GENETIC ALGORITHM BASED SIMULTANEOUS EIGENVALUE PLACEMENT OF POWER SYSTEMS

Youssef L. Abdel-Magid* and Maamar Bettayeb†

Electrical Engineering Department

and

Shokri Z. Selim

Systems Engineering Department
King Fahd University of Petroleum and Minerals
Dhahran, Saudi Arabia

الخلاصــة :

توضح هذه الورقة طريقة استخدام خوارزمية موروثية (جينية) لتصميم نظام تغذية رجعية ذات مُخرجٍ واحد لتحديد أماكن القيم الوحيدة مرة واحدة تحت مدىً واسع لظروف التشغيل. ولقد حوَّلنا مهمة اختيار كسب مخرج التغذية الرجعية إلى مسألة إيجاد الحدّ الأدنى حيث كانت دالة الهدف مبنيَّة على القيم الوحيدة. وتمَّ حلُّ هذه المسألة بالخوارزمية الموروثية. وتسمح دالة الهدف بأن تقع القيم الوحيدة في أسفل المستوى المركب بينما ينحصر أحد أنماط التذبذب في شريحة رأسية مع قيود على نسبة الهبوط. وتوضّح فاعلية الاستقرار الديناميكي في نظم الطاقة عن طريق تحليل القيم الوحيدة ونتائج المحاكاة.

*Address for correspondence:
KFUPM Box 91
King Fahd University of Petroleum & Minerals
Dhahran 31261
Saudi Arabia

†Now with Electrical/Electronics Engineering Department
College of Engineering
University of Sharjah
UAE

ABSTRACT

This paper demonstrates the use of genetic algorithms to design a single output feedback control law for the simultaneous eigenvalue placement of a power system running over a wide range of operating conditions. The task of selecting the output feedback gains is converted to a simple optimization problem with an eigenvalue-based objective function, which is solved by a genetic algorithm. An objective function is presented allowing the selection of the output feedback gains to place the closed-loop eigenvalues in the left-hand side of a vertical line in the complex s-plane while shifting a specific mode of oscillation to a vertical strip and with bounds on the damping ratio. Simultaneous placement of the closed-loop eigenvalues of the power system operating at different loading conditions, using a single output feedback stabilizer, is demonstrated. The effectiveness of the output feedback stabilizer in enhancing the dynamic stability of power systems is verified through eigenvalue analysis and simulation results.

Keywords: genetic algorithms; power system stabilizers; output feedback; simultaneous eigenvalue placement.

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1. INTRODUCTION

The application of genetic algorithms (GA) has recently attracted the attention of researchers in the control area [1–4]. From the literature it is clearly seen that genetic algorithms can provide powerful tools for optimization. The present paper demonstrates the use of genetic algorithms to calculate the gains of a power system simultaneous output feedback stabilizer (OFS).

The importance of increasing the dynamic stability boundaries of synchronous machines equipped with fast-acting static exciters is very well known. Several techniques have been used for the design of supplementary excitation controllers for this purpose [5–15]. Considerable work has been done using optimal control methods. The design of a power system stabilizer can be formulated as an optimal linear regulator control problem. However, the implementation of this technique requires the design of state estimators [16]. This approach increases the complexity and the cost of the control system and reduces its reliability. To avoid these problems, an approach based on output feedback control, which uses only some desired measurable state variables, has been suggested [17–20].

In this paper, the gains of a power system simultaneous output feedback stabilizer are determined using a simple genetic algorithm and an eigenvalue-based objective function. The system to be studied is that of a single machine connected to an infinite bus through a transmission line. This system, while relatively simple, is complex enough to permit the illustration of some stability concepts and results. It is assumed that the measurable states are limited to the machine torque angle and the machine speed. The procedure is extendible to the multimachine case.

The problem of the simultaneous placement of the closed-loop eigenvalues of a power system operating at a wide range of loading conditions, *via* a single output feedback stabilizer, is considered. In this case, the power system, operating at various loading conditions is treated as a finite set of plants.

The problem of simultaneous stabilization occurs frequently in power systems. In the daily operation of a power system, the operating condition changes as a result of load changes. Also, power systems are known to be nonlinear. Linearization around several operating conditions naturally leads to a simultaneous stabilization problem. The simultaneous eigenvalue placement approach considered in this work is useful to shape the transient behavior of the power system.

An objective function that will result in shifting the closed-loop eigenvalues to the left-hand side of a vertical line in the complex s-plane while shifting a specific mode of oscillation to a vertical strip and with bounds on the damping ratio is defined. The objective function is used in conjunction with a genetic algorithm to determine the gain of the simultaneous output feedback stabilizer. The advantage of the eigenvalue-based objective function is that the specification of weighting matrices is not required. Moreover, certain system specifications such as rise time, maximum overshoot, damping ratio, and steady state error can also be incorporated in the objective function.

