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Nonlinear adaptive back-stepping controller design for power system stabilizer in multi-machine power systems

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***Abstract*—This paper proposes a nonlinear adaptive back-stepping controller to damp the oscillations and improve the transient stability in multi-machine power systems. The designed controller is adaptive to unknown generator parameters. The proposed controller is designed based on a forth order nonlinear model of a synchronous generator and the automatic voltage regulator model is considered so as to decrease the steady state voltage error. The construction of both control law and associated Lyapunov function is consistently systematic within the design methodology. A 3-machine power system is used to demonstrate the effectiveness of the proposed controller over other two controllers: one is the conventional damping controller (power system stabilizer) and the other is the one designed by the feedback linearization technique.**

I. INTRODUCTION

In power system, power system stabilizers (PSSs) have been extensively used in modern power systems as an efficient means of damping of the low frequency oscillations [1-6]. The design of conventional power system stabilizer (CPSS) is based on the linearized model of power system at a steady state operating point. The damping effect of these PSSs may no longer be satisfactory when the operating condition and system parameters change significantly.

In the last decade, nonlinear control theory has been widely used to solve the transient stabilization problem in power systems [7-12]. The back-stepping technique in a single machine infinite bus (SMIB) power system has been utilized. In previous papers [8, 9], the back-stepping controllers increased the terminal voltage rise after a fault was cleared. This happened because the automatic voltage regulator (AVR) was not considered. Although the back-stepping design with a third order system model can be extended from SMIB systems to multi-machine systems [11-14], the controller design is all based on the assumption that parameters of generators are available for implementation of the control law. In addition, although the design of the back-stepping controller is easier in the third order model than that of the fourth order model, it may result in a steady state voltage error when the AVR is not considered in the system model.

In this paper, we propose a nonlinear adaptive back-stepping controller (ABC) design for multi-machine power systems. The adaptive control law is implemented based on the 4th order power system model including the unknown parameters. The AVR model is considered to decrease the voltage error of steady state. The stability of the proposed controller is verified by the LF and by MATLAB simulation package.

This paper is organized as follows. Section Ⅱ describes the dynamic model of a multi-machine power system. Section Ⅲ introduces the design of proposed ABC by recursive procedure. The two test power systems are used to verify the performance of the proposed controller and the simulation results compared to two other controllers are shown in Section Ⅳ. Finally, we conclude the paper in Section Ⅴ.

II. MULTI-MACHINE POWER SYSTEM MODEL

In this section, the generator system using the one-axis model is considered in which the model of the automatic voltage regulator (AVR) is included. The i^{th} generator of an n-machine power system is described as follows:

$$\dot{\delta}_i = \omega_0(\omega_i - 1) \tag{1}$$

$$\dot{\omega}_i = \frac{1}{M_i}(P_{mi} - P_{ei} - D_i(\omega_i - 1)) \tag{2}$$

$$\dot{E}'_{qi} = \frac{1}{\tau'_{d0i}}[-E'_{qi} + (x_{di} - x'_{di})i_{di} + E_{fdi}] \tag{3}$$

$$\dot{E}_{fdi} = \frac{1}{T_{Ai}}[-E_{fdi} + K_{Ai}(V_{refi} - V_{ti} + u_{fi})] \tag{4}$$

Where $i = 1,...,n$ (n is the number of machines) and u_{fi} is the control law. δ denotes the rotor angle, ω is the rotor angular speed, and ω_0 is the rated speed. E'_q is the

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transient EMF in quadrature axis and E_{fd} is the excitation field voltage. P_m and P_e are the mechanical and electrical power. V_t is the reference terminal voltage. M is the inertia coefficient, and D is the damping constant. x_d and $x_d^{'}$ are the direct axis reactance and transient reactance. v_d, v_q, i_d and i_q are the d, q axis voltage and current. The power, voltage and current equations representing the power system network are described as follows:

$$V_{di} = i_{qi} x_{qi}$$
$$V_{qi} = E_{qi}^{'} - i_{di} x_{di}^{'} \tag{5}$$

$$V_{ti} = \sqrt{{V_{di}}^2 + {V_{qi}}^2} \tag{6}$$

$$P_{ei} = V_{di} i_{di} + V_{qi} i_{qi} \tag{7}$$

$$i_{di} = \sum_{j=1}^{n} E_{qj}^{'} (G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) \tag{8}$$

$$i_{qi} = \sum_{j=1}^{n} E_{qj}^{'} (B_{ij} \sin\delta_{ij} + G_{ij} \cos\delta_{ij}) \tag{9}$$

