Stabilizing Nonlinear Control Using Damper Currents Sliding Mode Observer of Synchronous Generator

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Abstract: In this article, a new observer-based nonlinear controller for excitation control of synchronous generator is presented. First, a nonlinear sliding mode observer for the synchronous machine damper currents is developed. Second, the existence of a control law for the complete seventh order model of a generator, which takes into account the stator dynamics as well as the damper effects, is proved by using the theory of Lyapunov. The stabilizing feedback law for the power system is shown to be Globally Exponentially Stable (GES) in the context of Lyapunov theory. Simulation results, for a single-Machine-Infinite-Bus (SMIB) power system, are given to demonstrate the effectiveness of the proposed combined obsever-controller for the transient stabilization and voltage regulation.

Index Terms: Sliding mode, damper currents observer, Lyapunov stability, nonlinear control, synchronous generator.

1. Introduction

An important issue of power system control is to improve transient stability and to maintain steady acceptable voltage under normal operating and disturbed conditions of a synchronous power generator [1], [2]. The design of excitation controllers is one of the main techniques for enhancement dynamic performance and large disturbance stability of power systems. As a result, tremendous research has been conducted and numerous papers have been published.

Conventional excitation controllers are mainly designed by using linear model of the synchronous generator. The principal conventional excitation controllers are the Automatic Voltage Regulator (AVR), and the Power System Stabiliser (PSS) [3]-[7]. The high complexity and nonlinearity of power systems, together with their almost continuously time varying nature, require candidate controllers to be able to take into account the important non linearities of the power system model and to be independent of the equilibrium point. Recently, different techniques have been investigated to tackle the problem of transient stability by considering nonlinear generators models. Most of these techniques are based on feedback linearization approach [8]-[10]. Feedback linearization requires the exact cancellation of some nonlinear terms. 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 [11], [12]. Thus, there is a need for controllers which are insensitive to the uncertainty. Feedback linearization is recently enhanced by using robust control designs such as $H\infty$ control and L2 disturbance attenuation [13], [14]. The nonlinear model used in these studies was a third order reduced model of the machine. The damper windings of a generator have not been considered.

In [15], 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. This assumption is unrealistic from the technical point of view, because damper windings are metal bars placed in slots in the pole faces and connected together at each end. A technology for direct damper current measurement has not been fully developed yet.

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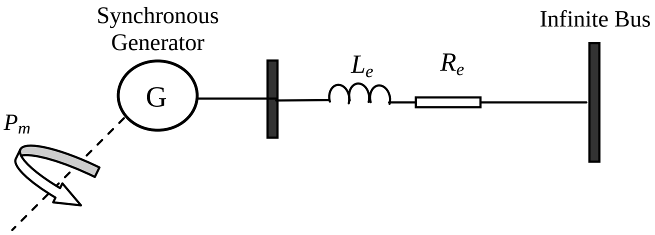


Figure 1. Single-machine connected to infinite-bus power system.

In this paper, a nonlinear excitation controller with observer of damper currents is proposed to enhance the transient stability and voltage regulation of a single-machine-infinite-bus power system. The model of synchronous machine is a 7^{th} order model. The nonlinear observer and excitation control law are found when using Lyapunov theory. The stability of the combined observer-controller is proved.

The rest of this paper is organized as follows. In section 2, the dynamic equations of the system under study are presented. A new nonlinear observer for damper winding currents is developed in section 3. In section 4, the nonlinear excitation controller is derived. The detailed stability of the combined nonlinear observer-controller is analyzed in section 5. Section 6 deals with a number of numerical simulations results of the proposed observer-based nonlinear controller. A comparison with the usual AVR/PSS excitation control structure in benchmark example is also provided. Finally, conclusions are mentioned in section 7.

2. Mathematical model of power system study and problem formulation

Our plant is a synchronous generator connected to an infinite bus via a transmission line as is shown in Fig.1. The synchronous generator is described by a 7^{th} order nonlinear mathematical model, which comprises three stator windings, one field winding and two damper windings. The mathematical model of the plant, which is presented in some details in [15], [16] has the following form:

$$
\begin{aligned}
\frac{di_d}{dt} &= a_{11}i_d + a_{12}i_{fd} + a_{13}\omega i_q + a_{14}i_{kd} + a_{15}i_{kq}\omega + a_{16}\cos(-\delta+\sigma) + b_1 u_{fd} \\
\frac{di_{fd}}{dt} &= a_{21}i_d + a_{22}i_{fd} + a_{23}\omega i_q + a_{24}i_{kd} + a_{25}i_{kq}\omega + a_{26}\cos(-\delta+\sigma) + b_2 u_{fd} \\
\frac{di_q}{dt} &= a_{31}i_d\omega + a_{32}i_{fd}\omega + a_{33}i_q + a_{34}i_{kd}\omega + a_{35}i_{kq} + a_{36}\sin(-\delta+\sigma) \\
\frac{di_{kd}}{dt} &= a_{41}i_d + a_{42}i_{fd} + a_{43}i_q\omega + a_{44}i_{kd} + a_{45}i_{kq}\omega + a_{46}\cos(-\delta+\sigma) + b_3 u_{fd} \\
\frac{di_{kq}}{dt} &= a_{51}i_d\omega + a_{52}i_{fd}\omega + a_{53}i_q + a_{54}i_{kd}\omega + a_{55}i_{kq} + a_{56}\sin(-\delta+\sigma) \\
\frac{d\omega}{dt} &= a_{61}i_d i_q + a_{62}i_{fd}i_q + a_{63}i_d i_{kq} + a_{64}i_q i_{kd} + a_{65}\omega + \frac{P_m}{\omega} \\
\frac{d\delta}{dt} &= \omega_R(\omega-1)
\end{aligned}
\tag{1}
$$

where $i_d, i_{fd}, i_q, i_{kd}, i_{kq}, \omega, \delta$ are the state variables, u_{fd} is the control input, ω_R is the electrical angular frequency, σ is the infinite bus phase angle, a_{ij} and b_i are coefficients which depend on the generator and the load parameters [15]. The mechanical power P_m is assumed to be constant.

The machine terminal voltage is calculated from Park components v_d and v_q as follows [15], [16]:

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

with

$$v_d = c_{11} i_d + c_{12} i_{fd} + c_{13}\omega i_q + c_{14} i_{kd} + c_{15} i_{kq}\omega + c_{16}\cos(-\delta+\sigma) + c_{17} u_{fd} \tag{3}$$

$$v_q = c_{21} i_d\omega + c_{22} i_{fd}\omega + c_{23} i_q + c_{24} i_{kd}\omega + c_{25} i_{kq} + c_{26}\sin(-\delta+\sigma) \tag{4}$$

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 in Appendix A.

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 [17]. In order to design a stabilizing tracking control law for terminal voltage, it is necessary to have an estimation of the damper currents i_{kd} and i_{kq}.

3. Development of a nonlinear observer for the damper winding currents

For continuous time systems, the state space representation of the electrical dynamics of the power system model (1) is:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_{fd} \\ i_q \end{bmatrix} = F_{11}\begin{bmatrix} i_d \\ i_{fd} \\ i_q \end{bmatrix} + F_{12}\begin{bmatrix} i_{kd} \\ i_{kq} \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \\ 0 \end{bmatrix} u_{fd} + H_1(t) \tag{5}$$

$$\frac{d}{dt}\begin{bmatrix} i_{kd} \\ i_{kq} \end{bmatrix} = F_{21}\begin{bmatrix} i_d \\ i_{fd} \\ i_q \end{bmatrix} + F_{22}\begin{bmatrix} i_{kd} \\ i_{kq} \end{bmatrix} + \begin{bmatrix} b_3 \\ 0 \end{bmatrix} u_{fd} + H_2(t) \tag{6}$$

where

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

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

$$F_{11} = \begin{bmatrix} a_{11} & a_{12} & a_{13}\omega \\ a_{21} & a_{22} & a_{23}\omega \\ a_{31}\omega & a_{32}\omega & a_{33} \end{bmatrix}, \quad F_{21} = \begin{bmatrix} a_{41} & a_{42} & a_{43}\omega \\ a_{51}\omega & a_{52}\omega & a_{53} \end{bmatrix}$$

$$F_{12} = \begin{bmatrix} a_{14} & a_{15}\omega \\ a_{24} & a_{25}\omega \\ a_{34}\omega & a_{35} \end{bmatrix}, \qquad F_{22} = \begin{bmatrix} a_{44} & a_{45}\omega \\ a_{54}\omega & a_{55} \end{bmatrix}$$

To construct the sliding mode observer of the damper currents i_{kd} and i_{kq}, let's define the switching surface S as follows:

$$S(t)=\begin{bmatrix}\hat{i}_d-i_d\\ \hat{i}_{fd}-i_{fd}\\ \hat{i}_q-i_q\end{bmatrix}\equiv\begin{bmatrix}e_1\\ e_2\\ e_3\end{bmatrix} \tag{7}$$