The above problem, treated in this paper, is concerned with designing optimal simultaneous output feedback stabilizers with constraints in the controller. Analytical solutions to such problems are not available. Even for the static output feedback case, only necessary conditions are given and iterative algorithms are used to search for the local minima. Artificial Intelligence techniques, such as GA, are the alternative in the absence of analytical solutions. The GA can easily incorporate most types of constraints and structures on the controller and often leads to the global optimum [1].

Simulation results and eigenvalue analysis are used throughout the paper to assess the effectiveness of the power system simultaneous output feedback stabilizers designed in this work.

2. GENETIC ALGORITHMS

Genetic algorithms are global search techniques, based on the operations observed in natural selection and genetics [1]. They operate on a population of current approximations — the individuals — initially drawn at random, from which improvement is sought. Individuals are encoded as strings (chromosomes) constructed over some particular alphabet, *e.g.*, the binary alphabet {0,1}, so that chromosomes values are uniquely mapped onto the decision variable domain. Once the decision variable domain representation of the current population is calculated, individual performance is assumed according to the objective function which characterizes the problem to be solved. It is also possible to use the variable parameters directly to represent the chromosomes in the GA solution.

At the reproduction stage, a fitness value is derived from the raw individual performance measure given by the objective function, and used to bias the selection process. Highly fit individuals will have increasing opportunities to pass on genetically important material to successive generations. In this way, the genetic algorithms search from many points in the search space at once and yet continually narrow the focus of the search to the areas of the observed best performance.

The selected individuals are then modified through the application of genetic operators, in order to obtain the next generation. Genetic operators manipulate the characters (genes) that constitute the chromosomes directly, following the assumption that certain genes code, on average, for fitter individuals than other genes. Genetic operators can be divided into three main categories [2], selection, crossover, and mutation.

1. Selection: Selects the fittest individuals in the current population to be used in generating the next population.
2. Crossover: Causes pairs, or larger groups of individuals to exchange genetic information with one another.
3. Mutation: Causes individual genetic representations to be changed according to some probabilistic rule.

Genetic algorithms are more likely to converge to global optima than conventional optimization techniques, since they search from a population of points, and are based on probabilistic transition rules. Conventional optimization techniques are ordinarily based on deterministic hill-climbing methods, which, may find local optima. Genetic algorithms can also tolerate discontinuities and noisy function evaluations.

3. SYSTEM DYNAMIC MODEL

The system considered in this paper is a synchronous machine connected to an infinite bus through a transmission line as shown in Figure 1. The linearized incremental model of this system, with the voltage regulator and the exciter included, is shown in Figure 2. The interaction between the speed and voltage control equations of the machine is expressed in terms of six constants $K_1 \dots K_6$. These constants, with the exception of K_3, which is only a function of the ratio of the impedance, are dependent upon the actual real and reactive power loading as well as the excitation levels in the machine [6]. The equations describing the block diagram of Figure 2 are as follows:

$$\Delta P_m - \Delta P - D\frac{d\delta}{dt} = M\frac{d^2\Delta\delta}{dt^2} \tag{1}$$

$$\Delta P = K_1\Delta\delta + K_2\Delta E_q' \tag{2}$$

$$\Delta E_q' = \frac{K_3}{1+sT_{d0}'K_3}\,\Delta E_{fd} - \frac{K_3K_4}{1+sT_{d0}'K_3}\,\Delta\delta \tag{3}$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E_q' \tag{4}$$

$$\Delta E_{fd} = \frac{1}{K_E+sT_E}\,\Delta V_a \tag{5}$$

$$\Delta V_f = \frac{K_F s}{1+sT_F}\,\Delta E_{fd} \tag{6}$$

$$\Delta V_a = (\Delta V_{ref} + U - \Delta V_t - \Delta V_f)\frac{K_A}{1+sT_A}\,. \tag{7}$$

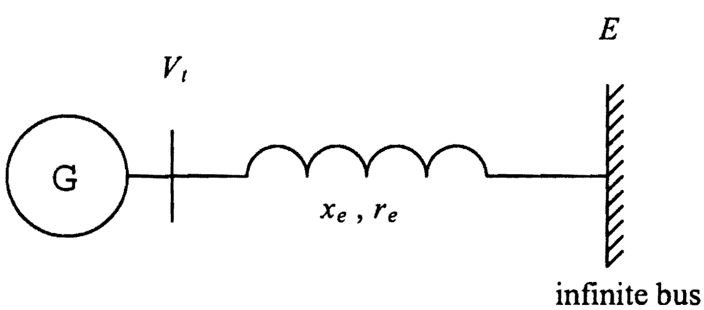

Figure 1. Single machine connected to an infinite bus.

