A real-time nonlinear decentralized control of multimachine power systems

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This paper proposes the application of a new nonlinear decentralized control to the multi-input multi-output model of multimachine power systems. The goal is to control the terminal voltage as well as the rotor angle to obtain high-performance transient stability and good post-fault voltage regulation. The proposed stabilizing feedback laws for the power system are shown to be globally asymptotically stable in the context of Lyapunov theory. The effectiveness of the proposed control action is demonstrated through some computer simulations on a two-area benchmark power system under a large sudden fault and a wide range of operating conditions. The results are compared with those of the traditional automatic voltage regulator (IEEE type I AVR) plus the power system stabilizer control structure and speed governor.

Keywords: multimachine power system; backstepping design; transient stability; decentralized control

1. Introduction

Electric power systems are becoming larger and more complex because they must meet the increasing power demand. These are highly nonlinear systems that include a number of synchronous machines as producers; consequently, it is important to enhance the transient stability.

Transient stability of the power system is defined as the ability of the power system to maintain synchronism when subjected to severe transient disturbances such as a fault on transmission lines, loss of generation and loss of a large load (Kundur, 1994). Transient stability is affected by the large-scale system and the nonlinear characteristics of the power system. Conventional controllers are mainly designed by using linear control theory. The linear controllers generally provide asymptotic stability in a small region around the equilibrium at which the power system model is linearized for controller design. The main disadvantages of this design such as the lack of reliability and robustness are well known.

Recently, to deal with the nonlinear behavior, the application of nonlinear control theory has been investigated for improving the transient stability of a power system. Most of these controllers are based on feedback linearization technique (Hill & Wang, 2000; King, Chapman, & Ilic, 1994; Wang, Guo, & Hill, 1997), Hamiltonian techniques (Guo, Hill, & Wang, 2000; Maschke, Ortega, & Van der Schaft, 2000; Wang, Cheng, Li, & Ge, 2003; Xi, Cheng, Lu, & Mei, 2002), passivity-based approach (Ortega, Stankovic, & Stefanov, 1998; Pogromsky, Fradkov, & Hill, 1996) and sliding-mode control (Colbia-Vega, de Léon-Morales, Fridman, Salas-Péña, & Mata-Jiménez, 2008; Huerta, Loukianov, & Cañedo, 2010) 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 (Abbadi, Nezli, & Boukhetala, 2013), adaptive control (Liu, Wechu, Hu, & Song, 2012; Segal, Kothari, & Madnani, 2000) and neurocontrol (Park, Harley, & Venayagamoorthy, 2003). 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. (Alkhatib & Duveau, 2013; Mrad, Karaki, & Copti 2000; Wang, 2013).

Two main modelling approaches exist for the design of power system controllers, single-machine infinite-bus approach and multimachine power system approach. The single-machine, infinite-bus approach is simple but 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 approach is based on the global N-generator modelling. The controllers based on this model dampen inter-machine and inter-area oscillations very well.

In view of the above the nonlinear dynamic model of the system and decentralized control should be considered (Karimi & Feliachi, 2008; Yan, Dong, Saha, & Majumder, 2010; Yao, Jiang, Fang, Wen, & Cheng, 2014). Therefore, the main objective of the research work presented in this

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paper is to present a systematic and decentralized control of rotor angle and terminal voltage, simultaneously, in order to enhance the transient stability and ensure good post-fault voltage regulation of the power system. To this end, the model of a multimachine power system adopted combines the advantages of both previous modelling approaches (Okou, Akhrif, & Dessaint, 2003). 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 stability theory. And, only local measurements are required for the proposed controllers.

The rest of this paper is organized as follows. First, in Section 2, a mathematical model of a multimachine power system is presented. In Section 3, backstepping controllers are designed for the multimachine power system to enhance the transient stability of the system. After that, in Section 4, simulation results are given for illustrating the performance of the proposed scheme. As an application example, the proposed control approach is applied to a two-area four-machine interconnected power system. Finally, the conclusions of this work are given.

2. Mathematical model of multimachine power system

The complete multimachine power system model consists of partitioning the power system into the generator to be controlled and the rest of the grid, represented by a time-varying impedance. The resulting model contains time-varying parameters that model operating-condition variations and interactions between generators. Each generator consists of a synchronous machine and a turbine providing the mechanical power.

