ROBUST VARIABLE STRUCTURE / GENETIC ALGORITHMS CONTROLLER FOR IMPROVING POWER SYSTEMS DYNAMIC STABILITY

Zakariya M. Al-Hamouz[1] **and Hussain N. Al-Duwaish**[1]

[1] *Associate Professor, Department of Electrical Engineering, KFUPM*
E-mail: zhamouz@kfupm.edu.sa

ABSTRACT

In this paper, a combined variable structure / genetic algorithms controller is presented to improve the dynamic stability of a power system. The design of variable structure controller is formulated as an optimization problem and genetic algorithms are used in the optimization process. Contrary to the design methods reported in the literature, which depend partially on trial and error approach for the selection of controller parameters, the proposed method provides an optimal and systematic design procedure. The proposed design method has been applied to the design of a power system controller of a single machine power system model. The system performance against step load and parameter variations has been simulated and compared to previous designs. Simulation results show improvements in the dynamic system performance and control effort.

Keywords: *Synchronous machines, power systems, variable structure control, genetic algorithms, dynamic stability, controller design.*

الملخص

في هذه المقالة تم تقديم متحكم مركب من بناء متغير وخوارزمية جينية لتحسين الاتزان الديناميكي لنظام طاقة كهربائي. ولقد تم تقييم متحكم البناء المتغير بعد صياغته كمشكلة (إيجاد حل أمثل) ثم أستخدام الخوارزميات الجينية لايجاد الحل الامثل. وعلى عكس طرق التصميم التي اقترحت في السابق، والتي تعتمد جزئيا على المحاولة والخطأ لاختيار عناصر المتحكم فإن الطريقة المقترحة تقدم حلا أمثل بطريقة سلسلة.

تم تطبيق طريقة التصميم المقترحة لايجاد متحكم نظام طاقة كهربائي يتكون من آلة واحده ونظام طاقة. ولقد تم محاكاة أداء النظام المصمم عند تعرضه لتغير مفاجئ في الحمل الكهربائي وعند تغير ثوابت النظام ومن ثم تمت المقارنة مـع التصاميم السابقة. ولقد اثبتت النتائج ان المتحكم الحالي حسّن الأداء الديناميكي وجهد التحكم للنظام المختبر.

1. INTRODUCTION

In recent years, there is an ongoing interest on the application of the variable structure controllers (VSC) to different engineering problems including power systems [Al-Hamouz, 1993, Lee, 1998, Sivarmakrishnan, 1984, Bhattacharya, 1995, Murty, 1998, Abdel-Magid, 1995, Balasubramanyam, 1998, Samarasinghe, 1997, Chern, 1997, 1996, Murty, 1996, Hsu, 1984], aerospace [Lu, 1997, Innocenti, 1997, Singh, 1997], robotics [Zribi, 1997, Lee, 1997], and many others. The VSC is essentially a switching feedback control where the gains in each feedback path switch between two values according to some rule. The switching feedback law drives the controlled system's state trajectory onto specified surface called the sliding surface which represent the desired dynamic behavior of the controlled system. The advantage of switching between different feedback structures is to combine the useful properties of each structure and to introduce new properties that are not present in any of the structures used. The design of VSC involves finding the switching vectors representing the sliding surface and the feedback gains.

The switching vectors are very important in improving the system dynamic performance. Selection of switching vectors can be done by pole placement [Al-Hamouz, 1993, Lee, 1998, Sivarmakrishnan, 1984, Bhattacharya, 1995, Murty, 1998, Abdel-Magid, 1995, Balasubramanyam, 1998, Samarasinghe, 1997, Chern, 1997, 1996, Murty, 1996] or linear optimal control theory [Al-Hamouz, 1993, Lee, 1998, Hsu, 1984]. Feedback gains selection represents the second step in the design of VSC. The objective of this step is to find the appropriate feedback gains that will drive the system's state trajectory to the switching surface defined by the switching vectors. Usually, feedback gains are chosen by trial and error such that certain performance requirements are satisfied. Recently, the problem of VSC feedback gains selection has been considered in [Lee, 1998, Bhattacharya, 1995, Chern, 1997] where the objective is to find a systematic way of feedback gains selection.

