A Non-linear Decentralized Control of Multimachine Power Systems Based on a Backstepping Approach

M. Ouassaid, M. Maaroufi and M. Cherkaoui

Abstract Power system requires high-performance control techniques due to their elevated complexity, high nonlinearity and almost continuously time-varying nature. Also, power systems are often subjected to small and large disturbances. To enhance the multimachine power system stability, a new approach to designing decentralized nonlinear control scheme is proposed. The approach seeks first build a novel mathematical model of multimachine power systems. The main characteristic of this model is that interactions between generators and changes in operating conditions are represented by time-varying parameters. More important, those parameters are update online, using only local measurements. Second, it develops a decentralized controller for the transient stabilization and voltage regulation. The controller consists of two controllers, known as the terminal voltage regulator and rotor speed stabilizer. The methodology adopted is based on backstepping design strategy. The proposed stabilizing feedback laws for the power system are shown to be globally asymptotically stable in the context of Lyapunov theory. Case studies are achieved in a two-area four machine power system to verify the effectiveness of the approach. Numerical results are presented to illustrate the usefulness and the performance of the proposed control scheme, under different contingencies.

Keywords Modeling of a multimachine power system · Backstepping design · Voltage regulation · Transient stability · Nonlinear decentralized control

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1 Introduction

Modern Electrical Power Systems (EPS) are increasingly operated closer to their transfer power and stability limits. The control systems, accordingly, will have to regulate the system, to improve its global stability including inter-area transfer capability and dynamic performance under a diversity of operating conditions. Traditionally, conventional controllers such as the Automatic Voltage Regulator (AVR), the Power System Stabiliser (PSS) and Speed Governor (SG), are mainly designed by using linear models of the power systems [16]. Those linear controllers, based mainly on classical control algorithms, can be used to insure asymptotic stability of the equilibrium following a small perturbation. Unfortunately, in the event of a large disturbance, the operating point of the system may vary significantly and a linear controller may not be able to guarantee asymptotic stability.

Therefore, 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 [16]. To meet this challenge, a lot of interest has been considered in the application of the nonlinear control theory for the control of power systems and consequently to enhance the power systems stability. Most of these controllers are based on feedback linearization [8, 34], Hamiltonian techniques [35, 37], sliding-mode control [4, 5, 9, 11, 17, 24, 25] have been successfully applied to improve the transient stability. New approaches have been proposed for power stability designs according to other sophisticated schemes such as fuzzy logic control [1, 6, 19], adaptive control [7, 10, 12, 13, 29, 36], and neurocontrol [18, 26, 32]. Combinations of the above techniques are also proposed in order to exploit the advantages of each method at the cost of the increase in complexity [2, 28, 33].

The backstepping is one of the most important techniques, which provides a powerful design tool to solve many design problems under restrictive conditions than those encountered in the other methods [15, 27]. Further, the adaptive backstepping approach is capable of guaranteeing almost all robustness properties of the mismatched uncertainties [30, 31]. This technique has been successfully applied for power system in [14, 22, 23].

Generally, the design of the controllers, for power system, is based on two main modeling approaches:

- The Single-Machine, Infinite-Bus (SMIB) approach is simple but it does not take into account dynamic phenomena in the rest of the electrical network. Therefore, controllers may not perform well when inter-area oscillations occur.
- The Multimachine Power System (MPS) approach is based on the global N-generator modeling [9, 34]. The controllers based on this model dampen intermachine and inter-area oscillations very well.

A new approach for modelling the EPS combines the advantages of both previous modelling approaches [20, 21]. The approach consists of partitioning the power system into the generator to be controlled and the rest of the network viewed as dynamic load. The time-varying parameters of the resulting model encapsulate operating-condition variations and interactions between generators. Nevertheless, wide area control laws are derived from a reformulation of the multimachine model, generator terminal voltages are used as state variables instead of internal field voltages, through complex transformations. In addition, time varying parameters of the model are unknown and must be estimated online by an adaptation process.

The main aim of this study is the design of controllers to guarantee the voltage regulation and enhance transient stability for multimachine power systems. These controllers are proposed to replace the traditional speed governor (SG), automatic voltage regulator (AVR) plus the power system stabilizer control structure (PSS). To this end, a novel modelling of multimachine power system is proposed. Contrary to the model proposed in Okou et al. [20, 21] which is based on a third order simplified model, in the resulting modelling, the model of synchronous machine is based on a seventh order model which takes into account both field effects and damper winding effects introduced by different rotor circuits. In addition, time varying parameters of the model, which depend on the steady-state active and reactive power delivered by each generator, and the interactions between generators, are update continuously online.

Furthermore, a backstepping control system is designed to control the rotor speed and terminal voltage, simultaneously, in order to enhance the transient stability and ensure good post-fault voltage regulation for power system. The theoretical bases of the proposed control technique are derived in detail where the feedback system is shown to be globally asymptotically stable in the sense of the Lyapunov's stability theory.

Finally, the decentralized proposed controller requires only local measurement, which owns highly desirable advantages in cost, reliability and can be easily implemented.

The rest of this chapter is organized as follows. In Sect. 2, a new dynamic mathematical model of a multimachine power system is developed. Section 3 is devoted to a design of a backstepping control for the multimachine power system to ensure the voltage regulation and enhance the transient stability of the system. The stability of this controller is proven. In Sect. 4, simulation results are given to validate the proposed model and illustrate the performance of the proposed scheme. Also, the performances of the developed controller are compared to the performance of a standard AVR/PSS and SG. Conclusions are finally made in Sect. 5.

2 New Dynamic Power System Model

2.1 Mathematical Model of Synchronous Generator

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 model takes into account both field effects and damper windings effects introduced by the different rotor circuits. The synchronous machine equations in terms of Park's d-q axis are expressed as follows [3, 16]

$$\begin{cases} v_d = -R_s i_d + L_q \omega i_q - L_{mq}\omega i_{kq} - L_d \frac{di_d}{dt} + L_{md}\left(\frac{di_{fd}}{dt} + \frac{di_{kd}}{dt}\right) \\ v_q = -R_s i_q + -L_d \omega i_d + L_{md}\omega(i_{fd} + i_{kd}) - L_q \frac{di_q}{dt} + L_{mq}\frac{di_{kq}}{dt} \\ v_{fd} = R_s i_{fd} - L_{md}\frac{di_d}{dt} + L_{fd}\frac{di_{fd}}{dt} + L_{md}\frac{di_{kd}}{dt} \\ 0 = R_{kd} i_{kd} - L_{md}\frac{di_d}{dt} + L_{md}\frac{di_{fd}}{dt} + L_{kd}\frac{di_{kd}}{dt} \\ 0 = R_{kq} i_{kq} - L_{mq}\frac{di_d}{dt} + L_{kq}\frac{di_{kq}}{dt} \end{cases} \tag{1}$$

where v_d and v_q are direct and quadrature axis stator terminal voltage components, respectively; v_{fd} excitation control input; 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; 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.

Mechanical equations are as follows

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

$$\frac{d\delta}{dt} = \omega - 1 \tag{3}$$

where ω is 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.

