Enhancing Low Frequency Oscillations Damping of a Power System by a TCSC Controlled with Sliding Mode Method

Hossein Amoutaghi[1*], Shahrokh Shojaeian[1], Ehsan Salleala Naeini[1]
1-Department of Electrical Engineering, Khomeinishahr Branch, Islamic Azad University, Isfahan, Iran.
Email: Amoutaghi@iaukhsh.ac.ir (Corresponding Author)

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ABSTRACT:
Sliding mode control is an efficient and robust control method widely used in nonlinear systems. Power systems are one of the largest nonlinear dynamic systems which their transient stability analyses have a lot of importance. In this paper, sliding mode control is applied for improving the low frequency oscillations damping of a single machine connected to an infinite bus. The performance of the system is analyzed in normal mode operation, post-fault state, after operation of relays (and opening the breakers in the both ends of the faulty line), and reclosing mechanism which returns the line to service. Here, TCSC is employed as an oscillation damper. TCSC can be considered as a controllable impedance determined by the sliding mode control. In addition, a dynamical observer is proposed for the sliding mode controller. Simulation results demonstrate that, the performance of the power system in damping the low frequency oscillations is improved significantly.

KEYWORDS: Sliding mode control, TCSC, Low frequency oscillation, Symmetrical three phase fault.

1. INTRODUCTION

Power systems are nonlinear systems with broad performance [1]. These systems are one of the most complicated systems in human history and indeed, they are the biggest nonlinear dynamic systems in the world [2]. Nowadays, by expansion of power systems and enhancing power transmission, the dynamic and transient stability is of importance for these systems safe performance [3].

Transient stability is ability of a synchronous power system to return to stable condition and maintain its synchronism following a relatively large disturbance [1]. Transient stability is one of the fundamental issues in power systems planning and performance studies. Stability basically shows the ability of damping the system low frequencies oscillations after disturbance [4], hence transient stability control is important in research in order to provide the first interaction to ensure stable operation of the power system [1]. The ability of the power system to maintain stability depends on the power system controllers for damping oscillations [5].

Local oscillations normally occur when a rapid excitation system is used in generators and trans-regional oscillations may appear where the system load is increased in align with weak lines [6]. Synchronous machine excitation control is done in different ways. One of these methods is using power system stabilizer. Damping of this method is limited due to excitation time constant and saturation issue. Meanwhile, in this method, feedback is done only by a state variable (speed) and the signal is stabilized and excitation is increased, hence the impact of other states variables is ignored. A signal formed by the state variables linear combination is applied for excitement system for exerting other states variables impact and optimal control is used for obtaining the state variables coefficients [7].

Today, with the development of power electronic technology, the advantages of using FACTS devices for improving the power systems stability (transient and dynamic), controllability, power system operation and elimination of power transmission limitations are fully known [8] [10]. FACTS controllers have the ability to fast control of network conditions and this feature of FACTS is used to improve power system stability [10] [11]. FACTS devices are able to reduce the distance between the lines thermal loading limit and stability limit due to creating flexibility in power systems and necessary modifications in transmission lines [10] [12]. The main objective of FACTS is usually enhancing the line capacity and power flow control in specified transmission lines. FACTS controller dynamic function includes improving transient stability, oscillation damping, voltage stability enhancement, current limiting and short-circuit area change [13].

In [14] tuning the load frequency controllers is modelled as a many-objective (MO) minimization problem. This MO optimization problem is solved using an MO optimization algorithm with clustering-based selection. Considering the maximum value of each objective among the non-dominated solutions found by the MO optimization algorithm, the worst solution is determined. Simulation results show that, in terms of different performance indices, the controllers designed by the proposed MO method are far superior to the controllers designed with the single-objective optimization algorithms.

In [15] a new scheme is proposed to provide necessary primary reserve from electric vehicles using hierarchical control of each individual vehicle. An EV aggregator based on the vehicle's information such as the required state of charge (SOC) for the next trip, departure time, and initial SOC is proposed. The proposed aggregation scheme determines the primary reserve and contracts it with system operator based on electricity market negotiation. A similar technique has been used in [16].