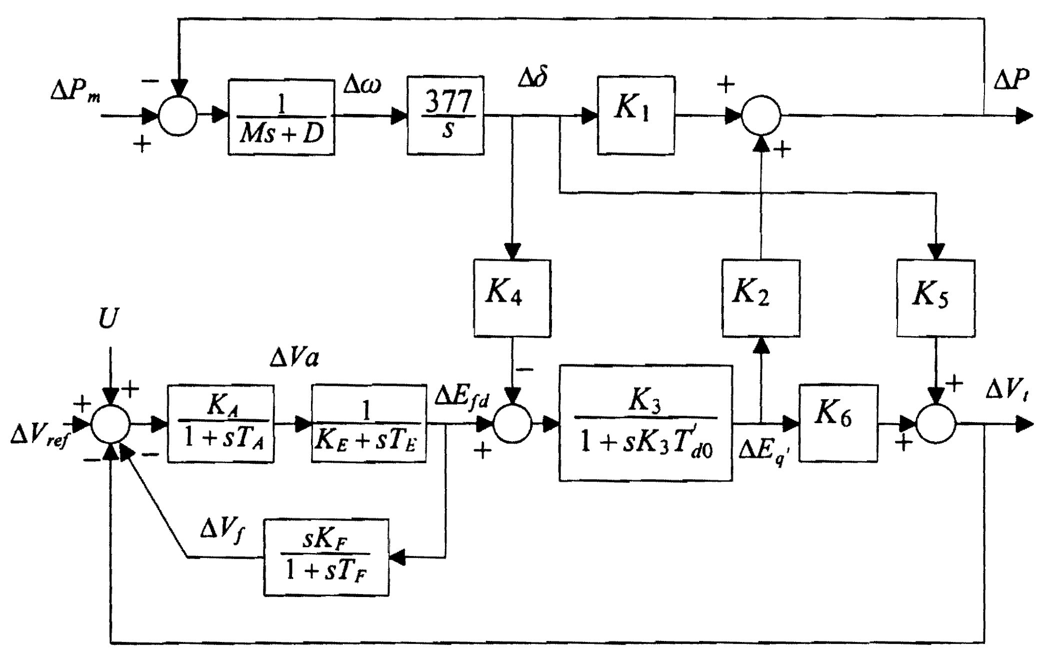

Figure 2. System Block Diagram.

The constants K_1 to K_6 are given in the Appendix. The system data are as follows [9]:

Machine (p.u.)

$x_d = 1.7$; $x'_d = 0.254$; $x_q = 1.64$;

$\omega_0 = 120\pi$ rad/s; $T'_{d0} = 5.9$ sec; $D = 0.0$; $M = 4.74$ sec.

Transmission line (p.u.)

$r_e = 0.02$; $x_e = 0.4$.

Exciter

$K_A = 400$; $T_A = 0.05$; $K_F = 0.025$; $T_F = 1.0$;

$K_E = -0.17$; $T_E = 0.95$.

Loading (p.u.)

$P_o = 1.0$; $Q_o = 0.62$; $V_{t0} = 1.172$;

$K_1 = 1.4479$; $K_2 = 1.3174$; $K_3 = 0.3072$; $K_4 = 1.8050$; $K_5 = 0.0294$; $K_6 = 0.5257$.

The state and output equations of the system under a particular loading condition can be written as:

$$\dot{X}(t) = A\,X(t) + B\,U(t) + \Gamma\,W(t) \tag{8}$$

$$Y(t) = C\,X(t) \tag{9}$$

where the state vector X and output vector Y are chosen to be:

$$X = [\Delta E'_q \;\Delta E_{fd} \;\Delta V_a \;\Delta V_f \;\Delta\delta \;\Delta\omega] \tag{10}$$

$$Y = [\Delta\delta \;\Delta\omega]. \tag{11}$$

The power system OFS is selected to be of the constant gain form:

$$U(t) = F\,Y(t) = [K_\delta \;K_\omega] \cdot \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix}, \tag{12}$$

where K_δ and K_ω are the stabilizer gains. The disturbance vector $W(t)$ is defined as:

$$W(t) = \begin{bmatrix} \Delta P_m \\ \Delta V_{ref} \end{bmatrix}. \tag{13}$$

The constant system matrices A, B, Γ, and C are given by:

$$A = \begin{bmatrix} \frac{-1}{K_3 T'_{d0}} & \frac{1}{T'_{d0}} & 0 & 0 & \frac{-K_4}{T'_{d0}} & 0 \\ 0 & \frac{-K_E}{T_E} & \frac{1}{T_E} & 0 & 0 & 0 \\ \frac{-K_6 K_A}{T_A} & 0 & \frac{-1}{T_A} & \frac{-K_A}{T_A} & \frac{-K_5 K_A}{T_A} & 0 \\ 0 & \frac{-K_F K_E}{T_F T_E} & \frac{K_F}{T_F T_E} & \frac{-1}{T_F} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 377 \\ \frac{-K_2}{M} & 0 & 0 & 0 & \frac{-K_1}{M} & \frac{-D}{M} \end{bmatrix} \tag{14}$$

$$B = \begin{bmatrix} 0 & 0 & \frac{K_A}{T_A} & 0 & 0 & 0 \end{bmatrix}^T ; \quad \Gamma = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \frac{1}{M} \\ 0 & 0 & \frac{K_A}{T_A} & 0 & 0 & 0 \end{bmatrix}^T \tag{15}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} . \tag{16}$$

4. PROBLEM FORMULATION AND RESULTS

In this section, the objective function used to optimize the gains of the OFS is formulated and the optimization problem solved with a genetic algorithm. The solutions and simulation results are also given.