The electromagnetic torque is

$$T_e = \left(L_q - L_d\right) i_d i_q + L_{mfd} i_{fd} i_q + L_{md} i_{kd} i_q - L_{mq} i_d i_{kq} \tag{4}$$

The steam turbine dynamics and valve are represented by the following equations [8].

$$\begin{cases} \frac{dP_m}{dt} = -\frac{1}{T_t}P_m + \frac{K_m}{T_t}X_e \\ \frac{dX_e}{dt} = -\frac{1}{T_g}X_e + \frac{K_g}{T_g}\left(u_g - \frac{1}{R\omega_R}\omega\right) \end{cases} \tag{5}$$

where X_e is the steam valve opening of the system; u_g the input power of control system; T_t the time constant of the turbine; K_t the gain of the turbine; R the regulation constant of the system; T_g the time constant of the speed governor; K_g the gain of the speed governor and ω_R is the power system frequency.

2.2 Mathematical Model of the Rest of the Network

The modelling of the rest of network is made by using the concept introduced in [20]. In this approach, each generator views the rest of the grid as a dynamic load. This load is represented by an instantaneous effective impedance and is given by the following equation in per-unit

$$v(t) = R_L(t)i(t) + X_L(t)\frac{di(t)}{dt} \tag{6}$$

where v and i are the generator's instantaneous terminal voltage and stator current, respectively. The time dependent parameters $R_L(t)$ and $X_L(t)$ summarize the dynamic exchange of active and reactive powers, respectively.

In the d-q reference frame, after applying a Park transformation, we obtain

$$\begin{cases} v_d = R_L(t)i_d - X_L(t)\omega i_q + X_L(t)\frac{di_d}{dt} \\ v_q = R_L(t)i_q + X_L(t)\omega i_d + X_L(t)\frac{di_q}{dt} \end{cases} \tag{7}$$

2.3 New Dynamic Mathematical Model of Multimachine Power System

The mathematical model is obtained by combining equations of the synchronous generator (1) with equation of the rest of the network (7). After some lengthy but straightforward algebraic manipulations, the resulting model has the following form

$$\begin{cases} \frac{di_d}{dt} = h_{11}(t)i_d + h_{12}(t)i_{fd} + h_{13}(t)\omega i_q + h_{14}(t)i_{kd} + h_{15}(t)i_{kq}\omega + g_1(t)u_{fd} \\ \frac{di_{fd}}{dt} = h_{21}(t)i_d + h_{22}(t)i_{fd} + h_{23}(t)\omega i_q + h_{24}(t)i_{kd} + h_{25}(t)i_{kq}\omega + g_2(t)u_{fd} \\ \frac{di_q}{dt} = h_{31}(t)i_d\omega + h_{32}(t)i_{fd}\omega + h_{33}(t)i_q + h_{34}(t)i_{kd}\omega + h_{35}(t)i_{kq} \\ \frac{di_{kd}}{dt} = h_{41}(t)i_d + h_{42}(t)i_{fd} + h_{43}(t)i_q\omega + h_{44}(t)i_{kd} + h_{45}(t)i_{kq}\omega + g_3(t)u_{fd} \\ \frac{di_{kq}}{dt} = h_{51}(t)i_d\omega + h_{52}(t)i_{fd}\omega + h_{53}(t)i_q + h_{54}(t)i_{kd}\omega + h_{55}(t)i_{kq} \\ \frac{d\omega}{dt} = h_{61}(t)\omega + h_{62}(t)\frac{P_m}{\omega} - h_{62}(t)T_e \end{cases} \tag{8}$$

The time-varying parameters $h_{ij}(t)$ and $g_i(t)$ depend on $R(t)$ and $X(t)$ and hence on the operating conditions of the power system. Their expressions are given as follow

$$h_{11}(t) = -(R_s + R_L(t))(L_{fd}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad h_{12}(t) = -R_{fd}(L_{mq}L_{kd} - L_{md}^2)\omega_R D_d^{-1}$$
$$h_{13}(t) = (L_q + X_L(t))(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad h_{14}(t) = R_{kd}((L_d + X_L(t))L_{md} - L_{md}^2)\omega_R D_d^{-1}$$
$$h_{15}(t) = -L_{mq}(L_{fd}L_{kd} - L_{md}^2)\omega_R D_d^{-1}$$

$$h_{21}(t) = -(R_s + R_L(t))(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad h_{22}(t) = -R_{fd}((L_d + X_L(t))L_{kd} - L_{md}^2)\omega_R D_d^{-1}$$
$$h_{23}(t) = (L_q + X_L(t))(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad h_{24}(t) = R_{kd}((L_d + X_L(t))L_{md} - L_{md}^2)\omega_R D_d^{-1}$$
$$h_{25}(t) = -L_{mq}(L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1}$$

$$h_{31}(t) = (L_d + X_L(t))L_{kq}\omega_R D_q^{-1} \quad h_{32}(t) = L_{md}.L_{kq}\omega_R D_q^{-1}$$
$$h_{33}(t) = -(R_s + R_L(t))L_{kq}\omega_R D_q^{-1} \quad h_{34}(t) = L_{md}L_{kq}\omega_R D_q^{-1}$$
$$h_{35}(t) = -L_{mq}.R_{kq}\omega_R D_q^{-1}$$

$$h_{41}(t) = -(R_s + R_L(t))(L_{fd}L_{md} - L_{md}^2)\omega_R D_d^{-1} \quad h_{42}(t) = R_{fd}((L_d + X_L(t))L_{md} - L_{md}^2)\omega_R D_d^{-1}$$
$$h_{43}(t) = (L_q + X_L(t))(L_{md}L_d - L_{md}^2)\omega_R D_d^{-1} \quad h_{44}(t) = -R_{kd}((L_d + X_L(t))L_{fd} - L_{md}^2)\omega_R D_d^{-1}$$
$$h_{45}(t) = -L_{md}(L_{mq}.L_{fd} - L_{md}^2)\omega_R D_d^{-1}$$

$$h_{51}(t) = -(L_d + X_L(t))L_{mq}\omega_R D_q^{-1} \quad h_{52}(t) = L_{md}L_{mq}\omega_R D_q^{-1}$$
$$h_{53}(t) = -(R_s + R_L(t))L_{mq}\omega_R D_q^{-1} \quad h_{54}(t) = L_{md}L_{mq}\omega_R D_q^{-1}$$
$$h_{55}(t) = -R_{kq}(L_q + X_L(t))\omega_R D_q^{-1}$$

$$h_{61}(t) = 1/2H \quad h_{62}(t) = -D/2H$$

$$g_1(t) = (L_{md}L_{kd} - L_{md}^2)\omega_R D_d^{-1} \quad g_2(t) = ((L_d + L_{fd})L_{kd} - L_{md}^2)\omega_R D_d^{-1}$$
$$g_3(t) = ((L_d + X_L(t))L_{md} - L_{md}^2)\omega_R D_d^{-1}$$

These parameters encapsulate the interactions between the generator to be controlled and the rest of the grid.

In order to reduce the controller complexity and hence to increase its reliability, we consider the two-axis model assumption, by neglecting the stator current dynamics. Hence, equations (7) have the following form

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = \begin{pmatrix} R_L(t) & -X_L(t)\omega \\ X_L(t)\omega & R_L(t) \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} \tag{9}$$

Therefore, the expressions of $R_L(t)$ and $X_L(t)$ in terms of the d-q axis voltage and current are derived of the forms

$$\begin{cases} R_L(t) = \frac{v_d i_d + v_q i_q}{i_d^2 + i_q^2} \\ X_L(t) = \frac{1}{\omega} \frac{v_q i_d - v_d i_q}{i_d^2 + i_q^2} \end{cases} \tag{10}$$

From (10), it is evident that, $R_L(t)$ and $X_L(t)$ are proportional to, respectively, the active and reactive power delivered by the generator and give information about the operating conditions of the rest of the grid. More important, they are update online using only local measurement.

