the desired imaginary part on the computed feedback gains ($K_{\Delta\omega}$ and $K_{\Delta\delta}$) are investigated. Fig. 7 gives the plots for the assigned imaginary part versus the computed absolute values of $K_{\Delta\omega}$ and $K_{\Delta\delta}$. As can be observed from Table II and Fig. 7, the absolute value of $K_{\Delta\omega}$ is far greater than that of $K_{\Delta\delta}$ and the value of $K_{\Delta\delta}$ remains essentially constant. Therefore, we focus on $K_{\Delta\omega}$. Fig. 7(a) reveals that $K_{\Delta\omega}$ is smallest if the desired imaginary part is set to be 9.2216. Since it is desirable to have a controller of low gain, the desired closed-loop electromechanical eigenvalues are determined to be $(-1.0 \pm j9.2216)$. That is, we choose to improve the damping of electromechanical mode without changing its oscillation frequency. This conclusion is consistent with some remarks made in [3]. The system eigenvalues and the computed controller parameters based on such selection are listed in Table III.

In order to demonstrate the effectiveness of the proposed feedback controller whose parameters are given in Table III, time domain responses of $\Delta\omega$ for the closed-loop system subject to a 0.05 per unit step change in ΔT_m or Δv_{ref} are performed, and the results are presented in Fig. 8. By comparing the open-loop system responses (Fig. 3) with the closed-loop system responses (Fig. 8), it can be concluded that installation of the proposed excitation controller has achieved significant improvement on the damping of the study system.

VII. CONCLUSIONS

A new approach which can achieve exact eigenvalue assignment has been presented for the design of synchronous generator excitation controller. This method is developed based on output feedback eigenstructure assignment technique. The excitation controller designed by the proposed method is of simple structure and can be easily implemented. From the numerical results obtained from frequency domain analysis and time domain simulation results, it is found that damping of the study system has been greatly improved. This establishes the validity of the proposed design approach.

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