Transient Stability Enhancement of Power Systems Using Observer-Based Sliding Mode Control

M. Ouassaid, M. Maaroufi and M. Cherkaoui

Abstract The high complexity and nonlinearity of power systems, together with their almost continuously time-varying nature, have presented a big challenge for control engineers, for decades. The disadvantages of the linear controllers/models, such as being dependent on the operating condition, sensibility to the disturbance such as parametric variations or faults can be overcome by using appropriate nonlinear control techniques. Sliding-mode control technique has been extensively used when a robust control scheme is required. This chapter presents the transient stabilization with voltage regulation analysis of a synchronous power generator driven by steam turbine and connected to an infinite bus. The aim is to obtain high performance for the terminal voltage and the rotor speed simultaneously under a large sudden fault and a wide range of operating conditions. The methodology adopted is based on sliding mode control technique. First, a nonlinear sliding mode observer for the synchronous machine damper currents is proposed. Next, the control laws of the complete ninth order model of a power system, which takes into account the stator dynamics as well as the damper effects, are developed. They are shown to be asymptotically stable in the context of Lyapunov theory. Finally, the effectiveness of the proposed combined observer-controller for the transient stabilization and voltage regulation is demonstrated.

Nomenculture

v_d, v_q	Direct and quadrature axis stator terminal voltage components, respectively
v_{fd}	Excitation control input

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v_t	Terminal voltage
i_d, i_q	Direct and quadrature axis stator current components, respectively
i_{fd}	Field winding Current
i_{kd}, i_{kq}	Direct and quadrature axis damper winding current components, respectively
λ_d, λ_q	Direct and quadrature axis flux linkages, respectively
R_s	Stator resistance
R_{fd}	Field resistance
R_{kd}, R_{kq}	Damper winding resistances
L_d, L_q	Direct and quadrature self inductances, respectively
L_{fd}	Rotor self inductance
L_{kd}, L_{kq}	Direct and quadrature damper winding self inductances, respectively
L_{md}, L_{mq}	Direct and quadrature magnetizing inductances, respectively
ω	Angular speed of the generator
δ	Rotor angle of the generator
T_m	Mechanical torque
T_e	Electromagnetic torque
D	Damping constant
H	Inertia constant
a	Phase angle *of* infinite bus voltage
$V^{\propto}$	Infinite bus voltage
L_e	Inductance of the transmission line
R_e	Resistance of the transmission line

1 Introduction

Nowadays, electric power systems have evolved through continuing growth in interconnections, use of new technologies and controls. They are operating more and more closely to their limit stability in highly stressed conditions. To maintain a high degree of reliability and security, different forms of system instability must be considered in the design of controllers.

Stability is a condition of equilibrium between opposing forces. Depending on the network topology, system operating condition and the form of disturbance, different sets of opposing forces may experience sustained imbalance leading to different forms of instability. Figure 1 identifies the categories and subcategories of the power system stability problem. The classification of power system stability is generally based on the physical nature of the resulting mode of instability, the size of the disturbance considered, the devices, processes, and the time span (Kundur 1994).

The reliability of the power supply implies much more than merely being available. Ideally, the loads must be fed at constant voltage and frequency at all times. However, small or large disturbances such as power changes or short circuits may transpire. One of the most vital operation demands is maintaining good stability and transient

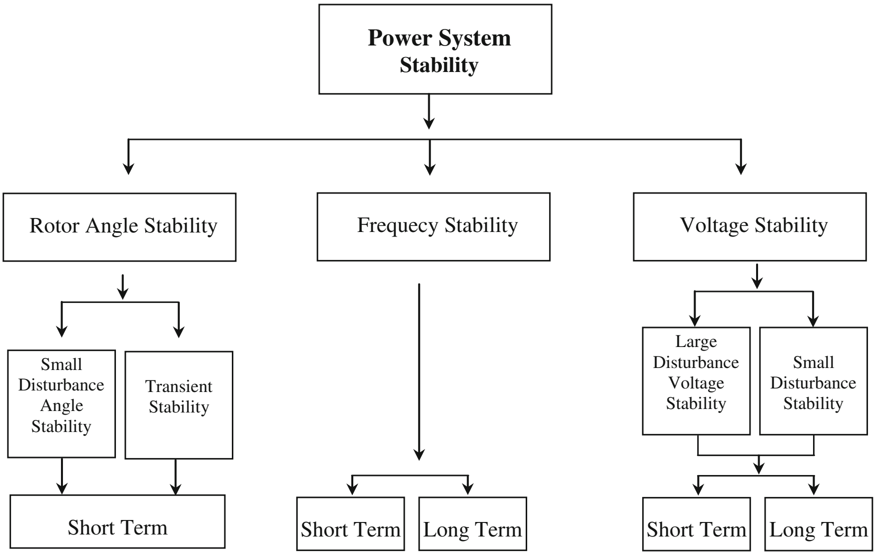

Fig. 1 Classification of power system stability

performance of the terminal voltage, rotor speed and the power transfer to the network (Guo et al. 2001; Jiawei et al. 2014). This requirement should be achieved by an adequate control of the system.

Traditionally, excitation controllers, which are mainly designed by using linear control theory, are used to regulate the terminal voltage at a specified value and ensure the stability under small and large disturbances. The principal conventional excitation controller is the automatic voltage regulator (AVR). Many different AVR models have been developed to represent the various types used in a power system. The IEEE defined several AVR types, the main one of which (Type 1) is shown in Fig. 2. The modern AVR employing conventional, fixed parameter compensators, whilst capable of providing good steady state voltage regulation and fast dynamic response to disturbances, suffers from considerable variations in voltage control performance as the generator operating change. Several forms of adaptive control have been investigated to address the problem of performance variation (Ghazizadeh and Hughes 1998).

Adversely, the generator automatic voltage regulator which reacts only to the voltage error weakens the damping introduced by damper windings. This detrimental effect of the AVR can be compensated using supplementary control loop which is the power system stabilizer (PSS). The structure of the PSS is given in Fig. 3. These stabilizers introduced additional system damping signals derived from the machine speed or power through the excitation system in order to improve the damping of power swings (Ghandakly and Farhoud 1992). Conventional fixed parameter stabilizers work reasonably well over medium range of operating conditions. However may diminish as the generator load changes or the network configuration is altered