The terminal voltage is defined by

$$v_t = \sqrt{v_d^2 + v_q^2} \tag{11}$$

The expressions of v_d and v_q as a function of the state variables can be expressed, by combining Eqs. (1) and (7), as follow

$$\begin{cases} v_d = \partial_{11}(t)i_d + \partial_{12}i_{fd} + \partial_{13}\omega i_q + \partial_{14}i_{kd} + \partial_{15}i_{kq}\omega + \partial_{16}(t)u_{fd} \\ v_q = \partial_{21}(t)i_d\omega + \partial_{22}(t)i_{fd}\omega + \partial_{23}(t)i_q + \partial_{24}(t)i_{kd}\omega + \partial_{25}(t)i_{kq} \end{cases} \tag{12}$$

where the time-varying parameters ∂_{ij} depend on $h_{ij}(t)$ and $g_i(t)$ and hence on the operating conditions of the power system. Their expressions are given as follows

$$\begin{array}{ll} \partial_{11}(t) = R_L + h_{11}(t)X_L(t)\omega_R^{-1} & \partial_{12}(t) = h_{12}(t)X_L(t)\omega_R^{-1} \\ \partial_{13}(t) = X_L(t)(h_{13}(t)\omega_R^{-1} - 1) & \partial_{14}(t) = h_{14}(t)X_L(t)\omega_R^{-1} \\ \partial_{15}(t) = h_{15}(t)X_L(t)\omega_R^{-1} & \partial_{16}(t) = g_1(t)X_L(t)\omega_R^{-1} \end{array}$$

$$\begin{array}{ll} \partial_{21}(t) = X_L(t) + h_{31}(t)X_L(t)\omega_R^{-1} & \partial_{22}(t) = h_{32}(t)X_L(t)\omega_R^{-1} \\ \partial_{23}(t) = h_{33}(t)X_L(t)\omega_R^{-1} + R_L(t) & \partial_{24}(t) = h_{34}(t)X_L(t)\omega_R^{-1} \\ \partial_{25}(t) = h_{35}(t)X_L(t)\omega_R^{-1} & \end{array}$$

Then, combining Eqs. (8), (11) and (12) with mechanical equation (2), and the equations of the turbine (5), we can formulate the new mathematical model of the power system in the following nonlinear state-space form

$$\frac{dv_t}{dt} = \partial_{16}(t)\frac{v_d}{v_t}\frac{du_{fd}}{dt} + g_3(t)\partial_{14}(t)\frac{v_d}{v_t}u_{fd} + f(t) \tag{13}$$

$$\frac{d\omega}{dt} = h_{61}(t)\omega + h_{62}(t)\frac{P_m}{\omega} - h_{62}(t)T_e \tag{14}$$

$$\frac{dP_m}{dt} = h_{81}(t)P_m + h_{82}(t)X_e \tag{15}$$

$$\frac{dX_e}{dt} = h_{91}(t)X_e + h_{92}(t)\omega + g_4(t)u_g \tag{16}$$

where

$$f(t) = \frac{v_d}{v_t}\left[\partial_{11}(t)\frac{di_d}{dt} + \partial_{12}(t)\frac{di_{fd}}{dt} + \partial_{13}(t)\left(\omega\frac{di_q}{dt} + i_q\frac{d\omega}{dt}\right)\right] + \frac{v_d}{v_t}\partial_{15}(t)\left[\omega\frac{di_{kq}}{dt} + i_{kq}\frac{d\omega}{dt}\right] \\ + \partial_{14}(t)\frac{v_d}{v_t}\left[h_{41}(t)i_d + h_{42}(t)i_{fd} + h_{43}(t)i_q\omega + h_{44}(t)i_{kd} + h_{45}(t)i_{kq}\omega\right] + \frac{v_q}{v_t}\frac{dv_q}{dt}$$

$$\begin{array}{ll} h_{81}(t) = -(T_m)^{-1} & h_{82}(t) = K_m(T_m)^{-1} \\ h_{91}(t) = -(T_g)^{-1} & h_{92}(t) = -K_g(T_gR\omega_R)^{-1} \\ g_4(t) = K_g(T_g)^{-1} & \end{array}$$

3 Backstepping Terminal Voltage and Rotor Speed Controllers Design

The control objectives are the terminal voltage magnitude v_t regulation and rotor speed ω stability enhancement. The form of the nonlinear system, described by (13)–(16), allows the use of the recursive backstepping procedure for the controller design. The basic idea of backstepping design is to select recursively some appropriate functions of state variables as pseudo-control inputs for lower dimension subsystems of the overall system. Each backstepping stage results in a new pseudocontrol design, expressed in terms of the pseudocontrol designs from preceding design stages. When the procedure terminates, a feedback design for the true control input results which achieves the original design objective by virtue of a final Lyapunov function, which is formed by summing up the Lyapunov functions associated with each individual design stage [15]. In the rest of this section, this idea is adopted to design a nonlinear controller for terminal voltage and rotor speed tracking of the power system.

3.1 Backstepping Control Design

To satisfy the first control objective, the terminal voltage control error is defined as

$$z_1 = v_t - v_t^{ref} \tag{17}$$

where v_t^{ref} is the desired trajectory. The time derivative of the z_1 , using (13), is

$$\frac{dz_1}{dt} = \partial_{16}\frac{v_d}{v_t}\frac{du_{fd}}{dt} + g_3\partial_{14}\frac{v_d}{v_t}u_{fd} + f(t) \tag{18}$$

The design procedure starts by defining the following Lyapunov-like function:

$$V_1 = \frac{1}{2}z_1^2 \tag{19}$$

Its time derivative can be written as

$$\frac{dV_1}{dt} = \left[\partial_{16}\frac{v_d}{v_t}\frac{du_{fd}}{dt} + g_3\partial_{14}\frac{v_d}{v_t}u_{fd} + f(t)\right]z_1 \tag{20}$$

To ensure the global asymptotic stability, we impose

$$\frac{dV_1}{dt} = -K_1 z_1^2 \tag{21}$$

where K_1 is a positive constant feedback gain. Then (20) can be rewritten as

$$\frac{dV_1}{dt} = -K_1 z_1^2 + \left[K_1 z_1 + \partial_{16} \frac{v_d}{v_t} \frac{du_{fd}}{dt} + g_3 \partial_{14} \frac{v_d}{v_t} u_{fd} + f(t) \right] z_1 \tag{22}$$

From the above expression, we can define the following control function

$$\frac{du_{fd}}{dt} = -\frac{v_t}{\partial_{16} v_d} \left[K_1 z_1 + g_3 \partial_{14} \frac{v_d}{v_t} u_{fd} + f(t) \right] \tag{23}$$

The second control objective is to keep the rotor speed tracks the desired trajectory $\omega_{ref} = 1$ p.u.

