ADAPTIVE CONTROL DESIGN FOR A SYNCHRONOUS GENERATOR

SAEED ABAZARI , MOHSEN HEIDARI, NAVID REZA ABJADI

Key words: Adaptive control, Lyapunov stability, Transient stability, Mechanical power.

The operating point of a power system changes to an unknown point with an unknown change in the mechanical input power. In this paper, a nonlinear adaptive controller is designed for excitation system of the generator based on the backstepping control technique, in order to achieve transient stability enhancement, in the presence of uncertainties in mechanical power. The designed controller guarantees the convergence of system states to new desired values corresponding to unknown mechanical power. A power system consisting of a synchronous generator connected to an infinite bus through a double circuit transmission line is used in control design and the simulation studies. Computer simulation verifies the effectiveness and the validity of the proposed control, considering faulted system with a clearance and change in network topology.

1. INTRODUCTION

There are various stability problems in power systems due to small and large disturbances. Among them, transient stability is a very important matter. For transient stability analysis and control design, the power system must be described by nonlinear differential equations [1, 2].

To maintain a high degree of reliability, the effect of disturbances such as 3-phase fault and mechanical power sudden change should be considered. Large disturbances on the transmission system cause difficulties in active power transmission especially during electrical fault. This leads to an acceleration of the rotors of the synchronous generators, due to unequal mechanical and electrical torques acting on the shafts. Rapid detection of the fault and fast acting circuit breakers are normally used to isolate the faulted sections of the transmission system. In addition to the rapid isolation of faulted sections of the transmission equipment, it is generally recognized that the auxiliary control action would be necessary to enhance the post fault region to assure the stability of a power system. The first power system stabilizers used in power systems operate with linear methods. Linear power system stabilizers (PSS) [3] are often used to provide supplementary damping through excitation control to improve the dynamic stability limits. An approximate linearized model, as a design model, and a linear controller are used for a specific operating point. Therefore, the usual stabilizer design based on approximate linearization models is not adequate for large

Sahrekord University, Faculty of Engineering, Shahrekord, Iran, E-mail: saeedabazari@yahoo.com, mh309.63@gmail.com, navidabjadi@yahoo.com

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disturbances. In other words, with large disturbances the operating point of power system changes and the linear designed controller may be failed.

The application of nonlinear control in this field has been discussed in research papers since 1980. Since there are always uncertainties in power system due sudden changes in input mechanical power and electrical faults, the overall system may become even unstable. To retain stability and to achieve good performance and generator synchronization, sophisticated control methods are needed. In recent two decades, nonlinear control theory has been applied to many practical control problems. In [4, 5], feedback linearization technique is employed for excitation system. By using direct feedback linearization (DFL) technique, an excitation controller and coordinated controller are proposed in [6] to achieve both transient stability enhancement and voltage regulation of a power system. However, the DFL method cannot work when there are uncertainties in power system. In [7, 8], adaptive feedback control is used for the same problem. In [9,10], robust nonlinear control and energy shaping approach are used for power system control; however, when a fault occurs at one-tenth of the transmission line from the generator terminal, the system using an adaptive controller, based on these research works, can no longer maintain transient stability. In [11, 12], a nonlinear adaptive controller is designed for power system with unknown mechanical power, but the speed of states convergence to equilibrium point is low. One of the nonlinear control methods which may guarantee global stability is backstepping approach [13–16]. In [13], an adaptive backstepping control is designed for a single machine with an infinite bus without considering any change in network topology. The estimation and control of [13] are complicated and the convergence may be failed. In [14], adaptive backstepping is used in a motor drive system. An adaptive backstepping control is designed for a power system with unified power flow controller (UPFC). In [16], an adaptive backstepping control is designed for a power system with a single machine. The present paper modifies the control method of [16]. The obtained control law results fast response compared to [16]. The obtained results show the proposed control retains the stability of the overall system even with changing the power system topology. Transient stability with voltage regulation of synchronous generator under an unknown input mechanical power is considered. An adaptive controller is designed for excitation system with an estimation function for input power. Using the proposed controller, the operating point of the system is shifted to new equilibrium point and the system will be stable. The organization of the paper is as follow: in section 2, the power

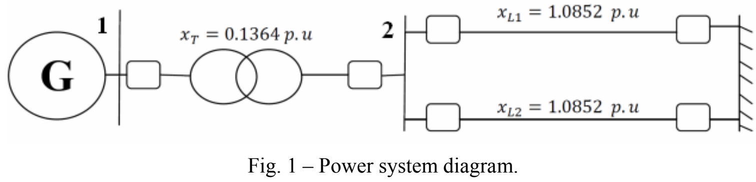


Fig. 1 – Power system diagram.

system model and control problem are presented; in section 3, an adaptive backstepping nonlinear controller is designed for the system and the simulation results are illustrated in section 4 including the comparison of the proposed controller to conventional power system stabilizer (PSS).

