Adaptive Controller Design for a Synchronous Generator with Unknown Perturbation in Mechanical Power

Xiaohong Jiao, Yuanzhang Sun, and Tielong Shen

Abstract: Transient stabilization with voltage regulation is investigated for a synchronous generator when the mechanical power is perturbed to any unknown value within its physical bounds so that the operating point of the system shifts to an unknown point. An adaptive excitation controller is designed based on the backstepping method with tuning functions. It will be shown that the adaptive control law proposed can achieve the convergence of the system states to the new equilibrium point in correspondence with the real value of the unknown mechanical power and the regulation of the terminal voltage to the required value. Simulation results are given to demonstrate the effectiveness of the proposed controller for the transient stabilization and voltage regulation.

Keywords: Adaptive control, mechanical power, synchronous generator, transient stabilization, voltage regulation.

1. INTRODUCTION

Transient stability of power systems is a classical dynamic control systems problem. The application of nonlinear control methods to design the excitation control in order to enhance transient stability has been given much attention throughout various literatures since the late 1980s. Since the uncertainty in practical power systems, represented by sudden mechanical (load shedding and generation tripping) and electrical (short circuits with changes in the power network structure) perturbations, may destabilize the operating conditions, the research of robustness issues is more challenging and widely applicable. Therefore, the transient stabilization problem consists in the design of an excitation feedback control for the power systems that will keep the generator at synchronous speed and the terminal voltage at the prescribed value when perturbation occurs.

In the last decade, nonlinear control theory has been exploited to solve the transient stabilization problem. Feedback linearization based excitation schemes have been proposed by [1-3]. Adaptive versions of the feedback linearizing controls are then developed in [4,5]. Robust nonlinear state feedback controls have also been investigated in [6,7]. In [8,9], robust adaptive nonlinear excitation controls with L_2 disturbance attenuation are developed for power systems with additive disturbances and unknown electrical parameters. Very recently, the adaptive control problem has been addressed in [10] for power systems involving unknown mechanical power. When the mechanical power is perturbed to a new constant value, the equilibrium of the system will shift to a new corresponding point, moreover, the new point will be unknown if the mechanical power is unknown. In [10] an estimation function is introduced for the unknown mechanical power and the angular speed, and with the estimation, the trajectories for the angle, the angular speed and the active power are given such that the excitation control drives the states of the system to track the trajectories and the trajectories to converge to the equilibrium point.

In this paper, we consider the transient stabilization with voltage regulation problem for synchronous generators with unknown perturbation in the mechanical power. Motivated by [10], we also introduce an estimation function in the proposed state feedback excitation control law. However, we will show that with some tuning functions, such a feedback controller can be directly constructed so that the system is stabilized at the new equilibrium corresponding to the unknown mechanical power. The remaining portion of the paper is organized as follows The problem is formulated in Section 2. In Section 3, based on the adaptive back-stepping design technique

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an adaptive state feedback controller achieving the transient stabilization and voltage regulation is designed. Simulation results will be given in Section 4 to support the theoretical claims. Concluding remarks follow in the final Section.

2. PROBLEM FORMULATION

We consider the classical third order dynamic model of a synchronous generator connected to an infinity-bus, which is given as follows [11]:

$$\begin{cases} \dot{\delta} = \omega - \omega_s \\ \dot{\omega} = -\frac{D}{H}(\omega - \omega_s) + \frac{\omega_s}{H}\{P_m - P_e(t)\} \\ \dot{E}_q' = \frac{1}{T_{d0}}\left\{-\frac{X_{d\Sigma}}{X_{d\Sigma}'}E_q' + \frac{X_d - X_d'}{X_{d\Sigma}'}V_s\cos\delta + u_f\right\}, \end{cases} \tag{1}$$

where $P_e(t)$ is the active power, here

$$P_e(t) = \frac{V_s E_q'}{X_{d\Sigma}'}\sin\delta - \frac{V_s^2}{2}\frac{X_q - X_d'}{X_{q\Sigma}X_{d\Sigma}'}\sin 2\delta .$$

$\delta(t)$ denotes the rotor angle, $E_q'(t)$ is the q-axis transient potential, and V_s is the voltage at the infinite bus. $\omega(t)$ is the angular speed of the generator and ω_s is the synchronous rotating speed. P_m is the mechanical power. D is the damping constant, H is the inertia constant. $X_{d\Sigma} = X_d + X_T + X_L$ is the total reactance that takes into account X_d, the generator direct axis reactance, X_T, the reactance of the transformer and X_L, the transmission line reactance. $X_{d\Sigma}' = X_d' + X_T + X_L$ with X_d' denotes the generator direct axis transient reactance. $X_{q\Sigma} = X_q + X_T + X_L$ with X_q denotes the generator q-axis transient reactance. T_{d0} is time constant of the field winding. u_f is the control input of the SCR amplifier of the generator.

