15th Triennial World Congress, Barcelona, Spain

A NONLINEAR DECENTRALIZED STEAM VALVING CONTROLLER FOR MULTIMACHINE POWER SYSTEMS

Zairong Xi

Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China

Abstract: In this paper we represent a multimachine power system with steam valve as a Hamiltonian control system. Then a decentralized steam valving control scheme is proposed. The property of attenuating disturbances is studied in the sense of H_∞ for the control scheme. *Copyright © 2002 IFAC*

Keywords: Multimachine power system, Steam valving control, H_∞ control, decentralized control, Hamiltonian control system.

1. INTRODUCTION

With the emergence of the large-scale power systems, finding the control law to enhance their transient stability has become imperative. Until recently, the majority of research in this field has been involved in the excitation control. However, the steam valving control contributes significantly not only to enhance the transient stability, but also to improve the dynamic performance of the large-scale power systems and suppress the system oscillation as well. Furthermore, under certain conditions steam valving control may have greater effects on the system stability than excitation control, since the latter only controls the field voltage, which in turn changes the synchronizing torque of the generator, while the former controls the mechanical output directly . Thus, studying and implementing the control schemes on valve opening of modern steam turbines will significantly enhance the stability of power system.

The nonlinear nature and the high-dimensional characteristic of the large-scale power system make the controller design difficult. Much work has been done on the linearized power system model. After the introduction of the differential geometric tools (Isidori, 1995), advanced nonlinear control techniques have been applied to the controller design (Lu, *et al.*, 1989, Chapman, *et al*., 1993, King, *et al*., 1994, Jain, *et al*., 1997, van der Schaft, 1999). Based on differential geometric tools (Isidori, 1995), the controller firstly tries to cancel the inherent system nonlinearities in order to obtain a feedback equivalent linear system, then the control law is proposed by means of the linear system design (Lu, *et al*, 1989, Chapman, *et al*, 1993, King, *et al*, 1994, Jain, *et al*, 1997, van der Schaft,1999).However, control law such designed has not fully utilized the nonlinear nature of the power system since some nonlinearities can be useful to dynamical system's stability itself, and should be utilized in the controller design. Moreover, due to the complete cancellation of the nonlinearities, the control law may be very complex, which will lead to the rising of the cost of the control action.

Very recently, port-controlled Hamiltonian (PCH) systems have been studied (van der Schaft, 1999, Cheng, *et al*., 1999a, 1999b Escobar, *et al*., 1999, Cheng, *et al*., 2000, Xi, *et al*., 2000, Maschke, *et al*., 1999). Indeed, the Hamiltonian function in PCH systems is the total energy, i.e. the sum of potential and kinetic energy in the physical systems, and can play the role of Lyapunov function for the system. As a matter of fact, the power system is a typical energy-producing and energy-consuming system. So it should be a natural way to model the power system as a PCH system and design controller sequentially. In this respect, a single-machine infinite bus power system has been represented by a PCH system in (Cheng, *et al*., 2000, Xi, *et al*., 2000, Cheng, *et al*., 1999b, Shen, *et al*., 2000). In Xi, *et al*., 2002, the representation of multimachine power system as PCH were also given. From Xi, *et al*., 2000, Cheng, *et al*., 1999b, Shen, *et al*., 2000, we have known that the Hamiltonian function method has some good properties. In this paper, further good properties will be shown and the nonlinear steam valving control will be studied by means of the generalized Hamiltonian control system .

Since physical limitation on the system structure makes information transfer among subsystems unfeasible, decentralized controllers for multimachine systems must be used. There have been numerous results on decentralized robust control of power systems (Wang, *et al*., 1997, Chapman, *et al*., 1993, King, *et al*., 1994, Lu, *et al*., 1996, Sun, *et al*., 1996, Jain, *et al*., 1994). The controller presented in this paper is also decentralized.

