

APPLICATION OF VARIABLE STRUCTURE CONTROL TECHNIQUES FOR IMPROVING POWER SYSTEM DYNAMIC STABILITY

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ABSTRACT

This paper presents a study on "application of variable structure control techniques for improving power system dynamic stability". The basic concepts of variable structure control (VSC) are discussed. The procedure of designing a variable structure controller for the linearized model obtained by linearizing non linear characteristics of a synchronous machine connected to infinite bus bar is explained. The possibility of a controller which would guarantee proper operation irrespective of machine output power, transmission line reactance and infinite bus voltage is discussed. The results of the simulation studies show that with the proposed controller, the stability of the synchronous machine is improved significantly.

INTRODUCTION

The power system stabilizers are used to improve the dynamic stability of synchronous machines connected to the power system. Most of the PSS designs which are based on classical or optimum control techniques use a linearized model of an electrical machine connected to power systems [1-4]. Although the controllers thus designed perform extremely well at the designed operating point, their performance at the other operating points may not be satisfactory.

Variable structure control techniques can be used for the non linear control design to ensure satisfactory operation over a wide range of operating conditions. In this paper, a variable structure controller which gives satisfactory operation irrespective of machine output power, system impedance and infinite bus voltage will be designed. The design of the variable structure controller is first explained for the linearized model obtained by linearizing non linear characteristics of a synchronous machine connected to infinite bus bar around a pre-selected operating point. The procedure is later extended to accommodate non linearities in the synchronous machine operation.

CONCEPTS OF VSC

Variable structure control systems (VSC) constitute an important class of control systems. The basic philosophy of VSC is for the system to change into different structures at certain instants so as to combine the desirable properties and at the same time to eliminate undesirable properties of each

of the structures.

The changes in the structure take place with respect to a certain predetermined surface known as the switching surface. In this case desired parts of the trajectories of two different structures can be combined to form a new structure with desired trajectory and new system properties. The benefit of introducing this additional complexity, as compared to other control methods, is the possibility of combining useful properties of each of the structures. More over, VSC can possess new properties which are not inherent in any of those structures.

Another aspect of VSC is the possibility of obtaining trajectory describing a new type of motion called "sliding regime" which is not inherent in any of the original structures. In this case, when ever the system state leaves the switching surface, the controller changes its structure so that system state is forced to constrain its motion on the switching surface. This motion is referred to as the sliding mode or the sliding regime. In the sliding mode the system dynamics are governed by the equation of the switching surface. Therefore operating the system in the sliding mode makes it robust and insensitive to parameter variation and disturbances.

1 VSC design

To illustrate the basic VSC design criteria, n^{th} order multivariable system with m number of inputs is considered in the following controller canonical form.

$$\begin{bmatrix} \dot{X}_1 \\ \dots \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & : & A_{12} \\ \dots & : & \dots \\ A_{21} & : & A_{22} \end{bmatrix} \begin{bmatrix} X_1 \\ \dots \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \dots \\ B_2 \end{bmatrix} u \quad (1)$$

The submatrices are of the dimension; $X_1 : (n-m) \times 1$, $X_2 : m \times 1$, $A_{11} : (n-m) \times (n-m)$, $A_{12} : (n-m) \times m$, $A_{21} : m \times (n-m)$, $A_{22} : m \times m$, $B_2 : m \times m$ and $u : m \times 1$.

The switching plane is given by the equation

$$\sigma = \begin{bmatrix} C_1 & : & C_2 \end{bmatrix} \begin{bmatrix} X_1 \\ \dots \\ X_2 \end{bmatrix} = 0, \quad (2)$$

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

A Design of switching hyperplane

By substituting equation (2) in (1), \dot{X}_1 can be reduced to;

$$\dot{X}_1 = [A_{11} - A_{12} C_2^{-1} C_1] X_1 \quad (3)$$

The above reduced system has the feedback structure " $A_{11} + A_{12} F$ " with $F = -C_2 C_1$. If the pair (A_{11}, A_{12}) is controllable, then it is possible to effectively use classical feedback control design techniques to compute F such that $A_{11} + A_{12} F$ has desired characteristics. Therefore it can be assumed that $C_2 = I$ = identity matrix and the pole placement technique can be used to select a suitable matrix C_1 such that the eigenvalues of the matrix $[A_{11} - A_{12} C_1]$ characterising the dynamics in the sliding mode have a desirable placement.

