L2 Disturbance Suppression Controller Design for Multiple Time Delays Offshore Wind Turbines

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\textbf{ABSTRACT} With the large-scale development of offshore wind power and the rapid development of smart grid, more and more attention has been paid to the stable operation of wind turbines under various conditions. In the actual operation process of wind turbines, there are inevitably many kinds of uncertain time delays, and also external or parameter disturbances, which affect the stable operation of wind turbines and make the system deviate from the original stable state. Based on Hamiltonian energy theory, the disturbance rejection of doubly fed wind turbines with multiple time delays is studied in this paper. Firstly, the doubly fed wind turbine is Hamiltonian realized to obtain its port controlled Hamiltonian with dissipation (PCH-D) model. Then, aiming at the PCH-D model, a multiple time delays controller is designed based on Casimir function, which can make wind turbines run stably under multiple time delays. Furthermore, based on the passive control theory, L2 gain disturbance rejection control technology is introduced to eliminate the steady-state error caused by external disturbance and improve the stability of wind turbines. Finally, the simulation results show that the proposed controller can effectively solve the multiple time delays and disturbance problems in the system, and improve the stability and anti-interference of wind turbines.

\textbf{INDEX TERMS} Offshore wind power, doubly fed wind turbines, multiple time delays, Hamiltonian energy theory, Casimir function, L2 disturbance attenuation.

\section*{I. INTRODUCTION}

Offshore wind energy resources are abundant, and their utilization becomes an important way to meet energy growth and implement sustainable development [1]–[3]. The development of offshore wind power shows the trend of more requirements on capacity, offshore distance and standardization of grid connection, which means that there are more requirements on the numbers of wind power units and the distance of power transmission. Considering that the environment of offshore wind farm is worse than that of land, some new control requirements for offshore wind farm system are put forward to realize the economic and reliable operation of offshore wind farm.

With the large-scale development of modern power systems with multiple interconnections, wide area measurement system (WAMS) is applied to the power system, which provides the possibility for synchronous measurement and stability control of modern power system. WAMS exists in phasor measurement unit of wind farm, communication system and control system of dispatching control center. The time delays produced in phasor measurement unit and remote measurement signal, may cause the change of the main eigenvalue and main oscillation frequency of the wind power system in the unstable state. Also, time delay leads to the preset controller parameters unavailable and decreases the stability margin of the system, even worsens the operation condition of the power system [4], [5]. In the WAMS, the time delay of signal transmission is usually large (from tens of milliseconds to hundreds of milliseconds), and presents random characteristics. During the implementation of the obtained controller, the total physical time delays resulting from measuring system variables and transmitting system signals may reach 0.14 s, thus the time delays are inevitable occurring
in power engineering and applications of offshore platforms [6]. Therefore, time delay control is of great significance to the stability analysis and control design of offshore wind turbine group system.

At present, many papers have been devoted to the stability analysis of wind turbine system with time delay. The method based on the network predictive control (NPC) is proposed for coordinated design to improve damping and compensate for the time delay in [7]. The novel decentralized sliding mode load frequency control (LFC) strategy is proposed for multiple area time delay power system with significant wind power penetration in [8]. In the paper [9], time delay is considered in command communication from the control unit to the motor driver in wind turbine, and an inertial supplementary scheme is proposed. However, the focus of most research papers is devoted to the stability analysis or controller design of single time delay power system. Also, for the wind power system with time delay, the universal nonlinear time delay system model is adopted, and the specific action position of time delay on the wind turbine model is not considered. The design process is complex and the calculation is large, which has certain limitations and conservatism in the process of transient stability analysis of large-scale power system.

WAMS involves all kinds of communication channels such as power lines, telephone lines and fiber-optics. Different channels have different and stochastic time delays due to different communication media and devices [10]. Therefore closed-loop large power systems ought to be modeled as nonlinear dynamic systems with multiple time delays. Other approaches are based on the definition of a Lyapunov function with the well-known difficulties to find such a function in the complex nonlinear power system [11], [12], or on the solution of a linear matrix inequality (LMI) problem [13], [14]. These methods have been applied to the control problems of some time delay objects. However, in the process of derivation, the matrix inequalities are magnified many times, the stability conditions are obviously conservative, and the computation burden is strenuous. For a complex multiple input & multiple output (MIMO) nonlinear system such as offshore wind turbine group, the time delay will have an adverse effect on the stability and control performance of the control system. In order to facilitate the research of wind power system with multiple time delays, a model with clearer structure and physical meaning is needed, as well as a time delay control method with simpler process and less conservatism.

The generalized Hamiltonian system is defined by generalized Poisson bracket, and the Casimir function is one of the special properties of Poisson manifold. Casimir function is used as a conserved quantity to determine the stability of Hamiltonian system at the equilibrium point, and reduce the dimension of finite dimensional Hamiltonian system. Therefore, Casimir has been widely used and studied in various fields. Casimir function is used to constrain the state of the finite dimensional port Hamiltonian system, the energy function of the controller is easily shaped to solve the regulation problem in [15]. The Energy-Casimir method is proposed to deal with the boundary stability of longitudinal beam vibrations in [16]. Casimir function is an important tool for Hamiltonian system design. The design process is simple and the Casimir function can be used to analyze and control the stability of Hamiltonian system [17]–[19]. In this paper, the time delays in transmission signal and wide area input signal between regions are considered, which are described as random constants of upper and lower bounds. The Casimir function method is applied to the multiple time delays controller design of PCH-D system of wind turbine, which can solve the stability control problem of nonlinear system with multiple time delays. In this design process, the use of multiple uncertain matrices is reduced, and the conservatism brought by multiple matrix amplification is overcome. Therefore, the process is simpler and easier to implement.

