論 文
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# 다수 연결된 전력계통에 대한 최적 다가변 구조 제어기

# Optimal Multidimensional Variable Structure Controller for Multi-Interconnected Power Systems

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**Abstract-** A controller of interconnected power systems is investigated using an optimal multidimensional variable structure control. The switching hyperplane of the variable structure stabilizer is obtained by minimizing a quadratic performance index in continuous-time. A special feature of the optimal multidimensional variable structure stabilizer is that, when it is operated in the so-called sliding mode, the system response becomes insensitive to changes in the plant parameters. A digital simulation is performed by a digital computer using the Advanced Continuous Simulation Language(ACSL) package, which shows that the dynamic performance of the power system in response to mechanical torque changes is improved when optimal multidimensional variable structure stabilizers are employed.

## 1. Introduction

From the early 70's, optimal control theory has been applied to improve the dynamic response of power system through excitation control using constant state feedback strategies[1] as well as to determine stabilizing singals for turbo-alternator models including exciter and governor. Although these approaches have been used for a single machine infinite bus system, criticisms were presented based on the following facts: (i) the resulting scheme requries feedback of all the state variables chosen to describe the dynamics of the system, (ii) the physical measurements of some states are not easily available. In answer to these criticisms, several works applying optimal control theory in power ststem stability have been developed by feeding back only physically available and measureable variables. But, in general, the output feedback strategies depend on initial conditions of plant states[2], several different approaches have been presented to overcome this dependance.

One of these different approaches is the use of a performance index which is optimal in an average sense for all impulse disturbances in the system[3]. In the development of this approach, several authors have used the expectation states, from which constant and

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dynamic output feedback gain controllers have been derived. However, the use of output feedback controllers involves complex iterative algorithms with convergence problems, and, its application for multi-machine power system is complicated.

In[4], a suboptimal output feedback has been suggested, neglecting the unmeasurable outputs. Some authors have defined system models in such a way that the matrix relating vectors of outputs and states in invertible and the state variables can be written in terms of output variables[5]. This approach shows that, by an adequate choice of feedback variables and weighting matrices for the cost function, considerable improvement of machine response can be obtained. The optimal state feedback controller has shown to be more effective than the conventional stabilizing signal because, for study of small oscillations, the constant gains and dominant eigenvalues do not change very much over a wide range of operating conditions. The complexity of the optimal controller scheme is further increased if it is applied to a multi-interconnected power system. Dynamic couplings of multi-interconected power systems must be always included in the stabilization studies. The control signal for each machine is a combination of all state variables of the system. Then crossfeedback signals among the generators are required. To date, few such studies have been completed.

An extension of the single machine optimal state feedback controller has been developed, but, no consideration has been devoted to difficulties of an actual implementation[6]. Two strategies of optimal controller have been used in multi-machine power systems with application to power system transients and load frequency control[7] : (i) optimal state feedback controller based on estimates of all states of the system ; (ii) optimal state feedback controller based on feedback of a combination of known state variable and estimated states. Also, damping signals obtained by decentralized feedback of available quantities at machine location have been used to improve to dynamic behavior of multi-machine power systems[8]

Coordinated application and computation of stabilizers in multi-machine power systems have drawn much attention recently. For example, Delmello et al.[9] is mainly concerned with the selection of the generating units to be equipped with stabilizers. In that paper an eigenvalue analysis technique sequentially indentifies effective stabilizer site locations. The paper does not consider the tuning of the stabilizer parameters. Eigenvalue methods were also used in[10] for choosing the generators at which stabilizers can be effectively applied and for computing the transfer function of these controllers. The technique is based on the pole shifting properties of infinitely small gain feedback compensators in linear systems. It uses the residues of an open loop transfer function to compute the gain and phase of a stabilizer that will approximately yield a specified increase in damping for some mechanical mode of oscillation. By repeatedly performing a single-input single-output analysis, several stabilizers can be computed. In[11] a sequential algorithm for tunning parameters of stabilizers in multi-machine power system is proposed. At each stage of the design, a pole assignment algorithm for single-input single-output systems yields the parameters of a stabilizer with fixed poles and structure which assigns a given mode of oscillation. Unfortunately, the sequential addition of stabilizers disturbs previously relocated eigenvalues. This undesirable effect could be avoided in the algorithm suggested only by using at each stage a stabilizer of increasingly higher order, which is neither practical nor theoretically desirable. An algorithm for simultaneously tunning the stabilizers of a multi-machine power system is illustrated in [12]. The iterative solution of algebraic nonlinear equations provides the "optimal" settings of these regulators which structure is fixed. Here the notions of synchronizing and damping torques are used rather than more system oriented procedures even if the determination of the stabilizer settings were treated as an eigenvalue problem. The analytical power of linear algebra is lost so that it becomes a nontrivial task to extend the ideas to large systems or to more detailed machine models. In all the papers that have been presented there were claims made that a patricular technique was superior for designing and tuning controllers for damping a multi-machine system.

