Journal of Vibration Engineering

Registered

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, itisfoundtohavebeneficialeffect.Inthispaper,attempt have been made to design a variable structure power system stabilizer(VSPSS)byselectingfavorablyplacedeigenvalues 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]Thecontrollerselectedhasmanyattractivefeatures 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 ofthesystemoscillationsareconsideredinthepaperi.eunitsat a generating station swinging with respect to the power system calledas'localplantmodeoscillations'andtheswingingofmany 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 controlof 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.

Inthispaper,aschematicapproachbasedonpoleplacement

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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 wasnot 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 performanceindex,theoptimalselectionofwhichisextremely difficult.Theoptimal$H-n/K$approachgivenbyChen and Malik [9] has some complexity like choosing both the uncertaintyweightingfunctionandtheperformanceweighting functioncarefully.Alsothecontrolsbasedonthelineartheory 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 VSPSSsuch 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 totheselectionofweightingmatricesneededtoachievethede- sireddynamicperformanceandhenceCasincaseofoptimum VSPSS. The controller uses in this paper possesses attractive features like robustness to parameter variations, modeling errorsandunknowndisturbances,simplicityindesign,reduced order dynamics when in sliding mode. The simulation results oftheVSCtheoryshowsdominanceoverconventionalcontrol theory,sensitivityanalysisshowingrobustnessoverparameter 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. SYSTEMUNDERCONSIDERATION

The system investigated, comprises a synchronousgenerator connected to an infinite bus through a double-circuittransmissionline.Atype1excitationsystemmodel

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

Two distinct types of the system oscillations are usually encounteredinaninterconnectedpowersystem[10].Onetype is associated with units at a generating station swinging with respecttothepowersystem.Suchoscillationsarereferred 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 manymachinesinonepartofthesystemagainstmachines in other parts. These are referred to as 'interarea mode oscillations', and have frequencies in the range 0.1 – 0.7 Hz. ThebasicfunctionofthePSSistoadddampingtoboth types of oscillations.

Itshouldbenotedthatonlyalocalmodeoftheoscillation is encountered in a simple machine-infinite bus system and hencetheeffectivenessofthePSSindampinginterareamodes 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. Enhancethesystemtransientstability.

3. Not adversely affect system performance during major system upsets which cause large frequency excursions.

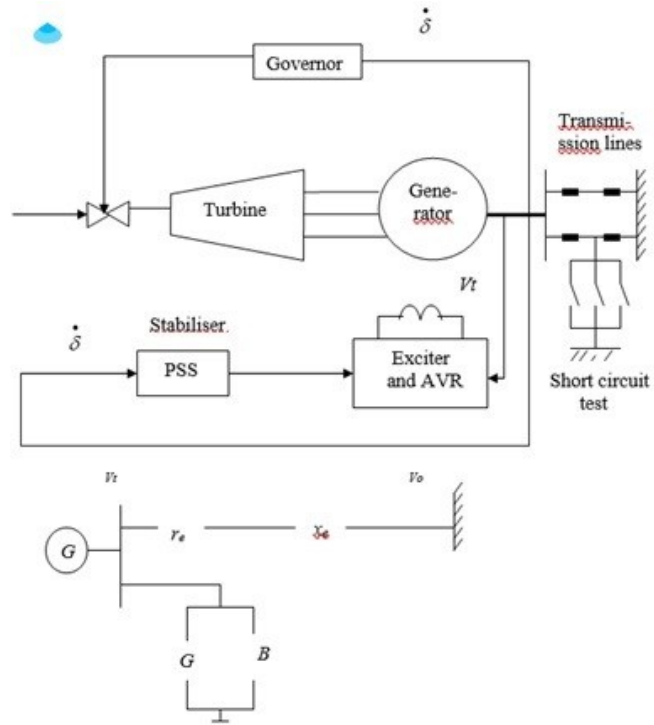4. Minimize the consequences of excitation system malfunction due to component failures.

Fig.1.Powersystemconfigurationforthesinglemachineinfinitebussystem

A.DynamicmodelforPSS

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 tosmall 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 asshown 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.