Consider the problem of determining the gains of an output feedback stabilizer that relatively stabilize a family of N plants:

$$\dot{X}(t) = A_k\, X(t) + B_k\, U(t); \quad k = 1, 2, \ldots, N \tag{17}$$

where $X(t) \in R^n$ is the state vector and $U(t) \in R^m$ is the control vector.

The GA technique can be used to obtain the gains of the output feedback stabilizer such that the closed-loop eigenvalues of the set of plants lie in the left-hand side of a vertical line in the complex s-plane while shifting a specific mode of oscillation to a vertical strip and with bounds on the damping ratio, as shown in Figure 3. Such a situation occurs in power systems, where it is desired to relocate the machine electromechanical oscillation mode. In order to do this, the following objective function is suggested:

$$\begin{aligned} J = & \max\left\{0, \left[\max \mathrm{Re}(\lambda^*_{k,i}) - \beta_1\right]\right\} + \max\left\{0, \left[\beta_2 - \min \mathrm{Re}(\lambda^*_{k,i})\right]\right\} \\ & + \max\left\{0, \left[\zeta_1 - \max\left(\frac{|\mathrm{Re}(\lambda^*_{k,i})|}{|(\lambda^*_{k,i})|}\right)\right]\right\} + \max\left\{0, \left[\min\left(\frac{|\mathrm{Re}(\lambda^*_{k,i})|}{|(\lambda^*_{k,i})|}\right) - \zeta_2\right]\right\} \\ & + \max\left\{0, \left[\max \mathrm{Re}(\lambda_{k,i}) - \beta\right]\right\} \end{aligned} \tag{18}$$

$$k = 1, 2, \ldots, N; \quad i = 1, 2, \ldots, n,$$

where $\lambda_{k,i}$ is the i^{th} closed-loop eigenvalue of the k^{th} plant and $\lambda^*_{k,i}$ is the i^{th} closed-loop eigenvalue of the k^{th} plant to be shifted. The first two terms ensure that the shifted modes $\lambda^*_{k,i}$ are in the pre-specified vertical strip, while the third and fourth terms restrict the damping ratio of the shifted modes to $\zeta_1 < \zeta < \zeta_2$. The last term of the objective function J is to guarantee the relative stability of the closed-loop system; more precisely the rest of the modes are required to be to the left of the vertical line $s = \beta$. If a solution is found such that $J = 0$, then the resulting gains simultaneously place the closed-loop eigenvalues of the collection of plants in the pre-specified vertical strip in the complex s-plane and the damping ratio of the shifted mode is within specifications. The existence of a solution is verified numerically by obtaining $J = 0$. To verify the above procedure, two cases are presented.

4.1. (A) The Single Plant Case ($N = 1$)

The closed-loop system matrix can be written as:

$$A_{cl} = \begin{bmatrix} \frac{-1}{K_3 T'_{d0}} & \frac{1}{T'_{d0}} & 0 & 0 & \frac{-K_4}{T'_{d0}} & 0 \\ 0 & \frac{-K_E}{T_E} & \frac{1}{T_E} & 0 & 0 & 0 \\ \frac{-K_6 K_A}{T_A} & 0 & \frac{-1}{T_A} & \frac{-K_A}{T_A} & \frac{(K_\delta - K_5)K_A}{T_A} & \frac{(K_\omega K_A)}{T_A} \\ 0 & \frac{-K_F K_E}{T_F T_E} & \frac{K_F}{T_F T_E} & \frac{-1}{T_F} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 377 \\ \frac{-K_2}{M} & 0 & 0 & 0 & \frac{-K_1}{M} & \frac{-D}{M} \end{bmatrix}. \quad (19)$$

To calculate the objective function as given by Equation 18, the eigenvalues of the closed-loop system matrix A_{cl} are computed for each of the individuals of the current population. The values of the objective function thus obtained are fed to the GA in order to produce the next generation of individuals. The procedure is repeated until the population has converged to a zero value of the objective function producing the gains of the output feedback stabilizer K_ω and K_δ. The GA used here utilizes direct manipulation of the parameters. The following GA parameters were used in the present study:

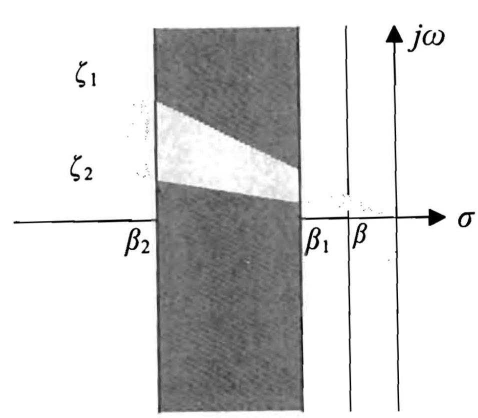

Figure 3. Vertical strip in the complex s-plane with bounds on the damping ratio.