On the other hand, one of the areas of control theory which has been developed rapidly over the last two decades in that of Variable Structure Systems(commonly abbreviated as VSS). The theory, which has been the subject of extensive research by Emelyanov in the USSR, provides a new approach to the control problem of linear time-varing plants through the enforcement of an invariant motion known as a sliding regime. The formation of such a regime is achieved by constraining the state point of the system to move on a predetermined hyperplane(or switching plane) in space thus giving a response which is insensitive to plant parameter variations and external disturbances[13, 14]

Research in Variable Structure Systems has so far been largely theoretical and has dealt specifically with the mathématical conditions leading to a stable sliding regime. As with any new theory, a credibility gap exists between the theory and application. This gap may only be bridged with a detailed investigation of test cases. The variable structure controller is slightly more complex than a fixed structure design based on standard methods such as state feedback of frequency response technique, but is a great deal less complex than some adaptive designs. Further, the decision type structure of the Variable Structure Controller make it attractive for implementaion as a micro computer program.

A practical for variable structure controller using variable structure theory has barely been reported in the literature[15, 16] Most approaches have concerned a single power plant, without considering optimal control theory in multi-interconnected power plants.

The object of this study is to demonstrate the effectiveness of the developed optimal multidimensional variable structure control in enhancing the dynamic performance of the presently used optimal intergral power system stabilizers.

## 2. Synthesis of Optimal Multidimensio-nal Variable Structure

Utkin[17] considers the problem of designing a multidimensional system with variable structure described by the equation (1). The control function is piecewise linear of the form (2) with switching of the coefficients $\Psi_{ij}$ occuring on the planes $\sigma_i(x)=0$. The $\sigma_i(x)$ are the components of the vector

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

$$u=-\sum_{i=1}^{k}\Psi_i x_i \quad 1\leq k\leq n-1$$
$$\Psi_i=\begin{cases}\alpha_i & \text{if } x_i\sigma>0\\ \beta_i & \text{if } x_i\sigma<0\end{cases} \tag{2}$$

where

$$\sigma=\sum_{i=1}^{n-1}c_i x_i+x_n$$
$$\sigma_i(x)=C_i^T x, \qquad i=1, 2, \cdots, n \tag{3}$$

where $C_i^T$ is called the its switching vector.

In designing such systems, one usually chooses the controls of that they give rise to the sliding mode on the intersection of the discontinuity surfaces $\sigma=0$. In this chapter we consider the problem of choosing a matrix $C_1{}^T$ and switching vector $\Psi_{ij}$ such that this sliding motion has desirable properties. The sliding equations in state-space systems and design procedures are proposed in the next section.

### 2.1 Sliding in State-Space Systems

To achieve the invariance conditions of a sliding motion, it was shown that it is necessary to obtain instantaneous values of the coordinate as well as its derivatives to the nth order which restricts the application of the technique to plants in phase-variable form. Drazenovic[18] has shown that VSS can be extended to encompass systems with more general structures, and using a state-space representation of linear systems has proved that a sliding motion can be realized using state-variables.

### 2.2 Sliding Equations

The following multi input system described by a set of first order differential equation is considered in equation (1). The switching hyperplane is defined by a linear combination of the states in equation (3). In an ideal sliding mode, the phase point does not leave the hyperplane, hence the phase velocity is given by,

$$\dot{\sigma}=C^T\dot{x}=0 \tag{4}$$

Substituting $x$ in equation (1) gives,

$$C^TAx+C^TBu_s=0 \tag{5}$$

where $u_s$ is the average value of the control input in the sliding mode, and is determinable uniquely from equation (5),

$$u_s=-(C^TB)^{-1}C^TAx \tag{6}$$

and substituting this value of $u_s$ in (1) gives the sliding mode equations,

$$\left.\begin{aligned}&\dot{x}_i=x_{i+1} \qquad i=1,\cdots,n-2\\ &\dot{x}_{n-1}=-\sum_{i=1}^{n-1}c_ix_i\end{aligned}\right] \tag{7}$$

$$\left.\begin{aligned}&\dot{x}=[I-B(C^TB)^{-1}C^T][Ax]\\ &C^Tx=0\end{aligned}\right] \tag{8}$$

Comparing equation (7) with equation (8), it can be seen that the latter is not completely independent of the plant's parameters. The stabilizing signals are

$$u=[u_1,\ u_2,\ \cdots,\ u_m]^T \tag{9}$$

where

$$u_i=-\Psi_i{}^Tx=-\sum_{j=1}\Psi_{ij}x_j,\qquad i=1,2,\cdots,m \tag{10}$$

and

$$\Psi_{ij}=\begin{bmatrix}\alpha_{ij} \text{ if } x_j\sigma_i>0, & i=1,2,\cdots,m\\ \beta_{ij} \text{ if } x_j\sigma_i<0, & j=1,2,\cdots,n\end{bmatrix} \tag{11}$$