Genetic algorithms (GA) are robust search and optimization techniques that have been applied to many practical problems [Caponetto, 1993, Goldberg, 1989]. The use of GA in control applications is increasing considerably [Wu, 1998, Lai, 1996, Pillay, 1997, Taranto, 1998, Hyun, 1998, Reformat, 1998, Al-Duwaish, 1997, Varsek, 1993, Porter, 1992, Lansberry, 1992, Krishnakumar, 1992, Porter, 1993, Itkis, 1976]. In the present work, a new approach based on GA is proposed for the design of VSC. This is accomplished by formulating the VSC design as an optimization problem and GA are used in the optimization process. The proposed method provides an optimal and systematic way of VSC design.

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2. THEORY OF VSC

The fundamental theory of variable structure systems may be found in [Utkin, 1978]. Different control goals such as stabilization, tracking, regulation can be achieved using VSC by the proper design of the sliding surface. The discussion here will be limited to the regulation problem where the objective is to keep the system's states as close to zero as possible. A block diagram of the VSC for the regulation problem is shown in Fig. 1. The control law is a linear state feedback whose coefficients are piecewise constant functions. Consider the linear time-invariant controllable system given by

$$\dot{X} = AX + BU \tag{1}$$

Where

- X n-dimensional state vector
- U m-dimensional control force vector
- A $n \times n$ system matrix
- B $n \times m$ input matrix

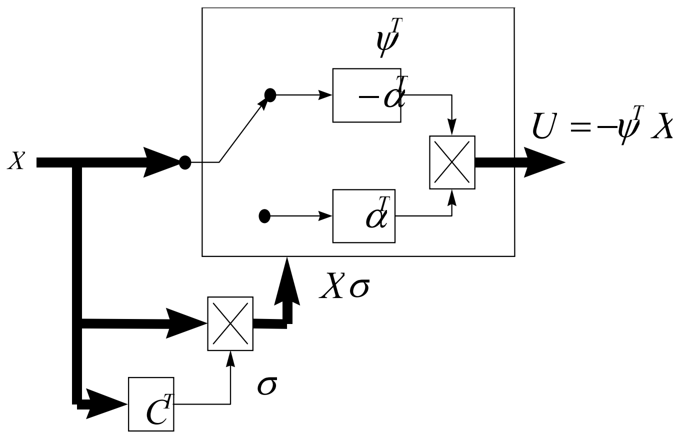

Fig. 1: Block diagram of variable structure controller

The VSC control laws for the system of Equation (1) are given by

$$u_i = -\psi_i^T X = -\sum_{j=1}^{n} \psi_{ij} x_j; \qquad i = 1,2,....,m \tag{2}$$

Where the feedback gains are given as

$$\psi_{ij} = \begin{cases} \alpha_{ij}, & if \quad x_i\sigma_j \rangle\, 0; \;\; i = 1,....,m \\ -\alpha_{ij}, & if \quad x_j\sigma_i \langle\, 0; \;\; j = 1,....,n \end{cases}$$

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and

$$\sigma_i(X) = C_i^T X = 0, \qquad i = 1,....,m \tag{3}$$

Where C_i's are the switching vectors which are selected by pole placement or linear optimal control theory.

The design procedure for selecting the constant switching vectors C_i using pole placement is described below .

Step1: Define the coordinate transformation

$$\boldsymbol{Y = MX} \tag{4}$$

such that

$$MB = \begin{bmatrix} 0 \\ .... \\ B_2 \end{bmatrix} \tag{5}$$

where M is a nonsingular $n\times n$ matrix and B_2 is a nonsingular $m\times m$ matrix.

From (4) and (5)

$$\dot{Y} = M\dot{X} = MAM^{-1}Y + MBU \tag{6}$$

Equation (6) can be written in the form

$$\begin{bmatrix} \dot{Y}_1 \\ \dot{Y}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} + \begin{bmatrix} 0 \\ B_2 \end{bmatrix} U \tag{7}$$

where A_{11}, A_{12}, A_{21}, A_{22} are respectively *(n-m)×(n-m), (n-m)×m, m×(n-m)* and (*m×m*) submatrices. The first equation of (7) together with equation (3) specifies the motion of the system in the sliding modem that is

$$\dot{Y}_1 = A_{11}Y_1 + A_{12}Y_2 \tag{8}$$

$$\sum(Y) = C_{11}Y_1 + C_{12}Y_2 \tag{9}$$

where C_{11} and C_{12} are *m×(n-m)* and *(m×m)* matrices, respectively satisfying the relation