The resulting model which is presented in some detail in Okou et al. (2003) and Ouassaid, Cherkaoui, and Maaroufi (2010) has the following form:

\[
\begin{align*}
\frac{dv_d}{dt} &= h_{11}(t)v_d + h_{12}(t)v_q + g_1(t)E_{fd}(t), \\
\frac{dv_q}{dt} &= h_{21}(t)v_d + h_{22}(t)v_q + g_2(t)E_{fd}(t), \\
\frac{d\omega}{dt} &= \frac{1}{2H}(T_m(t) - T_e(t)), \\
\frac{d\delta}{dt} &= \omega_R(\omega(t) - 1),
\end{align*}
\]

where \(E_{fd}(t)\) is the excitation control input, \(v_d(t)\) and \(v_q(t)\) the voltages at the terminals of the generator, \(\omega\) the angular speed, \(H\) the inertia constant, \(T_m\) the mechanical torque, \(T_e\) the electromagnetic torque, \(\delta\) the rotor angle of the generator and \(\omega_R\) the power system frequency. \(h_{ij}(t)\) and \(g_i(t)\) are the time-varying parameters which encapsulate the interactions between the generator to be controlled and the rest of the power system. Their expressions are given in Appendix 1.

Governor-turbine system dynamics (Ohtsuka, Taniguchi, Sato, Yokokawa, & Ueki, 1992) is given as follows:

\[
\frac{dT_m}{dt} = -\frac{1}{T_g}T_m(t) + \frac{K_g}{T_g}u_g(t),
\]

where \(u_g(t)\) is the input power of control system; \(T_g\) the time constant of the governor-turbine system; and \(K_g\) the gain of the governor-turbine system.

The machine terminal voltage is calculated from the Park components \(v_d(t)\) and \(v_q(t)\) as follows:

\[
v_i(t) = (v_d^2(t) + v_q^2(t))^{1/2}.
\]

Then, the mathematical model of a multimachine power system can be formulated in the following form:

\[
\frac{dv}{dt} = m(t)E_{fd}(t) + f(t),
\]

\[
\frac{d\omega}{dt} = h_{31}T_m(t) - h_{31}T_e(t),
\]

\[
\frac{d\delta}{dt} = \omega_R(\omega(t) - 1),
\]

\[
\frac{dT_m}{dt} = h_{41}T_m(t) + g_3u_g(t),
\]

where

\[f(t) = \frac{1}{v_i(t)}(h_{11}v_d^2(t) + (h_{12} + h_{21})v_d(t)v_q(t) + h_{22}v_q^2(t))\]

and

\[m(t) = \frac{1}{v_i(t)}(g_1v_d(t) + g_2v_q(t)).\]

Expressions of \(h_{ij}(t)\) and \(g_3\) are given in Appendix 1.

3. Development of decentralized controllers

The proposed control strategy adopted is one of the most important results, which has been successfully applied to a wide class of nonlinear system. The basic idea of the 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 final Lyapunov function is formed by summing up the Lyapunov functions associated with each individual design stage. The design objective is achieved by obtaining the true control inputs (Krstic’, Kanellakopoulos, & Kokotovic, 1995).

In this paper, the backstepping approach is employed to develop tracking controllers of the terminal voltage and rotor angle for a multimachine power system described in
the derivative of the rotor angle error is given as

\[ e_1(t) = v_t(t) - v_{\text{ref}}, \quad (11) \]

where \( v_{\text{ref}} \) is the desired trajectory. The derivative of the terminal voltage error is derived by using Equations (7) and (11):

\[ \frac{de_1}{dt} = m(t)E_{\delta d} + f(t). \quad (12) \]

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

\[ V_1(t) = \frac{1}{2} \lambda \delta_n^2(t) + \frac{1}{2} e_1^2(t), \quad (13) \]

where \( \delta_n(t) = \int_0^t e_1(\tau) \, d\tau \) is the integral of the terminal voltage error and \( \lambda \) is a positive constant feedback gain.

The time derivative of the \( V_1(t) \) can be written as

\[ \frac{dV_1}{dt} = (f(t) + m(t)E_{\delta d} + \lambda \delta_n) e_1(t). \quad (14) \]

Thus, Lyapunov’s stability criterion can be satisfied by making the term on the right-hand side of Equation (14) negative semi-definite in order to guarantee the global asymptotic stability of the system. The control function \( E_{\delta d}(t) \) guarantees the semi-definite criterion of the following equation:

\[ E_{\delta d}(t) = -\frac{1}{m(t)}(f(t) + K_1 e_1(t) + \lambda \delta_n(t)), \quad (15) \]

where \( K_1 \) is a positive constant feedback gain. Insertion of the control function \( E_{\delta d}(t) \) in the dynamics for the error variable of \( e_1(t) \) then gives

\[ \frac{de_1}{dt} = -K_1 e_1(t). \quad (16) \]

