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Transient Stability Improvement of Multi-machine Power System using Higher Order Sliding Mode Control

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Abstract: The main purpose of this paper is to design a non-linear second order sliding mode control for transient stability of two generator system (TGS). Second order sliding mode algorithms such as Twisting Algorithm (TA) and Super Twisting Algorithm (STA) have been applied and their simulation results are compared. The equilibrium point of TGS is maintained after the clearance of fault and the system is in post fault condition. Simulation results verify the proposed controller. The advantage with this type of control is that it does not require linearized model for its implementation and reduced chattering effect.

Keywords: Chattering, higher order sliding mode control (HOSM), sliding mode control (SMC), second order sliding mode (SOSM), transient stability, super twisting algorithm (STA), twisting algorithm (TA)

1. INTRODUCTION

Power demand is increasing day by day but the available large scale power system is limited due to economy and environmental effects. So as to avoid damage and loss to the exisisting network, various precautions are taken. In which the problem of transient stabilization which occurs due to short circuit, sudden faults introduced in the system or lightening is crucial one and is of interest in research community. The power system is highly nonlinear and distributed so the control strategy is supposed to suppress the instability and poorly damped power angle oscillations. Excitation control is one of the most favored, effective and economic method to improve the stability of power systems. Not only it enhances the power system stability, but also attenuates low-frequency oscillations inherent in power systems during transient conditions (Wagh Sushama and Kamath and, 2009)(Li-Ying and Jiaxin, 2009).

Different control techniques are proposed for excitation control of generators such as Immersion and Invariance (I and I) methodology is introduced in (Wissam and Ortega, 2011). Robust H_∞ control technique is proposed in (Li-Ying and Jiaxin, 2009)(S.S. Ahmed and L. Chen, 1996)(S. Hardiansyah and J., 2006). Direct Lyapunov method in J. Machowsky and S. Robak, 2000) and feedback linearization is discussed in (A. Kazemi and M.R. Jahed, 2007)(E. Tuglie and S.M., 2008). Passivity and energy functions analysis is proposed in (Romeo Ortega and Martha Galaz, 2005)(T. Shen and Y. Sun, 2005). Model Predictive Control (MPC) is shown in (Wagh Sushma and Kamath and, 2009)(F. Borrelli and A. Bemporad, 2011).

The difficulty in application of I and I is the need to solve a partial differential equation and assumes all generators are actuated and have the same relative damping. H_∞ control enhance the tuning of classical controllers but these were developed using linear models. To take into account the entire operation region of generators, nonlinear control design techniques are more suited. Nonlinear techniques such as Direct Lyapunov method, feedback linearization and interconnection and damping assignment passivity-based control (IDA-PBC) and energy functions analysis are introduced but these controllers requires exact knowledge of the plant parameters and disturbances. Application of the feedback linearization method cost computationally expensive control algorithm. Almost all systems today have to work under constraints and the system are multi-input and multi-output. So mentioned nonlinear methods lead to very elegant solutions, but their design procedures are complicated and unable to handle constraints in a systematic manner. The problem with model predictive control (MPC) is that it is a slow process whereas SMC has advantage it is robust to the system uncertainties and disturbances (exact knowledge of model is not required) and reduced order dynamics of the system (R. Benayache and W. Bahloul, 2010)(Wilfrid Perruquetti and Jean Pierre)(V.I. Utkin).

In this paper higher order sliding mode control (HOSM) technique is proposed for transient stabilization of two generator systems which is the extension to the single machine infinite bus system problem presented in (R. Benayache and W. Bahloul, 2010) using SOSM (SOSM is used for single machine infinite bus system (SMIBS)). The SMC approach is best known as an efficient tool to design robust controllers for complex high-order nonlinear dynamic systems operating under uncertain environment. The research in SMC area started by Russian engineers about 40 years ago, and gradually sliding mode control method has received much more attention from the international control community within the last few decades. The main advantage of sliding mode is low sensitivity to system parameter variations and disturbances which eliminates the necessity of exact modeling of system. SMC reduces the system dimension and the complexity of feedback design and also restricts the dynamics to the subspace (sliding surface) of state space and any deviation from sliding surface results control action and trajectory of the system is brought back to slide on the chosen surface. SMC implies that control actions are discontinuous state functions which may easily be implemented by conventional power converters with 'on-off ' as the only admissible operation mode. Sliding mode control has been proved to be applicable to a wide range of problems in robotics, power system, process control, vehicle and motion control (Asif Sabanovic and Leonid M.)(Siew-Chong and Yuk-Ming)(Leonid Fridman and Jaime Moreno).

