Aerodynamic load control strategy of wind turbine in micro-grid

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Abstract: A control strategy is proposed in the paper to optimize the aerodynamic load of the wind turbine in micro-grid. In grid-connection mode, the wind turbine adopts a new individual variable pitch control strategy. The pitch angle of the blade is rapidly given by the controller, and the pitch angle of each blade is fine tuned by the weight coefficient distributor. In islanding mode, according to the requirements of energy storage system, a given power tracking control method based on fuzzy PID control is proposed. Simulation result shows that this control strategy can effectively improve the axial aerodynamic load of the blade under rated wind speed in grid-connection mode, and ensure the smooth operation of the micro-grid in islanding mode.

1. Introduction
Wind power system is one of the important components of micro-grid. The random variation of wind speed will cause output power of wind turbine to fluctuate obviously. Therefore, the wind turbines connected-on the micro-grid will have a great influence on the system operation.¹ Meanwhile, blades, as the main carrier of the aerodynamic load of wind turbine, will directly affect the safe and stable operation of wind turbine.² Distinctly, it is important to control the blade load of wind turbine in micro-grid.

At present, the research on the load of wind turbine has achieved fruitful results. Paper [3] designed a model predictive controller to reduce the aerodynamic load by sacrificing the stability of power generation; paper [4] proposed a frequency-based synovial variable structure control algorithm to realize maximum wind energy capture and to reduce the fatigue load; paper [5] adopted PSO (particle swarm optimization) to control the fatigue load caused by the ramping events of wind turbine. Based on these studies, this paper presents a control strategy for effectively reducing aerodynamic loads. Different control strategies are adopted to realize the efficient operation of micro-grid in grid-connection and islanding modes.
2. Micro-grid structure
In this paper, the main structure of micro-grid consists of wind turbine system, gas turbine system, photovoltaic system, storage battery, etc., the structure is shown in Figure 1. The whole system is controlled by a central controller, a power controller and a load controller to ensure the system smooth operation.

![Figure 1. Block diagram of micro-grid](image)

**Figure 1. Block diagram of micro-grid**

**Figure 2. Force decomposition in a single blade element**

2.1. Maximum Wind Energy Capture Principle
When the wind at the speed \( v \) (m/s) along the wheel, mechanical output power of wind turbine:

\[
P_w = C_P P_v = \frac{1}{2} C_P (\lambda, \beta) \rho R^2 v^3
\]

Where \( P_w \) is mechanical output power of wind wheel, \( C_P \) is rotor power coefficient, \( P_v \) is input power of the wind wheel, \( \rho \) is air density, \( R \) is radius of wind wheel.

According to formula (1), when wind speed has been set, the mechanical output power is only related to the wind energy utilization coefficient(\( C_P \)), and \( C_P \) is determined by tip speed ratio (\( \lambda \)) and pitch angle(\( \beta \)) \[^6\].

2.2. Aerodynamic load analysis of blade
As one of the important loads in wind turbine, BEM(Blade Element Momentum) theory is adopted to solve the analysis of blade aerodynamic load which is the main object in this paper. Each blade is divided into several blade elements. The force and torque of one blade element are calculated by BEM. The blade load is obtained by these integrals.

Analysis of the force acting on one element is shown in Figure 2. The aerodynamic (\( dF \)) is decomposed into tangential force (\( dF_u \)) and axial force (\( dF_a \)) in parallel and perpendicular to wind turbine rotation plane. Thus, the tangential force (\( dF_u \)) and the axial force (\( dF_a \)) of one blade element under the action of air flow \[^7\]:

\[
dF_u = dL \sin \phi - dD \cos \phi = 0.5 \rho c W^2 (C_l \sin \phi - C_d \cos \phi) dr
\]

\[
dF_a = dL \cos \phi + dD \sin \phi = 0.5 \rho c W^2 (C_l \cos \phi + C_d \sin \phi) dr
\]

where \( L \) is lift force, \( D \) is resistance force, \( C_l \) is lift coefficient, \( C_d \) is resistance coefficient, \( \phi \) is inflow angle, \( c \) is chord length, \( W \) is synthesis of wind speed.

3. Control strategy of wind turbine in micro-grid
As micro-grid has two operating states which are very diverse, different control strategies are adopted for different running state.

3.1. The control strategy of wind turbine in the grid-connection mode
In this paper, the blade aerodynamic load optimization of wind turbine is accomplished by referring to the mature control strategy under rated wind speed. Meanwhile, considering that the main functions of wind turbine in II area (rated wind speed below) is mainly focused on the maximum wind energy tracking. Therefore, the control strategy of this paper is mainly for the second half of the II area. Block diagram of the system is shown in Figure 3.

3.1.1. Design of discrete fuzzy controller. The goal of discrete fuzzy controller is to quickly adjust blade pitch angle to ensure the control effect. A reference table of pitch angle based on wind turbine generator power is introduced into this controller. At the same time, in order to avoid the frequent fluctuation of pitch angle with the power change, the quantized power is processed by fuzzy processing and one dimension linear interpolation. The blade pitch angle reference table is shown in Table 1, which is composed of the generator output power of wind turbine and the blade pitch angle.

The design of the discrete controller is a two-dimensional fuzzy controller, the basic domain for the generator speed and speed rate of change, fuzzy subset is \{NB, NM, NS, ZE, PS, PM, PB\}.

