Variable Structure Control Design for Power System Stabilisers

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***Abstract*—In conventional integral control, increasing the gain K, though desirable value for reducing time error, can make the system response oscillatory . But in variable structure controller, it is found to have beneficial effect. In this paper, attempt have been made to design a variable structure power system stabilizer (VSPSS) by selecting favorably placed eigenvalues and the switching vector C, to achieve the desired dynamic performance. When the system is operates in the sliding mode, the response of the system is insensitive to plant parameter variations.[1] The controller selected has many attractive features like robustness towards parameter variations, modeling errors and unknown disturbances. It is simple in design and reduced order dynamics when in sliding mode.[2] Two distinct types of the system oscillations are considered in the paper i.e units at a generating station swinging with respect to the power system called as 'local plant mode oscillations' and the swinging of many machines in one part of the system against called as 'interarea mode oscillations'.**

***Index Terms*—VSS, Power system stabilizer, Pole placement technique, slide mode controller.**

I. INTRODUCTION

High initial responses, high gain excitation systems equipped with power system stabilizers (PSS) have been extensively used in modern power systems as an effective means of enhancing the overall system stability. A linear dynamic model of the system obtained by linearization of a nonlinear model around a normal operating point is usually adopted in PSS design.[3]

To ensure the quality of power system stabilizers, it is necessary to design a control system, which deals with the control of loading of the generator depending on the frequency. Many techniques for PSS have been proposed since 1980s. When controller is designed, one of the problems is the parametric uncertainty in the power systems.[4] Therefore, in the design of controllers the uncertainties have to be considered .The usual design approach for PSS frequency controller employs the linear control theory to develop control law on the basis of the linearised model with fixed system parameters. However, as the system parameter cannot be completely known , [5] so the controller designed based on fixed parameter model may not work properly for the actual plants. Hence, it is important to consider linearized model.

In this paper, a schematic approach based on pole placement technique is developed for specifying the elements of switching vector.[6] The VSS controller changes the structure in accordance with some law of structural change. This facilitates, the new system to possess new properties which was not present in any of the individual structures previously. It can further be integrated with slide mode control to enhance dynamic performance of system.[7]

Many techniques for PSS have been proposed since last two decades. Hsu and Chen [8] proposed optimal VSPSS for a machine infinite bus system as well as for a multi-machine system. The proposed VSPSS is optimal in the sense that the switching hyperplane is obtained by minimizing a quadratic performance index, the optimal selection of which is extremely difficult. The optimal $H - n/K$ approach given by Chen and Malik [9] has some complexity like choosing both the uncertainty weighting function and the performance weighting function carefully. Also the controls based on the linear theory are restricted in performance for controlling the non-linear plant like the power system [10].

The variable structure controllers are insensitive to system parameter variations therefore, their realization is simple. A systematic procedure for the selection of the switching vector is extremely important for the design of VSCs.[11]

In this paper, attempt have been made to design a VSPSS such that the resulting motion is described by equations with favorably placed eigenvalues. It should be noted that the desired locations of the poles of a closed loop system can be more conveniently prescribed to achieve the desired dynamic performance, and hence the switching vector C, as compared to the selection of weighting matrices needed to achieve the desired dynamic performance and hence C as in case of optimum VSPSS. The controller uses in this paper possesses attractive features like robustness to parameter variations, modeling errors and unknown disturbances, simplicity in design, reduced order dynamics when in sliding mode. The simulation results of the VSC theory shows dominance over conventional control theory, sensitivity analysis showing robustness over parameter variations and the model following approach is successfully applied as shown by changing parameters by 25% to 50% to show the efficacy of this control method.

II. SYSTEM UNDER CONSIDERATION

The system investigated, comprises a synchronous generator connected to an infinite bus through a double-circuit transmission line. A type 1 excitation system model

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[12], which neglects saturation of the exciter and voltage limits of the amplifier output, has been considered.

Two distinct types of the system oscillations are usually encountered in an interconnected power system [10]. One type is associated with units at a generating station swinging with respect to the power system. Such oscillations are referred to as 'local plant mode oscillations'.[13]The frequencies of these oscillations are typically in the range 0.8 – 2.0 Hz. The second type of oscillations is associated with the swinging of many machines in one part of the system against machines in other parts. These are referred to as 'interarea mode oscillations', and have frequencies in the range 0.1 – 0.7 Hz. The basic function of the PSS is to add damping to both types of oscillations.

It should be noted that only a local mode of the oscillation is encountered in a simple machine-infinite bus system and hence the effectiveness of the PSS in damping interarea modes of oscillations cannot be studied with a machine-infinite bus system.

The overall excitation control system (including PSS) is designed to:

1. Maximize the damping of the local plant mode oscillations as well as interarea mode without compromising the stability of other modes.
2. Enhance the system transient stability.
3. Not adversely affect system performance during major system upsets which cause large frequency excursions.
4. Minimize the consequences of excitation system malfunction due to component failures.

