Adaptive Sliding Mode Control for Multi-machine Power Systems under Normal and Faulted Conditions

A. Samanfar¹, M. R. Shakarami², *, J. Soltani³, and E. Rokrok⁴

1. A. Samanfar is Ph.D. student in the Department of Electrical Engineering of Lorestan University, Lorestan, Iran (e-mail: Samanfar.am@fe.lu.ac.ir & a.samanfar@gmail.com).
2. Dr. M. R. Shakarami is with the Department of Engineering of Lorestan University, Lorestan, Iran (e-mail: Shakarami.mr@lu.ac.ir), Tel: +989166675849.
3. Dr. J. Soltani currently is with the Department of Electrical Engineering of Islamic Azad University – Khomeinishahr branch, (e-mail: jsoltani@iaukhsh.ac.ir).
4. Dr. E. Rokrok is with the Department of Engineering of Lorestan University, Lorestan, Iran (e-mail: Rokrok.e@lu.ac.ir).

Abstract: This paper proposes a new adaptive sliding mode (ASM) decentralized excitation controller to improve the stability of multi-machine power systems under different perturbations such as system parametric and structural uncertainties. The stability of the closed-loop system is proved by Lyapunov stability theory. The proposed controller is evaluated through simulation on the standard IEEE 33-bus-bar power system which contains 6 synchronous machines and a HVDC-link. The simulation results indicate good robustness and satisfactory performance of the proposed controller. Moreover, in this paper, using the space-phasor based sequence networks method, a procedure for the dynamic analysis of modern power systems under the transient asymmetrical faults is presented. The method considers the complete dynamics of the synchronous machines and the HVDC-link and provides the possibility of taking into account the sequence networks dynamics.

Index Terms—Adaptive sliding mode control, power system stability, Lyapunov theory, sequence networks, space phasor

1. INTRODUCTION

As power demand grows rapidly, and expansion in transmission and generation is restricted with the limited availability of resources and the strict environmental constraints, power systems are today much more loaded than before. This causes the power systems to be operated near their stability limits [1]. In order to enhance the power systems stability and maintain their synchronism, a wide range of controllers have been introduced in the power system literatures to generate a supplementary control signal for the synchronous machine excitation system [2], FACTS devices [3], HVDC-link [4] and renewable energy plants [5]. Among these, the synchronous machine excitation system controllers are known as the flexible and economical way to improve power system stability [2]. Various methods have been used for designing of excitation system controllers. Linear control (LC) techniques are commonly used in designing the classical controllers that ensure the asymptotic stability of the operation point under small perturbations [6], [7]. A number of techniques in scientific resources have been developed to improve the performance of classical controllers [8], [9]. In practice, the efficiency of the controllers may be affected due to the wide variations in the operation point and the nonlinear behaviour of the power systems.

In order to consider the complete operation region and deal with the nonlinear behavior of the power systems, nonlinear controllers have been implemented in power systems studies. The direct Lyapunov method [10], and feedback linearization [11] are the most common nonlinear controllers in the power systems. These methods can solve the problems of the LC techniques, but they are not robust enough in the presence of the system uncertainties. Neural networks [12], and fuzzy logic [13], as the intelligent control techniques can avoid the former limitations. These are powerful methods and can help to improve the stability of the power system in different operation conditions. But, these methods are time-consuming which limits the use of them in practice. Also, in the neural network-based controllers, a lot of training data is needed which is difficult to get from the physical power systems.

The Sliding Mode Control (SMC) is a well-known technique to improve the stability of nonlinear systems, under parametric uncertainties and external disturbances [14]-[21]. In recent years, several power system stabilizers (PSS) based on SMC scheme have been proposed in literatures [16]-[21]. In these controllers, the control laws with fixed control gains have been used. Since the upper bound of the system’s uncertainties may not be easily obtained, a large quantity for this parameter is assumed to guarantee the stability of the system. This may lead to undesired chattering and a very high control input power [22]. Also, most of these controllers require not only the local generator information but also the power system information which limits their
application in large power systems. Moreover, these controllers have been evaluated just in balanced conditions, while the probability of unbalanced conditions and in particular asymmetrical faults is high in power systems [18]-[22].