The offshore wind farm is located in harsh environment, and the offshore platforms are subjected to more crucial environmental loading such as wind, wave, ice and earthquake. These parameter perturbations and uncertainties may degrade the control performance or even destabilize the offshore wind turbines [20]. Moreover, in the grid connected system, with the equivalent resistance of inductance and the resistance of load resistance changing, the voltage on the grid-side is generally disturbed, and the use of nonlinear load in wind power generation system will also generate external disturbances [21], [22]. These parameter changes and external disturbances may cause the oscillation of the wind turbine, reduce the control performance of the wind turbine, and even destabilize the offshore wind turbine, which have a great impact on its normal operation and safe operation. There are also some nonlinear control methods to suppress the disturbance of offshore wind turbine. A robust mixed H2/H∞ active control algorithm is proposed to improve the performance of offshore platform system in [23]. A dual loop control strategy is proposed to suppress the influence of voltage disturbance on doubly fed induction generator (DFIG) in [24]. However, the above methods are limited to a certain kind of specific disturbance, and a more general uncertain dynamic model for simulations and experiments is lacking. Therefore, the physical meaning in practical application is not intuitive enough, and the design method is relatively complex. In this paper, the gain controller of the multiple time delays system is designed, through introducing L2 gain disturbance control technology in passivity control theory. The steady-state error brought by the sudden change of disturbance in a large range is eliminated, and the parameter disturbance and external interference of the system is effectively suppressed, also the anti-interference ability of the system is enhanced. This method presents the research framework of control theory from the perspective of energy, which makes the physical concept more intuitive and the design process simpler. This method is easier to be accepted by engineers, and more suitable for the wide application of many practical physical systems.

To the authors’ best knowledge, there are few results on the disturbance controller design of power system with multiple
time delays, which motivate the research in this paper. In this paper, the expected stable closed-loop PCH-D system with good structure is obtained by Hamiltonian realization of doubly fed wind turbine. Then, considering that wind turbine is affected by multiple time delays, the PCH-D system with multiple time delays is restricted to invariant manifold by using Casimir function method and Hamiltonian energy shaping, making the multiple time delays system maintain the original expected equilibrium point. For the case that the wind turbine with multiple time delays is subjected to external disturbance or parameter perturbation, on the basis of Casimir time delay control, L2 gain controller is designed by the passivity control theory to determine a new storage function, and the L2 gain of the interference to the penalty signal is less than or equal to the given γ (γ > 0). The perturbed system with multiple time delays is γ dissipative, which can effectively suppress the system interference and ensure the stability of the system. Finally, the effectiveness of the control strategy for wind turbine with multiple time delays and disturbance is verified by simulation.

II. HAMILTONIAN MODEL OF DOUBLY FED WIND TURBINE

The doubly fed wind turbine includes windmill, transmission structure and DFIG. The stator of DFIG is directly connected to the power grid, and the rotor is connected to the power grid through a converter. A typical configuration of doubly fed wind turbine is shown schematically in Figure 1.

In the doubly fed wind turbine, if the windmill, gearbox, shafts and generator are lumped together into an equivalent mass $H_{tot}$, one-mass transmission can be represented by a first-order model with dynamic power [25]:

$$\frac{ds}{dt} = P_s - P_m$$

(1)

where, $H_{tot}$ is the inertia constant of the wind windmill and the generator as a whole; $s$ is the rotor slip rate; $P_m$ is the mechanical power input of the wind turbine; $P_s = -E'_d i_{ds} - E'_q i_{qs}$ is the active power output by the stator.

The accumulation of the transient stator flux caused by the variations of the stator voltage may bring harmful power and torque oscillations to the DFIG, and even lead to rotor over-current. Therefore, the second-order DFIG model ignoring electromagnetic transient of stator is adopted [26]:

$$\begin{align*}
\frac{dE_d}{dt} &= s\omega_S E'_q - E'_d + (X_s - X'_s) i_{qs} - \frac{L_m}{L_{qT}} u_{qT} \\
\frac{dE'_d}{dt} &= -s\omega_S E'_d - \frac{E'_q - (X_s - X'_s) i_{ds}}{T'_0} + \frac{L_m}{L_{dT}} u_{dT} \\
\frac{dE'_q}{dt} &= -s\omega_S E'_q - \frac{E'_r - (X_s - X'_s) i_{ds}}{T'_0} + \frac{L_m}{L_{dT}} u_{dT}
\end{align*}$$

(2)

where, $L_s$ is the self-inductance of the stator; $L_r$ is the self-inductance of the rotor; $R_s$ is the mutual inductance; $R_r$ is the resistance of the rotor; $\omega_S$ is the synchronous angular velocity; $X_s$ is the reactance; $X'_s$ is the transient reactance of the stator; $i_{ds}$ and $i_{qs}$ is the current of the stator on the $d$ shaft and $q$ shaft respectively; $E'_d$ and $E'_q$ is the voltage of the $d$ shaft and $q$ shaft under the transient reactance respectively; $u_{dT}$ and $u_{qT}$ is the voltage of the rotor on the $d$ shaft and $q$ shaft respectively; $X_s = \omega_S L_s$, $X'_s = \omega_S (L_s - L_r^2/L_{qT})$, and $T'_0 = L_{dT}/R_r$.