B Selection of control gains

Selection of control gains is the second phase of the VSC design procedure. Here the aim is to determine switched feedback gains which will drive the plant state trajectory to the switching surface and maintain a sliding mode condition. A necessary and sufficient condition for making this happen is

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

From equations (1) and (2), by substituting for $\dot{\sigma}$, the following condition can be obtained.

$$[(C_1 A_{11} + C_2 A_{21}) X_1 + (C_1 A_{12} + C_2 A_{22}) X_2 + C_2 B_2 u] \sigma < 0 \quad (4)$$

Let's assume the feed back control which satisfies this condition is

$$u = \Psi x; \quad (5)$$

where

$$\Psi = [\Psi_1 \quad \Psi_2 \quad \dots \quad \Psi_n]$$

By defining a quantity u_{eq} , equivalent to a form of feed back control such that,

$$\begin{aligned} u_{eq} &= -(C_2 B_2)^{-1} [(C_1 A_{11} + C_2 A_{21}) X_1 \\ &\quad + (C_1 A_{12} + C_2 A_{22}) X_2] \quad (6) \\ &= \Psi_{eq} x \quad (7) \end{aligned}$$

equation (4) can be simplified to the form,

$$C_2 B_2 [(\Psi - \Psi_{eq}) x] \sigma < 0 \quad (8)$$

As $C_2 B_2 > 0$, the above condition is satisfied if

$$\Psi_i = \begin{cases} \alpha_i < \Psi_{eqi} & \text{when } x_i \sigma > 0 \\ \beta_i > \Psi_{eqi} & \text{when } x_i \sigma < 0 \end{cases}$$

LINEARIZED MODEL

The linearized dynamic model of a single generator supplying an infinite bus through external impedance, including the effects of voltage regulator and excitation system, as treated in the reference [5] can be obtained in the following form. The parameters in these relations, K_1, \dots, K_6 are defined in reference [6].

$$\begin{aligned} \begin{bmatrix} \Delta v_t \\ \Delta P_e \\ \Delta w \\ \Delta e_{fd} \end{bmatrix} &= \begin{bmatrix} \frac{K_6 K_7}{K_9} & -\frac{K_6 K_8}{K_9} & K_5 & \frac{K_6}{T'_{do}} \\ \frac{K_2 K_7}{K_9} & -\frac{K_2 K_8}{K_9} & K_1 & \frac{K_2}{T'_{do}} \\ 0 & -\frac{w_s}{2H} & 0 & 0 \\ -\frac{K_c}{T_c} & 0 & 0 & -\frac{1}{T_c} \end{bmatrix} \begin{bmatrix} \Delta v_t \\ \Delta P_e \\ \Delta w \\ \Delta e_{fd} \end{bmatrix} \\ &+ \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & -\frac{w_s}{2H} \\ \frac{K_c}{T_c} & 0 \end{bmatrix} \begin{bmatrix} \Delta v_{ref} \\ \Delta P_m \end{bmatrix} \\ \Delta \delta &= \begin{bmatrix} \frac{K_2}{K_9} & -\frac{K_6}{K_9} & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta v_t \\ \Delta P_e \\ \Delta w \\ \Delta e_{fd} \end{bmatrix} \end{aligned}$$

where

$$K_7 = \frac{K_1 - K_2 K_3 K_4}{K_3 T'_{do}}, \quad K_8 = \frac{K_5 - K_3 K_4 K_6}{K_3 T'_{do}}, \quad K_9 = K_2 K_5 - K_1 K_6,$$

CONTROLLER DESIGN

A synchronous machine with the parameters given in appendix is assumed to be delivering $(0.8 + j 0.6)$ pu to an infinite bus of voltage 1.0 pu through a transmission line of impedance 0.4 pu. The mechanical power input is assumed constant.

The open loop poles of the above system are at the positions $-0.0752 \pm j 6.8284$, -2.6837 and -17.629 . To improve the stability of the system, the poles are to be located away from the imaginary axis. Therefore the eigen values of the closed loop system given by the matrix $[A_{11} - A_{12} C_1]$ are selected at $(-2 + j6)$, $(-2 - j6)$ and -10 .