After receiving the boost in 1990s, HOSM is introduced so as to avoid the drawbacks of SMC theory i.e. chattering effect (high frequency oscillations) and constrain on choosing the sliding variable due to relative degree r equal to one requirement because of these drawbacks HOSM is introduced which acts on higher order time derivatives of the sliding variable instead of first time derivative in standard sliding modes. Higher order sliding mode controllers are able to drive to zero not only the sliding variable, but also its $(r-1)$ successive derivatives (r^{th}order sliding mode). Chattering effect is significantly reduced, since the high frequency control switching is "hidden" in the higher derivative of the sliding variable. The main problem with HOSM implementation is increasing information demand i.e. it needs $s, \dot{s}, \ddot{s}, \dots, s^{r-1}$ to be available. The work done on robust exact differentiator technique can solve this problem (Wissam Dib and Romeo Ortega, 2011). Twisting algorithm (TA) and super twisting algorithm (STA) are robust non-linear second order sliding mode algorithms in which TA requires the first derivative of sliding variable s in its control design whereas the advantage of the STA is that the knowledge of the derivative of the sliding variable s is not required, therefore, it does not demand the robust differentiator which estimates the higher order derivatives of sliding variable (Y. Shtessel and C. Edwards) (Leonid Fridman and Jaime Moreno).

In this paper TA and STA are used for transient stabilization problem of two generators system. As this is the non-linear system, proposed control technique stabilizes the rotor angles δ_1, δ_2 and maintained the equilibrium after clearance of fault and better performance of the power system.

This paper is organized as follows. Section 2 deals with the two generators system model in which each subsystem is represented by 3^{rd} order model. Basics of SMC (TA and STA), sliding surface and control design (using algorithms) is presented in Section 3. Simulation results are shown in Section 4 followed by Section 5 with conclusion.

2. DYNAMICAL MODEL FOR TWO GENERATOR SYSTEM

The problem of transient stabilization of large scale power system consisting of n generators interconnected through transmission network (lossy) is discussed in (Romeo Ortega and Martha Galaz, 2005). The dynamics of i^{th} generator with excitation is given below (Equation 1):

$$\left.\begin{aligned} \dot{\delta}_i &= w_i \\ \dot{w}_i &= -D_i w_i + P_i - G_{ii}E_i^2 - E_i \sum_{j=1, j\neq i}^{n} Y_{ij}E_j \sin(\delta_i - \delta_j + \alpha_{ij}) \\ \dot{E}_1 &= -a_i E_i + b_i \sum_{j=1, j\neq i}^{n} E_j \cos(\delta_i - \delta_j + \alpha_{ij}) + E_{fi} + u_i \end{aligned}\right\}$$

(1)

where,

$$Y_{ij} \cong \sqrt{G_{ij}^2 + B_{ij}^2},\ \alpha_{ij} \cong \arctan\frac{\mathrm{G_{ij}}}{\mathrm{B_{ij}}}$$

$$a_i \cong \frac{1}{T_{di}}[1 - B_{Mii}(x_{di} - x'_{di})],\ b_i \cong \frac{x_{di} - x'_{di}}{T_{di}} Y_{ij}$$

δ_i= rotor angle

w_i= rotor speed

E_i= quadrture axis internal voltage

P_i= mechanical power

D_i= damping coefficient

u_i= field excitation signal

G_{ii}= self conductance of generator i

E_{fi}= constant component of the field voltage

G_{ij}= conductance

B_{ij}= susceptance

x_{di}= direct axis synchronous reactance

x'_{di}= direct axis transient reactance

In this paper the problem of transient stabilization of power system consisting of two generators is considered and the model of two generator system is shown in Fig. 1.