In this paper, based on the *generalized Hamilton system* theory, a decentralized nonlinear steam valving controller is proposed to improve the transient stability and disturbance attenuation of multimachine power systems. In section 2 generalized Hamiltonian system's concepts are briefly introduced. The model of multimachine power systems with steam valving control is represented as a generalized Hamiltonian system in section 3. Sections 4 and 5 discuss the stability and disturbances attenuation in the sense of H_∞ using the generalized Hamiltonian control system's theory respectively. Sections 6 and 7 give simulation results about a three machine system to support the theoretical claims. Simulations show that the resulting decentralized nonlinear controller can guarantee the overall stability of the multimachine power systems.

2. DYNAMICAL MODEL

Consider an n-machine system. Based on the rotor motion equations and the generator power output equations in a multi-machine system, we can obtain the swing equations of the generator (Lu, *et al.*, 1993, Lu, *et al*, 2001):

$$\begin{cases} \dot{\delta}_i(t) = \omega_i(t) - \omega_0, \\ \dot{\omega}_i(t) = -\frac{D_i}{H_i}\left[\omega_i(t) - \omega_0\right] + \frac{\omega_0}{H_i}\left[P_{Hi}(t) + C_{Mi}P_{m0i} - P_e\right] + w_{i1} \end{cases} \tag{1}$$

where δ_i is the power angle between the q-axis electrical potential vector $\vec{E}_{qi}$ and a reference bus voltage vector $\vec{V}_{REF}$ in the system, in rad; ω_i is the rotating speed of the i-th generator, in rad/s; P_{Hi} is the mechanical power of high-pressure (HP) turbine, in per unit; E_{qi}' and E_{qj}' are the q-axis internal transient electric potential of the i-th and j-th generator, respectively, in per unit; P_{mi0} is the initial mechanical power of the i-th generator, in per unit; H_i, C_{Hi} are moment of inertia in second and the power fraction of HP turbine respectively; G_{ii} and B_{ij} are self-conductance of the i-th bus and the mutual-susceptance between the i-th and the j-th bus respectively, w_{i1} are disturbances imposed on the mechanical part and

$$P_e = G_{ii}E_{qi}'^2 + E_{qi}'\sum_{j=1}^{n} B_{ij}E_{qj}'\sin\left(\delta_i(t) - \delta_j(t)\right).$$

If only the HP controlled valve is considered without consideration of the fast valving control, the dynamic equation of steam valving control system is (Lu, *et al.*, 1993, Lu, *et al*, 2001):

$$\dot{P}_{Hi}(t) = -\frac{1}{T_{H\Sigma i}}P_{Hi}(t) + \frac{C_{Hi}}{T_{H\Sigma i}}P_{m0i} + \frac{C_{Hi}}{T_{H\Sigma i}}u_{Hi} + w_{i2} \tag{2}$$

where $T_{H\Sigma i} = T_{Hgi} + T_{Hi}$ is the equivalent time constant of HP turbine, T_{Hgi} the time constant of oil-servomotor of regulated valve of HP turbine, T_{Hi} the time constant of HP turbine, u_{Hi} the electrical control signal from the controller for the regulated valve, w_{i2} are disturbances acting on the steam valving system.

Denote $a_i = \frac{D_i}{H_i}, b_i = \frac{\omega_0}{H_i}, c_i = \frac{\omega_0}{H_i}C_{Mi}P_{m0i} - \frac{\omega_0}{H_i}G_{ii}E_{qi}'^2,$ $d_{ij} = B_{ij}\frac{\omega_0}{H_i}E_{qi}'E_{qj}', e_i = \frac{1}{T_{H\Sigma i}},\quad k_i = \frac{C_{Hi}}{T_{H\Sigma i}}P_{m0i}$. Let $x_{i1} = \delta_i(t), x_{i2} = \omega_i(t) - \omega_0, x_{i3} = P_{Hi}(t)$ as state variables and $u_i = \frac{C_{Hi}}{T_{H\Sigma i}}u_{Hi}$ as controls. Then the dynamics can be described by

$$\begin{cases} \dot{x}_{i1} = x_{i2}, \\ \dot{x}_{i2} = -a_i x_{i2} + b_i x_{i3} + c_i - \sum_{j=1}^{n} d_{ij}\sin(x_{i1} - x_{j1}) + w_{i1}, \\ \dot{x}_{i3} = -e_i x_{i3} + k_i + u_i + w_{i2}. \end{cases} \tag{3}$$