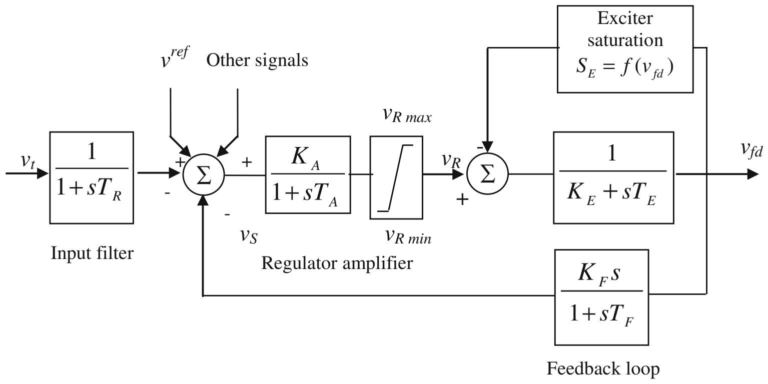

Fig. 2 Block diagram of the conventional IEEE type 1 AVR

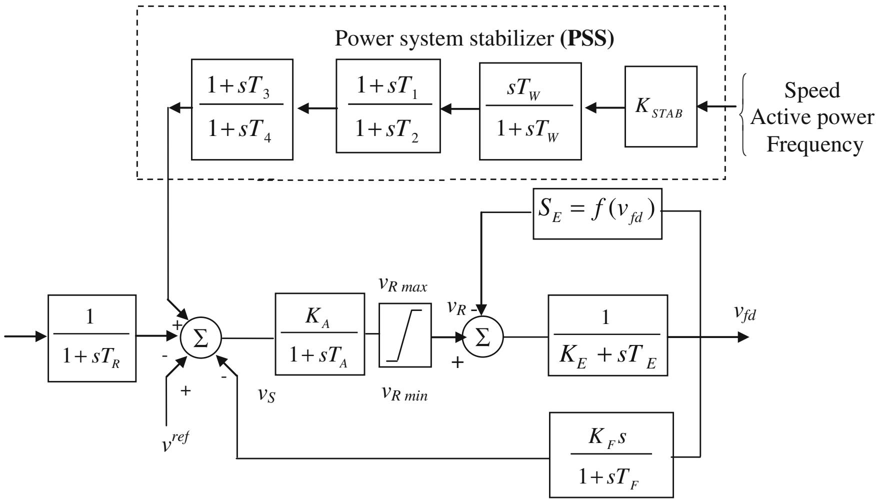

Fig. 3 Block diagram of the AVR+PSS structure

by faults or other switching conditions which lead to deterioration in the stabilizer performance. Remarkable efforts have been devoted to the design of appropriate PSS; various methods, such as root locus, eigenvalue techniques, pole placement, adaptive control, etc. have been used. But in all these methods, model uncertainties cannot be considered explicitly at the design stage (Zhao and Jiang 1995).

To deal with a high complexity and nonlinearity of power systems, together with their almost continuously time-varying nature, different techniques have been investigated in aim to:

- Tackle the problem of transient stability by considering nonlinear models of power systems.

- Overcome the drawbacks of the linear controllers via design of nonlinear controllers.

The main features of those controllers are summarized as follows:

- Independence of the equilibrium point and taking into account the important nonlinearities of the power system model.
- *Robustness* The designed controller must be insensible to all kinds of perturbations such as parametric variations or faults and the non-modeled dynamics.
- *Dynamics performance and Tracking* Terminal voltage, rotor speed and rotor angle converge to their references with accuracy and rapidity.
- *Enhancing the transient stability* Damping of all types of oscillations (local and inter area).

Several control approaches have been applied. As a summary, the main strategies are outlined as follows:

1.1 Feedback linearization

The essence of this technique is to first transform a nonlinear system into a linear on by a nonlinear feedback, and then uses the well-known linear design techniques to complete the controller design (Isidori 1995). Nevertheless these control designs require the exact cancellation of nonlinear terms. With parametric uncertainties present in the system, the cancellation is no longer applied. This constitutes an important drawback in the implementation of such controllers in the presence of model uncertainties and/or external disturbances, thus affecting the robustness of the closed loop system (Gao et al. 1992; King et al. 1994). Several adaptive versions of the feedback linearizing controls are then developed in (Jain et al. 1994; Tan and Wang 1998).

1.2 Passivity based control

The control based on the passivity has been the subject of several investigations. The aim of the method is to make the system passive closed loop (Byrnes et al. 1991; Kokotovic 1992; Ortega et al. 1998). This approach is limited to physical systems described by equations of motion Euler-Lagrange. The major problem with this approach is that the performance of the closed loop system depends on the knowledge of the model parameters used to define terms of energy dissipation. Therefore, the performance is not satisfactory if terms of energy, which are used to ensure the asymptotic stability of the controlled system dissipation, are used to ensure the passivity for all operating conditions (Nickllasson et al. 1997). References (Ortega et al. 1998) and (Galaz et al. 2003) present an application of this technique.

1.3 Robust control

To cope with parametric uncertainties in power systems, many robust voltage regulators have been proposed using the theory of linear robust control such as H ∞ (Ahmed et al. 1996) and the L ∞ stability theory (Guo et al. 2001; Jiawei et al. 2014). In (Ohtsuk 1992), several types of uncertainties and changes in variables are taken into account in the design of H ∞ controller. The maximum effects of these disturbances are minimized. The use of this type of control for electric power system is investigated in (Xi et al. 2002) and (Wang et al. 2003). The disadvantage of these regulators is excessive gain values, which makes it difficult their practical achievements.

1.4 Adaptive control

It should be noted that the model of a process, even relatively complex, is never perfect. This type of approach applies to systems whose dynamics are known but whose parameters are poorly identified or unknown or even slowly varying in time (Astrom and Wittenmark 1995). The weakness of this type of controller resides essentially in the fact that the dynamics of the estimator is not considered in the design process. The relatively slow convergence of the adaptation may result in some cases irreversible instability of the loop (Narendra and Balakrishnan 1997). In (Khorrami et al. 1994; Ghandakly and Dai 2000; Shen et al. 2003; Jiao et al. 2005; Wu and Malik 2006), regulators of power system are based on adaptive control.

1.5 Backstepping technique

This approach widely detailed by Krstic and Kokotovic Kanellakopolus in (Krstić et al. 1995) provides solutions to the aforementioned problems. Indeed, the backstepping, whose basic idea is to synthesize the control law in a recursive manner, is less restrictive compared to the control non-linear state feedback which cancels the nonlinearities that might be useful. Unlike the adaptive controllers, based on certain equivalence, which separate the design of the controller and the terms of adaptation, adaptive backstepping has emerged as an alternative. In adaptive backstepping, the control law takes into account the dynamic adaptation. These last two and the Lyapunov function which guarantees the stability and performance of the overall system are designed simultaneously. This technique has been successfully applied for power system in (Karimi and Feliachi 2008; Ouassaid et al. 2008, 2010).

1.6 Intelligent control

New approaches have been proposed for power stability such as fuzzy logic control (Mrad et al. 2000; Abbadi et al. 2013), neurocontrol (Shamsollahi and Malik 1997; Park et al. 2003; Venayagamoorthy et al. 2003; Mohagheghi et al. 2007) and algorithm genetic (Alkhatib and Duveau 2013). Combinations of the above techniques are also proposed in order to exploit the advantages of each method. These solutions are efficient, but they increase the cost and complexity of the control system (Segal et al. 2000; Wang 2013).

1.7 Sliding mode control

This method is a very interesting technique. It dates back to the 70 s with the work of Utkin (Utkin 1977). It is a robust control to the parametric uncertainties and neglected dynamics. Nevertheless, the problems of chattering inherent in this type of discontinuous control appear quickly. Note that the chattering may excite the high-frequency dynamics neglected sometimes leading to instability. Methods to reduce this phenomenon have been developed (Slotine and Li 1991). This technique was applied to electric power systems in (Morales et al. 2001; Colbia-Vega et al. 2008; Huerta et al. 2010).

Almost all the mentioned above controllers for EPS consider reduced order models, taking into account the generator mechanical dynamics only. In the most of those studies, the nonlinear model used was a reduced third order model of the synchronous machine. In (Loukianov et al. 2004; Cabrera-Vazquez et al. 2007) sliding mode controllers for infinite machine bus systems have been designed considering the mechanical rotor, and electrical stator dynamics. Likewise, In (Akhrif et al. 1999), the feedback linearization technique was used to improve the system's stability and to obtain good post-fault voltage regulation. It is based on a 7 order model of the synchronous machine which takes into account the damper windings effects. However the authors assumed that the damper currents are available for measurement. In fact, the technology for direct damper current measurement is not fully developed yet. Because, damper windings are metal bars placed in slots in the pole faces and connected together at each end.

Thanks to the mentioned assumption, implementation of a controller based on a complete 7th order model of power synchronous machine requires information about the entire states of the power system. As a result, the estimation problem of damper currents of synchronous generator arises. For this purpose, a nonlinear observer for damper currents is developed, based on the sliding mode technique (Ouassaid et al. 2012).

The rest of this chapter is organized as follows: In Sect. 2, a mathematical model of a power system is introduced. It is based on a detailed 9th order model of a system which consists of a steam turbine and Single Machine Infinite Bus (SMIB) and takes into account the stator dynamics as well as the damper winding effects and practical limitation on controls. A nonlinear observer for damper winding currents is developed in Sect. 3. Then, in Sect. 4, a sliding mode controller is constructed based on a time-varying sliding surface to control the rotor speed and terminal voltage, simultaneously, in order to enhance the transient stability and to ensure good post-fault voltage regulation for power system. Section 5 presents a number of numerical simulations results of the proposed observer-based nonlinear controller. Finally, conclusions are given in Sect. 6.

