Military Technical College
Kobry El-Kobbah
Cairo, Egypt

10th International Conference
On Aerospace Sciences&
Aviation Technology

Variable Structure-Based Synchronous Generator Excitation Controller for Power Systems

W. Sabry*

A. Eliwa*

Abstract

In this paper, an excitation controller is designed by the variable structure control theory to improve the transient stability of a single machine infinite bus system. The pole assignment techniques are employed for determining the switching hyper plane. The computer simulation and an experiment in a scaled power system show that the designed controller can provide effective damping torque and improve the dynamic performance for the power system.

Keywords

Variable structure control, Power system control, Generator, Excitation control, Disturbance parameters, Dynamic stability

---

* *Egyptian Armed Forces*

1. Introduction

The excitation control of synchronous generator is very important to improve

several decades. The literature on excitation control is extensive and various approaches have been proposed. Since the sixties the power system stabilizer (PSS) was already being investigated [1-2] and many papers had been published on this subject. Later, the coordinated application of stabilizers in multimachine power systems was presented [3].

Since the early seventies, the optimal control theory has been widely applied for the design of excitation control of synchronous generator and a method for selecting parameters of stabilizers in multimachine power system was addressed [4-5].

In recent years, along with the development of power electronics and nonlinear control theory, many researchers are exploring nonlinear excitation control, especially from differential geometric control approaches to enhance steady states performance as well as transient stability [6]. However, the complex computation has limited its further application to power system.

control theory. During the recent decade [7-10], VSC received much attention due to its robust response characteristics, for example:

a. VSC potentially can maintain a desired response characteristic almost independent of the system structure;

b. VSC is one of the most developed branches of nonlinear control theory and theoretically be used for any nonlinear system. But other nonlinear

c. Relative to most nonlinear controls, VSC is easy to realize;

d. The greatest advantage of VSC is its adaptiveness to external disturbances as well as to internal model perturbations.

To a large extent, the above features correspond to the transient stability control problem in power systems. The contribution of this paper is the design and application of a VSC law to synchronous generator excitation controller connected to an infinite bus power system.

The paper is organized as follows: the principle of VSC is briefly introduced in section 2. The design procedure of the controller is described in section 3. The simulation performance results of the controller are demonstrated and the variability of such a control strategy is established and further research is suggested in section 4.

2. Synthesis of the VSC

Consider the following system:

$$\dot{X} = A(X) + B(X).u \tag{1}$$

Where: $X = (x_1\ x_2\ \ \ _n)^T$ is a state vector, A(X) and B(X) are the appreciate nonlinear vector functions, and u is a scalar control variable.

Assuming discontinuous control:

$$u = \begin{cases} u^+ & \text{when} \quad S = C^T X > 0 \\ u^- & \text{when} \quad S = C^T X < 0 \end{cases} \tag{2}$$

Where: $u^+ \neq u^-$, S is a linear switching hyper plane, $C^T = (c_1\ c_2\ \ \ _n)$ is a constant vector. It is assumed that $S > 0$, when $t = 0$, then the system state vector X will reach at the plane $S = 0$ in a finite time t under the control action, a two phase variable case is shown in Fig. (1).

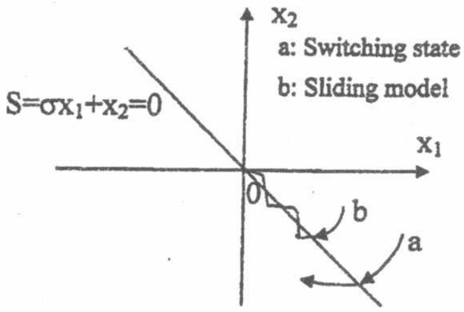

Fig. 1. The state trace

The state X passes through switching plane and enters the domain of $S < 0$, and the control suddenly changes from u^+ to u^-. Depending on the system parameters and σ, the state can be remained in the domain of $S < 0$, which forms a switching control. On the other hand, the state can pass through the switching plane again in the opposite direction and enters into the domain of S >0 once more, which forms a sliding mode control.

It is obvious that the state X can be restricted on the switching plane S = 0 by the discontinuous control u. Therefore, the condition to form a sliding mode is [7]:

$$\begin{cases} \lim\limits_{s \to 0^+} \dot{S} < 0 \\ \lim\limits_{s \to 0^-} \dot{S} > 0 \end{cases} \tag{3}$$

That is $S\dot{S} < 0$, which forces the system motion toward the hyper plane S = 0. The following approaching law is chosen in the design:

$$\dot{S} = -\varepsilon.\text{sgn}(S) - K.S \tag{4}$$

Where sgn(S) is the sign function of S and the term [ε.sgn(S)] generates the desired variable control structure for the different sides of the switching hyper plane in the state space. Item [K.S] makes the trajectories coverage exponentially in the ideal case. The control [u] can be found by the following procedures.

$$\dot{S} = C^T.\dot{X} = C^T(A.X + B.u) = C^T.A.X + C^T.B.u \tag{5}$$

From (5), the control [u] is obtained:

$$u = [-C^T.B]^{-1}[C^T.A.X - \dot{S}] \tag{6}$$

Substitution of (4) into (5) yields:

$$u = [-C^T.B]^{-1}[C^T.A.X + \varepsilon.\text{sgn}(S) + K.S] \tag{7}$$

Where [ε] and [K] are given positive constants which are not sensitive to system operating point.