Population size = 80
Maximum number of generations (Max. Gen.) = 150
Crossover probability: performed randomly between chromosomes
Mutation probability = 0.1.

Two examples are presented:

Example 1

$$\beta_1 = -1;\ \ \beta_2 = -2;\ \ \zeta_1 = 0.1395;\ \ \zeta_2 = 0.141;\ \ \beta = -1.$$

The open-loop system eigenvalues are:

$-0.2349 \pm j10.792;\ \ -1.5517;\ \ -3.0840;\ \ -8.1336 \pm j8.9844.$

The first two eigenvalues are called the electromechanical mode. The damping ratio of this mode is 0.0218. It is desired to have the damping ratio around 0.14. In addition, all the other closed-loop system eigenvalues must lie to the left of the line $s = -1$. The gains of the OFS as obtained from the GA are:

$K_\delta = -0.2279$ and $K_\omega = -11.2147$.

The closed-loop eigenvalues were found to be:

$-1.6143 \pm j11.4069;\ \ -1.3818 \pm j1.0877;\ \ -7.6904 \pm j7.5747.$

The damping ratio of the electromechanical mode has improved to 0.1401.

Figure 4 shows the dynamic response of the speed deviation $\Delta\omega$ for a 0.05 p.u. step change in the mechanical power. The gains obtained using the GA technique are in full agreement with those obtained in [20].

Example 2

$$\beta_1 = -2;\ \ \beta_2 = -3;\ \ \zeta_1 = 0.13;\ \ \zeta_2 = 0.25;\ \ \beta = -2.$$

The output feedback gains are:

$K_\delta = -0.1945$ and $K_\omega = -21.2664$.

The closed-loop eigenvalues were found to be:

$-2.9735 \pm j11.8561;\ \ -2.3415 \pm j0.9346;\ \ -5.3714 \pm j5.1724.$

The damping ratio of the electromechanical mode has improved to 0.2433. Figure 5 shows the dynamic response of the speed deviation $\Delta\omega$ for a 0.05 p.u. step change in the mechanical power.

4.2. (B) The Multiple Plants case ($N > 1$)

The problem of simultaneous eigenvalue placement of a finite number of plants *via* a single output feedback stabilizer can be easily addressed using the eigenvalue-based objective function J in conjunction with a GA. This procedure is next demonstrated.

Example 3

Consider the problem of a single machine infinite bus system operating under different loading conditions [8]. Here we consider four operating points ($N = 4$). The operating points were selected randomly as follows:

$(P_o, Q_o) = (1.0,\ 0.62);\ \ (1.0,\ 0.2);\ \ (1.0,\ \text{-}0.1);\ \ (0.8,\ 0.5);\ \ V_{to} = 1.172.$

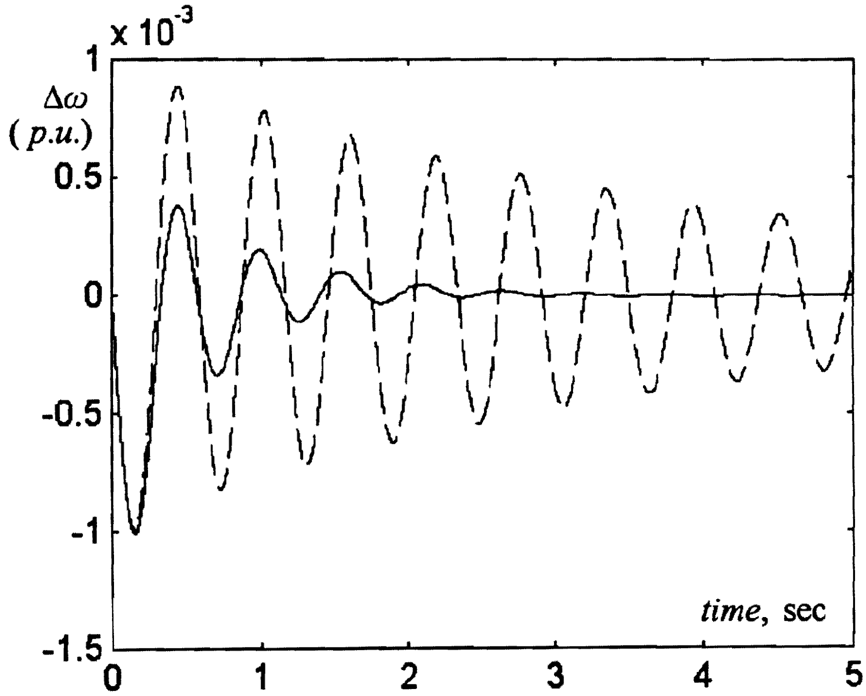

Figure 4. Dynamic responses of $\Delta\omega$ (Example 1).
(-- No stabilizer, $-\beta_1 = -1$; $\beta_2 = -2$; $\zeta_1 = 0.1395$; $\zeta_2 = 0.141$; $\beta = -1$).

