Excellence of Sliding Mode Controller for SVC Despite of Chattering

Babak Sadeghi
M.Sc. Student
Electrical Engineering Department
Shahed University
Tehran, Iran
babak.sadeghi@shahed.ac.ir

Mehrdad Rostami
Associate Professor
Electrical Engineering Department
Shahed University
Tehran, Iran
rostami@shahed.ac.ir

Mohammad Tavakoli Bina
Professor
Electrical Engineering Faculty
K.N.Toosi University of Technology
Tehran, Iran
tavakoli@eetd.kntu.ac.ir

Hamed Moazami Goodarzi
PhD Student
Electrical Engineering Department
Shahed University
Tehran, Iran
Hamed.Moazami.Godarzi@gmail.com

Abstract— **In this paper, a 3rd order nonlinear dynamical formation for the SVC (Static VAr Compensator) system is considered due to design a nonlinear sliding mode controller; Sliding Mode Control (SMC) technique is proposed for voltage variation amelioration and power system stability enhancement. Also SMC method is employed to face with both constant and time varying uncertainties in a power system with SVC. On the other hand, a PID controller is considered in order to distinguish which controller has a better performance, PID or SMC. The effectiveness of these two controllers for voltage stability enhancement is investigated by a case study. Through the use of SIMUINK environment of MATLAB software, two different simulations have been conducted to assess the performance of the PID and SMC controllers. Simulation results show that sliding mode controlled SVC has better response especially under high loading conditions and severe contingencies in comparison with PID controlled SVC. Also the results indicate that the proposed SMC is superior to conventional PID in terms of transiency and stability of voltage. However, using this method has some demerits that chattering is one of them. In order to eliminate or decrease chattering phenomena some methods are proposed. Using Artificial Neural Network (ANN) in SMC structure and substitution of sign function with saturation function or tangent hyperbolic function will ameliorate the chattering effect. Also a higher order SMC could be useful in chattering reduction.**

Keywords— Chattering; Linear & Nonlinear Control; PID; Reactive Power Compensation; SVC; SMC; TCR

I. INTRODUCTION

Nowadays, by denationalization of electrical systems and energy transfer, the problems like voltage deviation during load changes and power transfer limitation have a harsh effect on dependable and safe power transmission. SVC provides damping to improve transient stability using an auxiliary signal over SVCs voltage control loops [1]. Recently, the controller designs are through the use of linearized models. These models in a limited range of operating conditions are trustable. But, these linear procedures may not properly absorb the dynamics of a nonlinear power system. Researches show that a lead-lag damping controller designed could result in instability of power system by revising the nature of the load. Some lead-lag damping controllers have been designed using local measurements [2-6]. Nonlinear methods for controlling the SVC have also been proposed. A bang-bang controller uses a phase angle signal from the SVC bus voltage. Optimization of this control is mathematically complex and the nonlinearity of signal may introduce harmonics in voltages and currents that affect the control signal. Direct Feedback Linearization, has also been used to design nonlinear SVC damping controller mainly for a voltage stability problem [7, 8]. Some of the voltage instability problem can be avoided by providing appropriate reactive power support through capacitor banks or Flexible AC Transmission System (FACTS) devices such as SVC. Impact of SVC on power system oscillation damping and the capability of SVC to improve power system oscillatory stability have been investigated in [9]. Nonlinear controllers for SVC can prevent voltage instability in a power system. A 3rd order nonlinear model for the SVC system was developed and SMC technique was employed to design the nonlinear controller for SVC [10-13]. The value of some parameters is always difficult to know accurately in practice. For example, the reactance of the transmission line and the time constant of the SVC regulator may contain uncertainties. When the uncertainties are large enough, it will be necessary to re-tune the controller to handle such change. A SMC technique will be employed to overcome the problem. Given that the power system may change its structure over time, consequently, many of the system variables and parameters will change as a result; it is highly desirable to design a robust controller which is capable of maintaining its effectiveness subject to the system uncertainties. In this paper, a novel nonlinear controller is proposed for SVC to deal with time varying uncertainties without prior bounds. SMC techniques are employed to design the nonlinear controller for SVC. The effectiveness of the proposed nonlinear controller on voltage stability enhancement is demonstrated on a sample power system. The objectives of this paper consists of: Designing a nonlinear damping controller for a SVC based on the SMC technique, and Comparing the performance of the proposed controller with a conventional PID controller under different contingencies, loading conditions, and load characteristics. This paper is organized as follows. In Section 2, the SVC state space model is illustrated. In Section 3, the SMC and PID design is described. An example is described to demonstrate the validity of the proposed nonlinear controller in Section 4. The conclusion is explained in Section 5.

