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Application of Passivity-based Control to Stabilization of the SMIB System with Controllable Series Devices ⋆

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Abstract: A controllable series device (CSD) is used to damp the transient oscillations in a power system. The power system studied here is the single machine infinite bus (SMIB) and the CSD used is a controllable series capacitor (CSC). Interconnection and damping assignment passivity-based control (IDA PBC) is used for controller synthesis. The SMIB system is described with two different types of models - the second order swing equation model and the classical third order flux decay model. For the second order model the control objective of damping assignment as well as energy shaping is achieved. In case of the third order model the control objective is just damping injection.

Keywords: Nonlinear systems, IDA PBC, SMIB stabilization, CSC

1. INTRODUCTION

Power oscillation damping is a very important and critical issue in power system dynamics. These oscillations can occur due to sudden faults or transients. Here we address an important stabilization problem in power systems, transient stabilization of the SMIB system at an equilibrium point. For the SMIB system excitation control scheme is widely used in which the field excitation is used as actuation. Conventionally linear controllers are used with excitation control to improve the transient performance. However, limited stability margin and unpredictable load demand make the system nonlinearities more dominant and call for better control techniques.

Recently the application of nonlinear control theory has been investigated for improving the transient stability of a power system. See Kirschen et al. [2000] for an account of the new issues in power system operations. Nonlinear control using turbine control, see Lu and Sun [1989], and excitation control has been proposed. The excitation control law has been investigated to replace the traditional Automatic Voltage Regulator (AVR) and the Power System Stabilizer (PSS) control structure. In Chapman et al. [1993], Wang et al. [1993], King et al. [1994], Mielczarsky and Zajaczkowski [1994], Li [2006] feedback linearization was applied to the nonlinear control problem for single machine as well as multi-machine systems, using output feedback and state observers. However, this method is fragile, as it relies on nonlinearity cancellation, and the issue of robustness remains unanswered. This motivated the investigation of energy-based control technique for this control problem. The use of energy function for control application has been given in Pai [1989]. The work based on damping injection controllers, also known as L_gV controllers, is found in Moon et al. [2000], Shen et al. [December, 2000], Sun et al. [2000], Ghandhari et al. [2001b]. In Bazanella et al. [1997, 1999] a dynamic damping injection controller is presented. It is shown that the domain of attraction becomes larger. In Espinosa-Perez et al. [1997], Ortega et al. [1998] a passivation technique is proposed for power system stabilization. An observer-based controller is given in Leon-Morales et al. [2002]. Further, in Galaz et al. [2003] a passivity-based control law is proposed for the excitation control of synchronous generator by shaping the total energy function via modification of the energy transfer between the mechanical and electrical components of the system. This control law enlarges the domain of attraction, thus increasing the critical clearing time. An observer-based (adaptive) control is given in Karagiannis et al. [2002]. In Maya-Ortiz and Espinosa-Perez [2004] an output feedback excitation control of synchronous generators is proposed using a nonlinear observer. Ortega et al. [2005] deals with transient stabilization of a multimachine power system with nontrivial transfer conductances. Recently, in Jiao et al. [2006] energy shaping approach is applied to

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a power system using direct mechanical damping assignment.

An important factor, which decides the capacity of a transmission line to transfer the electrical power across the network, the stability margin of the power system, is the reactance of the transmission line. Many power electronic devices have been invented for increasing the capacity and stability margin of the power systems. The concept of Flexible AC Transmission System (FACTS) relies on the use of such power electronic devices, and offers greater control of power flow, secure loading and damping of power system oscillations see, e.g.,Ghandhari et al. [2001a]. These devices can be classified into two categories, one is shunt devices (the injected currents are controlled), and the other is series devices (the inserted voltages are controlled). Static VAR compensator is an example of shunt devices, while series devices include Unified Power Flow Controller (UPFC), Controllable Series Capacitor (CSC) and Quadrature Boosting transformer (QBT). These series devices are known as Controllable Series Devices (CSDs). See Ghandhari [2000], Ghandhari et al. [2001a] for use of CSDs in power system stabilization.

