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A SLIDING MODE CONTROLLER FOR SYNCHRONOUS GENERATOR EXCITATION

James Katende & Ayokunle Awolewa
Covenant University, Ota

Abstract:
This paper presents sliding mode excitation control for a synchronous generator connected to an infinite bus. A simplified system model is employed to design a sliding mode controller (SMC) that has the inherent ability of not only stabilizing the system, but also maintaining same in the face of system parameter variations. Simulation results, showing dynamic performance of the system under both constant excitation and SMC-controlled excitation are presented, and validation of the robustness feature of an SMC established.

Keywords: Power system control, sliding model control, robustness.

1. Introduction

Power systems have grown considerably in size in recent years just as much as efforts to make them operate optimally. Because of the principal position they occupy as an integral part of power systems, synchronous generators have continued to demand greater consideration in power system operation. Also, since power systems depend on synchronous generators for generation of electrical power, a major and necessary condition for satisfactory system operation is that all synchronous generators maintain synchronism with one another; this is greatly influenced or determined by the dynamics of generator rotor angles and power-angle relationships [1]. Power system stability refers to the tendency of a power system to react to disturbances by developing restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium [2], and these stability problems are concerned with the behaviour of the synchronous generators after they have been perturbed [3]. Various control strategies have been studied and applied to synchronous generator excitation to damp out oscillations and maintain dynamic stability of power systems; they range from optimal control techniques [4], feedback linearization control techniques [5], adaptive control techniques [6], and robust control techniques [5] to fuzzy logic control techniques [7]. This paper considers the deployment of sliding mode control (SMC), which is well-known for robustness with respect to system parameter variations. SMC utilizes a switching control action such that the system's representative point is driven onto and constrained to move towards the state-space origin along a surface defined in terms of state variables as [8,9]:

$$s = f(x) = 0 \tag{1}$$

where x is the n-dimensional state vector.

Motion on the surface s is referred to as the sliding mode [8]. The paper examines the performance of a single machine infinite bus (SMIB) system under sliding mode excitation control action when the system is assumed to have both constant and variable parameters.

Implementation of the SMC switching control is usually imperfect and the value of surface 's' is not known with infinite precision. Consequently, SMC is characterized by control signal chattering. In the control of synchronous generators, chattering is of minimal concern since switching can occur in the high kilohertz range, well beyond the structural frequency of the mechanical systems involved.

2. System modelling

A third-order non-linear state-space model describing the SMIB system can be written as [10]:

$$\begin{aligned} \dot{\delta} &= \omega \\ \dot{\omega} &= B_1 - A_1\omega - A_2\psi_f \sin\delta - \frac{B_2}{2}\sin 2\delta \\ \dot{\psi}_f &= u - C_1\psi_f + C_2\cos\delta \end{aligned} \tag{2}$$

where

δ = rotor angle (rad)
ω = speed deviation (rad/s)
ψ_f = field flux linkage

Expressions for system parameters A_1, A_2, B_1, B_2, C_1 and C_2 in eqn. (2) are given as [11]

$$A_1 = \frac{D}{M}, \quad A_2 = \frac{E}{M(X'_d + X_e)T'_{do}}$$

$$C_1 = \frac{(X_d + X_e)}{(X'_d + X_e)T'_{do}}, \quad C_2 = \frac{(X_d - X'_d)E}{(X'_d + X_e)}$$

Where

D = damping coefficient

M = inertial constant

P_m = mechanical power input

E = infinite busbar voltage

X_e = transmission line impedance

X_d = d-axis synchronous reactance

X_q = q-axis synchronous reactance

X_d' = d-axis transient reactance

T_{do}' = d-axis transient open-circuit time constant

By expanding the non-linear state model of eqn (2) into a Taylor's series about the steady-state operating point given by, $\mathbf{\Omega_0} = [\delta_0\ \omega_0\ \psi_{f0}]^t$ and neglecting all the higher-order terms, the resulting linear model becomes:

$$\Delta\dot{\Omega} = A\Delta\Omega + B\Delta u$$

(4a)

