A robust adaptive control method for reactive power of doubly-fed induction wind generator

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Abstract. Some of the existing control strategies for reactive power of doubly-fed wind generators are only based on the simplified transfer function model without considering the existence of disturbance and some require real-time adjustment of the algorithm to meet different operating conditions. In order to overcome the above problems, a robust adaptive control method is introduced into the field of reactive power control of doubly-fed induction wind generator in this paper. An adaptive reactive power control strategy for the grid-side converter of doubly-fed wind generator is proposed, and the effectiveness of the algorithm is verified through simulation verification.

1. Introduction
Due to the excellent control performance, the current converter capacity of the doubly-fed wind generator is only 30% of the rated capacity of the generator, which significantly reduces the cost of power electronic devices, and enables independent control of active and reactive power. Through the participation of reactive power in voltage and power factor adjustment, doubly-fed wind generators have become the mainstream models of high-power wind power generation [1-2].

At present, the reactive power control method of doubly-fed induction generator has become a research hotspot. Reference [3] studied the impact of large-scale wind farms on low-frequency oscillations in power systems after adopting reactive power control strategies. Reference [4] constructed a model-based predictive controller for direct power control of doubly fed induction generator

However, the existing control strategies for reactive power of doubly-fed wind generators are only based on the simplified transfer function model without considering the existence of disturbance and some require real-time adjustment of the algorithm to meet different operating conditions. In order to overcome the above problems, the robust adaptive control theory was introduced into the field of reactive power control of doubly-fed induction wind generator in this paper. A robust adaptive reactive power control strategy for the grid-side converter of doubly-fed wind generator was proposed, and the effectiveness of the algorithm was verified through simulation verification.

2. Mathematical Model of Doubly-fed Wind Generator
The classic modeling method of doubly-fed wind generator as described in reference [5] is adopted. The stator frequency of the generator is equal to the grid-side frequency, i.e. \( \omega_s = \omega_n \), and the slip ratio of the rotor is determined by \( \omega_r = S \omega_n \). The terminal voltage of doubly-fed wind generator is:

\[
\mathbf{u}_s = R_s \mathbf{i}_s + \frac{d \mathbf{\psi}_s}{dt} + j \omega_n \mathbf{\psi}_s
\]

(1)
\[ u_r' = R_r i_r' + \frac{d\psi_r}{dt} + jS\omega_n \psi_r \]  

(2)

where \( u_s \) and \( u_r' \) are the stator and rotor voltages of the doubly-fed induction generator respectively, \( R_s \) and \( R_r' \) are the stator resistance and rotor resistance, \( i_s \) and \( i_r' \) are the stator current and rotor current, \( \psi_s \) and \( \psi_r \) the stator flux linkage and rotor flux linkage.

The flux linkage of the generator is:

\[ \psi_s = L_s i_s + L_m i_r' \]  

(3)

\[ \psi_r = L_r' i_r' + L_m i_s \]  

(4)

In the formula, \( L_s \) is the stator inductance, \( L_m \) is the magnetization inductance, and \( L_r' \) is the rotor inductance.

The relationship between the d and q axis components of the stator and rotor of the doubly-fed induction generator is as follows:

\[ i_s^d = -\frac{L_m}{L_s} i_r^d \]  

(5)

\[ i_s^q = \frac{\psi_{sq}}{L_s} - \frac{L_m}{L_s} i_r^q \]  

(6)

For the grid-side converter, the vector control strategy of grid voltage direction is adopted, that is, the d-axis in the synchronous rotation coordinate system is oriented on the grid voltage. The grid voltage-oriented rotating coordinate system is applied, and the voltage drop on the main reactance is ignored. The voltage dynamic output model of the grid side converter should be as follows:

\[ u_{N*d} = R_f i_{nd} + L_f \frac{di_{nd}}{dt} - \omega_n L_f i_{nq} + u_{nd} \]  

(7)

\[ u_{N*q} = R_f i_{nq} + L_f \frac{di_{nq}}{dt} - \omega_n L_f i_{nd} + u_{nq} = 0 \]  

(8)

where \( L_f \) is the filter inductance, \( R_f \) is the filter resistance, \( u_n \) and \( u_N \) are the voltage of the grid–side converter and the junction voltage, \( i_n \) is the current of the grid-side converter, the subscripts \( d \) and \( q \) represent the d-axis component and q-axis component of the corresponding value respectively.