2 Power System Model

The system to be controlled is shown in Fig. 4. It consists of synchronous generator driven by steam turbine and connected to an infinite bus via a transmission line. The synchronous generator is described by a 7th order nonlinear mathematical model which comprises three stator windings, one field winding and two damper windings.

The synchronous machine equations in terms of the Park's d-q axis are expressed (Fig. 5) as follows (Cheng and Hsu 1992; Anderson and Fouad 1994):

Armature windings

$$v_d = -R_s i_d - \omega\lambda_q + \frac{d\lambda_d}{dt} \tag{1}$$

$$v_q = -R_s i_q + \omega\lambda_d + \frac{d\lambda_q}{dt} \tag{2}$$

where

$$\lambda_d = -L_d i_d + L_{md}(i_{fd} + i_{kd}) \tag{3}$$

$$\lambda_q = -L_q i_q + L_{mq} i_{kq} \tag{4}$$

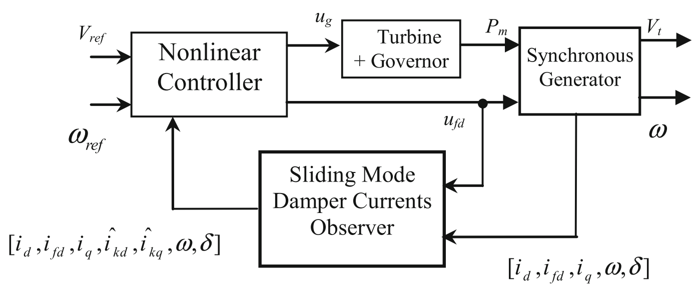

Fig. 4 Block diagram of the power system with observer based-controller

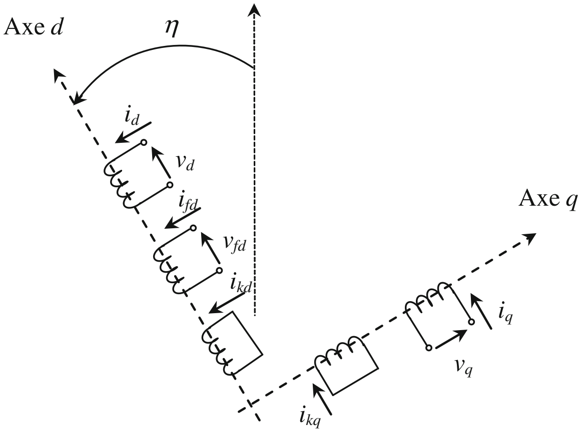

Fig. 5 Synchronous machine in Park's d-q axis

Field winding

$$v_{fd} = R_s i_{fd} - L_{md}\frac{di_d}{dt} + L_{fd}\frac{di_{fd}}{dt} + L_{md}\frac{di_{kd}}{dt} \tag{5}$$

Damper windings

$$0 = R_{kd} i_{kd} - L_{md}\frac{di_d}{dt} + L_{md}\frac{di_{fd}}{dt} + L_{kd}\frac{di_{kd}}{dt} \tag{6}$$

$$0 = R_{kq} i_{kq} - L_{mq}\frac{di_d}{dt} + L_{kq}\frac{di_{kq}}{dt} \tag{7}$$

Mechanical equations

$$\frac{d\delta}{dt} = \omega - 1 \tag{8}$$

$$2H\frac{d\omega}{dt} = T_m - T_e - D\omega \tag{9}$$

The electromagnetic torque is

$$T_e = \left(L_q - L_d\right) i_d i_q + L_{mfd} i_{fd} i_q + L_{md} i_{kd} i_q - L_{mq} i_d i_{kq} \tag{10}$$

The equation of transmission network in the Park's coordinates is

$$v_d = R_e i_d + L_e\frac{di_d}{dt} - \omega L_e i_q + V^{\infty}\cos(\delta - a) \tag{11}$$

$$v_q = R_e i_q + L_e\frac{di_q}{dt} + \omega L_e i_d - V^{\infty}\sin(\delta - a) \tag{12}$$

where R_e is the external resistance and L_e inductance. In state space form, the resulting system by combining Eqs. (1)–(12) is highly nonlinear not only in the state but in the input and output as well (Akhrif et al. 1999). By considering $x = [i_d, i_{fd}, i_q, i_{kd}, i_{kq}, \omega, \delta, P_m, X_e]^T$ the vector of state variables, the mathematical model of the generator system, in per unit, has the following form: Electrical equations:

$$\frac{dx_1}{dt} = x_1 a_{11} + a_{12}x_2 + a_{13}x_3x_6 + a_{14}x_4 + a_{15}x_6x_5 + a_{16}\cos(-x_7 + \sigma) + b_1 u_{fd} \tag{13}$$

$$\frac{dx_2}{dt} = a_{21}x_1 + a_{22}x_2 + a_{23}x_3x_6 + a_{24}x_4 + a_{25}x_6x_5 + a_{26}\cos(-x_7 + \sigma) + b_2 u_{fd} \tag{14}$$

$$\frac{dx_3}{dt} = a_{31}x_1x_6 + a_{32}x_2x_6 + a_{33}x_3 + a_{34}x_4x_6 + a_{35}x_5 + a_{36}\sin(-x_7 + \sigma) \tag{15}$$

$$\frac{dx_4}{dt} = a_{41}x_1 + a_{42}x_2 + a_{43}x_3x_6 + a_{44}x_4 + a_{45}x_6x_5 + a_{46}\cos(-x_7 + \sigma) + b_3 u_{fd} \tag{16}$$

$$\frac{dx_5}{dt} = a_{51}x_1x_6 + a_{52}x_2x_6 + a_{53}x_3 + a_{54}x_4x_6 + a_{55}x_5 + a_{56}\sin(-x_7 + \sigma) \tag{17}$$

Mechanical equations:

$$\frac{dx_6}{dt} = a_{61}x_6 + a_{62}\frac{x_8}{x_6} - a_{62}T_e \tag{18}$$

$$\frac{dx_7}{dt} = \omega_R(x_6 - 1) \tag{19}$$

Turbine dynamics (Hill and Wang 2000):

$$\frac{dx_8}{dt} = a_{81}x_8 + a_{82}x_9 \tag{20}$$

Turbine valve control (Hill and Wang 2000):

$$\frac{dx_9}{dt} = a_{91}x_9 + a_{92}x_6 + b_4 u_g \tag{21}$$

where, u_{fd} the excitation control input, u_g the input power of control system. The parameters a_{ij} and b_i are described as follow

$$a_{11} = -(R_s + R_e)(L_{fd}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad a_{41} = -(R_s + R_e)(L_{fd}L_{md} - L_{md}^2)\omega_R D_d^{-1}$$
$$a_{12} = -R_{fd}(L_{mq}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad a_{42} = R_{fd}((L_d + L_e)L_{md} - L_{md}^2)\omega_R D_d^{-1}$$
$$a_{13} = (L_q + L_e)(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad a_{45} = -L_{md}(L_{mq}.L_{fd} - L_{md}^2)\omega_R D_d^{-1}$$
$$a_{15} = -L_{mq}(L_{fd}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad a_{43} = (L_q + L_e)(L_{md}L_d - L_{md}^2)\omega_R D_d^{-1}$$
$$a_{14} = R_{kd}((L_d + L_e)L_{md} - L_{md}^2)\omega_R D_d^{-1} \quad a_{44} = -R_{kd}((L_d + L_e)L_{fd} - L_{md}^2)\omega_R D_d^{-1}$$