When $b$ is an $n\times1$ input coupling vector, it can be shown that a sliding regime exists on the hyperplane $\sigma=0$ if,

$$\begin{aligned}&\alpha_i>\frac{1}{C^Tb}[C^Ta_i-c_i(C^Ta_n)]\\ &\beta_i<\frac{1}{C^Tb}[C^Ta_i-c_i(C^Tan)]\end{aligned}\qquad i=1,\cdots,k \tag{12}$$

and

$$C^Ta_i=c_i(C^Ta_n) \quad i=k+1,\cdots,n-1$$

where $a_i$ are the column vectors of the plant matrix $A$. The equality constraint of (12) vanishes when $k=n-1$. Assuming that $k=n-1$ and that $A$ is a time verying matrix with step-wise changes in its elements, then if conditions expressed in (12) are fulfilled for all values of $a_{ij}$, a sliding regime will exist on the defined hyperplane. As indicated in equation (8), the sliding equations will differ for different $A$ matrices; the transient behaviour of the sliding motion changes accordingly. Figure (1) illustrates the trajectories in a third order system. The conditions for complete invariance to parametric and external disturbances are discussed in the next section.

The control law described by equations (10) and (11) can be expressed differently. Since,

$$\dot{\sigma}=C^TAx+C^Tbu \tag{13}$$

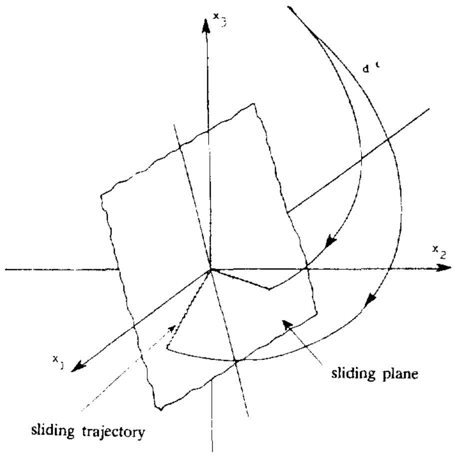


**Fig. 1** Sliding Trajectories for Different Plant Matrices

hence

$$\sigma^T\dot{\sigma}=\sigma^T[C^TAx+C^Tbu]\leq 0 \tag{14}$$

$$u>-(C^Tb)^{-1}C^TAx \text{ if } \sigma^T\to -0 \tag{15}$$

and

$$u<-(C^Tb)^{-1}C^TAx \text{ if } \sigma^T\to +0$$

provided that $C^Tb>0$. The inequalities of (15) can be simplified further if $C^T$ is chosen as the eigenvector row of $A$ corresponding to eigenvalue $\lambda$, i.e.

$$C^TAx=\lambda \qquad C^Tx=\lambda\sigma \tag{16}$$

The control law of (15) can thus be written as

$$u=-K|x_k| \text{ sign } \sigma \tag{17}$$

where '$K$' is an arbitrary positive number, $x_k$ is an arbitrary state variable and $\lambda$ is assumed negative. The $C^T$ vector must be such that the sliding equations described by (8) are stable.

An alternative way of selecting the $C^T$ vector is through the pole assignment procedure and starts with the determination of a continuous control $u=-\sum_{i=1}^{k}\theta_i x_i$ which places $(n-1)$ eigenvalues as close as possible to some desired locations, where $\theta_i$ is the average gain defined by,

$$\theta_i=\frac{1}{C^Tb}[C^Ta_j-c_j(C^Ta_n)] \tag{18}$$

solutions for $C^T$ can be estimated using equation (18) and the stability of the sliding motion can then be checked. Design values for $C^T$ and $\theta_i$ which result in satisfactory responses are unlikely to be derived in the first instance and several computations may be required.

### 2.3 Invariance Conditions

Even though sliding occurs in the system of (1), invariance to external and parametric disturbances is not necessarily guaranteed. External disturbances are included in the analysis by modifying the state-space equations of (1) to

$$\dot{x}=Ax+bu+df \tag{19}$$

where $d$ is $a$ nxl vector coupling the disturbance $f$ to the system. The sliding mode equation of

$$\dot{x}=[I-b(C^Tb)^{-1}C^T][Ax+df]$$

$$\sigma=C^Tx=0 \tag{20}$$

The disturbance $f$ disappears from the sliding equations if,

$$[I-b(C^Tb)^{-1}C^T]df=0 \tag{21}$$

It is shown in Appendix 2 that equation (21) can be satisfied for all possible value of $f$ if

$$\text{rank}[bd]=\text{rank}[b] \tag{22}$$

i.e. the vector $d$ is a linear combination of vector $b$. In practical terms, condition (22) demands that the points where the disturbances and controls enter into the system are the same.