In [17] damping of the low frequency oscillations of multi-machine multi-UPFC power systems is investigated based on adaptive input-output feedback linearization control approach. Considering a three-phase symmetrical fault, ignoring the subtransient states of the synchronous machines, the nonlinear state equations of the system are derived in order to obtain the UPFC reference control signals as well as the system parameters estimation laws.

Simulation of FACTS controllers is usually done in the following two states: [18]

a. The details of the calculation in three-phase systems

b. Stability mode and stability analysis.

In this paper, sliding mode control is applied for improving the low frequency oscillations damping of a single machine connected to an infinite bus. The performance of the system is analyzed in normal mode operation, post-fault state, after operation of relays (and opening the breakers in the both ends of the faulty line), and reclosing mechanism which returns the line to service. Here, TCSC is employed as an oscillation damper. TCSC can be considered as a controllable impedance determined by the sliding mode control.

2. NOTATION

The notation used throughout the paper is stated below.

V_t	terminal voltage of the synchronous generator
V_s	voltage of the infinite bus
δ	rotor angle of the synchronous generator
ω_r	rotor angle speed of the synchronous generator
ω_b	base value of the rotor angle speed
E_{pq}	voltage behind transient reactance of the d-axis of the synchronous generator
P_m	turbine mechanical power
D	friction coefficient of the synchronous machine
H	inertia constant of the synchronous machine
E	excitation voltage of the synchronous machine
T_{pdo}	no-load transient d-axis time constant of the synchronous machine
I_d	d-axis current of the synchronous generator

3. PROCEDURE

This paper proposes a first order sliding mode variable structure controller and adoption of an appropriate control law for TCSC controlled in a single machine power network which damps regional oscillations rapidly after short circuit fault. The stability of the proposed method is measured by changes in the network uncertain parameters. Numerous controlling methods have been proposed for controlling the first order FACTS devices which are mostly based on linear control methods. These methods are employed based on system state equations linearization and naturally depend on the system operating point and also its indefinites. This dependency prevents other controller working in case of changing operating point. Therefore, nonlinear and stable method is used for control of TCSC in this article. At first, a single machine model with its equations is proposed for a power system with a single machine connected to an infinite bus equipped with TCSC. A symmetric three phase fault is occurred in 0.1 second and the relays are operated in 0.2 second. The faulted lines are disconnected and reconnected in 1.2 seconds after complete elimination of fault. The relays reconnect the faulted lines and the network returns to the pre-fault state and excitation and TCSC is extracted in coordinated control system state.

4. SLIDING MODE CONTROL STRATEGY

Emelyanove in 1932 proposed the sliding variable structure for the first time in Russia. Basically, sliding mode control is a nonlinear controller. Not only this method is used for linear systems, but also it should especially be applied on nonlinear systems. It is obvious that if a nonlinear system is converted into a linear system by approximate linearization method and sliding control mode is designed for the linearized system, it will have weak performance relative to the state that it is designed directly for a nonlinear system.

Consider the following nonlinear system:

$$x^{n} = f(x) + b(x)\, v \tag{1}$$

Where x is output and v is control input. The system state vector is as follow:

$$x = \left[x\; x^{1} \ldots x^{n-1} \right]^{\tau} \tag{2}$$

Here the aim of the control system is that vector x tracks a variable state vector within time x_d in presence of uncertainties in f(x) and b(x):

$$x_d=\left[x_d\ x_d^{'}\ldots x_d^{n-1}\right]^{\tau} \quad (3)$$

Here x_d is called reference state vector. In this state tracking error vector is as follow:

$$\tilde{x}=x_d-\left[\tilde{x}\ \dot{x}\ldots\tilde{x}^{(n-1)}\right]^{\tau} \quad (4)$$

At first, switching surface should be identified for designing sliding mode controller. In engineering application, the sliding surface is mostly considered as total error between the controlled value, reference value and an error integral.