We consider a mathematical model of a wind turbine with one-mass transmission system and without the stator transients. The flux linkage has no influence on the decaying mode and oscillating mode of the system, under which the doubly fed turbine operation is possible [27]. The doubly fed wind turbine model with one-mass transmission and ignoring the transient state of stator is more suitable for practical application. Therefore, the doubly fed wind turbine is rewritten as a third-order model under the formula (1) (2):

$$\begin{align*}
2H_{tot} \frac{ds}{dt} &= -E'_d i_{ds} - E'_q i_{qs} - P_m \\
\frac{dE'_d}{dt} &= s\omega_S E'_r - E'_d + (X_s - X'_s) i_{qs} - \frac{L_m}{L_{qT}} u_{qT} \\
\frac{dE'_q}{dt} &= -s\omega_S E'_d - \frac{E'_q - (X_s - X'_s) i_{ds}}{T'_0} + \frac{L_m}{L_{dT}} u_{dT}
\end{align*}$$

(3)

therefore, equation (3) is a two-input and third-order model of the wind turbine in the d-q coordinate system, where $s$, $E'_d$, and $E'_q$ are states, $u_{dT}$ and $u_{qT}$ are inputs.

Douly fed wind turbine is a MIMO nonlinear model. Currently, there are many research methods for the design of nonlinear system. The controller designed by other methods of nonlinear system is complex and cannot deal with the uncertain varying MIMO model [28]–[30]. In the generalized Hamiltonian energy method, the nonlinear system is constructed as Hamiltonian system, and Hamiltonian energy function is selected as a Lyapunov function [31]. The difficulties of constructing Lyapunov function is avoid, also, the structural characteristics of the system and the nonlinear characteristics of the energy function are fully utilized. This method does not need accurate model, and the design process is simple, which is suitable for the transient stability analysis of high-order large power system, and has been widely used in practical engineering applications.

In this paper, the PCH-D model of doubly fed wind turbine is taken as the basic model to analysis. In order to transform
the mathematical model of the third-order wind turbine into the form of PCH-D, the third-order model (3) is rewritten into the matrix form as

\[
\frac{d}{dt} \begin{bmatrix} s E'_q \\ E'_d \end{bmatrix} = \begin{bmatrix} -\frac{i_{qs}}{2H_{tot}} E'_q - \frac{i_{ds}}{2H_{tot}} E'_d - \frac{P_m}{2H_{tot}} \\ -\frac{1}{T_0} E'_q - \frac{i_{ds}}{T_0} (X_s - X'_s) + \frac{i_{ds}}{T_0} (X_s - X'_s) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_s \frac{L_{m}}{L_{in}} \\ 0 \end{bmatrix} \begin{bmatrix} u_{dr} \\ u_{qr} \end{bmatrix}
\]

The Hamiltonian energy function of the system is taken as

\[
H = \frac{s^2}{2} + \frac{1}{2} \left( E'_q + \frac{P_m}{2i_{qs}} \right)^2 + \frac{1}{2} \left( E'_d + \frac{P_m}{2i_{ds}} \right)^2
\]

(5)

The model in (4) can be rewritten into PCH form, and then the control law \( u = \begin{bmatrix} u_{dr} \\ u_{qr} \end{bmatrix} = K + \mu \) is designed with pre-feedback \( K \) and output feedback \( \mu \), where

\[
K = \begin{bmatrix} -L_{rr} \left( \frac{i_{ds}}{T_0} (X_s - X'_s) + \frac{P_m}{2T_0 i_{qs}} \right) + \left( \omega_s P_m - \frac{i_{qs}}{2i_{ds}} \frac{P_m}{2H_{tot}} \right) s \\ L_{rr} \left( \frac{i_{qs}}{T_0} (X_s - X'_s) + \frac{P_m}{2i_{ds}} \right) - \left( \omega_s P_m + \frac{i_{ds}}{2H_{tot}} \right) s \end{bmatrix}
\]

(6)

The PCH-D form of the closed-loop system in (4) is obtained [32]:

\[
\frac{d}{dt} \begin{bmatrix} s E'_q \\ E'_d \end{bmatrix} = \begin{bmatrix} 0 & -\frac{i_{qs}}{2H_{tot}} & -\frac{i_{ds}}{2H_{tot}} \\ i_{qs} & -\frac{1}{T_0} - \frac{i_{ds}}{T_0} & \omega_s \frac{L_{m}}{L_{in}} \\ i_{ds} & \frac{1}{T_0} & -\omega_s \frac{L_{m}}{L_{in}} \end{bmatrix} \nabla H + \begin{bmatrix} 0 \\ \omega_s \frac{L_{m}}{L_{in}} \\ 0 \end{bmatrix} \begin{bmatrix} \mu_{dr} \\ \mu_{qr} \end{bmatrix}
\]

\[
y = G^T (x) \nabla H (x) = \begin{bmatrix} \omega_s \frac{L_{m}}{L_{in}} E'_q + \frac{P_m}{2i_{qs}} \\ -\omega_s \frac{L_{m}}{L_{in}} E'_q + \frac{P_m}{2i_{qs}} \end{bmatrix}
\]

(8)

FIGURE 2. The single line diagram of the wind farm.
the Casimir function introduced, and Hamiltonian energy function is introduced as the candidate function of Lyapunov function in the extended system. Through the design of controller, the extended system can operate stably with intact PCH-D structure of the wind turbine system.

1) PROBLEM DESCRIPTION

The PCH-D model of offshore wind turbine is as follows:

\[
\begin{align*}
\dot{x} &= (J(x) - R(x)) \nabla H(x) + \mathbf{G}(x) \mu \\
y &= \mathbf{G}^T(x) \nabla H(x)
\end{align*}
\]  

(9)

where, \(J(x)\) is skew symmetric matrix, \(R(x)\) is nonnegative symmetric matrix, and \(G(x)\) is nonnegative symmetric matrix, and \(G(x)\) is nonnegative symmetric matrix.