$$
\begin{aligned}
&a_{16} = -V^{\infty}((L_d + L_e)L_{kd} - L_{md}^2)\omega_R D_d^{-1} && a_{46} = -V^{\infty}(L_{md}.L_{fd} + L_{md}^2)\omega_R D_d^{-1}\\
&b_1 = (L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} && a_{51} = -(L_d + L_e)L_{mq}\omega_R D_q^{-1}\\
&a_{21} = -(R_s + R_e)(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} && a_{52} = L_{md}L_{mq}\omega_R D_q^{-1}\\
&a_{22} = -R_{fd}((L_d + L_e)L_{kd} - L_{md}^2)\omega_R D_d^{-1} && a_{53} = -(R_s + R_e)L_{mq}\omega_R D_q^{-1}\\
&a_{23} = (L_q + L_e)(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} && a_{54} = L_{md}L_{mq}\omega_R D_q^{-1}\\
&a_{24} = R_{kd}((L_d + L_e)L_{md} - L_{md}^2)\omega_R D_d^{-1} && a_{55} = -R_{kq}(L_q + L_e)\omega_R D_q^{-1}\\
&a_{25} = -L_{mq}(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} && a_{56} = -V^{\infty}L_{mq}\omega_R D_d^{-1}\\
&a_{26} = -V^{\infty}(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} && a_{61} = -D(2H)^{-1}\\
&b_2 = ((L_d + L_{fd})L_{kd} - L_{md}^2)\omega_R D_d^{-1} && a_{62} = (2H)^{-1}\\
&a_{31} = -(L_d + L_e)L_{kq}\omega_R D_q^{-1} && a_{81} = -(T_m)^{-1}\\
&a_{32} = L_{md}L_{kq}\omega_R D_q^{-1} && a_{82} = K_m(T_m)^{-1}\\
&a_{33} = -(R_s + R_e)L_{kq}\omega_R D_q^{-1} && a_{91} = -(T_g)^{-1}\\
&a_{34} = L_{md}L_{kq}\omega_R D_q^{-1} && a_{92} = -K_g(T_g R\omega_R)^{-1}\\
&a_{35} = -L_{mq}.R_{kq}\omega_R D_q^{-1} && b_4 = K_g(T_g)^{-1}\\
&a_{36} = V^{\infty}L_{kq}\omega_R D_q^{-1} &&\\
&b_3 = ((L_d + L_e)L_{md} - L_{md}^2)\omega_R D_d^{-1} &&
\end{aligned}
$$

Here we have denoted

$$
\begin{aligned}
D_d &= (L_d + L_e)L_{fd}L_{kd} - L_{md}^2(L_d + L_{fd} + L_{kd}) + 2L_{md}^3\\
D_q &= (L_q + L_e)L_{kq} - L_{mq}^2
\end{aligned}
$$

The machine terminal voltage is calculated from Park components v_d and v_q as follows (Anderson and Fouad 1994; Akhrif et al. 1999):

$$
v_t = \left(v_d^2 + v_q^2\right)^{\frac{1}{2}} \tag{22}
$$

with

$$
v_d = c_{11}x_1 + c_{12}x_2 + c_{13}x_3x_6 + c_{14}x_4 + c_{15}x_5x_6 + c_{16}\cos(-x_7 + \sigma) + c_{17}u_{fd} \tag{23}
$$

$$
v_q = c_{21}x_1x_6 + c_{22}x_2x_6 + c_{23}x_3 + c_{24}x_4x_6 + c_{25}x_5 + c_{26}\sin(-x_7 + \sigma) \tag{24}
$$

where c_{ij} are coefficients which depend on the coefficients a_{ij}, on the infinite bus phase voltage V^{∞} and the transmission line parameters R_e and L_e. They are described as follow

$$
\begin{aligned}
&c_{11} = R_e + a_{11}L_e\omega_R^{-1} && c_{17} = b_1L_e\omega_R^{-1}\\
&c_{12} = a_{12}L_e\omega_R^{-1} && c_{21} = L_e + a_{31}L_e\omega_R^{-1}\\
&c_{13} = L_e(a_{13}\omega_R^{-1} - 1) && c_{22} = a_{32}L_e\omega_R^{-1}\\
&c_{14} = a_{14}L_e\omega_R^{-1} && c_{23} = a_{33}L_e\omega_R^{-1} + R_e\\
&c_{15} = a_{15}L_e\omega_R^{-1} && c_{24} = a_{34}L_e\omega_R^{-1}
\end{aligned}
$$

$$c_{16} = V^{\infty} + a_{16} L_e \omega_R^{-1} \qquad c_{25} = a_{35} L_e \omega_R^{-1}$$
$$c_{26} = V^{\infty} + a_{36} L_e \omega_R^{-1}$$

Available states for synchronous generator are the stator phase currents i_d and i_q, voltages at the terminals of the machine v_d and v_q, field current i_{fd}. It is also assumed that the angular speed ω and the power angle δ are available for measurement (De Mello 1994). In the next section the construction an observer of the damper currents i_{kd} and i_{kq} will be given.

3 Sliding Mode Observer for the Damper Winding Currents

The state space representation of the electrical dynamics of the power system model (13)–(17) is given as

$$\frac{d}{dt}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = F_{11}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + F_{12}\begin{bmatrix} x_4 \\ x_5 \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \\ 0 \end{bmatrix} u_{fd} + H_1(t) \tag{25}$$

$$\frac{d}{dt}\begin{bmatrix} x_4 \\ x_5 \end{bmatrix} = F_{21}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + F_{22}\begin{bmatrix} x_4 \\ x_5 \end{bmatrix} + \begin{bmatrix} b_3 \\ 0 \end{bmatrix} u_{fd} + H_2(t) \tag{26}$$

where

$$H_1(t) = [a_{16}\cos(-x_7+\sigma), a_{26}\cos(-x_7+\sigma), a_{36}\sin(-x_7+\sigma)]^T$$

$$H_2(t) = [a_{46}\cos(-x_7+\sigma), a_{56}\sin(-x_7+\sigma)]^T$$

$$F_{11} = \begin{bmatrix} a_{11} & a_{12} & a_{13}x_6 \\ a_{21} & a_{22} & a_{23}x_6 \\ a_{31}x_6 & a_{32}x_6 & a_{33} \end{bmatrix}$$

$$F_{21} = \begin{bmatrix} a_{41} & a_{42} & a_{43}x_6 \\ a_{51}x_6 & a_{52}x_6 & a_{53} \end{bmatrix}$$

$$F_{12} = \begin{bmatrix} a_{14} & a_{15}x_6 \\ a_{24} & a_{25}x_6 \\ a_{34}x_6 & a_{35} \end{bmatrix}$$

$$F_{22} = \begin{bmatrix} a_{44} & a_{45}x_6 \\ a_{54}x_6 & a_{55} \end{bmatrix}$$

Considering the switching surface S as follows

$$S(t) = \begin{bmatrix} \hat{x}_1 - x_1 \\ \hat{x}_2 - x_2 \\ \hat{x}_3 - x_3 \end{bmatrix} \equiv \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = 0 \tag{27}$$

Hence, a sliding mode observer for (25) is defined as

$$\frac{d}{dt}\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \hat{x}_3 \end{bmatrix} = F_{11}\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \hat{x}_3 \end{bmatrix} + F_{12}\begin{bmatrix} \hat{x}_4 \\ \hat{x}_5 \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \\ 0 \end{bmatrix} u_{fd} + H_1(t) + K\begin{bmatrix} \text{sgn}(\hat{x}_1 - x_1) \\ \text{sgn}(\hat{x}_2 - x_2) \\ \text{sgn}(\hat{x}_3 - x_3) \end{bmatrix} \tag{28}$$

where $\hat{x}_1, \hat{x}_2$ and $\hat{x}_3$ are the observed values of i_d, i_{fd} and i_q, K is the switching gain, and sgn is the sign function.