$$\begin{bmatrix} C_{11} & C_{12} \end{bmatrix} = C^T M^{-1} \tag{10}$$

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Equations (8) and (9) uniquely determine the dynamics in the sliding mode over the intersection of the switching hyperplanes

$$\sigma_i(X) = C_i^T X = 0, \qquad i = 1,....,m$$

The subsystem described by equation (8) may be regarded as an open loop control system with state vector Y_1 and control vector Y_2 being determined by equation (9), that is

$$Y_2 = -C_{12}^{-1} C_{11} Y_1 \tag{11}$$

Consequently, the problem of designing a system with desirable properties in the sliding mode can be regarded as a linear feedback design problem. Therefore, it can be assumed, without loss of generality, that C_{12} = identity matrix of proper dimension.

Step 2: Equations (8) and (11) can be combined to obtain

$$\dot{Y}_1 = \left[A_{11} - A_{12} C_{11} \right] Y_1 \tag{12}$$

Utkin and Yang [34] have shown that if the pair (A, B) is controllable, then the pair (A_{11}, A_{12}) is also controllable. If the pair (A_{11}, A_{12}) is controllable, then the eigenvalues of the matrix $\left[A_{11} - A_{12} C_{11} \right]$ in the sliding mode can be placed arbitrarily by suitable choice of C_{11}. The feedback gains α_{ij} are usually determined by simulating the control system and trying different values until satisfactory performance is obtained.

3. GENETIC ALGORITHMS

Genetic algorithms are directed random search techniques, which can find the global optimal solution in complex multidimensional search spaces. GA were first proposed by Holland [Holland, 1975] and have been applied successfully to many engineering and optimization problems [Goldberg, 1989]. GA employ different genetic operators to manipulate individuals in a population of solutions over several generations to improve their fitness gradually. Normally, the parameters to be optimized are represented in a binary string . To start the optimization, GA use randomly produced initial solutions created by random number generator. This method is preferred when a priori knowledge about the problem is not available.

The flow chart of a simple GA is shown in Fig. 2. There are basically three genetic operators used to generate and explore the neighborhood of a population and select a new generation.

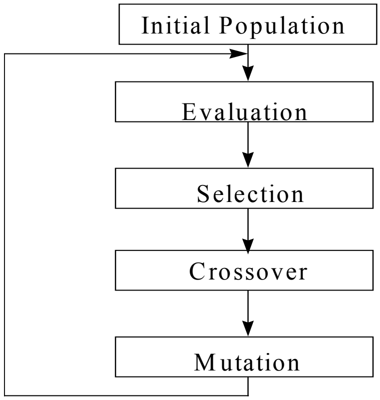

Fig. 2: Flow Chart for a Simple Genetic Algorithm

These operators are selection, crossover, and mutation. After randomly generating the initial population of say N solutions, the GA use the three genetic operators to yield N new solutions at each iteration. In the selection operation, each solution of the current population is evaluated by its fitness normally represented by the value of some objective function, and individuals with higher fitness value are selected. Different selection methods such as stochastic selection or ranking-based selection can be used.

The crossover operator works on pairs of selected solutions with certain crossover rate to yield N new solutions. The crossover rate is defined as the probability of applying crossover to a pair of selected solutions. There are many ways of defining this operator. The most common way is called the one-point crossover which can be described as follows. Given two binary coded solutions of certain bit length, a point is determined randomly in the two strings and corresponding bits are swapped to generate two new solutions.

The N new solutions generated by the crossover operation are subjected to mutation. Mutation is a random alteration with small probability of the binary value of a string position. This operation will prevent GA from being trapped in a local minimum. The fitness evaluation unit in the flow chart acts as an interface between the GA and the optimization problem. Information generated by this unit about the quality of different solutions is used by the selection operation in the GA. The algorithm is repeated until predefined number of generations have been produced or no more improvements in the value of the objective function are observed. Finally, one solution out of the N solutions corresponding to the minimum value of the objective function is selected. More details about GA can be found in [Goldberg, 1989, Davis, 1991].