The conditions for parametric invariance can be derived in a similar manner if the plant matrix $A$ is represented by,

$$A=A_v+A_c \tag{23}$$

where $A_v$ contains the variable elements and $A_c$ the constant ones. The sliding mode

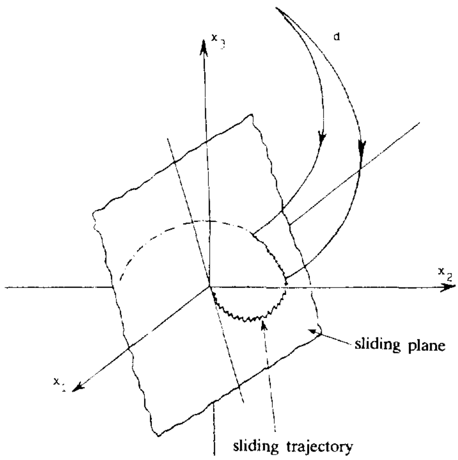


**Fig. 2** Invariance Conditions in Sliding System

equations become,

$$\dot{x}=[I-b(C^Tb)^{-1}C^T][A_cx+A_vx] \tag{24}$$

$$C^Tx=0$$

Again the parameters included in the matrix $A_v$ will disappear from the sliding mode equations if the following is fulfilled,

$$[I-b(C^Tb)^{-1}C^T]A_vx=0 \tag{25}$$

Equation (25) will be fulfilled if,

$$\text{rank}[bA_v]=\text{rank}[b] \tag{26}$$

Figure (4) illustrates the invariance conditions in a third order system ; the matrix $A_v$ only affects the initial conditions of the sliding mode but has no influence on the sliding trajectory.

Conditions (22) and (26) are automatically met in systems (27) since all the rows of the matrix $A_v$ and vectors $b$ and $d$ are zero except for the last one.

$$\dot{x}_i=x_{i+1} \qquad i=1, 2, \cdots, (n-1)$$

$$\dot{x}_n=-\sum_{i=1}^{n}a_ix_i-b_1\Psi_1x_1 \tag{27}$$

### 2.4 Derivation of Optimal multidimensional Variable Structure Controller

The design procedures for selecting the constant switching vectors $c_i$ and variable structure stabilizing signal $\Psi_{ij}$ follow in the next sections.

#### 2.4.1 Construction of the Equation in the Sliding Mode Using a "Cheap" Control Theory

Define the coordinate transformation

$$z=Mx \tag{28}$$

such that

$$MB=\begin{bmatrix}0\\B_2\end{bmatrix} \tag{29}$$

The matrix $M$ of the first n-m rows is a basis of a subspace orthogonal to the subspace spanned by the vectors of $\dot{B}$, a nonsingular $n\times n$ matrix, and $B_2$ is a nonsingular $m\times m$ matrix. Differentiating both sides of the equation (28) with respect to time and then substituting for the state equation (1), we can get

$$\dot{z}=MAM^{-1}z+MBu \tag{30}$$

Rearranging (30) using (29), the behavior of system (1) in $z$ space is described by the equations

$$\left.\begin{aligned}&\dot{z}_1=A_{11}z_1+A_{12}z_2\\ &\text{and}\\ &\dot{z}_2=A_{21}z_1+A_{22}z_2+B_2u\end{aligned}\right] \tag{31}$$

where $A_{11}$, $A_{12}$, $A_{21}$ and $A_{22}$ are $(n-m)\times(n-m)$, $(n-m)\times m$, $m\times(n-m)$ and $m\times m$ submatrices making up the matrix $MAM^{-1}$, respectively. By[14] it is necessary in order to obtain equations for the sliding mode to solve the systms of equations $\sigma(z)=0$ and $\sigma(z)=0$ for $u$ and $z_2$, substitute the solutions into the original system, and the discard the last $m$ equations. The solution for $u$ constitutes the equivalent control problem. For system (1), (3), (30) and (31) this procedure leads to the equations

$$\dot{z}_1=A_{11}z_1+A_{12}z_2 \tag{32}$$

$$\sigma(z)=C_1z_1+C_2z_2=0 \tag{33}$$

where $C_1$ and $C_2$ are $m\times(n-m)$ and $m\times m$

submatrices of $C^TM^{-1}$, respectively, satisfying the following condition

$$[C_1C_2]=C^TM^{-1} \tag{34}$$

The two equations (32) and (33) uniquely determines the dynamic motion of the system in the sliding mode over the intersection of the switching hyperplanes $\sigma(z)=0$. The subsystem (32) may be regarded as an open loop control system with state vector $z_1$ and control vector $z_2$, the form of the control being determined by the equation (25), that is,

$$z_2=-C_2^{-1}C_1z_1 \tag{35}$$

Therefore, the problem of designing an optimal multidimensional variable structure controller with certain desirable properties in the sliding mode can be regarded as a state feedback design problem.

#### 2.4.2 Calculation of the Switching Vector $C_i$ and Stablizing Signal $\Psi_{ij}$ in $z$-Optimal Sliding Modes

Consider the problem of minimizing the quadratic performance index

$$J=\frac{1}{2}\int_{t\epsilon}^{\infty}z^TQz\,dt \tag{36}$$

in the sliding mode, where $Q$ is a real, symmetric, and positive semidefinite matrix, $t_\epsilon$ is the time at which the sliding mode begins. Thus $t_\epsilon$ generally depends on the initial state and the switching hyperplane of the variable structure system. This problem can be interpreted as a linear optimal state regulator problem for the system (32) which consists in minimizing the functional

$$J=\frac{1}{2}\int_{t\epsilon}^{\infty}(z_1{}^TQ_{11}z_1+2z_1{}^TQ_{12}z_2+z_2{}^TQ_{22}z_2)\,dt \tag{37}$$

with respect to $z_2$, where $Q_{11}$, $Q_{12}$ and $Q_{22}$ are $(n-m)\times(n-m)$, $(n-m)\times m$ and $m\times m$ submatrices of $(M^{-1})^TQM^{-1}$, respectively.