Furthermore, the damper current observer is given from (26) as

$$\frac{d}{dt}\begin{bmatrix} \hat{x}_4 \\ \hat{x}_5 \end{bmatrix} = F_{21}\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \hat{x}_3 \end{bmatrix} + F_{22}\begin{bmatrix} \hat{x}_4 \\ \hat{x}_5 \end{bmatrix} + \begin{bmatrix} b_3 \\ 0 \end{bmatrix} u_{fd} + H_2(t) \tag{29}$$

where $\hat{x}_4$ and $\hat{x}_5$ are the observed values of i_{kd} and i_{kq}.

Subtracting (25) from (28), the error dynamics can be written in the following form

$$\frac{d}{dt}\begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = F_{11}\begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + F_{12}\begin{bmatrix} \tilde{x}_4 \\ \tilde{x}_5 \end{bmatrix} + K\begin{bmatrix} \text{sgnz}_1 \\ \text{sgnz}_2 \\ \text{sgnz}_3 \end{bmatrix} \tag{30}$$

where $\tilde{x}_4$and $\tilde{x}_5$ are the estimation errors of the damper currents x_4 and x_5.

The switching gain is defined as

$$K = \min\left\{ \begin{matrix} -a_{11}|z_1| - (a_{12}z_2 + a_{13}\omega z_3 + a_{14}\tilde{x}_4 + a_{15}\omega\tilde{x}_5)\,\text{sgnz}_1 \\ -a_{22}|z_2| - (a_{21}z_1 + a_{23}\omega z_3 + a_{24}\tilde{x}_4 + a_{25}\omega\tilde{x}_5)\,\text{sgnz}_2 \\ -a_{33}|z_3| - (a_{31}\omega z_1 + a_{32}\omega z_2 + a_{34}\omega\tilde{x}_4 + a_{35}\tilde{x}_5)\,\text{sgnz}_3 \end{matrix} \right\} - \xi \tag{31}$$

where ξ is a positive small value.

Theorem 1 *The globally asymptotic stability of* (30) *is guaranteed, if the switching gain is given by* (31).

Proof The stability of the overall structure is guaranteed through the stability of the direct axis and quadrature axis currents x_1, x_2, and field current x_3 observer. The

Lyapunov function of the sliding mode observer for damper currents is chosen as

$$V_{obs} = \frac{1}{2} S^T \Gamma S \tag{32}$$

where Γ is an identity positive matrix. Consequently, the derivative of the Lyapunov function is

$$\begin{aligned} \frac{dV_{obs}}{dt} &= S^T \Gamma \frac{dS}{dt} \\ &= \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}^T \Gamma \left(F_{11} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} + F_{12} \begin{bmatrix} \tilde{x}_4 \\ \tilde{x}_5 \end{bmatrix} + K \begin{bmatrix} \mathrm{sgnz}_1 \\ \mathrm{sgnz}_2 \\ \mathrm{sgnz}_3 \end{bmatrix} \right) \\ &= G_1 + G_2 + G_3 \end{aligned} \tag{33}$$

where

$$\begin{aligned} G_1 &= a_{11} z_1^2 + a_{12} z_1 z_2 + a_{13} \omega z_1 z_3 + a_{14} z_1 \tilde{x}_4 + a_{15} \omega z_1 \tilde{x}_5 + K\,|z_1| \\ G_2 &= a_{21} z_1 z_2 + a_{22} z_2^2 + a_{23} \omega z_2 z_3 + a_{24} z_2 \tilde{x}_4 + a_{25} \omega z_2 \tilde{x}_5 + K\,|z_2| \\ G_3 &= a_{31} \omega z_1 z_3 + a_{32} \omega z_2 z_3 + a_{33} z_3^2 + a_{34} \omega z_3 \tilde{x}_4 + a_{35} z_3 \tilde{x}_5 + K\,|z_3| \end{aligned}$$

Using the designed switching gain in (31), both G_1, G_2 and G_3 are negatives. Therefore, $\dot{V}_{obs}$ is a negative definite, and the sliding mode condition is satisfied (Slotine and Li 1991). Furthermore the global asymptotic stability of the observer is guaranteed.

According to (31) by a proper selection of ξ, the influence of parametric uncertainties of the SMIB can be much reduced. The switching gain must large enough to satisfy the reaching condition of sliding mode. Hence the estimation error is confined into the sliding hyperplane

$$\frac{d}{dt} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = 0 \tag{34}$$

Nevertheless, if the switching gain is too large, the chattering noise may lead to estimation errors. To avoid the chattering phenomena, the sign function is replaced by the following continuous function

$$\frac{S(t)}{|S(t)| + \varsigma_1}$$

where ς_1 is a positive constant.

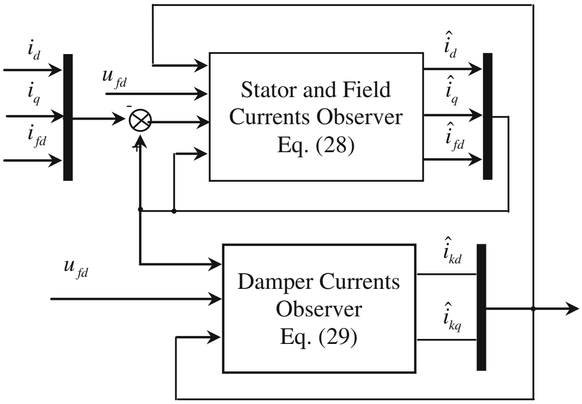

Fig. 6 Block diagram of the sliding mode damper currents observer

4 Design of Sliding Mode Controllers

This section deals with a procedure for the design of power system controllers, in order to improve the system's stability and damping properties under large disturbances and variation in operating points. The first objective is the terminal voltage regulation.

The dynamic of the terminal voltage (35), is obtained through the time derivative of (22) using (23) and (24) where the damper currents are replaced by the observer (29)

$$\begin{aligned}
\frac{dv_t}{dt} &= \frac{1}{v_t}\left(v_d\frac{dv_d}{dt} + v_q\frac{dv_q}{dt}\right) \\
&= \frac{v_q}{v_t}\frac{dv_q}{dt} + c_{17}\frac{v_d}{v_t}\frac{du_{fd}}{dt} \\
&\quad + \frac{v_d}{v_t}\left[\begin{array}{l} c_{11}\dfrac{dx_1}{dt} + c_{12}\dfrac{dx_2}{dt} + c_{13}x_6\dfrac{dx_3}{dt} + c_{13}x_3\dfrac{dx_6}{dt} + c_{14}\dfrac{d\hat{x}_4}{dt} \\ +c_{15}x_6\dfrac{d\hat{x}_5}{dt} + c_{15}\hat{x}_5\dfrac{dx_6}{dt} + c_{16}\dfrac{dx_7}{dt}\sin(-x_7+\sigma) \end{array}\right] \\
&= c_{17}\frac{v_d}{v_t}\frac{du_{fd}}{dt} + f(x)
\end{aligned} \tag{35}$$

where

$$f(x) = \frac{v_q}{v_t}\frac{dv_q}{dt} + \frac{v_d}{v_t}\left[\begin{array}{l} c_{11}\dfrac{dx_1}{dt} + c_{12}\dfrac{dx_2}{dt} + c_{13}x_6\dfrac{dx_3}{dt} + c_{13}x_3\dfrac{dx_6}{dt} + c_{14}\dfrac{d\hat{x}_4}{dt} \\ +c_{15}\hat{x}_5\dfrac{dx_6}{dt} + c_{15}x_6\dfrac{d\hat{x}_5}{dt} + c_{16}\dfrac{dx_7}{dt}\sin(-x_7+\sigma) \end{array}\right]$$