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

$$V_0=[(V_{t0}-I_{P0}r_e-I_{Q0}x_e)^2+(I_{P0}x_e-IQ0r_e)^2]^{1/2}(2)$$

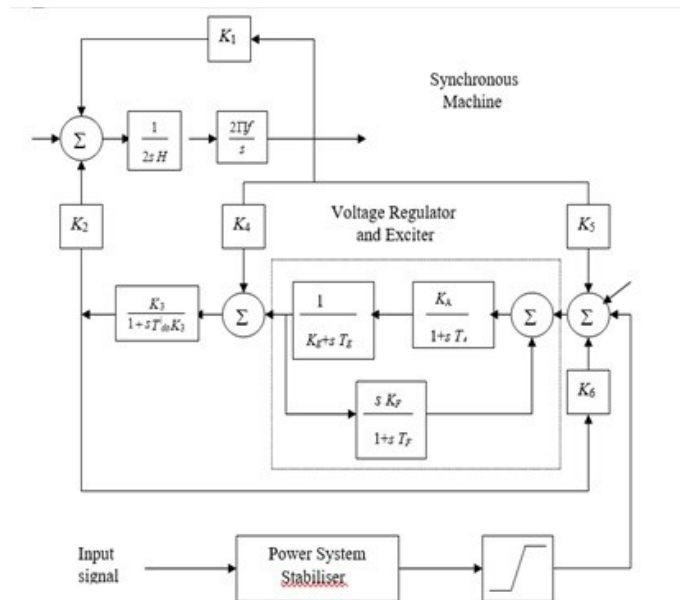$$sin\delta_0 \quad = \quad [V_{t0}-I_{p0}(x_q+x_e)-r_ex_q(I^2 \qquad +I^2)-$$

Fig.2.Linearisedsmallperturbationmodelofgeneratorconnectedtoinfinitebus through transmission line

$$V_{t0}Iq0r_e]E_{q0}V_0 \tag{3}$$

$$I_{Q0}=I_{P0}V_{t0}/E_{q0} \tag{4}$$

$$I_{do}=[I^2x_{q0}+I_{Q0}(V_{to}+I_{Q0}x_q)]/E_{qo} \tag{5}$$

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

$$V_{do}=I_{Q0}x_q \tag{7}$$

$$E'_{q0}=V_{qo}+x'_dI_{do} \tag{8}$$

Where,

I_d,I_q=directandquadratureaxiscomponentsofthearmature currents

V_d,V_q=directandquadratureaxiscomponentsoftheterminal voltage

E'_q=voltageproportional 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].

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

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

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

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

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

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

Thestateequationscanbewritten[24],

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

$$\dot{\Delta\delta}=2\Pi f\Delta\omega \tag{16}$$

$$\dot{\Delta E'_q}=-\frac{K_4}{T'_{d0}}\Delta\delta-\frac{1}{K_3T'_{d0}}\Delta E'_q+\frac{1}{T'_{d0}}\Delta E_{fd} \tag{17}$$

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

$$\dot{\Delta V_R}=-\frac{K_AK_5}{T_A}\Delta\delta-\frac{K_AK_6}{T_A}\Delta E'_q-\frac{1}{T_A}\Delta V_R-\frac{K_A}{T_A}\Delta V_E \\ +\frac{K_A}{T_A}u+\frac{K_A}{T_A}\Delta V_{Ref} \tag{19}$$

$$\dot{\Delta V_E}=-\frac{K_FK_E}{T_FT_E}\Delta E_{fd}+\frac{K_F}{T_FT_E}\Delta V_R-\frac{1}{T_A}\Delta V_E \tag{20}$$

The dynamic model of the system is obtained from the transferfunctionmodel(Figure.6.2)instatespaceformas.

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

Where,

x=Statevariablevector

u=Controlinputvector

Δd=Disturbances or nonlinearities input vector

A=State matrix (6 X 6)

B=Controlmatrix(6X1)

F=Disturbances or nonlinearities matrix (6 X 1)

Here in PSS the,

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

$$\Delta d=\Delta T_m$$

$$A=\begin{bmatrix} 0 & -\frac{K_1}{2H} & -\frac{K_2}{2H} & 0 & 0 & 0 \\ 2\Pi f & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_4}{T'_{d0}} & -\frac{1}{T'_{d0}K_3} & \frac{1}{T'_{d0}} & 0 & 0 \\ 0 & 0 & 0 & -\frac{K_E}{T_E} & \frac{1}{T_E} & 0 \\ 0 & -\frac{K_AK_5}{T_A} & -\frac{K_AK_6}{T_A} & 0 & -\frac{1}{T_A} & -\frac{K_A}{T_A} \\ 0 & 0 & 0 & -\frac{K_EK_F}{T_ET_F} & \frac{K_F}{T_ET_F} & -\frac{1}{T_F} \end{bmatrix}$$

$$B=\begin{bmatrix}0\\0\\0\\0\\\frac{K_A}{T_A}\\0\end{bmatrix}; \qquad F=\begin{bmatrix}\frac{1}{2H}\\0\\0\\0\\0\\0\end{bmatrix} \tag{23}$$