Where δ_{ij} is the relative rotor angle for the i^{th} generator with respect to the j^{th} generator. All active and reactive loads are represented with a constant impedance model.

III. Adaptive Backstepping Controller Design

In this section, we formulate the nonlinear adaptive backstepping controller for multimachine power systems.

In order to transform system (1)-(4) into an appropriate representation form for the back-stepping design, let us denote the positive constants:

$$a_{1i} = \omega_0,\ b_{1i} = P_{mi} / M_i,\ b_{2i} = 1 / M_i,\ b_{3i} = D_i / M_i$$
$$c_{1i} = (x_{di} - x_{di}^{'}) / \tau_{d0i}^{'},\ c_{2i} = 1 / \tau_{d0i}^{'}$$
$$d_{1i} = 1 / T_{Ai},\ d_{2i} = V_{refi} K_{Ai} / T_{Ai},\ d_{3i} = K_{Ai} / T_{Ai}$$

then system (1)-(4) is transformed into the following form:

$$\dot{x}_{i1} = -a_{1i} + a_{1i} x_{i2} \tag{10}$$
$$\dot{x}_{i2} = b_{1i} + b_{3i} x_{i2} - b_{2i} * F_{1i} - x_{i2} \theta_i$$
(11)
$$\dot{x}_{i3} = -c_{1i} * i_{di} - c_{2i} * x_{i3} + c_{2i} * x_{i4} \tag{12}$$
$$\dot{x}_{i4} = -d_{1i} * x_{i4} + d_{2i} - d_{3i} * V_{ti} + d_{3i} * u_{fi} \tag{13}$$

Where u_f is the control signal and θ_i is the unknown parameter which is estimated by the adaptive backstepping control design.

$$x_i = \begin{bmatrix} x_{i1} & x_{i2} & x_{i3} & x_{i4} \end{bmatrix}^{'} = [\delta_i\ \omega_i\ E_{q_i}^{'}\ E_{fd_i}]^{'},\ \theta = D_i / M_i$$
$$F_{1i} = E_{qj}^{'} \sum_{j=1}^{n} E_{qj}^{'} (B_{ij} \sin\delta_{ij} + G_{ij} \cos\delta_{ij})$$

Because it is possible to determine the rotor angle δ and speed ω with phasor measurement units (PMU) [16], the controller designed here use δ and ω as input. Then the output equation of the system (1)-(4) can be expressed by

$$y_i = \begin{bmatrix} 1 & 1 & 0 & 0 \end{bmatrix} x_i \tag{14}$$

In addition, the PMU can estimate the ac voltage and current, therefore, the voltage and the current at the generator bus are considered as measurable states. So, the flux observer can be used to estimate the unknown states x_{i3} and x_{i4} of every generator.

$$\dot{\hat{x}}_{i3} = -c_{1i} i_{di} - c_{2i} \hat{x}_{i3} + c_{2i} \hat{x}_{i4} \tag{15}$$
$$\dot{\hat{x}}_{i4} = -d_{1i} \hat{x}_{i4} + d_{2i} - d_{3i} V_{ti} + d_{3i} u_{fi} \tag{16}$$

It can be easily verified that $e_{i3} = x_{i3} - \hat{x}_{i3}$ and $e_{i4} = x_{i4} - \hat{x}_{i4}$ with $\hat{x}_{i3}$ and $\hat{x}_{i4}$ defined in (15)-(16) satisfy

$$\dot{e}_{i3} = -c_{2i} e_{i3} + c_{2i} e_{i4} \tag{17}$$
$$\dot{e}_{i4} = -d_{1i} e_{i4} \tag{18}$$

It is evident that equations (17) and (18) ensure the convergence of the estimates to the true state as $t \to \infty$.