Suppose that the mechanical power P_m is constant. Then, it is well known that for given nominal values of the angle δ_s, the angular speed ω_s and the transient potential E_{qs}', if we set the excitation control u_f as

$$u_f = \frac{X_{d\Sigma}}{X_{d\Sigma}'}E_{qs}' - \frac{X_d - X_d'}{X_{d\Sigma}'}V_s\cos\delta_s .$$

δ_s and E_{qs}' should satisfy

$$\frac{V_s E_{qs}'}{X_{d\Sigma}'}\sin\delta_s - \frac{V_s^2}{2}\frac{X_q - X_d'}{X_{q\Sigma}X_{d\Sigma}'}\sin 2\delta_s = P_{es} = P_m .$$

Then the closed loop system is asymptotically stable at the point of equilibrium

$$\delta = \delta_s, \quad \omega = \omega_s, \quad E_q' = E_{qs}', \tag{2}$$

where $\delta_s \in (0, \frac{\pi}{2})$. Correspondingly, the generator terminal voltage will be regulated at V_{tr}, which is determined by the following well known relation [11]

$$V_t = \left[\frac{X_s^2 P_e^2}{V_s^2\sin^2\delta} + \frac{X_d^2 V_s^2}{X_{d\Sigma}^2} + \frac{2X_s X_d}{X_{d\Sigma}}P_e\cot\delta\right]^{\frac{1}{2}} \tag{3}$$

with the stable equilibrium and $X_s = X_T + X_L$.

However, for system (1) there exists another unstable equilibrium $(\delta_u, \omega_s, E_{qs}')$ with $\sin\delta_u = \sin\delta_s$, which may be close to the stable one. This fact signifies that the stable equilibrium may have a very small stability region so that a disturbance, for instance the perturbation in the mechanical power P_m, may drive the generator to be unstable or prompt loss of synchronousness and inability to achieve voltage regulation. Therefore, under unknown mechanical power, the design problem of the adaptive controller, which stabilizes the generator at an appropriate equilibrium corresponding to the mechanical power and guarantees terminal voltage to be regulated to its prescribed value V_{tr}, is an important issue in the power system.

The design problem considered in this paper is as follows. Suppose the mechanical power P_m is an unknown constant, and let the corresponding unknown equilibrium be $(\delta_s, \omega_s, E_{qs}')$. Find an adaptive state feedback controller of the form

$$\begin{cases} u = \alpha(\delta, \omega, E_q', \hat{P}_m) \\ \dot{\hat{P}}_m = \beta(\delta, \omega, E_q', \hat{P}_m) \end{cases} \tag{4}$$

such that the resulting closed-loop system is stable at the unknown equilibrium and $\delta \to \delta_s$, $\omega \to \omega_s$, $E_q' \to E_{qs}'$ as $t \to \infty$, where $\hat{P}_m$ is the estimate of P_m. Furthermore, the terminal voltage V_t is regulated to the prescribed value V_{tr}.

3. CONTROLLER DESIGN

For the sake of simplicity, we define the state variable by $x_1 = \delta$, $x_2 = \omega - \omega_s$, $x_3 = E_q'$, the control law $u = u_f$ and the unknown equilibrium $(\delta_s, 0, E'_{qs}) = (x_{1e}, 0, x_{3e}) = x_e$, then the dynamics of the system can be represented by the following state space model:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -a_1 x_2 + a_2 P_m - a_3 x_3 \sin x_1 + a_4 \sin 2x_1 \\ \dot{x}_3 = -c_1 x_3 + c_2 \cos x_1 + c_3 u, \end{cases} \tag{5}$$

where the parameters are defined by

$$a_1 = \frac{D}{H},\ a_2 = \frac{\omega_s}{H},\ a_3 = \frac{\omega_s V_s}{H X'_{d\Sigma}},\ a_4 = \frac{\omega_s V_s^2}{2H} \frac{X_q - X'_d}{X_{q\Sigma} X'_{d\Sigma}},$$

$$c_1 = \frac{1}{T_{d0}} \frac{X_{d\Sigma}}{X'_{d\Sigma}},\ c_2 = \frac{1}{T_{d0}} \frac{X_d - X'_d}{X'_{d\Sigma}} V_s,\ c_3 = \frac{1}{T_{d0}}.$$

In the following, we will seek a solution to the design problem by recursively constructing a Lyapunov function.