III. DESIGN OF VARIABLE STRUCTURE CONTROLLER:

Thebasicphilosophyofthevariablestructureapproach is simply obtained by contrasting it with the linear state regulator design for the single input system.

$$\dot{x}=Ax+Bu \tag{24}$$

In the state regulator design, the structure of the feedback isfixed as

$$u=-K_x^T \tag{25}$$

ThestatefeedbackgainvectorKischosenaccordingto variousdesignprocedures,suchaseigenvalueplacementor

quadraticminimization.

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

$$s=C^T\underline{x}=0 \tag{26}$$

Where C is a constant vector. This hyper plane is also calledas the switching hyper plane.

Whenthecontrolsignaluisafunctionofthestatevector x undergoes discontinuities on the plane s = 0, the velocity vector also undergoes discontinuities on the same plane. Ifthe trajectories are directed towards the plane s = 0, sliding mode will appear in the plane. The pair of inequalities,

$$\lim_{x\to 0}-s^{\cdot}>0 \text{ and } \lim_{x\to 0}-s^{\cdot}<0 \tag{27}$$

aresufficientconditionfortheslidingmodetoexist.

The control signal is a piecewise linear function of x with discontinuous coefficients $u = -\Psi^T x$

$$\Psi = \begin{array}{l} \alpha_i \dots\dots\dots\dots\dots\dots\dots fx_i s>0 \\ \beta_i \dots\dots\dots\dots\dots\dots\dots\dots fx_i s<0 \end{array}$$

where α_i and β_i areconstantsandi=1,2,.............,n.

Itshouldbenotedthattheswitchingofthestatefeedback gainsoccurondiscontinuityItshouldbenotedthattheswitchingofth estatefeedbackgainsoccurondiscontinuity

plane s = 0. The choice of controls should ensure that theygiverisetotheslidingmodeondiscontinuityplanes=0. The switching vector C is chosen so that sliding motion hasthe desired properties.

Sincen=6andm=1,

$$\begin{bmatrix} C_1 C_2 C_3 C_4 C_5 C_6 \end{bmatrix}^T \quad \text{iscalledtheswitching}$$
vector.

Thecontrollawisoftheform

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

wherethepreciseconstantgainsΨaregivenbyaboveequation (28). Thedesignprocedureconsistofdeterminingtheelements

oftheswitchingvectorCandthefeedbackgainsΨsothat thecontroluwhichdependsonthemcansatisfycertain

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, settlingtime of the systemor performance index ofthe 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,

$$x^{\cdot}=Ax+Bu \tag{30}$$

where x is a state vector of dimension (nx1), u is controlvector of dimension (mx1) and A and B are constant matrices of dimensions (n x n) and (n x m) respectively. Definethecoordinatetransformation

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

Suchthat

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

WhereMisanon-singular(nxn)matrixandB2isa non-singular (m x m) matrix.

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

Fromequation(24)and(31)andusingequation(32),equation (33)canbewrittenintheform,

$$\begin{array}{c} z^{\cdot}_1 \\ z^{\cdot}_2 \end{array} = \begin{array}{cc} A_{11} & A12 \\ A_{21} & A22 \end{array} \begin{array}{c} z_1 \\ z_2 \end{array} + \begin{array}{c} 0 \\ B_2 \end{array} \tag{34}$$

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

Hence,

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

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

$$s=C^T x=0 \qquad i=1,2,3 \dots\dots n$$
Hence,weget,
$$s=C^T M^{-1}z=0 \qquad i=1,2,3 \dots\dots n$$

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

$$C^T M^{-1}=C^T_1 \quad C_2 \tag{36}$$

where C_1 and C_2 are n-1 column vector and scalar respectively.