Let $H = \sum_{i=1}^{n}\left[\frac{1}{2}x_{i2}^2 - \left(c_i + \frac{b_i k_i}{e_i}\right)x_{i1} - \frac{1}{2}\sum_{j=1}^{n} d_{ij}\cos(x_{i1} - x_{j1}) + \frac{1}{2p_i}\left(x_{i3} - \frac{k_i}{e_i}\right)^2\right].$

Then the dynamics can be written as a generalized Hamiltonian control system

$$\begin{pmatrix} \dot{x}_{i1} \\ \dot{x}_{i2} \\ \dot{x}_{i3} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ -1 & -a_i & b_i p_i \\ 0 & 0 & -e_i p_i \end{pmatrix}\nabla_{x_i}H + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}u_i + \begin{pmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} w_{i1} \\ w_{i2} \end{pmatrix}.$$

where $p_i > 0,\ x_i = (x_{i1} \quad x_{i2} \quad x_{i3})^T$. It is easy to see that $H(x)$ is bounded from below because of $x_{i1} \in [-\pi \quad \pi]$.

3. STABILIZATION OF THE STEAM VALVING SYSTEM

In this section consider the stabilization of the steam valving system. Suppose that $w_{i1} = w_{i2} = 0$ throughout the section. Firstly, choosing $u_i = -b_i p_i x_{i2} + v_i$, the closed-loop system has the following form

$$\begin{pmatrix} \dot{x}_{i1} \\ \dot{x}_{i2} \\ \dot{x}_{i3} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ -1 & -a_i & b_i p_i \\ 0 & -b_i p_i & -e_i p_i \end{pmatrix} \nabla_{x_i} H + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} v_i .$$

Next select

$$v_i = -\frac{l_i}{p_i}\left(x_{i3} - \frac{k_i}{e_i} \right),$$

where $l_i > 0$ are control gain which can be arbitrarily selected. Then the equilibrium point of the closed-loop system is determined by

$$\begin{aligned} & c_i + \frac{b_i k_i}{e_i} = \sum_{j=1}^{n} d_{ij} \sin\left(x_{i1}{}^{e} - x_{j1}{}^{e} \right), \\ & x_{i3}{}^{e} = \frac{k_i}{e_i}, \\ & x_{i2}{}^{e} = 0. \end{aligned} \qquad (4)$$

Selecting $H(x)$ as Lyapunov function, we have

$$\frac{dH}{dt} = -\sum_{i=1}^{n} a_i x_{i2}{}^{2} - \sum_{i=1}^{n} \frac{e_i p_i + l_i}{p_i{}^{2}} \left(x_{i3} - \frac{k_i}{e_i} \right)^2 ,$$

Then the closed-loop system is convergent to the largest invariant set contained in

$$A = \left\{ x : x_{i2} = 0, x_{i3} = \frac{k_i}{e_i} \right\}.$$

From $x_{i2} = 0$ and $x_{i3} = \frac{k_i}{e_i}$, we know that $c_i + \frac{b_i k_i}{e_i} = \sum_{j=1}^{n} d_{ij} \sin(x_{i1} - x_{j1})$. It is easy to see that the closed-loop contained in set A is asymptotically stable. From the *La Salle Invariant Principle* (Slotine, *et al.*, 1991), we know that the closed-loop system is asymptotically stable. So we have the following *Proposition*.

Proposition 1: The multimachine power system model (1)-(2) can be stabilized by the decentralized static state feedback

$$u_i = -\frac{\omega_0}{H_i} p_i (\omega_i - \omega_0) - \frac{l_i}{p_i} (P_{Hi} - C_{Hi} P_{m0i}), \qquad (5)$$

where $l_i > 0, p_i > 0$ and $i = 1, \cdots, n.$

4. DYNAMICAL MODEL WITH EXTERNAL DISTURBANCES

In this section consider the effect of the previous control (5) on attenuating disturbances for a power system which consists of n synchronous machines. Select *The Penalty Signals* as follows:

$$z_i = \begin{pmatrix} \omega_i - \omega_0 \\ \frac{P_{Hi} - C_{Hi} P_{m0i}}{p_i} \end{pmatrix} = \begin{pmatrix} x_{i2} \\ \frac{1}{p_i}\left(x_{i3} - \frac{k_i}{e_i} \right) \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \nabla_{x_i} H, i = 1, \cdots, n, \qquad (6)$$