In this paper we synthesize a passivity-based controller for power oscillation damping using a CSC. We use the injection model of the CSC as described in Ghandhari [2000], Ghandhari et al. [2001a] and consider the SMIB system with the CSC. The SMIB system is modeled using two simplified models. The control objective here is to assign suitable damping and interconnection structure to the closed-loop system in order to effectively suppress the transient oscillations and thus enhance the transient stability of the system. We use IDA PBC controller synthesis to compute the control law. The paper is organized as follows: The dynamics of the SMIB control system is given in Section 2. In Section 3 we give the main results in the paper. For the second order model a control scheme based on damping injection and energy shaping is proposed. For the third order model a couple of damping assignment control laws along with two conditions on the achievable damping are provided. The simulation plots for one of the control laws are given in Section 4. And finally Section 5 concludes the paper.

2. MODEL OF THE SMIB SYSTEM WITH A CSC

Consider the SMIB system with a CSC as shown in Figure 1. The generator internal bus 1 is connected to the infinite bus 2 through the transient reactance x'_{d_1}. The controllable series capacitor is represented by the variable capacitor $-jx_c$. The infinite bus represents a large power system with a very large center of inertia, and is considered as a reference.

We use the following notation: δ_1 is the swing angle and ω_1 is the rotor speed deviation with respect to a synchronously rotating reference, respectively, for the generator. Further, x_{d_1}, x_{q_1}, E'_{q_1}, T'_{d0_1} and E_{fd_1} are the d-axis synchronous reactance, q-axis synchronous reactance, the

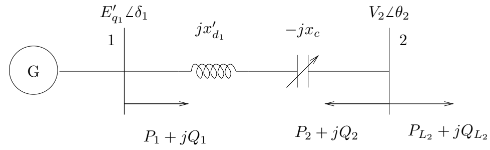

Fig. 1. SMIB system with CSC

q-axis voltage behind transient reactance, the d-axis transient open-circuit time constant, and the exciter voltage (assumed to be constant), respectively, for the generator. Let $D_1 > 0$, $M_1 > 0$, P_{m_1}, P_{G_1} be the damping constant, moment of inertia constant, the mechanical power input, and power injected into the system, respectively. Next we assume that the rotor is round rotor type, and hence neglect the effect of the saliency of the rotor. Since the bus 2 is the infinite bus, V_2 is constant. Also θ_2 is constant and is assumed to be zero. We take the following energy function of the system:

$$H(\delta_1, \omega_1, E'_{q_1}) = T + V \tag{1}$$

where T denotes the kinetic energy and V denotes the potential energy term,

$$\begin{aligned} T &= \frac{1}{2} M_1 \omega_1^2 \\ V &= -P_{m1}\delta_1 + \frac{1}{2x'_{d_1}}\left[E'^2_{q_1} + V_2^2 - 2E'_{q_1}V_2\cos\delta_1\right] \\ &\quad - \frac{E_{fd1}E'_{q_1}}{x_{d_1} - x'_{d_1}} + \frac{E'^2_{q_1}}{2(x_{d_1} - x'_{d_1})}. \end{aligned}$$

The energy function is given here in terms of system variables, e.g. δ_1, ω_1, E'_{q_1} etc. In subsequent discussion we use the same energy function expressed in state variables to write the port-Hamiltonian representation of the two models of the SMIB system.

We describe the SMIB system using two different models, one is the swing equation model and the other is the classical third order model. The swing equation is the second order differential equation which describes the rotor dynamics. Using the injection model of the CSC given in Ghandhari [2000],Ghandhari et al. [2001a] we can write the following second order state space model:

$$\begin{aligned} \dot{x} &= f(x) + g(x)u_c \\ &= \begin{bmatrix} x_2 \\ \frac{1}{M_1}\left[P_{m_1} - D_1 x_2 - P_{\max_1}\sin x_1\right] \end{bmatrix} + \\ &\quad \begin{bmatrix} 0 \\ -\frac{1}{M_1}P_{\max_1}\sin x_1 \end{bmatrix} u_c \end{aligned}$$

with the state variables as $x_1 = \delta_1$, $x_2 = \omega_1$ and $x = [x_1\ x_2]^T$ as the state vector. We denote $P_{\max_1} = \frac{E'_{q_1}V_2}{x'_{d_1}}$ and the control action $u_c = \frac{x_c}{x'_{d_1} - x_c}$. Using the energy function $H(x)$ given in (1) we can rewrite the system dynamics in the following port-Hamiltonian representation:

$$f(x) = [J(x) - R(x)] \frac{\partial H}{\partial x}(x)$$

with

$$J(x) = -J^T(x) = \begin{bmatrix} 0 & \frac{1}{M_1} \\ -\frac{1}{M_1} & 0 \end{bmatrix},$$

$$R(x) = R^T(x) = \begin{bmatrix} 0 & 0 \\ 0 & \frac{D_1}{M_1^2} \end{bmatrix} \geq 0.$$