The tracking error between terminal voltage and its reference is given as

$$e_1 = v_t - v_t^{ref} \tag{36}$$

Hence, its dynamic is derived, using (35), as follows:

$$\frac{de_1}{dt} = c_{17}\frac{v_d}{v_t}\frac{du_{fd}}{dt} + f(x) \tag{37}$$

According to the (36), the proposed time-varying sliding surface is defined by

$$S_1 = K_1 e_1(t) \tag{38}$$

where K_1 is a positive constant feedback gain. The next step is to design a control input which satisfies the sliding mode existence law. The control input have the following structure

$$u(t) = u_{eq}(t) + u_n(t) \tag{39}$$

where $u_{eq}(t)$ is an equivalent control-input that determines the system's behavior on the sliding surface and $u_n(t)$ is a non-linear switching input, which drives the state to the sliding surface and maintains it on the sliding surface despite the presence of the parameter variations and disturbances. The equivalent control-input is obtained from the invariance condition and is given by the following condition (Utkin et al. 1999):

$$S_1 = 0 \text{ and } \frac{dS_1}{dt} = 0 \Rightarrow u(t) = u_{eq}(t)$$

From the above equation

$$\dot{S}_1 = K_1 c_{17}\frac{v_d}{v_t}\frac{du_{fd}}{dt} + K_1 f(x) = 0 \tag{40}$$

Therefore, the equivalent control-input is given as

$$u_{eq}(t) = -\frac{v_t}{c_{17} v_d} f(x) \tag{41}$$

By choosing the nonlinear switching input $u_n(t)$ as follows

$$u_n(t) = -\alpha_1 \frac{v_t}{c_{17} v_d}\text{sgn}(e_1) \tag{42}$$

where α_1 is a positive constant. The control input is derived from (39), (41) and (42) as follows:

$$u(t) = \frac{du_{fd}}{dt} = -\frac{v_t}{c_{17}v_d}\left(f(x) + \alpha_1 \mathrm{sgn}(e_1)\right) \tag{43}$$

Using the proposed control law (43), the reachability of sliding mode control of (37) is guaranteed.

Now, the attention is focused to the rotor speed tracking objective. The sliding mode-based rotor speed control methodology consists of three steps

Step 1: The rotor speed error is

$$e_2 = x_6 - \omega^{ref} \tag{44}$$

where $\omega^{ref} = 1$ p.u. is the desired trajectory. The sliding surface is selected as follow

$$S_2 = K_2 e_2(t) \tag{45}$$

where K_2 is a positive constant. By using (44) and (18), the derivative of the sliding surface (45) is calculated as:

$$\frac{dS_2}{dt} = K_2\left(a_{61}x_6 + a_{62}x_8/x_6 - a_{62}T_e\right) \tag{46}$$

The x_8 can be viewed as a virtual control in the above equation. To ensure the Lyapunov stability criteria i.e. $\frac{dS_2}{dt}S_2 \prec 0$ we define the nonlinear control input x^*_{8eq} as

$$x^*_{8eq} = \frac{x_6}{a_{62}}\left(a_{62}T_e - a_{61}x_6\right) \tag{47}$$

The nonlinear switching input x^*_{8n} can be chosen as follows

$$x^*_{8n} = -\alpha_2 \frac{x_6}{a_{62}} \mathrm{sgn}(e_2) \tag{48}$$

where α_2 is a positive constant.
Then, the stabilizing function of the mechanical power is obtained as

$$x^*_8 = \frac{x_6}{a_{62}}\left(a_{62}T_e - a_{61}x_6 - \alpha_2 \mathrm{sgn}(e_2)\right) \tag{49}$$

When a fault occurs, large currents and torques are produced. This electrical perturbation may destabilize the operating conditions. Hence, it becomes necessary to account for these uncertainties by designing a higher performance controller.

In (49), as electromagnetic load T_e is unknown, when fault occurs, it has to be estimated adaptively. Thus, let us define

$$\hat{x}_8^* = \frac{x_6}{a_{62}}\left(a_{62}\hat{T}_e - a_{61}x_6 - \alpha_2 \text{sgn}(e_2)\right) \tag{50}$$

where $\hat{T}_e$ is the estimated value of the electromagnetic load which should be determined later. Substituting (50) in (46), the rotor speed sliding surface dynamics becomes

$$\frac{dS_2}{dt} = K_2\left(-\alpha_2 \text{sgn}(e_2) - a_{62}\tilde{T}_e\right) \tag{51}$$

where $\tilde{T}_e = T_e - \hat{T}_e$ is the estimation error of electromagnetic load.

Step 2: Since the mechanical power x_8 is not our control input, the stabilizing error between x_8 and its desired trajectory x_8^* is defined as

$$e_3 = x_8^* - x_8 \tag{52}$$

To stabilize the mechanical power x_8, the new sliding surface is selected as

$$S_3 = K_3 e_3(t) \tag{53}$$

where K_3 is a positive constant. The derivative of S_3 using (52) and (20) is given as

$$\frac{dS_3}{dt} = K_3\left(a_{81}x_8 + a_{82}x_9 - \frac{dx_8^*}{dt}\right) \tag{54}$$

By considering the steam valve opening x_9 as a second virtual control, the equivalent control x_{9eq}^* is obtained as the solution of the equation $\frac{dS_3(t)}{dt} = 0$.

$$x_{9eq}^* = \frac{1}{a_{82}}\left(\frac{dx_8^*}{dt} - a_{81}x_8\right) \tag{55}$$

As a result, the stabilizing function of the steam valve opening x_9^* the mechanical power is computed as

$$x_9^* = \frac{1}{a_{82}}\left(\frac{dx_8^*}{dt} - a_{81}x_8 - \alpha_3 \text{sgn}(e_3)\right) \tag{56}$$

where α_3 is a positive constant. Substituting (56) in (54), the steam valve opening sliding surface dynamics becomes

$$\frac{dS_3}{dt} = -\alpha_3 K_3 \text{sgn}(e_3) \tag{57}$$

Step 3: Finally, the steam valve opening error is defined as

$$e_4 = x_9 - x_9^* \tag{58}$$

By defining a sliding surface $S_4(t) = K_4 e_4(t)$, the derivative of S_4 is calculated by time-differentiation of (58) and using (21)

$$\frac{dS_4}{dt} = K_4\left(a_{91}x_9 + a_{92}x_6 + b_4 u_g - \frac{dx_9^*}{dt}\right) \tag{59}$$

To assure the reaching condition $\frac{dS_4}{dt}S_4 \prec 0$, the equivalent control $u_{geq}(t)$ is obtained as

$$u_{geq} = \frac{1}{b_4}\left(\frac{dx_9^*}{dt} - a_{91}x_9 - a_{92}x_6\right) \tag{60}$$

Subsequently, the control law is written as

$$u_g = \frac{1}{b_4}\left(\frac{dx_9^*}{dt} - a_{91}x_9 - a_{92}x_6 - \alpha_4 \text{sgn}(e_4)\right) \tag{61}$$

Theorem 2 *The dynamic sliding mode control laws* (43) *and* (61) *with stabilizing functions* (50) *and* (56) *when applied to the single machine infinite power system, guarantee the asymptotic convergence of the outputs* v_t *and* $x_6 = \omega$ *to their desired values* v_{tref} *and* ω_{ref} *=1, respectively.*

Proof Consider the following positive definite Lyapunov function

$$V_{con} = \frac{1}{2}S_1^2 + \frac{1}{2}S_2^2 + \frac{1}{2}S_3^2 + \frac{1}{2}S_4^2 + \frac{1}{2\mu}\tilde{T}_e^2 \tag{62}$$

By considering (40), (51), (57) and (59), the derivative of (62) can be derived as follows:

$$\begin{aligned}\dot{V}_{con} &= \frac{dS_1}{dt}S_1 + \frac{dS_2}{dt}S_2 + \frac{dS_3}{dt}S_3 + \frac{dS_4}{dt}S_4 + \tilde{T}_e\frac{1}{\mu}\frac{d\tilde{T}_e}{dt} \\ &= K_1 c_{17}\frac{v_d}{v_t}\frac{du_{fd}}{dt} + K_1 f(x) + K_2\left(-\alpha_2 \text{sgn}(e_2) - a_{62}\tilde{T}_e\right) \\ &\quad - \alpha_3 K_3 \text{sgn}(e_3) + K_4\left(a_{91}x_9 + a_{92}x_6 + b_4 u_g - \frac{dx_9^*}{dt}\right) + \tilde{T}_e\frac{1}{\mu}\frac{d\tilde{T}_e}{dt}\end{aligned} \tag{63}$$