II. SVC MODEL

Convincing operation of the transmission system in future years is the aim of reactive power. The explanation of convincing operation is related to factors such as decreasing losses, minimizing voltage variations, ensuring load flow balance and maximizing voltage collapse margins [14-17]. The focus in this paper is on the SVC. SVC is one of controllers based on Power Electronics known as FACTS Controllers, which can provide a fast variable source or sink of reactive power. Conceptually, it is a variable shunt reactance injecting or absorbing reactive power to control the voltage. It also decreases the losses and enhances the unstable capacity of existing transmission lines. SVC can permit to increase the system loadability. It can also be used for balancing unsymmetrical loads. It is normally constituted by one TCR (thyristor controlled reactor) and a number of TSC (thyristor switched capacitor) branches. The value of the reactance of the inductor is changed continuously by controlling the firing angle of the thyristors, while each capacitor can only be switched on and off at the instants corresponding to the current zero crossings, in order to avoid inrush currents in the capacitors. Fig. 1 shows a single phase SVC consisting of a TCR and a parallel capacitor (C). This system is connected to an infinite bus behind a power system impedance of inductance (Ls) and resistance (Rs). The thyristor controlled reactor is modeled as an inductance (Lr) and resistance (Rr) in series with back to back thyristors. The switching element of the thyristor controlled reactor consists of two back to back thyristors which conduct on alternate half cycles of the supply frequency. Thyristor firing pulses are assumed to be supplied periodically and the system is controlled by varying the timing delay of the firing pulses. It regulates the lagging reactive power flow, in accordance with current flowing through the reactor, which is controlled by the thyristor firing angle α. When a thyristor is on, the system state vector x(t) specifies TCR current, capacitor voltage and the source current:

$$\mathrm{X(t)} = (Ir(t), Vc(t), Is(t))$$

and the system dynamics are described by:

$$\dot{X} = \mathrm{A}\, X + \mathrm{B}\, u \tag{1}$$

Where $A=\begin{pmatrix} \frac{-\mathbf{Rr}}{\mathbf{Lr}} & \frac{\mathbf{1}}{\mathbf{Lr}} & \mathbf{0} \\ \frac{-\mathbf{1}}{\mathbf{C}} & \mathbf{0} & \frac{\mathbf{1}}{\mathbf{C}} \\ \mathbf{0} & \frac{-\mathbf{1}}{\mathbf{Ls}} & \frac{-\mathbf{Rs}}{\mathbf{Ls}} \end{pmatrix}$, and $B=\begin{pmatrix} \mathbf{0} \\ \mathbf{0} \\ \frac{\mathbf{1}}{\mathbf{Ls}} \end{pmatrix}$

III. CONTROLLER DESIGN

A. SMC

1) Back Ground

Sliding mode control is a famous discontinuous feedback control method which has been completely explored by many authors. The technique is naturally suited for the regulation of switched controlled systems, such as power electronics devices, in general, and DC-to-DC power converters, in particular. Sliding mode control was studied primarily by Russian scientists in the former Soviet Union. Sliding control (SC) is a robust control technique suitable for nonlinear systems with bounded uncertainties. The basic idea is to define the control objective in terms of a generalized tracking error (sliding surface), which must be forced to zero. The control is then composed of two terms: a continuous term to deal with the known part of the dynamics, and a discontinuous high-gain term to deal with the uncertain parts of the system. In general, higher discontinuous gains can deal with larger uncertainties. However, this comes at the price of having large, high-frequency, discontinuous control activity known as chattering, which is not desirable [18, 19]. In practice, one could approximate the discontinuous control term with a smooth function. This approximation eliminates the chattering effect at the price of a small tracking error [20].

2) Sliding Surfaces

In the context of single switch, n-dimensional systems, a sliding surface denoted by S or σ(x) is represented by the set of state vectors in R^n where the algebraic restriction, h(x) = 0, is satisfied, where h: $R^n \rightarrow R$ is a smooth scalar output function of the system. We define

$$S = \{x \in R^n \mid h(x) = 0\} \tag{2}$$

The set S represents a smooth variety or smooth manifold of dimension n–1 in R^n. There exist feedback control actions u(x), possibly of discontinuous nature, that render the restriction: h(x) = 0 to be locally satisfied by the state trajectory x(t). The motions of the system state(x) on the smooth surface S ideally produces an overall desired, local, behavior for the state of the controlled system [21].

3) Principle Theory of SMC

The nonlinear state equations of system are given as (1). The control signal U should be determined so that the state trajectory from any point in state space plane drives to switching surface S=CX=0.