In order to achieve the voltage regulation performance, δ_s with the real value of the mechanical power P_m, and the set point V_{tr} must satisfy (3), i.e.

$$x_{1e} = arc\cot\left(\frac{b_1}{P_m}\left(-b_2 + \sqrt{V_{tr}^2 - \frac{P_m^2}{b_1^2}}\right)\right), \tag{6}$$

where $b_1 = \frac{V_s}{X_s}$ and $b_2 = \frac{X_d V_s}{X_{d\Sigma}}$.

Motivated by this equation, we can use the following estimation for the equilibrium point δ_s corresponding the estimate $\hat{P}_m$:

$$\hat{x}_{1e} = arc\cot\left(\frac{b_1}{\hat{P}_m}\left(-b_2 + \sqrt{V_{tr}^2 - \frac{\hat{P}_m^2}{b_1^2}}\right)\right). \tag{7}$$

Clearly, $\hat{x}_{1e} \to x_{1e}$ when $\hat{P}_m \to P_m$.

We start the recursive design process with this estimation. First, we define a positive definite function

$$W_1(x_1) = \frac{1}{2}\tilde{x}_1^2 \tag{8}$$

with $\tilde{x}_1 = x_1 - \hat{x}_{1e}$. The time derivative of W_1 along the trajectory of subsystem x_1 is obtained

$$\dot{W}_1(x_1) = \tilde{x}_1 x_2 - \tilde{x}_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m} \dot{\hat{P}}_m. \tag{9}$$

Define $\tilde{x}_2 = x_2 - \alpha_1(\tilde{x}_1)$ and choose the virtual control law $\alpha_1(\tilde{x}_1)$ as

$$\alpha_1(\tilde{x}_1) = -(x_1 - \hat{x}_{1e}) \tag{10}$$

then, we obtain the following equality

$$\dot{W}_1(x_1) = -\tilde{x}_1^2 + \tilde{x}_1\tilde{x}_2 - \tilde{x}_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m} \dot{\hat{P}}_m. \tag{11}$$

Let $z_3 := a_3 x_3 \sin x_1 - a_4 \sin 2x_1$ and consider the subsystem (x_1, x_2)

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -a_1 x_2 + a_2 P_m - z_3. \end{cases} \tag{12}$$

From here, we construct a positive definite function

$$W_2(\tilde{x}_1, \tilde{x}_2) = W_1(\tilde{x}_1) + \frac{1}{2}\tilde{x}_2^2. \tag{13}$$

Then, we can obtain the time derivative of W_2 as:

$$\dot{W}_2 = \tilde{x}_2\left\{-a_1 x_2 + a_2 P_m - z_3 + \tilde{x}_1 - \frac{\partial \alpha_1}{\partial x_1} x_2\right\}$$
$$-\tilde{x}_1^2 - \tilde{x}_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m - \tilde{x}_2 \frac{\partial \alpha_1}{\partial \hat{x}_{1e}} \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m. \tag{14}$$

Define $\tilde{z}_3 = z_3 - \alpha_2(\tilde{x}_1, x_2, \hat{P}_m)$ and choose the virtualcontrol law $\alpha_2(\cdot)$ as

$$\alpha_2 = -a_1 x_2 + \tilde{x}_1 - \frac{\partial \alpha_1}{\partial x_1} x_2 + \tilde{x}_2 + a_2 \hat{P}_m - v_1,$$

where $v_1(\tilde{x}_1, x_2, \hat{P}_m)$ is a smooth function determinedlater, so that the time derivative of W_2 satisfies

$$\dot{W}_2 = -\tilde{x}_1^2 - \tilde{x}_2^2 - \tilde{x}_2\tilde{z}_3 + \tilde{x}_2 a_2(P_m - \hat{P}_m)$$
$$+\tilde{x}_2\left(v_1 - \frac{\partial \alpha_1}{\partial \hat{x}_{1e}} \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m\right) - \tilde{x}_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m. \tag{16}$$