### 2.5 The Proposed Design Procedure

A design procedure of the variable structure system can be formulated as follows:

(1) Find the coordinate transformation matrix $M$ in (28).

(2) Solve the algebraic matrix Riccati equation for $P$.

(3) Calculate the switching vector $C_i$.

(4) Choose the equation for the switching hyperplanes in the form

$\sigma=[C_1I]Mx=Cx=0$

(5) Compute the variable structure stablizing signal $\Psi$ in equation (12).

## 3. State-Space Model of Power System

An important part of investigation system stability and designing controllers is to simulate the complete system with the state-space formulation. State-space methods for assessing stability are applicable to linearized representations of the physical plant. If the operation of the system under lage signal operating is concerned, the linearized equations could be simulate on a digital computer and plots of time domain transients obtained for pre-selected parameters and disturbances to the system. Advanced continuous simulation language(ACSL) programs are used extensively for this purpose in the simulation of the electric multi-machine power system.

### 3.1 State-Space Model Including the Voltage Regulator and Exciter

When the electromechanical oscillations are of interest, as in this study, the turbine dynamic can be ignored since the corresponding time constants can be assumed to be large compared with the period of these oscillations. Therefore, the turbine and the governor are not modelled here and each generator is assumed to be driven by a constant mechanical power. The excitation system dynamics are included and the multi-machine plant model is extended to include

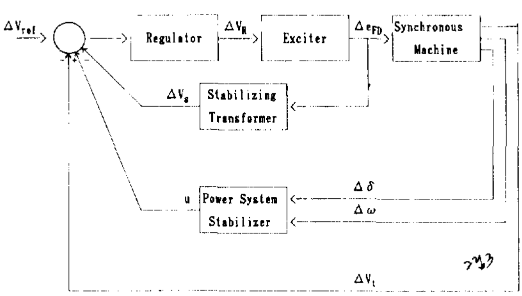


**Fig. 3** Functional block diagram of a synchronous machine with an exciter and stabilizer.

them.

The detailed block diagram of the complete model of a synchronous machine with an exciter and stabilizer is shown in Fig. 3.

Assuming that each machine is equipped with such an excitation system the following vectors can be defined :

State vector $(4m\times1)$ $\quad x=[\Delta\delta\Delta\omega\Delta Eq'\Delta E_{FD}]^T$ (38)

Input vector $(m\times1)$ $\quad u=[\Delta V_{ref}]$

The state equations are :

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

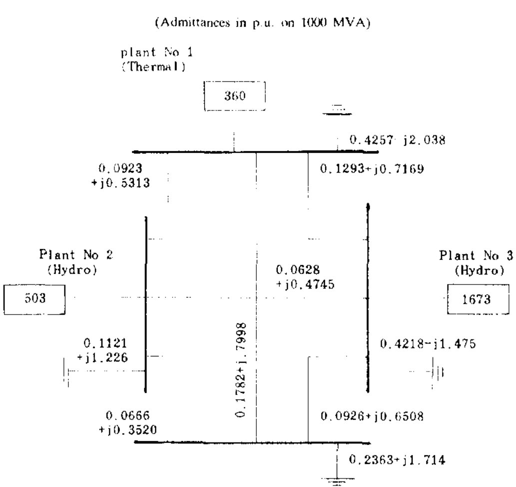


**Fig. 4** Three Machine/Infinite Bus Power System

### 3.2 Example system studies

The layout of the system studies is shown the three plant/infinite bus power system(plant No. 4 effectively represents an infintebus) in Figure 4.

Each plant is represented by a single equivalent machine with machines 1, 2 and 3 rated 360 $MVA$, 503 $MVA$ and 1673 $MVA$ respectively. These ratings are used as base values for the per unit data. Each machine was provided with a static exciter(IEEE Type 1). For the purposes of this study the linearized equations were reordered into the form (1). x is the state vector comprising $\Delta\delta_i$, $\Delta\omega_i$, $\Delta E_{qi}'$ and $\Delta E_{FDi}$ for each machine, and $u$ is the input vector comprising of $\Delta V_{ref}$ of each machine. The stabilizing signal $\alpha$ and $\beta$ are calculated by (12).