Step 1: We first consider the tracking objective of the terminal voltage. We define the terminal voltage error as

\[ \delta(t) = \delta(t) - \delta_{\text{ref}}, \quad (17) \]

where \( \delta_{\text{ref}} \) is the rotor angle reference. From Equation (9), the derivative of the rotor angle error is given as

\[ \frac{de_2}{dt} = \omega_R(\omega(t) - 1). \quad (18) \]

The second Lyapunov function is chosen as

\[ V_2(t) = \frac{1}{2} e_1^2(t) + \frac{1}{2} e_2^2(t). \quad (19) \]

Using Equations (16) and (18), the derivative of Equation (19) can be derived as follows:

\[ \frac{dV_2}{dt} = -K_1 e_1^2(t) + \omega_R(\omega(t) - 1)e_2(t). \quad (20) \]

The \( \omega(t) \) can be viewed as a virtual control in the above equation. Then, the stabilizing function \( \alpha_1(t) \) of \( \omega(t) \) (\( \alpha_1(t) \)) tends to \( \omega(t) as t \to \infty \) would be

\[ \alpha_1(t) = -\frac{K_2 e_2(t)}{\omega_R} + 1, \quad (21) \]

where \( K_2 \) is a positive constant feedback gain. Substituting \( \omega(t) \) by this stabilizing function \( \alpha_1(t) \) into Equation (20), the following equation can be obtained:

\[ \frac{dV_2(t)}{dt} = -K_1 e_1^2(t) - K_1 e_2^2(t). \quad (22) \]

Since the rotor speed \( \omega(t) \) is not our control input, we define

\[ e_3(t) = \omega(t) - \alpha_1(t), \quad (23) \]

which is the stabilizing error between \( \omega(t) \) and its desired trajectory \( \alpha_1(t) \). Thus, from Equations (18), (21) and (23), the dynamics of the rotor angle error is obtained as

\[ \frac{de_2}{dt} = -K_2 e_2(t) + \omega_R e_3(t). \quad (24) \]

Step 3: To stabilize the rotor speed \( \omega(t) \), one defines the following derivative of \( e_3(t) \) using Equations (8) and (23) as

\[ \frac{de_3}{dt} = h_{31} T_m(t) - h_{31} T_e(t) - \frac{d\alpha_1}{dt}. \quad (25) \]

Now, we can define a new Lyapunov function which includes the rotor speed error \( e_3(t) \) as follows:

\[ V_3(t) = \frac{1}{2} e_1^2(t) + \frac{1}{2} e_2^2(t) + \frac{1}{2} e_3^2(t). \quad (26) \]

By using Equations (16), (24) and (25), the derivative of Equation (26) is given as follows:

\[ \frac{dV_3}{dt} = -K_1 e_1^2(t) - K_2 e_2^2(t) \]

\[ + e_3 \left( h_{31} T_m(t) - h_{31} T_e(t) - \frac{d\alpha_1}{dt} + \omega_R e_2(t) \right). \quad (27) \]

If we consider \( T_m(t) \) as a second virtual control, one easily obtains the following stabilizing function:

\[ \alpha_2(t) = \frac{1}{h_{31}} \left( \frac{d\alpha_1}{dt} - K_3 e_3(t) - \omega_R e_2(t) + h_{31} T_e(t) \right) \]

\[ = \frac{1}{h_{31}} \left( -K_2(e_2(t)) + K_3 e_3(t) - \omega_R e_2(t) \right) + h_{31} T_e(t), \quad (28) \]

where \( K_3 \) is a positive constant feedback gain.
Step 4. Since the mechanical torque $\alpha_2(t)$ is not our control input, we define:

$$e_4(t) = T_m(t) - \alpha_2(t),$$  \hspace{1cm} (29)

which substituted into Equation (25) using Equation (28) yields

$$\frac{de_4}{dt} = -K_3 e_3(t) + h_{31} e_4(t) - \omega_R e_2(t).$$ \hspace{1cm} (30)

Hence, the derivative of $e_4(t)$ is found by time differentiation and reordering of Equation (29), that is,

$$\frac{de_4}{dt} = h_{41} T_m(t) + g_3 u_6(t) - \psi(t),$$  \hspace{1cm} (31)

where

$$\psi(t) = \frac{\alpha_2}{h_{31}} \equiv \frac{(K_2 + K_3)}{h_{31}}(T_e - T_m) - \frac{K_3 K_2 + \omega_R^2}{h_{31}}(\omega - 1).$$