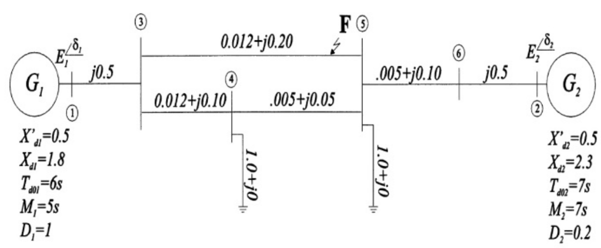

Fig.1. Two Generators System

Equations of the system are obtained using (1) with $n=2$.

$$\left.\begin{aligned} \dot{\delta}_1 &= w_1 \\ \dot{w}_1 &= -D_1 w_1 + P_1 - G_{11} E_1^2 - Y E_1 E_2 \sin(\delta_1 - \delta_2 + \alpha) \\ \dot{E}_1 &= -a_1 E_1 + b_1 E_2 \cos(\delta_1 - \delta_2 + \alpha) + E_{f1} + u_1 \\ \dot{\delta}_2 &= w_2 \\ \dot{w}_2 &= -D_2 w_2 + P_2 - G_{22} E_2^2 + Y E_1 E_2 \sin(\delta_1 - \delta_2 - \alpha) \\ \dot{E}_2 &= -a_2 E_2 + b_2 E_1 \cos(\delta_2 - \delta_1 + \alpha) + E_{f2} + u_2 \end{aligned}\right\} \quad (2)$$

Assume that the model has stable equilibrium at $[\delta_i', 0, E_i']$ with $E_i' > 0$. Assumptions on equilibrium will restrict $|\delta_i' - \delta_j'|$ to be small. Also assume that line conductances are sufficiently small. Model considered has critical clearing time almost equal to zero.

3. SMC OF TWO GENERATOR SYSTEM

3.1 Basics of SOSM

Consider an uncertain SISO nonlinear system which is

affine in

$$\dot{x} = f(x,t) + b(x,t)u \quad (3)$$

$$s = s(x,t) \quad (4)$$

with $x \in \chi \subset \mathbb{R}^n$ the state variable and $u \in U \subset \mathbb{R}$ the input, such that $\chi = x \in \mathbb{R} \mid |x_i| \leq x_{iMAX}, 1 \leq i \leq n$ and $u = x \in \mathbb{R} \mid |u| \leq u_{MAX}$. $s(x,t)$ is the output function, called *sliding variable*. *f*, *b* and *s* are smooth uncertain functions. The objective is to enforce, possibly in a finite time, the zeroing of the measurable sliding (or constraint) variable $s = s(x,t)$. By differentiating twice *s*, under the assumption that system (3) has relative degree versus *s* equal to 2, it leads to the following relationship:

$$\ddot{s}(t) = \varphi(x,t) + \gamma(x,t)u(t) \quad (5)$$

The dynamics in (5) are assumed to satisfy the following:

$$0 < K_m \leq \gamma(x,t) \leq K_M \quad |\varphi(x,t)| < C_0 \quad (6)$$

where *Km; KM* and C_0 are some positive constants. Essentially this is a requirement that the uncertainty levels in the process are bounded and that some worse case bounds on the uncertainty can be assumed. Let us set $y_1(t) = s(x,t)$, it has been shown that, under sensible conditions, apart from a possible initialization phase, the second order sliding mode (SOSM) problem is equivalent to the finite time stabilization problem for the following uncertain second order system (R. Benayache and W. Bahloul, 2010)(Wilfrid Perruquetti and Jean Pierre):

$$\left.\begin{aligned} \dot{y}_1 &= y_2 \\ \dot{y}_2 &= \varphi(x,t) + \gamma(x,t)v(t) \end{aligned}\right\} \quad (7)$$

If system (7) has relative degree *r = 2* with respect to $y_1 = s$, then $v = u$, while, if *r = 1*, $v = \dot{u}$.

