Passivation controller design for turbo-generators based on generalised Hamiltonian system theory

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Passivation controller design for turbo-generators based on generalised Hamiltonian system theory

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Abstract: A method of pre-feedback to formulate the generalised forced Hamiltonian system model for speed governor control systems is proposed. Furthermore, passivation controllers are designed based on the scheme of Hamiltonian structure for single machine infinite bus and multimachine power systems. In particular, in the case of multimachine systems, all the variables in the control law are only relevant to the state variables of the local generator, which means that a decentralised controller is achieved. Simulation results of a four-machine system show that the controller can enhance power system transient stability.

1 Introduction

Modern power systems are large, distributed and highly nonlinear systems, and thus it is becoming more and more urgent to design nonlinear decentralised controllers for modern power systems to improve their stability and dynamic performance. Hamiltonian system theory is an active field in nonlinear science. Recent studies [1, 2] have shown that a class of generalised forced Hamiltonian system can be defined based on generalised Hamiltonian vector fields and pseudo-Poisson brackets. The generalised forced Hamiltonian system is free from the dimension restriction of the classical Hamiltonian system and is an open system with energy dissipation and exchange with the environment from the point of view of energy. Hence, it is suitable for passivity-based design for controllers. The latest research has successfully introduced the control theory in generalised Hamiltonian systems into the field of nonlinear control in power systems: the excitation control system [3] can be described as a port-controlled Hamiltonian system and can guarantee asymptotic stability at the operation point by feedback. Reference [4] illustrates that in power systems the Hamiltonian function may act as the storage function and contribute to the disturbance attenuation control in the sense of L_2-gain. However, all the results published so far are only applicable to simple power system models like the single machine infinite bus (SMIB) system and multimachine systems when neglecting the network transfer conductance. This is partly because the transfer conductance will introduce a route-dependent item into the potential energy [5], which is generally difficult to deal with. As is well known, since the transfer conductance mainly corresponds to the network loads in the multimachine reductive model, so the validity of the system model and the effectiveness of the designed controllers will be greatly weakened without consideration of the transfer conductance. The power system in practical operation is a multimachine one, so a more realistic model should be used in the application of Hamiltonian theory to power system control.

The paper first presents concisely the definition and theorem in passivation control which will be used in the following sections, and then illustrates how to transform the speed governor control system into a generalised forced Hamiltonian system model. In particular, the multimachine system of turbo-generators is discussed in detail taking into account the effect of transfer conductance. Based on the model obtained, a passivation controller [6] is designed for multimachine systems while the variables in the control law are all locally measurable, namely the goal of decentralised control is achieved. Simulation results are given and the effectiveness of the controller is confirmed.

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2 Passivity and passivation control

The concept of system passivity is an extension of network passivity, which is extremely important in studying nonlinear system stability. If the energy stored in a system is always smaller than or equal to the sum of the stored energy at initial time and the total externally supplied energy, there can be no internal energy creation and only internal dissipation is possible. Then the system is said to be passive. The definition is given as follows.

Definition 1 [7]. Consider the nonlinear system given by

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ y = h(x) \end{cases} \tag{1}$$

where u and y are the input and output, respectively, with the same dimension; f and h satisfy $f(0) = 0$, $h(0) = 0$, respectively. The system is passive if there exists a positive definite function $V(x)$ such that the passivity inequality

$$\dot{V} \le u^T y \quad \forall T \ge 0 \tag{2}$$

holds for all inputs u.

The stabilisation problem of nonlinear systems can be formulated as the passivity problem. As for system (1), if a proper feedback control law

$$u = \beta(x) + v$$

is achieved by turning the system into a passive one from new input v to output y, then the control strategy to ensure a closed-loop system to be globally stable is

$$u = \beta(x) - \varphi(y) \tag{3}$$

where φ is any vector function satisfying $\varphi(0) = 0$ and $\varphi(y) y > 0, \forall y \neq 0$.