$$\begin{cases} \alpha_{11}=\alpha_{13}=\alpha_{14}=\alpha_{15}=\alpha_{16}=\alpha_{17}=\alpha_{18}=\alpha_{19} \\ =\alpha_{111}=\alpha_{112}=10,\ \alpha_{12}=60,\ \alpha_{16}=-10, \\ \alpha_{110}=-20 \\ \alpha_{21}=\alpha_{22}=\alpha_{23}=\alpha_{24}=\alpha_{25}=\alpha_{27}=\alpha_{28}=\alpha_{29} \\ =\alpha_{211},\ \alpha_{212}=1,\ \alpha_{22}=5,\ \alpha_{26}=\alpha_{210}=-5 \\ \alpha_{31}=\alpha_{32}=\alpha_{33}=\alpha_{34}=\alpha_{35}=\alpha_{36}=\alpha_{37}=\alpha_{38} \\ =\alpha_{39}=\alpha_{310}=\alpha_{311}=\alpha_{312}=800 \end{cases}$$

$$\begin{cases} \beta_{11}=\beta_{13}=\beta_{14}=\beta_{15}=\beta_{16}=\beta_{17}=\beta_{18}=\beta_{19} \\ =\beta_{111}=\beta_{112}=-10,\ \beta_{12}=-60,\ \beta_{16} \\ =-10,\ \beta_{110}=-20 \\ \beta_{21}=\beta_{23}=\beta_{24}=\beta_{25}=\beta_{27}=\beta_{28}=\beta_{29}=\beta_{211} \\ =\beta_{212}=-1,\ \beta_{22}=-5,\ \beta_{26}=\beta_{210}=5 \\ \beta_{31}=\beta_{32}=\beta_{33}=\beta_{34}=\beta_{35}=\beta_{36}=\beta_{37}=\beta_{38} \\ =\beta_{39}=\beta_{310}=\beta_{311}=\beta_{312}=-800 \end{cases}$$

### 3.3 Digital Continuous System Simulation

Simulation of physical systems is a standard analysis tool used in the evalution of hardware design prior to actual construction. The Advanced Continuous Simulation Language(ACSL) has been used for the purpose of modeling systems described by time dependent, transfer functions and nonliner differential equations. Typical application areas are control system design, missile and aircraft simulation or fluid flow and heat

**Table 1.** Response Data of 0.05 step change of $\Delta T_m$

| | Plant | Peak Value (p.u.) | Rising Time (sec.) | Settling Time (sec.) | Final Value(p.u.)at 10 sec. |
|---|---|---|---|---|---|
| Optimal | 1 | 0.15 | 0.23 | 4.4 | 0.088 |
| MVS | 2 | 0.08 | 0.43 | 5.8 | 0.037 |
| Controller | 3 | 0.029 | 0.62 | 5.8 | 0.0148 |
| | 1 | 0.15 | 0.23 | 8.2 | 0.087 |
| Optimal | 2 | 0.07 | 0.45 | 7.6 | 0.034 |
| Controller | 3 | 0.027 | 0.60 | 7.6 | 0.0139 |

transfer analysis.

**3.3.1 Simulation Results of Power System Stabilizer**

Representative dynamic performances of the power system stabilizer are digitally simulated by a Univac 1100 system using the ACSL package. Graphic subroutine program(GSP) plots follow accordingly. Table 1. shows the computer outputs of the simulated programs when the system is subjected to a 0.05 p.u. step change in the mechanical torque($\Delta T_m$) at the machine 1.

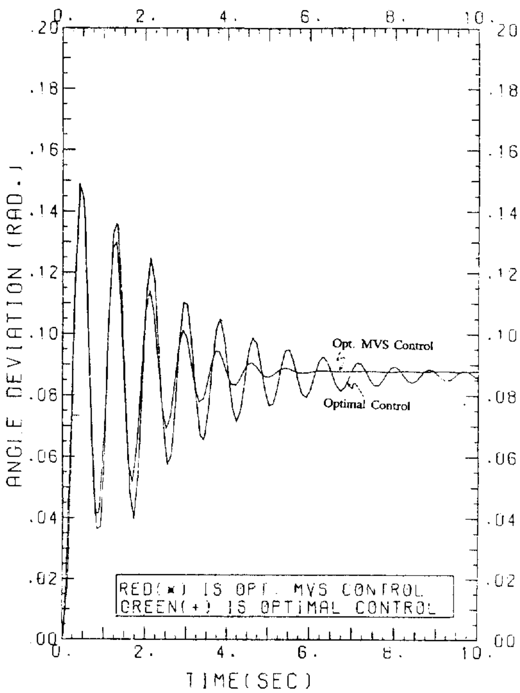


**Fig. 5** Angle deviation in machine 1.

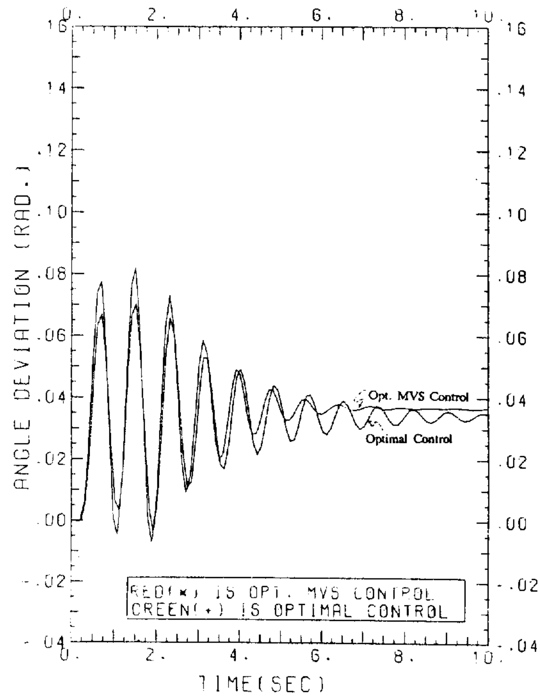


**Fig. 6** Angle deviation in machine 2.

The Y-axis scales are all per-unit(p.u.) values shown in Figure 8 through Figure 10, in some plots, Figure 5-7 and 11 are all radian(Rad.). The X-axis scales are all times(sec.) from zero sec. to the maximum 10 sec.