Note that (6) is formulated in input output terms. These conditions are satisfied at least locally for any smooth system (1) having a well-defined relative degree at a given point with $s, \dot{s}, \ddot{s}, \dots, s^{r-1} = 0$. Then, it is possible to generate different kinds of algorithms (ideal twisting, sampled twisting, super twisting, sub-optimal...) such that the system evolve featuring a second order sliding mode, after a finite time, i.e. the trajectories lie in the second order sliding set defined by:

$$S^2 = \{x \in \mathbb{R}^n \mid s = \dot{s} = 0\} \quad (8)$$

The second order sliding mode (SOSM) approach (G. Bartolini and A. Ferrara, 1999) (Wilfrid Perruquetti and Jean Pierre) solves the stabilization problem for (10) by requiring the knowledge of y_1 and just the sign of y_2. Some algorithms, which propose a solution to the above control problem, have been presented in the literature (Wilfrid Perruquetti and Jean Pierre)(Bartolini and A. Ferrara 1997) (S. V. Emel'yanov and S. V. Korovin, 1986)(Bartolini and A. Ferrara, 1997). There are many SOSM algorithms such as TA, STA, sub optimal algorithm, drift algorithm which ensures second order sliding modes. In the present paper the focus is on the so-called twisting and super twisting second order sliding mode algorithms for two generators system.

a. Twisting Algorithm

The twisting controller is historically the first proposed

2-sliding controller. TA requires the knowledge of $\dot{s}$ (Y. Shtessel and C. Edwards).It is defined by the formula:

$$u(t) = -r_1 sign(s) - r_2 sign(\dot{s}), \qquad r_1 > r_2 > 0 \quad (9)$$

r_1, r_2 are given by

$$(r_1 + r_2)K_m - C > (r_1 - r_2)K_M + C, (r_1 - r_2)K_M > C \quad (10)$$

b. Super Twisting Algorithm

The super twisting algorithm has the advantage that it does not require any knowledge of the derivative of the sliding variable s ($\dot{s}$). This algorithm can be defined by the following control law:

$$u(t) = u_1(t) + u_2(t) \quad (11)$$

where $u_1(t), u_2(t)$ are obtained as follow

$$\dot{u}_1(t) = \begin{cases} -u & si\ |u| > 1 \\ -W sign(s) & si\ |u| \leq 1 \end{cases} \quad (12)$$

$$u_2(t) = \begin{cases} -\lambda_1 |s_0|^\rho sign(s) & si\ |s| > s_0 \\ -\lambda_1 |s|^\rho sign(s) & si\ |s| \leq s_0 \end{cases} \quad (13)$$

This algorithm defines the control law, as a combination of two terms. The first is defined in terms of a discontinuous time derivative while the second is a continuous function of the sliding variable. The corresponding sufficient conditions for the finite time convergence to the sliding manifold are:

$$W > \frac{C_0}{K_m}, \ \lambda_1^2 \geq \frac{4C_0 K_M (W + C_0)}{K_m^2 K_m (W - C_0)}, \quad 0 < \rho \leq 0.5 \quad (14)$$

where W, ρ and λ_1 are variable controller parameters, C_0 is positive norm bound on the smooth uncertain function, s_0 is the boundary layer thickness, the choice of $\rho = 0.5$ assures that sliding order 2 is achieved (R. Benayache and W. Bahloul, 2010) (G. Bartolini and A. Ferrara, 1999)(Wilfrid Perruquetti and Jean Pierre).

3.2 Sliding Variable and Control Design for TGS

δ_{d1} *and* δ_{d2} are desired power angles of machines.