The wind turbine is connected to a distant power system, and the time delays exist inevitably in the system. Considering that the time delays not only exist in the feedback control input \(u_{dt}\) and \(u_{dr}\), but also exist in the Hamiltonian function of the system. Therefore, the wind turbine system is modeled as PCH-D with multiple time delays as follows:

\[
\begin{align*}
\dot{x} &= (J(x) - R(x)) \nabla H(x) \\
&+ (J_1(x) - R_1(x)) \nabla H(x (t - \tau_1)) \\
&+ G(x) \mu (t - \tau_2) \\
\dot{y} &= \mathbf{G}^T(x) \nabla H(x)
\end{align*}
\]  

(10)

where, \(J_1(x)\) is skew symmetric matrix, \(R_1(x)\) is nonnegative symmetric matrix, \(r_1\) is the random bounded time delay constant in Hamiltonian function, and \(\tau_2\) is the random bounded time delay constant in input port. The internal time delays \(\tau_1\) and \(\tau_2\) of wind turbine is varying randomly. \(r_{1,\text{min}}\) and \(r_{2,\text{min}}\) are lower bounds of time delays in wind turbine, \(r_{1,\text{max}}\) and \(r_{2,\text{max}}\) are upper bounds of time delays in wind turbine, \(r_1\) satisfies \(r_{1,\text{min}} \leq r_1 \leq r_{1,\text{max}}\), \(r_2\) satisfies \(r_{2,\text{min}} \leq r_2 \leq r_{2,\text{max}}\). \(r_1\) and \(r_2\) are unknown random constants. The time delays of each units in a wind farm are different from that of other units and are constants in the range.

2) CASIMIR FUNCTION DESIGN

In order to make the PCH-D system of closed-loop wind turbine have the expected operation state under multiple time delays, the source system interconnected with the system (10) is proposed as

\[
\begin{align*}
\dot{\xi} &= (J(\xi) - R(\xi)) \nabla H' (\xi) + G'(\xi) \mu' (t - \tau_2) \\
\dot{y'} &= G'^T (\xi) \nabla H' (\xi)
\end{align*}
\]  

(11)

where, \(\xi \in R^n\), \(y' \in R^m\), \(\mu' (t - \tau_2) \in R^m\), \(H' (\xi)\) is the Hamiltonian function after the expansion of dynamic control.

The feedback interconnection controller is designed as

\[
\begin{align*}
\mu (t - \tau_2) &= \mu_1 (t - \tau_1) + \mu_2 (t - \tau_2) \\
\mu_1 (t - \tau_1) &= \mu_1 (t - \tau_1) - (t - \tau_2) y' \\
\mu_2 (t - \tau_2) &= \mu_2 (t - \tau_2) y'
\end{align*}
\]  

(12)

Through interconnection with source system (11), the system is extended as

\[
\begin{align*}
\dot{\xi} &= \left( J(\xi) - R(\xi) \right) - G(x) (t - \tau_2) G'^T (\xi) \\
&+ \left( J'(\xi) - R'(\xi) \right) \nabla H' (\xi) \\
\dot{y'} &= \mathbf{G}^T(x) \nabla H(x) + G(x) \mu_1 (t - \tau_1)
\end{align*}
\]  

(13)

For system (13), a set of Casimir functions in the form \(\xi_i - c_i (x, t - \tau_2), i = 1, 2, \ldots, n\), might be found to construct an invariant Casimir manifold. A necessary and sufficient condition was revealed in [35], which states that \(\xi_i - c_i (x, t - \tau_2)\) are Casimir functions of system (13) if and only if

\[
\begin{align*}
\left( \nabla C (x, t - \tau_2) \right) \dot{C} (x, t - \tau_2) &= J'(\xi) \\
&+ \left( \nabla C (x, t - \tau_2) \right) \dot{C} (x, t - \tau_2) = 0
\end{align*}
\]  

(14)

where \(C (x, t - \tau_2) = (c_1 (x, t - \tau_2), c_2 (x, t - \tau_2), \ldots, c_n (x, t - \tau_2))\).

If this kind of Casimir function exists, an invariant manifold can be defined as

\[B = \{(x, \xi) | \xi_i = c_i (x, t - \tau_2) + d_i, i = 1, 2, \ldots, n\}\]

(15)

where, \(d_i\) are constants. Thus, the system (13) is restricted on the invariant manifold \(B\), and a new energy function satisfied positive definite condition, can be regarded as a Lyapunov function. Based on the above Casimir function, the control strategy of wind turbine is designed. The specific theorem is as follows:

Theorem 1: Considering the doubly fed wind turbine (10) with multiple time delays on the offshore wind farm, the feedback controller is designed as

\[
\begin{align*}
\mu (t - \tau_2) &= \mu_1 (t - \tau_1) + \mu_2 (t - \tau_2)
\end{align*}
\]  

(16)

where,

\[
\mu_1 = -\frac{1}{2} \left( G^T(x) G(x) \right)^{-1} G^T(x) (J_1(x) - R_1(x)) \\
\mu_2 (t - \tau_2) = -(t - \tau_2) G'^T (\xi) \nabla H' (\xi) \bigg|_{\xi = c(x, t - \tau_2) + d_i},
\]

and \(Q\) is a real symmetric invertible matrix. Considering that the Casimir function of system satisfies the existence condition in (14), the closed-loop system can maintain stable operation under the multiple time delays.

Proof of Theorem 1: The feedback controller can be divided into two parts: \(\mu_1\) and \(\mu_2\), which control the time
delays in the Hamiltonian function and the input port, respectively.