Equations(35)and(36)uniquelydeterminethedynamics in the sliding mode over the intersection of the switching hyperplane s(x)=0. We can write,

$s=C^T z_1 + C_2 z_2 = 0$ (37)

Thesubsystemdescribedbyequation(35)mayberegarded as an open loop control system with state vector $z_1$and controlvectorz_2,withoutlossofgenerality,weassumethat $C_2=1$ and the form of control $z_2$being determined by equation (1.36), that is,

$z_2 = C^T z_1$ (38)

Using equation (35) and (38) we obtain the equations of the sliding mode in closed loop form as
$\dot{z}_1 = (A_{11} - A_{12} C^T) z_1 = A_c z_1$ (39)

The eigenvalue of the matrix $A_c$may be placed arbitrarilyinthecomplexplane.Ifpair(A,B)iscontrollablethent hepair($A_1 1, A_{12}$)isalsocontrollable.Ifthepair (A_{11}, A_{12})iscontrollablethentheeigenvaluesofthematrix $A_{11} - A_{12} C$i.e.A_c^Tintheslidingmodecanbeplaced arbitrarilybyasuitablechoiceofvectorC_1.
Hence, the algorithm for realization of switching vector and switching hyperplane can be summarized as follows:

1) SelecttransformationmatrixMthatsatisfyequation(32).

2) ComputethevectorC1suchthattheeigenvalues $\lambda_1, \lambda_2 \ldots \ldots \lambda_{n-1}$ofthematrix$(A_1 - A_1 C^T)$ or$A_c$characterizing the dynamics in the sliding mode has desired placement.

3) Choosetheequationoftheswitchinghyperplanetobe oftheform$s = [C1 T1] Mx = 0$

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

V. Example

ConsiderthePSSsystemasshowninFigure2andthe

problemofasinglecontrolarea.Thenominalparametersof thesystemandtheoperatingconditionsusedforthesample probleminvestigatedaregivenbelow[14],[15]. Alldataaregiveninperunitofvalue,exceptthatHand

time constants are in seconds.
Generator:

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

IEEEtype-1excitationsystem:

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

Transmissionline:

$x_e=0.4 \quad r_e=0.0$

Operationcondition:

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

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:

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

TheconstantsK1–K6areevaluatedusingtherelationsgiven (9)to(14)consideringzeroexternalresistancei.e.re=0.0 forthesampleprobleminvestigated.Wegetthesevaluesas:

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

Afterdesigningtheswitchingvectorusingpoleassignment technique the results are :
Thestatespacemodelisgivenbyspecifying

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

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

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1000 \\ 0 \end{bmatrix} u + \begin{bmatrix} 0.1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \Delta T_m$$

Letusassume,

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

Now,herewehavetofindtheC1Tforthedesiredeigenvalues 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)reducesto,

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

Here,letthedesiredpolesareatlocations,

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

Fromthiswegetthedesiredcharacteristicequation.As

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

Bycomparing(43)and(44),wewillget,

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

FurthermakingthemanipulationT^{-1}C$^T_1$,weget,

$$C_1=C_{11} \quad C_{12} \quad C_{13} \quad C_{14} \quad C_{15}{}^T$$

$$C_1=[-82146.27 \; 6188.81 \; 82647.96 \; 1-32.67 \; 4539.925]$$

Hence,theswitchingvector$C=MC^T_1 \; C^T_2$andC2=1

$$\therefore C= [-82146.27 \; 6188.81 \; 82647.96 \; 1-32.6741.05 \; 39.925](45)$$

Also,thecontrolsignaluisgivenbytheequation(30)and
canbewrittenas

$$u=-\Psi_1x_1-\Psi_2x_2 \quad -\Psi_3x_3 \quad -\Psi_4x_4 \quad -Psi_5x_5 \quad -\Psi_6x_6 \quad (46)$$

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

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

VI. VARIABLE STRUCTURE MODEL FOLLOWINGCONTROLLERDESIGNFORPSSSYSTEM

Thestatespacemodelofplantisconsideredas,

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

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

Letthemodelselectediscriticallydampedmodelsuch that ,

Ifthismodelhastheeigenvaluesas–1,-2,-3,-4,-5and –6 and we are representing state model in (6.61) in phase canonical form, then we have,