In the following section, we apply the backstepping procedure to design a controller for (10)-(14) based on observer (15)-(16).

Step 1: define $z_1 = x_1 - x_{10}$, where x_{10} is the rotor angle on the operating point.

If we choose the LF candidate as

$$v_1 = z_1^2 / 2 \tag{19}$$
$$\dot{v}_1 = z_1 \dot{z}_1 = z_1 \dot{x}_1 = -z_1^2 + a_1 z_1 (x_2 - 1 + z_1 / a_1) \tag{20}$$

We can stabilize the subsystem (10) when the control law x_2 is viewed as

$$\alpha_1 = 1 - z_1 / a_1 \quad (21)$$

However x_2 is not a real control, therefore, define the new state z_2, which is to be regulated in step 2.

Step 2: let us define $z_2 = x_2 - \alpha_1$ and new LF candidate is defined as

$$v_2 = v_1 + z_2^2 / 2 \quad (22)$$

$$\dot{v}_2 == -z_1^2 - z_2^2 - b_2 z_2 (F_1 - \alpha_2) - z_2 x_2 \tilde{\theta} \quad (23)$$

Where α_2 is a stabilizing function which satisfies the inequality $\dot{v}_2 \leq 0$ when $F_1 = \alpha_2$.

$$\alpha_2 = \frac{1}{b_2}(a_1 z_1 + z_2 + b_1 - x_2 \tilde{\theta} - \frac{\partial \alpha_1}{\partial x_1} \dot{x}_1) \quad (24)$$

Here, F_1 is a virtual control, therefore the new stabilizing function should be designed.

Step 3: define $z_3 = F_1 - \alpha_2$ and new LF

$$v_3 = v_2 + z_3^2 / 2 + \tilde{\theta}^2 / 2$$
(25)

$$\begin{aligned} \dot{v}_3 = &-\sum_{i=1}^{3} z_i^2 + c_2 (i_q + \hat{x}_3 g_{ii}) + z_3 (\hat{x}_4 - \alpha_3) \\ &- (i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})) k_1 (z_3 + e_3 / 2k_1)^2 \\ &+ (i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})) k_1 z_3^2 \\ &+ (i_d \dot{x}_1 + c2 (i_q + \hat{x}_3 g_{ii})) e_3^2 / (4k_1) + + \tilde{\theta} (\dot{\tilde{\theta}} - z_2 x_2) \\ < &-\sum_{i=1}^{3} z_i^2 + c_2 (i_q + \hat{x}_3 g_{ii}) z_3 (\hat{x}_4 - \alpha_3 - s) \\ &+ (i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})) e_3^2 / (4k_1) + + \tilde{\theta} (\dot{\tilde{\theta}} - z_2 x_2) \end{aligned} \quad (26)$$

Where α_3 is defined in (27) and s is the nonlinear damping term which is used to counteract the destabilizing effect of the observer error e_3.

$$\begin{aligned} \alpha_3 = &-1 / [c_2 (i_q + \hat{x}_3 g_{ii})] * [-b_2 z_2 + z_3 - \hat{x}_3 i_d \dot{x}_1 \\ &+ (i_q + \hat{x}_3 g_{ii})(-c_1 i_d - c_2 \hat{x}_3) \\ &- \frac{\partial \alpha_1}{\partial x_1} \dot{x}_1 - \frac{\partial \alpha_1}{\partial x_2} \dot{x}_2 + - \frac{\partial \alpha_2}{\partial \tilde{\theta}} \dot{\tilde{\theta}}] \end{aligned} \quad (27)$$

Where

$$s = -[i_d \dot{x}_1 / (c_2 * (i_q + \hat{x}_3 g_{ii})) + 1] k_1 z_3$$
$$k_1 = 1.0 * sign(i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii}))$$
(28)

To stabilize the error state e_3, the LF is augmented by

$$v_3 = v_2 + \frac{1}{2} z_3^2 + \frac{1}{2k_1 (1 - k_2) c_2} (i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})) e_3^2$$
$$(0 < k_2 < 1) \quad (29)$$