where

$$\Delta\Omega = \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta\psi_f \end{bmatrix}$$

$$A = \begin{bmatrix} \frac{\partial f_1}{\partial\delta} & \frac{\partial f_1}{\partial\omega} & \frac{\partial f_1}{\partial\psi_f} \\ \frac{\partial f_2}{\partial\delta} & \frac{\partial f_2}{\partial\omega} & \frac{\partial f_2}{\partial\psi_f} \\ \frac{\partial f_3}{\partial\delta} & \frac{\partial f_3}{\partial\omega} & \frac{\partial f_3}{\partial\psi_f} \end{bmatrix}_{\Omega_0}, \quad B = \begin{bmatrix} 0 \\ 0 \\ \frac{\partial f_3}{\partial u} \end{bmatrix}_{u_0}$$

And the perturbations from the steady-state values are defined as:

$$\Delta\delta = \delta - \delta_0$$
$$\Delta\omega = \omega - \omega_0$$
$$\Delta\psi_f = \psi_f - \psi_{f0}$$
$$\Delta u = u - u_0$$

Let the system parameters (in per unit)[11]:

$$X_d = 1.25 \qquad X_d' = 0.3$$
$$X_q = 0.7 \qquad T_{d0}' = 9.0$$
$$M = 0.0185 \qquad D = 0.005$$
$$X_e = 0.2 \qquad E = 1.0$$

The per unit steady-state values of the system variables are given as [11]:

$\delta_0 = 0.7438$, $\omega_0 = 0$, $\psi_{f0} = 7.7438$, and u = 1.1. based on these data, the values of A_1, A_2, B_1, B_2, C_1, C_2 are computed as A_1=0.270, A_2= 12.012, B_1 = 39.189, B_2 = -48.048, C_1 = 0.323, and C_2 = 1.9, and are used to evaluate all the elements of the Jacobian matrices, **A** and **B**, for the linear system model as follows:

$$\left.\frac{\partial f_1}{\partial\delta}\right|_{\Omega_0,u_0} = 0,\ \left.\frac{\partial f_1}{\partial\omega}\right|_{\Omega_0,u_0} = 1,\ \left.\frac{\partial f_1}{\partial\psi_f}\right|_{\Omega_0,u_0} = 0,$$

$$\left.\frac{\partial f_2}{\partial\delta}\right|_{\Omega_0,u_0} = 48.048\cos 2\delta_0 - 12.012\psi_{f0}\cos\delta_0 = -64.534$$

$$\left.\frac{\partial f_2}{\partial\omega}\right|_{\Omega_0,u_0} = -0.270,\ \left.\frac{\partial f_2}{\partial\psi_f}\right|_{\Omega_0,u_0} = -12.012\sin\delta_0 = -8.1533$$

$$\left.\frac{\partial f_3}{\partial\delta}\right|_{\Omega_0,u_0} = -1.9\sin\delta_0 = -1.2896,\ \left.\frac{\partial f_3}{\partial\omega}\right|_{\Omega_0,u_0} = 0,$$

$$\left.\frac{\partial f_3}{\partial\psi_f}\right|_{\Omega_0,u_0} = -0.323,\ \left.\frac{\partial f_3}{\partial u}\right|_{\Omega_0,u_0} = 1$$

Substituting these values into eqn (4) leads to the following linear model.

$$\begin{pmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{\psi}_f \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ -64.534 & -0.270 & -8.1533 \\ -1.2896 & 0 & -0.323 \end{pmatrix} \begin{pmatrix} \Delta\delta \\ \Delta\omega \\ \Delta\psi_f \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \Delta u$$

(4b)

1. SMC design

The SMC design problem here is to determine the switching surface, s, and the switching control gain vector K such that the system trajectory, from any initial position, is forced to hit the switching surface s = 0 and slide along it to the state-space origin. For the purpose of designing the SMC system, matrices A and B are suitably partitioned so that eqn. (4) is rewritten as

$$\begin{bmatrix} \dot{\Omega}_1 \\ \dot{\Omega}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \Omega_1 \\ \Omega_2 \end{bmatrix} + \begin{bmatrix} 0 \\ B_2 \end{bmatrix} u_e$$