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

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

Theswitchingsurface$\sigma= Ce$ischosenas,

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

$$\dot{e}_1=e_2$$
$$\dot{e}_2=e_3+0.0001\Delta T_m$$
$$\dot{e}_3=e_4+0.0023\Delta T_m$$
$$\dot{e}_4=e_5-0.0066\Delta T_m$$
$$\dot{e}_5=e_6-0.0941\Delta T_m$$

$$\dot{e}_6=-720x_{m1}-1764x_{m2}-1204x_{m3}-665x_{m4}-175x_{m5}-21x_{m6}+720r+11021x_1+6095x_2+8923x_3+1011x_4+284x_5+22x_6-u+1.2674\Delta T_m \quad (51)$$

Theswitchingvectorwasdesignedbyusingpoleplacement technique as explained before.
Thepolesofthematrix$[A^{11}_m-A^{12}_mC_{11}]$werechosenas:-
-8.0 , -8.5 , -9.0 , -9.5 and -10.0 . The transformation matrixconsidered was,

$$M=I_6=6X6 \qquad IdentityMatrix$$

Hence,weget,

$$C^T = 5814032501.57256.25808.75451 \qquad (52)$$

Theerrorisdefinedas,

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

Andcontrolfunctionis

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

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)wecanwrite,

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

Afterreductionwecanwrite,

$\sigma\dot{\sigma} = (K_1 - 720)\sigma e_1 + (K_2 + 56376)\sigma e_2 + (K_3 + 31297.5)\sigma e_3 + (K_4 + 6591.25)\sigma e_4 + (K_5 + 633.75)\sigma e_5 + (K_6 + 24)e_6 + (K_7 - 10271)\sigma x_1 + (K_8 - 4331)\sigma x_2 + (K_9 - 7719)\sigma x_3 + (K_{10} - 346)\sigma x_4 + (K_{11} - 109)\sigma x_5 + (K_{12} - 1)\sigma x_6 + (K_{13} + 720)\sigma r + (K_{14} + 11.6346\Delta T_m)\sigma \qquad (56)$

We will find the controller by satisfying condition $\sigma\dot{\sigma} \leq 0$. In addition, we can take term s instead of $\sigma$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.
Wegetthecontrollergainsas,

$K = 0 \qquad ifse > 0 K = 721 ifse < 0$

$K_2 = -56377 \ ifse_2 > 0 \ K_2 = 0 \ ifse_2 < 0$
$K_3 = -31298 ifse_3 > 0 K_3 = 0 ifse_3 < 0$
$K_4 = -6592 \ ifse_4 > 0 \ K_4 = 0 \ ifse_4 < 0$
$K_5 = -634 \ ifse_5 > 0 \ K_5 = 0 \ ifse_5 < 0$
$K_6 = -25 \ ifse_6 > 0 \ K_6 = 0 \ ifse_6 < 0$
$K_7 = -10272 ifsx_1 > 0 K_7 = 0 ifsx_1 < 0$
$K_8 = -4332 \ ifsx_2 > 0 \ K_8 = 0 \ ifsx_2 < 0$
$K_9 = -7720 \ ifsx_3 > 0 \ K_9 = 0 \ ifsx_3 < 0$
$K_{10} = -347 \ ifsx_4 > 0 \ K_{10} = 0 \ ifsx_4 < 0$
$K_{11} = -110 ifsx_5 > 0 K11 = 0 ifsx_5 < 0$
$K_{12} = -2 ifsx_6 > 0 \ K12 = 0 \ ifsx_6 < 0$
$K_{13} = -721 \ ifsr > 0 \ K13 = 0 \ ifsr < 0$
$K_{14} = -12 ifs > 0 K14 = 0 ifs < 0$

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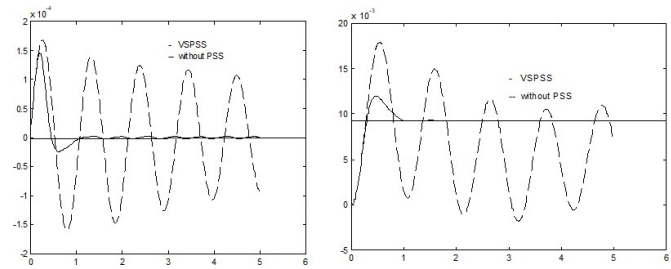
$$x_1 = x_2 = x_3 = x_4 = x_5 = x_6 = 0.1 \qquad (57)$$