For the whole system constructing the positive definite function

$$W_3(\tilde{x}_1, \tilde{x}_2, \tilde{z}_3) = W_2(\tilde{x}_1, \tilde{x}_2) + \frac{1}{2}\tilde{z}_3^2, \tag{17}$$

we have the time derivative of W_3 along the trajectories of (5)

$$\dot{W}_3 = \tilde{z}_3\{-\tilde{x}_2 + a_3(-c_1 x_3 + c_2 \cos x_1 + c_3 u)\sin x_1\}$$
$$+\tilde{z}_3\left\{a_3 x_3 x_2 \cos x_1 - 2a_4 x_2 \cos 2x_1 - \frac{\partial \alpha_2}{\partial x_1} x_2\right\}$$
$$-\tilde{z}_3 \frac{\partial \alpha_2}{\partial x_2}(-a_1 x_2 + a_2 P_m - a_3 x_3 \sin x_1 + a_4 \sin 2x_1)$$

$$-\tilde{z}_3\frac{\partial\alpha_2}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m-\tilde{z}_3\frac{\partial\alpha_2}{\partial\hat{P}_m}\dot{\hat{P}}_m+\tilde{x}_2a_2(P_m-\hat{P}_m) \quad (18)$$
$$+\tilde{x}_2\left(v_1-\frac{\partial\alpha_1}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m\right)-\tilde{x}_1\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m-\tilde{x}_1^2-\tilde{x}_2^2.$$

The control law chosen as

$$u=\frac{1}{a_3c_3\sin x_1}\{\tilde{x}_2-a_3x_3x_2\cos x_1+2a_4x_2\cos 2x_1$$
$$+\frac{\partial\alpha_2}{\partial x_2}(-a_1x_2+a_2\hat{P}_m-a_3x_3\sin x_1+a_4\sin 2x_1) \quad (19)$$
$$+\frac{\partial\alpha_2}{\partial x_1}x_2+v_2-\tilde{z}_3\}+\frac{1}{c_3}(c_1x_3-c_2\cos x_1),$$

where $v_2(\tilde{x}_1,x_2,x_3,\hat{P}_m)$ is a smooth function determined later, renders

$$\dot{W}_3=-\tilde{x}_1^2-\tilde{x}_2^2-\tilde{z}_3^2+\tilde{x}_2\left(v_1-\frac{\partial\alpha_1}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m\right)-\tilde{x}_1\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m$$
$$-\tilde{z}_3\left\{v_2-\frac{\partial\alpha_2}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m-\frac{\partial\alpha_2}{\partial\hat{P}_m}\dot{\hat{P}}_m\right\} \quad (20)$$
$$+\left(\tilde{x}_2-\tilde{z}_3\frac{\partial\alpha_2}{\partial x_2}\right)a_2(P_m-\hat{P}_m).$$

Furthermore, we choose a positive definite function

$$V(\tilde{x}_1,\tilde{x}_2,\tilde{z}_3,\hat{P}_m)=W_3(\tilde{x}_1,\tilde{x}_2,\tilde{z}_3)+\frac{r}{2}\tilde{P}_m^2, \quad (21)$$

where $\tilde{P}_m=P_m-\hat{P}_m$, and r is a given positive constant. Then, we calculate the time derivative of V as follows:

$$\dot{V}=-\tilde{x}_1^2-\tilde{x}_2^2-\tilde{z}_3^2-\tilde{x}_1\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m+\tilde{x}_2\left(v_1-\frac{\partial\alpha_1}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m\right)$$
$$-\tilde{z}_3\left\{v_2-\frac{\partial\alpha_2}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\dot{\hat{P}}_m-\frac{\partial\alpha_2}{\partial\hat{P}_m}\dot{\hat{P}}_m\right\} \quad (22)$$
$$+\tilde{P}_m\left\{\tilde{x}_2a_2-\tilde{z}_3\frac{\partial\alpha_2}{\partial x_2}a_2-r\dot{\hat{P}}_m\right\}.$$