The main contribution of this paper is to propose an adaptive sliding mode (ASM) decentralized excitation controller to improve modern power systems stability. The proposed controller has an adaptive control gain that despite of the conventional sliding mode (CSM) controllers, its initial setting should be smaller than the upper bound of the system uncertainties. This feature of the proposed controller eliminates the requirement of knowing the upper bound of the system uncertainties, which is difficult to obtain in practice. Furthermore, the adaptive control gain could reduce the probability of occurrence of the chattering phenomena and also reduce the control costs [23]. It is necessary to note that the proposed decentralized controller requires only local generator information which is a merit in large power systems. The proposed controller does not need observers and the controller considers the neglected dynamics as internal or external perturbations. In this study, the proposed controller not only has been evaluated for the symmetrical faults, but also for the asymmetrical faults. The dynamic analysis of the faulty systems is performed by space-phasor based sequence networks method. The method considers complete dynamics of synchronous machines, HVDC-links, and sequence networks.

2. ASM CONTROLLER DESIGN

Here, an ASM controller is designed to improve the stability of the practical multi-machine modern power systems. In this study, a local controller is designed for each synchronous machine and the effect of other synchronous machines is considered as a perturbation by means of the power oscillations. So, the communication among the controllers is not needed [21]. For designing the ASM controller, the third order model of the synchronous machine [1] is used:

\[
\frac{d\delta}{dt} = \omega_r - \omega_0 \tag{1}
\]

\[
\frac{2H}{\omega_0} \frac{d\omega_r}{dt} = T_L - T_e - D(\omega_r - \omega_0) \tag{2}
\]

\[
\frac{dE_q}{dt} = \frac{1}{T_{do}} \left[ E_{fd} - E_q - (X_q - X_d') i_{qs}'i_{ds}' \right] \tag{3}
\]

On the other hand, the electrical torque is:

\[
T_e = E_q i_{qs}' + (X_q - X_d') i_{qs}'i_{ds}' \tag{4}
\]

Due to the slow variations of \(i_{qs}'\) and \(i_{ds}'\), the derivations of these currents are assumed to be zero. Hence, derivation of \(T_e\) with respect to time, gives:

\[
\frac{dT_e}{dt} \approx \frac{dE_q}{dt} i_{qs}' \tag{5}
\]

Substituting for (3) in (5), and defining \(B = \frac{1}{T_{do}}\) leads to:

\[
\frac{dT_e}{dt} = i_{qs}' B \left[ E_{fd} - E_q - (X_d - X_d') i_{ds}' \right] \tag{6}
\]

The nominal values of the parameters in (6) can be defined as:

\[
B_n, X_{d-n}, X_{d-n}' \tag{7}
\]

The equations between the real and nominal values of these parameters are considered as follows:

\[
B = B_n + \Delta B \tag{8}
\]

\[
X_d = X_{d-n} + \Delta X_d \tag{9}
\]

\[
X_d' = X_{d-n}' + \Delta X_d' \tag{10}
\]

Substituting for (8), (9) and (10) in (4) and (6) gives:

\[
T_e = E_q i_{qs}' + (X_{q-n} - X_{d-n}) i_{qs}'i_{ds}' + \zeta_1 \tag{11}
\]

\[
\frac{dT_e}{dt} = i_{qs}' B_n \left[ E_{fd} - E_q' - (X_{d-n} - X_{d-n}') i_{ds}' \right] + \zeta_2 \tag{12}
\]
where, $\zeta_1$ and $\zeta_2$ as the model uncertain functions can be expressed as:

$$\zeta_1 = (\Delta X_q - \Delta X_d) i_{qs}^r i_{qs}^s$$  \hspace{1cm} (13)
$$\zeta_2 = i_{qs}^r \Delta B \left[ E_{fd} - E_q - (X_d - X_q) i_{ds}^r \right] - i_{qs}^r B_n \left[ (\Delta X_d - \Delta X_q) i_{ds}^r \right]$$  \hspace{1cm} (14)

Since all parameters in (13) and (14) are bounded, it can be concluded that $\zeta_1$ and $\zeta_2$ are bounded functions.