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

$$V_4(t) = V_3(t) + \frac{1}{2} e_4^2(t)$$

$$= \frac{1}{2} e_1^2(t) + \frac{1}{2} e_2^2(t) + \frac{1}{2} e_3^2(t) + \frac{1}{2} e_4^2(t).$$ \hspace{1cm} (32)

By differentiating the Lyapunov function $V_4(t)$ (32), one obtains

$$\frac{dV_4}{dt} = -K_1 e_1^2 - K_2 e_2^2 - K_3 e_3^2$$

$$+ e_4(h_{31} e_3 + h_{41} T_m + g_3 u_6 - \psi).$$ \hspace{1cm} (33)

Next, the following choice of feedback control law is made:

$$u_6(t) = \frac{1}{g_3} (\psi(t) - K_4 e_4(t) - h_{31} e_3(t) - h_{41} T_m(t)).$$ \hspace{1cm} (34)

Then, Equation (31) becomes

$$\frac{de_4}{dt} = -K_4 e_4(t) - h_{31} e_3(t),$$ \hspace{1cm} (35)

where $K_4$ is a positive constant feedback gain.

Theorem. The control laws (15) and (34) render the derivative of the Lyapunov function (33), for the system defined by Equations (7)–(10), negative semi-definite. Consequently, the tracking errors which include terminal voltage, rotor angle, rotor speed and mechanical torque will converge to zero asymptotically.

Proof. As demonstrated previously, the resulting error dynamics of the system can be written as

$$\frac{de_1}{dt} = -K_1 e_1(t),$$

$$\frac{de_2}{dt} = -K_2 e_2(t) + \omega_R e_3(t),$$

$$\frac{de_3}{dt} = -\omega_R e_2(t) - K_3 e_3(t) + h_{31} e_4(t),$$

$$\frac{de_4}{dt} = -h_{31} e_3(t) - K_4 e_4(t).$$ \hspace{1cm} (36)

This system has an equilibrium at $e_1(t) = e_2(t) = e_3(t) = e_4(t) = 0$. Furthermore, the derivative of the Lyapunov function (32) along the solution of Equation (36) yields

$$\frac{dV}{dt} = -K_1 e_1^2(t) - K_2 e_2^2(t) - K_3 e_3^2(t) - K_4 e_4^2(t).$$ \hspace{1cm} (37)

So, one defines the following equation:

$$W(t) = K_1 e_1^2(t) + K_2 e_2^2(t) + K_3 e_3^2(t) + K_4 e_4^2(t) \geq 0.$$ \hspace{1cm} (38)

Furthermore, by using Lasalle-Yoshizawa’s principle (Krstic’ et al., 1995), it can be shown that $W(t)$ tends to zero as $t \to \infty$. Therefore, the tracking errors which include terminal voltage, rotor angle and rotor speed will converge to zero asymptotically as $t \to \infty$. 

4. Simulation result

In this section, the dynamic performances of the controllers are evaluated. The interconnected power system
chosen is composed of four machines (Kundur, 1994) whose schematic is shown in Figure 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 Table A1 (Appendix 2). The Matlab/Simulink software is used for the time-domain simulations.

Figure 2 shows the decentralized control system configuration of the multimachine power system. In order to prove the performance and usefulness of the proposed controllers, the results are compared with those of the conventional automatic voltage regulator (AVR) + power system stabilizer (PSS) and speed governor (SG). Simulation studies are carried out under different contingencies. The following cases are considered:

4.1. Effect of small disturbance on the dynamic performance of the system: variation of loading condition

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 damping controllers to wide variation in the loading condition, the load at bus 7 (LD7 = 967 MW) is disconnected at t = 8 s for 100 ms.