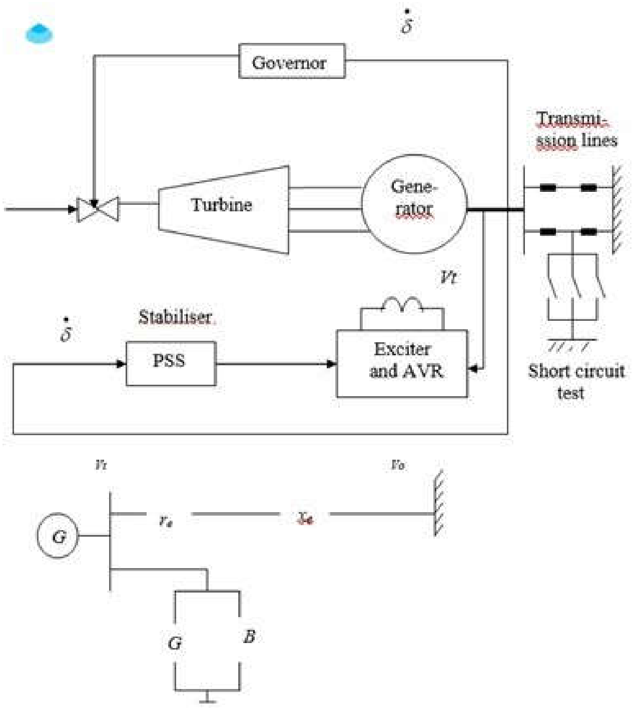

Fig. 1. Power system configuration for the single machine infinite bus system

A. Dynamic model for PSS

In general, the power system models are complex, nonlinear, dynamic in nature.[10] The usual practice is to linearise the model around the operating point and then develops the control laws. Since the system is exposed to small changes in loads during its normal operation, the linearised model will be sufficient to represent the power system dynamics. The simplified schematic diagram of a single-bus system is shown in Figure 1 [9].

The Linerised model is shown in Figure 2, where the expressions for parameters K1, K2 , ..., K6 are as shown below [10]

The steady-state values of the d-q axis voltage and current components for the machine infinite-bus system for the nominal operating conditions are given below. These are expressed as functions of the steady-state terminal voltage V_{to} and steady-state real and reactive load currents I_{PO} and I_{QO} respectively.

$$E_{q0} = [(V_{t0} + I_{Q0}x_q)^2 + (I_{p0}x_q)^2]^{1/2} \quad (1)$$

$$V_0 = [(V_{t0} - I_{P0}r_e - I_{Q0}x_e)^2 + (I_{P0}x_e - I_{Q0}r_e)^2]^{1/2} \quad (2)$$

$$sin\delta_0 = [V_{t0} - I_{p0}(x_q + x_e) - r_e x_q(I^2_{P0} + I^2_{Q0}) -$$

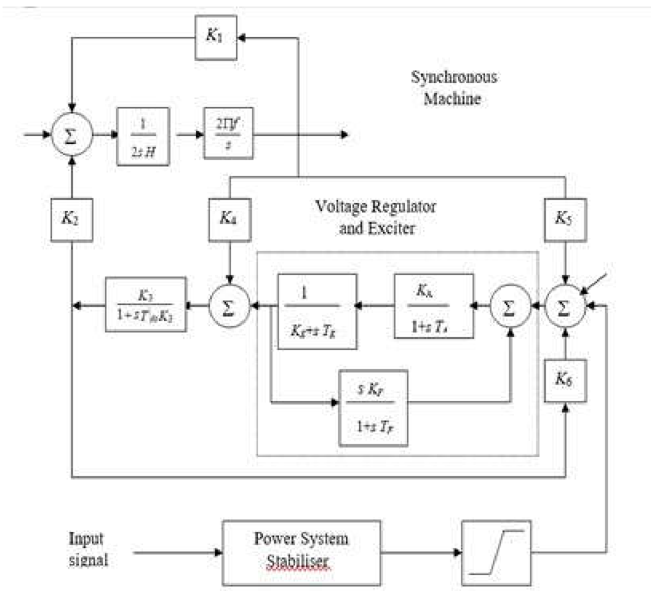

Fig. 2. Linearised small perturbation model of generator connected to infinite bus through transmission line

$V_{t0} I q0 r_e] E_{q0} V_0$ (3)

$I_{Q0} = I_{P0} V_{t0} / E_{q0}$ (4)

$I_{do} = [I_{po}^2 x_q + I_{Q0}(V_{to} + I_{Q0} x_q)] / E_{qo}$ (5)

$V_{q0} = [(V_{t0} + I_{Q0} x_q) / E_{q0}] V_{t0}$ (6)

$V_{do} = I_{Q0} x_q$ (7)

$E'_{q0} = V_{qo} + x'_d I_{do}$ (8)

Where,

I_d, I_q = direct and quadrature axis components of the armature currents

V_d, V_q=direct and quadrature axis components of the terminal voltage

E'_q=voltage proportional to direct axis flux linkages

δ=angle between quadrature axis and infinite bus

V_0=infinite bus volta

E_q=open-circuited terminal voltage

Subscript 0=steady state value

The constants K1 – K6 are evaluated using the relations given below considering zero external resistance i.e. r_e = 0 for the sample problem investigated [14].

