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Small Signal Stability Investigation of SMIB System Using Variable Structure Control

Balwinder Singh, Rashmi Vikal, Ashish Dutta

Abstract— **This paper aims at investigation of small signal stability for a synchronous machine connected to the infinite bus system by variable structure control. Power systems inherently being non linear, so first the linearized model of the dynamic system is obtained and then the procedure for designing a variable structure controller is explained. The robustness and effectiveness of the designed controller is verified by the change in the operating points. The results of the simulation shows that the proposed controller has significantly improved the power system stability.**

Index Terms— **PSS, Variable structure control, sliding mode, SMIB, small signal stability.**

I. Introduction

A sudden change of load, fault and generator shaft speed change may give rise to oscillations of low frequency. These oscillations are undesirable as they affect the power transfer capability of transmission lines and induce stress in generator shaft. Among various oscillatory problems, a frequency, typically in the range of 0.1-0.4 Hz is considered as severe [1] The small disturbances lead to a steady increase or decrease in rotor angle caused by the lack of synchronizing or damping torque. Power system stabilizers (PSS) are used on a synchronous generator to improve the damping of oscillations of the rotor/turbine shaft [2]. PSS give the supplementary control signal to damp out the oscillations in the system. Conventional PSS is most popular due to its fixed gains and operational simplicity [3].CPSS is designed to give desired damping at a fixed operating point which is defined by the terminal voltage and real and reactive power of the generator. With the change in operating point many PSS based on classical theory are not able to give desired performance. Different method are proposed based on controlling techniques of non linear system, adaptive control techniques and artificial intelligence techniques to design power system stabilizer. Modern control methods based on optimal control techniques are quiet effective for system control design. These methods use state space representation of the power system model to calculate the gain matrix which when applied as state feedback control will minimize a prescribed objective function. In the implementation of variable structure control in non linear systems, linearization of the non linear system is first performed, and variable structure control theories for linear system are then applied in the design of the controller [4].

Variable structure control for non linear control design ensures satisfactory operation over a wide range of operating conditions. By appropriately selection of the control law, the closed loop dynamics of the system are made to follow a predetermined path known as switching plane. Firstly, a sliding surface is determined and then the control gain matrix is selected [5].

In the present paper inherently non linear power systems, is the linearized and the dynamics are presented. The procedure for designing a variable structure controller is also explained. The robustness and effectiveness of the designed controller has been verified by the variation in the operating points. The results of the simulation of the proposed controller embedded with SMIB has been presented.

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Balwinder Singh Suurja Faculty *, Electrical Engineering Department, PEC University of Technology, Chandigarh, Chandigarh, India , 98152 95005.*
Prof Rashmi Vikal Faculty, *Electrical Engineering Department, PEC University of Technology, Chandigarh*
Ashish Dutta,*, PG Student, Electrical Engineering Department, PEC University of Technology, Chandigarh*

II. Linearized model[6-8]

The Linearized dynamic model of a single generator supplying an infinite bus through external impedance, including the effect of voltage regulator and excitation system [6] can be obtained in the following form.

$$\begin{bmatrix} \frac{\Delta V_t}{dt} \\ \frac{\Delta P_e}{dt} \\ \frac{\Delta \omega}{dt} \\ \frac{\Delta e_{fd}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{K_6 K_7}{K_9} & -\frac{K_6 K_8}{K_9} & K_5 & \frac{K_6}{T'_{do}} \\ \frac{K_2 K_7}{K_9} & -\frac{K_2 K_8}{K_9} & K_1 & \frac{K2}{T'do} \\ 0 & -\frac{\omega_s}{2h} & 0 & 0 \\ -\frac{K_A}{T_A} & 0 & 0 & -\frac{1}{TA} \end{bmatrix} \begin{bmatrix} \Delta V_t \\ \Delta P_e \\ \Delta \omega \\ \Delta e_{fd} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{K_A}{T_A} \end{bmatrix} [\Delta V_{ref}] \quad (1)$$

Parameters K_1-K_6 are defined in[7] and

$$K_7 = \frac{K_1 - K_2 K_3 K_4}{K_3 T'_{do}} \;, K_8 = \frac{K_5 - K_3 K_4 K_6}{K_3 T'_{do}}$$

$$K_9 = (K_2 K_5 - K_1 K_6)$$

A synchronous machine is assumed to be delivering power to an infinite bus of through a transmission line with some impedance.