The generator G1 is equipped with the proposed control scheme when the generators G2, G3 and G4 are equipped with the conventional controllers (AVR+PSS and SG). Figure 3 shows the tracking performance of the terminal voltage and rotor speed. It is seen how the dynamics of the terminal voltage and rotor speed exhibit large overshoots during the 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. The oscillations in the rotor angles of all generators, G1 generator taken as a reference, are shown in Figure 4. It is observed that the rotor angles settle to the post-fault values. Figure 5 shows the variations of the inter-area and local mode of oscillation. It is evident that the proposed controller is robust to the type of disturbance and provides efficient damping to power system oscillations.
4.2. Effect of severe disturbance on the dynamic performance of the system: temporary three-phase fault disturbance

Symmetric three-phase short-circuit fault occurs at location F (in the middle of the transmission line between bus B7 and bus B9, see Figure 1) at 4 s. The faulted transmission line is cut off at 4.2 s. The original system is restored after the fault clearance. Figure 6 illustrates the terminal voltage and rotor speed. According to this figure, the proposed nonlinear controller has better damping and stabilization effect than AVR/PSS. The oscillations in the rotor angles of all the generators, with generator G1 taken as the reference generator, are shown in Figure 7. Also, Figure 8 shows the variations in the inter-area and local mode of oscillation disturbance. From these figures, it can be seen that the inter-area modes of oscillations are quickly damped out. Further, the proposed controller is also effective in suppressing the local mode of oscillations.

4.3. Robustness to the modelling errors and parameter variations

The performances of the proposed controller are evaluated with respect to modelling errors and parameter variations of generator. A robustness test has been carried out by introducing a random change of generator parameters from their nominal values (within the range of ±20%). The parameters $x_d$, $x_q$, $T_{dd0}$, $T_{dq0}$ and $H$ are considered for this test. 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 Figures 9 and 10 that the proposed scheme can still provide consistent control performance even if system parameters have changed and, furthermore, the controller is not sensitive to parameter variations.
5. Conclusion

This paper presents a decentralized and nonlinear controller of the excitation and rotor angle, for multimachine power systems, based on the backstepping design. The developed approach is based on a multi-input multi-output power system model with time-varying parameters representing the inter-machine interactions. The proposed method effectively decentralizes the feedback controllers and hence, only needs the local variables. The feedback system is globally asymptotically stable in the sense of a 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. The results show that the proposed decentralized controller provides good performance in improving voltage regulation, transient stability and the robustness with respect to modelling errors and parameter variations of the multimachine power system.

References

Abbadi, A., Nezli, L., & Boukhetala, D. (2013). A nonlinear voltage controller based on interval type 2 fuzzy logic control system for multi-machine power systems. International Journal of Electrical Power & Energy Systems, 45(1), 456–467. Retrieved from http://dx.doi.org/10.1016/j.ijepes.2012.09.020

Alkhatib, H., & Duveau, J. (2013). Dynamic genetic algorithms for robust design of multi-machine power system stabilizers. International Journal of Electrical Power & Energy Systems, 45(1), 242–245. Retrieved from http://dx.doi.org/10.1016/j.ijepes.2012.08.080

Colbia-Vega, A., de León-Morales, J., Fridman, L., Salas-Péna, O., & Mata-Jiménez, M. T. (2008). Robust excitation control design using sliding-mode technique for multimachine power systems. Electric Power Systems Research, 78, 1627–1634. Retrieved from http://dx.doi.org/10.1016/j.epsr.2008.02.011

Guo, Y., Hill, D., & Wang, Y. (2000). Nonlinear decentralized control of large scale power systems. Automatica, 36, 1275–1289. Retrieved from http://dx.doi.org/10.1016/S0005-1098(00)00038-8

Hill, D., & Wang, Y. (2000). Nonlinear decentralized control of large scale power systems. Automatica, 36, 1275–1289. Retrieved from http://dx.doi.org/10.1016/S0005-1098(00)00038-8

Huerta, H., Loukianov, A. G., & Cañedo, J. M. (2010). Decentralized sliding mode block control of multimachine power systems. International Journal of Electrical Power and Energy Systems, 32(1), 1–11. Retrieved from http://dx.doi.org/10.1016/j.ijepes.2009.06.016

Karami, A., & Feliachi, A. (2008). Decentralized adaptive backstepping of electric power systems. Electric Power Systems Research, 78(3), 484–493. Retrieved from http://dx.doi.org/10.1016/j.epsr.2007.04.003

King, C. A., Chapman, J. W., & Ilic, M. D. (1994). Feedback linearizing excitation control on a full scale power system model. IEEE Transactions Power Systems, 9(2), 1102–1110. doi:10.1109/59.317620

Kristic’, M., Kanellopoulos, I. P., & Kokotovic, V. (1995). Nonlinear and adaptive control design. New York: Wiley Interscience.

Kundur, P. (1994). Power system stability and control. New York: McGraw-Hill.