The controller \( \mu(t - \tau_2) \) is substituted into PCH-D model (10) of wind turbine, we obtain:

\[
\dot{x} = \left( J(x) - R(x) - \frac{1}{2}Q \right) \nabla H(x) - G(x)(t - \tau_2) G^T(\xi) \nabla H'(\xi) - \frac{1}{2}(J_1(x) - R_1(x)) Q^{-1}(J_1(x) - R_1(x))^T \nabla H(x) + (J_1(x) - R_1(x)) \nabla H(x(t - \tau_1))
\]

Set

\[
\mathbf{I} = J(x) - R(x) - \frac{1}{2}Q - \frac{1}{2}(J_1(x) - R_1(x)) \nabla H(x(t - \tau_1))
\]

then

\[
\dot{x} = \left[ \begin{array}{c} \nabla H(x) + \nabla C(x, t - \tau_2) \nabla H'(\xi) \\
+ (J_1(x) - R_1(x)) \nabla H(x(t - \tau_1)) \end{array} \right] \nabla H(x(t - \tau_1))
\]

Through further calculation, we have

\[
\dot{x} = \left[ \begin{array}{c} \nabla H(x) + \nabla C(x, t - \tau_2) \nabla H'(\xi) \\
+ (J_1(x) - R_1(x)) \nabla H(x(t - \tau_1)) \end{array} \right] \nabla H(x(t - \tau_1))
\]

where

\[
H_a(x, t - \tau_2) = H(x) + H'(x, t - \tau_2)
\]

The interconnection system (13) is expressed as

\[
\dot{\xi} = \left[ \begin{array}{c} \nabla H(x) + \nabla C(x, t - \tau_2) \nabla H'(\xi) \\
+ (J_1(x) - R_1(x)) \nabla H(x(t - \tau_1)) \end{array} \right] \nabla H(x(t - \tau_1))
\]

After introducing Casimir function, Hamiltonian function is expressed as

\[
H'(x, t - \tau_2) = H'(c_1(x, t - \tau_2)
+ d_1, \ldots, c_n(x, t - \tau_2) + d_n)
\]

Take the interconnection system to satisfy:

\[
\left\{ \begin{array}{l}
H'(\xi) = \xi \\
C(x_1, x_2, x_3, t - \tau_2) = \frac{1}{2} \tau_2 x_1^2 \\
G'(x) = \left( \begin{array}{c}
\frac{i_{qs} L_m x_1 \tau_2}{2H_{tot} L_m \omega_k(t - \tau_2)} - \frac{i_{ds} L_m x_1 \tau_2}{2H_{tot} L_m \omega_k(t - \tau_2)}
\end{array} \right)
\end{array} \right.
\]

Then, we have

\[
\nabla H'(\xi) = 1, \nabla C(x_1, x_2, x_3, t - \tau_2) = \left( \begin{array}{c}
\tau_2 x_1 \\
0 \\
0
\end{array} \right)
\]

This satisfies the necessary and sufficient condition in (14) for the existence of Casimir function.

Take the Lyapunov function of the system as

\[
V(x, t) = H_a(x, t - \tau_2) + \frac{1}{2} \int_{t - \tau}^t \nabla H(x(t - t_1)) Q \nabla H(x(t - t_1)) \nabla H(x(t - t_1)) dt
\]

Lyapunov function \( V \) is related to the continuous state variable \( x \), and the time-derivative of Lyapunov function can be obtained, we have

\[
\dot{V}(x, t) = \frac{dV(x, t)}{dt}
\]

Due to

\[
\nabla H_a(x, t - \tau_2)(J_1(x) - R_1(x)) \nabla H(x(t - \tau_1)) \nabla H(x(t - \tau_1)) Q^{-1}(J_1(x) - R_1(x)) \nabla H_a(x, t - \tau_2)
\]

Then

\[
\dot{V}(x, t) \leq -\nabla H_a(x, t - \tau_2) R(x) \nabla H_a(x, t - \tau_2) \leq 0
\]

Through the operation of multiple time delays controller, the PCH-D system with multiple time delays of wind turbine can be restrained on the invariant manifold \( B \). And through choosing a new Lyapunov function, the multiple time delays system (10) can maintain global stability under the source system (11). The proof is complete.

Based on the analysis, when the wind turbine has multiple time delays, the Casimir function method is used in the PCH-D model of the system to design the multiple time delays feedback controller, so that the wind turbine can maintain the effective form of stable PCH-D, eliminate the influence of multiple time delays on the system, and maintain the stable operation of the system.

**IV. L2 DISTURBANCE ATTENUATION CONTROL FOR DOUBLY FED WIND TURBINE**

Due to the harsh and changeable marine environment, the operation characteristics of the wind turbine will be affected by complex nonlinear factors such as environmental
loading, magnetic circuit saturation, magnetic field distortion, eddy current skin effect and other complex nonlinear factors. Especially, under the various complex nonlinear factors affecting, the wind turbine with multiple time delays also is affected by external interference, which may deviate the system from the equilibrium state, and even cause off-grid fault of system [36], [33]. For this kind of nonlinear control problem, some researches have introduced time delay control to further design the interference suppression control of offshore platform. The application of time delay feedback control in the interference suppression of offshore platform is studied, but only low vibration mode is considered, also the time delay design method is relatively complex [37], [38]. For a complex MIMO wind turbine system, L2 gain disturbance control technology combined with Casimir time delay control is adopted to design a controller. The multiple time delays system can still track the desired equilibrium point under the disturbance, and the affect of disturbance is reduced, also the anti-interference ability of the multiple time delays system is improved. In the design process of time delay control, the use of uncertain matrices is reduced. And in the case of disturbance, the L2 gain controller is designed based on energy dissipation. Thus, the physical concept is more intuitive, the design process is simpler, and the stability condition is less conservative, which is more suitable for the transient stability analysis of high-order complex power system.