III. Controller design

A variable structure system is a dynamical system whose structure changes in accordance with the current value of its state. A variable structure system can be understood as a system composed of independent structures together with the switching logic between each of the structures. With appropriate switching logic, a variable structure system can utilize the desirable properties of each of the structures the system is composed of. The undesirable properties of each of the structure are also eliminated. Whenever the system leaves the switching surface the control changes its structure forcing the system to constrain its motion to the switching surface and the motion is called sliding regime. The motion of system in sliding regime is equivalent to motion of certain new system with fixed structure which differs from any of the structures based on original system. Motion of system in sliding mode makes it insensitive to small variations and disturbances. In sliding the system behavior is governed by a reduced set of equations referred to as order reduction. With small chattering motions the system is finally moved towards equilibrium point[5].

A. Sliding mode[5]

The motion of the system while confined to the switching line or a surface is referred to as sliding. A sliding mode will exist if in the vicinity of the switching surface the state vectors are directed towards the surface. The switching surface attracts the trajectories when they are in its vicinity, and once a trajectory intersects the switching surface, it will stay on it thereafter. A surface σ(x) = 0 is attractive if 1. Any trajectory starting on surface remains there. 2. Any trajectory starting outside the surface tends to it at least asymptotically. Thus for a sliding motion to occur we need

$$lim_{\sigma \to o^+} \ \dot{\sigma} \ < \ 0 \ \ and \ \ lim_{\sigma \to o^-} \ \dot{\sigma} > 0$$

In the neighborhood of the switching surface the two equations may be combined to give

$$\sigma\dot{\sigma} \ < \ 0$$

B. VSC design[1,5]

First obtain the linearized state space model of the given power system at some predefined operating point [1]

$$\dot{\mathbf{X}} = \mathbf{A\,X} + \mathbf{B\,u}$$

where x is the state vector with dimension n × 1, A and B are the constant matrices with dimension n × n and n × 1, u is the control vector of size 1×1. Now using the state transition matrix T obtain the controller companion form of the model of the form

$$\dot{\bar{\mathbf{X}}} = \bar{\mathbf{A}}\bar{\mathbf{X}} + \bar{\mathbf{B}}\,\mathrm{u} \qquad (2)$$

Where $\bar{A} = T^{-1}A\,T$, $\bar{B} = T^{-1}B$

The system in the transformed form can be expressed as:-

$$\frac{d\bar{x}_1}{dt} = \bar{x}_2$$

$$\frac{d\bar{x}_2}{dt} = \bar{x}_3$$

$$\vdots \qquad \vdots$$

$$\frac{d\bar{x}_{n-1}}{dt} = \bar{x}_n$$

$$\frac{d\bar{x}_n}{dt} = -\left(a_1\bar{x}_1 + a_2\bar{x}_2 + \cdots + a_n\bar{x}_n\right) + u \qquad (3)$$

Where $\bar{x}_1, \bar{x}_2, \ldots \bar{x}_n$ are the transformed state vector elements. With the variation of the operating point T varies and also the coefficients of the state variables.