2. MODELING AND CONTROL PROBLEM

The power system under study is shown in Fig. 1. The parameters of the system are given in Appendix. To simplify the process of controller design, a third order model in considered for synchronous machine, but in system simulation, the synchronous machine is modeled with a more accurate model close to the physical real machine. The state equations of the system for controller design are as follow:

$$\dot{\delta} = \omega_r - \omega_0$$

$$\dot{\omega}_r = \frac{\omega_0}{2H}(P_m - P_e) - \frac{D}{2H}(\omega_r - \omega_0) \tag{1}$$

$$\dot{E}_q = \frac{x_q - x'_d}{x_{ed}} V_s \sin\delta(\omega_r - \omega_0) - \frac{x_{ed}}{x_{ed}'\tau'_{do}} E_q + \frac{x_d - x_q}{x_{ed}'\tau'_{do}} V_s \cos\delta + \frac{x_{eq}}{x_{ed}'\tau'_{do}} U_f(t),$$

where δ is the power angle of generator, ω_r is the rotor speed of the generator, ω_0 is the synchronous speed, P_m is the mechanical power, P_e is the electrical power, E_q is the q-axis potential, x_q is the q-axis reactance, x_d is the d-axis reactance, x'_d is the d-axis transient reactance, x_{eq} is the q-axis total reactance, x_{ed} is the d-axis total reactance, x'_{ed} is the d-axis total transient reactance, x_T is the transformer reactance, x_L is the transmission reactance, V_s is the infinite bus voltage, V_t is the terminal voltage and V_{tr} is the prescribed value of the terminal voltage, $P_e = \frac{V_s.E_q}{x_{eq}}\sin\delta$, $x_{ed}' = x'_d + x_T + x_L$, $x_{eq} = x_q + x_T + x_L$, $x_{ed} = x_d + x_T + x_L$,

$$x_s = x_T + x_L \ .$$

The operating point of the system is determined as $\delta_0 = \operatorname{arccot}\left(\frac{b_1}{P_m}\left(-b_2 + \sqrt{V_{tr}^2 - \frac{P_m^2}{b_1^2}}\right)\right)$ with: $b_1 = \frac{V_s}{x_s}$, $b_2 = \frac{x_q V_s}{x_{eq}}$,

$$\frac{V_s E_{q0}}{x_{eq}} \sin\delta_0 = P_e = P_m \ \rightarrow \ E_{q0} = \frac{P_m x_{eq}}{V_s \sin\delta_0} \ . \tag{2}$$

First, assuming the mechanical power in each instant and during each disturbance occurrence is measurable. One can see that from (1)–(3), after a known disturbance, the new operating point $(\delta_0 , 1 , E_{q0})$ is obtained. The following excitation control can stabilize the system.

$$U_f(t) = \frac{x_{ed}'\tau'_{d0}}{x_{eq}}[-\frac{x_q - x'_d}{x_{ed}} V_s \sin\delta(\omega_r - \omega_0) + \frac{x_{ed}}{x_{ed}'\tau'_{d0}} E_{q0} - \frac{x_d - x_q}{x_{ed}'\tau'_{d0}} V_s \cos\delta]. \tag{3}$$

When a disturbance occurs in the system and the states depart from the operating point, this controller returns them to the operating point. The following equation gives the terminal voltage

$$V_t = \left(\frac{x_s^2 P_e^2}{V_s^2 \sin\delta^2} + \frac{x_s^2 V_s^2}{x_{eq}^2} + \frac{2 x_s x_q}{x_{eq}} P_e \cot\delta \right)^{\frac{1}{2}}. \tag{4}$$

If the input mechanical power is not known or it is changed to an unknown value due a disturbance in turbine, the new operating point $(\delta_0 , 1 , E_{q0})$ can not be determined. In the following an adaptive excitation control is designed.