Let

$$\dot{\hat{P}}_m=\frac{1}{r}\left\{\tilde{x}_2a_2-\tilde{z}_3\frac{\partial\alpha_2}{\partial x_2}a_2\right\}, \quad (23)$$

$$v_1=\frac{1}{r}a_2\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\tilde{x}_1+\frac{1}{r}a_2\frac{\partial\alpha_1}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\tilde{x}_2, \quad (24)$$

$$v_2=\frac{1}{r}\left\{\frac{\partial\alpha_2}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}+\frac{\partial\alpha_2}{\partial\hat{P}_m}\right\}\left\{\tilde{x}_2a_2-\tilde{z}_3\frac{\partial\alpha_2}{\partial x_2}a_2\right\}$$
$$-\frac{1}{r}\frac{\partial\alpha_1}{\partial\hat{x}_{1e}}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\frac{\partial\alpha_2}{\partial x_2}a_2\tilde{x}_2-\frac{1}{r}\frac{\partial\hat{x}_{1e}}{\partial\hat{P}_m}\frac{\partial\alpha_2}{\partial x_2}a_2\tilde{x}_1, \quad (25)$$

we obtain the following equality

$$\dot{V}=-\tilde{x}_1^2-\tilde{x}_2^2-\tilde{z}_3^2. \quad (26)$$

With this equality, we can reach the following conclusion:

Proposition 1: For system (5), if the state feedback controller is chosen as (19) and the parameter adaptation law as (23)~(25), then for any constant mechanical power P_m that guarantees the existence of the operating point $x_e(x_{1e}<\frac{\pi}{2})$, the closed loop system is locally Lyapunov stable at the point of equilibrium, and $\hat{P}_m\to P_m$, $x_1\to x_{1e}$, $x_2\to 0$, $x_3\to x_{3e}$, $V_t\to V_{tr}$, as $t\to\infty$.

Proof: For the closed loop system coordinated by $(\tilde{x}_1,\tilde{x}_2,\tilde{z}_3,\hat{P}_m)$, the Lyapunov function V that satisfies the equality (26) ensures stability at the origin. Furthermore, with the equality, we can conclude from Barbalat's Lemma that $\tilde{x}_1\to 0$, $\tilde{x}_2\to 0$ and $\tilde{z}_3\to 0$ as $t\to\infty$, i.e. $x_1\to x_{1e}$, $x_2\to 0$ and $z_3=a_3x_3\sin x_1-a_4\sin 2x_1\to\alpha_2(0,0,\hat{P}_m)$ as $t\to\infty$.

To complete the proof, we will show that $(\hat{x}_{1e},0,\hat{x}_{3e},\hat{P}_m)$ will converge to the unknown equilibrium $(x_{1e},0,x_{3e},P_m)$. Since $x_2=\tilde{x}_2+\alpha_1(\tilde{x}_1)=0$ at the origin $\tilde{x}_1=0$, $\tilde{x}_2=0$, we obtain from the defini-tion of $\tilde{z}_3$ that $z_3\to\alpha_2(0,0,\hat{P}_m)$. Note that the tuning function $v_1(0,0,\hat{P}_m)=0$. Therefore, we have from (15) that

$$z_3=a_3x_3\sin x_1-a_4\sin 2x_1$$
$$\to a_3\hat{x}_{3e}\sin\hat{x}_{1e}-a_4\sin 2\hat{x}_{1e}\to a_2\hat{P}_m.$$

Alternatively, from the second equation of the dynamics of the generator,

$$0=a_2P_m-a_3\hat{x}_{3e}\sin\hat{x}_{1e}+a_4\sin 2\hat{x}_{1e}.$$

This means $\hat{P}_m\to P_m$, as $t\to\infty$. Consequently, $x_1\to x_{1e}$, $x_3\to x_{3e}$, as $t\to\infty$. Furthermore, from (6), it follows $V_t\to V_{tr}$. □

Remark 1: It should be noted that in both [10] and this paper, the convergence to the new equilibrium point corresponding the real value of the unknown mechanical power is achieved by introducing the estimation function. However, in [10] the estimations for both the mechanical power and the angular speed are required to construct the trajectories tracked by the states of the system. In this paper, the mechanical power is estimated to design the adaptive stabilizing controller with the help of the tuning functions allowing the design algorithm to be simple. Moreover, the proof of the result is given by analyzing directly the physical character of the system.