Then the switching plane can be determined as given by the following equation.

$$\sigma = 100.42 \Delta v_t - 46.88 \Delta P_e - 7.65 \Delta w + \Delta e_{fd} \quad (9)$$

The equivalent control gain Ψ_{eq} is given by

$$\Psi_{eq} = [1.0999 \quad 0.5386 \quad -0.1162 \quad 0.0129] \quad (10)$$

Therefore sufficient condition for the existence of sliding mode on the switching surfaces are

Table 1: Selection of control gains

	Ψ_1	Ψ_2	Ψ_3	Ψ_4
α_i	< 1.0999	< 0.5386	< -0.1162	< 0.0129
β_i	> 1.0999	> 0.5386	> -0.1162	> 0.0129

1 Extension of the design for non linear systems

As the operating point of the machine varies, the parameters of the model varies and the set of values obtained for the

equivalent control gains varies. For example the variation of the parameter K_1 and the equivalent control gain 1 with operating power is shown in the following diagrams. Similar variations can be observed in other parameters and equivalent control gains.

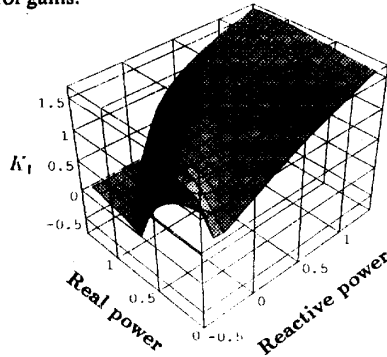


Fig. 1: Variation of parameter K_1

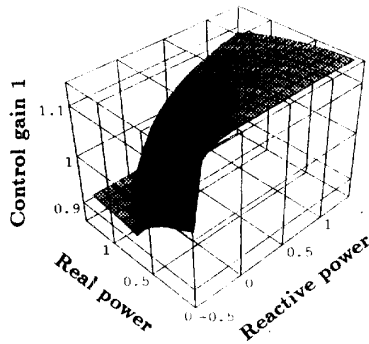


Fig. 2: Variation of control gain 1

The variation of the controller equivalent feedback gains over the stable operating region of the machine, keeping infinite bus voltage (E) and transmission line external reactance (x_e) constant at 1.0 pu and j 0.4 pu respectively has been studied and the results are shown in the following table.

Table 2: variation of equivalent control gains

	Ψ_1	Ψ_2	Ψ_3	Ψ_4
maximum value	1.1351	5.1643	0.2743	0.0129
minimum value	0.8786	0.2597	-1.9589	0.0129

2 Effect of system impedance and infinite bus voltage

Studies have been extended to determine the variation of the equivalent control gains with the variation of system impedance and infinite bus voltage. For various values of system impedance and infinite bus voltage, the variation of equivalent control gains over the stable operating region of the machine has been studied. The analysis has been carried out for the values of system impedance (x_e) of 0.2, 0.4, 0.6 and 0.8 pu and for the values of infinite bus voltage (E) of 0.8, 1.0, 1.4 and 1.8 pu. The variation of extreme values (maxima and minima) of equivalent control gains within the

feasible operating region, for different values of x_e and E is represented in the following table.

Table 3: Global variation of equivalent control gains

	Ψ_1	Ψ_2	Ψ_3	Ψ_4
maximum value	1.2415	10	0.4675	0.0132
minimum value	0.7732	-5.9	-5.31	0.0127

3 Universal controller design

The maximum and minimum values of table (3) indicate the global range of the variation of the equivalent control gains for all practically feasible operating power settings, for different magnitudes of infinite bus voltage and for different magnitudes of system impedance. Therefore in the VSC design the switched feed back gains can be selected so that the whole possible operating region is encompassed. This will guarantee the sliding mode operation for any operating state, infinite bus voltage and system impedance. Therefore for the controller design the switched feed back gains can be selected so that

Table 4: Global selection of control gains

	Ψ_1	Ψ_2	Ψ_3	Ψ_4
α_i	< 0.7732	< -5.9	< -5.31	< 0.0127
β_i	> 1.2415	> 10	> 0.4675	> 0.0132

TRANSIENT PERFORMANCE OF THE CONTROLLER

For the variable structure controller, the switched feed back gains have been selected as follows.

Table 5: Selected control gains

	Ψ_1	Ψ_2	Ψ_3	Ψ_4
α_i	-2	-8	-5.5	0.01
β_i	2	12	3	0.02

Simulation studies have been carried out to determine the transient and dynamic stability of a generator connected to an infinite bus through a double circuit transmission line.

The transient response of the machine for a three phase fault of 0.08 s duration in one of the transmission lines near the machine terminals has been studied. The fault is cleared by opening the faulted line. The transient responses of the machine subjected to the above fault condition for prefault output powers of the machine of $0.8 + j0.6$, $1.0 - j0.2$, $1.2 + j0.8$ and the control variation corresponding to prefault output power of $0.8 + j0.6$ are shown in the figures (3)- (6). A simulation time step of 1 ms and a control time step of 10 ms were used in the simulation. The response of the VSC controller has been compared with that of a pole placement controller with poles placed at the same positions as placed in the VSC controller.