$K_1 = \frac{x_q - x'_d}{x_e + x'_d} I_{Q0} V_0 sin\delta_0 + \frac{E_{q0} V_0 cos\delta_0}{x_e + x_q}$ (9)

$K_2 = \frac{V_0 sin\delta_0}{x_e + x'_d}$ (10)

$K_3 = \frac{x'_d + x_d}{x_d + x_e}$ (11)

$K_4 = \frac{x_d - x'_d}{x_e + x'_d} V_0 sin\delta_0$ (12)

$K_5 = \frac{x_q}{x_e + x_q} \frac{V_{d0}}{V_{to}} V_0 cos\delta_0 - \frac{x'_d}{x_e + x'_d} \frac{V_{q0}}{V_{t0}} V_0 cos\delta_0$ (13)

$K_6 = \frac{x_e}{x_e + x'_d} \frac{V_{qo}}{V_{to}}$ (14)

The state equations can be written [24],

$$\dot{\Delta w} = -\frac{K_1}{2H}\Delta\delta - \frac{K_2}{2H}\Delta E'_q + \frac{1}{2H}\Delta T_m \quad (15)$$

$$\dot{\Delta\delta} = 2\Pi f \Delta\omega \quad (16)$$

$$\dot{\Delta E'_q} = -\frac{K_4}{T'_{d0}}\Delta\delta - \frac{1}{K_3 T'_{d0}}\Delta E'_q + \frac{1}{T'_{d0}}\Delta E_{fd} \quad (17)$$

$$\dot{\Delta E_{fd}} = -\frac{K_E}{T_E}\Delta E_{fd} + \frac{1}{T_E}\Delta V_R \quad (18)$$

$$\dot{\Delta V_R} = -\frac{K_A K_5}{T_A}\Delta\delta - \frac{K_A K_6}{T_A}\Delta E'_q - \frac{1}{T_A}\Delta V_R - \frac{K_A}{T_A}\Delta V_E + \frac{K_A}{T_A}u + \frac{K_A}{T_A}\Delta V_{Ref} \quad (19)$$

$$\dot{\Delta V_E} = -\frac{K_F K_E}{T_F T_E}\Delta E_{fd} + \frac{K_F}{T_F T_E}\Delta V_R - \frac{1}{T_A}\Delta V_E \quad (20)$$

The dynamic model of the system is obtained from the transfer function model (Figure.6.2) in state space form as.

$\dot{x} = Ax + Bu + F\Delta d$ (21)

Where ,

x=State variable vector

u=Control input vector

Δd=Disturbances or nonlinearities input vector

A=State matrix (6 X 6)

B=Control matrix (6 X 1)

F=Disturbances or nonlinearities matrix (6 X 1)

Here in PSS the,

$$x = \begin{bmatrix} \Delta w \\ \Delta\delta \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta V_R \\ \Delta V_E \end{bmatrix} \quad (22)$$

$\Delta d = \Delta T_m$

$$A = \begin{bmatrix} 0 & -\frac{K_1}{2H} & -\frac{K_2}{2H} & 0 & 0 & 0 \\ 2\Pi f & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_4}{T'_{d0}} & -\frac{1}{T'_{d0}K_3} & \frac{1}{T'_{d0}} & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_E}{T_E} & \frac{1}{T_E} & 0 \\ 0 & -\frac{K_A K_5}{T_A} & -\frac{K_A K_6}{T_A} & 0 & -\frac{1}{T_A} & -\frac{K_A}{T_A} \\ 0 & 0 & 0 & -\frac{K_E K_F}{T_E T_F} & \frac{K_F}{T_E T_F} & -\frac{1}{T_F} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \\ 0 \end{bmatrix}; \quad F = \begin{bmatrix} \frac{1}{2H} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (23)$$

III. DESIGN OF VARIABLE STRUCTURE CONTROLLER:

The basic philosophy of the variable structure approach is simply obtained by contrasting it with the linear state regulator design for the single input system.

$\dot{x} = Ax + Bu$ (24)

In the state regulator design, the structure of the feedback is fixed as

$u = -K_x^T$ (25)

The state feedback gain vector K is chosen according to various design procedures, such as eigenvalue placement or

quadratic minimization.
The variable structure controller design problem is then select the parameters of each of the structures and to define the switching logic [4]. .
The change in structure of the controller takes place on the hyper plane

$$s = C_x^T = 0 \tag{26}$$

Where C is a constant vector. This hyper plane is also called as the switching hyper plane.
When the control signal u is a function of the state vector x undergoes discontinuities on the plane s = 0, the velocity vector also undergoes discontinuities on the same plane. If the trajectories are directed towards the plane s = 0, sliding mode will appear in the plane. The pair of inequalities,

$$\lim_{x\to 0} -\dot{s} > 0 \quad and \quad \lim_{x\to 0} -\dot{s} < 0 \tag{27}$$

are sufficient condition for the sliding mode to exist.
The control signal is a piecewise linear function of x with discontinuous coefficients $u = -\Psi^T x$

$$\Psi = \begin{cases} \alpha_i \text{..........................} fx_i s > 0 \\ \beta_i \text{..........................} fx_i s < 0 \end{cases}$$

where α_i and β_i are constants and i= 1,2,......,n.
It should be noted that the switching of the state feedback gains occur on discontinuity It should be noted that the switching of the state feedback gains occur on discontinuity plane s = 0. The choice of controls should ensure that they give rise to the sliding mode on discontinuity plane s = 0. The switching vector C is chosen so that sliding motion has the desired properties.
Since n = 6 and m = 1,

$\begin{bmatrix} C_1 & C_2 & C_3 & C_4 & C_5 & C_6 \end{bmatrix}^T$ is called the switching vector.