Then, an observer for (5) is constructed as:

$$\frac{d}{dt}\begin{bmatrix}\hat{i}_d\\ \hat{i}_{fd}\\ \hat{i}_q\end{bmatrix}=F_{11}\begin{bmatrix}\hat{i}_d\\ \hat{i}_{fd}\\ \hat{i}_q\end{bmatrix}+F_{12}\begin{bmatrix}\hat{i}_{kd}\\ \hat{i}_{kq}\end{bmatrix}+\begin{bmatrix}b_1\\ b_2\\ 0\end{bmatrix}u_{fd}+H_1(t)+K\begin{bmatrix}\mathrm{sgn}(\hat{i}_d-i_d)\\ \mathrm{sgn}(\hat{i}_{fd}-i_{fd})\\ \mathrm{sgn}(\hat{i}_q-i_q)\end{bmatrix} \tag{8}$$

where $\hat{i}_d, \hat{i}_{fd}$ and $\hat{i}_q$ are the observed values of i_d, i_{fd} and i_q, K is the switching gain, and sgn is the sign function. Moreover, the damper current observer is given from (6) as:

$$\frac{d}{dt}\begin{bmatrix}\hat{i}_{kd}\\ \hat{i}_{kq}\end{bmatrix}=F_{21}\begin{bmatrix}\hat{i}_d\\ \hat{i}_{fd}\\ \hat{i}_q\end{bmatrix}+F_{22}\begin{bmatrix}\hat{i}_{kd}\\ \hat{i}_{kq}\end{bmatrix}+\begin{bmatrix}b_3\\ 0\end{bmatrix}u_{fd}+H_2(t) \tag{9}$$

where $\hat{i}_{kd}$ and $\hat{i}_{kq}$ are the observed values of i_{kd} and i_{kq}. Subtracting (5) from (8), the error dynamics can be written as:

$$\frac{d}{dt}\begin{bmatrix}e_1\\ e_2\\ e_3\end{bmatrix}=F_{11}\begin{bmatrix}e_1\\ e_2\\ e_3\end{bmatrix}+F_{12}\begin{bmatrix}\tilde{i}_{kd}\\ \tilde{i}_{kq}\end{bmatrix}+K\begin{bmatrix}\mathrm{sgn}\,e_1\\ \mathrm{sgn}\,e_2\\ \mathrm{sgn}\,e_3\end{bmatrix} \tag{10}$$

where $\tilde{i}_{kd}$ and $\tilde{i}_{kq}$ are the estimation errors of the damper currents i_{kd} and i_{kq}. The switching gain K is designed as [18].

$$K=\min\begin{pmatrix}\left(-a_{11}\left|e_1\right|-\left(a_{12}e_2+a_{13}\omega e_3+a_{14}\tilde{i}_{kd}+a_{15}\omega\tilde{i}_{kq}\right)\mathrm{sgn}\,e_1\right),\\ \left(-a_{22}\left|e_2\right|-\left(a_{21}e_1+a_{23}\omega e_3+a_{24}\tilde{i}_{kd}+a_{25}\omega\tilde{i}_{kq}\right)\mathrm{sgn}\,e_2\right),\\ \left(-a_{33}\left|e_3\right|-\left(a_{31}\omega e_1+a_{32}\omega e_2+a_{34}\omega\tilde{i}_{kd}+a_{35}\tilde{i}_{kq}\right)\mathrm{sgn}\,e_3\right)\end{pmatrix}-\xi \tag{11}$$

where ξ is a positive small value.

Hence, it can be shown that the estimation errors $\tilde{i}_{kd}$ and $\tilde{i}_{kq}$ will converge to zero if the sliding mode occurs and the errors e_1, e_2 and e_3 converge to zero asymptotically. Selection of switching gain K will be discussed in Section 5.

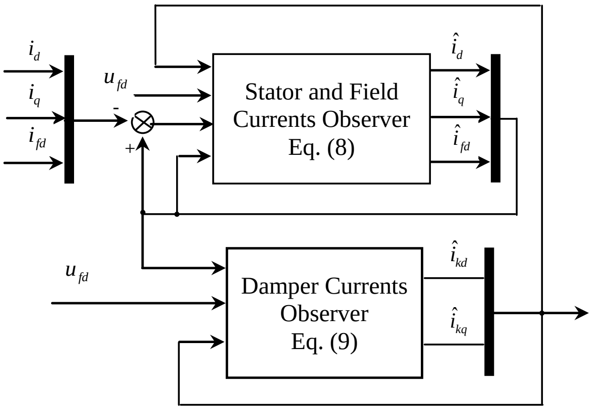


Figure 2. Block diagram of nonlinear observer.