C. Sliding Plane Selection [1,5]

The open loop Eigen values of the system for a particular operating point are available. We can choose the Eigen values such that the closed loop system is satisfactorily stable. The Eigen values can be selected far away from the origin to the left hand side to get the efficient damping. It is the choice of designer to select the Eigen values.. With the selection of the Eigen values at desired location the characteristic equation of the system can be written as:-

$$(s - \lambda_1)(s - \lambda_2) \ldots\ldots(s - \lambda_n) = 0 \qquad (4)$$

Let the switching surface be given by:-

$$\sigma = \bar{C}\bar{X} = \bar{c}_1\bar{x}_1 + \bar{c}_2\bar{x}_2 + \bar{c}_3\bar{x}_3 + \cdots \bar{c}_{n-1}\bar{x}_{n-1} + \bar{x}_n = 0 \quad \text{i.e}$$

$$\bar{x}_n = \bar{c}_1\bar{x}_1 - \bar{c}_2\bar{x}_2 - \bar{c}_3\bar{x}_3 - \cdots \bar{c}_{n-1}\bar{x}_{n-1} \qquad (5)$$

System dynamics on the surface is given by the characteristic equation

$$s^{n-1} + \bar{c}_{n-1}s^{n-2} + \bar{c}_{n-2}s^{n-3} + \ldots\ldots + \bar{c}_1 = 0 \qquad (6)$$

by comparing equations 3 and 5 we can evaluate the conatants $\bar{c}_1, \bar{c}_2, \bar{c}_3 \ldots\ldots\ldots \bar{c}_{n-1}$

However other effective way to evaluate the sliding plane coefficients is using optimization technique. For one operating point evaluate the equivalent control gain using the sliding plane coefficients keeping the equivalent control gain in state feedback closed loop so that required performance index is minimized. The evaluated coefficients are optimum for that operating point. Various optimization techniques are available and can be effectively used. Genetic algorithm and particle swarm optimization give better optimal results. Particle Swarm optimization (PSO) technique by Dr Russ Eberhart and Dr. James Kennedy inspired from birds flocking & fish schooling is used in this paper.

D. Determining control law [5]

Now we determine the switched feedback gains which will bring the state trajectory to the switching plane and will maintain there[1,5]. As the necessary and sufficient condition to obtain sliding is $\sigma\dot{\sigma} < 0$ substituting for the $\dot{\sigma}$ obtain the equation as:-

$$\sigma\left[\frac{d\bar{x}_n}{dt} + \bar{c}_{n-1}\frac{d\bar{x}_{n-1}}{dt} + \cdots \bar{c}_1\frac{d\bar{x}_1}{dt}\right] < 0$$

$$\sigma\left[-a_1\bar{x}_1 - \cdots - a_n\bar{x}_n + u + \bar{c}_{n-1}\bar{x}_n + \cdots \bar{c}_2\bar{x}_3 + \bar{c}_1\bar{x}_2\right] < 0 \qquad (7)$$

Define $\psi = [\psi_1 \ \psi_2 \ \psi_3 \ldots\ldots \psi_n]$

Such that the state feedback control is given by

$$u = \psi X$$

defining the quantities u_{eq} and K_{eq} as:-

$$u_{eq} = a_1\bar{x}_1 + (a_2 - \bar{c}_1)\bar{x}_2 + \cdots + (a_n - \bar{c}_{n-1})\bar{x}_n$$

$$= \bar{\psi}_{eq}\,\bar{X} = \bar{\psi}_{eq}\,T^{-1}X = \psi_{eq}X \qquad (8)$$

The equation (6) can be simplified as:-

$$[(\psi - \psi_{eq})X]\,\sigma < 0 \qquad (9)$$

Fulfilling the above conditions requires the selection of controller gains ψ_i shall be equal to constants α_i and β_i so that $\alpha_i < \psi_{eqi}$ and $\beta_i > \psi_{eqi}$ and

$$\psi_i = \{\alpha_i \text{ when } x_i\,\sigma > 0$$
$$\beta_i \text{ when } x_i\,\sigma < 0\} \quad (10)$$

For robust control the operating point is varied for the entire feasible range. With the change in operating point ψ_{eqi} changes. We can find the maximum and minimum of ψ_{eqi} in the entire range of operating points[1]. Suitably α_i, β_i can be so selected to guarantee the sliding mode.

$$\psi_i = \{\alpha_i < (\psi_{eqi})\min \; when \; x_i\,\sigma > 0$$
$$\beta_i > (\psi_{eqi})\max \text{ when } x_i\,\sigma < 0\} \quad (11)$$

IV. Objective Function

The optimum values for VSC which includes c_i's is evaluated such that the performance index that reflects the objective of the design is minimized.