The control law and estimation law are considered as follows

$$U_f = F\left(\delta, \omega_r, E_q, \hat{P}_m\right), \quad \dot{\hat{P}}_m = Y\left(\delta, \omega_r, E_q, \hat{P}_m\right), \tag{5}$$

where $\hat{P}_m$ is an estimation of P_m and the main aim of control design is the following convergences: $\delta \to \delta_0$, $\omega_r \to \omega_0$, $E_q \to E_{q0}$. According to (2), E_q is the same as electrical power of generator which is sent to power network.

3. ADAPTIVE CONTROLLER DESIGN

In this section, adaptive backstepping control theory is employed to achieve the mentioned control aims.

To achieve the desired terminal voltage, δ_0 and P_m should satisfy the following relation

$$\delta_0 = \operatorname{arccot}\left(\frac{b_1}{P_m} \left(-b_2 + \sqrt{V_{tr}^2 - \frac{P_m^2}{b_1^2}} \right) \right). \tag{6}$$

Based on the above equation, an estimation of δ_0, E_{q0} corresponding to mechanical power is obtained as follow

$$\hat{\delta}_0 = \operatorname{arccot}\left(\frac{b_1}{\hat{P}_m}\left(-b_2 + \sqrt{V_{tr}^2 - \frac{\hat{P}_m^2}{b_1^2}}\right)\right), \tag{7}$$

$$\hat{E}_{q0} = \frac{\hat{P}_m x_{eq}}{V_s \sin\hat{\delta}_0}. \tag{8}$$

It is evident that if $\hat{P}_m \to P_m$ then $\hat{\delta}_0 \to \delta_0$ and $\hat{E}_{q0} \to E_{q0}$; to simplify the control design, the following new states and notations are introduced

$$\begin{aligned}&(\hat{\delta}_0, 1, \hat{E}_{q0}) = (\hat{x}_{1e}, 1, \hat{x}_{3e}),\\ &x_1 = \delta_0 - x_{1e}\ ,\ x_2 = \omega_r - \omega_0\ ,\ x_3 = E_q - \hat{x}_{3e}\end{aligned}. \tag{9}$$

The system dynamic is given by

$$\begin{aligned}\dot{x}_1 &= x_2 - \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m,\\ \dot{x}_2 &= aP_m + f_2 + g_2 x_3\\ \dot{x}_3 &= f_3 + g_3.U_f(t),\end{aligned} \tag{10}$$

where $f_2 = -\beta x_2 - J\hat{x}_{3e}\sin(\hat{x}_{1e} + x_1)$, $g_2 = -J\sin(\hat{x}_{1e} + x_1)$, $g_3 = L$,

$$f_3 = -\frac{\partial \hat{x}_{3e}}{\partial \hat{P}_m}\dot{\hat{P}}_m + KV_s\sin(\hat{x}_{1e} + x_1)\ x_2 - M(\hat{x}_{3e} + x_3) + NV_s\cos(\hat{x}_{1e} + x_1),$$

$$a = \frac{\omega_0}{2H}\ ,\ \beta = \frac{D}{2H}\ ,\ J = \frac{\omega_0}{2H}\frac{V_s}{x_{eq}}\ ,\ K = \frac{x_q - x'_d}{x_{ed}},$$

$$M = \frac{x_{ed}}{x_{ed}'.\tau'_{d0}}\ ,\ N = \frac{x_d - x_q}{x_{ed}'.\tau'_{d0}}\ ,\ L = \frac{x_{eq}}{x_{ed}'.\tau'_{d0}}.$$

Now, based on state equations (10), the excitation control is designed in such a way that the derivative of a positive definite Lyapunov function around equilibrium point becomes negative definite. This condition should be satisfied for $x_{1e} < \frac{\pi}{2}$ to achieve local asymptotically stability. Here, backstepping control theory is used. Consider the following primary Lyapunov function

$$V_1(x) = \frac{1}{2}x_1^2. \tag{11}$$

Differentiating it, one can obtain

$$\dot{V}_1 = x_1 \dot{x}_1 = x_1 \left(x_2 - \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m} \dot{\hat{P}}_m \right). \tag{12}$$

Adding and subtracting virtual input x_{2_0} in the bracket,

$$\dot{V}_1 = x_1 (x_2 - x_{2_0} + x_{2_0} - \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m} \dot{\hat{P}}_m). \tag{13}$$

If the virtual input x_{2_0} is considered as $x_{2_0} = k_1 x_1$ $(k_1 > 0)$, then

$$\dot{V}_1 = -k_1 x_1^2 + x_1 (x_2 - x_{2_0}) - x_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m} \dot{\hat{P}}_m. \tag{14}$$