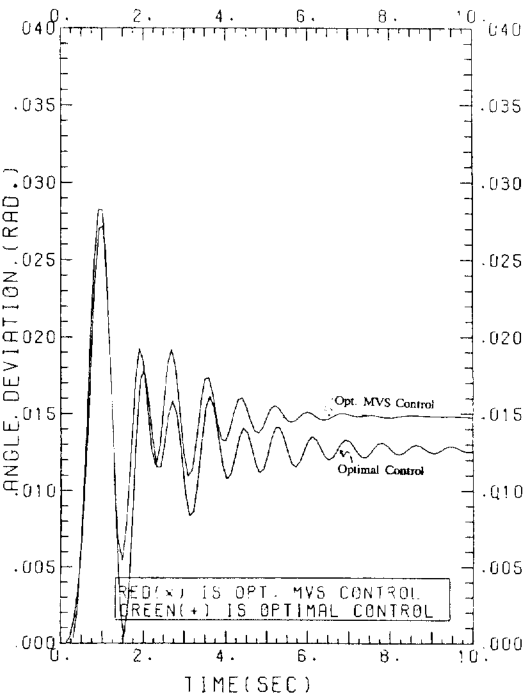


**Fig. 7** Angle deviation in machine 3.

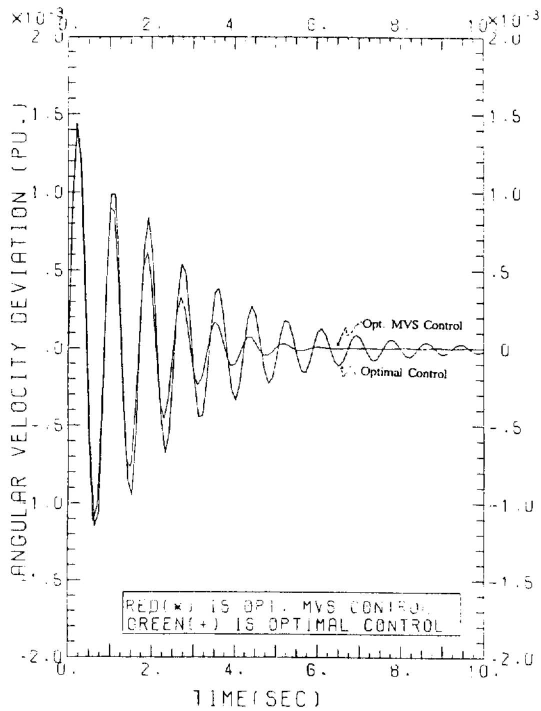


**Fig. 8** Angle deviation in machine 1.

### 3.3.2 Summary of Simulation Results

According to the simulated time histories shown in Figure 5 through 11, some observations and analyses are summarized as follows:

(1) The dynamic performance of the power system stabilizer is successfully improved via excitation control by using the optimal multidimensional-variable structure (MVS) method. This dynamic stability improvement can be seen clearly when we compare the optimal MVS stabilizer and the optimal stabilizer from Figure 5 to Figure 11.

(2) Figure 5, 6 and 7 respectively show the dynamic responses of the angle deviation ($\Delta\delta$) in machine 1, 2 and 3 when the system is subjected to 0.05 p.u. step change inmechanical torque($\Delta T_m$) at machine 1. Note that the Figure 5, 6 and 7the responses obtained from using the optimal power system stabilizer and

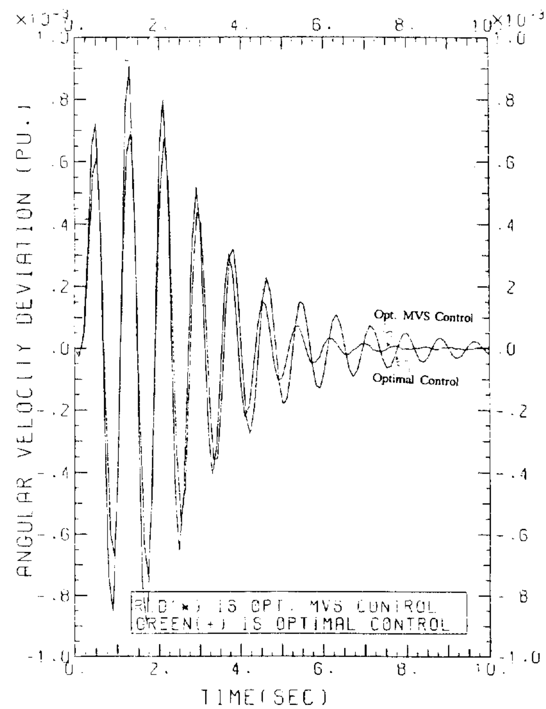


**Fig. 9** Angle deviation in machine 2.

the optimal multidimensional-variable structure stabilizer are all included for comparison purposes.