3 Generalised forced Hamiltonian model for turbo-generators

3.1 SMIB system

Suppose the steam turbine is of reheat type and only the high pressure (HP) stage is under consideration [8]. Suppose that E_q' in the generator keeps constant in transient dynamics, and the dynamic model is as follows:

$$\begin{cases} \dot{\delta} = \omega_0 \omega_r \\ \dot{\omega}_r = \frac{1}{M}(P_m - D\omega_r - P_{em}\sin\delta) \\ \dot{P}_m = \frac{1}{T_s}(-P_m + P_{ms} + u_g) \end{cases} \tag{4}$$

where δ is the rotor angle (rad), $\omega_r = \omega - 1$ p.u. is the deviation of rotor speed from ω_0, $\omega_0 = 2\pi f_0$ is the synchronous speed (rad/s), and P_m is the mechanical power produced by the boiler (p.u.). Constant $P_{em} = E_q' V_t / X_{d\Sigma}'$, where E_q' is transient EMF in the q-axis of the generator, $V_t = 1.0$ p.u. is the voltage at the infinite bus, and parameters D, M, and T_s are the damping constant, inertia constant and time constant of the HP stage with its valving system, respectively. u_g is the speed governor control and (δ_s, 0, P_{ms}) is the initial operation point.

The system above does not agree with the Hamiltonian structure, and a transformation for the speed governor has to be adopted. One feasible approach is to introduce a proper pre-feedback into the system such as

$$\alpha(x) = \delta - \delta_s \tag{5}$$

The system with pre-feedback is

$$\begin{cases} \dot{\delta} = \omega_0 \omega_r \\ \dot{\omega}_r = \frac{1}{M}(P_m - D\omega_r - P_{em}\sin\delta) \\ \dot{P}_m = \frac{1}{T_s}\left(-P_m + P_{ms} + (\delta - \delta_s) + u_g'\right) \end{cases} \tag{6}$$

Construct its Hamiltonian function as

$$H(\delta, \omega_r, P_m) = \frac{1}{2} M\omega_0\omega_r^2 - [P_m(\delta - \delta_s) + P_{em}(\cos\delta - \cos\delta_s)] + \frac{1}{2}(P_m - P_{ms})^2 \tag{7}$$

Then,

$$\frac{\partial H}{\partial x}(x) = \left[\frac{\partial H}{\partial \delta}\ \frac{\partial H}{\partial \omega_r}\ \frac{\partial H}{\partial P_m}\right]' = \begin{bmatrix} -P_m + P_{em}\sin\delta \\ M\omega_0\omega_r \\ (P_m - P_{ms}) - (\delta - \delta_s) \end{bmatrix} \tag{8}$$

The generalised forced Hamiltonian structure for system (6) is

$$\dot{x} = [J(x) - R(x)]\frac{\partial H}{\partial x} + g(x)u_g' \tag{9}$$

where

$$J(x) = \begin{bmatrix} 0 & \frac{1}{M} & 0 \\ -\frac{1}{M} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad R(x) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{D}{M\omega_0} & 0 \\ 0 & 0 & \frac{1}{T_s} \end{bmatrix}$$

$$g(x) = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_s} \end{bmatrix}$$

System model (9) is also known as the standard port-controlled Hamiltonian system with dissipation (PCHD).

3.2 Multimachine system

Taking the same assumption as SIMB system above, the dynamic model for the multimachine power system is

$$\begin{cases} \dot{\delta}_i = \omega_0 \omega_{ri} \\ \dot{\omega}_{ri} = \frac{1}{M_i}P_{mi} - \frac{D_i}{M_i}\omega_{ri} - \frac{1}{M_i}P_{ei} \\ \dot{P}_{mi} = \frac{1}{Tsi}(-P_{mi} + P_{msi}) + \frac{1}{T_{si}}u_{gi} \end{cases} \tag{10}$$

$$P_{ei} = E_{qi}' \sum_{j=1}^{n} E_{qj}'[B_{ij}\sin(\delta_i - \delta_j) + G_{ij}\cos(\delta_i - \delta_j)]$$

where the subscript i identifies the ith unit and other notations are the same as system (4). Similarly, rotor angle feedbacks, (11), are introduced to turn the new closed-loop system, (12), into a generalised forced Hamiltonian system:

$$u_{gi} = \alpha_i + u_{gi}' = (\delta_i - \delta_{si}) + u_{gi}' \tag{11}$$

$$\begin{cases} \dot{\delta}_i = \omega_0 \omega_{ri} \\ \dot{\omega}_{ri} = \frac{1}{M_i}P_{mi} - \frac{D_i}{M_i}\omega_{ri} - \frac{1}{M_i}P_{ei} \\ \dot{P}_{mi} = \frac{1}{Tsi}(-P_{mi} + P_{msi} + (\delta - \delta_s)) + \frac{1}{T_{si}}u_{gi}' \end{cases} \tag{12}$$