The control law is of the form

$$u = -\sum_{i=1}^{6} \Psi_i x_i$$

where the precise constant gains Ψ are given by above equation (28).
The design procedure consist of determining the elements of the switching vector C and the feedback gains Ψ so that the control u which depends on them can satisfy certain practically acceptable dynamic performance measures and retain the nominal frequency of the system in steady state. These dynamic measures relate to the rise time, overshoot, settling time of the system or performance index of the system

IV. Selection of a Switching Vector using Pole Assignment Technique

The design procedure is to select a switching vector using pole assignment technique as described below [4], [6]:
Consider the linear system,

$$\dot{x} = Ax + Bu \tag{30}$$

where x is a state vector of dimension (nx1), u is control vector of dimension (mx1) and A and B are constant matrices of dimensions (n x n) and (n x m) respectively.
Define the coordinate transformation

$$z = Mx \tag{31}$$

Such that

$$MB = \begin{bmatrix} 0 \\ B_2 \end{bmatrix} \tag{32}$$

Where M is a non-singular (n x n) matrix and B2 is a non-singular (m x m) matrix.

$$\dot{z} = MAM^{-1} z + MBu \tag{33}$$

From equation (24) and (31) and using equation (32), equation (33) can be written in the form,

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A12 \\ A_{21} & A22 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} 0 \\ B_2 \end{bmatrix} \tag{34}$$

where, $A_{11}, A_{21}, A_{12}, A_{22}$ are respectively [(n-m) x (n- m)], [(n-m) x m],[m x (n-m)], and [m x m] submatrices.
Hence,

$$\dot{z}_1 = A_{11}z_1 + A_{12}z_2$$
$$\dot{z}_2 = A_{21}z_1 + A_{22}z_2 + B_2u \tag{35}$$

The equation for the switching surface as (26) referring again i.e.,

$$s = C_i^T x = 0 \qquad i = 1, 2, 3 \,..... n$$

Hence, we get,

$$s = C_i^T M^{-1} z = 0 \qquad i = 1, 2, 3 \,..... n$$

specifies the motion of the system in the sliding mode.
Writing,

$$C^T M^{-1} = \begin{bmatrix} C_1^T & C_2 \end{bmatrix} \tag{36}$$

where C_1 and C_2 are n-1 column vector and scalar respectively.
Equations (35) and (36) uniquely determine the dynamics in the sliding mode over the intersection of the switching hyperplane s(x)=0. We can write,

$$s = C_1^T z_1 + C_2 z_2 = 0 \qquad (37)$$

The subsystem described by equation (35) may be regarded as an open loop control system with state vector z_1 and control vector z_2, without loss of generality, we assume that $C_2 = 1$ and the form of control z_2 being determined by equation (1.36), that is,

$$z_2 = C_1^T z_1 \qquad (38)$$

Using equation (35) and (38) we obtain the equations of the sliding mode in closed loop form as

$$\dot{z}_1 = (A_{11} - A_{12}C_1^T)z_1 = A_c z_1 \qquad (39)$$

The eigenvalue of the matrix A_c may be placed arbitrarily in the complex plane. If 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 $A_{11} - A_{12}C_1^T$ i.e. A_c in the sliding mode can be placed arbitrarily by a suitable choice of vector C_1.
Hence, the algorithm for realization of switching vector and switching hyperplane can be summarized as follows:

1) Select transformation matrix M that satisfy equation (32).

2) Compute the vector C1 such that the eigenvalues $\lambda_1, \lambda_2 \ldots\ldots \lambda_{n-1}$ of the matrix $(A_1 - A_1 C_1^T)$ or A_c characterizing the dynamics in the sliding mode has desired placement.

3) Choose the equation of the switching hyperplane to be of the form $s = [C1T\,1]Mx = 0$

4) Generally assume , $C1 = [C11 C12 \ldots\ldots C1n - 1]T$ (40)

V. Example

Consider the PSS system as shown in Figure 2 and the problem of a single control area. The nominal parameters of the system and the operating conditions used for the sample problem investigated are given below [14], [15].
All data are given in per unit of value, except that H and time constants are in seconds.
Generator:

$H = 5.0s \quad T'_{d0} = 6.0s$
$x_d = 1.6 \quad x'_d = 0.32 \quad x_q = 1.55$

IEEE type-1 excitation system:

$K_A = 50.0 \quad T_A = 0.05s$
$K_E = -0.05 \quad T_E = 0.5s$
$K_F = 1.55 \quad T_F = 0.5s$

Transmission line:

$x_e = 0.4 \quad r_e = 0.0$

Operation condition:

$P = 1.0 \quad Q = 0.05$
$V_{r0} = 1.0 \quad f = 50Hz$

The initial d-q axis current and voltage components and torque angle needed for evaluating the K constants are obtained from the steady-state equations given in (1) to (8). These are as follows:

$V_{d0} = 0.8211 p.u \quad I_{d0} = 0.8496 p.u \quad E_{q0} = 0.8427 p.u$
$V_{q0} = 0.5708 p.u \quad I_{q0} = 0.5297 p.u. \quad V_0 = 1.0585 p.u.$
$\delta_0 = 77.40^0 p.u.$

The constants K1 – K6 are evaluated using the relations given (9) to (14) considering zero external resistance i.e. re = 0.0 for the sample problem investigated. We get these values as:

$K_1 = 1.15839 \quad K_2 = 1.43471 \quad K_3 = 0.36$
$K_4 = 1.83643 \quad K_5 = -0.11133 \quad K_6 = 0.31711$

After designing the switching vector using pole assignment technique the results are :
The state space model is given by specifying

$$x = \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta V_R \\ \Delta V_E \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix}$$

$$\dot{x} = \begin{bmatrix} 0 & -0.1158 & -0.1435 & 0 & 0 & 0 \\ 314 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.3061 & -0.4630 & 0.1667 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 2.0 & 0 \\ 0 & 111.330 & -317.11 & 0 & -20.0 & -1000 \\ 0 & 0 & 0 & 0.01 & 0.2 & -2.0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1000 \\ 0 \end{bmatrix} u + \begin{bmatrix} 0.1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \Delta T_m$$

Let us assume ,

$$C_1 = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} \end{bmatrix}^T \qquad (41)$$

Now, here we have to find the C1T for the desired eigenvalues or pole placement.

The characteristic equation of the described system is $S^5 + (C_{15} - a_{55})S^4 + (C_{14} - a_{54})S^3 + (C_{13} + a_{53}S^2) + (C_{12} - a_{52})S + (C_{11} - a_{51}) = 0$ (42)

Equation (42) reduces to,

$$S^5 + (C_{15} + 2.363)S^4 + (C_{14} + 37.053)S^3 + (C_{13} + 72.068)S^2 + (C_{12} - 1.477)S + (C_{11} - 0.61) = 0 \quad (43)$$

Here, let the desired poles are at locations,

$\lambda_1 = -8.0 \quad \lambda_2 = -8.5 \quad \lambda_3 = -9.0 \quad \lambda_4 = -9.5 \quad \lambda_5 = -10.0$

From this we get the desired characteristic equation. As

$$S^5 + 45.0S^4 + 808.75S^3 + 7256.25S^2 + 32501.5S + 58140 = 0 \quad (44)$$

By comparing (43) and (44), we will get,

$C_{15} = 42.637$
$C_{14} = 771.697$
$C_{13} = 7184.182$
$C_{12} = 32502.977$
$C_{11} = 58140.61$

Further making the manipulation $T^{-1}C^T_1$, we get,

$$C_1 = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} \end{bmatrix}^T$$

$$C_1 = [-82146.276 \quad 188.818 \quad 2647.961 \quad -32.674 \quad 539.925]$$

Hence, the switching vector $C = M \begin{bmatrix} C_1^T & C_2 \end{bmatrix}^T$ and C2 = 1

$$\therefore C = [-82146.276 \quad 188.818 \quad 2647.961 \quad -32.674 \quad 1.0 \quad 539.925] \quad (45)$$

Also, the control signal u is given by the equation (30) and can be written as

$$u = -\Psi_1 x_1 - \Psi_2 x_2 - \Psi_3 x_3 - \Psi_4 x_4 - Psi_5 x_5 - \Psi_6 x_6 \quad (46)$$

The gains Ψ are chosen in such a way that control effort required is moderate and making use of the performance index [5]. Their values are taken as

$\alpha_1 = \alpha_2 = 15 \quad \alpha_3 = 0 \quad \alpha_4 = 0 \quad \alpha_5 = 0 \quad \alpha_6 = 0$
$\beta_1 = \beta_2 = -15 \quad \beta_3 = 0 \quad \beta_4 = 0 \quad \beta_5 = 0 \quad \beta_6 = 0$

VI. Variable Structure Model Following Controller Design For PSS System

The state space model of plant is considered as,

$$\dot{x} = Ax + Bu + F\Delta T_m \quad (47)$$

and

$$x = \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E'_q \\ \Delta E_{fd} \\ \Delta V_R \\ \Delta V_E \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix}$$

For the above values of A, B and F, and when $x_e = 0.4$,we get the characteristic equation as,

$$S^6 + 22S^5 + 284S^4 + 1011S^3 + 8923S^2 + 6095S + 11021$$

Let the model selected is critically damped model such that ,

If this model has the eigenvalues as –1, -2, -3, -4, -5 and –6 and we are representing state model in (6.61) in phase canonical form, then we have,

$$A_m = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -729 & -1764 & -1204 & -665 & -175 & -21 \end{bmatrix} \quad (49)$$

$$B_m = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 720 \end{bmatrix} \quad (50)$$