To design the proposed ASM controller, the electrical torque and the mechanical speed error variables are defined as:

$$e_T^* = T_e^* - T_e, \quad e_{\omega_0} = \omega_r - \omega_0$$  \hspace{1cm} (15)

where, these errors are the difference between the real and reference values. The output speed error $e_{\omega_0}$ can be eliminated by definition the reference value of the electrical torque $T_e^*$ as:

$$T_e^* = K_e \int (\omega_r - \omega_0) dt$$  \hspace{1cm} (16)

where, $K_e$ is a positive scalar. At first, the controller is designed by taking into account the nominal values of the model and neglecting the model uncertain functions ($\zeta_1$ and $\zeta_2$). The sliding surface is selected as:

$$S = e_T + e_{\omega_0} + K \int (e_T + e_{\omega_0}) dt$$  \hspace{1cm} (17)

where, $K$ is a positive scalar. In accordance with sliding mode technique, the derivation of the sliding surface is set to zero:

$$\dot{S} = 0 \rightarrow \dot{e}_T + \dot{e}_{\omega_0} + K \left( e_T + e_{\omega_0} \right) = 0$$  \hspace{1cm} (18)

Or:

$$\dot{S} = M + N = 0$$  \hspace{1cm} (19)

where,

$$M = \dot{e}_T + K e_T, \quad N = \dot{e}_{\omega_0} + K e_{\omega_0}$$  \hspace{1cm} (20)

It is claimed that by setting $M$ to zero, $N$ will also be zero.

$$M = \dot{e}_T + K e_T = 0 \xrightarrow{t \to \infty} e_T = 0, \quad \dot{e}_T = 0$$  \hspace{1cm} (21)

As,

$$\dot{e}_T = 0 \rightarrow T_e^* - T_e^r = 0 \rightarrow K_e \left( \omega_r - \omega_0 \right) - T_e^r = 0$$  \hspace{1cm} (22)

From (2), and assuming that $T_L$ is a constant, one can derive that:

$$T_e = -\frac{2H}{\omega_0} \dot{e}_{\omega_0} - D e_{\omega_0}$$  \hspace{1cm} (23)

By substituting for (23) in (22) gives:

$$\frac{2H}{\omega_0} \ddot{e}_{\omega_0} + D \ddot{e}_{\omega_0} + K_e e_{\omega_0} = 0 \xrightarrow{t \to \infty} e_{\omega_0} = 0, \quad \dot{e}_{\omega_0} = 0, \quad \ddot{e}_{\omega_0} = 0 \quad \Rightarrow N = 0$$  \hspace{1cm} (24)

In this way, the claim is proven. So, for obtaining the equivalent ASM controller, just $M$ is considered. Combining (15), (16) and (20) leads to:

$$M = K_e e_{\omega_0} - T_e^r + K e_T$$  \hspace{1cm} (25)

Setting (25) into zero and replacing (6) in it, gives the control law as:

$$E_{fd} = E_q + (X_d - X_q) i_{ds}^r + \frac{K_e}{i_{qs}^r B_n} e_{\omega_0} + \frac{K}{i_{qs}^r B_n} e_T$$  \hspace{1cm} (26)
In (26) the parameters have nominal values. If the model parameters are not equal to the nominal values, system responses will not settle on the sliding surface. By considering equation (19) and substituting for M and N in it, gives:

\[ \dot{S} = M + N = K_e e_\omega - T_e + K e_T + \dot{e}_\omega + Ke_\omega \]  

(27)