The other model used in this paper is the classical third order model. It includes the flux decay effect in addition to the swing equation. For this model

$$\begin{aligned} \dot{x} \quad & f(x) + g(x)u_c \\ = & \begin{bmatrix} x_2 \\ \frac{1}{M_1}\left[P_{m_1} - D_1 x_2 - \frac{V_2}{x'_{d_1}} x_3 \sin x_1\right] \\ \frac{1}{T'_{d01}}\left[E_{f_{d_1}} - V_2 \cos x_1 + \frac{x_{d_1}}{x'_{d_1}}(V_2 \cos x_1 - x_3)\right] \end{bmatrix} + \\ & \begin{bmatrix} 0 \\ -\frac{V_2}{M_1 x'_{d_1}} x_3 \sin x_1 \\ \frac{x_{d_1}}{T'_{d01} x'_{d_1}} [V_2 \cos x_1 - x_3] \end{bmatrix} u_c \end{aligned}$$

with $x = [x_1 \; x_2 \; x_3]^T$ as the state vector, the state variables as $x_1 = \delta_1$, $x_2 = \omega_1$, $x_3 = E'_{q_1}$, and the control action $u_c = \frac{x_c}{x'_{d_1} - x_c}$. Using the energy function $H(x)$ given in (1) we can rewrite the system dynamics in the following port-Hamiltonian representation:

$$f(x) = [J(x) - R(x)] \frac{\partial H}{\partial x}(x)$$

with

$$J = -J^T = \begin{bmatrix} 0 & \frac{1}{M_1} & 0 \\ -\frac{1}{M_1} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$R = R^T = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{D_1}{M_1^2} & 0 \\ 0 & 0 & \frac{x_{d_1} - x'_{d_1}}{T'_{d_{01}}} \end{bmatrix} \geq 0.$$

3. CONTROLLER SYNTHESIS USING IDA-PBC

Synchronous generators generally exhibit poor mechanical damping. In addition there is no coupling available between the electrical damping and the mechanical damping. Thus the system undergoes heavy oscillations under fault conditions. In order to avoid any damage to the system these oscillations need to be damped effectively. This damping injection can be achieved by feeding back the passive output $g^T(x)\frac{\partial H}{\partial x}(x)$. In addition we can aim at assigning a coupling between the mechanical subsystem and the electrical subsystem.

Here we assume that the region of operation is

$$\mathcal{D} = \left\{ (\delta_1, \omega_1, E'_{q_1}) \mid \delta_1 \in (0, \frac{\pi}{2}), E'_{q_1} > 0 \right\}.$$

Following the discussion in Galaz et al. [2003] it can be shown that there are two equilibria in $\mathcal{D}$. One of them is a stable equilibrium denoted by $x_\star$ and the other is an unstable equilibrium which we denote by x_u. We assume that $x_\star$ is known to us and state the control objective as "to synthesize a control law u_c in order to make the system asymptotically stable at $x_\star$ and to improve the transient stability of the system by assigning suitable damping and interconnection structure to the closed-loop system."

3.1 IDA-PBC Control

Consider the state space model of the system

$$\dot{x} = f(x) + g(x)u_c.$$

Let $x_\star$ be the stable equilibrium of the system. We assume that the closed system is of the form:

$$\dot{x} = [J_d(x) - R_d(x)] \frac{\partial H_d}{\partial x}$$

where $J_d(x) = -J_d^T(x)$ is a desired interconnection structure matrix, $R_d(x) = R_d^T(x) \geq 0$ is a desired damping matrix, and $H_d(x)$ is a desired Hamiltonian function such that $x_\star = \arg\min H_d(x)$, and satisfying the following equations Ortega and Garcia-Canseco [2004]:

$$g^\perp(x) \left\{ f(x) - [J_d(x) - R_d(x)] \frac{\partial H_d}{\partial x} \right\} = 0, \qquad (2)$$

where $g^\perp(x)$ is a full rank left annihilator of the input matrix $g(x)$. Then the feedback control law is given by Ortega and Garcia-Canseco [2004]

$$\begin{aligned} & u_c(x) \\ & = \left[g^T(x)g(x)\right]^{-1} g^T(x) \left[[J_d(x) - R_d(x)] \frac{\partial H_d}{\partial x} - f(x) \right] \end{aligned} \qquad (3)$$