3. Power systems with VSC

In this paper, we consider the power system is a single generating unit connected to an infinite bus which is shown in Fig. (2) [5].

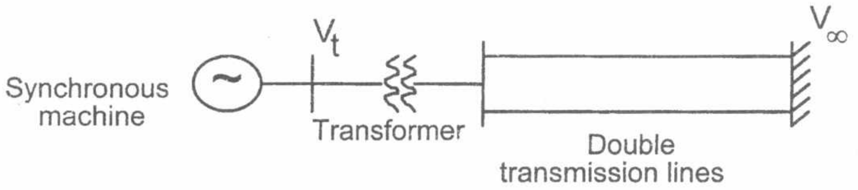

Fig. 2. A single generator infinite system

On the system operating point $\delta = 70^o$, the model of the system can be written as:

$$\dot{X} = A.X + B.u \tag{8}$$

Where:

$$X = [\Delta P_e \quad \Delta\omega \quad \Delta U_t]^T \quad , \quad u = \Delta E_f$$

$$A = \begin{bmatrix} \frac{S_E - S_v}{T_d' S_v} & S_E & \frac{-S_E R_v}{T_d' S_v} \\ -\frac{\omega_o}{H} & -\frac{D}{H} & 0 \\ \frac{S_E - S_v}{T_d' R_v S_v} & 0 & \frac{-S_E}{T_d' S_v} \end{bmatrix} = \begin{bmatrix} -0.215 & 0.691 & -0.125 \\ -39.5 & -0.625 & 0 \\ -0.134 & -0.0015 & -0.078 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{R_E'}{T_{do}} & 0 & \frac{R_E'}{T_{do} R_v} \end{bmatrix}^T = \begin{bmatrix} 0.081 \\ 0 \\ 0.051 \end{bmatrix}$$

Once the system has been established, the next step is to construct the sliding surface so that restricted to this surface the system has a desired response.

In this paper, the selection of the switching vector is done using a pole assignment technique as outlined below.

Suppose the state equation of the system (8) can be expressed as:

$$\dot{X}_1 = A_{11}.X_1 + A_{12}.X_2$$
$$\dot{X}_2 = A_{21}.X_1 + A_{22}.X_2 + B_2.u \qquad (9)$$

The switching plane is:

$$S = C_1.X_1 + C_2.X_2 \qquad (10)$$

i.e.

$$X_1 = X_1$$

$$X_2 = C_2^{-1}.S - C_2^{-1}.C_1.X_1$$

Therefore the system (8) is transformed as:

$$\dot{X}_1 = (A_{11} - A_{12}.C_2^{-1}.C_1).X_1 + A_{12}.C_2^{-1}.S$$

$$\dot{S} = [(C_1.A_{11} + C_2.A_{11}) - (C_1.A_{12} + C_2.A_{22}).C_2^{-1}.C_1].X_1 + (C_1.A_{12} + C_2.A_{22}).C_2^{-1}.S + C_2.B_2.u$$

In the subspace $S_o = \ker C$, there are:

$$S = C_1.X_1 + C_2.X_2 = 0$$

$$\dot{S} = C_1.\dot{X}_1 + C_2.\dot{X}_2 = 0$$

i.e.

$$\dot{X}_1 = (A_{11} - A_{12}.C_2^{-1}.C_1).X_2$$

$$u_{eq} = (C_2.B_2)^{-1}.[(C_1.A_{11} + C_2.A_{11}) - (C_1.A_{12} + C_2.A_{22}).C_2^{-1}.C_1].X_1$$

Let $k = C_2^{-1}.C_1$ and $\det(A_{11} - A_{12}.K) = P(S)$ where:

$$P(S) = (s - p_1).(s - p_2).(s - p_3).....(s - p_n),$$

And the p_i

As $C=[C_1,C_2]=[C_2.K,C_2]=C_2.[K,I_m]$ if let $C_2=I_m$, then the $C=[K,I_m]$ can only be determined. For the case power system:

$$X=[\Delta P_e \quad \Delta\omega \quad \Delta U_t]^T u=\Delta E_f$$

$$A=\begin{bmatrix} -0.215 & 0.691 & -0.125 \\ -39.5 & -0.625 & 0 \\ -0.134 & -0.0015 & -0.078 \end{bmatrix}$$

$$B=\begin{bmatrix} 0.081 \\ 0 \\ 0.051 \end{bmatrix}$$

$$X_1=\Delta\omega, \qquad A_{11}=A_{12}-0.625, \qquad X=[\Delta P_e \quad \Delta V_t]^T, \qquad A_{21}=\begin{bmatrix} 0.691 \\ -0.0015 \end{bmatrix},$$

$$A_{21}=\begin{bmatrix} -0.215 & -0.125 \\ -0.134 & -0.078 \end{bmatrix}, \; B=\begin{bmatrix} 0.081 \\ \\ 0.051 \end{bmatrix}, \text{ do linear transform:}$$

$$X'=T.X, \; T=\begin{bmatrix} t_1 & 0 & t_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \text{ then:}$$

$$\dot{X}=A.X+B.u \Rightarrow (\dot{X})'=A'.X'+B'.u$$

Where:

$$A'=T.A.T^{-1}=\begin{bmatrix} t_1 & 0 & t_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} -0.215 & 0.691 & -0.125 \\ -39.5 & -0.625 & 0 \\ -0.134 & -0.0015 & -0.078 \end{bmatrix} \begin{bmatrix} t_1 & 0 & t_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1}$$

$$= \begin{bmatrix} -0.00194 & 0.691 & -0.00098 \\ -39.5 & -0.625 & 0 \\ -0.134 & -0.0015 & -0.078 \end{bmatrix}$$

$$B' = T.B = \begin{bmatrix} t_1 & 0 & t_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 0.081 \\ 0 \\ 0.051 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0.051 \end{bmatrix},$$

$$t_1 = 1,\ t_2 = -\frac{0.081}{0.051} = -1.59,\ X_1' = \begin{bmatrix} \Delta P_e' \\ \Delta\omega' \end{bmatrix},\ X_2' = \Delta V_t',\ S = C_1.X_1' + C_2.X_2' .$$

Let $K = C_2^{-1}.C_1 = [k_1 \quad k_2]$, then the characteristic equation is:

$$\det[S.I - (A_{11} - A_{12}.K)] = P(S) = (s - p_1)(s - p_2) = 0 \tag{11}$$

If the poles are assigned at: $s_{1,2} = 4 \pm j3$, the $K = [k_1 \quad k_2] = [8547.9 \quad 375.69]$ can be solved from (11). As $S = C_1.X_1' + C_2.X_2' = C.X' = C'.X$ where:

$$C' = C.T = [C_1 \quad C_2]T = C_2.[C_2^{-1}.C_1 \quad 1]T = C_2.[K \quad 1]T$$

$$= C_2.[8547.9 \quad 375.69 \quad 1] \begin{bmatrix} 1 & 0 & -1.59 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= C_2.[8547.9 \quad 375.69 \quad -13590.16]$$

Let $C_2 = 8547.9$, then $C = [1 \quad 0.044 \quad -1.59]$. Therefore, the switching hyper plane S is below:

$$S = \Delta P_e + 0.044\Delta\omega - 1.59\Delta V_t \tag{12}$$

According to the VSC theory, the control is to force system motion toward the hyper plane [S = 0]. In this paper, a control [u(t)] is synthesized, which has two possible structures:

$$u = \begin{cases} u^+ & \text{when} \quad S = C^T X > 0 \\ u^- & \text{when} \quad S = C^T X < 0 \end{cases} \tag{13}$$

switch hyper plane [S(X) = 0], the u^+ and u^- as follows:

$$u^+ = 20\Delta P_e + 9\Delta\omega + 15\Delta V_t$$
$$u^- = -18\Delta P_e - 9\Delta\omega - 13\Delta V_t \quad (14)$$

4. Simulation results

In the simulation study, we consider that the power system shown in Fig. (2) with a large sudden fault at 100 ms and the fault was removed at 250 ms. The response of power angle δ(t) and generator terminal voltage $V_t(t)$ are shown in Fig. (3) and Fig. (4), which are controlled by the variable structure excitation controller (solid line) and general PID controller (dash line).

From the simulation results given above, we see that using the variable structure controller proposed in this paper can maintain transient stability and achieve voltage regulation and has better dynamic performance using the general PID excitation controller.