Substituting the control laws (43) and (61) in (63) gives

$$\begin{aligned}\dot{V}_{con} &= -\alpha_1 K_1^2 e_1 \mathrm{sgn}(e_1) - \alpha_2 K_2^2 e_2 \mathrm{sgn}(e_2) - \alpha_3 K_3^2 e_3 \mathrm{sgn}(e_3) \\ &\quad - \alpha_4 K_4^2 e_4 \mathrm{sgn}(e_3) - K_2^2 a_{62} \tilde{T}_e e_2 + \tilde{T}_e \frac{1}{\mu}\frac{d\tilde{T}_e}{dt} \\ &= -\alpha_1 K_1^2 |e_1| - \alpha_2 K_2^2 |e_2| - \alpha_3 K_3^2 |e_3| - \alpha_4 K_4^2 |e_4| \\ &\quad + \left(\frac{1}{\mu}\frac{d\tilde{T}_e}{dt} - K_2^2 a_{62} e_2\right)\tilde{T}_e\end{aligned} \tag{64}$$

By choosing the adaptive law (65), the time derivative of V_{con} is strictly negative.

$$\frac{d\tilde{T}_e}{dt} = \mu a_{62} K_2^2 e_2 \tag{65}$$

Thus

$$\begin{aligned}\frac{dV_{con}}{dt} &= -\alpha_1 K_1^2 |e_1| - \alpha_2 K_2^2 |e_2| - \alpha_3 K_3^2 |e_3| - \alpha_4 K_4^2 |e_4| \\ &= -\sum_{i=1}^{4} \alpha_i K_i^2 |e_i| < 0\end{aligned} \tag{66}$$

From the above analysis, it is evident that the reaching condition of sliding mode is guaranteed.

Remark In order to eliminate the chattering, the discontinuous control components in (43), (50), (56) and (61) can be replaced by a smooth sliding mode component to yield

$$\begin{aligned}\frac{du_{fd}}{dt} &= -\frac{v_t}{c_{17} v_d}\left(f(x) + \alpha_1 \frac{S_1(t)}{|S_1(t)| + \tau_2}\right) \\ x_8^* &= \frac{x_6}{a_{62}}\left(a_{62} T_e - a_{61} x_6 - \alpha_2 \frac{S_2(t)}{|S_2(t)| + \tau_3}\right) \\ x_9^* &= \frac{1}{a_{82}}\left(\frac{dx_8^*}{dt} - a_{81} x_8 - \alpha_3 \frac{S_3(t)}{|S_3(t)| + \tau_4}\right) \\ u_g &= \frac{1}{b_4}\left(\frac{dx_9^*}{dt} - a_{91} x_9 - a_{92} x_6 - \alpha_4 \frac{S_4(t)}{|S_4(t)| + \tau_5}\right)\end{aligned}$$

where $\tau_i \succ 0$ is a small constant. This modification creates a small boundary layer around the switching surface in which the system trajectory remains. Therefore, the chattering problem can be reduced significantly (Utkin et al. 1999).

5 Validation and Discussion

To verify the effectiveness of the developed observer based-controller, some simulation works are carried out for the power system under severe disturbance conditions which cause significant deviation in generator loading. Also, different operating points load are considered. The performance of the nonlinear controller was tested on the complete 9th order model of SMIB power system (202 MVA, 13.7 KV), including all kinds of nonlinearities such as exciter ceilings, control signal limiters, etc. and speed regulator. The parameter values used in the simulation are given in the Tables 1, 2 and 3. The physical limits of the plant are

$$\max \left| v_{fd} \right| = 10\,\text{p.u.}, \text{ and } 0 \leq X_e(t) \leq 1$$

The system configuration is presented as shown in Fig. 7. The proposed sliding mode observer is implemented based on the scheme shown in Fig. 6.

In order to verify the stability and asymptotic tracking performance of the proposed control system, a symmetrical three-phase short circuit occurs closer to the generator bus, at t = 10 s and removed by opening the barkers of the faulted line at t = 10.1 s. The operating points considered are $P_m = 0.6$ p.u. and $P_m = 0.9$ p.u. The

Table 1 Parameters of the transmission line in p.u.

Paramseter	Value
L_e, inductance of the transmission line	0.4
R_e, resistance of the transmission line	0.02

Table 2 Parameters of the synchronous generator in p.u

Parameter	Value
R_s, stator resistance	$1.096\ 10^{-3}$
R_{fd}, field resistance	$7.42\ 10^{-4}$
R_{kd}, direct damper winding resistance	$13.1\ 10^{-3}$
R_{kq}, quadrature damper winding resistance	$54\ 10^{-3}$
L_d, direct self-inductance	1.700
L_q quadrature self-inductances	1.640
L_{fd}, rotor self inductance	1.650
L_{kd}, direct damper winding self inductance	1.605
L_{kq}, quadrature damper winding self inductance	1.526
L_{md}, direct magnetizing inductance	1.550
L_{mq}, quadrature magnetizing inductance	1.490
$V^{\propto}$, infinite bus voltage	1
D, damping constant	0
H, inertia constant	2.37 s

Table 3 Parameters of the steam turbine and speed governor

Parameter	Value
T_t, time constant of the turbine	0.35 s
K_t, gain of the turbine	1
R regulation constant of the system	0.05
T_g, time constant of the speed governor	0.2 s
K_g, gain of the speed governor	1

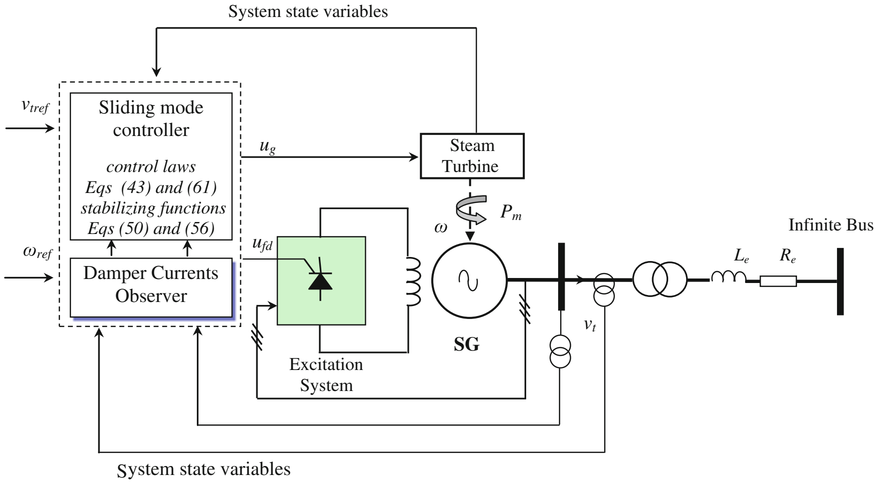

Fig. 7 Control system configuration

simulated results are given in Figs. 8 and 9. It is shown terminal voltage, rotor speed and rotor angle of the power system, respectively. The results are compared with those of the linear IEEE type 1 AVR+PSS and speed regulator. It is seen how dynamics of the terminal voltage and rotor speed exhibit large overshoots during post-fault state with the standard controller than with the nonlinear controller. It is evident that the proposed combined observer-controller can quickly and accurately converge to the desired terminal voltage and rotor speed for different operating points.