In the presence of uncertainties, according to (11) and (12), \( \dot{T}_e \) and \( T_e \) contain \( \zeta_1 \) and \( \zeta_2 \) respectively, as uncertainty terms. So, the derivation of the sliding surface can be defined as follows:

\[ \dot{S} = \dot{S}_n + \eta \]  

(28)

where, \( \dot{S}_n \) is the derivation of the sliding surface for the nominal values and \( \eta \) is the system uncertain function. \( \dot{S}_n \), and \( \eta \) are obtained as:

\[ \dot{S}_n = M = K_e e_\omega - T_e + K e_T \]  

(29)

\[ \eta = -\zeta_1 - \zeta_2 + N = -\zeta_1 - \zeta_2 + \dot{e}_\omega + Ke_\omega \]  

(30)

In this paper, the modified control law is proposed to be:

\[ E_{fd} = E_{fd-n} + \tilde{E}_{fd} \]  

(31)

where, \( E_{fd-n} \) is the same as (26) used for nominal conditions. Also, the adaptive term \( \tilde{E}_{fd} \) is modified as below to deal with the bounded uncertainties expressed in (30):

\[ \tilde{E}_{fd} = \frac{1}{\eta} (K_e S + \Gamma \text{sgn}(S)) \]  

(32)

where, \( \Gamma \) is an adjustable gain constant. The desired value of this parameter is called \( \Gamma_d \) and must satisfy the following condition:

\[ |\eta| < \Gamma_d \]  

(33)

The adaptive law for adjusting \( \Gamma \) is:

\[ \dot{\Gamma} = \frac{1}{\alpha} |S| \]  

(34)

In (34), \( \alpha \) is a positive scalar and called the adaption gain. The adaption speed can be tuned by \( \alpha \). Also, choosing a suitable adaption gain \( \alpha \) can effectively avoid high control activity in the reaching mode [23]. It can be proved that the proposed controller makes the closed-loop system stable in the presence of uncertainties and disturbances, and the system response will certainly be on the sliding surface. In this regard, \( \dot{S} \) can be simplified as following by combining (28)-(32) and some mathematical manipulations:

\[ \dot{S} = - (K_e S + \Gamma \text{sgn}(S)) + \eta \]  

(35)

In order to examine the validity of the proposed control law, the following Lyapunov function is defined as:

\[ V = \frac{1}{2} S^2 + \frac{1}{2} \Gamma^2 \]  

(36)

where, \( \Gamma = \Gamma - \Gamma_d \), by taking the time derivative of \( V \), one can obtain:

\[ \dot{V} = SS + \alpha \Gamma \dot{\Gamma} \]  

(37)

By substituting for (35) in (37) and considering \( \dot{\Gamma} = \dot{\Gamma} \), (37) becomes:

\[ \dot{V} = S ( -K_e S - \Gamma \text{sgn}(S) + \eta ) \]  

\[ + (\Gamma - \Gamma_d ) S \text{sgn}(S) \]  

(38)

Finally, according to \( S \cdot \text{sgn}(S) = |S| \), the derivation of Lyapunov function can be written as:

\[ \dot{V} = -K_e S^2 + \eta S - \Gamma_d |S| \]  

(39)

Based on (33), one can derive \( \eta S < \Gamma_d |S| \), then:

\[ \dot{V} < 0 \]  

(40)

Hence, the derivation of the Lyapunov function is a negative function. Therefore, the convergence of \( S \) and \( \dot{\Gamma} \) is guaranteed and both of them reach zero in finite time. This completes the proof.
3. POWER SYSTEM DYNAMIC ANALYSIS

In [24], a method based on space phasors has been introduced for dynamic analysis of transient symmetrical or asymmetrical faults in power systems. In this section, by developing the method described in [24], the dynamic analysis of a transient single-line-to-ground (SLG) fault in the IEEE 33-bus standard network including a HVDC-link is discussed. The method described here can easily be implemented to analyze other symmetrical and asymmetrical series or shunt faults. Fig. 1 shows the IEEE 33-bus standard network.