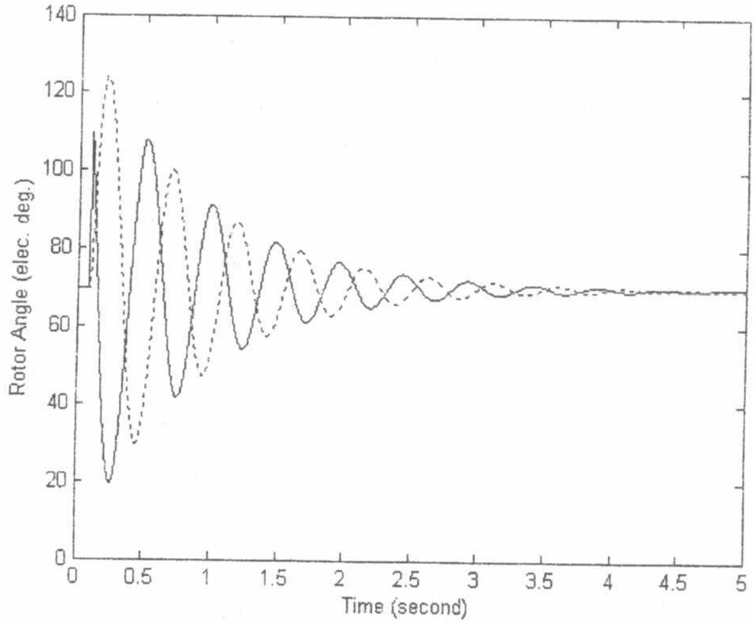

Fig. 3. The rotor angle response

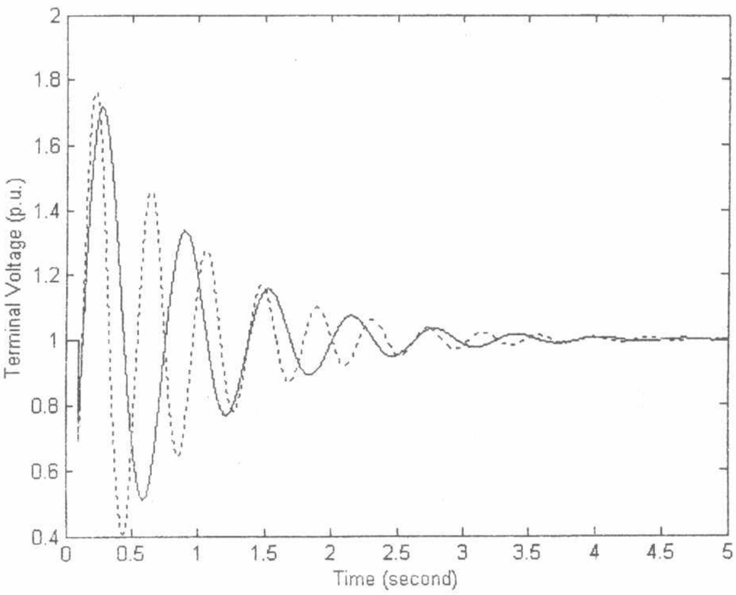

Fig. 4. The voltage response

5. Conclusion

In this paper, transient stabilization and voltage regulation of power system with a variable structure excitation control law have been discussed. The variable structure excitation control scheme has been given. The variable structure excitation control proposed in this paper can transiently stabilize a class of power systems with a large sudden fault and can achieve voltage regulation. Simulation results show that the variable structure excitation controller possesses a good dynamic performance.

References

[1] DeMello, P. F. and C. Concordia, Concepts of synchronous machine stability as affected by excitation system control, IEEE Trans. On Power Apparatus and Systems, PAS-88, No. 2, 1969.

[2] Moussa, H. A. and Yu, Y. N., Dynamic interaction of multimachine power system and excitation control, IEEE Trans. On Power Apparatus and Systems, PAS-94, No. 4, 1975.

[3] DeMello, P. F. et al., Coordinated application of stabilizers in multi-machine power systems, IEEE Trans. On Power Apparatus and Systems, PAS-99, No. 3, 1980.

[4] Yu, Y. N. and Siggers, C., Stabilization and optimal control signals for a power system, IEEE Trans. On Power Apparatus and Systems, PAS-90, No. 4, 1971.

[5] Yu, Y. N., Electric power system dynamics, Academic Press, 1983.

[6] Lu, Q. and Y. Sun, Nonlinear control of power systems, Chinese Academic Press, 1993.

[7] Utikin, I. V., Sliding modes in control and optimization, Springer-Verlag, Berlin, Heideberg, 1992.

[8] Wang, Y. et al., Variable structure FACTS controllers for power system transient stability, IEEE Trans. On Power Systems, 7, No. 1, 1992.

[9] Wang, Y. et al., Transient stabilization of power systems with an adaptive control law, Automatica, 30, No. 9, 1994.

[10] Wang, Y. et al., Variable structure braking resistor control in multimachine power system, IEEE Trans. On Power Systems, 9, No. 3, 1994.