The simulation results given in figures (3) - (6) show that a significant improvement in system damping can be obtained with the variable structure controller when compared with the performance of the pole placement controller. The proposed variable structure controller gives satisfactory performance over a wide operating range.

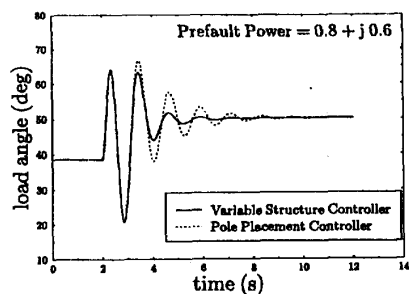


Fig. 3: Transient response of the machine : prefault output power $0.8 + j0.6$

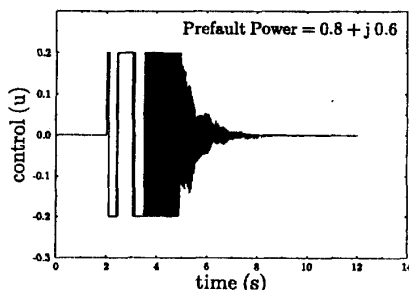


Fig. 4: Control variation : prefault output power $0.8 + j0.6$

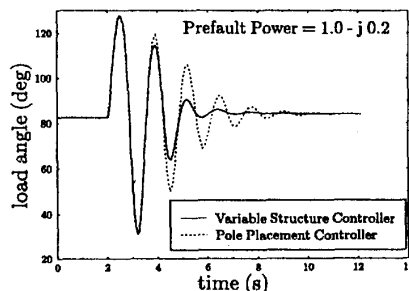


Fig. 5: Transient response of the machine : prefault output power $1.0 - j0.2$

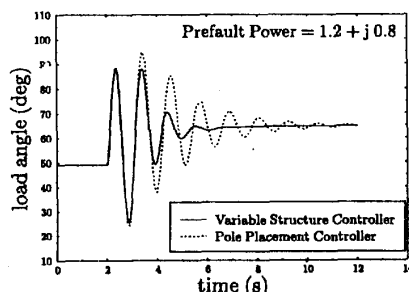


Fig. 6: Transient response of the machine : prefault output power $1.2 + j0.8$

CONCLUSION

Variable structure control techniques have been used to improve the dynamic stability of a synchronous machine connected to an infinite bus. The variable structure control design procedure has been presented for the linear dynamic model obtained by linearizing the non linear equations describing dynamics of a synchronous machine connected to an infinite bus. The procedure has been extended to accommodate non linearities in the synchronous machine operation. The designed VSC would guarantee proper operation irrespective of machine output power, transmission line reactance and infinite bus voltage. The performance of the variable structure controller has been investigated and also compared with that of a pole placement controller by using simulation studies. The results show that a significant improvement in the performance of the stabilizer can be obtained with variable structure control.

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REFERENCES

- [1] H. A. M. Moussa and Y. N. Yu, "Optimal power system stabilization through excitation and/or governor control," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS 91, pp. 1166-1173, May 1972.
- [2] A. B. R. Kumar, "Optimal control of power systems to improve dynamic stability," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS 101, pp. 1570-1577, Jan. 1982.
- [3] N. D. Rao, Elmetwally, and O. P. Malik, "Experimental results on the implementation of an optimal control for synchronous machines," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS 94, pp. 1192-1200, July 1975.
- [4] Iyer, S. Narayana, and B. J. Cory, "Optimisation of turbo generator transient performance by differential dynamic programming," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS 90, pp. 2149-2157, Sept. 1971.
- [5] W. G. Heffron and R. A. Phillips, "Steady state stability of synchronous machines as affected by voltage regulator characteristics," *AIEE Trans. (Power Apparatus and Systems)*, vol. 71, pp. 692-697, Aug. 1952.
- [6] F. P. Demello and C. Concordia, "Concepts of synchronous machine stability as affected by excitation control," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS 88, pp. 316-329, Apr. 1969.
- [7] U. Itkis, *Control systems of variable structure*. John Wiley and Sons, New York, 1976.

APPENDIX

Machine and exciter data

Machine Constants

$x_d = 1.6$, $x_q = 1.55$, $x'_d = 0.32$, $T'_{do} = 6.0$, $H = 5.0$

Exciter

$K_e = 25.0$, $T_e = 0.05$