3.2 Energy Shaping and Damping Assignment for the Second Order Model

For the second order model of the the SMIB system we assume that the operating equilibrium is $x_\star = (x_{1_\star}, 0)$. We state our control objective as to add damping in x_2 coordinate so as to improve the transient response of the system. In addition we modify the energy function $H(x)$ to $H_d(x) = H(x) + H_a(x)$ so as to make $H_d(x)$ strongly convex in $\mathcal{D}$. This convexity property of the energy function could be exploited to give an estimate of the domain of attraction, see, e.g. Galaz et al. [2003]. Thus we take $J_d(x) = J(x) + J_a(x)$, $R_d(x) = R(x) + R_a(x)$, and $H_d(x) = H(x) + H_a(x)$ with $H(x)$ given in (1) and

$$J_a(x) = \begin{bmatrix} 0 & \alpha_1 \\ -\alpha_1 & 0 \end{bmatrix}, \; R_a(x) = \begin{bmatrix} \gamma_1 & 0 \\ 0 & \gamma_2 \end{bmatrix},$$

with $\alpha_1 = \gamma_1 = 0$ and $\gamma_2 \geq 0$. Also we wish to make the desired Hamiltonian $H_d(x)$ a positive definite function in $\mathcal{D}$ with its minimum at $x_\star$. In this direction we modify the energy function by taking $H_a(x) = \frac{1}{2}\beta(x_1 - x_{1_\star})^2$ with some $\beta > 0$. With this choice of $J_a(x), R_a(x)$ and $H_a(x)$ and taking $g^\perp(x) = [1\ 0]$ as a full rank left annihilator of $g(x)$ it can be shown that (2) is satisfied. We next compute the feedback control law as given by (3)

$$u_c(x) = \left(\frac{M_1}{P_{\max_1}\sin x_1}\right)^2 \begin{bmatrix} 0 & -\frac{1}{M_1}P_{\max_1}\sin x_1 \end{bmatrix} \begin{bmatrix} 0 \\ -\frac{\beta}{M_1}(x_1 - x_{1_\star}) - \gamma_2 M_1 x_2 \end{bmatrix}$$
$$= \frac{M_1}{P_{\max_1}\sin x_1} \begin{bmatrix} 0 \\ \frac{\beta}{M_1}(x_1 - x_{1_\star}) + \gamma_2 M_1 x_2 \end{bmatrix}.$$

3.3 Interconnection and Damping Assignment for the Third Order Model

Consider the third order model of the SMIB system given in Section 2. We assume that the SMIB system is operating at a stable equilibrium $x_\star = (x_{1_\star}, 0, x_{3_\star})$. For simplicity we denote the i-th component function of the input vector $g(x)$ by g_i, for $i = 1, \ldots, 3$. As stated earlier the control objective is to improve the transient response of the system. We can achieve this control objective by suitably assigning the interconnection and the damping structure. In IDA PBC damping injection is achieved by feeding back the passive output $g^T(x)\frac{\partial H}{\partial x}(x)$. In this case $g^T(x)\frac{\partial H}{\partial x}(x) = g_2(x)\frac{\partial H}{\partial x_2}(x) + g_3(x)\frac{\partial H}{\partial x_3}(x)$.

Here we assume

$$J_a(x) - R_a(x) = \begin{bmatrix} -\gamma_1 & \alpha_1 & \alpha_2 \\ -\alpha_1 & -\gamma_2 & \alpha_3 \\ -\alpha_2 & \alpha_4 & -\gamma_3 \end{bmatrix},$$

for some nonnegative $\gamma_1, \gamma_2, \gamma_3$ and real $\alpha_1, \alpha_2, \alpha_3$. Note that all γ_i and α_i for $i = 1, \ldots, 3$ are real valued functions of x. Now suppose that we assign a positive damping $\gamma_2(x)$, then in order to feed back the passive output and at the same time to satisfy the matching equations, $\gamma_3(x)$ has to take a specific form, which can result in injection of negative damping in x_3 dynamics.