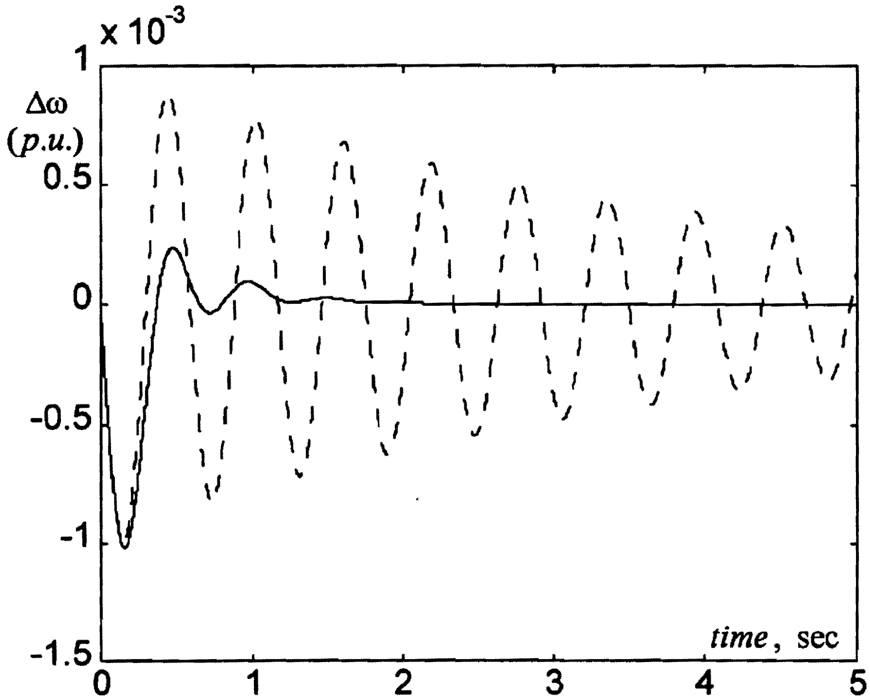

Figure 5. Dynamic responses of $\Delta\omega$ (Example 2).
(-- No stabilizer, $-\beta_1 = -2.0$; $\beta_2 = -3.0$; $\zeta_1 = 0.13$; $\zeta_2 = 0.25$; $\beta = -2$).

The eigenvalues of the system at the four operating points considered, without OFS, are:

$[-0.2350 \pm j10.7853; \ -1.5520; \ -3.0830; \ -8.1340 \pm j8.9851]$

$[-0.2956 \pm j11.5532; \ -1.7131 \pm j0.8164; \ -8.6778 \pm j9.1726]$

$[-0.2983 \pm j12.1958; \ -1.3149 \pm j1.0433; \ -9.0732 \pm j9.4920]$

$[-0.2818 \pm j10.5746; \ -3.0260; \ -1.5411; \ -8.1210 \pm j8.8397]$.

The damping ratios of the electromechanical modes are respectively:

[0.0218; 0.0256; 0.0244; 0.0266].

We used the objective function J with the GA and $N = 4$ to place the electromechanical mode of each of the four systems in the vertical strip defined by the lines $s = -1$; $s = -2$ and damping ratio between 0.13 and 0.25. In addition, all the closed-loop eigenvalues are to be located to the left of the line $s = -1$.

This means $\beta_1 = -1$; $\beta_2 = -2$; $\zeta_1 = 0.13$; $\zeta_2 = 0.25$; $\beta = -1$.