If choosing

$$u_i = -b_i p_i x_{i2} - \frac{l_i}{p_i}\left(x_{i3} - \frac{k_i}{e_i} \right), i = 1, \cdots, n,$$

then the closed-loop system can be written as

$$\begin{pmatrix} \dot{x}_{i1} \\ \dot{x}_{i2} \\ \dot{x}_{i3} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ -1 & -a_i & b_i p_i \\ 0 & -b_i p_i & -e_i p_i - l_i \end{pmatrix} \nabla_{x_i} H + \begin{pmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} w_{i1} \\ w_{i2} \end{pmatrix}.$$

Theorem 2: For the multimachine power system model (1)-(2)-(6), there exists a $\gamma^* > 0$ such that for every $\gamma \geq \gamma^*$, there exist control laws

$$u_i = -b_i p_i x_{i2} - \frac{l_i}{p_i}\left(x_{i3} - \frac{k_i}{e_i} \right), i = 1, \cdots, n,$$

such that the closed-loop system satisfies

$$\int_0^T \|z(t)\|^2 dt \leq \gamma^2 \int_0^T \|w(t)\|^2 dt, \forall w \in L^2[0 \quad T], \forall T > 0, \qquad (7)$$

and the closed-loop system is asymptotically stable when $w = 0$.

Proof. It is well known that if there exists a smooth function $V(x)$ which is bounded from below such that

$$\frac{\partial V}{\partial x} \dot{x} + \frac{1}{2} z^T z - \frac{\gamma^2}{2} w^T w \leq 0, \forall w \in L^2[0 \quad T], \forall T > 0, \qquad (8)$$

then the inequality (7) is satisfied. And the inequality (8) is equivalent to

$$\frac{\partial V}{\partial x}(J-R)\nabla H+\frac{1}{2\gamma^2}\frac{\partial V}{\partial x}GG^T\left(\frac{\partial V}{\partial x}\right)^T+\frac{1}{2}z^Tz\le 0. \tag{9}$$

Choosing $V(x)=\alpha H(x)$, where $\alpha>0$, (9) is converted into

$$\frac{\partial H}{\partial x}\left[-\alpha R+\left(\frac{\alpha^2}{2\gamma^2}+\frac{1}{2}\right)GG^T\right]\nabla H\le 0, \tag{10}$$

It is easy to see that there exist positive numbers $\alpha, l_i, \gamma,$ such that (10) is satisfied. In fact, (10) is equivalent to

$$\begin{cases}\gamma^2\ge\dfrac{\alpha^2}{2a_i\alpha-1},\\ \gamma^2\ge\dfrac{\alpha^2}{2(e_ip_i+l_i)\alpha-1}\end{cases}. \tag{11}$$

From previous section, the closed-loop system is asymptotically stable when $w=0$.

Next consider the selection of α, l_i, γ in detail.

In fact, for any positive numbers α and γ, it is sure that there exist $l_i>0$ and $p_i>0$ ($i=1,\cdots,n$) such that

$$\gamma^2\ge\frac{\alpha^2}{2(e_ip_i+l_i)\alpha-1},$$

So the selection of α and γ is dependent on the inequalities

$$\gamma^2\ge\frac{\alpha^2}{2a_i\alpha-1},$$

i.e., the limitation of attenuating disturbances in the sense of H_∞ is determined by the system itself.

It is easy to see that $x=\frac{1}{a}$ is the minimum point of $f(x)=\frac{x^2}{2ax-1}$ in the constraint $2ax-1>0$. So the minimum $\gamma^*=\max_i\left\{\frac{1}{a_i}\right\}$. The corresponding α^* is the same as γ^*.The corresponding l_i and p_i must satisfies

$$l_i\ge\frac{1}{2\alpha^*}-e_ip_i,$$
$$l_i>0,$$
$$p_i>0.$$

Remark: In fact, we give a new design method for nonlinear control system other than differential geometric method. The procedure is as follows.