4. SIMULATION

The physical parameters of the power system employed for the simulation are given as follows:

$\omega_s = 1p.u.$, $D = 0.1p.u.$, $H = 7s$, $V_s = 0.995p.u.$, $T_{d0} = 8s$,

$X_d = 1.8p.u.$, $X_d^{'} = 0.3p.u.$, $X_q = 1.76p.u.$,

$X_T = 0.15p.u.$, $X_L = 0.3252p.u.$

and X_s, $X_{d\Sigma}$, $X_{d\Sigma}^{'}$, $X_{q\Sigma}$ can be calculated as

$X_s = X_T + X_L = 0.4752$, $X_{d\Sigma} = X_d + X_s = 2.2852$,

$X_{d\Sigma}^{'} = X_d^{'} + X_s = 0.7752$, $X_{q\Sigma} = X_q + X_s = 2.2352$.

Moreover, according to the definition in Section 3, the values of the parameters in model (5) are obtained as follows:

$a_1 = 0.0143$, $a_2 = 0.1429$, $a_3 = 0.1834$, $a_4 = 0.0596$,

$c_1 = 0.3685$, $c_2 = 0.2423$, $c_3 = 0.1250$

and when the mechanical power $P_m = 0.9$ and the excitation control input signal is a constant $u_{fs} = 2.2097$, the system has a stable equilibrium at $x_e = (1.1999, 0, 0.9879)$ and the terminal voltage of the generator V_t is prescribed as $V_{tr} = 1.0475$.

Now, we consider the following two cases in which there exists the unknown perturbation in the mechanical power:

(a) Unknown disturbance occurs to the mechanical power when the synchronous generator is operating at stable equilibrium, and after several occurrences the mechanical power is recovered, i.e.

$$P_m = \begin{cases} 0.9 & 0 \le t < 4.0[\text{sec}] \\ 0.9 + \Delta P_m & 4.0 \le t \le 5.2[\text{sec}] \\ 0.9 & 5.2 < t \end{cases}$$

(b) Sudden turbine failure happens and the fault is not recovered so that the mechanical power abruptly changes to an unknown value, i.e.

$$P_m = \begin{cases} 0.9 & 0 \le t < 4.0[\text{sec}] \\ 0.9 + \Delta P_m & 4.0 \le t \end{cases}$$

The adaptive controller is designed as shown in (19) and (23)~(25) for the transient stabilization with voltage regulation of the generator.

We first give the simulation research for case (a). When the system (5) is not forced by any feedback excitation control law but only the constant u_{fs}, the response of the system under case (a) (in simulation $\Delta P_m = 0.3$) is shown in Fig. 1. It can be seen that the equilibrium can be recovered and the terminal voltage can be regulated to the prescribed value, however, the recovering time is 56s. When the system is forced by the proposed adaptive control law (19) with (23)~(25), the response of the closed loop system is presented in Fig. 2, where the control parameter r is chosen as $r = 0.15$. It follows from the results of Fig. 2 that the adaptive controller guarantees the system to recover quickly the operating equilibrium and the prescribed value of the terminal voltage (the recovering time is 15s).

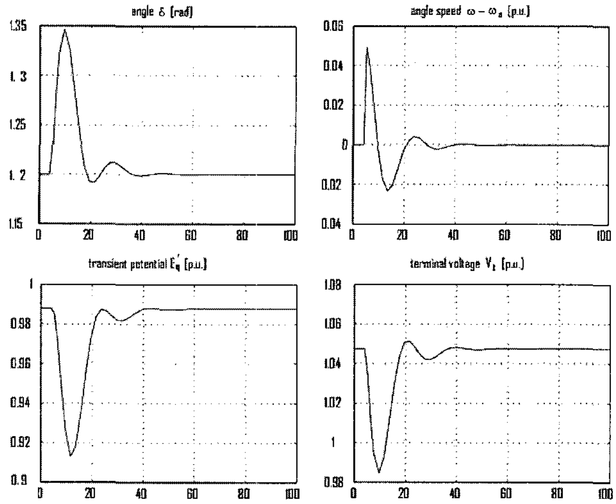

Fig. 1. The response of the system without feedback control under case (a).