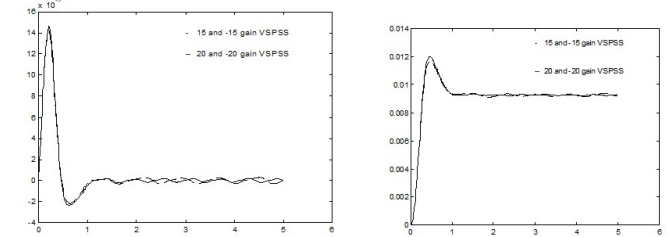Fig.3.Thedynamicresponseof$\Delta\omega$and$\Delta\delta$for1%stepincreaseofΔT_m withnominalparameters

Fig.4.Thedynamicresponseof$\Delta\omega$and$\Delta\delta$for1%stepincreaseofΔT_m withnominalparameterswithdifferentfeedbackgains.
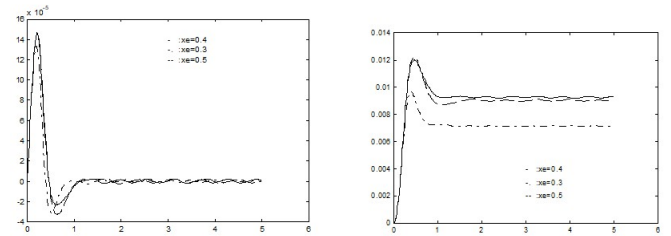

Fig.5.Thedynamicresponseof$\Delta\omega$and$\Delta\delta$for1%stepincreaseofΔT_m withVariationsinparametersi.e.linereactancechange

Theinitialconditionsformodelwerechosenas,

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

VII. SIMULATION RESULTS AND DISCUSSIONS

Figure3showsthesimulationresultsofdynamicresponse of $\Delta\omega$and $\Delta\delta$when the system is subject to 1% step changeofΔT_m.Resultsusingtheintegralcontrolleralone (withoutVSS)arealsoincludedforcomparisonpurposes 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 lawis seen to comprise high frequency components which leadsto control chattering is highly undesirable because it involves extremely high control activities and it may excite high frequencyun-modeleddynamics.[1]Howeverthisdrawback
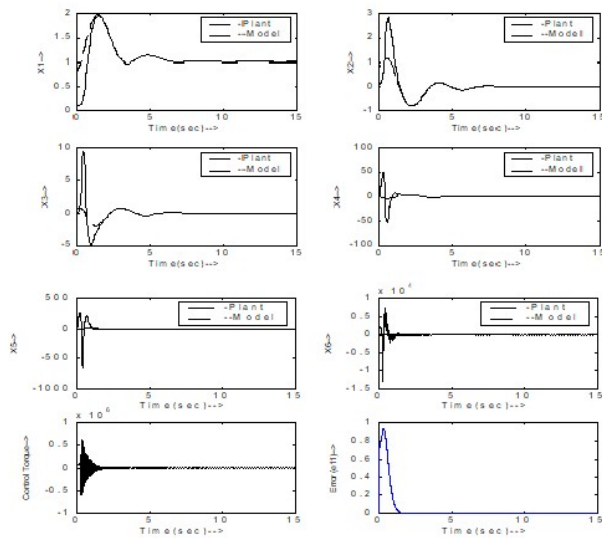
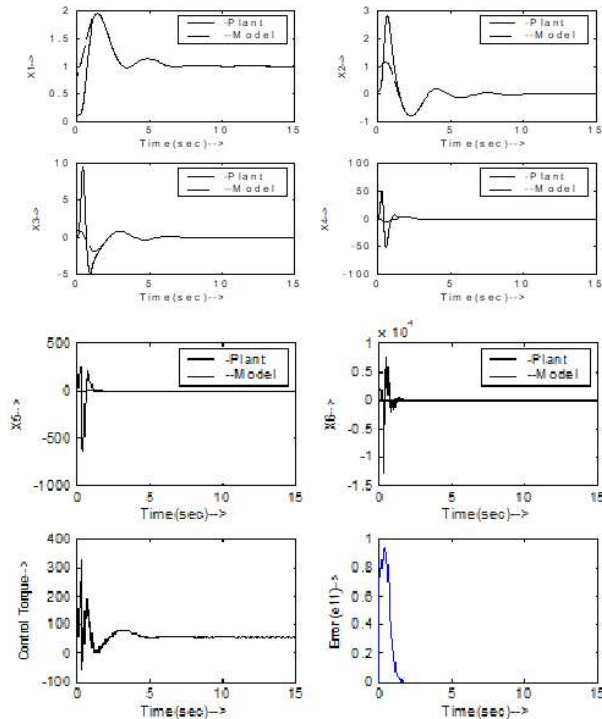Fig.6.ThemodelfollowingcontrolforPSSwithnominalparametersi.e. x_e=0.4(withoutinsertionoflowpassfilter)

