Variable Structure Control Based Power System Stabilizer for Single Machine Infinite Bus System Using Particle Swarm Optimization

Rashmi Vikal and Balwinder Singh Surjan

***Abstract*—This paper presents the design of variable structure control (VSC) based Power System Stabilizer (PSS) for Single Machine Infinite Bus (SMIB) system. Optimal VSC based PSS has been tuned to minimize the low frequency oscillations in torque angle deviation using Particle Swarm Optimization (PSO). The robustness and effectiveness of the designed controller is verified by the change in the operating points. The results of the simulation show that the proposed controller has significantly improved the power system stability.**

***Index Terms*—Variable structure control, small signal stability. SMIB, PSO.**

I. Introduction

Power systems are in general nonlinear systems and the operating conditions can vary over a wide range. Recently, small signal stability has received much attention [1]. The increasing size of generating units, the loading of the transmission lines and the high-speed excitation systems are the main causes affecting the small signal stability. 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. The conventional PSS was first proposed in the 1960s and classical control theory, described in transfer functions, was employed for its design. Since the pioneering work of DeMello and Concordia [2] in 1969, control engineers, as well as power system engineers, have showed great interest and made significant contributions in PSS design and applications for both single and multi-machine power systems. Conventional PSS is most popular due to its fixed gains and operational simplicity. 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 methods 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 quite effective for system control design [3], [4]. 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 this paper, the design of optimal PSS based on VSC is presented [5]-[7]. 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.

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II. Modeling of SMIB with PSS

A. Power System Under Study

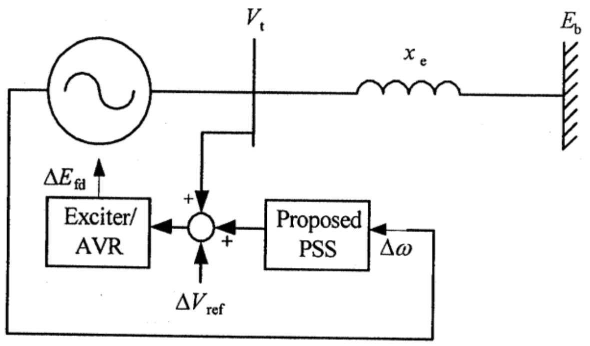

Fig. 1. Single-machine infinite-bus power system

A synchronous generator connected to an infinite bus through lossless transmission line having an external reactance x_ε and fitted with an automatic voltage regulator, an excitation system, and the proposed PSS is shown in Fig. 1.

A linearized model describing the system dynamics used in this study is given by the following equations [8]-[10].

$$\Delta\dot{v}_t = \frac{K_6 K_7}{K_9}\Delta v_t - \frac{K_6 K_8}{K_9}\Delta P_e + K_5\Delta\omega + \frac{K_6}{T'_{d0}}\Delta e_{fd} \qquad (1)$$

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$$\dot{\Delta P_e} = \frac{K_2 K_7}{K_9}\Delta v_t - \frac{K_2 K_8}{K_9}\Delta P_e + K_1 \Delta\omega + \frac{K_2}{T'_{d0}}\Delta e_{fd} \quad (2)$$

$$\dot{\Delta\omega} = -\frac{\omega_s}{2H}\Delta\omega \quad (3)$$

$$\dot{\Delta e}_{fd} = -\frac{K_e}{T_e}\Delta v_t - \frac{1}{T_e}\Delta e_{fd} + \frac{K_e}{T_e}\Delta v_{ref} \quad (4)$$

where K_1 and K_2 are the constants derived from electrical torque; K_3 and K_4 are the constants derived from field voltage equation; K_5 and K_6 are the constants derived from terminal voltage magnitude; T_A is the voltage regulator time constant; K_A is the voltage regulator gain; T_E is the exciter time constant; K_E is the exciter constant related to self-excited field; T_F is the regulator stabilizing circuit time constant; T'_{d0} is the d-axis transient open circuit time constant; H is the inertia moment coefficient; U_E is the supplementary excitation control input.