To overcome this difficulty we assign some positive damping $\gamma_2(x)$ and assign $\gamma_1 = \gamma_3 = \alpha_1 = \alpha_2 = 0$ with $H_d(x) = H(x)$. Then the matching equations dictate the remaining parameters, that is $\alpha_3 = 0$, $\alpha_4 = -\frac{\gamma_2(x) g_3(x)}{g_2(x)}$. Here we need to satisfy a constraint that the symmetric part of the $J_d(x) - R_d(x)$ matrix be negative semi-definite. This constraint ensures that the damping injection is non-negative. Further this constraint gives rise to a bound on $\gamma_2(x)$ as follows: $0 \leq \gamma_2(x) \leq r_2(x)$ where

$$r_2(x) = 2\left(\frac{g_2}{g_3}\right)^2 \left[\frac{x_{d_1} - x'_{d_1}}{T'_{d_{01}}} + \sqrt{\left(\frac{x_{d_1} - x'_{d_1}}{T'_{d_{01}}}\right)^2 + \left(\frac{g_3}{g_2}\right)^2 \frac{D_1}{M_1^2}\frac{x_{d_1} - x'_{d_1}}{T'_{d_{01}}}}\right].$$

The above condition gives a bound on the achievable damping $\gamma_2(x)$. A feedback control law which achieves this interconnection and damping assignment can be computed from (3) as

$$u_c(x) = -\frac{\gamma_2(x) M_1 x_2}{g_2(x)}.$$

In a similar way we can assign damping $\gamma_3(x)$ in the state x_3. Here we take $\gamma_1 = \gamma_2 = \alpha_1 = \alpha_2 = 0$, and $H_d(x) = H(x)$. We get $\alpha_3 = -\frac{\gamma_3(x) g_2(x)}{g_3(x)}$ and $\alpha_4 = 0$. Following the same procedure as above we get a condition on achievable $\gamma_3(x)$ as: $0 \leq \gamma_3 \leq r_3(x)$ where

$$r_3(x) = 2\left(\frac{g_3}{g_2}\right)^2 \left[\frac{D_1}{M_1^2} + \sqrt{\left(\frac{D_1}{M_1^2}\right)^2 + \left(\frac{g_2}{g_3}\right)^2 \frac{D_1}{M_1^2}\frac{x_{d_1} - x'_{d_1}}{T'_{d_{01}}}}\right].$$

The control law which achieves this control objective can be computed as

$$u_c(x) = -\frac{\gamma_3(x)}{g_3(x)}\frac{\partial H}{\partial x_3}(x).$$

Thus we get a couple of conditions which give bounds on assigning damping in the system. It should be noted that in both the cases $r_2(x)$ and $r_3(x)$ are functions of the state vector x, and the conditions are dominant in different regions in $\mathcal{D}$ depending upon x. Using the above control laws we modify the interconnection structure in addition to damping injection. The derivations of the above results are omitted for brevity.

4. SIMULATION RESULTS

In this section we provide a few simulation results. For simulations we consider only the second order model with the energy shaping and damping assignment control law. We omit other simulation results for brevity.

For simulation we take the following system parameters given in Ghandhari [2000]: $M_1 = \frac{8}{100\pi}, D_1 = \frac{2}{100\pi}, E'_{q_1} = 1.075(\text{p. u.}), V_2 = 1(\text{p. u.}), x'_{d_1} = 0.85, P_{m1} = 1.1(\text{p. u.})$ and the tuning parameters are γ_2 and β. The performance of the controller was assessed using the following two different transients:

(1) A short circuit fault occurs at the far end of the transmission line at time $t = 20$ s for a duration of about 0.1 s
(2) sudden loss of one of the two parallel transmission lines resulting in change in x'_{d_1} at time $t = 60$ s for a duration of about 1.1 s