Liu, H., Wechu, Hu, & Song, Y. (2012). Lyapunov-based decentralized excitation control for global asymptotic stability and voltage regulation of multi-machine power systems. IEEE Transactions on Power Systems, 27(4), 2262–2270. doi:10.1109/TPWRS.2012.2196716

Maschke, B., Ortega, R., & Van Der Schaft, A. J. (2000). Energy-based Lyapunov functions for forced Hamiltonian systems with dissipation. IEEE Transactions Automatic Control, 45(8), 1498–1502. doi:10.1109/9.871758

Mrad, F., Karaki, S., & Copti, B. (2000). An adaptive fuzzy-synchronous machine stabilizer. IEEE Transactions on Systems, Man & Cybernetics-Part C, 30(1), 131–137. doi:10.1109/5326.827486

Ohtsuka, K., Taniguchi, T., Sato, T., Yokokawa, S., & Ueki, Y. (1992). A $H_{\infty}$ optimal theory based generator control system. IEEE Transactions on Power Systems, 7(1), 108–113. doi:10.1109/60.124549

Okou, F., Akhrif, O., & Dessaint, L.-A. (2003). A novel modelling approach for decentralised voltage and speed control in multimachine power systems. International Journal of Control, 76(8), 845–857. doi:10.1080/0020717031000116524

Ortega, R., Stankovic, A., & Stefanov, P. (1998). A passivation approach to power systems stabilization. Proceedings of the IFAC NOLCOS, Enschede, pp. 320–325.

Ouassaid, M., Cherkaoui, M., & Maaroufi, M. (2010). A nonlinear decentralized control of multimachine power system. Proceedings of the 18th IEEE Mediterranean conference on control and automation, Marrakech, pp. 111–116. doi:10.1109/MED.2010.5547607

Park, J. W., Harley, R. G., & Venayagamoorthy, G. K. (2003). Adaptive-critic-based optimal neurocontrol for synchronous generators in a power system using MLP/RBF neural networks. IEEE Transactions on Industry Applications, 39(5), 1529–1540. doi:10.1109/TIA.2003.816493

Pogromsky, A. Y., Fradkov, A. L., & Hill, D. J. (1996). Passivity based damping of power system oscillations. Proceedings of the IEEE CDC, Kobe, pp. 512–517. doi:10.1109/CDC.1996.577268

Segal, R., Kothari, M. L., & Madnani, S. (2000). Radial basis function (RBF) network adaptive power system stabilizer.
Appendix 1

\[ h_{11} = \left( -T_{g0}(a_{x_d} - bR_s) \right) \left( bR_s - a_{x_d} - T'_{d0} \left( \frac{\partial b}{\partial t} R_s - \frac{\partial a}{\partial t} \right) \right) \]

\[ h_{12} = \left( T'_{d0}(bR_s - a_{x_q}) \right) \left( 1 + aR_s + bx_q + T'_{g0} \left( \frac{\partial b}{\partial t} x_q + \frac{\partial a}{\partial t} R_s \right) \right) / D, \]

\[ h_{21} = \left( T_{g0}(x_{d}' - bR_s) \right) \left( 1 + aR_s + bx_q + T'_{g0} \left( \frac{\partial b}{\partial t} x_q + \frac{\partial a}{\partial t} R_s \right) \right) / D, \]

\[ h_{22} = \left( -T_{g0}(ax_{q}' - bR_s) \right) \left( ax_{q} - bR_s - T_{g0} \left( \frac{\partial b}{\partial t} R_s - \frac{\partial a}{\partial t} \right) \right) \]

\[ -T_{g0}(1 + aR_s + bx_d + T'_{g0} \left( \frac{\partial b}{\partial t} x_d + \frac{\partial a}{\partial t} R_s \right) ) / D, \]

\[ b(t) = \frac{v_q l_q + v_d l_d}{v_i^2}; \quad a(t) = \frac{v_d l_d - v_q l_q}{v_i^2}. \]

Here, we have denoted

\[ D = -T_{g0}T_{d0}((bR_s - a_{x_q})(ax_{d}' - bR_s)) + (1 + aR_s + bx_d')(1 + aR_s + bx_{q}'). \]

Appendix 2

Table A1. Parameters of the power synchronous generators.

| Parameter | Value |
|-----------|-------|
| S_{base} | 900 MVA |
| x_{1}, leakage reactance | 0.2 p.u. |
| r_s, 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'_{g0}, q-axis open-circuit time constant | 0.4 s |
| H, inertia constant | 6.5 s |

Table A2. Parameters of the governor-turbine system.

| Parameter | Value |
|-----------|-------|
| T_t, time constant of the governor-turbine system | 0.2 s |
| K_r, gain of the governor-turbine system | 1 |