(5)

where

$$\Omega_1 = \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix}, \quad \Omega_2 = [\Psi_f] \quad u_e = \Delta u$$

$$A_{11} = \begin{bmatrix} 0 & 1 \\ -64.534 & -0.270 \end{bmatrix}, A_{12} = \begin{bmatrix} 0 \\ -8.1533 \end{bmatrix}$$

$$A_{21} = [-2.2896 \quad 0] \; A_{22} = [-0.323], \text{ and}$$

$$B_2 = [1]$$

Let the switching surface and the control law are given by

(6)

and

(7)

where C_1 and C_2 are 1 x 2 and 1 x 1 matrices while K_1 and K_2 are likewise 1 x 2 and 1 x 1 matrices.

3.1 Switching surface design

Substitution of eqn (6) into eqn (5) results in the following equation for

(8)

A pole-placement design technique can therefore be applied to equation (8) in order to obtain a suitable value for, $C_2^{-1}C_1$ and hence C_1 when it is assumed that C_2 is an identity matrix [9]. To avoid rotor angle oscillations after a system disturbance, the real eigenvalues with negative real parts are assigned for motion on the switching surface. For a given selection of sliding eigenvalues, it can be shown that the switching surface is described by:

$$s = -8.0294x_1 - 2.7878x_2 + x_3$$

(9)

where

(10)

3.1 Control law design

Control gains are selected so that the system state trajectory is driven onto the switching surface and remains in a sliding mode condition. A necessary and sufficient condition for realizing this is to choose a Lyapunov function [6, 11, 12].

$$V = \frac{1}{2}s^2$$

which can satisfies

$$\dot{V} = s\dot{s} < 0$$

(11)

By substituting for and combining eqns (6) and (8), the following condition can be written:

(12)

Let the control law which satisfies this condition be given as

(13)

Where

$$K = [k_1 \quad k_2 \quad k_3]$$

From eqn (10), an equivalent control law, u_{eeq}, can be formed such

$$u_{eeq} = -(C_2B_2)^{-1}[(C_1A_{11} + C_2A_{21})\Omega_1 + (C_1A_{12} + C_2A_{22})\Omega_2]$$

(14)

$$= K_{eq}\Omega$$

Therefore, combining eqns (11) and (12), eqn (10) can be reduced to

(15)

From this last expression, the control gains are selected so that

$$k_j \begin{cases} k_{eqj} & \text{when } \Omega_j s > 0 \\ k_{eqj} & \text{when} \Omega_j s < 0 \end{cases}$$

(16)

By introducing a signum function, the general control law can be formed as:

(17)

By solving eqn (13) completely, K_{eq} could be found as K_{eq} = [-177.6183 7.2767 -22.4068]

(18)

While p_1, p_2, and p_3 are arbitrary parameters whose values are chosen as described below, and x_1, x_2, and x_3 which are the same as $\dot{U}_1$, $\dot{U}_2$, and $\dot{U}_3$ are defined in eqn (9).

Since p_1, p_2, and p_3 are usually chosen to be positive and large [13], their values are given here to be twice the absolute values of equivalent control gains.

The control law is now given as

$$\mathbf{u}_e = [-177.6183 - 356.2366\,\mathrm{sgn}(x_1 s)]x_1 + [7.2767 - 14.5534\,\mathrm{sgn}(x_2 s)]x_2 + [-22.4068 - 44\,\mathrm{sgn}(x_3 s)]x_3$$

(19)

1. Simulation results

It is desired that the system quickly returns to the steady-state nominal state following a disturbance. Figure 1a is a response of the system under constant excitation while Figure 1b shows the result obtained on application of the designed sliding mode controller to the non-linear system. Effect of variation of parameters is also observed, and Figures 2 to 5 show the system response when parameters A_1, B_2, C_1 and C_3 are varied.