4. VSC GAINS DESIGN USING GA

The design of VSC as explained in Section 2 centers around finding the switching vectors and the feedback gains. In this section, the proposed GA approach for the selection of the switching vectors and feedback gains is explained. To start the proposed GA method, a performance index must be defined. The selection of the performance index depends on the objective of the control problem. The performance index used here is the well-known optimal regulator performance index given by [Kirk, 1970]

$$J = \frac{1}{2}\int_0^\infty [X^T(t)QX(t) + U^T(t)RU(t)] \quad dt \tag{13}$$

Where Q is real symmetric positive semidefinite state weighting matrix and R is a real symmetric positive definite control weighting matrix. The positive semidefiniteness on Q is to ensure that the system is not rewarded for large negative errors in state, while the positive definite restriction on R prevents the possibility of the optimal control $U(t)$ being an unbounded value. Minimizing J will keep the states ($X(t)$) close to zero while using small amount of control ($U(t)$). The following step by step procedure describes the proposed method:

1) Generate randomly a set of possible switching vectors and feedback gains depending on the size of the search space.
2) Evaluate the performance index given by Equation 13 for all possible switching vectors and feedback gains generated in step 1.
3) Use genetic operators (selection, crossover, and mutation) to produce new generation of switching vectors and feedback gains.
4) Evaluate the performance index in step 2 for the new generation of switching vectors and feedback gains. Stop if certain predetermined number of generations has been used, otherwise go to step 3.

5. SIMULATION RESULTS

In this section, the proposed method is applied and compared to the design of a power system stabilizer (PSS) of a single machine power system model [Lee, 1998]. Fig. 3 shows the block diagram of the linearized power system model for low-frequency oscillation studied [Lee, 1998]. The dynamic model in state-variable form can be obtained from the transfer function model and is given as

$$\dot{X}(t) = AX(t) + Bu(t) + Fd(t)$$

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where

$$X(t) = \left[\Delta\omega(t) \quad \Delta\delta(t) \quad \Delta e'_q(t) \quad \Delta e_{fd}(t)\right]^T, \; u(t) = u_{(from\,VSC)}, \; d(t) = \Delta T_m(t)$$

$$A = \begin{bmatrix} -\dfrac{D}{M} & -\dfrac{K_1}{M} & -\dfrac{K_2}{M} & 0 \\ \omega_0 & 0 & 0 & 0 \\ 0 & -\dfrac{K_4}{T'_{d0}} & -\dfrac{1}{T'_{d0}K_3} & \dfrac{1}{T'_{d0}} \\ 0 & -\dfrac{K_4K_5}{T_A} & -\dfrac{K_4K_6}{T_A} & -\dfrac{1}{T_A} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & \dfrac{K_A}{T_A} \end{bmatrix}^T$$

$$F = \begin{bmatrix} \dfrac{1}{M} & 0 & 0 & 0 \end{bmatrix}^T$$

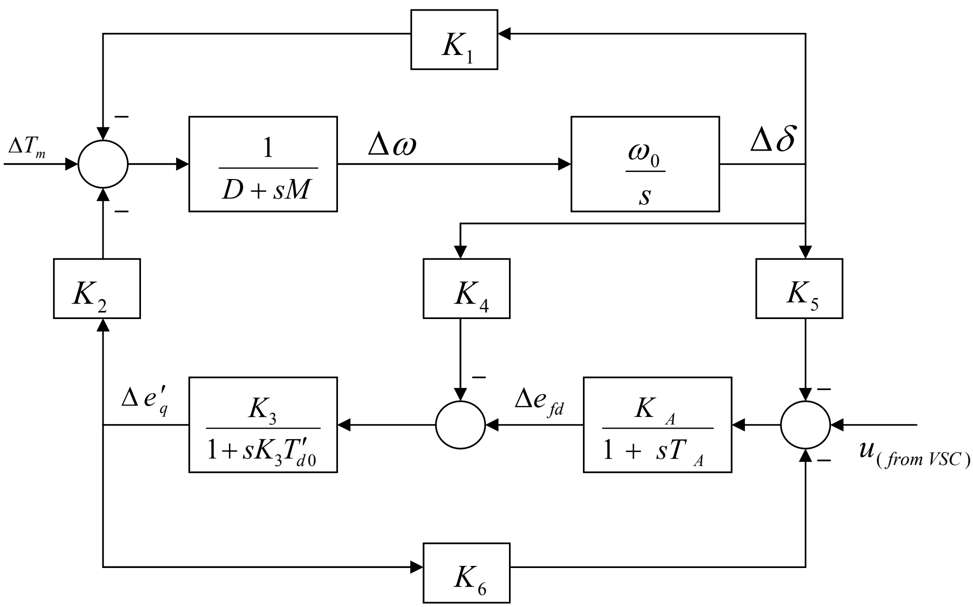

Fig. 3: Block diagram of a single machine infinite bus system

The control objective in the PSS problem is to keep the change in frequency ($\Delta\omega$) as close to zero as possible when the system is subjected to a load disturbance (*d*) by manipulating the input (*u*).