Fig.7.ThemodelfollowingcontrolforPSSwithnominalparametersi.e. x_e=0.4(withinsertionoflowpassfilter)

Fig.8.ThemodelfollowingcontrolforPSSwith+50%variationsinallparameters (with insertion of low pass filter)

Fig.9.ThemodelfollowingcontrolforPSSwith-50%variationsinallparameters (with insertion of low pass filter)

canbeovercomebymaintainingslidingmotioninsidea   small boundary layer neighbouring the switching line or by insertion of low pass filter ahead of the plant to yield asmooth control signal. The transfer function of low pass filter used is [9].
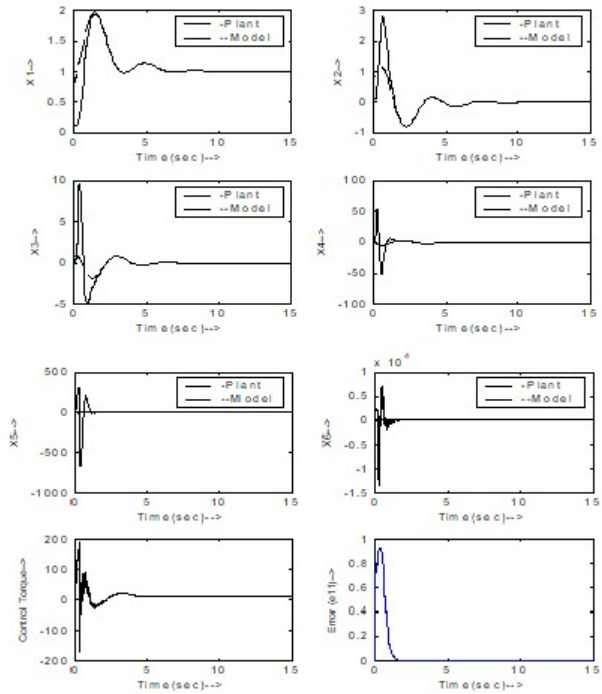
$G(S)=0.1/(S+20)$
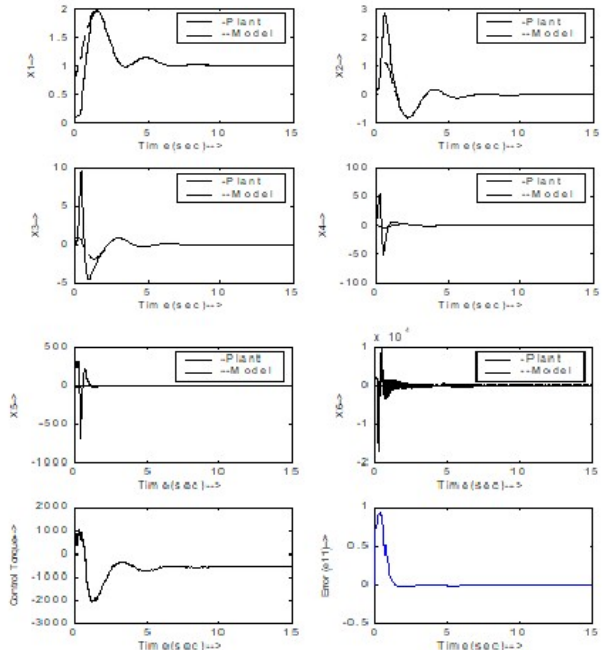
It is observed that the system remains insensitive to such parameter variations and the model following control is successively implemented. It is noticeable that the other methods of switching vector design can be implemented with little effort.

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 switchingvectorisveryimportantforprovidinglargeimprove- mentinsystemperformanceandtheconceptofpoleplacement establishes a systematic procedure for the proper choice oftheswitchingvector.TheVSScontrollerexhibitsinsensitivity to such parameter variations and disturbances. The switching logicoftheVSScontrollerissimpleandseemsamenable   for practical implementation. It is observed that the system remainsinsensitivetosuchparametervariationsandthemodel following control is shown to be effective for power system stabilizers.

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