The switching surface $\sigma = Ce$ is chosen as,

$$\sigma = C_1e_1 + C_2e_2 + C_3e_3 + C_4e_4 + C_5e_5 + C_6e_6$$
$$\dot{\sigma} = C_1\dot{e}_1 + C_2\dot{e}_2 + C_3\dot{e}_3 + C_4\dot{e}_4 + C_5\dot{e}_5 + C_6\dot{e}_6$$

where,

$$\dot{e}_1 = e_2$$
$$\dot{e}_2 = e_3 + 0.0001\Delta T_m$$
$$\dot{e}_3 = e_4 + 0.0023\Delta T_m$$
$$\dot{e}_4 = e_5 - 0.0066\Delta T_m$$
$$\dot{e}_5 = e_6 - 0.0941\Delta T_m$$
$$\dot{e}_6 = -720x_{m1} - 1764x_{m2} - 1204x_{m3} - 665x_{m4} - 175x_{m5} - 21x_{m6} + 720r + 11021x_1 + 6095x_2 + 8923x_3 + 1011x_4 + 284x_5 + 22x_6 - u + 1.2674\Delta T_m \quad (51)$$

The switching vector was designed by using pole placement technique as explained before.
The poles of the matrix $[A_m^{11} - A_m^{12}C_{11}]$ were chosen as :- -8.0 , -8.5 , -9.0 , -9.5 and -10.0 . The transformation matrix considered was,

$$M = I_6 = 6X6 \quad Identity Matrix$$

Hence, we get,

$$C^T = 58140 \quad 32501.5 \quad 7256.25 \quad 808.75 \quad 45 \quad 1 \qquad (52)$$

The error is defined as,

$$e_i = x_{mi} - x_i \qquad i = 1, 2, 3, 4, 5, 6 \qquad (53)$$

And control function is

$$u = -K^T V - K_{14} \qquad (54)$$

where,

$$K^T = [\, K_1 \; K_2 \; K_3 \; K_4 \; K_5 \; K_6 \; K_7 \; K_8 \; K_9 \; K_{10} \; K_{11} \; K_{12} \; K_{13} \,]$$
$$V^T = [\, e_1 \; e_2 \; e_3 \; e_4 \; e_5 \; e_6 \; x_1 \; x_2 \; x_3 \; x_4 \; x_5 \; x_6 \; r \,] \qquad (55)$$

equation (51) , (52) , (53) , (54) and (55) we can write,

$$\dot{\sigma} = 58140e_2 + 32501.5(e_3 + 0.0001\Delta T_m) + 7256.25(e_4 + 0.0023\Delta T_m) + 808.75(e_5 - 0.0066\Delta T_m) + 45(e_6 - 0.0941\Delta T_m) + 1(-720x_{m1} - 1764x_{m2} - 1204x_{m3} - 665x_{m4} - 175x_{m5} - 21x_{m6} + 720r + 11021x_1 + 6095x_2 + 8923x_3 + 1011x_4 + 284x_5 + 22x_6) - (-K_1e_1 - K_2e_2 - K_3e_3 - K_4e_4 - K_5e_5 - K_6e_6 - K_7x_1 - K_8x_2 - K_9x_3 - K_{10}x_4 - K_{11}x_5 - K_{12}x_6 - K_{13}r - K_{14}) + 1.2674\Delta T_m$$

After reduction we can write,

$$\sigma\dot{\sigma} = (K_1 - 720)\sigma e_1 + (K_2 + 56376)\sigma e_2 + (K_3 + 31297.5)\sigma e_3 + (K_4 + 6591.25)\sigma e_4 + (K_5 + 633.75)\sigma e_5 + (K_6 + 24)\, e_6 + (K_7 - 10271)\sigma x_1 + (K_8 - 4331)\sigma x_2 + (K_9 - 7719)\sigma x_3 + (K_{10} - 346)\sigma x_4 + (K_{11} - 109)\sigma x_5 + (K_{12} - 1)\sigma x_6 + (K_13 + 720)\sigma r + (K_{14} + 11.6346\Delta T_m)\sigma \qquad (56)$$

We will find the controller by satisfying condition $\sigma\dot{\sigma} \le 0$. In addition, we can take term s instead of σ to understand that this is related to switching hyperplane. Letting each term in bracket of above equation equating separately less than zero we can obtain the controller gains.