4. Excitation control law

The objective, in this section, is to obtain the SMIB control terminal voltage in order to ensure a good steady and transient stability. The GES nonlinear control law for terminal voltage is derived by using Laypunov method.

The dynamic of the terminal voltage (12) is obtained through the time derivative of (2) using (3) and (4) where the damper currents are replaced by the observer (9).

$$\begin{aligned}\frac{dv_t}{dt} &= \frac{1}{v_t}\left(v_d\frac{dv_d}{dt} + v_q\frac{dv_q}{dt}\right)\\ &= c_{17}\frac{v_d}{v_t}\frac{du_{fd}}{dt} + c_{14}b_3\frac{v_d}{v_t}u_{fd} + f(t)\end{aligned} \tag{12}$$

where

$$f(t) = \frac{v_d}{v_t}\left[c_{11}\frac{di_d}{dt} + c_{12}\frac{di_{fd}}{dt} + c_{13}\left(\omega\frac{di_q}{dt} + i_q\frac{d\omega}{dt}\right)\right] + \frac{v_d}{v_t}\left[c_{15}\left(\omega\frac{d\hat{i}_{kq}}{dt} + \hat{i}_{kq}\frac{d\omega}{dt}\right) + c_{16}\sin(-\delta + a)\right]$$
$$+ c_{14}\frac{v_d}{v_t}\left[a_{41}i_d + a_{42}i_{fd} + a_{43}i_q\omega + a_{44}\hat{i}_{kd}\right] + \left[a_{45}\hat{i}_{kq}\omega + a_{46}\cos(-\delta + a)\right] + \frac{v_q}{v_t}\frac{dv_q}{dt}$$

To reach our objective, we define the terminal voltage error as:

$$e = v_t - v_t^{ref} \tag{13}$$

Then

$$\frac{de}{dt} = \frac{dv_t}{dt} = c_{17}\frac{v_d}{v_t}\frac{du_{fd}}{dt} + c_{14}b_3\frac{v_d}{v_t}u_{fd} + f(t) \tag{14}$$

Consider a positive definite Lyapunov function as:

$$V_{con} = \frac{1}{2}e^2 \tag{15}$$

The basis of the Lyapunov's stability theory is that the time derivative of $V_{con}(e)$ must be negative semi definite along the prefault and the post fault trajectories. The time derivative of the V_{con} can be written as:

$$\frac{dV_{con}}{dt} = \left[c_{17}\,\frac{v_d}{v_t}\,\frac{du_{fd}}{dt} + b_3 c_{14}\,\frac{v_d}{v_t} u_{fd} + f(t) \right] e \qquad (16)$$

Thus, in order to guarantees the asymptotic stability of the terminal voltage, the Lyapunov's stability criterion can be satisfied by making term on the right hand side of Eq. (16) negative semi definite [19]. Hence, the excitation control law is given as:

$$\frac{du_{fd}}{dt} = -\frac{v_t}{c_{17} v_d} \left[K_v e + b_3 c_{14}\,\frac{v_d}{v_t} u_{fd} + f(t) \right] \qquad (17)$$

where K_v is a positive constant feedback gain.

Insertion of the control function u_{fd} in the dynamics for the error variable of e_1 then gives:

$$\frac{de}{dt} = -K_v e \qquad (18)$$

5. Stability analysis

Theorem 1: The globally asymptotic stability of (10) and (14) are guaranteed, if the switching gain is given by (11) and the control law by (17) respectively.

Proof: The stability of the overall structure is guaranteed through the stability of the direct axis, quadrature axis currents and field current i_d , i_q , i_{fd} observers and terminal voltage control law. The global Lyapunov function is chosen as:

$$V = V_{con} + V_{obs} = \frac{1}{2} e^2 + \frac{1}{2} S^T \Gamma S \qquad (19)$$

where Γ is identity matrix.

Using (10) and (18), the derivative of the Lyapunov function is

$$\begin{aligned}
\dot{V} &= -K_v e^2 + S^T \Gamma \dot{S} \\
&= -K_v e^2 + \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}^T \Gamma \left(F_{11} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} + F_{12} \begin{bmatrix} \tilde{i}_{kd} \\ \tilde{i}_{kq} \end{bmatrix} + K \begin{bmatrix} \operatorname{sgn} e_1 \\ \operatorname{sgn} e_2 \\ \operatorname{sgn} e_3 \end{bmatrix} \right) \\
&= -K_v e^2 + a_{11} e_1^2 + a_{12} e_1 e_2 + a_{13} \omega e_1 e_3 + a_{14} e_1 \tilde{i}_{kd} + a_{15} \omega e_1 \tilde{i}_{kq} + K |e_1| \\
&\quad + a_{21} e_1 e_2 + a_{22} e_2^2 + a_{23} \omega e_2 e_3 + a_{24} e_2 \tilde{i}_{kd} + a_{25} \omega e_2 \tilde{i}_{kq} + K |e_2| \\
&\quad + a_{31} \omega e_1 e_3 + a_{32} \omega e_2 e_3 + a_{33} e_3^2 + a_{34} \omega e_3 \tilde{i}_{kd} + a_{35} e_3 \tilde{i}_{kq} + K |e_3|
\end{aligned} \qquad (20)$$