Taking the Hamiltonian function for system (12) as

$$H = \frac{1}{2}\omega_0 \sum_{i=1}^{n} M_i\omega_{ri}^2 + \frac{1}{2}\sum_{i=1}^{n}(P_{mi} - P_{msi})^2 - \sum_{i=1}^{n} P_{mi}(\delta_i - \delta_{si}) - \sum_{i=1}^{n} \int_{\delta_i}^{\delta_{si}} P_{ei}d\delta_i \tag{13}$$

we have:

$$\frac{\partial H}{\partial \delta_i} = -P_{mi} + P_{ei} - \frac{\partial}{\partial \delta_i}\left(\sum_{j=1, j\neq i}^{n} \int_{\delta_j}^{\delta_{sj}} P_{ej}d\delta_j\right) = -P_{mi} + P_{ei} + \Sigma_i$$

$$\frac{\partial H}{\partial \omega_{ri}} = \omega_0 M_i \omega_{ri}$$

$$\frac{\partial H}{\partial P_{mi}} = -(\delta_i - \delta_{si}) + (P_{mi} - P_{msi})$$

Seting $x_{i1} = \delta_i$, $x_{i2} = \omega_{ri}$, $x_{i3} = P_{mi}$, $i = 1, 2, \ldots, n$, system (12) can be rewritten as the following generalised forced Hamiltonian system:

$$\dot{x}_i = [J_i - R_i]\frac{\partial H}{\partial x_i} + g_{i1}(x_i)\Sigma + g_{i2}(x_i)u_{gi} \tag{14}$$

where

$$J_i = \begin{bmatrix} 0 & \frac{1}{M_i} & 0 \\ -\frac{1}{M_i} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad R_i = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{D_i}{\omega_0 M_i} & 0 \\ 0 & 0 & \frac{1}{T_{si}} \end{bmatrix}$$

$$g_{i1} = \begin{bmatrix} 0 \\ \frac{1}{M_i} \\ 0 \end{bmatrix} \qquad g_{i2} = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{si}} \end{bmatrix}$$

$$\Sigma_i = -\frac{\partial}{\partial \delta_i}\left(\sum_{j=1,j\neq i}^{n} \int_{\delta_i}^{\delta_{si}} P_{ei} d\delta_i\right)$$

In this model, Σ_i stands for the coupling effect between the ith unit and the other generator sets, containing the network transfer conductance.

4 Nonlinear decentralised passivation controller for turbo-generators

For the multimachine system, (14), define the output variable of the ith unit as

$$y_i = g_{i2}^T \frac{\partial H}{\partial x_i} = \frac{1}{T_{si}}[-(\delta_i - \delta_{si}) + (P_{mi} - P_{msi})] \qquad (15)$$

The decentralised passivation feedback controller takes the form of

$$u'_{gi} = \beta_i(x) + v_i \qquad (16)$$

The closed-loop system is passive if there exists a storage function $V(x_1, x_2, \ldots, x_n)$ such that the passivity inequality

$$\dot{V} \le y^T v \qquad \forall t \ge 0 \qquad (17)$$

holds for all the inputs v, where $y^T = [y_1, y_2, \ldots, y_n]$ is the output and $v^T = [v_1, v_2, \ldots, v_n]$ is the new input. In fact, the Hamiltonian function can act as a storage function in the system.

Since, in real power systems, the coupling effects among different sets are finite, we may safely set a boundary for Σ_i. Assume that

$$\|\Sigma_i\|^2 \le \rho_i(x_i) \frac{\partial^T H}{\partial x_i} g_{i2} g_{i1}^T \frac{\partial H}{\partial x_i} \qquad i = 1, 2, \ldots, n \qquad (18)$$

where $\rho_i\ (x_i)$ is a positive function called the boundary function.

Then the differential of the Hamiltonian function along the trajectory of system (6) is

$$\begin{aligned} \dot{H} &= \sum_{i=1}^{n} \frac{\partial^T H}{\partial x_i}[J_i - R_i]\frac{\partial H}{\partial x_i} + \sum_{i=1}^{n} \frac{\partial^T H}{\partial x_i} g_{i1}\Sigma_i + \sum_{i=1}^{n} \frac{\partial^T H}{\partial x_i} g_{i2} u'_{gi} \\ &= -\sum_{i=1}^{n} \frac{\partial^T H}{\partial x_i} R_i \frac{\partial H}{\partial x_i} + \frac{1}{2}\sum_{i=1}^{n}\left\{\lambda_i \frac{\partial^T H}{\partial x_i} g_{i1} g_{i1}^T \frac{\partial H}{\partial x_i}\right. \\ &\quad \left. + \frac{1}{\lambda_i}\rho_i \frac{\partial^T H}{\partial x_i} g_{i2} g_{i1}^T \frac{\partial H}{\partial x_i}\right\} \\ &\quad - \frac{1}{2}\sum_{i=1}^{n}\left\{\frac{1}{\lambda_i}\rho_i \frac{\partial^T H}{\partial x_i} g_{i2} g_{i1}^T \frac{\partial H}{\partial x_i} - \frac{1}{\lambda_i}\|\Sigma_i\|^2\right\} \\ &\quad - \frac{1}{2}\sum_{i=1}^{n}\left\|\sqrt{\lambda_i} g_{i1}^T \frac{\partial H}{\partial x_i} - \frac{1}{\sqrt{\lambda_i}}\Sigma_i\right\|^2 + \sum_{i=1}^{n} \frac{\partial H}{\partial x_i} g_{i2} u'_{gi} \end{aligned} \qquad (19)$$