A variable structure controller for the above system was designed in [Lee, 1998]. The system parameters used in the design are $K_1 = 0.5698$, $K_2 = 0.9709$, $K_3 = 0.6584$, $K_4 = 0.5233$, $K_5 = -0.0500$, $K_6 = 0.8454$, $M = 9.26$, $D = 0.0$, $T'_{d0} = 7.76$, $K_A = 50.0$, and $T_A = 0.05$. The switching vector was designed by pole placement and was given to be

$$C = \begin{bmatrix} -13052 & -13 & 175 & 1 \end{bmatrix}^T$$

The values of the feedback gains obtained using H_∞ are

$$\alpha_1 = -53.7168 \quad ,\alpha_2 = 0.9945 \quad ,\alpha_3 = 1.7125, \quad \alpha_4 = 0.0091.$$

In the present work, since the objective of the PSS is to keep the variation in the frequency ($\Delta\omega$) as close to zero as possible by manipulating the control effort (*u*), the weighting matrices in the objective function (Equation 13) are selected as

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \qquad R = 0$$

The proposed design procedure is used to find the switching vector and feedback gains that minimize the performance index when the system is subjected to a step load disturbance of 0.01 p.u.. Following the GA design procedure described in Section 4 with single point crossover and mutation probabilities of 0.7 and 0.001 respectively, the optimal switching vector is found to be

$$C = \begin{bmatrix} -30000 & -97.2134 & 107.0026 & 1 \end{bmatrix}^T$$

and the feedback gains are

$$\alpha_1 = 2.9310 \quad ,\alpha_2 = 1.9974 \quad ,\alpha_3 =,0.2217 \quad \alpha_4 = 0.1203.$$

The above mentioned values of crossover and mutation probabilities were selected based on the authors' experience with GA and from literature survey for many optimization problems of this size.

Figure 4 shows the simulation results of the change in frequency ($\Delta\omega$) for the two designs when the system is subjected to a step disturbance load of of 0.01 p.u which clearly shows the improvement in the behavior of $\Delta\omega$ using the proposed method. The control effort of the two designs is shown in Fig. 5 which indicates that the improvement in the damping properties was accomplished on the expense of higher control effort.

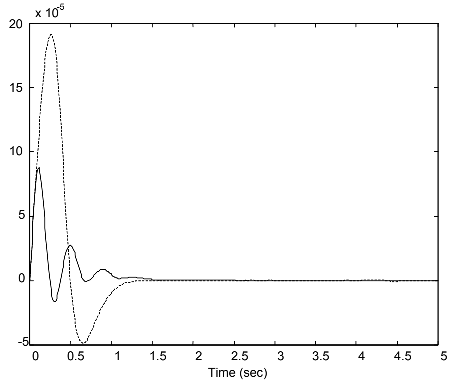

Fig. 4: Change in Frequency ($\Delta\omega$) in p.u:
Proposed Method (__), Method of [Lee, 1998] (- -)

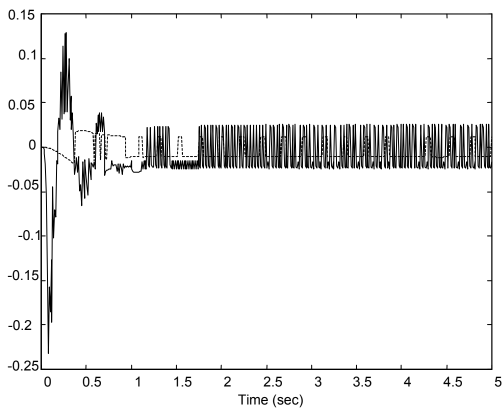

Fig. 5: Control effort (u) in p.u. : Proposed Method (__), Method of [Lee, 1998] (- -)