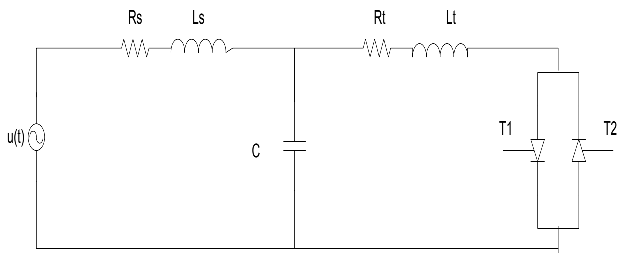

Figure 1. Schematic diagram of single phase TCR

For convenience an exponential law is adopted for the sliding surface as:

$$S' = - Qs\, Sgn(S) - Ks\, S \tag{3}$$

Where Sgn is the sign function and Qs, Ks are positive constants. Besides

$$S' = CX' = C[A(X) + B(X)U] \tag{4}$$

From the above equations the following control law is obtained,

$$U = -[CB(X)]^{-1}[CA(X)]+Qs\, Sgn(S) +Ks\, S \tag{5}$$

Constant factors, Ks and Qs, can be determined by trial and error. Consider the system given in (1). Assuming that A, B is controllable, there exists a stabilizing feedback gain K such that A+BK=As is asymptotically stable. It follows that there exists a positive define matrix P that solves the lyapunov equation.

$$PAs + As^{T}P = - Q \tag{6}$$

Now we choose the switching surface

$$S(X) = DB^{T}PX = 0 \tag{7}$$

D is a nonsingular matrix. A special choice of $D = (BTPB)^{-1}$ will diagonalize the control coefficient matrix to the dynamics for S:

$$S'=DB^{T}PAX+U \tag{8}$$

So we have the following control law:

$$U = - (DB^{T}PA+Ks\, DB^{T}P)\, X - Qs\, Sgn(S) \tag{9}$$

In this case in obtaining the desired response the parameter Qs can be determined independent of other parameters [22].

4) Chattering Problem and its Solution

In real life applications, it is not reasonable to assume that the control signal time evolution can switch at infinite frequency, while it is more realistic, due to the inertias of the actuators and sensors, and to the presence of noise and/or exogenous disturbances, to assume that it commute at a very high (but finite) frequency. The control oscillation frequency turns out to be not only finite but also almost unpredictable. The main consequence is that the sliding mode takes place in a small neighbour of the sliding manifold, whose dimension is inversely proportional to the control switching frequency. The notions of ideal sliding mode and real sliding mode is here adopted to distinguish the sliding motion that occurs exactly on the sliding manifold from a sliding motion that, due to the nonidealities of the control law implementation, takes place in a vicinity of the sliding manifold, which is called boundary layer (Fig. 2). The effects of the finite switching frequency of the control are referred in the literature as chattering. Basically, the high frequency components of the control propagate through the system, therefore exciting the unmodeled fast dynamics, and undesired oscillations affect the system output. This can degrade the system performance or may even lead to instability. Moreover, the term chattering has been also designated to indicate the bad effect, potentially disruptive, that a switching control can produce on a controlled plant.

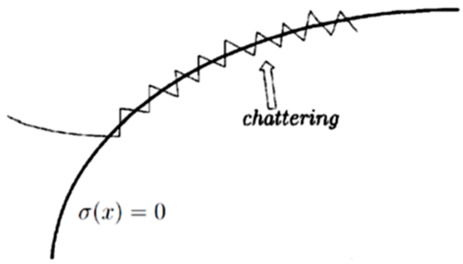

Figure 2. The Chattering Effect

Chattering and high control activity, are the major drawbacks of the sliding mode approach in the practical realization of sliding mode control schemes.

In order to overcame these drawbacks, a research activity aimed at finding a continuous control action, robust against uncertainties and disturbances, guaranteeing the attainment of the same control objective of the standard sliding mode approach has been carried out in recent years. The most used in practice approach is based on the use of continuous approximations of the sign function (such as the sat function, the tanh function and so on) in the implementation of the control law. A consequence of this method is that invariance property is lost. The system possesses robustness that is a function of the boundary layer width. This methodology is highly sensitive to the unmodeled fast dynamics, and in some cases can lead to unacceptable performance.

An interesting class of smoothing functions, characterized by time-varying parameters, was proposed in Slotine and Li (1991), attempting to find a compromise between the chattering elimination aim and the possible excitation of the unmodeled dynamics.

In conclusion, continuation approaches eliminate the high-frequency chattering at the price of losing invariance. The most recent and interesting approach for the elimination of chattering is represented by the second order sliding mode methodology [23]. Also, to eliminate the chattering problem, the discontinuous part of the control signal in the classical SMC is substituted by neuro sliding mode controller. In the whole design process, no strict constraints and prior knowledge of the controlled plant are required, and the asymptotic stability of the control system can be guaranteed. The controller benefits from the well-established theory of the sliding mode control and uncertainty dealing potential of the neural networks [20].