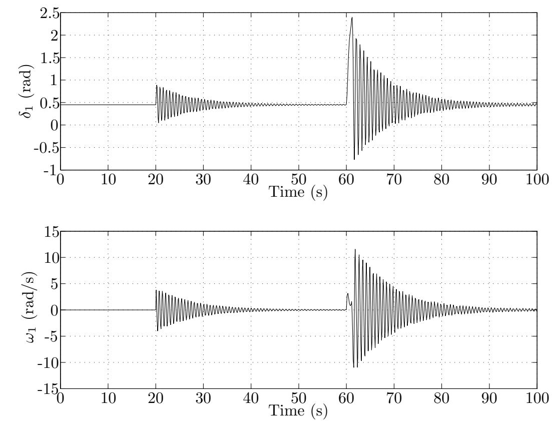

Fig. 2. Open loop performance to the transients

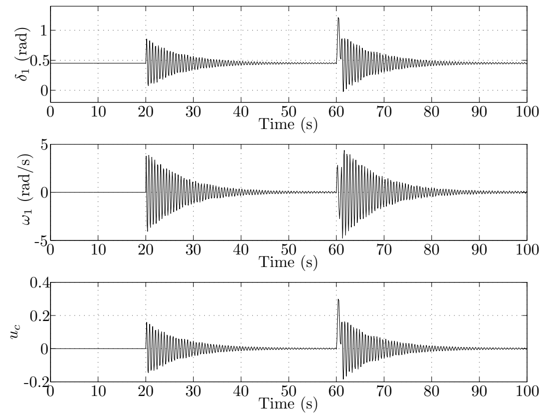

Fig. 3. Closed-loop performance with $\gamma_2 = 0.2, \beta = 0.01$

The open loop performance as well as closed-loop performance is presented in the plots. Figure 2 shows the open loop response of the system to both the transients. Due to the transients the load angle and the angular velocity undergo heavy oscillations.

To examine the closed-loop response we consider the following tuning parameters:

(1) $\gamma_2 = 0.2$ and $\beta = 0$
(2) $\gamma_2 = 0.2$ and $\beta = 0.01$
(3) $\gamma_2 = 20$ and $\beta = 0$.

In all the three cases load angle, angular velocity and the control effort are plotted. In the first case the closed-loop system shows a similar response as shown in Figures 2 to the transients. In the second case damping γ_2 is the same as the first case but $\beta = 0.01$. Here the magnitude of the swing is significantly reduced as compared to the first case as plotted in Figure 3. For the third case $\beta = 0$ and $\gamma_2 = 20$, and the results are plotted in Figure 4. The closed-loop system shows heavy oscillations, but the oscillations die out comparatively quickly. This shows the effect of the damping injection. Due to the control action the oscillations caused by the transients diminish quickly, and the system again returns to the stable operating condition as shown in the figures.

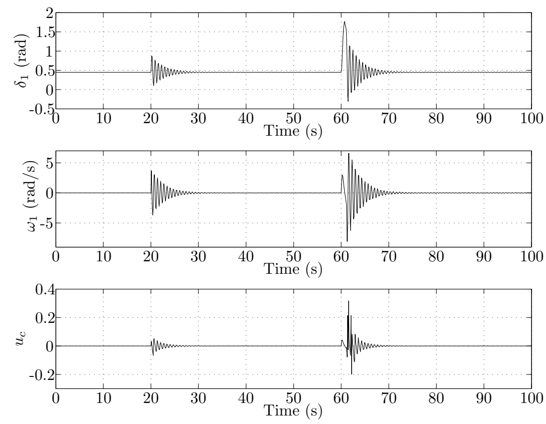

Fig. 4. Closed-loop performance with $\gamma_2 = 20, \beta = 0$

5. CONCLUSION

In this paper we presented a few results on passivity based control of the SMIB stabilization problem. A power electronic device, a CSC, was used as an actuator. With such an actuation the control input vector $g(x)$ was found to be a nonlinear function of x. This makes the control synthesis quite a challenging problem. For the second order model we could achieve a two-fold control objective. First to suppress the oscillatory behaviour of the system by assigning additional damping to the inherent dissipation of the system. And the second control objective achieved was to modify the energy function in a suitable manner so as to render it positive definite in some neighbourhood of the operating equilibrium. The simulation results were provided to examine the controller performance. The control laws obtained were found to be of simple form. For the third order model we achieved damping and interconnection assignment to the system. In this case we presented two bounding conditions on achievable damping.

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REFERENCES

A. Bazanella, A. S. e Silva, and P. Kototovic. Lyapunov design of excitation control of synchronous machines. In *IEEE Conference on Decision & Control*, pages 211–216, San Diego, 1997.

A. Bazanella, P. Kototovic, and A. S. e Silva. A dynamic extension for L_gV controllers. *IEEE Trans. on Automatic Control*, pages 588–592, 1999.

J. W. Chapman, M. Ilic, C. A. King, L. Eng, and H. Kaufman. Stabilizing a multimachine power system via decentralized feedback linearizing excitation control. *IEEE Trans. on Power Systems*, 8(1):830–839, 1993.