3. Robust Adaptive Reactive Power Control

For the grid side converter of the doubly-fed induction generator, the following equation of reactive power can be obtained by using the grid voltage-oriented coordinate system:

\[ q_n = -\frac{3}{2} u_{N*d} i_{nq} \]  

(9)

The calculated reactive power reference needs to be sent to the control loop after filtering, therefore, the open-loop control object of reactive power is essentially a second-order transfer function structure:

\[ G_{p_{qn}} = \frac{K_{qn}}{(sT_{sum} + 1)(sT_{eq} + 1)} \]  

(10)

where \( T_{eq} \) is the system filtering time constant, and:

\[ K_{qn} = -(3/2)u_{N*d} \]  

(11)

In the derivation design process of the following robust adaptive control algorithm for reactive power, there are a few basic facts that require special attention: The voltage amplitude of the grid connection point is not zero. According to the coordinate establishment method, \( u_{N*d} \) is a positive value signal. \( K_{qn} \) is a negative value signal. This basic fact will be used to ensure the stability of the algorithm.

For ease of derivation and use, equation (10) is rewritten as the following functional model:

\[ \frac{q_n}{i_{qn}} = \frac{K_{qn}}{(sT_1 + 1)(sT_2 + 1)} \]  

(12)

where \( T_1 = 2T_{sum}, T_2 = T_{eq} \).

By applying the Laplace transform theory, equation (12) can be transformed into:
Considering the external disturbance added to the system current, equation (13) can be further transformed into:

\[ \ddot{q}_n T_1 T_2 + \dot{q}_n (T_1 + T_2) + q_n + h(\cdot) = K_n i_{qn} \]  

(14)

where \( h(\cdot) \) is the external disturbance link.

The amount of reactive power error of the system is as follows:

\[ e = q_n - q_n^* \]  

(15)

At the same time, the variable \( \epsilon \) is introduced, and is defined as:

\[ \epsilon = \alpha e + \dot{e} \]  

(16)

where \( \alpha > 0 \) is a design constant.

When \( \epsilon \) converges to zero with time, \( e \) and \( \dot{e} \) converge to zero as well. This indicates that if the system can construct a controller which can make the variable \( \epsilon \) converge to zero, the stability of the reactive power control system can be guaranteed.

Set

\[ \varphi(q_n) = 1 + |q_n| + |\dot{q}_n| + |\ddot{q}_n| \]  

(17)

The parameter \( s \) was introduced in this paper and the following definition was adopted

\[ s = \epsilon + \beta \int_0^t e \, d\tau \]  

(18)

where \( \beta \) is a positive design constant.

If \( s \) converges to zero over time, then \( \epsilon \) will also converge to zero, which means: If the system can construct a controller so that the variable \( s \) can converge to zero and then the variable \( \epsilon \) can converge to zero, the stability of the reactive power control system can be guaranteed.

In this paper, the controller is designed as shown below:

\[ u = -k_0 s - \hat{\gamma} \frac{\varphi(q_n)s}{|s|} \]  

(19)

where \( k_0 \) is a positive design constant, \( \hat{\gamma}(0) \geq 0 \) and:

\[ \dot{\gamma} = -\sigma_0 \hat{\gamma} + \sigma_1 \frac{\varphi(q_n)s}{|s|} \]  

(20)

with \( \sigma_0 > 0 \) and \( \sigma_1 > 0 \), all the signals are ensured to be bounded.

4. Simulation and Result Analysis

Corresponding simulation experiments were built to verify the effectiveness of the proposed robust control algorithm in this paper. Matlab/Simulink was selected for the simulation environment. The doubly-fed wind power generator is used as a dynamic reactive power compensation device, and its reference reactive power is selected as \( q_n^* = 20 + 2\sin(4\pi t) \) KVar by simulation. The reference reactive power and actual reactive power tracking curves are shown in Fig. 1, and its real-time tracking error is shown in Fig. 2. Simulation results show that the robust adaptive reactive power control strategy can be applied to dynamic reactive power regulation, which can guarantee good tracking effect of the system.

Fig.1 Dynamic adjustment of reactive power control
5. Conclusion
Doubly-fed induction wind generator has double converter structure, which can realize the decoupling control of active power and reactive power. Aiming at the problem of reactive power control of doubly-fed induction wind generator, a reactive power control strategy based on robust adaptive method is proposed. This control strategy has superior anti disturbance performance, and it can ensure the performance without reconstruction algorithm under different conditions.

Acknowledgments
This work was supported by the Chongqing Research Program of Basic Research and Frontier Exploration (No.cstc2018jcyjAX0082), the science and technology research program of Chongqing Education Commission (No.KJQN201903107).

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