For the disturbance of wind turbine with multiple time delays, L2 gain controller is designed for the system. First, in the PCH-D model under the original equilibrium state of the system, the expected equilibrium point of the system is obtained. Then, in the PCH-D model with multiple time delays, the L2 gain controller is designed through the dissipation theory, and a new Lyapunov function is selected as the candidate to ensure the stability and anti-interference of the system. When external interference exists in the PCH-D model (10) of the system, the problem of L2 interference suppression can be solved based on the γ dissipative technique [39]. Considering that the PCH-D system with multiple time delays is subjected to external disturbance in the input port, it can be expressed as

\[
\begin{align*}
\dot{x} &= (J(x) - R(x)) \nabla H(x) \\
&\quad + (J_1(x) - R_1(x)) \nabla H(x(t - \tau_1)) \\
&\quad + G(x)(\mu(t - \tau_2) + w) \\
y &= G^T(x) \nabla H(x)
\end{align*}
\]

(17)

where \(w \in \mathbb{R}^m\), the expected equilibrium point of the original system (9) is

\[
x_1 = 0, x_2 = -\frac{P_m}{2i\omega_s} x_3 = -\frac{P_m}{2i\omega_s}
\]

(18)

The goal of L2 gain interference suppression is to design a feedback control law \(\mu_3\) and a positive definite storage function \(V(x)\), at the desired equilibrium point \(x_0 \in \mathbb{R}^n\). \(z\) is the penalty signal and \(\gamma > 0\) is the interference attenuation level, so that the \(\gamma\) dissipation inequality of the closed-loop system is established.

Define a penalty signal \(z\) as follows:

\[
z = h(x) G^T(x) \nabla H_a(x, t - \tau_2)
\]

(19)

where, \(h(x) \in \mathbb{R}^{q \times m}\) is the weighted matrix. Positive storage function \(V\) of dissipative inequality satisfies

\[
\dot{V}(x, t) + M(x) \leq \frac{1}{2} \left( \gamma^2 \|\nu\|^2 - \|z\|^2 \right), V(x_0, t) = 0
\]

(20)

where, \(M(x)\) is a given nonnegative definite function.

Assumption 1: a real symmetric invertible matrix \(Q\) satisfies

\[
-R(x) + \frac{1}{2} Q + \frac{1}{2} (J_1(x) - R_1(x)) Q^{-1} (J_1(x) - R_1(x))^T < 0
\]

(21)

where, matrix \(J_1(x)\) and \(R_1(x)\) are the system matrix of multiple time delays system (10).

Theorem 2: Consider the disturbance of external input, the \(L_2\) gain control strategy is designed as

\[
\mu = -\frac{1}{2} \left( G^T(x) G(x) \right)^{-1} G^T(x)(J_1(x) - R_1(x)) \times Q^{-1} (J_1(x) - R_1(x))^T \nabla H(x) \\
- \frac{1}{2} \left( h^T(x) h(x) G^T(x) + \frac{1}{\gamma^2} G^T(x) \right) \nabla H(x) \\
- \frac{1}{2} \left( G^T(x) G(x) \right)^{-1} G^T(x) Q \nabla H(x) \\
- (t - \tau_2) G^T(\xi) \nabla H'(\xi) \|_{\xi=\xi(x, t - \tau_2)+d_i}
\]

(22)

If assumption 1 holds, based on the above control strategy (22), the wind turbine with multiple time delays can achieve stable operation under disturbance and maintain the expected output power, and reduce the steady-state error.

Proof of Theorem 2: The control strategy \(\mu\) is substituted into the system (17), we have

\[
\begin{align*}
\dot{x} &= \nabla H_a(x, t - \tau_2) + (J_1(x) - R_1(x)) \nabla H(x(t - \tau_1)) \\
&\quad + \left( -\frac{1}{2} G^T h^T(x) h(x) G^T(x) - \frac{1}{2\gamma^2} G^T G^T(x) \right) \\
&\quad \times \nabla H(x) + G(x) w
\end{align*}
\]

Take the Lyapunov function \(V\) of the system as

\[
V(x, t) = H_a(x, t - \tau_2) + \frac{1}{2} \int_{t - \tau_1}^{t} \nabla^T H(x(t - \tau_1)) \\
\times Q \nabla H(x(t - \tau_1)) \, dt
\]

Taking the derivative of the Lyapunov function \(V\), we have

\[
\dot{V}(x, t) = -\frac{1}{2} \nabla^T H_a(x, t - \tau_2) (J_1(x) - R_1(x))^T Q^{-1} \cdot \\
(J_1(x) - R_1(x))^T \nabla H_a(x, t - \tau_2) - \frac{1}{2} \nabla^T H_a(x, t - \tau_2) \cdot \\
\left( G(x) h^T(x) h(x) G^T(x) + \frac{1}{\gamma^2} G^T G^T(x) \right)
\]
\[\begin{align*}
\dot{V} (x, t) &\leq -\nabla^T H_a (x, t - \tau_2) R (x) \nabla H_a (x, t - \tau_2) \\
&\quad + \nabla^T H_a (x, t - \tau_2) G (x) w \\
&\quad - \frac{1}{2} \nabla^T H_a (x, t - \tau_2) \frac{1}{\gamma^2} G (x) G^T (x) \\
&\quad \times \nabla H_a (x, t - \tau_2) \\
&\quad - \frac{1}{2} \nabla H_a (x, t - \tau_2) \left( \nabla H_a (x, t - \tau_2) \right) \\
&\quad = -\nabla^T H_a (x, t - \tau_2) R (x) \nabla H_a (x, t - \tau_2) \\
&\quad + \frac{1}{2} \left( \gamma^2 \|w\|^2 - \|z\|^2 \right) \\
&\quad - \frac{1}{2} \left( \gamma^2 \|w\|^2 - \|z\|^2 \right)
\end{align*}\]

and then
\[\begin{align*}
\dot{V} (x, t) + \nabla^T H_a (x, t - \tau_2) R (x) \nabla H_a (x, t - \tau_2) \\
&\leq \frac{1}{2} \left( \gamma^2 \|w\|^2 - \|z\|^2 \right) \\
&\quad - \frac{1}{2} \left( \gamma^2 \|w\|^2 - \|z\|^2 \right) \\
&\quad \leq \frac{1}{2} \left( \gamma^2 \|w\|^2 - \|z\|^2 \right)
\end{align*}\]

where, \(M = \nabla^T H_a (x, t - \tau_2) R (x) \nabla H_a (x, t - \tau_2)\), and \(\gamma\) dissipative inequality holds.