To minimize the control effort and to keep the variation in the frequency ($\Delta\omega$) as close to zero as possible, the weighting matrices in the objective function (Equation 13) are changed to

$$Q = \begin{bmatrix} 1000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \qquad R = 1$$

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The optimal switching vector is given by

$$C = [-9240.700 \quad -11.2506 \quad 125.000 \quad 1]^T$$

and the feedback gains are

$$\alpha_1 = 2.9989 \qquad ,\alpha_2 = 0.0109 \qquad ,\alpha_3 =,0.0021 \qquad \alpha_4 = 0.0711.$$

The control effort of the new design with different weighting matrices is shown in Fig. 6 which indicates that the control effort has been reduced greatly compared to the H_∞ design, and at the same time the change in frequency ($\Delta\omega$) is improved as shown in Fig. 7.

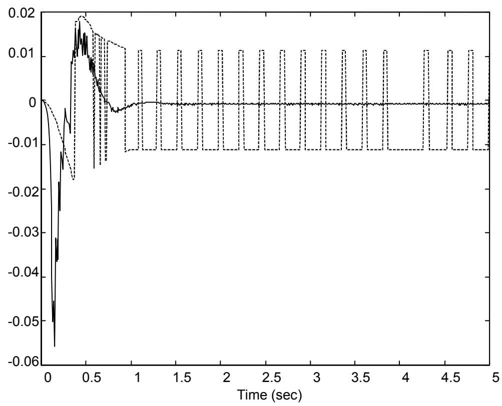

Fig. 6: Control effort (*u*) in p.u. : Proposed Method (__), Method of [Lee, 1998] (- -)

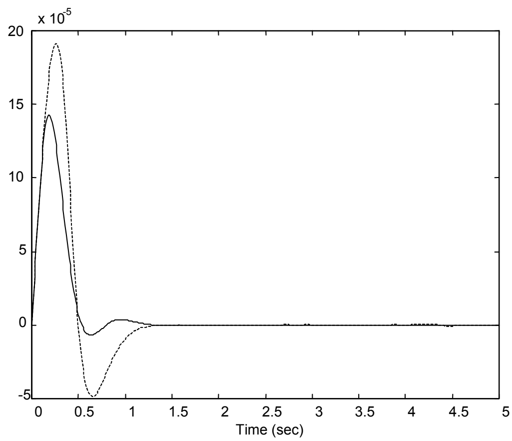

Fig. 7: Change in Frequency ($\Delta\omega$) in p.u.
Proposed Method (__), Method of [Lee, 1998] (- -)

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To test the robustness of the proposed design method against parameter variation, a simulation is performed with 20% increase in the value of automatic voltage regulator gain (K_A). A comparison of the change in frequency ($\Delta\omega$) for $K_A = 50.0$ and $K_A = 60.0$ is shown in Fig. 8 which demonstrates the robustness of the design method.

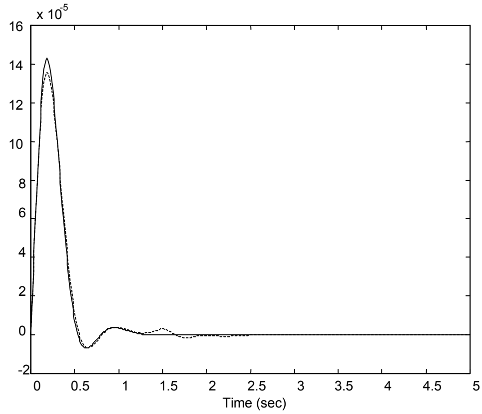

Fig. 8: Change in Frequency ($\Delta\omega$) in p.u.: $K_A = 50.0$ (__), $K_A = 60.0$ (- -)

6. CONCLUSIONS

The use of genetic algorithms in the design of variable structure controllers has been investigated in this paper. This is accomplished by formulating the VSC design as an optimization problem and GA are used in the optimization process. The proposed method provides an optimal and systematic procedure for the design of VSC and eliminates the need for trial and error approaches used in the literature. Moreover, the two step VSC design procedure of finding the switching vectors and the feedback gains has been reduced to one step where the switching vectors and the feedback gains are selected simultaneously such that a certain performance index is minimized. The application of the proposed method to the design of a power system stabilizer of a single machine power system model reveals that superior results can be obtained compared to previous methods.

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