Objective function used is :-

$$J = \int_0^{t\,sum} t\,[\,|\Delta\delta|\,]\,dt \quad (12)$$

where
$\Delta\delta$ – rotor angle deviation.
Particle swarm optimization technique can be effectively used using the equivalent control gain in the closed loop and minimizing the performance index.

V. System Response and Analysis

The test system taken for the designed controllers has the following parameters:-[9]

TABLE I SYSTEM DATA

Parameter	Magnitude
P	0.6
Q	0.022
V_t	1.00
f	50
X_d	0.02224
X_q	1.5845
X'_d	0.4245
X'_q	1.04
δ_o	44.37°
T'_{do}	6.66
T'_{qo}	0.44
ω_B	377
H	3.542
M	7.084
K_A	400
T_A	0.025
R_{line}	0.00
X_{line}	0.8125
$X_{Transformer}$	0.1364

The open loop poles of the system are at position:-19.98 +j28.83, -19.98 -j28.83, -0.16 + j5.41, -0.16 - j5.41. To improve the system damping poles must be located away from the imaginary axis. Using the PSO optimization technique such as using the equivalent control in the closed loop and minimizing the rotor angle deviation the sliding plane obtained is as:-

$$\sigma = \bar{C}X = [\ 15205 \quad 1941 \quad 150 \quad 1]$$

In the transformed space the switching surface system is given by $\bar{C}T^{-1}$ i.e

$$\sigma = 0.4240\Delta V_t - 0.2661\Delta P_e - 0.0258\Delta\omega - 0.0001\Delta e_{fd}$$

The equivalent control gain is given by

$$\psi_{eq} = [1.0335 \quad -1.3709 \quad 0.1268 \quad -0.0069]$$

With the change of operating point for a machine the parameters change and equivalent gain for each operating point is different. The variation of equivalent control gain is evaluated by varying the real and the reactive power of the machine. The real power is varied between 0.2 – 1 pu and reactive power in the range 0 -1 pu. Thus the entire feasible region is encompassed to get the minimum and maximum values of equivalent control gains.

TABLE II

EQUIVALENT CONTROL GAIN VARIATION

	ψ_1	ψ_2	ψ_3	ψ_4
Maximum value	1.0480	-.2663	0.4893	-0.0069
Minimum value	1.0180	-3.8733	0.1016	-0.0069

TABLE III

SELECTED CONTROL GAIN VARIATION

α_i	.03	-5	0.1	-.009
β_i	1.5	-.7	0.6	-.002

With the selection of the control gains, the effectiveness of the controller was studied. The input applied to the system is 5% variation in terminal voltage. Operating point P = 0.6, Q = 0.02224