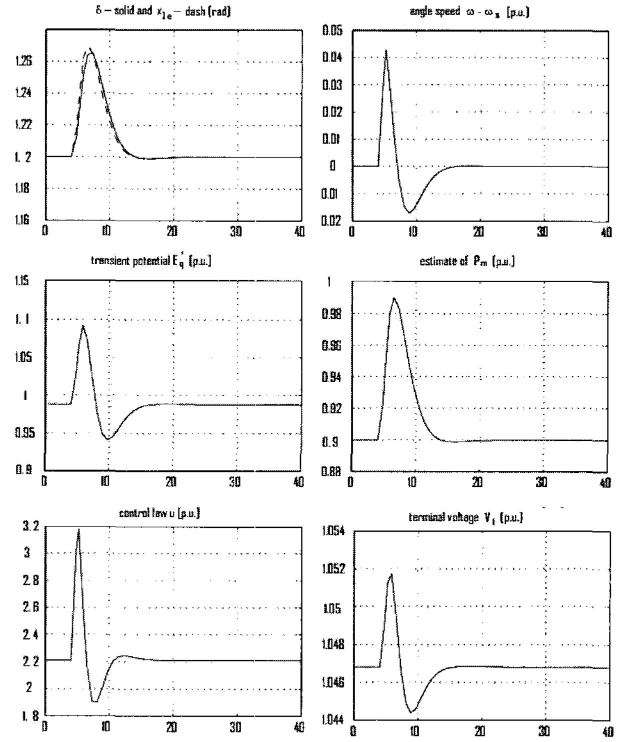

Fig. 2. The response of the system with feedback control under case (a).

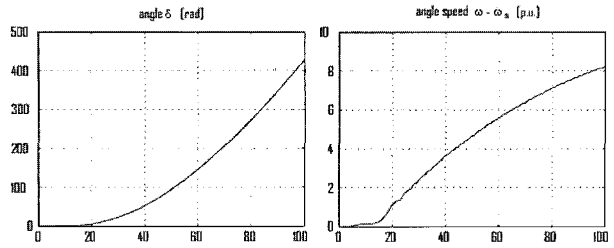

Fig. 3. The response of the system without feedback control under case (b).

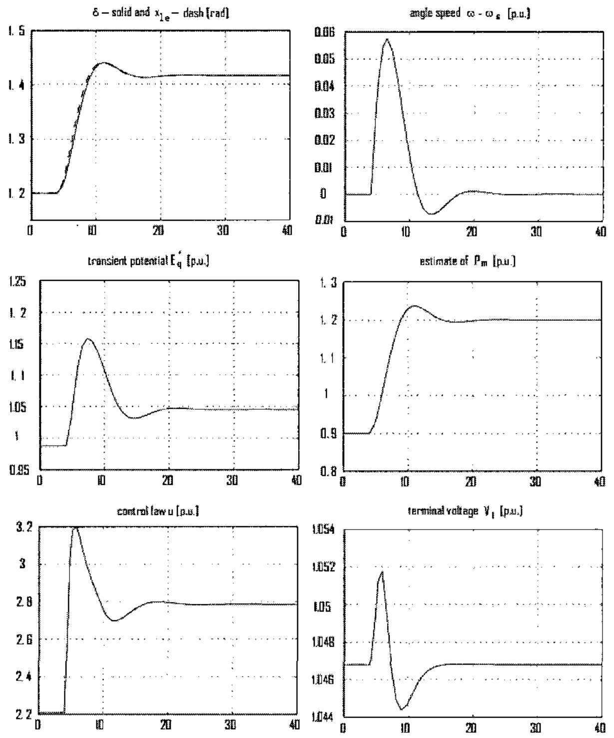

Fig. 4. The response of the system with feedback control under case (b).

Now, we consider case (b), i.e. the mechanical power is varied from the normal value 0.9 to some unknown constant (in the simulation it is chosen as 1.2). The response of system (5) with the constant input u_{fs} is shown in Fig. 4. It is seen that the system is unstable. However, from the simulation result given by Fig. 4, it is indicated that the proposed adaptive control law can render the closed loop system to converge quickly to a new equilibrium point corresponding the real value of the unknown mechanical power and the terminal voltage can be regulated to the prescribed value quickly.

5. CONCLUSIONS

In this paper, we investigated the transient stabilization with the voltage regulation for the synchronous generator when the mechanical power is perturbed to an unknown constant value so that the operating point of the system is also unknown. We designed a nonlinear adaptive excitation controller by way of backstepping method with tuning functions. It was shown that the presented excitation controller can drive the system to a stable equilibrium corresponding to the real value of the unknown mechanical power, and simultaneously achieve good regulation of the generator terminal voltage.

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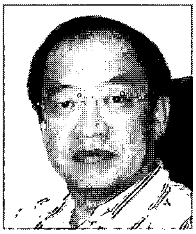

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