B. Proportional-Integral-Derivative Control

The PID algorithm is the most popular feedback controller used within the process industries. It has been successfully used for over 50 years. As the name suggests, the PID algorithm consists of three basic modes, the Proportional mode, the Integral and the Derivative modes. Closed-loop control system design has several objectives:

- to achieve a stable closed-loop system,
- to ensure that output is close to a desired set point value,
- to filter out residue noise from the control signal.

There are two main categories of controller tuning procedures:

1) Trial and Error Method

The trial and error tuning of PID controllers is said to be widespread in industrial practice. The method starts from some intelligently guessed PID controller parameters. Using these initial controller parameters, the output of the closed-loop system is observed and the controller parameters are modified until the desired output is obtained. Success is highly dependent on the tuning skill of the industrial control engineer and the knowledge available about the process to be controlled.

2) Systematic Tuning Methods

Systematic tuning methods introduce engineering science into the controller tuning procedure. This usually means using some form of model for the real process. The multitude of different control design methods available in control engineering textbooks and the literature arise from the different assumptions made for the type of process model and the actual information available for the system model.

C. Comparison with Classical Linear Approach

Comparison between the SMC and classical linear approach that is proportional integral (PI) control has been discussed in many papers. In [24], the diagnostic tests between the sliding mode and PI controllers have been analyzed. A simple SMC is applied to a permanent magnet synchronous motor. The comparisons of the performance responses for both control schemes are analyzed in terms of which technique results an excellent robustness in responses to system parameter uncertainties, load disturbances and in case of noisy measurement. The simulation results show that the SMC performs better compared to the classical PI control. The PI control is subject to limitations due to the intrinsic conflict between the steady state accuracy and dynamic response speed. In PI control, the dynamic performance specification can be achieved only if the compromise has been made to solve the conflict between excessive oscillation or overshoot and long settling time. Besides that, to meet higher system specification, the challenge faced by the design engineers due to multi loop system structure and trial and error design approach which lead to the control design time consuming and expensive. It was concluded that the principal weakness of the PI control is its sensitivity to parameter system variations and also not capable of rejecting any external disturbances or load variations. In addition, the results of the SMC scheme show improvements with regard to robustness, dynamic response and chattering reduction.

IV. SVC SIMULATION

SVC model will be established through the use of Simulink environment of MATLAB software and the block diagram of simulation could be seen in Fig. 3. In order to calculate the firing angles of thyristors, PID controller and SMC are used, so that they will compensate reactive demand of power system. Also these controllers could maintain the voltage amplitude in the range of reference voltage signal. In order to diagnose better performance of two controllers that mentioned above (SMC and PID), the power system and a load in parallel with a SVC (consisted of a capacitor and a TCR or a variable reactor) have been simulated. Simulation data are considered as in TABLE I.

A variable AC voltage source is used for this study. Voltage source is varying between 0.8 (v) to 1.2 (v) and is illustrated in Fig. 4. In this way SVC's response could be investigated and 3 state variables are drawn in different figures.

At first i_s that is the transformer current, could be studied as x_1 (the first state variable), also second state variable, V_c is capacitor voltage and determined by x_2 and at last third state variable, i_t or i_{tcr} is the thyristor branch current and is determined by x_3 . These signals are represented in Fig. 5 to Fig. 10 in order to compare two SMC and PID controllers; For example when Fig. 5 compared with Fig. 6, it's evident that transformer current with SMC has a smoother shape rather than transformer current with PID. Indeed, current transient reduction is clear through the use of SMC method.

It's clear that capacitor voltage via SMC has better regulation rather than capacitor voltage via PID controller, when Fig. 7 compared with Fig. 8. In fact, voltage transient decrease is clear through the use of SMC method. It could be seen that TCR current with SMC has higher amount rather than TCR current with PID, when Fig. 9 compared with Fig. 10. It means that, when the faults take place, by use of SMC method better compensation will be accessible.

Through the use of SMC some parameters of control loop play a vital role in controller performance. For instance, it could be tangible that sign of the sliding surface or Sgn(S) doesn't change when an error or fault occurs and as a result desirable criteria are not obeyed, but if the reference signal was equal to actual signal, then sign of the sliding surface would change rapidly. In Fig. 11 sign of the sliding surface or Sgn(S) is illustrated.