We get the controller gains as,

$K_1 = 0 \quad if s e_1 > 0 \quad K_1 = 721 \quad if s e_1 < 0$
$K_2 = -56377 \quad if s e_2 > 0 \quad K_2 = 0 \quad if s e_2 < 0$
$K_3 = -31298 \quad if s e_3 > 0 \quad K_3 = 0 \quad if s e_3 < 0$
$K_4 = -6592 \quad if s e_4 > 0 \quad K_4 = 0 \quad if s e_4 < 0$
$K_5 = -634 \quad if s e_5 > 0 \quad K_5 = 0 \quad if s e_5 < 0$
$K_6 = -25 \quad if s e_6 > 0 \quad K_6 = 0 \quad if s e_6 < 0$
$K_7 = -10272 \quad if s x_1 > 0 \quad K_7 = 0 \quad if s x_1 < 0$
$K_8 = -4332 \quad if s x_2 > 0 \quad K_8 = 0 \quad if s x_2 < 0$
$K_9 = -7720 \quad if s x_3 > 0 \quad K_9 = 0 \quad if s x_3 < 0$
$K_{10} = -347 \quad if s x_4 > 0 \quad K_{10} = 0 \quad if s x_4 < 0$
$K_{11} = -110 \quad if s x_5 > 0 \quad K11 = 0 \quad if s x_5 < 0$
$K_{12} = -2 \quad if s x_6 > 0 \quad K12 = 0 \quad if s x_6 < 0$
$K_{13} = -721 \quad if s r > 0 \quad K13 = 0 \quad if s r < 0$
$K_{14} = -12 \quad if s > 0 \quad K14 = 0 \quad if s < 0$

The initial conditions for plant were chosen as,

$$x_1 = x_2 = x_3 = x_4 = x_5 = x_6 = 0.1 \qquad (57)$$

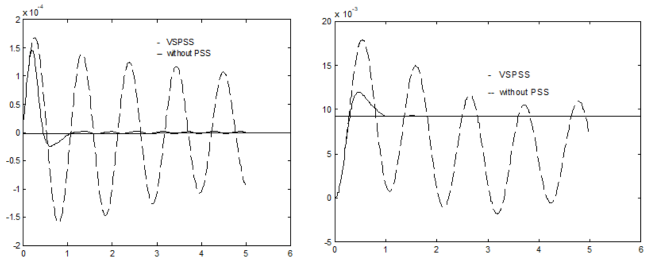

Fig. 3. The dynamic response of $\Delta\omega$ and $\Delta\delta$ for 1% step increase of ΔT_m with nominal parameters

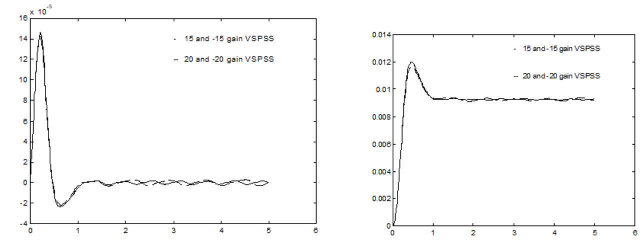

Fig. 4. The dynamic response of $\Delta\omega$ and $\Delta\delta$ for 1% step increase of ΔT_m with nominal parameters with different feedback gains.

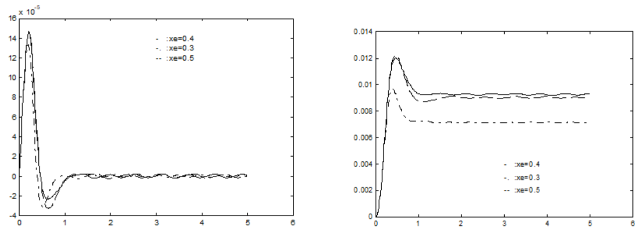

Fig. 5. The dynamic response of $\Delta\omega$ and $\Delta\delta$ for 1% step increase of ΔT_m with Variations in parameters i.e. line reactance change

The initial conditions for model were chosen as,

$$x_{m1} = x_{m2} = x_{m3} = x_{m4} = x_{m5} = x_{m6} = 0.8 \qquad (58)$$

VII. Simulation Results and Discussions

Figure 3 shows the simulation results of dynamic response of $\Delta\omega$ and $\Delta\delta$ when the system is subject to 1% step change of ΔT_m. Results using the integral controller alone (without VSS) are also included for comparison purposes and they clearly demonstrate the improvement in dynamic performance in the sense of maximum deviation in frequency, rise and settling time. It can be clearly seen that the responses obtained with VSPSS are well damped

There is one major drawback associated with VSC, namely chattering. The control signal emerging from the control law is seen to comprise high frequency components which leads to control chattering is highly undesirable because it involves extremely high control activities and it may excite high frequency un-modeled dynamics.[1] However this drawback

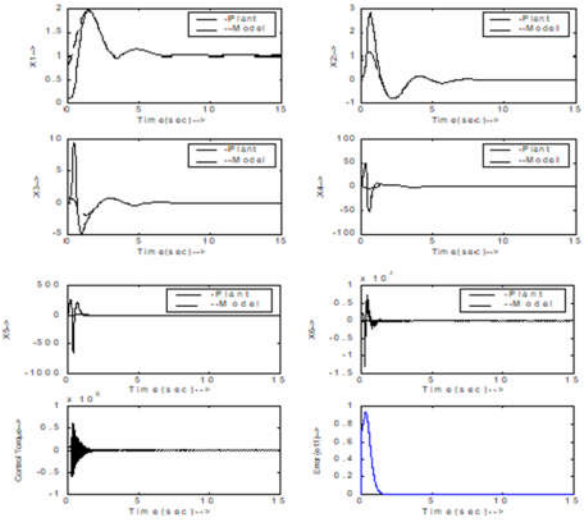

Fig. 6. The model following control for PSS with nominal parameters i.e. $x_e = 0.4$ (without insertion of low pass filter)