Therefore, the sliding mode condition is satisfied if [20]:

$$\begin{aligned}
& a_{11} e_1^2 + a_{12} e_1 e_2 + a_{13} \omega e_1 e_3 + a_{14} e_1 \tilde{i}_{kd} + a_{15} \omega e_1 \tilde{i}_{kq} + K |e_1| \\
& + a_{21} e_1 e_2 + a_{22} e_2^2 + a_{23} \omega e_2 e_3 + a_{24} e_2 \tilde{i}_{kd} + a_{25} \omega e_2 \tilde{i}_{kq} + K |e_2| \\
& + a_{31} \omega e_1 e_3 + a_{32} \omega e_2 e_3 + a_{33} e_3^2 + a_{34} \omega e_3 \tilde{i}_{kd} + a_{35} e_3 \tilde{i}_{kq} + K |e_3| \prec 0
\end{aligned}$$

Thus,

$$K \prec \min\begin{pmatrix} \left(-a_{11}\left|e_1\right| - \left(a_{12}e_2 + a_{13}\omega e_3 + a_{14}\tilde{i}_{kd} + a_{15}\omega\tilde{i}_{kq}\right)\operatorname{sgn} e_1\right), \\ \left(-a_{22}\left|e_2\right| - \left(a_{21}e_1 + a_{23}\omega e_3 + a_{24}\tilde{i}_{kd} + a_{25}\omega\tilde{i}_{kq}\right)\operatorname{sgn} e_2\right), \\ \left(-a_{33}\left|e_3\right| - \left(a_{31}\omega e_1 + a_{32}\omega e_2 + a_{34}\omega\tilde{i}_{kd} + a_{35}\tilde{i}_{kq}\right)\operatorname{sgn} e_3\right) \end{pmatrix}$$

Furthermore the global asymptotic stability of the system is guaranteed.
According to (11) 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 hyerplane:

$$\frac{d}{dt}\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = 0 \tag{21}$$

However, 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 in simulation:

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

where ς_1 is a positive constant.

6. Simulation studies and performance evaluation

In order to evaluate the effectiveness and the performance of the designed nonlinear observer and controller, simulations have been carried out for different operating conditions, small perturbations and severe disturbance conditions. Simulation studies have been undertaken on a single machine infinite bus power system. The performance of the nonlinear controller was tested on the complete 7th order model of the generator system with the physical limit of the excitation voltage of the generator. The system parameters are given in Appendix B. The system configuration is presented as shown in Figure 1.
The fault considered in this paper is a symmetrical three-phase short circuit, which occurs at the terminal of generator. For comparison purposes, the performances of the proposed observer-based controller are compared to those of the conventional IEEE type 1 AVR and PSS.

A. Observer performance evaluation

Figure 2 depicts the block diagram for the damper currents observer. The initial conditions of the damper current estimates were fixed to $\hat{x}_4(0) = 0.1$ p.u and $\hat{x}_5(0) = 0.1$ p.u. The estimation errors of the damper currents are shown in Fig. 3. It can be seen that the estimated damper current converge to their real values very quickly.

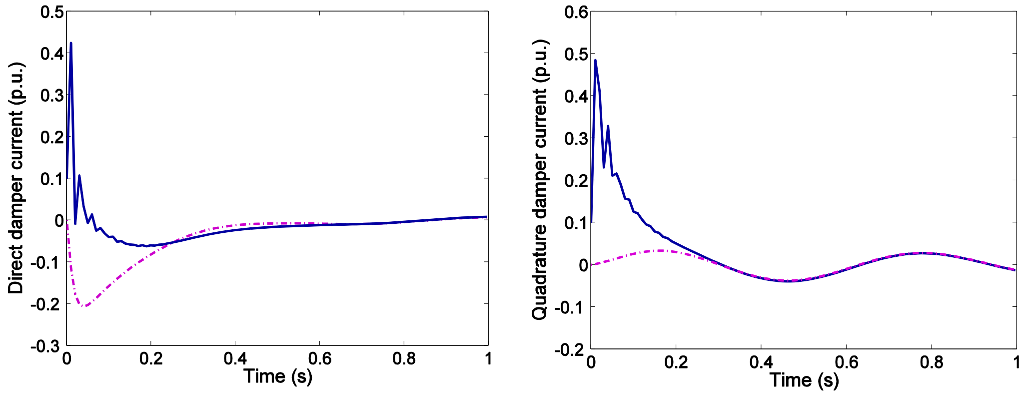


Figure 3. Performance result of direct and quadrature currents observer: (solid) observed current; (dot) actual current.