The system behavior is called sliding mode when it is in vicinity of s(t,x).

If a sliding mode exists in s(x)=0 thus s(x) is called a sliding surface and switching is done so that the correct response is confined to s(x)=0 and a desired behavior exists on the sliding surface [19].

Sliding mode controller is designed in two steps:

1. Formation of an appropriate sliding surface which the system dynamic is confined to it and an ideal behavior is seen around the sliding surface.
2. Designing a discrete controller that brings the system into the sliding surface and remains on it.

After designing switching surface, the next step in sliding mode control is assurance of existence of a sliding mode. The system state trajectory stability on the sliding surface s(x)=0 or in its vicinity $\{x \mid s_i(x)=0\}$ is necessary for a sliding mode. It means that the system state converges asymptotically to the surface. The biggest neighborhood is called absorption region.

The switching surface condition is necessary for reaching the system state from a point to the switching surface. There are different conditions which one of them is Lyapunov function. Unfortunately, there is no standard method for obtaining this function for any desired system. For all single-input systems, a Lyapunov function can be defined as (5).

$$V(t,x,s)=\frac{1}{2}s^2(x) \quad (5)$$

It is obvious that the function is a positive definite function. In sliding mode control, $\dot{s}$ depends on the control law. Hence, if the switched feedback rate is chosen as follow:

$$V(t,x,s)=s\frac{\partial s}{\partial t}<0 \quad (6)$$

In the absorption domain the state trajectory is converged and remains on the surface all times. The equation (6), is called accessibility condition V<0 [20] and it ensures that the system state is asymptotically converged to the sliding surface.

Equation (6) is replaced by accessibility condition.

$$V(t,x,s)=s\frac{\partial s}{\partial t}\leq\eta|s|<0 \quad (7)$$

Where ensures convergence to surface s(x)=0 in definite time. Integrating Eq. (7) we have:

$$\left|s[x(t)]\right|-\left|s\{x(0)\}\right|\leq-\eta t \quad (8)$$

By beginning from the primary condition s[(x(0)], the required time to reach the surface s(x) is calculated as follow:

$$t_s=\frac{1}{\eta}\left|s[x(0)]\right| \quad (9)$$

The sliding surface derivative (n) relative to time is calculated as follow:

$$\begin{cases} s=s(t,x) \\ \dot{s}=\frac{\partial}{\partial t}s(t,x)+\frac{\partial}{\partial x}s(t,x)\dot{x} \\ s^n=\left[\rho(t,x)+\gamma(t,x)v(t)\right] \end{cases} \quad (10)$$

Where n is called sliding order so that $\frac{\partial s^n}{\partial v}\neq 0$, $\frac{\partial s^{n-1}}{\partial v}=0$. In simple way sliding order equals sliding surface derivative which has occurred for the first time.

Sliding order (n) equals to continuous total derivatives number. Sliding order does not depend on zero dynamic attribute and only it depends on the dynamicity feature. Thus, sliding mode equals sliding variable derivative order which converged into zero. So, a set of sliding variable and its derivatives is obtained.

The sliding order (n) relative to sliding variable is expressed by Eq. (11).

$$s=\dot{s}=\ddot{s}=\ldots=s^{n-1}=0 \quad (11)$$

If sliding order in Eq. (10) equals 1, then controller is first order sliding controller, where sliding set consists of continuous and discreet sliding. Higher order sliding mode control is related to the state that the relativity order varies between sliding variable and control more than 1, so that control input is entered in higher derivatives of limit function.

Due to disadvantages of switching in the system, the system trajectories are located inside a boundary layer around sliding surface which the size of this boundary layer is reduced by increasing the order of the system. The main problem in implementation of the higher order sliding mode control is need for more information on the sliding variable derivatives.