The corresponding derivative of v_3 is

$$\begin{aligned} \dot{v}_3 < &-\sum_{i=1}^{3} z_i^2 + c_2 (i_q + \hat{x}_3 g_{ii}) z_3 (\hat{x}_4 - \alpha_3') \\ &- (3/4k_1)(i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})) e_3^2 \\ &+ (i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})) e_4^2 / (4(1 - k_2) k_1 k_2) \end{aligned} \quad (30)$$

The above stabilizing function α_3' is defined as

$$\alpha_3' = \alpha_3 + s \quad (31)$$

Step 4: define $z_4 = \hat{x}_4 - \alpha_3'$ and new LF is introduced as

$$v_4 = v_3 + \frac{1}{2} z_4^2 + \frac{1}{2k_1 (1 - k_2) d_1} (i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})) e_4^2 \quad (32)$$

$$\begin{aligned} \dot{v}_4 < &-\sum_{i=1}^{4} z_i^2 + d_3 z_4 (u_f - \alpha_4) + \frac{d_1}{4k_3} e_4^2 \\ &- [3/(4k_1)] * [i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})] e_3^2 \\ &- [3/(4(1 - k_2) k_1 k_2)] * [i_d \dot{x}_1 + c_2 (i_q + \hat{x}_3 g_{ii})] e_4^2 \\ &+ \tilde{\theta} (\dot{\tilde{\theta}} - z_2 x_2 + \frac{1}{b_2} (2 - \hat{\theta}) x_2 z_3) \end{aligned} \quad (33)$$

The above α_4 is defined as follows.

$$\begin{aligned} \alpha_4 = &-(1/d_3)(c_2 (i_q + \hat{x}_3 g_{ii}) z_3 + z_4 - d_1 \hat{x}_4 + d_2 \\ &- d_3 V_t + d_1 k_3 z_4 - \frac{\partial \alpha_3}{\partial x_1} \dot{x}_1 - \frac{\partial \alpha_3}{\partial x_2} \dot{x}_2 - \frac{\partial \alpha_3}{\partial \hat{x}_3} \dot{\hat{x}}_3) \end{aligned} \quad (34)$$

$$\dot{\tilde{\theta}} = -\dot{\hat{\theta}} = -z_2 x_2 + \frac{1}{b_2} (2 - \hat{\theta}) x_2 z_3 \quad (35)$$

In order to stabilize the e_4, the LF (32) is expressed by

$$v_4' = v_4 + e_4^2/(2k_3) \tag{36}$$

$$\dot{v}_4' < -\sum_{i=1}^{4} z_i^2 + d_3 z_4(u_f - \alpha_4) - \frac{3d_1}{4k_3} e_4^2$$
$$-[3/(4k_1)]*(i_d\dot{x}_1 + c_2(i_q + \hat{x}_3 g_{ii}))e_3^2 \tag{37}$$
$$-[3/(4(1-k_2)k_1k_2)]*(i_d\dot{x}_1 + c_2(i_q + \hat{x}_3 g_{ii}))e_4^2$$

Therefore, we can design the control law u_f as

$$u_f = \alpha_4 \tag{38}$$

Then the stability of the control law (38) can be established by using the LF (36) whose derivative satisfies

$$\dot{v}_4' < -\sum_{i=1}^{4} z_i^2 - \frac{3d_1}{4k_3} e_4^2 - \frac{3}{4k_1}(i_d\dot{x}_1 + c_2(i_q + \hat{x}_3 g_{ii}))e_3^2$$
$$-[3/(4(1-k_2)k_1k_2)]*(i_d\dot{x}_1 + c_2(i_q + \hat{x}_3 g_{ii}))e_4^2 \tag{38}$$

Where
$c_1 = (i_d\dot{x}_1 + c_2(i_q + \hat{x}_3 g_{ii}))*3/4k_1$
$c_2 = (i_d\dot{x}_1 + c_2(i_q + \hat{x}_3 g_{ii}))*(3/(4(1-k_2)k_1k_2)) + 3d_1/4k_3$

With the application of the controller (38) and the parameter update laws (35), the closed loop system is globally asymptotically stable in sense of Lyapunov method.