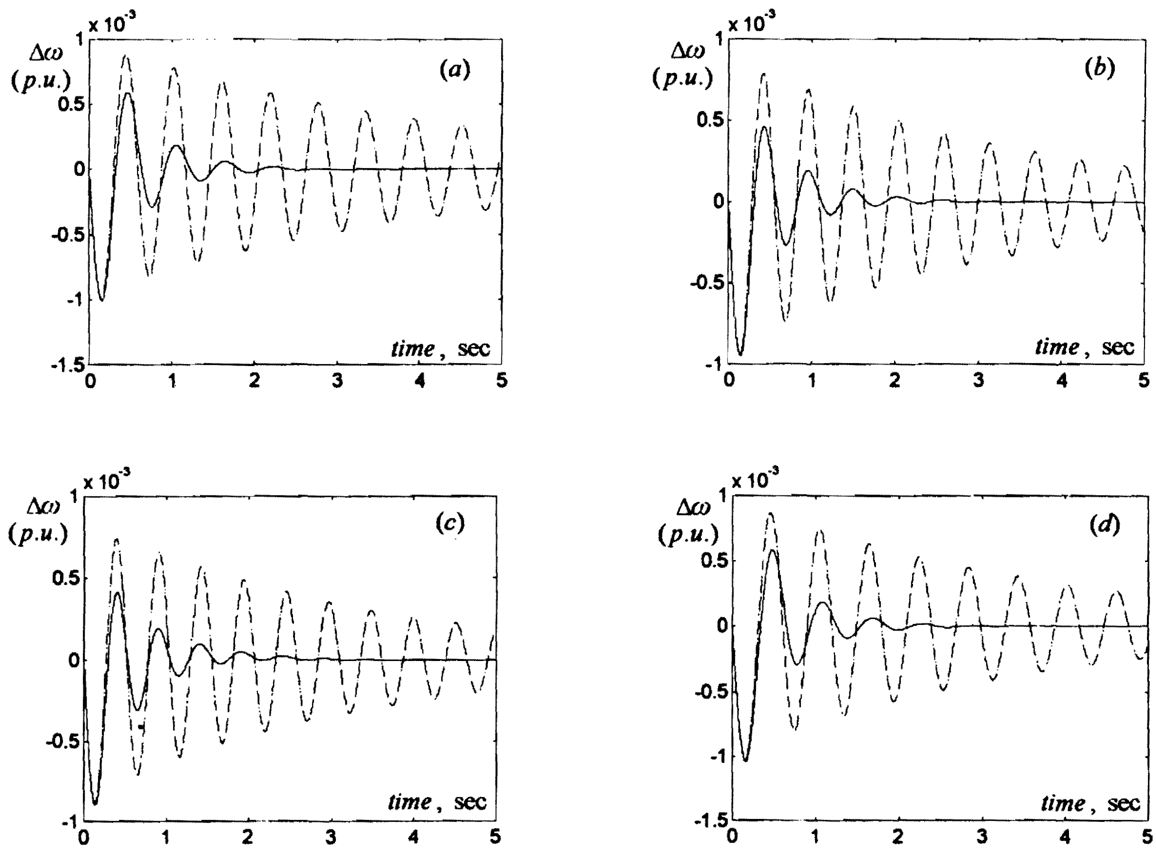

Figure 6. Dynamic responses of $\Delta\omega$ (Example 3) ($N = 4$):
(a) $(P_o, Q_o) = (1.0, 0.62)$; (b) $(P_o, Q_o) = (1.0, 0.2)$;
(c) $(P_o, Q_o) = (1.0, -0.1)$; (d) $(P_o, Q_o) = (0.8, 0.5)$.
(-- No stabilizer, $-\beta_1 = -1.0$; $\beta_2 = -2.0$; $\zeta_1 = 0.13$; $\zeta_2 = 0.25$; $\beta = -1$).

The gains of the OFS in this case were found to be:

$K_\delta = -0.0793$ and $K_\omega = -12.2704$.

The eigenvalues of the four stabilized systems are:

$$[-1.9376 \pm j10.6583;\ \ -6.0773 \pm j7.7525;\ \ -3.6687;\ \ -1.6743]$$

$$[-1.8830 \pm j11.7383;\ \ -7.1298 \pm j7.6226;\ \ -1.6735 \pm j1.1159]$$

$$[-1.7934 \pm j12.4942;\ \ -7.7847 \pm j7.9454;\ \ -1.1083 \pm j1.2636]$$

$$[-1.8778 \pm j10.4176;\ \ -6.2113 \pm j7.7048;\ \ -3.5318 \pm j1.6627].$$

The damping ratios of the electromechanical modes are: eigenvalues

$$[0.1789;\ 0.1584;\ 0.1421;\ 0.1774],$$

indicating that the OFS will simultaneously improve the response of the four systems. The dynamic response of the speed deviation $\Delta\omega$, for the four systems following a 0.05 p.u. step-change in the mechanical power is shown in Figure 6.

The extension of this approach to the multimachine system is evident. In this case, the formulation of the problem is parallel to the simultaneous stabilization case. In general, for a system consisting of m machines, each represented by 6 state variables and equipped with an OFS of the type considered in the paper, the system order will be $6m$, and the number of parameters to be tuned using the GA will be $2m$. If j operating points are selected for simultaneous stabilization, the GA will tune the $2m$ parameters such that the $6mj$ eigenvalues are located in the required region as stipulated by the particular objective function used. The multimachine case differs from the single machine infinite bus case in the amount of computation time.

5. CONCLUSION

The use of genetic algorithms to design a simultaneous output feedback controller to place the eigenvalues of a power system is investigated in this paper. The problem of selecting the output feedback gains is converted to a simple optimization problem with an eigenvalue-based objective function, which is solved by a genetic algorithm. The design method does not need the specification of weighting matrices. An objective function is presented allowing the selection of the output feedback gains to place the closed-loop eigenvalues in the left-hand side of a vertical line in the complex s-plane while shifting a specific mode of oscillation to a vertical strip and with bounds on the damping ratio. Objective functions allowing the selection of the output feedback gains to optimally place the closed-loop eigenvalues in the left-hand side of a vertical line in the complex s-plane, within an open sector in the complex s-plane, or within a vertical strip in the complex s-plane, are special cases of the work presented in this paper.