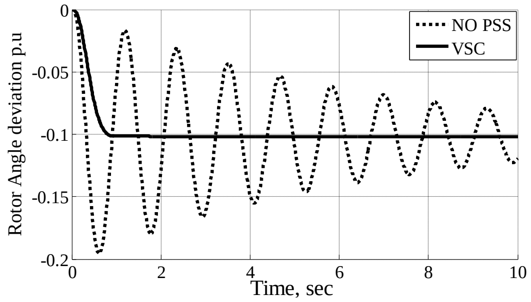

Fig. 1 Rotor Angle deviation

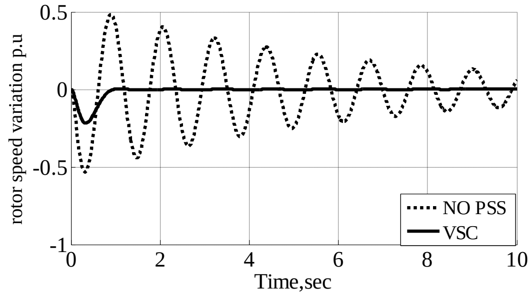

Fig. 2 Rotor Speed deviation

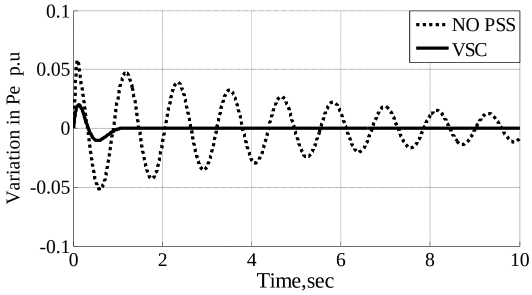

Fig. 3 Electrical Power deviation

The effectiveness of the controller is analysed by increasing the real power loading on machine by 25%. The control is robust in nature as the equivalent control gains are determined for the entire feasible range of the operating points. The controller is robust in nature. Operating point P = 0.75, Q = 0.02224 and the input to the system is 5% change in terminal voltage.

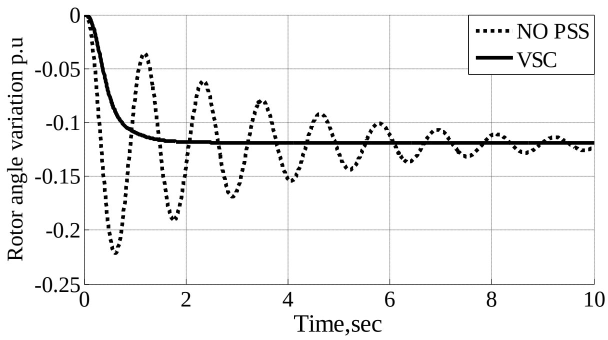

Fig. 4 Rotor Angle deviation

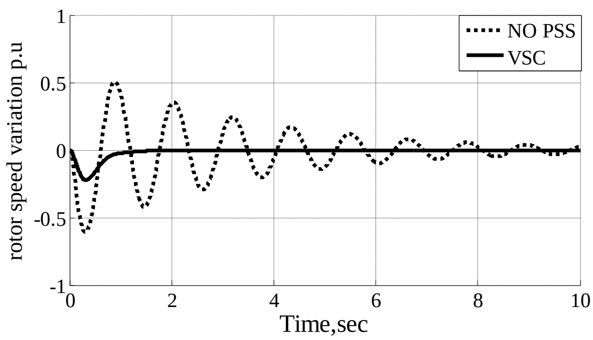

Fig. 5 Rotor Angle deviation

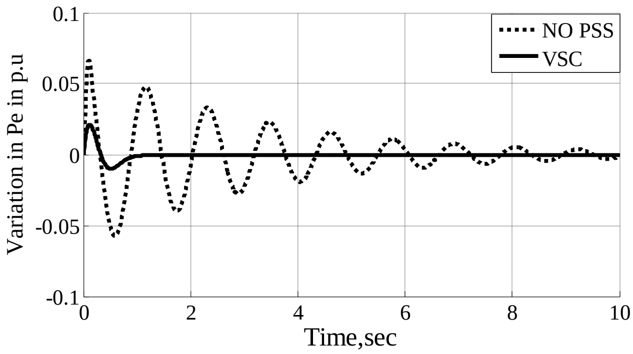

Fig. 6 Rotor Angle deviation

VI. CONCLUSION

Small signal stability of a synchronous machine connected to an infinite bus has been improved using variable structure control. By linearizing the non linear equations that describe dynamics of the synchronous machine connected to an infinite bus the design procedure for variable structure control is presented. The change in the operating point of the system is well accommodated by the designed variable structure controller. The results indicate that with the proposed VSC there is significant damping in the system. The PSS design using this approach can be implemented for large power systems which has many modes of low frequency oscillations.

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