Fig. 1.

This network consists of three areas, 33-bus, 6 synchronous machines, and a HVDC-link. Fig. 2 depicts the HVDC general circuit and the proposed models for a HVDC-link in positive- and negative-SNs. So, a HVDC-link can be modelled in the sequence networks by means of its positive- and negative-sequence current space phasors.

Fig. 2.

Before the occurrence of a fault, the network equilibrium point is obtained through the Newton-Raphson AC load flow. When a SLG fault occurs at point “P” (between the buses 17 and 24), a virtual bus is considered at this point with the number 34. Fig. 3 shows the sequence networks of the system.

Fig. 3.

In this figure, the PSN, NSN, and ZSN expressions indicate the positive-, negative-, and zero-sequence networks, respectively. Then, the bus-impedance matrices of the positive-, negative- and zero-sequence networks with the titles $Z^+, Z^-$ and $Z^0$ are composed. The dimensions of these matrices are $34 \times 34$ in this example. In order to calculate the fault-current sequence components, the equivalent circuits of the sequence networks are configured at “P”.

The type of fault determines how to connect the sequence networks at the point “P”. Fig. 4 illustrates how to connect these equivalent circuits for a SLG fault.

According to Fig. 4, the fault current sequence components are as follows:

$$I_f^+ = I_f^- = I_f^0 = \frac{E_{mn}^+ + E_{mn}^-}{(z_{mh}^+ + z_{ih}^- + z_{ih}^0 + z_f^-)}$$ (41)

In (41), quantities with the superscripts (+), (-), and (0) denote the positive-, negative-, and zero-sequence quantities, respectively. $I_f^-$ is the fault current and $z_f^-$ is the impedance of the fault. After calculating the fault-current sequence components, each component is injected as an injection-current source into the “P” in the corresponding sequence network. Fig. 5 shows how to model the fault current in positive- and negative-sequence networks.

Fig. 4.

The fault current sequence components are considered in the currents vectors of positive and negative sequence networks. Then, the terminal sequence voltages $(V_f^+, V_f^-)$ of the synchronous machines in different sequence networks are obtained through the quasi-static Y-matrix equations of sequence networks. These voltages are in the synchronous reference frame and must be transferred to the rotor reference frame according to transform functions as below:

$$F_f^r+ = F_r^+ e^{-j\delta}$$ (42)

$$F_f^r- = F_r^- e^{-j(2\pi f t + \delta)}$$ (43)

In these Equations, $F_f^+$ & $F_f^-$ are the electrical variables (voltage or current) of the synchronous machines in the synchronous reference frame, respectively, and $F_r^+$ & $F_r^-$ are those variables in the rotor reference frame. In Equations (42) and (43), $\delta$ is the angle between the quadrature axes of the rotor and the synchronous reference frames. These Equations guarantee the eliminating of time-varying inductances in the Park’s voltage equations in unbalanced conditions. So, the conventional full-order differential equations of the synchronous machine in the rotor reference frame could be used in unbalanced condition [24]. In the next section, the procedure of this method is presented.

4. DYNAMIC ANALYSIS PROCEDURE

In the previous section, the method for obtaining the mathematical model of the power system during fault time was developed. Here, the steps of the procedure for the dynamic analysis of a faulted power system are presented as follows:

1. Solve the power system load-flow equations to get the system’s initial values
2. Form the $[Y]$ matrices of the three-sequence networks
3. According to the fault type, expand and modify the $[Y]$ matrix of the sequence networks to include the fictitious bus
4. Inject the current space phasors of synchronous machines and HVDC-link at their related bus or buses in each sequence network
5. Determine the Thevenin equivalent circuits seen from the fault point and then calculate the fault-current space phasors
6- Separate the sequence networks and inject the current sequence components of the synchronous machines, HVDC-link, and fault in their related buses in each sequence network (Fig. 5)
7- Solve the Y-matrix equations of positive- and negative-sequence networks to obtain the terminal sequence voltages of synchronous machines and HVDC-link
8- For each synchronous machine, transfer the values of the terminal sequence voltages to its rotor reference frame (Equations (42) and (43)). Then, solve the differential equations of the synchronous machine and update the values of its state variables. Using the updated state variables, calculate the output-current sequence components of the synchronous machine and transfer them to the synchronous reference frame by (42) and (43)
9- For the HVDC-link, solve the differential equations and calculate its injection currents at the both ends in the positive- and negative-sequence networks
10- If the fault is cleared, print the results; otherwise, go to Step 4

Based on the above procedure, a MATLAB code program has been developed. The program uses the numerical fourth order static Range-Kutta method with a time step \( \Delta t \) of \( 10^{-4} \) to solve nonlinear equations of synchronous machines and the HVDC-link. The program can be used for the dynamic analysis of power systems faced to any kind of shunt faults.

5. SIMULATION RESULTS

Here, the proposed ASM controller is tested on the IEEE standard 33-bus network (Fig. 1), including the full-order model of synchronous machines and complete dynamics of the HVDC-link. For the synchronous machines, two damper windings on the q-axis and a damper winding on the d-axis are considered [25]. Also, the HVDC-link is fully modelled that includes its filters and switching circuits. In this study, network loads, transmission lines, power transformers, and fault are modelled as constant impedances. The machine specifications, the HVDC-link parameters, and the network load-flow data are provided in [3], [26], and IEEE website, respectively. In this network, it is supposed that the excitation systems of G2-G6 are equipped with the proposed ASM controller. In the following, the proposed controller is evaluated by performing different scenarios in the network.

A. SCENARIO 1

In this scenario, the performance of the proposed ASM controller is evaluated by using it in the IEEE 33-bus network. It is assumed that before \( t=0 \)sec, the HVDC-link is not in service and the network has been in a steady state condition. Then, the following events are applied in the network at \( t=0 \)sec:
1- An initial error of +20% is considered in the reactance of the transmission lines 1-22 and 2-23.
2- An initial error of -20% is considered in the direct axis transient reactance of the synchronous machines G3-G6.

Fig. 6 shows the rotor angles of synchronous machines before installing controllers in the network.

Fig. 6.

In order to cope with the mentioned uncertainties and to achieve the minimum network stabilizing time, G2-G6 synchronous machines are equipped with the proposed ASM controller. The controllers’ parameters are obtained by trial and error method. Fig. 7 and Fig. 8, respectively, show the rotor angles and rotor angular speeds of the synchronous machines after installing the proposed ASM controllers on G2-G6.

Fig. 7.

Fig. 8.

As shown in these figures, the rotor angles and the angular speeds of all the synchronous machines reach their reference values in finite time despite of the uncertainties. Fig. 9 illustrates the variation of the adjustable gain \( \Gamma \) for the ASM controllers in this study. A small positive initial value (0.001) has been chosen for \( \Gamma \) in all controllers.

Fig. 9.

In this section, another study is conducted to compare the performance of the proposed controller with the CSM controller. The design of ASM and CSM controllers has the same stages, except that in the design of CSM controllers, (considering (32)) \( \Gamma \) is considered as a numerical constant which is greater than the amount of the system’s uncertain function, so that the condition (33) is satisfied. The main limitation of the CSM controllers is the determination of the amount of the system’s uncertain function, which is complex in practice.

Here, to compare the performance of the ASM and CSM controllers, the value of \( \Gamma \) in CSM controllers is determined in two ways.
First, as shown in Fig. 9, the maximum value of this parameter is related to the G6, which is 0.625. It is assumed that G2-G6 are equipped with CSM controllers that the value of \( \Gamma \) in all of them is 0.625. Fig. 10 compares the control signal \( E_{fd} \) of G3-G6 in both cases.

Fig. 10.