Now, consider the following extended Lyapunov function

$$V_2 = V_1 + \frac{1}{2}(x_2 - x_{2_0})^2. \tag{15}$$

Again with differentiating

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + (x_2 - x_{2_0})(\dot{x}_2 - \dot{x}_{2_0}) = \\ &= -k_1 x_1^2 + (x_2 - x_{2_0})(x_1 + aP_m + f_2 + g_2 x_3 - \dot{x}_{2_0}) - x_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m} \dot{\hat{P}}_m. \end{aligned} \tag{16}$$

Suppose there is another virtual input notated with x_{3_0}; if x_{3_0} is designed as

$$x_{3_0} = -\frac{1}{g_2}(k_2 (x_2 - x_{2_0}) + x_1 + f_2 + v_1), \tag{17}$$

where $k_2 > 0$ and v_1 is determined later, then

$$\begin{aligned} \dot{V}_2 &= -k_1 x_1^2 - k_2 (x_2 - x_{2_0})^2 + (x_2 - x_{2_0}) g_2 (x_3 - x_{3_0}) + \\ &+ (x_2 - x_{2_0})(aP_m - \dot{x}_{2_0} - v_1) - x_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m} \dot{\hat{P}}_m. \end{aligned} \tag{18}$$

The overall system Lyapunov function is considered as follow

$$V_3 = V_2 + \frac{1}{2}(x_3 - x_{3_0})^2. \tag{19}$$

Differentiating V_3, one can obtain

$$\begin{aligned}\dot{V}_3 &= \dot{V}_2 + (x_3 - x_{3_0})(\dot{x}_3 - \dot{x}_{3_0}) = \\ &= -k_1 x_1^2 - k_2(x_2 - x_{2_0})^2 + (x_3 - x_{3_0})\Big((x_2 - x_{2_0})g_2 + f_3 + g_3 U_f - \dot{x}_{3_0}\Big) + \\ &+ (x_2 - x_{2_0})(aP_m - \dot{x}_{2_0} - v_1) - x_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m.\end{aligned} \tag{20}$$

The excitation control input is appeared in the above expression. If it is considered as follow, the derivative of the Lyapunov function becomes negative

$$U_f = -\frac{1}{g_3}[k_3(x_3 - x_{3_0}) + g_2(x_2 - x_{2_0}) + f_3 + v_2] \quad , \quad k_3 > 0\,, \tag{21}$$

where v_2 another function which is determined later.

Substituting for U_f, one can obtain

$$\begin{aligned}\dot{V}_3 &= -k_1 x_1^2 - k_2(x_2 - x_{2_0})^2 - k_3(x_3 - x_{3_0})^2 - x_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m + \\ &+ (x_3 - x_{3_0})(-\dot{x}_{3_0} - v_2) + (x_2 - x_{2_0})(aP_m - \dot{x}_{2_0} - v_1).\end{aligned} \tag{22}$$

To estimate the input mechanical power and to achieve an adaptive control, the last Lyapunov function is completed as follow

$$V_4 = V_3 + \frac{1}{2} r \bar{P}^2, \tag{23}$$

where $r > 0$ and $\bar{P} = P_m - \hat{P}_m$.

Differentiating V_4,

$$\begin{aligned}\dot{V}_4 &= \dot{V}_3 - r\bar{P}\dot{\hat{P}}_m = -k_1 x_1^2 - k_2(x_2 - x_{2_0})^2 - k_3(x_3 - x_{3_0})^2 - x_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m + \\ &+ (x_3 - x_{3_0})\left(-\dot{x}_{3_0} - v_2 + \left(\frac{-k_1 - k_2 + \beta}{g_2}\right)a\bar{P} - \left(\frac{-k_1 - k_2 + \beta}{g_2}\right)a\bar{P}\right) + \\ &+ (x_2 - x_{2_0})\Big(a(\bar{P} + \hat{P}_m) - \dot{x}_{2_0} - v_1\Big) - r\bar{P}\dot{\hat{P}}_m = \\ &= -k_1 x_1^2 - k_2(x_2 - x_{2_0})^2 - k_3(x_3 - x_{3_0})^2 - x_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m +\end{aligned} \tag{24}$$

$$+(x_3 - x_{3_0})\left(-\dot{x}_{3_0} - v_2 + (\frac{-k_1 - k_2 + \beta}{g_2})a\overline{P}\right) + (x_2 - x_{2_0})\left(a\hat{P}_m - \dot{x}_{2_0} - v_1\right) +$$

$$+P\left(a(x_2 - x_{2_0}) - a(x_3 - x_{3_0})(\frac{-k_1 - k_2 + \beta}{g_2}) - r\dot{\hat{P}}_m\right).$$