Robustness of the proposed observer-based controller is evaluated with respect to the variation of system parameters and error model. The values of the transmission line (L_e, R_e) and the inertia constant H increased by $+20$ and $-20\,\%$ from their original values, respectively. In addition to the abrupt and permanent variation of the power system parameters a three-phase short-circuit is simulated at the terminal of the generator. Figure 10 shows the performances of the terminal voltage and rotor speed of the combined observer-controller. It can be seen that the designed control scheme is not sensitive to the uncertainties of parameters and ensures the global stability of the system with good performances in transient and steady states.

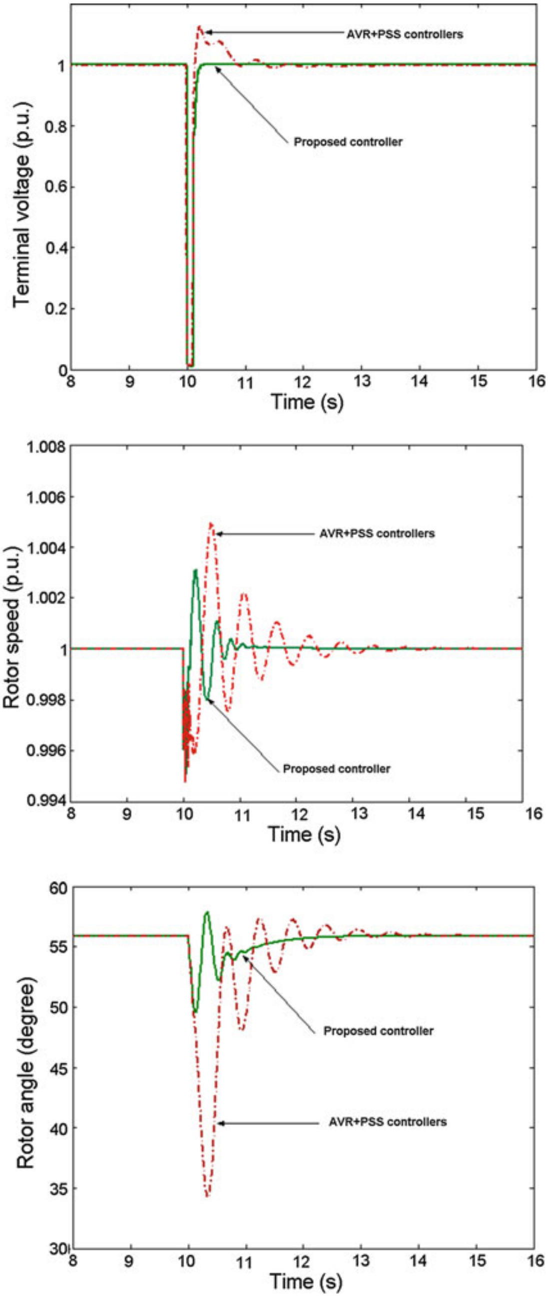

Fig. 8 Performance results of the proposed controller under large sudden fault for $P_m = 0.6$ p.u

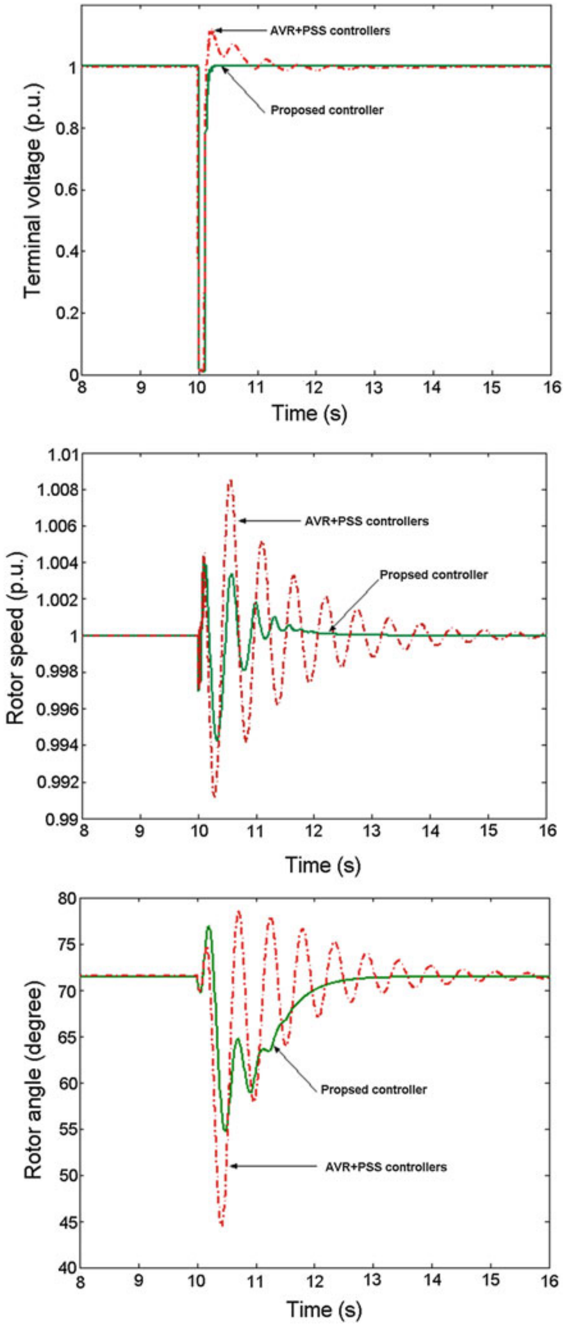

Fig. 9 Performance result of the proposed controller under large sudden fault for $P_m = 0.9$ p.u

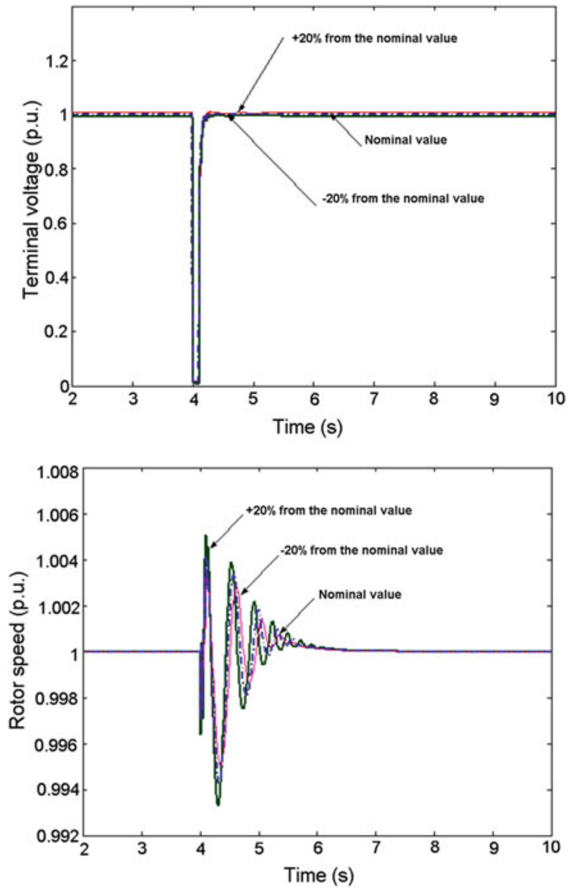

Fig. 10 Dynamic tracking performance control scheme under parameter perturbations

6 Conclusion

A nonlinear observer-controller has been developed and applied to the single machine infinite-bus power system. The synchronous generator is based on the complete 7th order model. The aim is to achieve both transient stability improvement and good post-fault performance of the generator terminal voltage and frequency.

The sliding mode technique was adopted to construct a nonlinear observer of damper currents winding. Then nonlinear control laws of terminal voltage and rotor speed has been provided. Global and exponential stability of both the control laws and the observer has been proven by applying Lyapunov stability theory.

Test results show the effectiveness of the proposed control strategy in improving transient stability of system under large disturbances in comparison with conventional controllers (IEEE type 1 AVR+PSS). Also, the combined observer-controller is independent of the operating point and possesses a great robustness to deal with parameter uncertainties.

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