Let us define sliding surface s_1 and s_2 for given two generator system as follows:

$$s_1 = p_1(\delta_1 - \delta_{d1}) + q_1(\dot{\delta}_1 - \dot{\delta}_{d1}) + r_1(\ddot{\delta}_1 - \ddot{\delta}_{d1}) \quad (15)$$

$$s_2 = p_2(\delta_2 - \delta_{d2}) + q_2(\dot{\delta}_2 - \dot{\delta}_{d2}) + r_2(\ddot{\delta}_2 - \ddot{\delta}_{d2}) \quad (16)$$

where $p_1, q_1, r_1, p_2, q_2, r_2$ are obtained using Routh-Hurwitz criterion. Here the task is to generate a second order sliding mode on the second order sliding manifold given by the equalities:$S = \dot{S} = 0$

s_i and its first time derivative $\dot{s}_i$ for $i = 1\ to\ 2, l = 1\ to\ 2\ (i \neq l)$ is given by:

$$s_i = p_i(\delta_i - \delta_{di}) + q_i(\dot{\delta}_i - \dot{\delta}_{di}) + r_i(\ddot{\delta}_i - \ddot{\delta}_{di}) \quad (17)$$

$$\dot{s}_i = \tilde{\alpha}_i + \tilde{\beta}_i u_i \quad (18)$$

where,

$$\tilde{\alpha}_i = p_i(w_i - \dot{\delta}_{di}) + q_i(\dot{w}_i - \ddot{\delta}_{di}) + r_i(-D_i\dot{w}_i - 2G_{ii}E_i(-a_iE_i + b_iE_l\cos(\delta_i - \delta_l + \alpha) + E_{fi}) \mp Y\dot{E}_iE_l\sin(\delta_1 - \delta_2 + \alpha) \mp YE_i\dot{E}_l\sin(\delta_1 - \delta_2 + \alpha) \mp YE_iE_l\cos(\delta_1 - \delta_2 + \alpha)(w_i - w_l) - \dddot{\delta}_{di}) \quad (19)$$

$$\tilde{\beta}_i = -2r_iE_i \quad (21)$$

The final controller is designed using linearizing controller coupled to a second order sliding mode.

$$u_i = \tilde{\beta}_i^{-1}(-\tilde{\alpha}_i + v_i) \quad (22)$$

The term $-\tilde{\beta}_i^{-1}\tilde{\alpha}_i$ is called as equivalent control (V. I. Utkin). As it is not able to cancel all nonlinearities, to overcome this effect second order sliding mode is introduced.

Assuming δ_1 and δ_2 and their first and second time derivatives are bounded. Also assume that E_1 and E_2 are bounded.

Now apply twisting and super twisting algorithms to the given system:

a. Twisting Algorithm

v_1 and v_2 required in the system using TA are obtained as follow:

$$v_1 = -c_1 sign(s) - c_2 sign(\dot{s}) \quad (23)$$

$$v_2 = -c_3 sign(s) - c_4 sign(\dot{s}) \quad (24)$$

where $c_1 > c_2 > 0$ & $c_3 > c_4 > 0$.

b. Super Twisting Algorithm

v_1 and v_2 required in the system using STA are obtained as follow:

$$v_1 = v_{11} + \dot{v}_{12} \quad (25)$$

with

$$v_{11} = -c_1|s|^\rho sign(s_1) \quad (26)$$

$$\dot{v}_{12} = -c_2 sign(s_1) \quad (27)$$

$$v_2 = v_{21} + \dot{v}_{22} \quad (28)$$

with

$$v_{21} = -c_3|s|^\rho sign(s_2) \quad (29)$$

$$\dot{v}_{22} = -c_4 sign(s_2) \quad (30)$$

where c_1, c_2, c_3 *and* c_4 are positive constants.

With proper choice of c_1, c_2, c_3 *and* c_4,in finite time $s_1, \dot{s}_1, s_2$ & $\dot{s}_2$ converge to zero i.e.($s_1 = \dot{s}_1 = s_2 = \dot{s}_2 = 0$) (R. Benayache and W. Bahloul, 2010) (Y. Shtessel and C. Edwards) (Wilfrid Perruquetti and Jean Pierre).