The simultaneous placement of the closed-loop eigenvalues of a power system operating at different loading conditions *via* a single output feedback stabilizer was successfully demonstrated using the eigenvalue-based objective function.

The effectiveness of the output feedback stabilizer in enhancing the dynamic performance stability is verified through eigenvalue analysis and simulation results.

Several extensions of this work are possible: Dynamic output feedback power system stabilizers can be designed with the same techniques described in the paper. A combination of partial pole placement with linear quadratic minimization to improve some error performance such as disturbance rejection is also easily incorporated in our formulation.

6. ACKNOWLEDGMENT

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7. NOMENCLATURE

$r_e + jx_e$	Transmission line impedance
K_A, K_E	Voltage regulator gain
T_A, T_E	Voltage regulator time constant
K_F, T_F	Stabilizing transformer gain, time constant
K_1 to K_6	Constants of the linearized model of synchronous machine
T'_{do}	d-Axis open circuit field time constant
M, H	Inertia coefficient, constant ($M = 2H$)
D	Damping coefficient
i_d, i_q	Armature current direct and quadrature axis components
v_d, vi_q	Armature voltage direct and quadrature axis components
x'_d, x_d, x_q	Direct axis transient, direct axis and quadrature axis reactances
P_m	Mechanical power input to machine
P, Q	Electric and reactive power output from machine
δ	Torque angle
ω	Angular velocity
V_f	Stabilizer transformer voltage
E_{fd}	Field voltage
E'_q	q-Axis voltage behind transient reactance
E	Infinite bus voltage
V_{ref}	Reference input voltage
V_a	Regulator voltage
V_t	Terminal voltage
A, B, Γ, C	System, control, disturbance, and output matrices
A_{cl}	Closed-loop system matrix
X, Y, U, W	State, output, control, and disturbance vectors
F	Feedback gain matrix
J	Objective function
K_δ, K_ω	Elements of feedback gain matrix

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APPENDIX

All variables with subscript 0 are values of the variables evaluated at their pre-disturbance steady-state operating point from known values of V_{t0}, P_0, and Q_0 as given by Equations (20)–(26). All variables preceded by Δ

are deviations of these variables from their respective values at the steady-state operating point. The constants K_1 to K_6 are given in Equations (27)–(32).

$$i_{qo} = \frac{P_o V_{to}}{\sqrt{(P_o x_q)^2 + V_{to}^2 + Q_o x_q)^2}} \tag{20}$$

$$v_{do} = i_{qo} x_q \tag{21}$$

$$v_{qo} = \sqrt{V_{to}^2 - v_{do}^2} \tag{22}$$

$$i_{do} = \frac{Q_o + x_q i_{qo}^2}{v_{qo}} \tag{23}$$

$$E_{qo} = v_{qo} + i_{do} x_q \tag{24}$$

$$E_o = \sqrt{(v_{do} + x_e i_{qo} - r_e i_{do})^2 + (v_{qo} - x_e i_{do} - r_e i_{qo})^2} \tag{25}$$

$$\delta_o = \tan^{-1} \frac{(v_{do} + x_e i_{qo} - r_e i_{do})}{(v_{qo} - x_e i_{do} - r_e i_{qo})} \tag{26}$$

$$K_1 = \frac{E_o E_{qo}}{Z}[r_e \sin\delta_o + (x_e + x'_d)\cos\delta_o] + \frac{i_{qo} E_o}{Z}[(x_q - x'_d)(x_e + x_q)\sin\delta_o - r_e(x_q - x'_d)\cos\delta_o] \tag{27}$$

$$K_2 = \left[\frac{r_e E_{qo}}{Z} + i_{qo}\left(1 + \frac{(x_e + x_q)(x_q - x'_d)}{Z}\right)\right] \tag{28}$$

$$K_3 = \left[1 + \frac{(x_e + x_q)(x_d - x'_d)}{Z}\right]^{-1} \tag{29}$$

$$K_4 = \frac{E_o(x_d - x'_d)}{Z}[(x_e + x_q)\sin\delta_o - r_e\cos\delta_o] \tag{30}$$

$$K_5 = \frac{v_{do}}{V_{to}}\frac{x_q E_o}{Z}[r_e \sin\delta_o + (x_e + x'_d)\cos\delta_o] + \frac{v_{qo}}{V_{to}}\frac{x'_d E_o}{Z}[r_e\cos\delta_o + (x_e + x_q)\sin\delta_o] \tag{31}$$

$$K_6 = \frac{v_{qo}}{V_{to}}\left[1 + \frac{x'_d(x_e + x_q)}{Z}\right] + \frac{v_{do}}{V_{to}} x_q \frac{r_e}{Z} \tag{32}$$

$$Z = r_e^2 + (x_e + x'_d)(x_e + x_q)$$

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