Considering that \(V\) is the track derivative of the system (17), \(\mu = 0\), and \(w = 0\), we have
\[\begin{align*}
\dot{V} (x, t) &\leq -\nabla^T H_a (x, t - \tau_2) \left( J (x) - R (x) + \frac{1}{2} Q \right) \\
&\quad \times \nabla H_a (x, t - \tau_2) \\
&\quad + \frac{1}{2} \nabla^T H_a (x, t - \tau_2) (J (x) - R_1 (x)) Q^{-1} \\
&\quad \times \left( J (x) - R_1 (x) \right)^T \nabla H_a (x, t - \tau_2) \\
&\quad = \nabla^T H_a (x, t - \tau_2) \left[ -R (x) + \frac{1}{2} Q + \frac{1}{2} (J (x) - R_1 (x)) \right] \\
&\quad \times Q^{-1} (J (x) - R_1 (x))^T \nabla H_a (x, t - \tau_2) \\
&\quad \leq -\lambda_{\min} (-\nabla^T H_a (x, t - \tau_2) Q \nabla H_a (x, t - \tau_2)) \\
&\quad \leq -\alpha \|\nabla H_a (x, t - \tau_2)\|^2 \leq 0
\end{align*}\]

**TABLE 1. Wind turbine parameters.**

| Parameters | Value | Units | Parameters | Value | Units |
|------------|-------|-------|------------|-------|-------|
| \(H_{\text{rot}}\) | 6 | m/s | \(L_{\text{n}}\) | 0.556 | pu |
| \(L_s\) | 0.17 | pu | \(\omega_s\) | 3.14 | pu |
| \(L_r\) | 0.156 | pu | \(i_s\) | 1.8 | pu |
| \(L_m\) | 0.4 | pu | \(i_s\) | 1.7 | pu |
| \(R_s\) | 0.085 | pu | \(p_m\) | 18 | KW |

where
\[Q = -R (x) + \frac{1}{2} Q + \frac{1}{2} (J (x) - R_1 (x)) Q^{-1} \times (J (x) - R_1 (x))^T,\]
\[a = \lambda_{\min} (-Q) > 0.\]

As a result, \(\gamma\) dissipation can be guaranteed for multiple time delays system with disturbance under the controller (22). Meanwhile, an appropriate Lyapunov function is selected for the new system to make the system (17) stable under the controller (22), and the equilibrium point of the system maintains stable at \(x_0\), as same as the original one. The proof is complete.

Based on the analysis, when the multiple time delays exist in the wind turbine system, the time delay controller can be designed by Casimir function method to maintain the system stable. When external disturbance exists in the system with multiple time delays, an \(L_2\) gain interference controller with multiple time delays can be designed. While the multiple time delays is controlled, the interference of the system can be effectively suppressed, which greatly improves the anti-interference and robustness of the system.

**V. SIMULATION VERIFICATION**

In this section, MATLAB software is used to simulate and verify the effectiveness of wind turbine under multiple time delays control and \(L_2\) gain control. Validation is divided into two parts: Firstly, in the case of doubly fed wind turbine with multiple time delays, the Casimir function method is introduced to control the stable operation of the system, and the effectiveness of the control method is verified by being compared with delay-free control, LMI time delay control. Then, When the doubly fed wind turbine with multiple time delays is disturbed, on the basis of Casimir control for multiple time delays, \(L_2\) gain controller is designed to adjust the steady-state error of the system, and the effectiveness of \(L_2\) gain controller is verified by comparison under the conditions both with or without disturbances in improving the control performance.

The numerical values of the wind turbine used in the simulation are shown in Table 1.
A. DESIGN OF MULTI TIME DELAYS CONTROLLER

Considering the PCH-D model of doubly fed wind turbine, time delays $\tau_1$ and $\tau_2$ exist in inevitably Hamiltonian function and input of system respectively, which satisfy $\tau_{\text{min}} \leq \{\tau_1, \tau_2\} \leq \tau_{\text{max}}$. For convenience of analysis, consider $\tau_{\text{min}} = 0.03$ s and $\tau_{\text{max}} = 0.3$ s. Take

$$J_1 = \begin{bmatrix} 0 & 2.5 & 0.53 \\ -2.5 & 0 & -0.34 \\ -0.53 & 0.34 & 0 \end{bmatrix}.$$  

$$R_1 = \begin{bmatrix} 0.2 & 0.1 & 0.001 \\ 0.1 & 1 & 0.02 \\ 0.01 & 0.02 & 0.5 \end{bmatrix}.$$  

We take a real symmetric matrix $Q$ satisfied equation (21), and select the appropriate initial value to simulate.

The simulation results of wind turbine are shown in Figures 3. The simulation results of the output response and active power of wind turbine with multiple time delays are shown in Figure 3(a) and 3(c), respectively. The simulation results of the output response and active power of wind turbine with multiple time delays, under the Casimir function and LMI, are shown in Figure 3(b) and 3(d), respectively.

Figure 3(a) and (c) illustrate that the output response and active power curves of wind turbine are unstable with great oscillating amplitudes, when there are multiple time delays in the wind turbine. The maximum active power is $P_{\text{smax}} = 29.96$ kW, and the maximum of power changing within 1 s is $\Delta P_{\text{smax}} = 14.92$ kW. The stable PCH-D form of the wind turbine is destroyed by the multiple time delays, which makes the system deviate from the expected operation state of the original design.