for $\forall t \ge 0$, where $\lambda_i > 0$, $i = 1, \ldots, n$, are given constants. If they are small enough such that $R_i - \frac{1}{2}\lambda_i g_{i1} g_{i1}^T \ge 0$, then

$$\begin{aligned} \dot{H} \le &-\sum_{i=1}^{n} \frac{\partial^T H}{\partial x_i}\left\{R_i - \frac{1}{2}\lambda_i g_{i1} g_{i1}^T\right\}\frac{\partial H}{\partial x_i} \\ &+ \sum_{i=1}^{n} \frac{\partial^T H}{\partial x_i} g_{i2}\left\{u'_{g2} + \frac{1}{2\lambda_2}\rho_i g_{i1}^T \frac{\partial H}{\partial x_i}\right\} \end{aligned} \qquad (20)$$

Take the control law to be

$$u'_{gi} = \beta_i + v_i = -\frac{1}{2\lambda_i}\rho_i g_{i1}^T \frac{\partial H}{\partial x_i} + v_i \qquad (21)$$

Hence the passivity inequality

$$\dot{H} \le \sum_{i=1}^{n} y_i v_i = y^T v \quad \forall t \ge 0 \qquad (22)$$

holds, and according to Definition 1 the closed-loop system is a passive system with storage function H.

Furthermore, set $v_i = -k_i y_i$, where $k_i > 0$, $i = 1, 2, \ldots, n$; then

$$\dot{H} \le -\sum_{i=1}^{n} k_i y_i^2 \qquad (23)$$

To summarise the results above, we come to the nonlinear decentralised control law for turbo-generators:

$$\begin{cases} u_{gi} = \alpha_i + \beta_i + v_i \\ \alpha_i = \delta_i - \delta_{si} \\ \beta_i = -\frac{1}{2\lambda_i}\rho_i g_{i1}^T \frac{\partial H}{\partial x_i} = -\frac{1}{2\lambda_i}\rho_i \omega_0 \omega_{ri} \\ v_i = -k_i y_i = -k_i \frac{1}{T_{si}}[-(\delta_i - \delta_{si}) + (P_{mi} - P_{msi})] \end{cases} \qquad (24)$$

In practical engineering, $\Delta\delta_i$ is usually not measured directly, so it is replaced by the integral of rotor speed, namely $\Delta\delta_i = \int_0^t \Delta\omega_i dt$, and the final control strategy is

$$\begin{aligned} u_{gi} = &\int_0^t \Delta\omega_i d\tau - \frac{\rho_i}{2\lambda_i}\omega_0\omega_{ri} \\ &- \frac{k_i}{T_{si}}\left[-\int_0^t \Delta\omega_i d\tau + (P_{mi} - P_{msi})\right] \end{aligned} \qquad (25)$$

where all the variables are locally measurable. Since the control law is only relevant to the local variables, it is decentralised.

5 Simulation results

A 4-machine power system, as shown in Fig. 1, is used for numerical studies, and the system data are listed in Reference [9]. The speed governor control system designed according to the strategy (25) is installed on G1 to G4. In simulation, we set $k_i = 5$, $\lambda_i = 0.1$. From the consideration of practical engineering, we estimate the boundary function as

$$\rho_i = l_i \frac{\partial^T H}{\partial x_i} g_{i2} g_{i1}^T \frac{\partial H}{\partial x_i} = l_i\left[-\int_0^t \Delta\omega_i d\tau + (P_{mi} - P_{msi})\right],$$

$$l_i = 0.1$$

To investigate the effectiveness of the proposed controller in improving transient stability, comparisons are made with the traditional PID speed governor controller from Reference [9] and the nonlinear controller by feedback linearisation from Reference [10].