IV. TESTS AND RESULTS

A 3-machine power system (Fig. 1) was studied to assess the performance of the proposed controller in this section. The details of the system are given in [17] and the excitation control input constraint was:

$$-5.0\,p.u. \le E_{fd} \le 5.0\,p.u. \tag{40}$$

System responses of backstepping control are simulated and compared with two other control schemes:

- A conventional Lead-Lag PSS
- A nonlinear controller designed by a direct feedback linearization technique

The structure of conventional PSS considered here is shown in Fig. 2 and parameters of the PSSs used are tuned by optimal control method and listed in Appendix. Generator G_2 and G_3 in Fig. 1 were equipped with an ABC respectively.

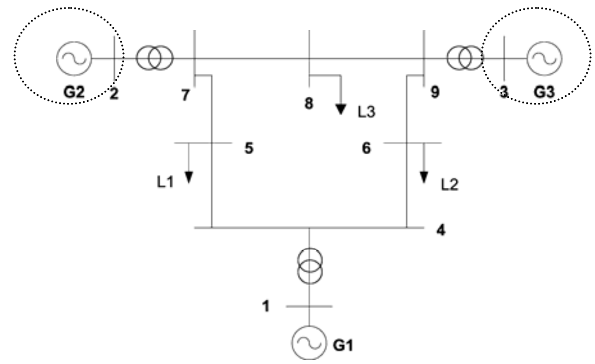

Fig.1. 3-machine 9-bus power system (--PSS installations)

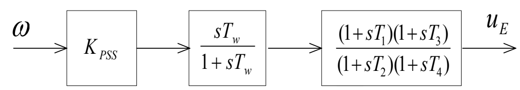

Fig. 2. Structure of conventional Lead-Lag PSS

To verify the efficiency of the proposed controllers, the following two cases are

Case 1: For the normal operating condition, a three-phase short circuit fault occurred at line 6-9 at t=1.0 seconds. The faulted line was tripped off after 100ms. After that the lines were reconnected at t=1.3 seconds.

Case 2: For a 10% increase in loads with respect to the normal operating condition, a 100 ms three-phase fault occurred at the same location as in case 1. The fault was cleared with the tripping off of the faulted line without re-closing.

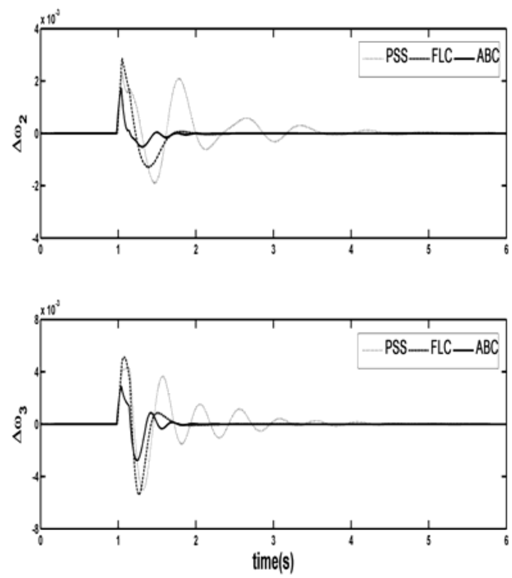

Fig. 3. Response of angular speed for generator 2 and 3(case 1)

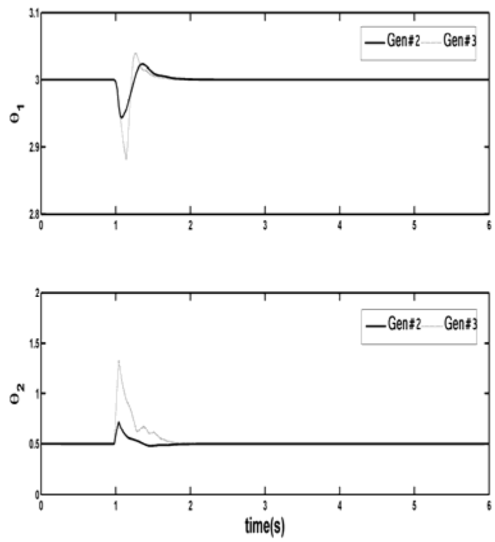

Fig. 4. Estimated parameter for generator 2 and 3 (case 1)