The last three terms of the above expression may become positive or negative, so they should be omitted and the following estimation law and functions for v_1 and v_2 are obtained

$$\dot{\hat{P}}_m = \frac{1}{r}\left[a(x_2 - x_{2_0}) - a(x_3 - x_{3_0})(\frac{-k_1 - k_2 + \beta}{g_2})\right], \tag{25}$$

$$v_1 = a\hat{P}_m - \dot{x}_{2_0} = a\hat{P}_m + k_1 x_2 - k_1 \frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m, \tag{26}$$

$$v_2 = -\dot{x}_{3_0} + (\frac{-k_1 - k_2 + \beta}{g_2})a\overline{P} \ , \tag{27}$$

or $\dot{x}_{3_0} = -\dfrac{1}{g_2}(k_2(\dot{x}_2 - \dot{x}_{2_0}) + \dot{x}_1 + \dot{v}_1 + \dot{f}_2 + \dot{g}_2 x_{3_0})$

$$v_2 = \frac{1}{g_2}[k_2\dot{x}_2 - k_2\dot{x}_{2_0} + \dot{x}_1 + a\dot{\hat{P}}_m + k_1\dot{x}_2 - k_1\ddot{\hat{x}}_{1e} - \beta\dot{x}_2 - J\hat{x}_{3e}\cos(\hat{x}_{1e} + x_1)x_2 +$$

$$+\dot{g}_2 x_{3_0}] + (\frac{-k_1 - k_2 + \beta}{g_2})a\overline{P}$$

$$-\left(J\hat{x}_{3e}\cos(\hat{x}_{1e} + x_1) + J\cos(\hat{x}_{1e} + x_1)x_{3_0}\right)x_2]. \tag{28}$$

Using these expression one can obtain

$$\dot{V}_4 = -k_1 x_1^2 - k_2(x_2 - x_{2_0})^2 - k_3(x_3 - x_{3_0})^2 - x_1\frac{\partial \hat{x}_{1e}}{\partial \hat{P}_m}\dot{\hat{P}}_m \ . \tag{29}$$

It is clear that after an unknown disturbance in input mechanical power, the system equilibrium point of the system is changed and the excitation input should be changed such that the system converges to the new equilibrium point. The above control and estimation laws guarantees that for $t \to \infty$ $\lim \dot{V}_4 = 0$ which yields, as time tends to infinite, $x_1 = 0$, $x_2 = x_{2_0} = k_1 x_1 = 0$ and $x_3 = x_{3_0}$.

Using (10), (17) and (26) one can obtain

$$0 = aP_m + f_2 + g_2 x_3 \ , 0 = v_1 + f_2 + g_2 x_{3_0} \ , v_1 = a\hat{P}_m \quad \to \hat{P}_m = P_m \, .$$

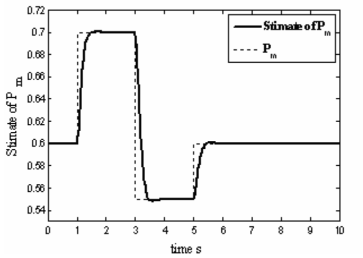
One may note from (7)–(8), with convergence of estimated mechanical power to its real value, $\hat{x}_{1e} \to x_{1e}$, $\hat{x}_{3e} \to x_{3e}$ and terminal voltage regulation is achieved. In fact, estimated equilibrium point $(\hat{x}_{1e}, 1, \hat{x}_{3e})$ converges to new equilibrium point $(x_{1e}, 1, x_{3e})$.

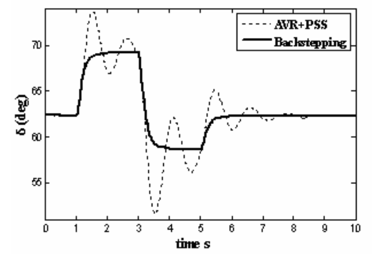
4. SIMULATION AND DISCUSSION

Using system parameters given in appendix, considering mechanical power as $P_m = 0.6$ p.u and excitation input as $U_f = 1.6156$ p.u the operating point of system becomes (62.2924, 1, 1.5340) which is stable. The terminal voltage becomes $V_{tr} = 1.0007$ p.u. In this section through two tests, the performance of the proposed controller is investigated and compared to PSS. The tuned controller parameters are $k_1 = 3, k_2 = 0.1, k_3 = 40, r = 50$.