Step 1: To reach the control objective, the rotor speed error is defined as

$$z_2 = \omega - \omega_{ref} \tag{24}$$

From (14), the derivative of the rotor speed error is given as

$$\frac{dz_2}{dt} = h_{61}\omega + h_{62} \frac{P_m}{\omega} - h_{62} T_e \tag{25}$$

Consider the second Lyapunov function

$$V_2 = \frac{z_1^2}{2} + \frac{z_2^2}{2} \tag{26}$$

Using (21) and (25), the derivative of (26) can be derived as follows

$$\frac{dV_2}{dt} = -K_1 z_1^2 + \left(h_{61}\omega + h_{62} \frac{P_m}{\omega} - h_{62} T_e \right) z_2 \tag{27}$$

The P_m can be viewed as a virtual control in the above equation. Define the following stabilizing function

$$\alpha_1 = \frac{\omega}{h_{62}} \left(h_{62} T_e - h_{61}\omega - K_2 z_2 \right) \tag{28}$$

where K_2 is a positive constant feedback gain. Since the mechanical power P_m is not our control input, we define

$$z_3 = P_m - \alpha_1 \tag{29}$$

which is the stabilizing error between P_m and its desired trajectory α_1. When a fault occurs, large currents and torque 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 (28), as electromagnetic load T_e is unknown, when fault occurs, it has to be estimated adaptively. Thus, let us define

$$\hat{\alpha}_1 = \frac{\omega}{h_{62}} \left(h_{62} \hat{T}_e - h_{61} \omega - K_2 z_2 \right) \tag{30}$$

where $\overset{\wedge}{T_e}$ is the estimated value of the electromagnetic load. Thus from (25), (29) and (30), the following rotor speed error dynamics is obtained

$$\frac{dz_2}{dt} = -K_2 z_2 + h_{62} \frac{z_3}{\omega} - h_{62} \overset{\sim}{T_e} \tag{31}$$

where $\overset{\sim}{T_e} = T_e - \overset{\wedge}{T_e}$.

Step 2: To stabilize the mechanical power P_m, one defines the following derivative of z_3 using (15), (29) and (30) as

$$\frac{dz_3}{dt} = h_{81} P_m + h_{82} X_e - \frac{d\hat{\alpha}_1}{dt} \tag{32}$$

Now, we can define a new Lyapunov function including the mechanical power error variable z_3 as

$$V_3 = \frac{1}{2} z_1^2 + \frac{1}{2} z_2^2 + \frac{1}{2} z_3^2 + \frac{1}{2\mu} \tilde{T}_e^2 \tag{33}$$

where μ is a positive adaptive gain. Its derivative, using (21), (31) and (32), is given as follows

$$\begin{aligned} \dot{V}_3 = &-K_1 z_1^2 - K_2 z_2^2 - K_3 z_3^2 + \tilde{T}_e \left(\tfrac{1}{\mu} \dot{\hat{T}}_e - h_{62} z_2 \right) \\ &+ \left(h_{81} P_m + h_{82} X_e - \tfrac{d\hat{\alpha}_1}{dt} + h_{62} \tfrac{z_2}{\omega} + K_3 z_3 \right) z_3 \end{aligned} \tag{34}$$

Similarly, if we consider X_e as a second virtual control, one easily obtains the following stabilizing function

$$\alpha_2 = \frac{1}{h_{82}} \left(\frac{d\hat{\alpha}_1}{dt} - K_3 z_3 - h_{62} \frac{z_2}{\omega} - h_{81} P_m \right) \tag{35}$$

where K_3 is a positive constant feedback gain. And the following update law can be derived as

$$\dot{\hat{T}}_e = \mu h_{62} z_2 \tag{36}$$

Step 3: Define the steam valve opening error as

$$z_4 = X_e - \alpha_2 \tag{37}$$

Its derivative along the trajectory, using (16), is

$$\frac{dz_4}{dt} = h_{91} X_e + h_{92} \omega + g_4 u_g - \frac{d\alpha_2}{dt} \tag{38}$$

By substituting (37) into (32), one can get

$$\frac{dz_3}{dt} = h_{82}z_4 - K_3 z_3 - h_{62}\frac{z_2}{\omega} \tag{39}$$

Finally, let us define a Lyapunov function for the closed-loop system as follows

$$V_4 = V_3 + \frac{1}{2}z_4^2 = \frac{1}{2}z_1^2 + \frac{1}{2}z_2^2 + \frac{1}{2}z_3^2 + \frac{1}{2\mu}\tilde{T}_e^2 + \frac{1}{2}z_4^2 \tag{40}$$

By differentiating the Lyapunov function V_4 in (40) one obtains

$$\dot{V}_4 = -K_1 z_1^2 - K_2 z_2^2 - K_3 z_3^2 + z_4\left(h_{82}z_3 + h_{91}X_e + h_{92}\omega + g_4 u_g - \dot{\alpha}_2\right) \tag{41}$$

From (41), a backstepping control law is designed as follows

$$u_g(t) = \frac{1}{g_4}\left(\frac{d\alpha_2}{dt} - K_4 z_4 - h_{82}z_3 - h_{91}X_e - h_{92}\omega\right) \tag{42}$$

where K_4 is a positive constant feedback gain.
By substituting (42) into (41), one can get

$$\dot{V}_4 = -K_1 z_1^2 - K_2 z_2^2 - K_3 z_3^2 - K_4 z_4^2 \le 0 \tag{43}$$

3.2 Stability Analysis

Theorem *The globally asymptotic stability of the system defined by (13)–(16), is guaranteed, if the control laws and the adaptive control are given by (23), (42) and (36), respectively.*

Proof The system error dynamics of the resulting closed loop adaptive system can be written as

$$\begin{aligned}
\tfrac{dz_1}{dt} &= -K_1 z_1 \\
\tfrac{dz_2}{dt} &= -K_2 z_2 + h_{62}\tfrac{z_3}{\omega} - h_{62}\,\widetilde{T}_e \\
\tfrac{dz_3}{dt} &= h_{82}z_4 - K_3 z_3 - h_{62}\tfrac{z_2}{\omega} \\
\tfrac{dz_4}{dt} &= -K_4 z_4 - h_{82}z_3 \\
\tfrac{d\tilde{T}_e}{dt} &= h_{62}\mu z_2
\end{aligned} \tag{44}$$

This system has an equilibrium at $z_1 = z_2 = z_3 = z_4 = 0$.

It is then clear that a Lyapunov function (40) for the system defined by (13)–(16), the control laws (23), (42) and the adaptive law (36) make it derivative negative semi-definite. So, define the following equation

$$W(t) = K_1 z_1^2 + K_2 z_2^2 + K_3 z_3^2 + K_4 z_4^2 \geq 0$$

Using Lasalle–Yoshizawa's principle [15], it can be shown that $W(t)$ tend to zero as $t \to \infty$. Therefore, the tracking errors which include terminal voltage, rotor speed, mechanical power and steam valve opening will converge to zero asymptotically as $t \to \infty$.

4 Validation and Discussion

The developed dynamic model and control strategy were tested on the two-area four-machine interconnected power system [16] whose schematic is shown in Fig. 1. At the steady state of the full load case, about 700 MW power is generated from each of the generators. The loads on buses LD7 and LD9 are 967 and 1767 MW, respectively. About 400 MW power is transferred from area 1 to area 2 through the parallel tie lines. The numerical values of the studied system parameters are presented in the Tables 1, 2 and 3. The Matlab/Simulink software is used for the time-domain simulations. Nonlinearities were taken into account incorporating both exciter ceilings, control signal limiters and rate of opening and closing in the turbine valve.