As shown in Fig. 10, the amplitude of the control signal \( E_{fd} \) is higher when synchronous machines are equipped with CSM controllers. The lower amount of control signal \( E_{fd} \) in the proposed ASM controller has the following benefits: 1- lower
control costs; 2- reducing the probability of control blocks saturation. Also, setting the maximum value for $\Gamma$ is a conservative choice and may result in increasing the probability of occurrence the chattering phenomenon. Second, as shown in Fig. 9, the minimum value of $\Gamma$ is related to the G2, which is 0.1. It is assumed that G2-G6 are equipped with CSM controllers that the value of $\Gamma$ in all of them is 0.1. Fig. 11 illustrates the angular speeds of the synchronous machines in this case.

Fig. 11.

By comparing Fig. 11 with Fig. 8, it can be inferred that the settling time and amplitude of the oscillations have increased. Hence, the simulation results show the superiority of the ASM controllers to the CSM controllers. It should be noted that after stabilizing of the system, in ASM controllers the values of $\Gamma$ are reset to the initial values.

B. Scenario 2

In this scenario, the performance of the proposed controller is evaluated in the face of structural and parametric uncertainties of the network. It is assumed that before $t=0$ sec, the HVDC-link is not in service and the network has been in a steady state condition. The structural uncertainties applied to the network are:

1- In $t=0$ sec, the HVDC-link is switched on.
2- In $t=3$ sec, a 100ms SLG fault is considered at the middle of the line 17-24. This fault is cleared at $t=3.1$ sec with line interruption and reclosing the line at $t=4.1$ sec.

On the other hand, as parametric uncertainties, the following items are considered in the network:

1- An initial error is considered in the reactance of the transmission lines 1-22 and 2-23.
2- An initial error is considered in the direct axis transient reactance of the synchronous machines G3 and G6.

The initial errors of the mentioned parameters is considered in the range of $\pm 20\%$ with a step of 5%. Many simulations have been performed to ensure the correctness of the controller evaluation. In each simulation, the uncertainty of the above parameters is randomly selected and the simulation results are stored. At the end, the results of the simulations are averaged.

In this scenario, the HVDC-link controllers are adjusted to: 1- Injecting the desired active and reactive powers to the receiving end bus; 2- The buses of the both ends of the HVDC-link have the desired voltage magnitudes.

The process of analyzing the network during and after the fault has been performed according to the procedure described in Section IV. Fig. 12 and Fig. 13, respectively, show the rotor angles and angular speeds of the synchronous machines in this scenario.

Fig. 12.

Fig. 13.

Fig. 14 shows the dampers and field windings currents for the synchronous Machine 3, as an example. This figure shows that during the fault-time, transient currents are generated in the damper windings, and when the fault is cleared, these currents converge to zero.

Fig. 14.

In this study, the HVDC-link is modelled in details. Fig. 15 shows the voltage magnitude of the HVDC-link both sides’ buses, the voltage of the DC-link and the injected active power to the receiving end of the HVDC-link.

Fig. 15.

This figure illustrates the transients and dynamics of the HVDC-link waveforms in the face of system’ parametric uncertainties and an asymmetrical fault. At last, Fig. 16 shows the rotor angular speeds of the synchronous machines in scenario 2 if instead of a SLG fault, a three-line-to-ground (TLG) fault is considered.

Fig. 16.

The simulation results in these scenarios indicate that the proposed controller improves the network stability under the structural and parametric uncertainties.

6. Conclusion

In this paper, an ASM decentralized excitation controller has been proposed to improve the stability of power systems under different uncertainties. Designing of the proposed controller is comparatively simple and effective and it requires only local generator information. Simulation results on a multi-machine power system including a HVDC link show the satisfactory performance of the proposed controller. Also, the results show that the proposed controller need low control cost in comparing to the CSM controller. Therefore, by using this controller the probability of occurrence the chattering phenomenon is reduced. Furthermore, in this paper, using the space-phasor based sequence networks method, a procedure has been proposed for the dynamic analysis of power systems. The method is systematic, so that it is simply possible to repeat the study of asymmetrical faults in different parts of the network by making minor changes to the admittance matrixes of the sequence networks.