$$K_7 = \frac{K_1 - K_2 K_3 K_4}{K_3 T'_{d0}} \quad (5)$$

$$K_8 = \frac{K_5 - K_3 K_4 K_6}{K_3 T'_{d0}} \quad (6)$$

$$K_9 = K_2 K_5 - K_1 K_6 \quad (7)$$

B. Variable Structure Control

VSC systems constitute an important class of control systems. Unlike other control systems, in VSC the structure is not fixed but is varied during the control process. The changes in the structure take place with respect to a certain predetermined surface known as the switching surface in the state space of the system. In other words, the structure of the feedback system is altered or switched, whenever its state crosses the switching surface. Consequently, the closed loop system is described as a VSC system [10]-[13].

The design technique has two main stages:

Sliding Surface Design: As described above, in variable structure control, the system state is made to follow a specific trajectory defined by the switching surface or the sliding surface in state space of the system.

Let this surface in the transformed state space be

$$\sigma = \bar{c}_1 \bar{x}_1 + \bar{c}_2 \bar{x}_2 \ldots\ldots\ldots\ldots \bar{x}_n = 0 \quad (8)$$

where $\bar{c}_1, \ldots\ldots \bar{c}_{n-1}$ are constants. These constants can be selected so that the system dynamics in the sliding mode has a desirable response (8). When the system trajectory is on the sliding surface

$$\sigma = \bar{c}_1 \bar{x}_1 + \bar{c}_2 \bar{x}_2 \ldots\ldots\ldots\ldots \bar{x}_n = 0 \quad (9)$$

i.e.

$$\bar{x}_n = -\bar{c}_1 \bar{x}_1 - \bar{c}_2 \bar{x}_2 \ldots\ldots\ldots\ldots - \bar{c}_{n-1} \bar{x}_{n-1} \quad (10)$$

It can be shown that the characteristic equation of the system dynamics when it is on the surface is given by

$$s^{n-1} + c_{n-1}s^{n-2} + c_{n-2}s^{n-3} \ldots\ldots + c_1 = 0 \quad (11)$$

Since, the open loop eigenvalues of the linear system given in eqn. 1 are readily available. Therefore, the closed loop eigenvalues of the system can always be selected to improve the stability of the system.

By comparing eqns. (7) and (8), the constants $\bar{c}_1, \ldots\ldots \bar{c}_{n-1}$ can be calculated. The transformation $\bar{X} = T^{-1}X$ yields the sliding surface in original state space as given below

$$\sigma = \bar{C}T^{-1}X = CX = c_1 x_1 + c_2 x_2 \ldots\ldots\ldots\ldots x_n \quad (12)$$

where $c_1, \ldots\ldots c_{n-1}$ are the coefficients of the sliding plane in the original state space.

Control law: Selection of control gains is the next phase of the VSC design procedure. The aim is to determine the switched feedback gains which will drive the plant state trajectory to the switching surface and maintain sliding mode condition. A necessary and sufficient condition to making this happen is (10)

$$\sigma\dot{\sigma} < 0 \quad (13)$$

Equation (10) can be simplified as (11)

$$[(\psi - \psi_{eq})X]\sigma < 0 \quad (14)$$

The satisfaction of the above condition is guaranteed if the controller gains ψ_i (associated with each state x_i) are selected to be equal to two constants α_i and β_i where

$\alpha_i < \psi_{eqi}$ and $\beta_i > \psi_{eqi}$ and

$$\psi_i = \begin{cases} \alpha_i ; x_i\sigma > 0 \\ \beta_i ; x_i\sigma < 0 \end{cases} \quad (15)$$

The feedback control law is

$$u = \psi X \quad (16)$$

C. Problem Formulation as an Optimization Problem

In this work, coefficients in the design of sliding surface are selected to be the elements of the decision vector to minimize design objective as given in (17)

$$J = \int_0^{t_{sim}} \Delta\delta^2 dt \quad (17)$$

where Δδ is the rotor angle deviation

The design optimization problem is posed as an unconstrained problem. The optimization technique used is

Particle swarm optimization (PSO).