Figure 2 shows the decentralized control system configuration of the multimachine power system. In order to prove the usefulness and supremacy robustness of the proposed modelling and controllers, the results are compared with those of the conventional AVR + PSS and SG. Simulation studies are carried out for the power system under different contingencies.

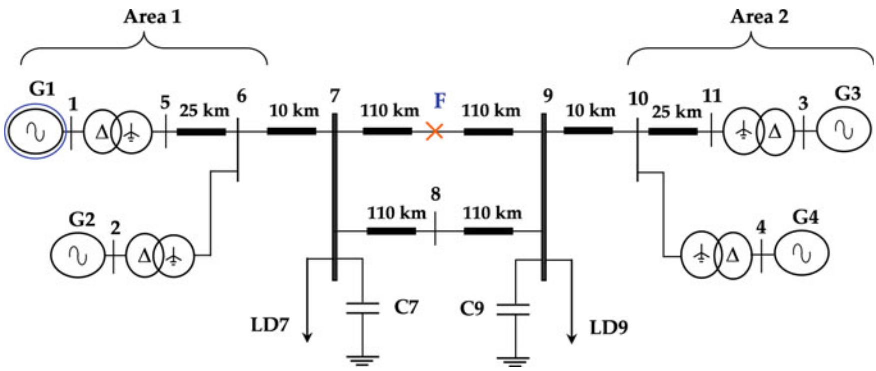

Fig. 1 Single-line diagram of the two-area four-machine power system

Table 1 Parameters of the power synchronous generator (# 1) in p.u.

Parameter	Value
S_{base}	900 MVA
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 2 Parameters of the power synchronous generators (# 2, 3, 4) in p.u.

Parameter	Value
S_{base}	900 MVA
x_l leakage reactance	0.2 p.u.
r_{a} resistance	0.0025 p.u.
x_{d} d-axis synchronous reactance	1.8 p.u.
x'_{d} d-axis synchronous transient reactance	0.25 p.u.
T'_{d0} d-axis open circuit time constant	8 s
x_{q} q-axis synchronous reactance	1.7 p.u.
x'_{q} q-axis synchronous transient reactance	0.25 p.u.
T'_{q0} q-axis open circuit time constant	0.4 s
H inertia constant	6.5 s

4.1 *Effect of Severe Disturbance on the Dynamic Performance of the System*

A symmetric three-phase short circuit fault occurs at location F (in the middle of the transmission line between bus B7 and bus B9), see Fig. 1, at 3 s. The transmission line subject to a fault is cut off at 3.1 s. The original system is restored after the fault clearance. Figure 3 illustrates terminal voltage and rotor speed. According to this figure, the trajectories command can be well tracked and the tracking error

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

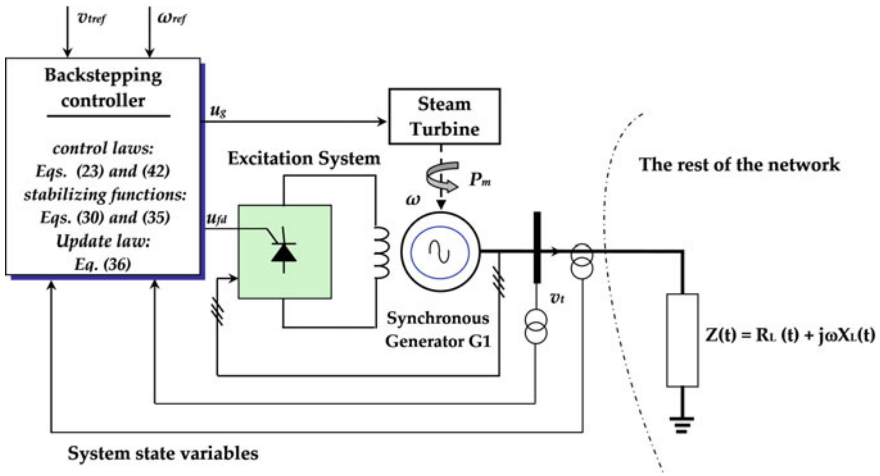

Fig. 2 Decentralized control system configuration

converged to zero. The electrical power of controlled generator and tie-line power flow are shown in Fig. 4. It is seen how dynamics of the terminal voltage, rotor speed and electrical power exhibit large overshoots during post fault state before they settle to their steady state values with the standard controllers (AVR + PSS + SG) rather than with the nonlinear decentralized scheme. It is quite evident that the developed decentralized controller achieves very good voltage regulation and transient stability.

Also, Fig. 5 shows the variations of the inter-area and local mode of oscillation. From these figures, it can be seen that, the inter-area modes of oscillations are very quickly damped out with the application of the proposed controller. Further, the proposed approach is also effective in suppressing the local mode of oscillations.

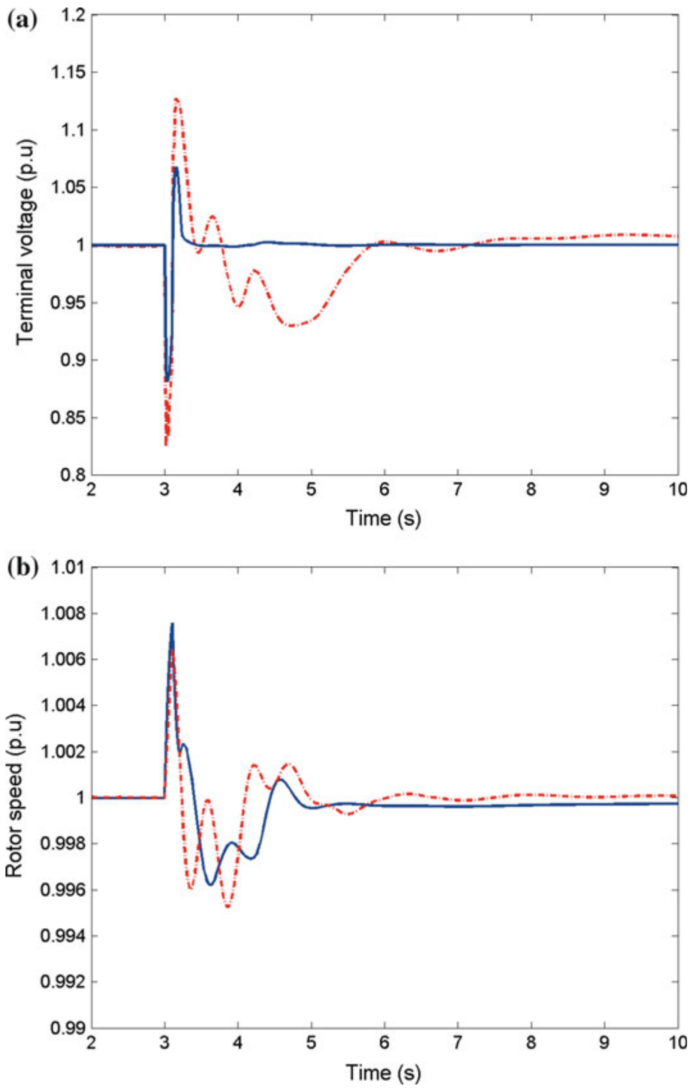

Fig. 3 Dynamic performance tracking of generator G1, following temporary three-phase short circuit fault. *Solid* proposed nonlinear control scheme; *dot* conventional controllers

