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A control strategy of Hamilton realization and mechanics Lagrangization in doubly-fed wind power generation system ☆

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ABSTRACT

With the nonlinear characteristic of doubly-fed wind power generation (DFWPG) system, Hamilton realization based on analytical mechanics plays a significant role in the system problems of stability analysis and controller design. Hamilton system expression of grid-side converter (GSC) and machine-side converter (MSC) is obtained and the stability control is designed with Lagrange theory of analytical mechanics in this paper. Firstly, to obtain the differential equations which satisfy satisfies self-adjoint conditions, coordinate transformations of dynamic equations of GSC and MSC are conducted. The system Hamilton function and Hamilton realization expression are determined based on Euler–Lagrange process and generalized force method. On the basis of feedback control theory the controller is designed, which can make the system tend to be asymptotically stable in the neighborhood of the equilibrium point. With Hessian matrix positive-definite the Hamilton system is determined to be stable. Additionally, within Matlab/Simulink environment, the transient simulation of DFWPG system is carried out and the effectiveness of controller derived in this paper is verified, by comparisons of response effects with PI control and regulation performances under different wind speeds. The rapid response of the dc bus voltage control, grid-side unit power factor control, a maximum capture of wind energy can be realized, using control design process of Hamilton realization. The system analysis and control design process of Hamilton realization have broad prospects of applications and developments.

Introduction

Nowadays, with more wind power combined into modern power system, DFWPG system has become the mainstream research direction due to the requirement of low-capacity excitation converter, the wide-range speed regulation, and the independent control of active and reactive powers [1]. The doubly-fed machine model is nonlinear, multi-variable and strong-coupling, so the stability analysis and control design problems are more significant [2,3].

Depending on the characteristics of DFWPG system, the vector control approach is widely used, such as stator flux orientation or stator voltage orientation [4]. With PI (Proportional Integral), LQG (Linear Quadratic Gaussian) and polynomial RST (Rotation Scaling Translation) controls, the process of controller design is simple and the closed-loop feedback strategy has certain robustness [5–7]. The vector and decoupling control process of DFWPG system is designed in [8], which is vulnerable to uncertain conditions such as load disturbances and machine parameters. The current vector control of doubly-fed induction generator wind turbine is presented in [9], based on an integrated control strategy which is developed for wind energy extraction and grid voltage controls. With uncontrollability of wind speed and influence from mechanical damping, it is difficult for traditional vector control approach to guarantee the system performance under rapid variation of wind speed and parameter perturbation of machines, which can result in system instability [10]. With deep study of modern control theory, some advanced control methods begin to play a role in wind power generation, and especially Hamilton realization provides an effective solution for the stability control of wind power generation system [11–13]. The power angle and excitation controls of wind energy conversion system are proposed in [14] using

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Hamilton energy theory, which guarantees the stability of closed-loop system. The derived controller is simple and the system has obvious robustness. The control strategy of GSC and MSC of DFWPG system is constructed in [15] by port-controlled Hamilton and energy-shaping theory, which has robustness and rapid convergence compared with PI control. Based on Hamilton energy method, nonlinear control is studied in [16] for doubly-fed induction generation system, lead to the desired stability of closed-loop system.

The energy function expression is directly given from above literatures about Hamilton realization and controller design of DFWPG system. But the system stability control is studied without giving the construction process of Hamilton function in detail. The construction of Lyapunov function is important for the stability judgment and control of nonlinear system, which is difficult, considering the unified expression not obtained at present. Hamilton realization plays a significant role in the system stability analysis and control design with Lyapunov approach. Analytical mechanics theory provides a construction approach for energy function expression of dynamic system with Lagrangization and Hamilton method [17]. At present, Hamilton realization process with analytical mechanics has been used in many fields, but not in the stability research of DFWPG system.

According to mechanics Lagrangization and Hamilton realization theory, stability analysis and control design of GSC and MSC of DFWPG system are carried out in this paper. To obtain differential equations satisfying self-adjoint conditions, coordinate transformations of system dynamic equations are conducted. Hamilton realization is derived and then controller is designed based on system stability judgment and feedback control strategy, which can make the system tend to be asymptotically stable in the neighborhood of equilibrium points. In addition, the simulation platform of DFWPG system is constructed in Simulink environment, and those stability performances of the derived control and PI control strategies are compared to each other under system transient faults. Finally, the obtained control strategy is verified to be accurate and effective.

Problem description and basic theory

Problem description

The Hamilton realization of nonlinear system can be obtained as the following form:

$$\dot{x} = [J(x) - \Re(x)]\frac{\partial H}{\partial x} + g(x)u, \tag{1}$$

where $x \in R^n$ is state vector, $J^T = -J \in R^{n\times n},\ \Re^T = \Re \in R^{n\times n} \geqslant 0$, are natural interconnection and damping matrices, H is Hamilton function, control input $u \in R^m,\ g \in C(R^n \times R^m)$ is $n \times m$ matrix. When $u = 0$, suppose the equilibrium point of system (1) satisfying $\min H(x)$ is x^*, and the system is stable in neighborhood of equilibrium point. However, the system stability is usually discussed with $u \neq 0$, and x^* may not be the extreme point of $H(x)$.