(3) Figure 8, 9 and 10 respectively show the dynamic responses of the angular velocity deviation ($\Delta\omega$) in machine 1, 2 and 3 when he system is subjected to 0. 05 p.u. step change in mechanical torque ($\Delta T_m$) at machine 1.

(4) The settling times of the optimal multidimensional-variable structure stabilizer appear to be a little longer than the same case with the optimal stabilizer, no matter what peak values and rising times have. One of the detailed comparison of the dynamic responses is given in Table 1.

(5) Finally, Figure 11 show in three comparison of machine 1, 2 and 3 all together between the optimal controllers and optimal multidimensional-variable structure controllers when a step change in mechanical torque $\Delta T_m$ of 0.05 p.u. is considered. The most effect has occured to machine 3. The reason is 0.05 p.u. step change in mechanical torque at machine 1.

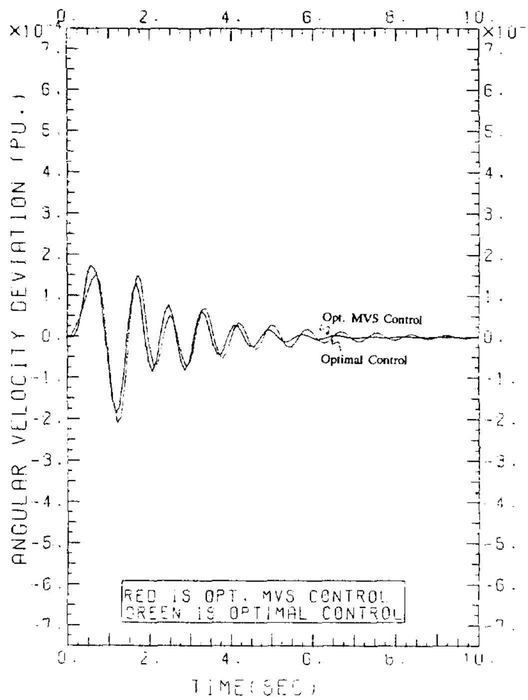


**Fig. 10** Angle deviation in machin 3.

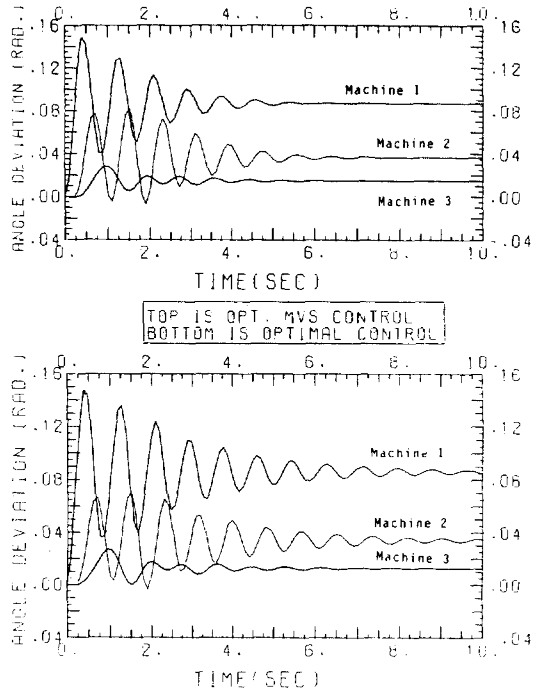


**Fig. 11** Angle deviation in machin 1, 2, 3.

All the above observations and analyses indicate that the use of excitation control via stabilizing signals does more quickly stabilize the power system and improve the system performance. It is possible to use further control schemes to enhance the control capability and further improve the power system stability.

## 4. Conclusion

This research has shown ways in which optimal multidimensional-variable structure(MVS) control technique may be used to design improved stabilizers for power systems. A procedure was presented to perform a feasible design of optimal MVS controllers in actual power systems. The simulation results shown in this investigation illustrate the ability of optimal MVS designs to provide good system damping in the presence of mechanical torque changes.

The main purpose of this research has been to study and clarify the control mechanism in MVS for the power system stabilizer through the simulation, and, to show how such systems can be designed and made to operate satisfactorilly. The MVS controller behaves in a similar way to an integral controller and has the ability of shifting in average level over a certain dynamic range defined by the control law to compensate for disturbances on the plant. In the case of an input disturbance, the compensation is much faster than an equivalent optimal linear control system. An essential part of the controller was shown to be the switching of the input reference.

Simulation studies show that the optimal MVS power system stabilizer yields better results that the optimal power system stabilizer in the sense of dynamic performance in response to a mechanical step change.

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