4.2 Effect of Small Disturbance on the Dynamic Performance of the System

In any power system, the operating load varies over a wide range. It is extremely important to investigate the effect of variation of the loading condition on the dynamic performance of the system. In order to examine the robustness of the

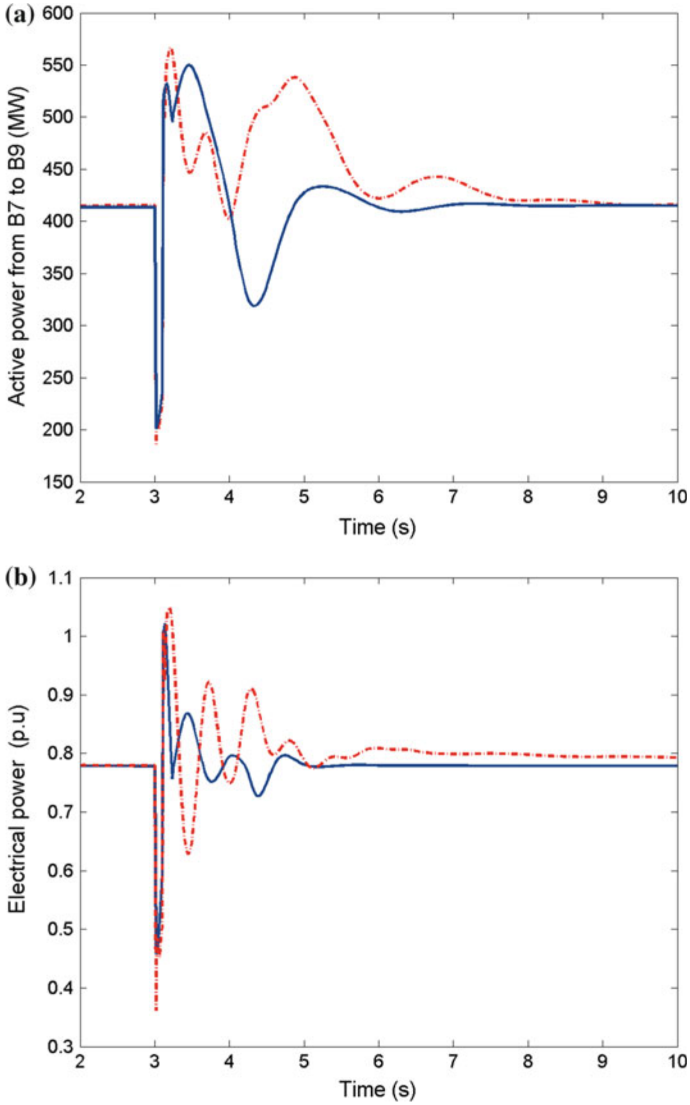

Fig. 4 Tie-line power flow (**a**) and electrical power of generator G1 (**b**) following temporary three-phase short circuit fault. *Solid* proposed nonlinear control scheme; *dot* conventional controllers

damping controllers to wide variation in the loading condition, the load at bus 7 (LD7 $= 967\,\mathrm{MW}$) is disconnected at $t = 5\,\mathrm{s}$ for $100\,\mathrm{ms}$.

Figures 6 and 7 show the tracking performance of the proposed controller. As it can be seen, the state variables reach a steady state condition, exhibiting the stability of the closed-loop system.

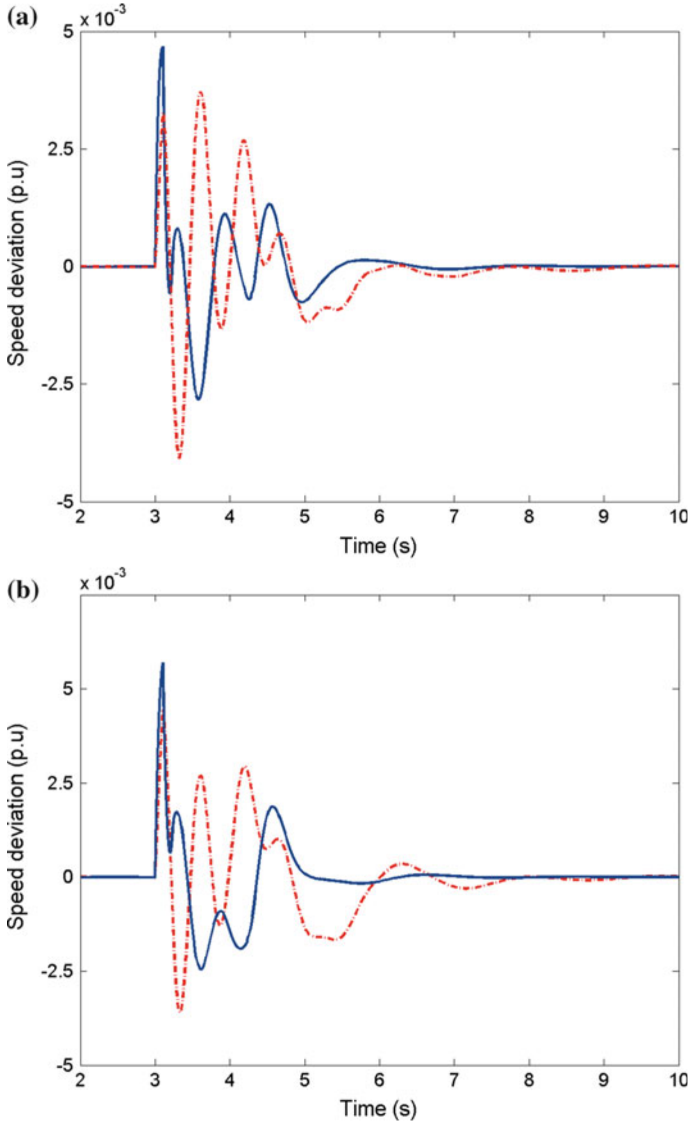

Fig. 5 Local mode of oscillation $\omega 1$-$\omega 2$ (**a**) and inter-area mode of oscillation $\omega 1$-$\omega 3$ (**b**) following temporary three-phase short circuit fault. *Solid* proposed nonlinear control scheme; *dot* conventional controllers

Figure 8 shows the variations of the inter-area and local mode of oscillation. It can be seen that, the transient response of the classical controllers (PSS/AVR and SG) is more oscillatory than the response given by the designed nonlinear controller. The developed decentralized controller provides significantly better damping enhance-