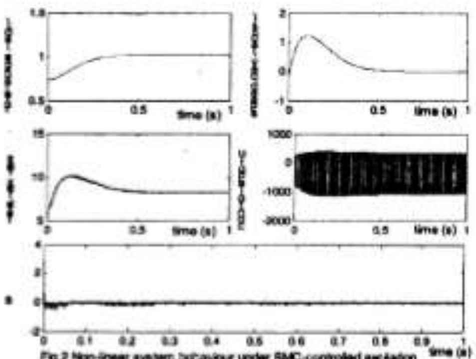


Fig 2 Non-linear system behaviour under SMC-controlled excitation for 29% reduction in A2.

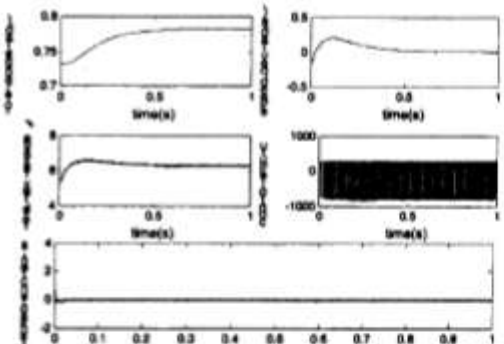


Fig 3 Non-linear system behavior under SMC-controlled excitation for 42% reduction in B2

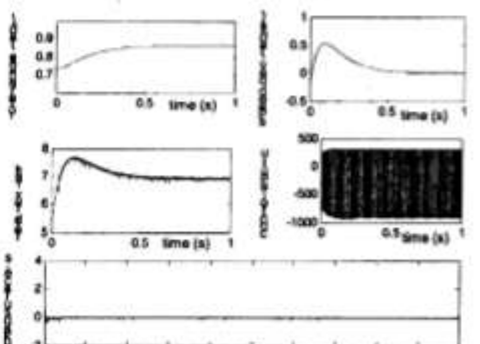
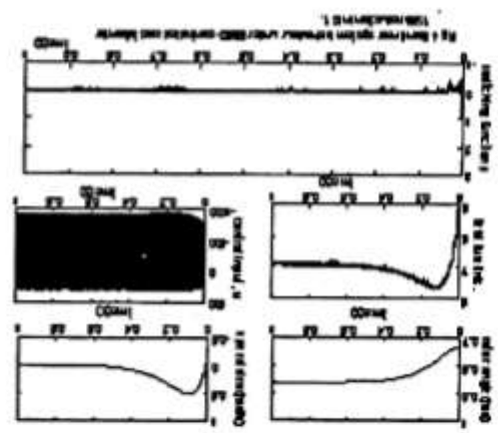


Fig1b Non-linear system characteristics under SMC-controlled excitation.



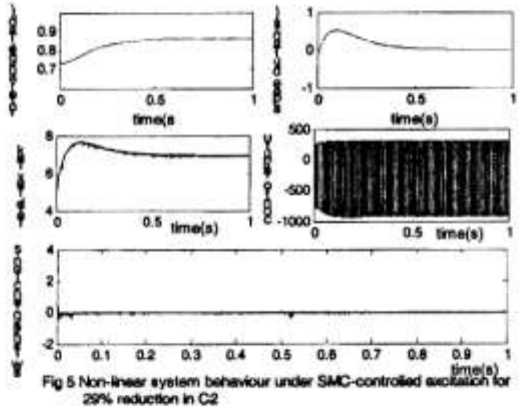


Fig 5 Non-linear system behaviour under SMC-controlled excitation for 29% reduction in C2

3 Conclusion

A sliding mode controller has been designed and applied to the excitation of a synchronous generator connected to an infinite bus to damp out oscillations. The controller has been designed based on a linearized system model. Simulation results show that the controller performs well on the non-linear system: zero steady-state error, restoration of system to the steady-state within 0.5s, and the rotor angle is driven back to the steady-state without oscillations. The designed system is robust with respect to parameter variations. This is achieved at the expense of high control signal chattering. Further work is in progress to reduce the control chatter so as to minimize wear of the control actuators

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■ James Katende[1] Ayokunle Awolewa[2]
Covenant University, Ota