B. Observer-based controller performance evaluation under severe disturbance

The configuration of the complete system is shown in Fig. 4. The stability and asymptotic tracking of the nonlinear observer-based controller is verified under large disturbance. A three-phase short-circuit is simulated at the terminal of the generator and the fault is cleared after 100 ms. The operating point considered is P_{mo}=0.75p.u. The responses of the closed-loop system for the above fault are depicted in Fig.5. It is seen how dynamics of the terminal voltage exhibit large overshoots during post fault state before it settles to its steady state value with the standard linear scheme rather than with the proposed observer based controller.

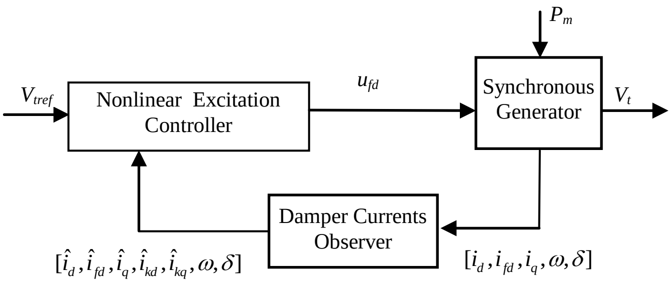
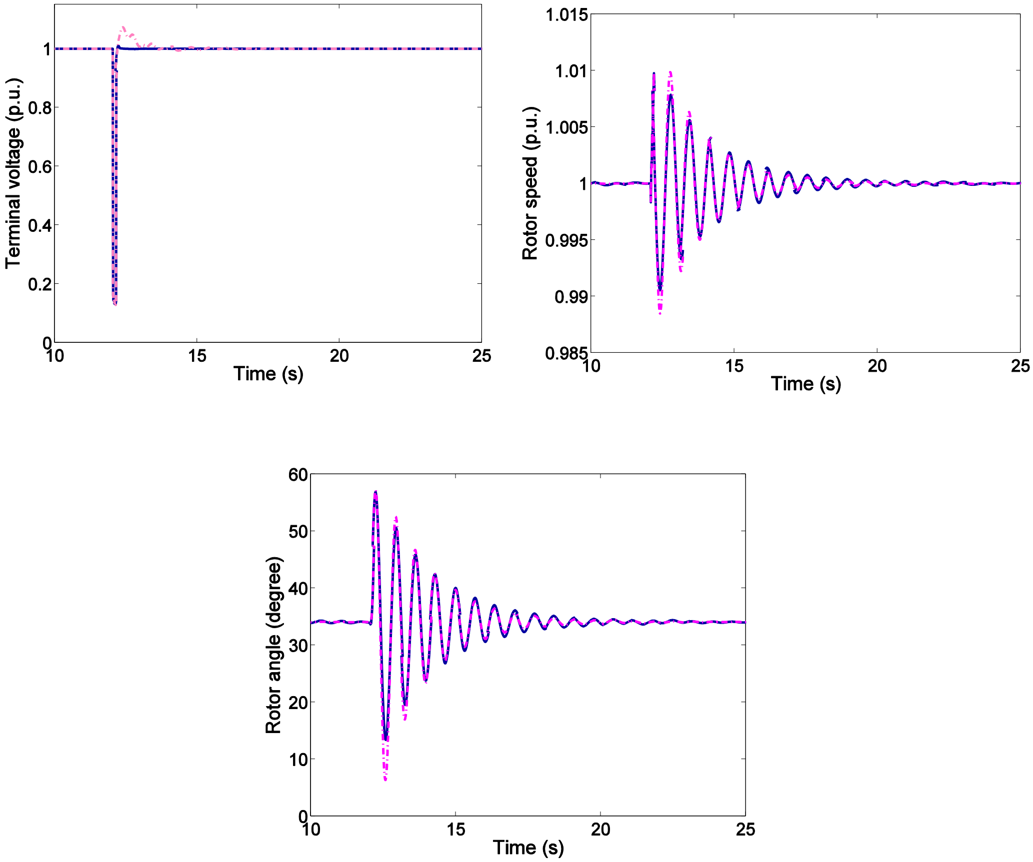


Figure 4. Observer based controller system configuration.