The system (1) can be extended as

$$\dot{x} = [J(x) - \Re(x)]\frac{\partial H}{\partial x} + g(x)\bar{u} + g(x)u_0, \tag{2}$$

Selecting $u = \bar{u} + u_0,\ \bar{u}$ is a new control variable and u_0 is a constant $(\bar{u}, u_0 \in R^m)$. Suppose that $\bar{x}$ satisfies

$$[J(\bar{x}) - \Re(\bar{x})]\frac{\partial H(\bar{x})}{\partial x} + g(\bar{x})u_0 = 0. \tag{3}$$

Let $\overline{H}(x) = H(x) - H(\bar{x})$, and it is obvious that $\overline{H}(\bar{x}) = 0$. Then there exists control strategy $\bar{u} = -kg^T\frac{\partial \overline{H}}{\partial x}$ ($k \in R$ is positive), which can make the dynamic system (2) tend to be asymptotically stable in the neighborhood of equilibrium point $\bar{x}$.

Mechanics Euler–Lagrange method

For the first-order differential equations

$$F_s(t, \boldsymbol{q}, \dot{\boldsymbol{q}}) = 0, \quad s = 1, \ldots, n, \tag{4}$$

where q is generalized coordinate, Lagrangization can be realized under certain conditions, and Eq. (4) can be expressed as

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_s}\right) - \frac{\partial L}{\partial q_s} = F_s(t, q, \dot{q}). \tag{5}$$

$L = L(t, q, \dot{q})$ is a first-order Lagrange function. The necessary and sufficient conditions of Lagrange realization of first-order equations are self-adjoint conditions, i.e. $(s, k = 1, \ldots, n)$:

$$\frac{\partial F_s}{\partial \dot{q}_k} = -\frac{\partial F_k}{\partial \dot{q}_s}; \tag{6a}$$

$$\frac{\partial F_s}{\partial q_k} = \frac{\partial F_k}{\partial q_s} - \frac{d}{dt}\left(\frac{\partial F_k}{\partial \dot{q}_s}\right). \tag{6b}$$

If the equations do not satisfy self-adjoint conditions, a part of them can be extracted from function F_s and the rest are treated as non-conservative forces, which is called the partial Lagrangization process.

For $2n$ first-order equations

$$\dot{x}_\mu = f_\mu(t, x_\nu), \quad (\mu, \nu = 1, \ldots, 2n), \tag{7}$$

multiply two sides of above equation by $(\omega_{\mu\nu}) = \begin{bmatrix} 0_{n\times n} & -1_{n\times n} \\ 1_{n\times n} & 0_{n\times n} \end{bmatrix}$, and the sum about ν can be obtained as

$$\omega_{\mu\nu}\dot{x}_\nu = F_\mu(t, x_\nu), \tag{8}$$

where $F_\mu = \omega_{\mu\nu} f_\nu$. If functions F_μ satisfy $\frac{\partial F_\mu}{\partial x_\nu} = \frac{\partial F_\nu}{\partial x_\mu}$, the form of Eq. (8) is self-adjoint. Meanwhile, Hamilton realization of Eqs. (8) are followed that $\omega_{\mu\nu}\dot{x}_\nu = \frac{\partial H}{\partial x_\mu}$, where H is the Hamilton function and $H = x_\mu \int_0^1 F_\mu(t, \tau x_\nu) d\tau$. If self-adjoint conditions are not satisfied, both sides of Eq. (8) can be multiplied by some functions and Hamilton realization can be achieved as well[18].

Lagrangization and Hamilton realization process of analytical mechanics can fully reflect the physical meaning of system energy. The operation and control process of DFWPG system is accompanied by mutual energy conversions, so Hamilton realization and stability control can be analyzed with Euler–Lagrange approach.

Hamilton realization and control design of doubly-fed wind power generation system

The model construction of doubly-fed wind power generation system (Fig. 1)

At any rotating speed, d–q coordinate system of two phase dynamic mathematical model of doubly-fed wind power system is more convenient, rather than ABC coordinates in three-phase static model. In this transformation system order decreases, but it doesn't change the characteristics of nonlinear, multivariable, strong coupling.

The MSC model of DFWPG system under dq rotational coordinates is[1]:

$$V_{sd} = R_s i_{sd} + \dot{\varphi}_{sd} - \omega_s \varphi_{sq}; \tag{9a}$$

$$V_{sq} = R_s i_{sq} + \dot{\varphi}_{sq} + \omega_s \varphi_{sd}; \tag{9b}$$