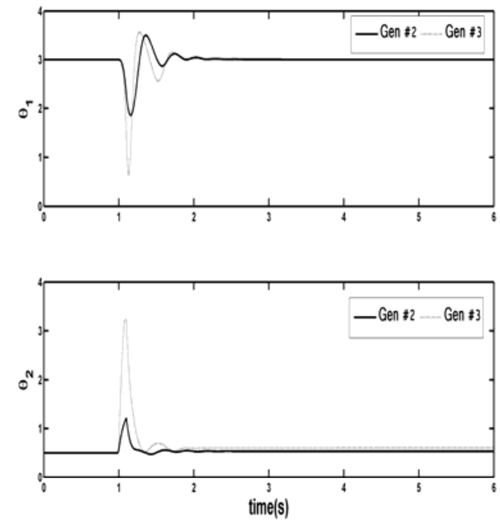

Fig. 6. Estimated parameter for generator 2 and 3 (case 2)

The fault in case 1 was a temporary fault and the perturbation was a 6-cycle three-phase fault which did not change the states of the system too far from the initial values. The efficiency of the ABCs was verified as shown in figure 3. It can be seen that the oscillations were damped faster with the proposed controller than with the tuned PSSs and the FL controller. The estimation of parameters is indicated in figure 4.

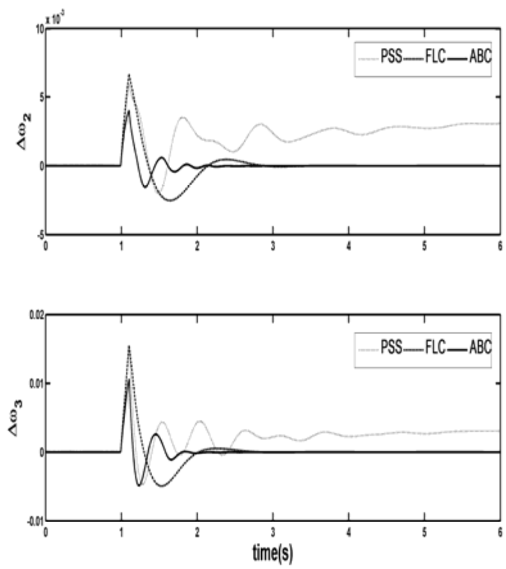

Fig. 5. Response of angular speed (case 2)

In Case 2, the system configuration in the pre-fault stage was quite different from that of post-fault stage. So this case can be used to check the transient stability responding to a large disturbance. The results are shown in figure 5. Meanwhile the damping of the proposed controllers could not be affected and the ABCs can still provided a satisfactory performance. Figure 6 showed the estimated parameters and the control inputs.

V. CONCLUSIONS

A systematic methodology for the design of a nonlinear adaptive back-stepping controller for a multi-machine power system was presented in this paper. In order to guarantee the postfault voltage is in a satisfactory level, the automatic voltage regulator is considered in design the nonlinear adaptive controller. With the adaptive design methodology, both the construction of the control law and the associated final LF were consistently systematic. Moreover, the unknown parameters in the system were estimated and compensated by the adaptive control scheme. So the proposed method offers a design tools to accommodate parameter uncertainties and system nonlinearities. The results obtained from the test power system validated the improvement in damping of oscillations with the proposed adaptive backstepping controller compared to the other two controllers. The simulations also confirmed that the proposed control law was adaptive to the parameter uncertainties.

APPENDIX

A. Parameters of the PSSs for the three-machine system

Parameter	Unit 2	Unit 3
K	2.2860	3.1190
T1	0.0055	0.0051
T2	0.0500	0.0500
T3	0.4135	0.2674
T4	0.0500	0.0500

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