4. SIMULATION RESULTS

The second order sliding mode control is applied to two generator system shown in Fig. (1) and simulated using MATLAB Simulink.

The two algorithms TA and STA are implemented & compared. The sequence of fault introduction and stabilization is given as follow: The system is in pre fault state. A fault is introduced at $t = 2s$ and is cleared after $t_{cl} = 50ms$. Then the system is in post fault-state (faulty line is removed). The parameters of the system given in (1) is shown in Appendix A. Rotor angle, angular frequency, quadrture axis internal voltage, excitation control and sliding variable are considered. The results are as follow:

Simulation Results using TA:

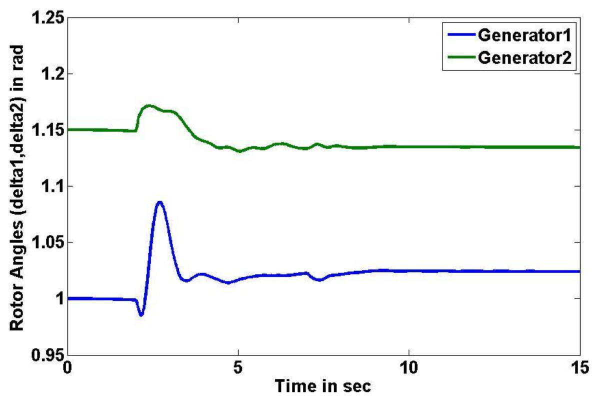

Fig. 2. Variation of rotor angle delta with Twisting SMC

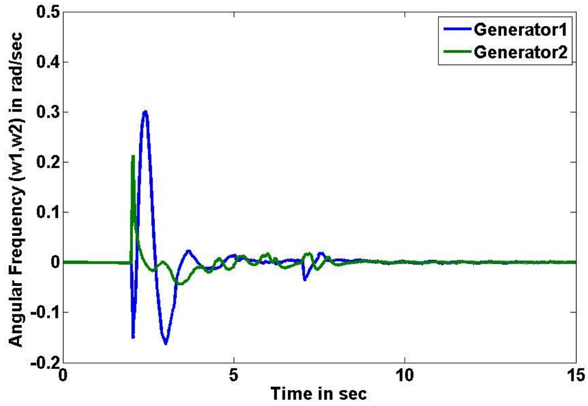

Fig. 3. Variation of angular frequency with Twisting SMC

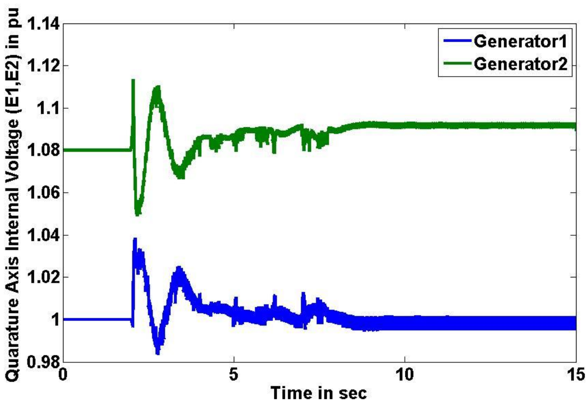

Fig. 4. Variation of Quadrture Axis Internal Voltage with Twisting SMC

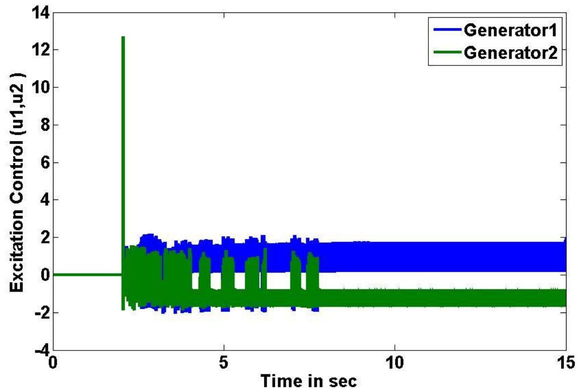

Fig. 5. Variation of Excitation Control with Twisting SMC

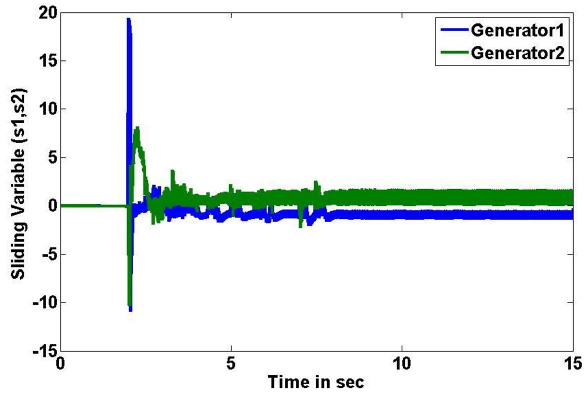

Fig. 6. Sliding Variable s_1, s_2 with Twisting SMC

Simulation Results Using STA

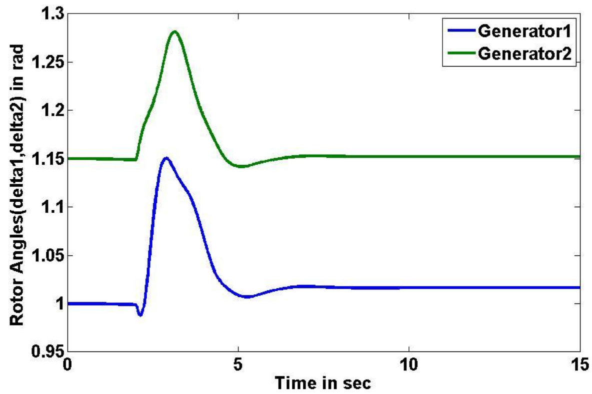

Fig. 7. Variation of rotor angle delta with Super-twisting SMC