III. Overview of Particle Swarm Optimization

The Particle swarm optimization is an evolutionary computation technique developed by Eberhart and Kennedy [14]; later applied by others [15], [16], inspired by social behavior of bird flocking or fish schooling. PSO algorithm applied in this study can be described as follows:

Step 1: Initialize a population (array) of particles with random positions and velocities v on d dimension in the problem space. The particles are generated by randomly selecting a value with uniform probability over the d^{th} optimized search space $[x_d^{\min}, x_d^{\max}]$.

Step 2: For each particle x, evaluate the desired optimization fitness function J in d variables.

Step 3: Compare particles fitness evaluation with x_{pbest}, which is the particle with best local fitness value. If the current value is better than that of x_{pbest}, then set x_{pbest} equal to the current value and x_{pbest} locations equal to the current locations in d-dimensional space.

Step 4: Compare fitness evaluation with population overall previous best. If current value is better than x_{pbest}, the global bets fitness value than reset x_{pbest} to the current particle's array index and value.

Step 5: Update the velocity v. There are two ways of updating the velocities and are given below:

a) Inertia weight (PSO-iw):

$$v_{id}(k) = K[v_{id}(k-1) + \varphi_1.rand_1(x_{idpbest}(k-1) - x_{id}(k-1)) + \varphi_2.rand_2(x_{idgbest}(k-1) - x_{id}(k-1))]$$

$$K = \frac{2}{|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}|}$$

where $\varphi = \varphi_1 + \varphi_2$, $\varphi > 4$. $k, i, d, rand_{1,2}$, are similar to Inertia weight method. For both methods the particle's velocity in the d^{th} dimension is limited by some maximum value $v_d^{\max}$ is proposed as:

$$v_d^{\max} = \eta . x_d^{\max}$$

where η is a small constant value chosen by the user, usually between 0.1-0.2 of $x_d^{\max}$ (17). For this study it was found empirically that a value of 0.1 for η provides satisfactory results.

Step 6: Update position of the particles

$$x_{id}(t) = v_{id}(t) + x_{id}(t-1)$$

Step 7: Loop to 2, until a criterion is met, usually a good fitness value or a maximum number of iterations (generations) m is reached.

IV. Simulation Results and Discussions

The controller feedback gains have been optimized over the operating region of the machine considering a variation of 20 - 120% of real power and -20 – 140% of reactive power.

The controller feedback gain vector is obtained such that it satisfies (21).

$$\psi = [0.0054 \;\; -5.19 \;\; 0.0247 \;\; -0.0159] \tag{18}$$

Simulation results for the test point P_e = 0.6 p.u. and Q_e = 0.02 p.u. are shown for a small disturbance of 5% in ΔV_{ref}.

The parameters [13] used in PSO are given in Table I.

TABLE I: PSO

Parameter	Value/Type
Swarm Size	25
Cognitive acceleration	2.8
Social acceleration	1.3
Maximum no. of iterations	150
Maximum function evaluations	2500
Maximum CPU time	2500

Fig.2 shows the variation of $\Delta\delta$ with and without VSC based controller.

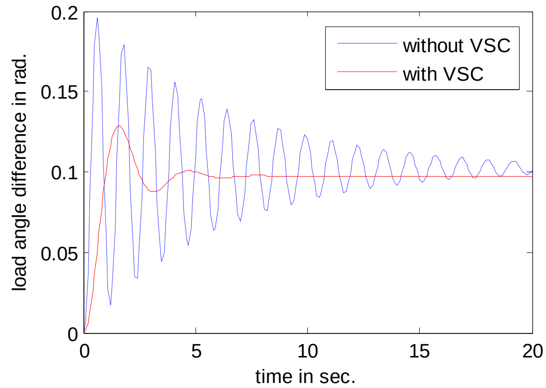

Fig. 2. $\Delta\delta$ variation with and without VSC

With VSC based controller, $\Delta\delta$ oscillations are damped out very fast in less than 8 sec. than as compared to when without controller. Also, the steady state error is less as can be observed from Fig. 2.