G. Espinosa-Perez, M. Godoy-Alcantar, and G. Guerrero-Ramirez. Passivity-based control of synchronous generators. pages SS101–SS106, Portugal, 1997.

M. Galaz, R. Ortega, A. Bazanella, and A. Stankovic. An energy-shaping approach to the design of excitation control of synchronous generators. *Automatica*, pages 111–119, 2003.

M. Ghandhari. *Control Lyapunov Functions: A Control Strategy for Damping of Power Oscillations in Large Power Systems*. Doctoral Dissertation, 2000.

M. Ghandhari, G. Andersson, and I. A. Hiskens. Control Lyapunov functions for controllable series devices. *IEEE Trans. on Power Systems*, 16(4):689–694, November 2001a.

M. Ghandhari, G. Andersson, M. Pavella, and D. Ernst. A control strategy for controllable series capacitor in electrical power systems. *Automatica*, pages 1575–1583, 2001b.

X. Jiao, Y. Sun, and T. Shen. Energy-shaping control of power systems with direct mechanical damping assignment. In *Proceedings of IFAC*, 2006.

D. Karagiannis, A. Astolfi, and R. Ortega. Adaptive Output feedback stabilization of a class of nonlinear systems. In *IEEE Conference on Decision & Control*, pages 1491–1496, Las Vegas, 2002.

C. A. King, J. W. Chapman, and M. D. Ilic. Feedback linearizing excitation control on a full-scale power system model. *IEEE Trans. on Power Systems*, pages 1102–1109, 1994.

D. S. Kirschen, R. Bacher, and G. T. Heydt. Special Issue on the Technology of Power System Competition. *Proceedings of the IEEE*, 88(2):91–98, February 2000.

J. De Leon-Morales, G. Espinosa-Perez, and I. Macias-Cardoso. Observer-based control of a synchronous generator: a Hamiltonian approach. pages 655–663, 2002.

X. Y. Li. Nonlinear controller design of thyristor controlled series compensation for damping inter-area power oscillations. *Electric Power Systems Research*, pages 1040–1046, 2006.

Q. Lu and Y. Z. Sun. Nonlinear stabilizing control of multimachine power systems. *IEEE Trans. on Power Systems*, pages 236–241, 1989.

P. Maya-Ortiz and G. Espinosa-Perez. Output feedback excitation control of synchronous generators. *International Journal of Robust and Nonlinear Control*, pages 879–890, 2004.

W. Mielczarsky and A. M. Zajaczkowski. Nonlinear field voltage control of a synchronous generator using feedback linearization. *Automatica*, pages 1625–1630, 1994.

Y-H. Moon, B-K Choi, and T-H Roh. Estimating the domain attraction for power systems via a group of damping-reflected energy functions. *Automatica*, pages 419–425, 2000.

R. Ortega, M. Galaz, A. Astolfi, Y. Sun, and T. Shen. Transient stabilization of multimachine power systems with nontrivial transfer conductances. *IEEE Trans. on Automatic Control*, 50(1):60–75, January 2005.

R. Ortega and Eloisa Garcia-Canseco. Interconnection and Damping Assignment Passivity-Based Control: Towards a Constructive Procedure-Part I. In *Proceedings of* 43^{rd} *IEEE Conference on Decision & Control*, pages 3412–3417, Atlantis, 2004.

R. Ortega, A. Stankovic, and P. Stefanov. A passivation approach to power systems stabilization. In *Proceedings of IFAC*, 1998.

M. A. Pai. *Energy Function Analysis for Power System Stability*. Kluwer Academic Publishers, Boston, MA, 1989.

T. Shen, R. Ortega, Q. Lu, S. Mei, and K. Tamura. Adaptive L_2 control of hamiltonian systems with parametric perturbation and application to power systems. In *IEEE Conference on Decision & Control*, Sydney, Australia, December, 2000.

Y. Z. Sun, Y. H. Song, and X. Li. Novel energy-based Lyapunov function for controlled power systems. *IEEE Power Engineering Review*, pages 55–57, May 2000.

Y. Wang, D. J. Hill, R. H. Middleton, and L. Gao. Transient stability enhancement and voltage regulation of power systems. *IEEE Trans. on Power Systems*, pages 620–627, 1993.