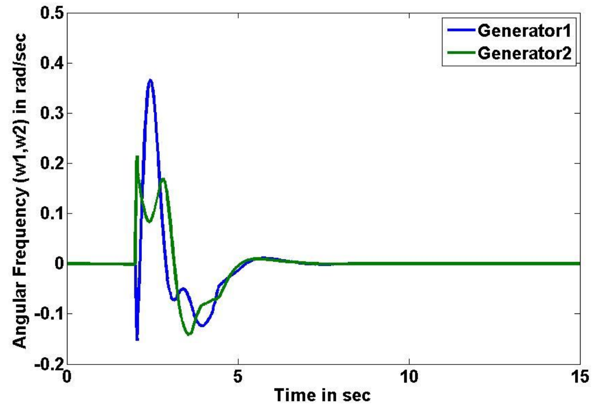

Fig. 8. Variation of angular frequency with Super-twisting SMC

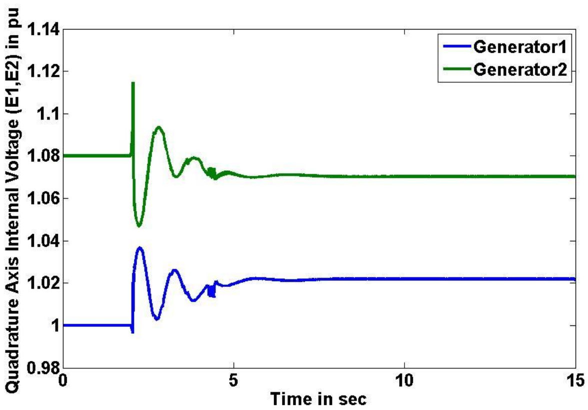

Fig. 9. Variation of Quadrture Axis Internal Voltage with Super-twisting SMC

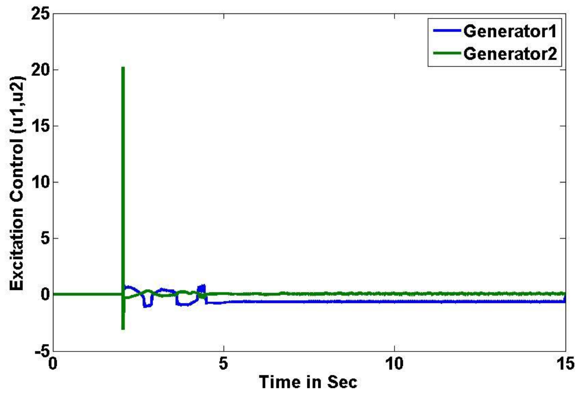

Fig. 10. Variation of Excitation Control with Super-twisting SMC

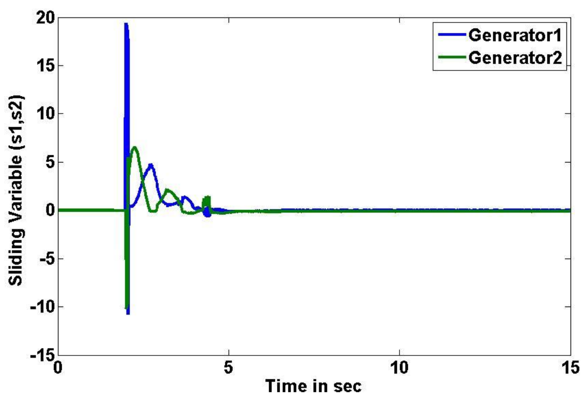

Fig. 11. Sliding Variable s_1, s_2 with Super-twisting SMC

In this paper algorithms are compared. Simulation results of TGS are shown above Fig. 2 to Fig. 11 using TA and STA. Equilibrium is achieved using both algorithms but there are some differences. Settling time of power angles is less for STA as compared to TA i.e. post fault oscillation damping is better in STA as shown in Fig. 2 and Fig. 7. Excitation control values u_1, u_2 are near to zero with STA after equilibrium is achieved Fig. 10, also chattering effect is considerably reduced in STA. Sliding Variables s_1, s_2 and $\dot{s}_1, \dot{s}_2$ are almost zero i.e.($s_1 = s_2 = \dot{s}_1 = \dot{s}_2 = 0$) in STA, which means second order sliding mode is achieved in finite time. So proposed algorithms improve the transient response and also robust to disturbances and parameter uncertainties. From above plots, new equilibrium points are:

For TA:

Machine-1:[1; 0; 1;0] → [1.025; 0; 1.01]

Machine-2:[1.15; 0; 1.08] → [1.13; 0; 1.09]

For STA:

Machine-1:[1; 0; 1:00] → [1:02; 0; 1:03]

Machine-2:[1.15; 0; 1.08] → [1.16; 0; 1.07]

5. CONCLUSION

In this paper nonlinear SOSM algorithms TA and STA have been implemented on two generator system and their comparison is done . Both algorithms are able to stabilize the transients in power system due to faults introduced in the system. Chattering is also reduced in STA as compared to TA. The results show that STA is better than TA. Overall transient response is improved. More advancements in HOSM control (3^{rd} order & more) can be implemented which will result in reduced chattering (high frequency oscillations) and can be extended to more than two machine system (multi-machine system).

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Appendix A. PARAMETERS OF TGS

Symbol	Pre-fault	Fault	Post-fault
D_1	0.2	0.2	0.2
D_2	0.2	0.2	0.2
Y_1	54.6185	59.6954	51.2579
Y_2	39.0132	42.6396	36.6127
P_1	52.2556	52.2556	52.2556
P_2	48.4902	48.4902	48.4902
G_{11}	30.7851	34.1891	28.9008
G_{22}	19.0704	17.1830	20.9008
a_1	17.72	19.1996	16.7255
a_2	14.606	15.1217	14.2937
b_1	11.834	12.9340	11.1059
b_2	10.032	10.9645	9.4147
E_{f1}	5.8158	5.8158	5.8158
E_{f2}	7.9268	7.9268	7.9268
α	0.5225	0.4892	0.5430