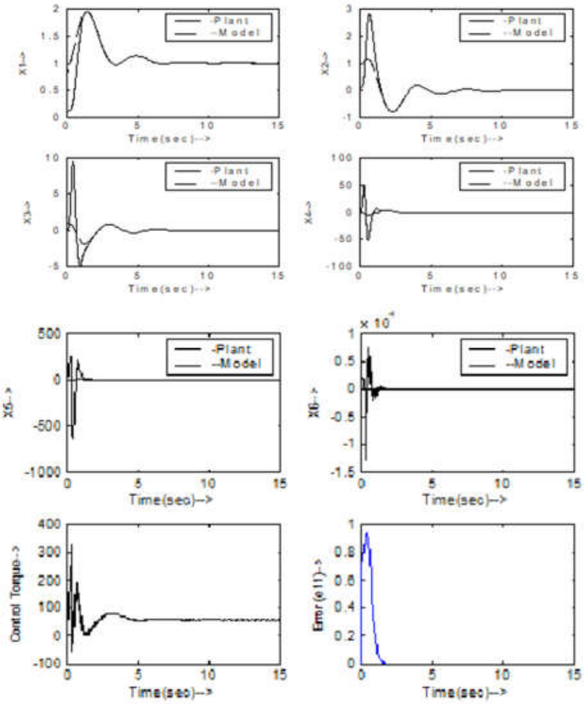

Fig. 7. The model following control for PSS with nominal parameters i.e. $x_e = 0.4$ (with insertion of low pass filter)

can be overcome by maintaining sliding motion inside a small boundary layer neighbouring the switching line or by insertion of low pass filter ahead of the plant to yield a smooth control signal. The transfer function of low pass filter used is [9].

$G(S) = 0.1/(S + 20)$

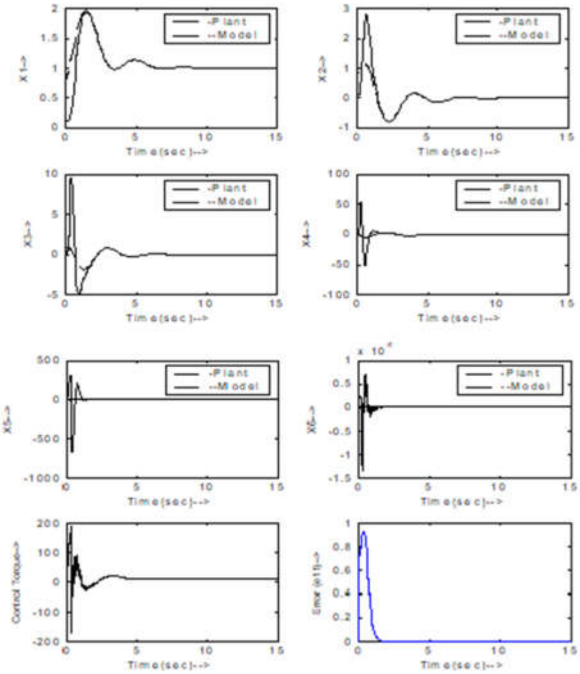

Fig. 8. The model following control for PSS with +50% variations in all parameters (with insertion of low pass filter)

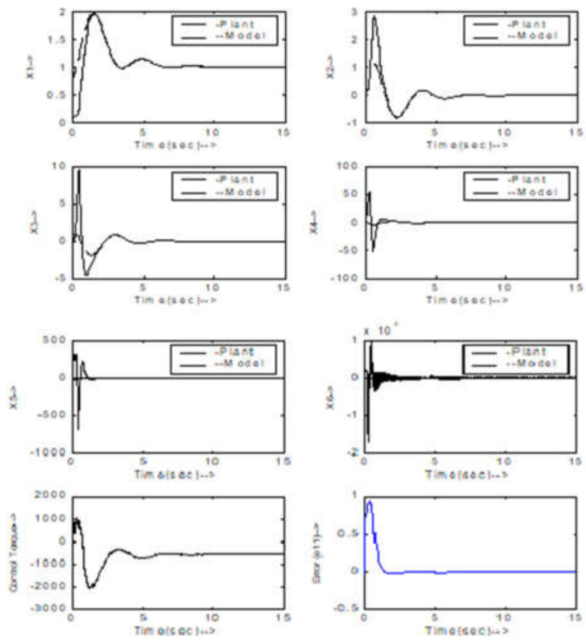

Fig. 9. The model following control for PSS with -50% variations in all parameters (with insertion of low pass filter)

It is observed that the system remains insensitive to such parameter variations and the model following control is successively implemented. It is noticeable that the other methods of switching vector design can be implemented with little effort.

VIII. Conclusion

In this paper a design technique based on the concept of pole placement has been applied for the design of the variable structure power system stabilizers. Appropriate selection of switching vector is very important for providing large improvement in system performance and the concept of pole placement establishes a systematic procedure for the proper choice of the switching vector. The VSS controller exhibits insensitivity to such parameter variations and disturbances. The switching logic of the VSS controller is simple and seems amenable for practical implementation. It is observed that the system remains insensitive to such parameter variations and the model following control is shown to be effective for power system stabilizers.

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