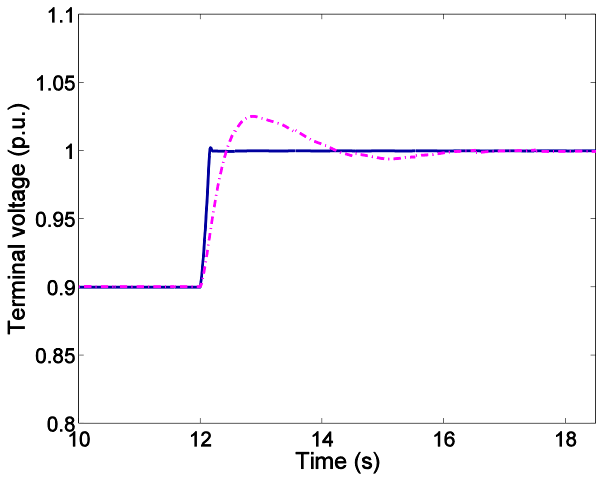
(solid) proposed controller; (dot) linear controllers.

Figure 5. Comparison performance of the AVR+PSS controllers and the proposed observer-based controller for a large sudden fault.

C. Observer-based controller performance evaluation under small disturbance

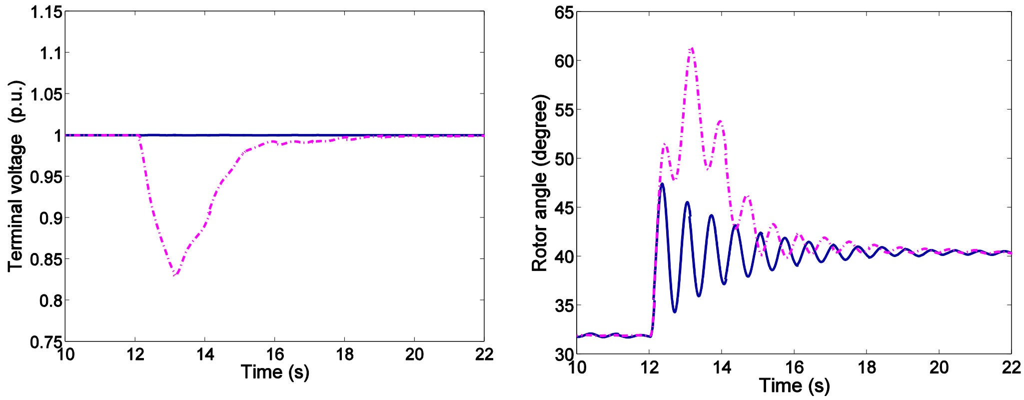
Step changes of 10% were applied to the terminal voltage reference set point of the synchronous generator. The responses of Fig. 6 show the terminal voltage of the AVR+PSS controllers and those of the proposed nonlinear controller. According to this figure, the trajectory command can be well tracked and the terminal voltage error converged to zero in notime for the proposed controller. It can be seen that the terminal voltage for AVR/PSS controllers shows remarkable transient within large overshoots before it settles to the terminal voltage reference. The settling time is around 4s.

Another simulated terminal voltage responses for a sudden increase in the mechanical power is shown in Fig.7. The power system is started at mechanical power of P_{mo}=0.7p.u. Around t = 12s, the mechanical power is set at P_{mo}=0.9p.u. It is shown that the terminal voltage of the linear controller shows remarkable transient before to converge to desired value, while the terminal voltage of the proposed controller is unaffected by this variation. Earlier results show again the superiority of the nonlinear observer-based controller.



(solid) proposed controller; (dot) linear controllers.

Figure 6. Comparison performance of the AVR+PSS controllers and the proposed observer-based controller for a sudden variation in terminal voltage.



(solid) proposed controller; (dot) linear controllers.

Figure 7. Comparison performance of the AVR+PSS controllers and the proposed observer-based controller for a sudden increase in mechanical power (ΔP_m= 0.2 p.u at t= 2s).