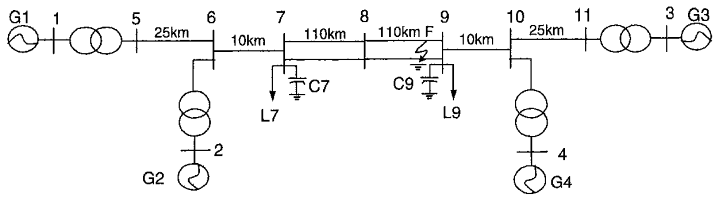

Fig. 1 *Four-machine system*

System transients are stimulated by a three-phase short-circuit fault occurring on line 8–9 close to bus 9 (see Fig. 1), and cleared by tripping the faulted line in 0.15 s. The simulation results are shown in Figs. 2–5, where the solid lines represent the response of the proposed decentralised passivation controller, the broken lines represent that of the traditional PID controller and the dash-dotted lines represent that of the controller designed by the feedback linearisation method. It is clear that the proposed controller produces better performances in the first-swing and subsequent dynamics.

6 Conclusions

With an innovative pre-feedback method, the paper has formulated a generalised forced Hamiltonian model for the turbo-generator systems and consequently achieves a nonlinear passivation controller taking the Hamiltonian function as a storage function. For the multimachine power system, the model takes into consideration the network transfer conductance, which makes it more feasible to apply the Hamiltonian system theory into the field of power system control. The passivation control strategy obtained for the multimachine system is only relevant to the local measurement, so a decentralised controller is realised. Numerical simulations for a 4-machine system illustrate the effectiveness of the proposed controller.

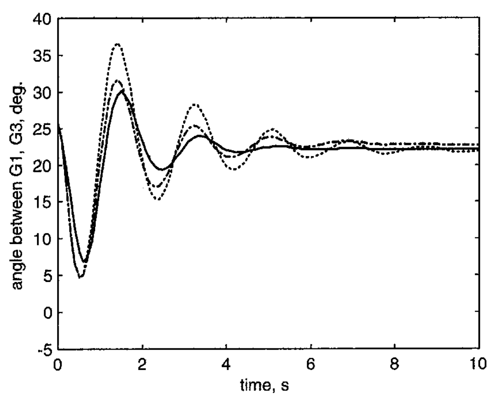

Fig. 2 *Rotor angle between generators G1 and G3*

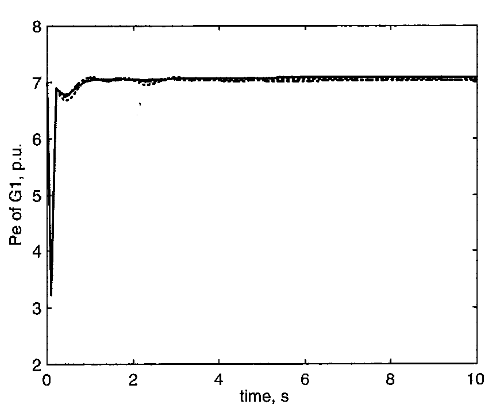

Fig. 3 *Output active power of G1*

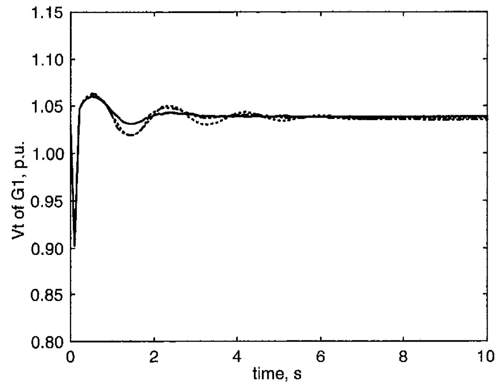

Fig. 4 *Terminal voltage of G1*

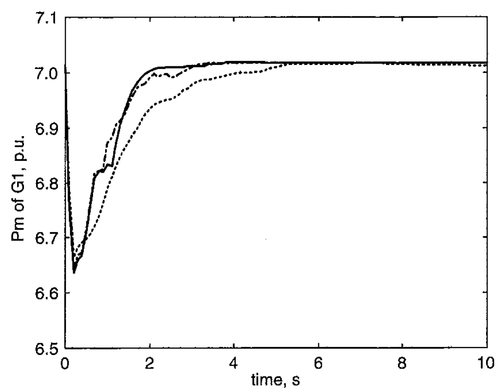

Fig. 5 *Input mechanical power of G1*

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