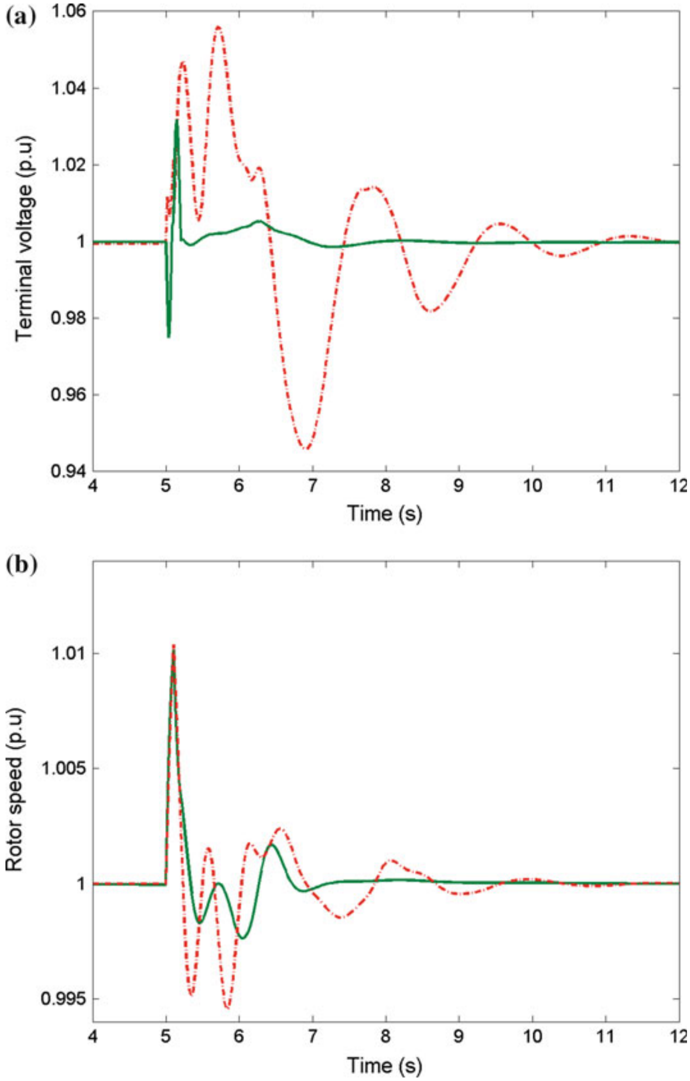

Fig. 6 Dynamic performance tracking of generator G1, following load variation *Solid* proposed nonlinear control scheme; *dot* conventional controllers

ment in the power system oscillations. It is possible to observe that the overshoot and settling time are reduced as well.

It is evident that the proposed controller is robust to this type of disturbance and provides efficient damping to power system oscillations even under small disturbance.

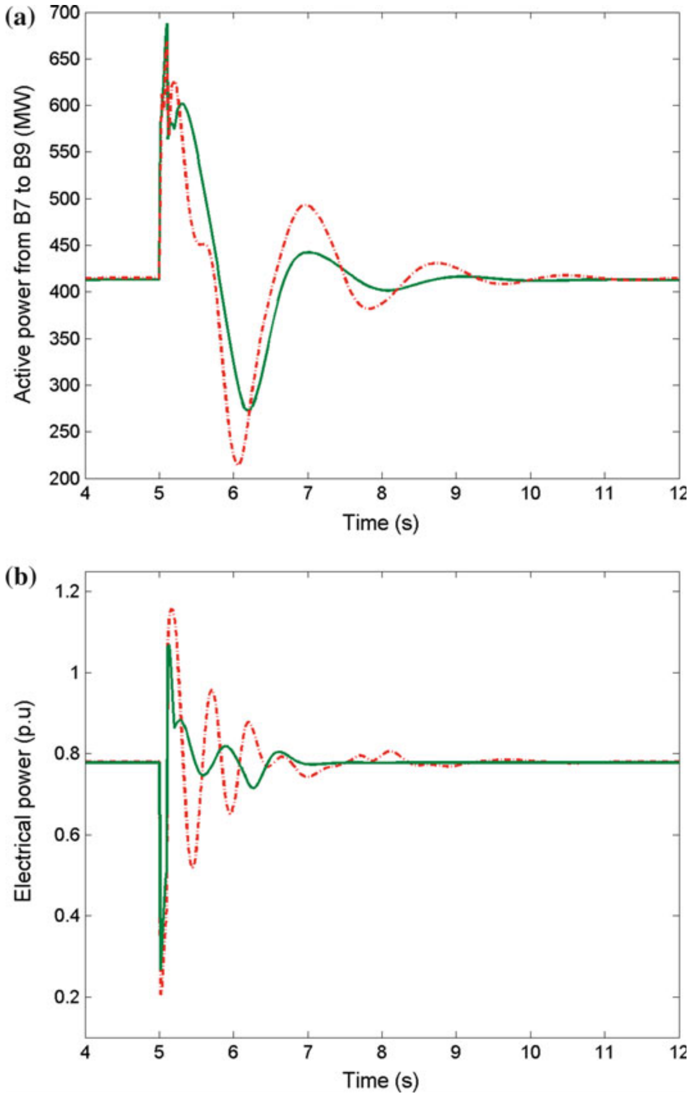

Fig. 7 Tie-line power flow (**a**) and electrical power of generator G1 (**b**) following load variation. *Solid* proposed nonlinear control scheme; *dot* conventional controllers

4.3 Robustness to Parameters Uncertainties and Modelling Errors

The variation of system parameters and model errors are considered for robustness evaluation of the proposed controller. In fact, an accurate model of power system is

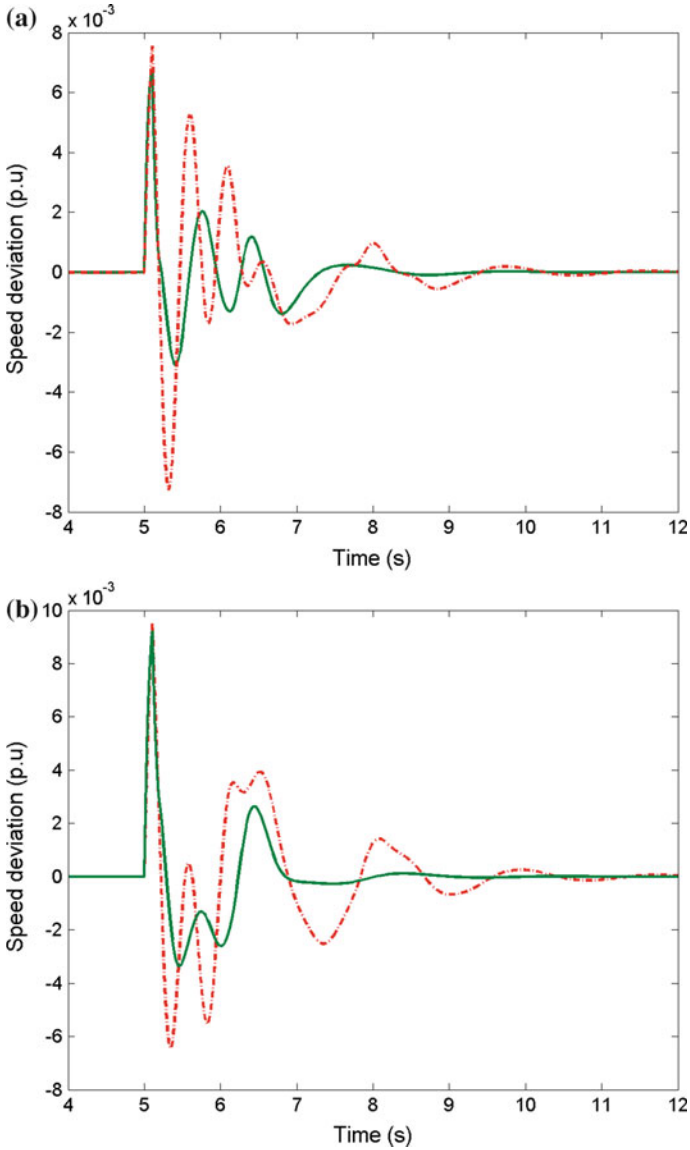

Fig. 8 Local mode of oscillation $\omega1$-$\omega2$ (**a**) and inter-area mode of oscillation $\omega1$-$\omega3$ (**b**) following load variation *Solid* proposed nonlinear control scheme; *dot* conventional controllers

not available. Therefore, it is required to investigate the robustness of the proposed controller with system parameter variation and model errors.