TABLE I. SIMULATION DATA

Parameters	**The per unit component values**		
	Explanation	***Unit***	***Value***
ω	Frequency of source voltage u(t)	rad/s	$2\pi 60$
T	Period of source voltage u(t)	s	$2\pi/\omega$
Ls	Power system inductance	mH	0.195
Rs	Power system resistance	mΩ	0.9
Lr	Thyristor controlled reactor inductance	mH	1.66
Rr	Thyristor controlled reactor resistance	mΩ	31.3
C	Parallel capacitor	mF	1.5

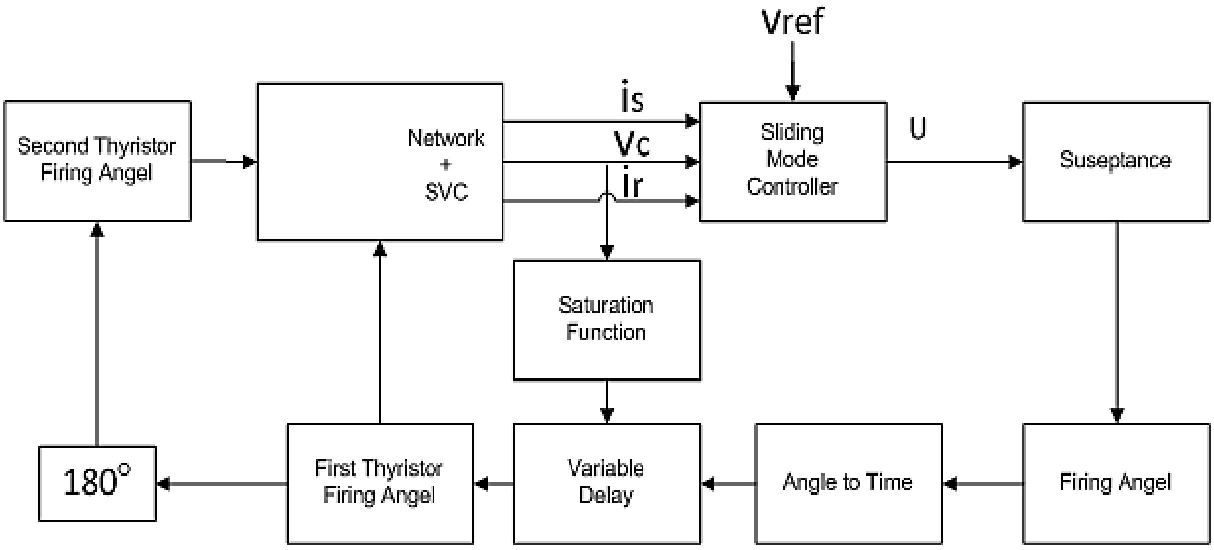

Figure 3. Block Diagram of SVC simulated model in MATLAB

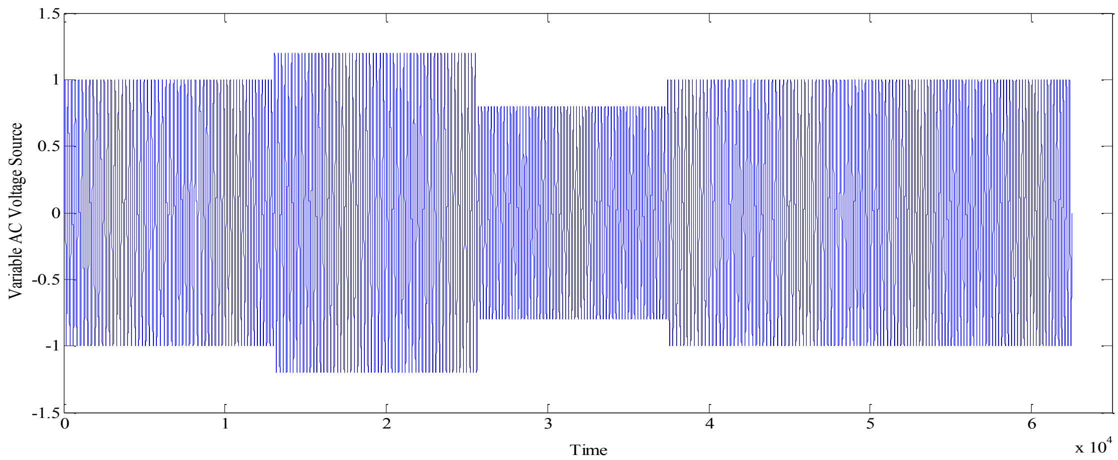

Figure 4. Variable AC voltage source

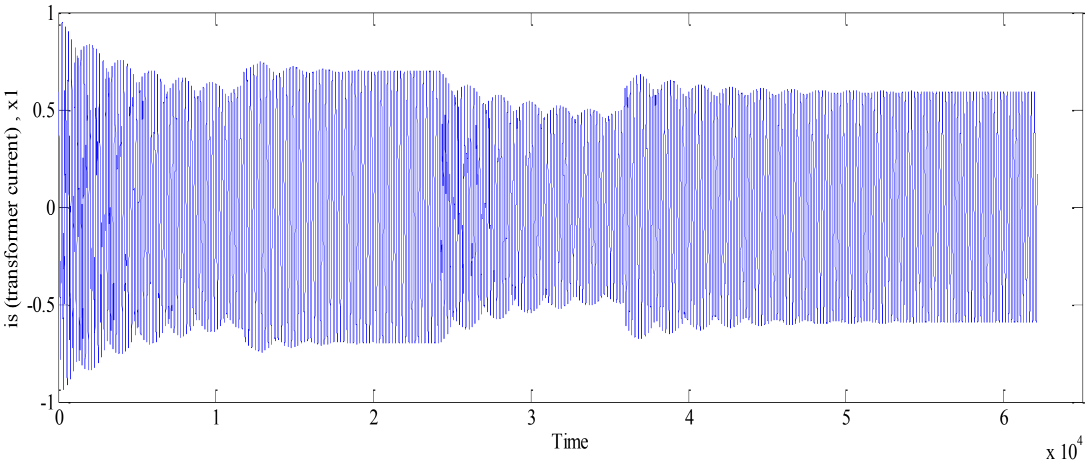

Figure 5. X_1 or i_s (transformer current) via PID controller

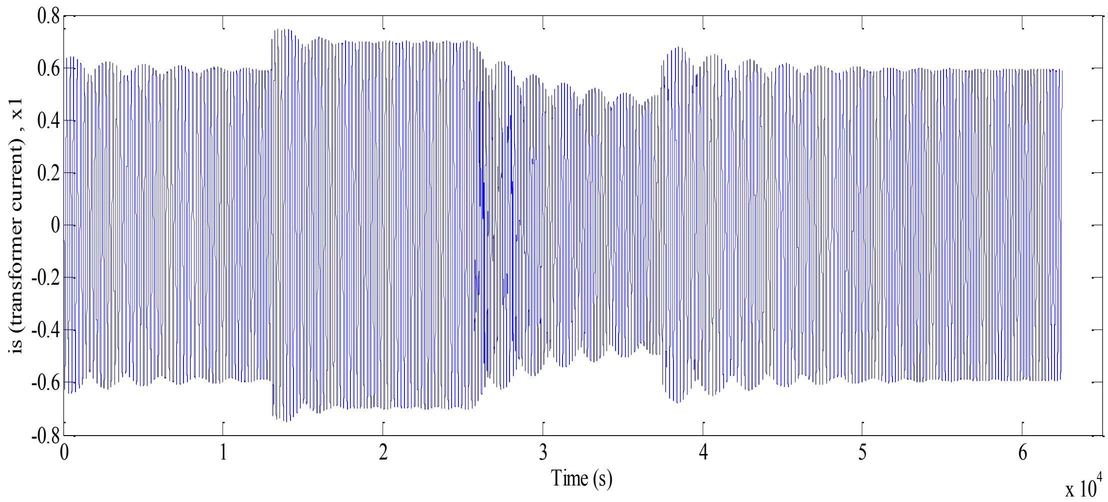

Figure 6. X_1 or i_s (transformer current) via SMC

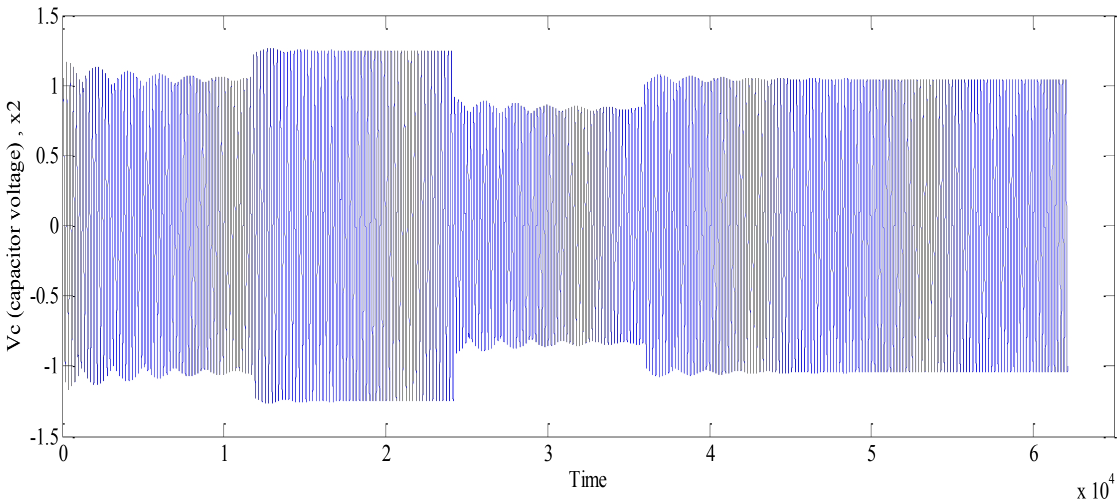

Figure 7. X_2 or V_c (capacitor voltage) via PID controller