Generally, n^{th} order sliding mode controller needs, s^{n-1}, and $\dot{s}$; Except torsional, meta-torsional and sub-optimal control methods which are related to second order sliding mode algorithms so that torsional and sub-optimal control requires only sliding derivative sign and meta-torsional controller does not need sliding variable derivative information.

Following system is considered for specifying control law:

$$x^{n}(r)=f(t,x)+v(t) \tag{12}$$

In this state, n^{th} derivative of sliding surface is expressed as follow:

$$s^{n}=\left[\rho(t,x)+v(t)\right] \tag{13}$$

Assume that the state trajectory has reached to switching surface in t and sliding behavior exists on the surface in $t > t_0$. The first step for specifying control law is finding input v_{eq} which is called equivalent control. It should be bear in mind that by beginning of the trajectory from $s(x)=0$ by controlling v_{eq} , it remains on the surface $s(x)=0$ next times, hence $\dot{s}(x)=0$ .As a result, $s(x)=0$ surface is invariant.

Equivalent control v_{eq} is achieved by $s^n=0$ as follow:

$$s^{n}=\left[\rho(t,x)+v_{eq}\right]=0 \tag{14}$$

Then:

$$v_{eq}=-\rho(t,x) \tag{15}$$

Presence of uncertainties in the system causes that the system states do not remain on the switching surface. This condition adds another controlling component to v_{eq} in the controlling signal.

$$v=v_{eq}+v_{N} \tag{16}$$

Where the control law v_N differs depending on sliding order and type of controller which will be expressed in the following.

If we have a system as below:

$$x^{n}=f(x)+b(x)v \tag{17}$$

Then n^{th} derivative of sliding surface is converted into Eq. (10) as:

$$s^{n}=\rho(t,x)+\gamma(t,x)v(t) \tag{18}$$

Where control law is obtained as below:

$$v=-[\gamma(t,x)]^{(-1)}(v_{eq}+v_{N}) \tag{19}$$

Where by replacing v_{eq} from Eq. (15), control law v is achieved as follow:

$$v=-\left[\gamma(t,x)\right]^{-1}\left(-\rho(t,x)+v_{N}\right) \tag{20}$$

In the next step, different conventional control structures for v_N are introduced.

If sliding order in (10) equals 1, then controller will be first order sliding controller which sliding set consists of continuous s and discrete $\dot{s}$.

The controller sign is changed by passing the system state from switching and returning to the sliding surface. Since this controller is not ideal in the real system and physical condition and on the other hand, checking frequency and control of the system state variables are limited hence maintaining state variables completely on sliding surface is impossible and as a result, chattering phenomenon is unavoidable. Figure 1 shows this phenomenon which stimulates the system non-modeled dynamics and as a result leads to instability of total system.

The impact of high switching on the controlling system has been discussed in [21]. Basically, the control higher frequency stimulates higher frequency dynamics (unwanted external disturbances, non-modeled structural states, ignored delays and etc.) which are ignored during modeling and as a result jeopardize the system performance and stability. In addition, higher oscillations affect the force and torque switching control in a mechanical system which their impacts have been explained [22]. Generally, chattering and high controlling activity are the main defects of first order sliding control method in practical implementation of the sliding state control method.

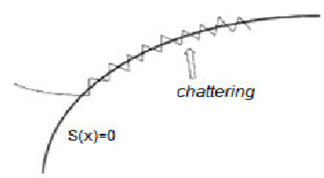

Fig 1. Chattering phenomenon

5. SIMULATION RESULTS

In this paper a third order model called Heffron-Phillips model was used and the proposed control method was implemented on the sample system with TCSC. As figure (2) shows, in computer simulation in MATLAB, a symmetric three phase short connection fault was occurred in line L4(at 0.1 second) and after 0.2 second the relays responded to line L4 disconnection and 1 second after disconnection the line was reconnected and the fault system was eliminated.