A robustness test has been carried out by changing the controlled generator parameters from their nominal values. Two cases are examined in the following:

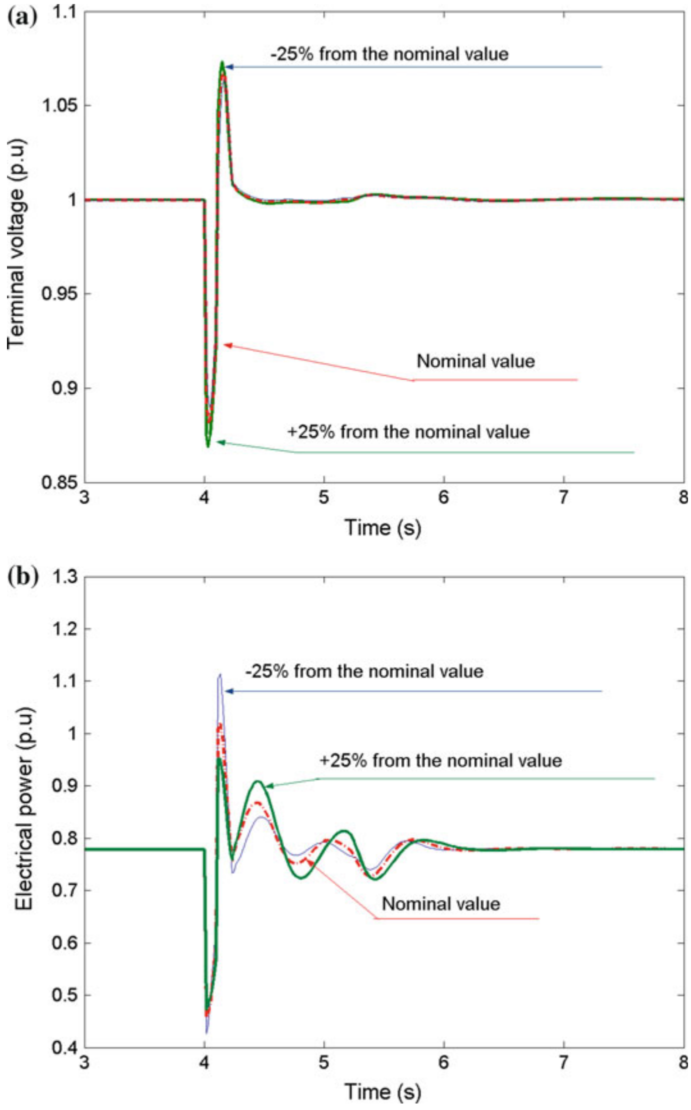

Fig. 9 Terminal voltage (**a**) and Electrical power of generator G1 (**b**) under parameter variations

- Case 1: The parameters of the controlled generator have +25 % perturbations of the nominal values.
- Case 2: The parameters of the controlled generator have −25 % perturbations of the nominal values.

In addition to the abrupt and permanent variation of the power system parameters a three-phase short-circuit is simulated at t = 4 s. It can be seen in Figs. 9 and 10 that

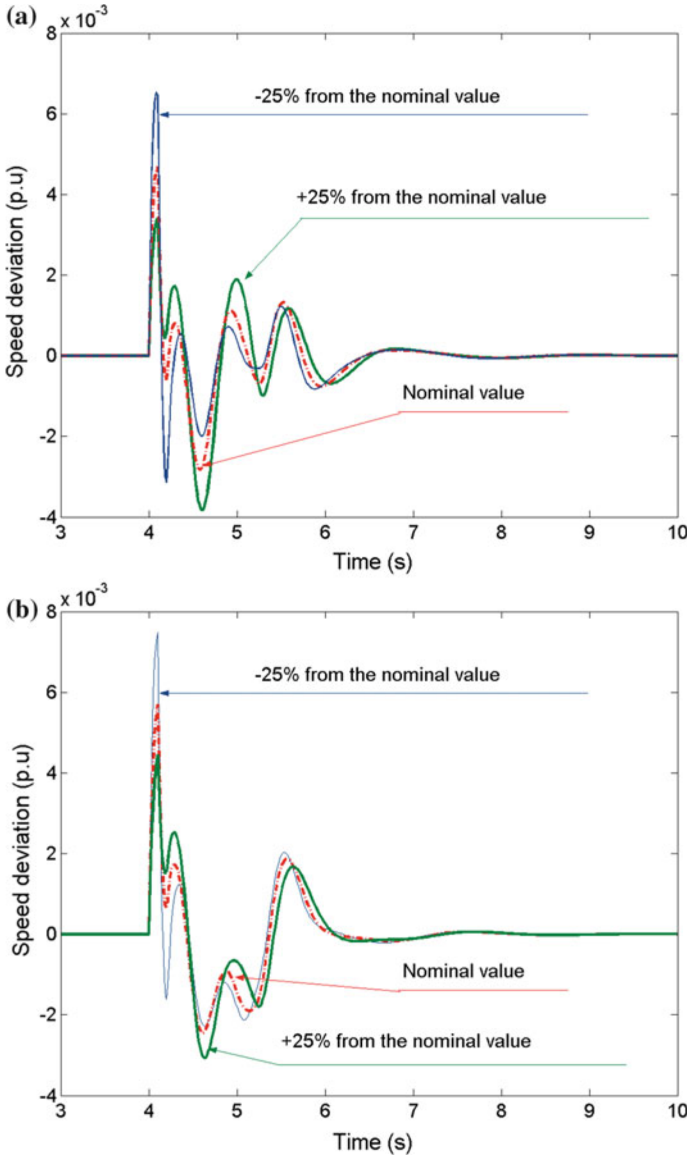

Fig. 10 Local mode of oscillation $\omega 1$-$\omega 2$ (**a**) and inter-area mode of oscillation $\omega 1$-$\omega 3$ (**b**) under parameter variations

the proposed scheme can still provide consistent control performance even if system parameters have changed and furthermore the controller is not sensitive to the model errors.

5 Conclusion

A nonlinear decentralized controller based on a new dynamic model of multimachine power systems is developed. In our solution a nonlinear nine order model for synchronous generator, driven by steam turbine and connected to EPS was used. This novel model, with time-varying parameters representing intermachine interactions, takes into account all interactions in EPS between the electrical and mechanical dynamics and load constraints. The only local information is required; therefore, the proposed control scheme can be implemented in a decentralized way.

The proposed nonlinear decentralized controllers, of terminal voltage and speed rotor, are constructed using adaptive backstepping design. The feedback system is globally asymptotically stable in the sense of Lyapunov method despite the nature of the contingencies.

The designed nonlinear controller is tested through simulation under the most important perturbations in the power systems: (a) load variation, (b) large fault (a 100 ms short circuit) and (c) generator parameter variations. Digital simulation results confirm that the developed decentralized control gains much priority over conventional controllers (AVR/PSS and speed governor) in damping oscillation, improving voltage regulation and enhancing transfer capability.

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