Step 1: Represent a nonlinear control system as a generalized Hamiltonian control system. This step always can be realized.

Step 2: Find a controller such that the closed-loop system can be represented as

$$\dot{x}=(J-R)\nabla H+g_1v+g_2w.$$

Step 3: Check whether the dynamical system $\dot{x}=(J-R-g_1Kg_1)\nabla H$ is asymptotically stable in the largest invariant set of $B=\{x: R\nabla H=0, g_1Kg_1{}^T\nabla H=0\}$, where K is a positive matrix. If so, then the system can be stabilized. If not, go back to step 1.

Step 4: Find the desired gain matrix K such that the closed-loop system has the property of attenuating disturbances.

5. A THREE MACHINE EXAMPLE

A three-machine example system shown in Figure 1 is chosen to demonstrate the effectiveness of the proposed nonlinear decentralized controller.

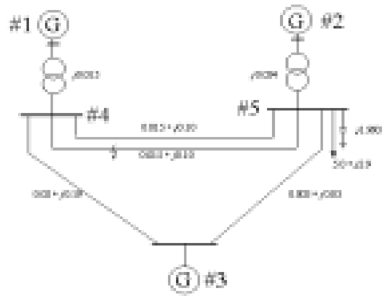


Fig. 1 A three machine example

The system parameters used in the simulation are as follows (Wang, *et al*., 1997):

Table 1 System parameters

Syst para	Gen #1	Gen #2
x_d (p.u.)	1.863	2.36
x_d' (p.u.)	0.257	0.319
x_T (p.u.)	0.129	0.11
D (p.u.)	5	3
T_{d0}' (p.u.)	6.9	7.96
H (s)	8	10.2
x_{ad} (s)	1.712	1.712
k_c	1	1
ω_0 (rad/s)	314.159	314.159
C_M	0.7	0.72
C_H	0.3	0.29
P_{m0}	0.82	0.8
$T_{H\Sigma i}$	0.398	0.4

In the example system, since the generator #3 is a slack bus, we have $E_{q3}' = const = 1\angle 0^{\circ}$. It is easy to see that

$$u_1 = -b_1 p_1 x_{12} - \frac{l_1}{p_1}\left(x_{13} - \frac{k_1}{e_1}\right) = -\frac{\omega_0 p_1}{H_1} x_{12} - \frac{l_1}{p_1}\left(x_{13} - C_{H1} P_{m01}\right),$$

$$u_2 = -b_2 p_2 x_{22} - \frac{l_2}{p_2}\left(x_{23} - \frac{k_2}{e_2}\right) = -\frac{\omega_0 p_2}{H_2} x_{22} - \frac{l_2}{p_2}\left(x_{23} - C_{H2} P_{m02}\right),$$

where l_1, l_2 and p_1, p_2 are positive. In simulation we select $l_1 = 0.1, l_2 = 0.2, p_1 = 2, p_2 = 3$.

6. SIMULATIONS

In this section the simulation results concerning the dynamic behavior of the three-machine system under the presented control law are shown. A symmetrical three-phase short-circuit fault occurring on the transmission line near bus 4 is considered.

From figure 2, it is well shown that under the proposed control law, the dynamic system is stabilized under the fault that occurs at 0.1sec and is cleared at 0.3sec.