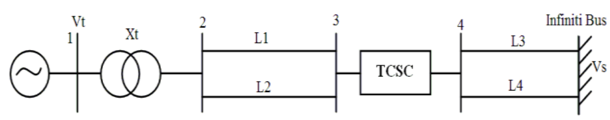

Fig 2. a single studied machine network.

The system information is: $X_t=0.127$, $2H=4$, $V_s=1\measuredangle 0$, $L_1=L_2=L_3=L_4=0.2426$, $T_{pdo}=6.9$

The generator flows the network a desired flow such as I=0.4-0.3i in stationary state.

Assuming that in the stationary state: $X_{TCSC}=0$:

$$V_t=V_s+j[X_t+\frac{X_{L1}X_{L2}}{X_{L1}+X_{L2}}+X_{TCSC}+\frac{X_{L3}X_{L4}}{X_{L3}+X_{L4}}].I \tag{21}$$

Which damps the oscillation and it is affectless in permanent condition.

$$V_t=V_s+j[X_t+\frac{X_{L1}X_{L2}}{X_{L1}+X_{L2}}+\frac{X_{L3}X_{L4}}{X_{L3}+X_{L4}}].I \tag{22}$$

$$E=jX_q I+V_t \rightarrow \delta=\measuredangle E \tag{23}$$

$$\varphi = \measuredangle I \quad , \quad I_d = |I| \sin(\delta + \varphi) \tag{24}$$

$$E_f = |E| + (X_d - X_{pd}) I_d \tag{25}$$

$$E_{pq} = E_f - (X_d - X_{pd}) I_d \tag{26}$$

$$\omega_r = 1 \tag{27}$$

There are three states in the beginning of dynamic conditions:

1) Pre-fault and post-fault state which the line is reconnected.

$$X_{th} = X_t + \frac{X_{L1} X_{L2}}{X_{L1} + X_{L2}} + X_{TCSC} + \frac{X_{L3} X_{L4}}{X_{L3} + X_{L4}}, \quad V_{th} = V_s$$

2) During fault

$$X_{th} = X_t + \frac{X_{L1} X_{L2}}{X_{L1} + X_{L2}} + X_{TCSC} + \frac{X_{L3} (X_{L4}/2)}{X_{L3} + (X_{L4}/2)},$$

$$V_{th} = V_s \frac{(X_{L4}/2)}{X_{L3} + (X_{L4}/2)}$$

3) During disconnection of faulted line

$$X_{th} = X_t + \frac{X_{L1} X_{L2}}{X_{L1} + X_{L2}} + X_{TCSC} + X_{L3}, \quad V_{th} = V_s$$

The equations governing the system dynamic states in presence of TCSC are as follows:

$$\dot{\delta} = \Delta\omega_r \times \omega_b, \quad \omega_b = 314.16_{rad/sec}, \quad \Delta\omega_r = \omega_r - 1$$

$$\Delta\dot{\omega}_r = \frac{1}{2H}\left(P_m - \frac{E_{pq} \times V_{th} \times \sin\delta}{X_{pd\Sigma} + X_{TCSC}}\right) - \frac{D}{2H}\Delta\omega_r,$$

$$X_{pd\Sigma} = X_{pd} + X_{th}$$

$$\Delta\dot{E}_{pq} = \frac{1}{T_{pdo}}[E_f - E_{pq} - (X_d - X_{pd}) I_d]$$

Since X_{TCSC} is the system input so we have

$$\Delta\dot{\omega}_r = \frac{1}{2H}(P_m - E_{pq} . V_{th} . \sin\delta) - \frac{D}{2H}\Delta\omega_r$$

$$u \triangleq (X_{pd\Sigma} + X_{TCSC})^{-1}$$

The sliding surface for sliding mode control is defined as below:

$$s = \Delta\omega_r = \omega_r - 1$$

It should be bear in mind that since this controller is assumed to work in any condition for each fault, so δ or E_{pq} cannot be exerted in the controller design with related sliding surface since their final values are unknown after fault in general state, thus, Lyapunov function is chosen only by emphasis on the return speed that certainly returns on synchronous value.