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**BIOGRAPHIES**

**Amin Samanfar** received his B.Sc. degree in electronic engineering from Semnan University, Semnan, Iran in 2001 and his M.Sc. degree from Tarbiat Modares University, Tehran, Iran, in 2004. He is currently studying for his Ph.D. degree in the Faculty of Technical & Engineering, Lorestan University, Lorestan, Iran. His research interests are nonlinear control, power system control and dynamics and Flexible Ac Transmission Systems.

**Dr. Mahmoud Reza Shakarami** Mahmoud Reza Shakarami was born in Khorraramabad, Iran, in 1972. He received his M.S. and Ph.D. degrees in Electrical Engineering from Iran University of Science and Technology in Tehran, Iran, in 2000 and 2009, respectively. He is an Associate Professor in the Department of Electrical Engineering, Lorestan University. His current research interests are: power system dynamics and stability and FACTS Devices.

**Dr. Jafar Soltani Zamani** graduated from Tabriz University, Tabriz, IRAN, in 1974 and received his M.Sc. and Ph.D. degrees from the University of Manchester Institute of Science and Technology, Manchester (U.M.I.S.T), U.K. in 1983 and 1987 respectively. He is currently a Professor in the Department of Electrical Engineering Khomeinishar Branch, Islamic Azad University, Isfahan, Iran. He is also an emeritus professor with the Faculty of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran. His main area of research is electrical machines and drive, power electronics and power system control. He has published many international journal and conference papers and is the holder of a U.K. patent. Dr. Soltani is a member of IEEE and IET. In addition, he is the reviewer of some international journals in European and IEEE Transactions.

**Dr. Esmaeel Rokrok** was born in Khorraramabad, Iran, in 1972. He received his B.Sc., M.Sc., and Ph.D. degree in Electrical Engineering from Isfahan University of Technology, in 1995, 1997 and 2010, respectively. He is an Associate Professor in the Department of Electrical Engineering, Lorestan University. His major research interests lie in the area of power system control and dynamics, dispersed generation, microgrid, power electronic and robust control.
Fig. 1. IEEE 33-Bus Standard Network with a HVDC-link

Fig. 2. HVDC Model, a) Schematic b) In Positive Sequence Network c) In Negative Sequence Network

Fig. 3. The Sequence Networks of Fig. 1.
PSN: Positive Sequence Network, NSN: Negative Sequence Network, ZSN: Zero Sequence Network
Fig. 4. Connecting Sequence Networks for a SLG Fault

Fig. 5. Modelling the Fault Current Sequence Components in PSN (Positive Sequence Network) and NSN (Negative Sequence Network)

Fig. 6. Rotor Angles of the Synchronous Machines without Controllers in Scenario 1

Fig. 7. Rotor Angles of the Synchronous Machines with ASM Controllers in Scenario 1
Fig. 8. Rotor Angular Speeds of the Synchronous Machines with ASM Controllers in Scenario1

Fig. 9. Adjustable Gains (Γ) for ASM Controllers

Fig. 10. Control Signal $E_{id}$: Solid Line- with ASM Controllers; Dash-dotted Line- with CSM Controllers

Fig. 11. Rotor Angular Speeds of the Synchronous Machines with CSM controllers in Scenario1
Fig. 12. Rotor Angles of the Synchronous Machines in Scenario 2

Fig. 13. Rotor Angular Speeds of the Synchronous Machines in Scenario 2

Fig. 14. Currents of Field and Damper Windings of the Synchronous Machine3 in Scenario 2

Fig. 15. Waveforms Related to HVDC in Scenario 2
Fig. 16. Rotor Angular Speeds of the Synchronous Machines in Scenario 2 for a TLG fault