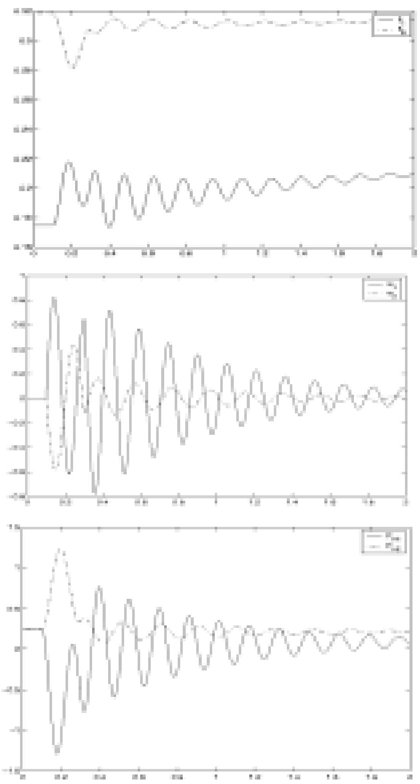


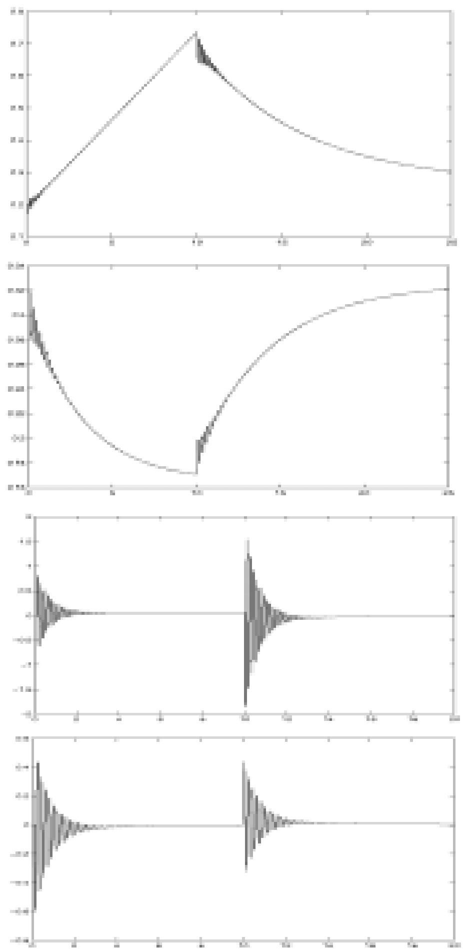
Fig. 2 The responses of closed-loop systemsunder the fault that occurs at 0.1sec and is cleared at 0.3sec.

To verify the effects of the proposed control law, further simulation is conducted. In Figure 3, the fault occurs at 0.1sec, and is cleared at 10sec which endangers the transient stability of the dynamic system much more seriously. From these Figures, it is well shown that:

1. Due to the long interval of the fault, during the fault time (0.1sec to10sec), the machine rotor angle δ_1 increases rapidly while δ_2 decreases in a fast way. The speeds of the machine begin to oscillate, and the system is in the great danger of losing synchronous stability. It verifies the well known fact that the system stability is in much relevance to the clearing time.

2. However, even in such a serious fault, after the clearing of the fault, the proposed control law has still stabilized the dynamic system under investigation .

3. Carefully scrutinizing the Figure 3, another interesting but meaningful conclusion can be drawn. Figure 3 shows that, even during the fault, the speed oscillation died away under the proposed control law, which shows the damping effects of our controller. Further investigation shows that damping effects of the controller is a natural result of Hamiltonian control which based on the Lyapunov's energy function.



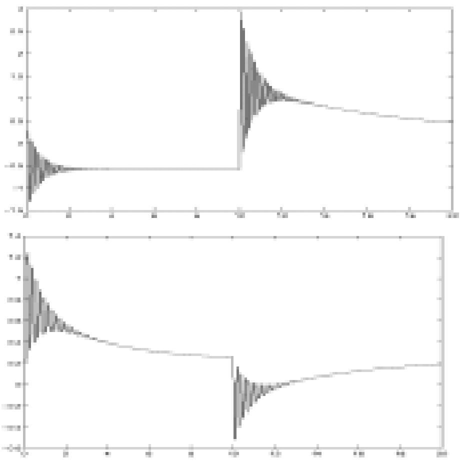


Fig. 3 The responses of closed-loop systemsunder the fault that occurs at 0.1sec and is cleared at 10sec.

7.CONCLUSION

In this paper we apply the generalized Hamiltonian control system's theory to large-scale power systems with steam valving control. A simple decentralized control scheme is obtained, which fully utilizes the nonlinear nature of power systems and is easy to be implemented technically. Simulation shows that the proposed control law is effective to enhance the transient stability, and to improve the dynamic performance of the large-scale power systems.