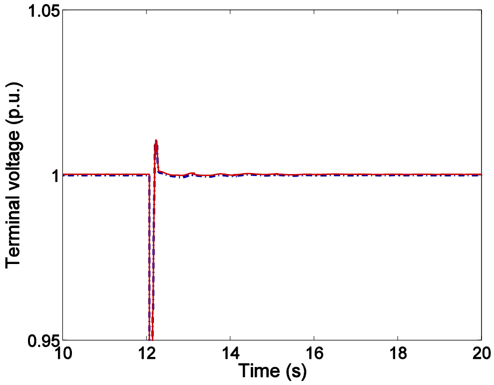
D. Robustness to parameters uncertainties

Now, the variation of system parameters is considered for robustness evaluation of the proposed observer-based controller. Two cases are examined in the following:

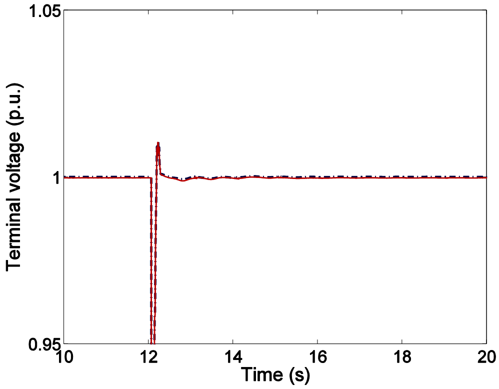
- Case 1: The parameters of the generator and the transmission line have +25% perturbation of the nominal values.
- Case 2: The parameters of the generator and the transmission line have -25% perturbations of the nominal values.

The responses of the terminal voltage and excitation voltage are shown in Figure 8.

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. From Figure 8, it can be seen that the combined nonlinear observer-controller is robust to the parameter perturbations and the post fault terminal voltage value is regulated to its prefault value very quickly.



(dot) nominal parameters; (solid) +25% parameter perturbation.



(dot) nominal parameters; (solid) -25% parameter perturbation.

Figure 8. Performance of the proposed observer-based controller under parameter perturbation.

Conclusion

In this paper, a new nonlinear observer-controller scheme has been developed and applied to the single machine infinite bus power system, based on the complete 7th order model. The proposed scheme considers a sliding-mode technique and Lyapunov theory in order to enhance the system stability and voltage regulation performance through excitation control. A nonlinear observer is used to produce estimates of damper winding currents. The detailed derivation for the excitation control law has been provided. Globally exponentially stable of observer-based controller has been proven by applying Lyapunov stability theory.

Simulation results have confirmed that the observer-based nonlinear controller can effectively improve the transient stability and voltage regulation under small disturbance and large sudden fault. The combined sliding mode observer-controller scheme demonstrates consistent superiority opposed to a system with linear controllers. It can be seen from the simulation study that the designed controller possesses a great robustness to deal with parameter uncertainties.

Appendix A

$$c_{11} = R_e + a_{11}L_e\omega_R^{-1}, \quad c_{12} = a_{12}L_e\omega_R^{-1}, \quad c_{13} = L_e(a_{13}\omega_R^{-1} - 1), \quad c_{14} = a_{14}L_e\omega_R^{-1},$$
$$c_{15} = a_{15}L_e\omega_R^{-1}, \quad c_{16} = V^{\infty} + a_{16}L_e\omega_R^{-1}, \quad c_{17} = b_1L_e\omega_R^{-1},$$
$$c_{21} = L_e + a_{31}L_e\omega_R^{-1}, \quad c_{22} = a_{32}L_e\omega_R^{-1}, \quad c_{23} = a_{33}L_e\omega_R^{-1} + R_e,$$
$$c_{24} = a_{34}L_e\omega_R^{-1}, \quad c_{25} = a_{35}L_e\omega_R^{-1}, \quad c_{26} = V^{\infty} + a_{36}L_e\omega_R^{-1}.$$

Appendix B

Table 1

PARAMETERS OF THE POWER SYNCHRONOUS GENERATOR IN p.u.

Parameter	Value
R_s , stator resistance.	$3\ 10^{-3}$
R_{fd}, field resistance.	$6.3581\ 10^{-4}$
R_{kd}, direct damper winding resistance.	$4.6454\ 10^{-3}$
R_{kq}, quadrature damper winding resistance.	$6.8460\ 10^{-3}$
L_d, direct self-inductance.	1.116
L_q quadrature self-inductances.	0.416
L_{fd}, rotor self inductance.	1.083
L_{kd}, direct damper winding self inductance.	0.9568
L_{kq}, quadrature damper winding self inductance.	0.2321
L_{md}, direct magnetizing inductance.	$9.1763\ 10^{-1}$
L_{mq}, quadrature magnetizing inductance.	$2.1763\ 10^{-1}$
$V^{\propto}$, infinite bus voltage	1
D, damping constant.	0
H, inertia constant.	3.195s

Table 2

PARAMETERS OF THE TRANSMISSION LINE IN p.u.

Parameter	Value
L_e, inductance of the transmission line.	$11.16\ 10^{-3}$
R_e, resistance of the transmission line.	$60\ 10^{-3}$

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