Figure 3(b) and Figure 2(d) show that the output response and active power curves of wind turbine have certain oscillating amplitudes in a short period of time. After a period of time, the oscillating amplitudes of the curves decrease, and finally converge stably. The whole system operates stably...
TABLE 2. Performance parameter.

| Parameters   | Casimir | LMI   |
|--------------|---------|-------|
| $P_{\text{max}}$ / KW | 26.98   | 28.78 |
| $P_s$ / KW     | 18.07   | 18.13 |
| $\sigma$      | 49.9%   | 58.7% |
| $t_r$ / s      | 0.58    | 3.47  |
| $t_s$ / s      | 6.02    | 16.6  |
| $e_{ss}$       | 0.07    | 0.13  |

under the multiple time delays controller. The performance parameters of system under the Casimir function control and LMI are shown in Table 2.

Through the comparison in Table 2, it can be seen that the system is in oscillating mode under the multiple time delays. Compared with LMI time delay method, the wind turbine controlled by Casimir function method has smaller oscillating amplitude, faster convergence speed, fewer oscillating times and smaller steady-state error. It is shown that the multiple time delays controller designed in this paper can effectively solve the multiple time delays problem of the system, maintain the stability of the system and enhance the stability performance of the system than LMI time delay method.

B. L2 GAIN CONTROLLER DESIGN

In the process of practical operation, the system with multiple time delays is easily affected by external disturbance, which makes the system deviate from the expected equilibrium state. In order to reduce the steady-state error of the multiple time delays system after disturbance, L2 gain controller is designed to suppress the disturbance.

Given an disturbance attenuation level satisfied $\gamma = 1.5$, choose $z = h(x)G^T(x) \nabla H_a(x,t - \tau_2)$ as the penalty function, and take the weighting matrix as

$$h(x) = \begin{pmatrix} 0.1 & 0.1 \end{pmatrix}^T$$

The real symmetric invertible matrix $Q$ is obtained by using MATLAB toolbox to calculate the inequality (21), and $Q$ can be taken as

$$Q = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

Considering the harmonic disturbance of wind power system, the disturbance signal: $w = \sin(t)$, which occurs during the time period [10s,15s]. The simulation results of wind turbine are shown in Figure 4.

The simulation results of output response and active power for multiple time delays system with disturbance, under the control both with or without L2 controller, are shown in Figure 4 (a) and Figure 4 (b), respectively.

Figure 4(a) and (b) illustrate that the output response and active power of wind turbine without control have oscillating mode during [10s,15s]. After 15s, the wind turbine without control is stable after coordination in a short time, but the Steady state value of $y$ is not 0, and the active power output $P_s$ converges to 20.26kw. In the entire curves without control, the maximum active power is $P_{s_{\text{max}}} = 25.8$KW, and the steady value of active power is $P_s = 20.26$KW. The peak time and transient time of active power are $t_p = 0.56s$, $t_s = 1.31s$ respectively. The overshoot and the steady-state error of the active power are $\sigma = 27.34\%$, $e_{ss} = 2.26$ respectively. It shows that the external disturbance affects the stability of multiple time delays wind turbine. The system deviates from the expected equilibrium state and the system has a great steady-state error, which can not meet the operation requirements of the system.

However, the output and active power of the wind turbine with L2 gain control fluctuate slightly during [10s,15s]. After 15s, the output and active power of the wind turbine converges to 0 and 18kw respectively, by a short period of coordination. The maximum active power is $P_{s_{\text{max}}} = 21.93$KW, and the steady value of active power is $P_s = 18$KW. The peak
time and transient time of active power are $t_p = 0.91s$, $t_s = 2.34s$ respectively. The overshoot and the steady-state error of the system are $\sigma = 21.8\%$, $\varepsilon_{ss} = 0$ respectively. The system achieves the expected stable state, and the oscillating times are reduced.

It can be seen from the comparison that, through the L2 gain controller, the steady state error and overshoot of the disturbed wind turbine with multiple time delays are smaller, and the oscillating times are reduced. The L2 gain controller based on multiple time delays control can effectively adjust the stability state of the system, and improve the stability and control accuracy of wind turbine. This method has a good control effect in the control of multiple time delays system under disturbance.

VI. CONCLUSION

In this paper, for the influence of multiple time delays and external disturbances during the operation of offshore wind turbine, Casimir function method and L2 gain interference suppression technology based on Hamiltonian energy method, are introduced to stabilize the wind turbine system. The main innovations of this paper can be summarized as follows: (1) Based on Hamiltonian energy theory, the model of doubly fed wind turbines with multiple time delays is transformed into PCH-D model as the basic model for multiple time delays analysis. PCH-D structure has the advantages of clear structure characteristics, simplified model and convenient controller design, which is suitable for scholars and engineers in power system research. (2) Based on the PCH-D model with multiple time delays, the Casimir function method is used to design the feedback controller to keep the system stable. This method does not need a large number of matrix inequalities to obtain the stability conditions of the system, so it reduces the conservativeness of the stability conditions. Casimir method can effectively solve the problem of oscillation caused by multiple time delays, also improve the stability and control accuracy of the system. (3) For the external disturbance in the multiple time delays wind turbine, combined with the Casimir function, the L2 gain controller is designed based on the dissipative theory, to adjust the state of the equilibrium point of the system, which makes the disturbed system stable in the expected steady state and reduces the steady-state error of the system. Through that, the disturbance is effectively suppressed, and the stability and anti-interference of the wind turbine system is greatly improved. The method in this paper reduces the oscillating amplitude of the system, improves the stability of the system, prolongs the life of the power equipment, reduces the maintenance and inspection costs of the offshore platform, and even ensures the safety and reliability of the offshore platform. In a word, the method proposed in this paper has technically and economically advantageous in power generation performance, system simplification and cost-effectiveness.

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