$$V = \frac{1}{2}s^2 \rightarrow \dot{V} = s.\dot{s} = \frac{\Delta\omega_r}{2H}[(P_m - E_{pq} . V_{th} . \sin\delta . u) - D.\Delta\omega_r]$$

It should be proposed an appropriate u to negate this relation. Below relation is proposed:

$$u = \frac{P_m + K \ \mathrm{sign}(\Delta\omega_r)}{E_{pq} \times V_{th} \times \sin\delta}$$

Where K is a positive value. By replacing this phrase in above relation below relation is obtained:

$$\dot{V} = -\frac{K}{2H}\Delta\omega_r \times \mathrm{sign}(\Delta\omega_r) - \frac{D}{2H}(\Delta\omega_r)^2 \le 0$$

Thus the system is stabilized by this control:

$$X_{TCSC} = \frac{E_{pq} V_{th} \cdot \sin\delta}{P_m + K \cdot \mathrm{sign}(\Delta\omega_r)} - X_{pd\Sigma}$$

A. Single Machine Control with TCSC

As figure (2) shows, the proposed model for TCSC is as impedance serial jX_{TCSC} added in the network impedance and $X_{TCSC} = X_0 + \Delta X$ where X_0 and ΔX are the TCSC reactance value respectively in the system stability operation and TCSC reactance changes value. The former is obtained by control law in any programming step.

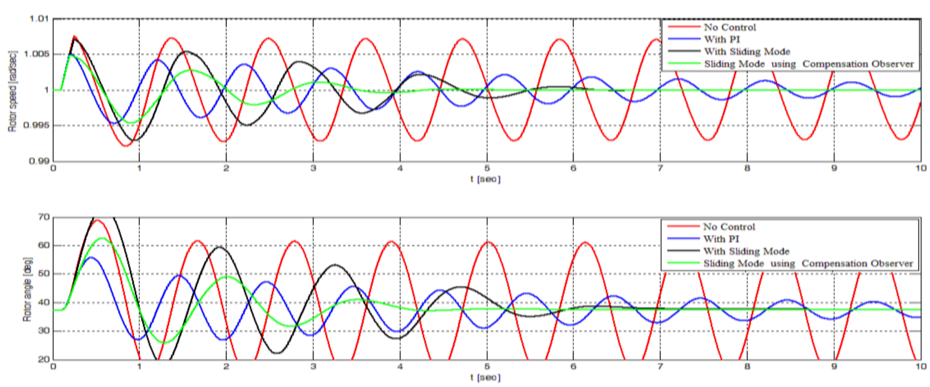

Fig 3. Speed of the generator rotor and generator rotor angle (PI: K_P=0.6785, K_I=10, SMC: K=9.5).

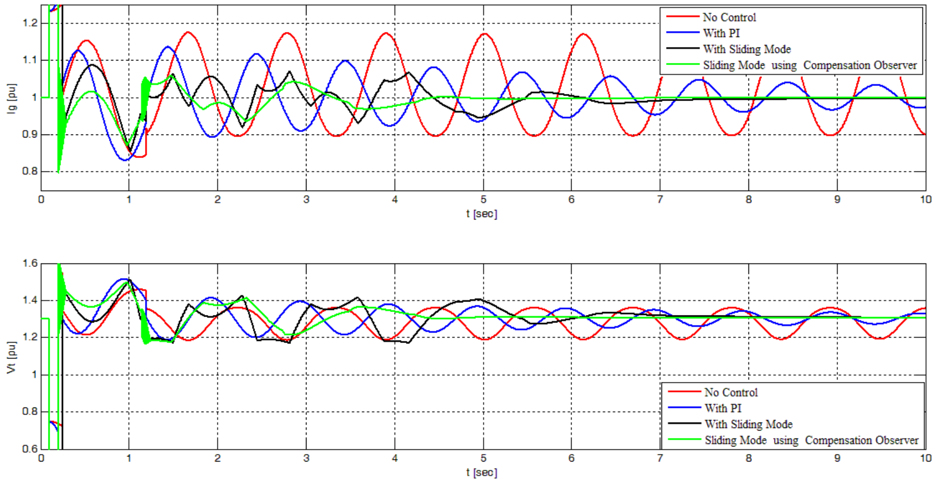

Fig 4. Generator current and generator terminals voltage (PI: K_P=0.6785, K_I=10, SMC: K=9.5).