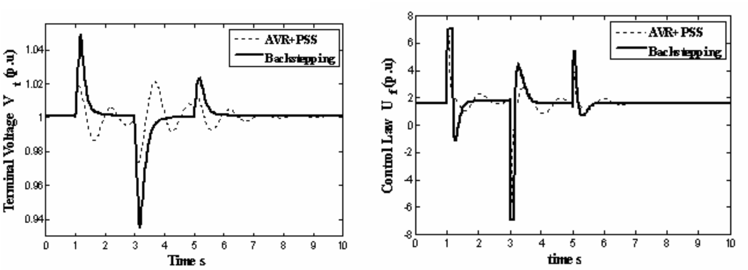
a) *Test a*. Considering an unknown change in input mechanical power for a small duration as in Fig. 2a. The simulation results of this test are shown in Figs. 2a to 2d. As can be seen from Figs. 2a and 2d with the change $\Delta P_m = 0.1$ p.u ,then $\Delta P_m = -0.15$ p.u, then $\Delta P_m = 0.05$ p.u, the proposed excitation control input, with mechanical power estimation and new equilibrium point estimation, tries to stabilize the system and regulates the terminal voltage. After this change is omitted, the system states return to their previous values. The results with AVR+PSS are also illustrated in Figs. 2a to2d, it can be seen that the convergence and damping of the proposed controller are much better compared to conventional AVR+PSS. The proposed controller causes a fast dynamic.

b) *Test b*. Short circuit in a duration time and clearing the fault with changing the network topology: In this test, a short-circuit fault at *t* = 1 s inline L_2, very close to bus 2, is appeared. The fault is cleared by opening line 2 at *t* = 1.05 s. Simulation results are shown in Fig 3a to 3b. It is clear that, the proposed controller is able to stabilize the system very quickly with changing network topology in the new equilibrium point.



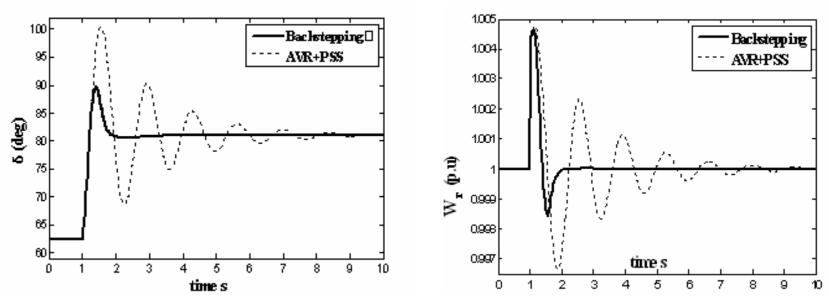


(a) estimate of mechanical power(b) machine angle



(c) terminal voltage (d) control law

Fig. 2 – Simulation results of *Test a*, considering an unknown change in input mechanical power for a small duration.



(a) machine angle (b) Angular velocity

Fig. 3 – Simulation results with changing the network topology.

5. CONCLUSION

In this paper, considering changes in input mechanical power as an unknown disturbance, an adaptive excitation control is designed for power system based on backstepping control. Since the designed control is based the original nonlinear state equations, it has superiority over conventional control obtained for linearized equations. By using adaptive technique with Lyapunov direct method which is applied for each subsystem separately, the mechanical input power is estimated. The effectiveness and validity of the proposed control is illustrated through simulation results. The stability of the power system is guaranteed even in the presence of uncertainties in power network. The performance of the proposed controller is compared to conventional AVR+PSS. It can be seen that the damping and dynamic of the proposed controller are much better that conventional AVR+PSS. It is shown that the proposed controller is able to stabilize the network even in the case of network topology changing and even if the fault point is near to terminals of synchronous generator. The transient stability is tested by applying a three phase fault near the sending end with considering a clearance time.

APPENDIX

System parameters: $P_m = 0.6$ p.u, $V_s = 1$ p.u, $V_{te} = 1.0007$ p.u

$x_d = 1.7572$ p.u, $x_q = 1.5845$ p.u, $x'_d = 0.5945$ p.u, $x_T = 0.1364$ p.u

$\omega_0 = 1$ p.u , $D = 0.1$ p.u, $H = 3.542$ s ,

$\tau'_{d0} = 6.66$ s, $x_L = x_{L1} \,||\, x_{L2} = 0.5426$ p.u .

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