ACKNOWLEDGMENT

The research is partially supported by a National Natural Science Foundation of China (No. 59837270) and National Key Project of China (No. G1998020308, No. G1998020309).

REFERENCES

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

Cheng, D., H. Qin, Y. Hong, and Z. Xi (1999a). From conservation to openness--generalized Hamiltonian control theory and its application. *Control theory and applications*, vol.**16**:156--162.

Cheng, D., Z. Xi, Y. Hong, and H. Qin (1999b). Energy-based stabilization of forced Hamiltonian systems with its application to power systems. In: *Proceedings of the 14th IFAC*, vol.**O**: 297--302.

Cheng, D., Z. Xi, Q. Lu, and S. Mei (2000). Geometric structure of generalized controlled Hamiltonian systems and its application. *Science in China (Series E)*, vol.**43**:365--379.

Escobar, G., A.J. van der Schaft, and R. Ortega (1999). A Hamiltonian viewpoint in the modeling of switching power converters.*Auotmatica*, vol.**35**:445--452.

Isidori, A (1995). *Nonlinear Control Systems*. Springer-Verlag, New York, 3rd edition.

Jain, S. and F. Khorrami (1997). Robust decentralized control of power systems utilizing only swing angle measurements. *International Journal of Control*, vol.**66**(4):581--601.

Jain, S., F. Khorrami, and B. Fardanesh (1994). Adaptive nonlinear excitation control of power system with unknown interconnections. *IEEE Transactions on Control Systems Technology*, vol.**2**:436--446.

King, C. A. J.W. Chapman, and M.D. Ilic (1994). Feedback linearizing excitation control on a full-scale power system model. *IEEE Transactions on Power Systems*, vol.**9**:1102--1109.

Lu, Q. and Y. Sun (1989). Nonlinear stabilization control of multimachine systems. *IEEE Transactions on Power Systems*, vol.**4**:236--241.

Lu, Q. and Y. Sun (1993). *Nonlinear control in power system*. Scientific Press House, Beijing, China

Lu, Q., Y. Sun, and S. Mei (2001). *Nonlinear Control Systems and Power System Dynamics*. Kluwer Academic Pub.

Lu, Q., Y. Sun, Z. Xu, and T. Mochizuki (1996). Decentralized nonlinear optimal excitation control. *IEEE Transactions on Power Systems*, vol.**11**:1957--1962.

Maschke, B.M.J., R.Ortega, A.J. van der Schaft, and G. Escobar (1999). An energy-based derivation of Lyapunov functions for forced systems with application to stabilizing control. In: *Proceedings of the 14th IFAC*, Beijing.

Shen, T., R. Ortega, Q. Lu, S. Mei, and K. Tamura (2000). Adaptive L_2 disturbance attenuation of Hamiltonian systems with parametric perturbation and application to power systems. *preprint*.

Slotine, J.J.E. and W. Li (1991). *Applied nonlinear control*. Prentice Hall, New Jersey.

Sun, C., Z. Zhao, Y. Sun, and Q. Lu (1996). Design of nonlinear robust excitation control for multimachine power systems. *IEE Proceedings of Generation, Transmission and Distribution*, vol.**143**:253--257.

van der Schaft, A.J (1999). *L_2 Gain and Passivity Techniques in Nonlinear Control*. Springer-Verlag, London Limited, 2nd edition.

Wang, Y., G. Guo, and D.J. Hill (1997). Robust decentralized nonlinear controller design for multimachine power systems. *Automatica*, vol.**33**:1725--1733.

Xi, Z., and D. Cheng (2000). Passivity-based stabilization and H_∞ control of the Hamiltonian control systems with dissipation and its applications to power systems. *International Journal of Control*,vol.**73**:1686--1691.

Xi, Z., D. Cheng, Q. Lu, and S. Mei (2002). Nonlinear decentralized controller design for multimachine power systems using Hamiltonian function method. *Automatica*, vol.**38**:527--53