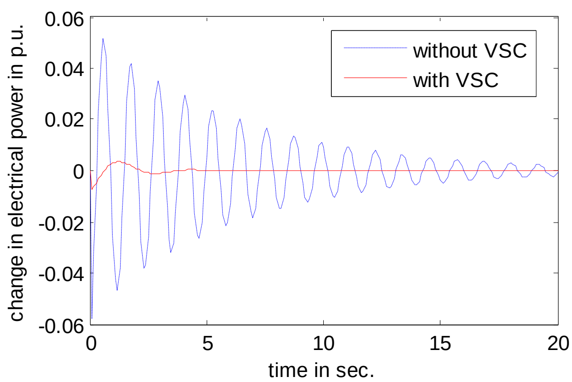

Fig. 3. ΔP_e variation with and without VSC

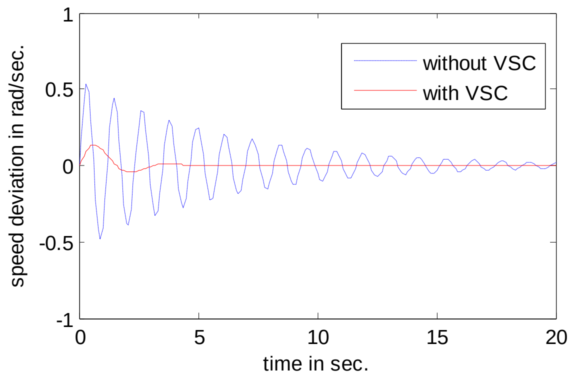

Fig. 4. $\Delta\omega$ variation with and without VSC

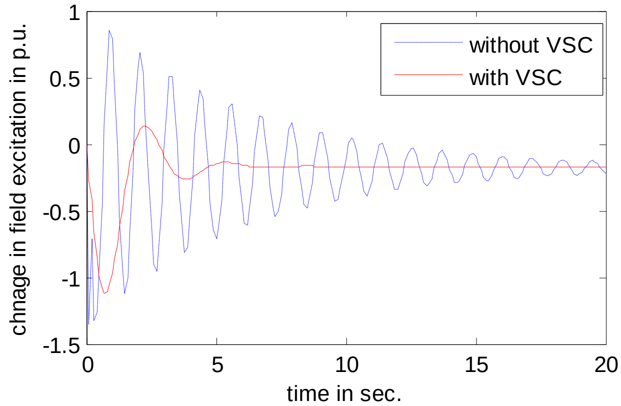

Fig. 5. $\Delta e\ fd$ variation with and without VSC

From Fig. 3 – Fig. 5, it can be seen that the oscillations in the respective states decay in less than 5 sec. with VSC controller. Also, the overshoot in these states is less with VSC controller than as compared to without VSC controller.

The proposed VSC based controller has been tested for its robustness under various operating conditions. The proposed controller succeeds in damping out in $\Delta\delta$ oscillations in terms of settling time, steady state error and overshoot under these operating conditions.

V. Conclusions

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.

Appendix

System parameters:

$P_e = 0.6$ p.u. ; $Q_e = 0.02$ p.u.; $V_t = 1.0$ p.u.; $X_d = 1.75$ p.u.; $X_q = 1.5845$ p.u.; $X'_d = 0.4245$ p.u.; $X''_q = 1.04$ p.u.; $\delta_0 = 44.37°$; $T_{d0} = 6.66$ sec.; $\omega_B = 377$ rad/sec.; H=3.542 sec.;

$K_A = 400$; $T_A = 0.025$ sec.

Transmission line and transformer data:

$X_e = 0.8125$ p.u.; $X_T = 0.1364$ p.u.

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