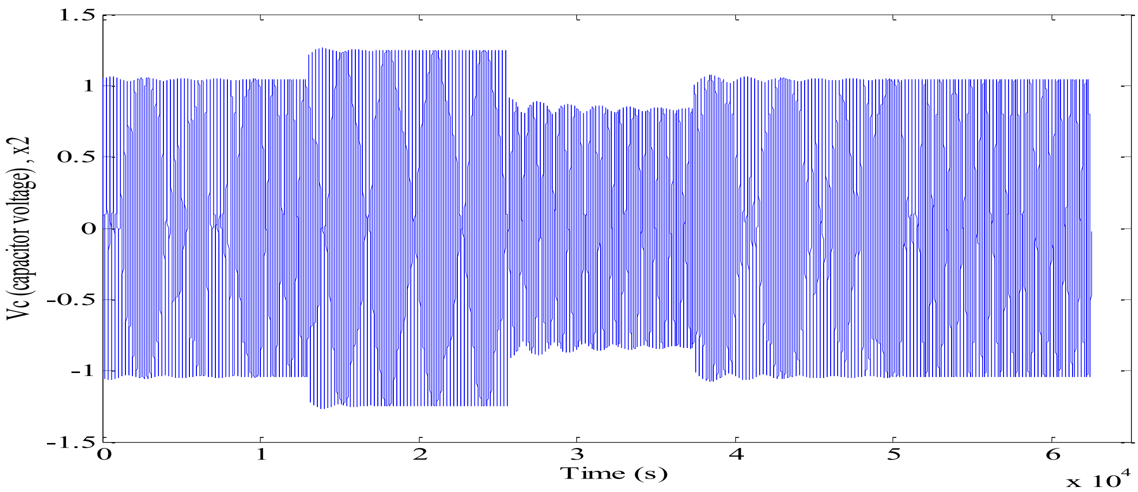

Figure 8. X_2 or V_c (capacitor voltage) via SMC

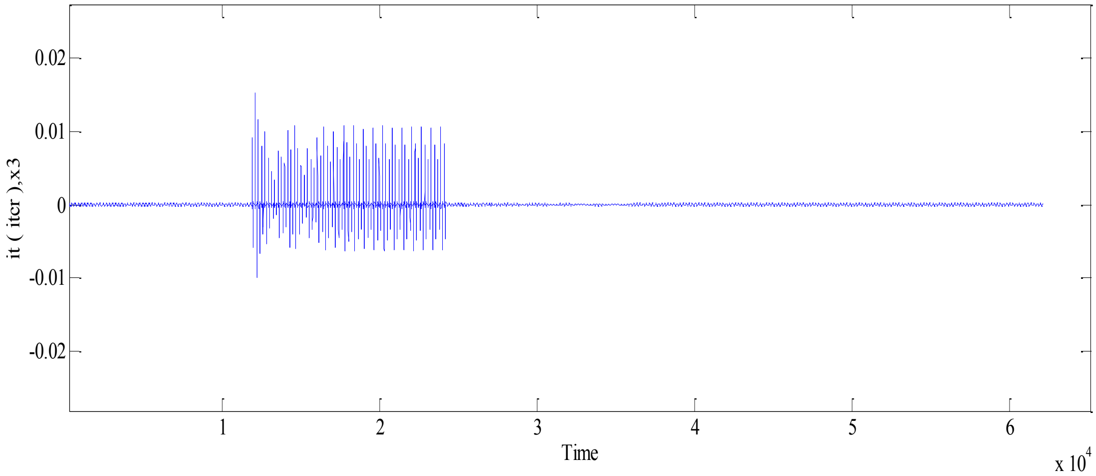

Figure 9. X_3 or i_t (TCR current) via PID controller

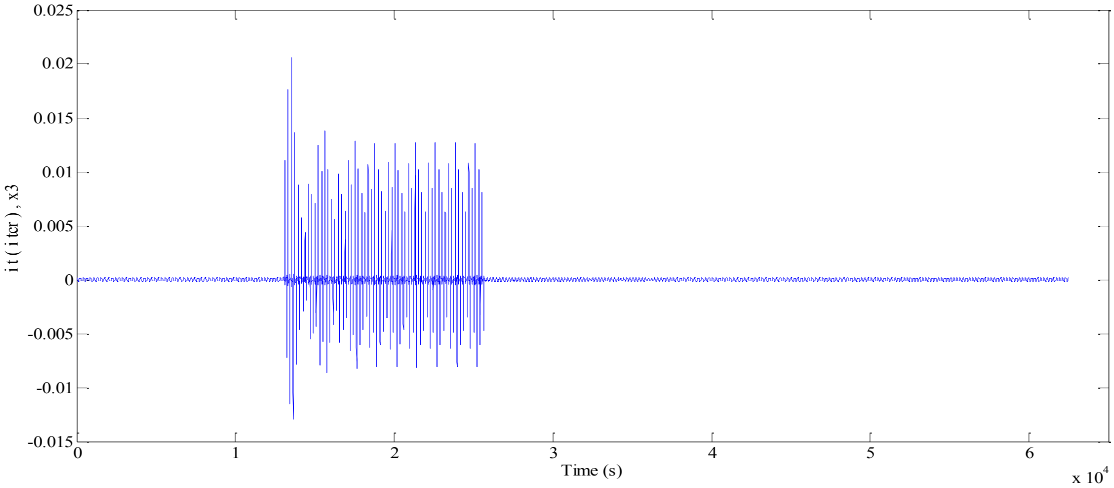

Figure 10. X_3 or i_t (TCR current) via SMC

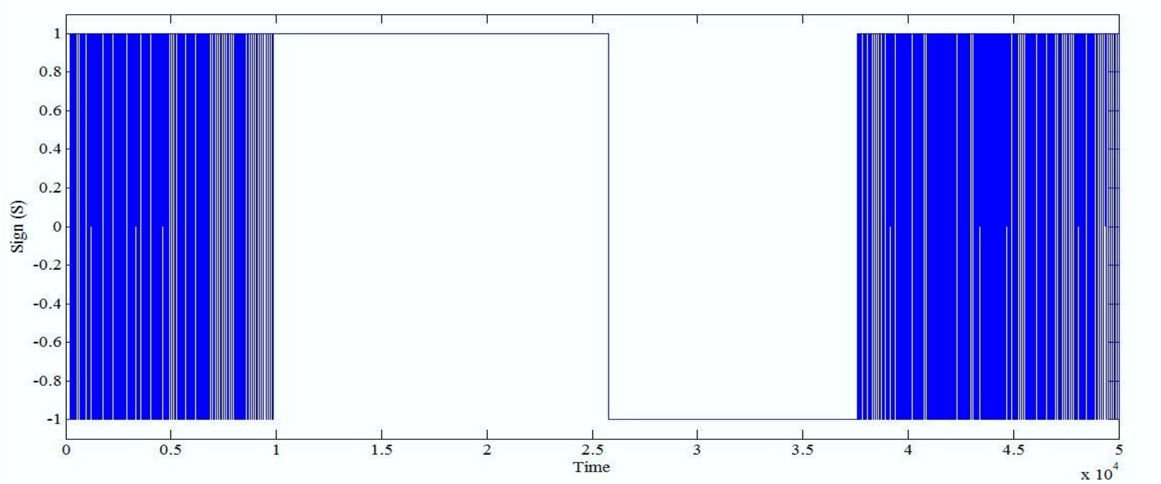

Figure 11. Sign of the sliding surface

V. CONCLUSION

A systematic approach has been presented for the design of a controller for static VAR systems operating in the sliding mode. Simulation results reveal that the sliding mode concept of designing a VAR controller provides significant improvement in damping and transient stability performance. The post-fault recovery of the SVC bus voltage is significantly faster than most of the SVC case studies presented earlier using other controllers such as PID. In this paper, a nonlinear SVC controller was proposed to voltage regulation enhancement and power system stability improvement. Modeling inaccuracies can have strong adverse effects on nonlinear control systems. One of the most important approaches to dealing with model uncertainty is robust control. The sliding mode is strongly requested knowing its facility of establishment, its robustness against the disturbances and models uncertainties. SMC and PID control techniques were employed to deal with both constant and time varying uncertainties in a power system with SVC. The SIMUINK simulation results showed that the proposed SMC is superior to conventional PID especially under severe conditions. The main advantages of the sliding mode control approach are the simplicity of both, design and implementation, the high efficiency and the robustness with respect to matched uncertainties. However, it has been shown that imperfections in switching devices and delays were inducing a high frequency motion called chattering (the states are repeatedly crossing the surface rather than remaining on it), so that no ideal sliding mode can occur in practice. Chattering and high control activities were the reasons that fomented a generalized criticism towards sliding mode control. To avoid chattering some approaches were proposed. The most recent and interesting approach for the elimination of chattering is represented by the second order sliding mode methodology. Also, in order to eliminate or decrease chattering phenomena, Artificial Neural Network (ANN) proposed to be used in SMC structure. Besides substitution of sign function with saturation function or tangent hyperbolic function will ameliorate the chattering effect.

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