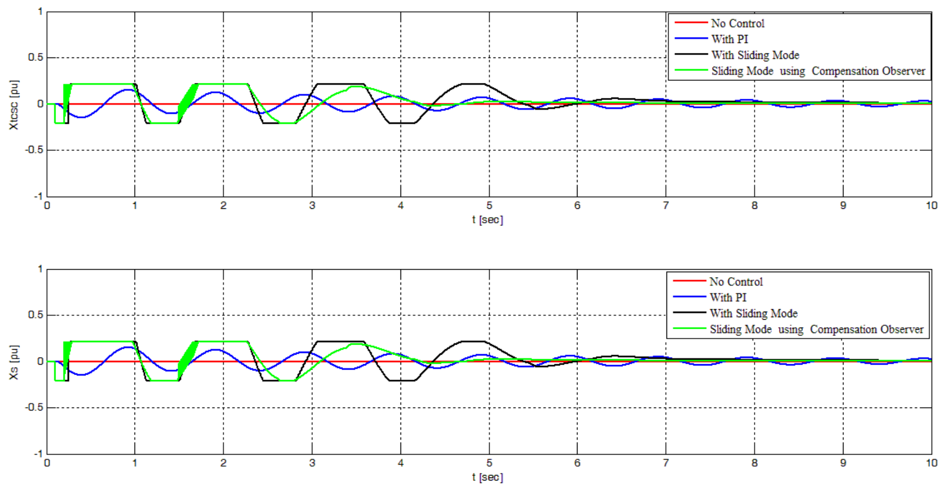

Fig 5. TCSC reactance changes in per- unit (PI: K_P=0.6785, K_I=10, SMC: K=9.5).

B. Simulation in the presence of TCSC

Figures (3) and (4) depict the impact of coordinated control of TCSC and excitation system in improving the system damping. Figure (5) shows TCSC reactance changes in any step as per-unit.

Simulation results obtained by PI and sliding mode controller are shown in Figures 3-6. Comparing these results, it can be easily recognized that the PI regulators are nearly failed to damp the low frequency oscillations of the power system or leastwise its settling time is high. Hereby, the superiority of the sliding mode controller with respect to PI controllers has been demonstrated.

6. CONCLUSION

The role of excitation control and TCSC control by sliding mode controller in two states of dynamic compensation observer and without observer in improving the network electrical fault oscillations damping was investigated in this paper. TCSC can be used for damping these oscillations. Machine excitation system and TCSC feedbacks were applied while designing reference optimal signals. The proposed method was studied on a single machine connected to an infinite bus and the response of the controllers to symmetric three phase fault was also investigated. The results demonstrate the efficacy of coordinated control of synchronous machine excitation and TCSC in damping the oscillations resultant from fault.

The mentioned single network behavior depicts that this network encounters with post-fault intensive oscillations in the mentioned distance from the generator which causes to the infinite bus voltage disconnect for 0.1 second that even it cannot be damped even after 10 seconds. Application of the proposed controller for improving the studied system stability shows that this controller damps the post-fault oscillations in 0.1 second in the state without observer within 6.2 seconds and less than 4 seconds with observer. As shown in the simulation results, the PI regulators are nearly failed to damp the low frequency oscillations of the power system or leastwise its settling time is high, but the proposed sliding mode controller has much better efficiency.

7. ACKNOWLEDGMENT

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