![Control block diagram of wind turbine system](image)

**Figure 3.** Control block diagram of wind turbine system

| The quantized power | The pitch angle (degree) |
|---------------------|--------------------------|
| 6                   | 2.68                     |
| 7                   | 3.06                     |
| 8                   | 3.29                     |
| 9                   | 3.49                     |
| 10                  | 3.67                     |
| 11                  | 3.84                     |
| 12                  | 4.17                     |
| 13                  | 4.52                     |
| 14                  | 5.07                     |
| 15                  | 5.25                     |

3.1.2. Design of discrete fuzzy controller. Under the wind shear effect, wind turbine will be affected by unbalanced aerodynamic load, which makes the pitch angle of blades not the same \(^8\). So a weight coefficient distributor is designed to adjust pitch angle of each blade, reducing the axial aerodynamic load of each blade more effectively. One azimuth angle of the blade is \(\theta\), and the pitch angle of the remaining two blades in the counterclockwise direction are \(\theta + 120^\circ\) and \(\theta + 240^\circ\). From the wind resource model formula, the average wind speed through each blade is \(^2\):
\[ V_i = \left[ 1 + \frac{R}{2H_0} \sin(\theta + (i-1) \times 120^\circ) \right]^{sh} \times V \]  

where \( V_i \) (i=1,2,3) is average wind speed of blades, \( H_0 \) is wind wheel center height, \( r \) is blades length, \( sh \) is wind shearing factor, \( V \) is center of the wheel speed.

In this paper, the design of the individual pitch control is based on wind turbine output power and wind shear effect to determine the blade pitch angle as shown in Figure 3. \( \theta_1, \theta_2 \) and \( \theta_3 \) in the figure represent three blades of the azimuth angle, \( \beta \) for the uniform pitch controller given the pitch angle, \( \beta_1, \beta_2 \) and \( \beta_3 \) represent the pitch angle of each blade after adjustment by the weight coefficient distributor. The pitch angle of each blade is:

\[ \beta_i = k_i \beta, i = 1,2,3 \]

where \( k_i \) is the leaf weight coefficient, its value is:

\[ k_i = \frac{3 \times \left[ \frac{R}{2H_0} \sin(\theta + (i-1) \times 120^\circ) \right]^2}{\sum_{j=1}^{3} \left[ \frac{R}{2H_0} \sin(\theta + (j-1) \times 120^\circ) \right]^2} \]  

3.2. Control strategy of wind turbine in the islanding mode

In micro-grid, the power tracking control of wind turbine is different according to the remaining capacity of energy storage system, and the two kinds of tracking control modes are the maximum power tracking control and the given power tracking control. And the maximum power tracking control takes the same control strategy as the grid-connection mode. But the given power of the power tracking control is calculated and analyzed by the energy storage system.

![Figure 4. Energy flow of grid operation mode in micro-grid](image)

As shown in Figure 4, it reflects the energy flow, energy absorption or release formula in energy storage system is:

\[ P_s = P_l + P_{db} - P_{source} \]

where \( P_s \) is the power absorbed or released by energy storage device, \( P_l \) is the load power, \( P_{db} \) is the DC bus capacitor to absorb power, \( P_{source} \) is the power output power.

Through the energy change of the energy storage system, the given power of the wind turbine under islanding mode can be determined, and then the controller can be designed. The control of the fixed power is controlled by a fuzzy PI controller. The control block diagram is similar to that of Figure 3.

4. System simulation and analysis

In this paper, the object of this study is three-blade horizontal axis wind turbine. The main parameters are: rated power is 1.5 MW, cut-in speed at 4 m/s, rated wind speed 12.5 m/s, diameter of the air wheel is 70.5 m, rotor moment of inertia is 6208971 kg m², gear box ratio about 90.11, generator rated speed is about 1800 r/min, generators inertia for 60 kg m².

4.1. Simulation and analysis of wind turbine in grid-connection mode
The wind speed range is about 8.5 ~ 12 m/s. In first 15 s, wind speed is around 8.5 m/s. In second 15 s, wind speed around 12 m/s. Suppose wind speed curve shown in Figure 5(a).

Figure 5(b) shows the comparison of the output power with synchronous variable pitch control and individual variable pitch control. It can be seen from the curve that under this control strategy, the output power is nearly the same.

Figure 5(c) shows the average axial aerodynamic load curve of three blades under two control strategies. The figure shows that the maximum load of the blade under synchronous variable pitch control is $3.99 \times 10^5 \text{ N} \cdot \text{m}$, the minimum is $2.68 \times 10^5 \text{ N} \cdot \text{m}$ and the fluctuation range is 27.36%. However, the maximum load of the blade under the control of the individual variable pitch is $3.49 \times 10^5 \text{ N} \cdot \text{m}$, the minimum is $2.73 \times 10^5 \text{ N} \cdot \text{m}$, the fluctuation range is 21.68%. Under this control strategy, the load curve of the blade is relatively stable, less volatile.

(a) Wind speed simulation  
(b) Comparison of output power of wind turbine  
(c) Comparison curve of axial aerodynamic load for wind turbine’s blade

**Figure 5.** Simulative results for grid-connected microgrid

4.2. Simulation analysis of wind turbine in islanding mode

The wind speed of working condition is the same as that of grid-connection mode, as shown in Figure 5(a).

When the power grid is in the light load condition, the given power of wind turbine is 85% energy of the energy storage system, and the output power is shown in Figure 6(a). This control strategy makes the output power more stable. The generator speed of the wind turbine is shown in Figure 6(b). It can be seen that generator speed is smoother.
5. Conclusion

This paper mainly analyzes the working condition of the wind turbine under rated wind speed in micro-grid. In grid-connection mode, a new independent variable pitch control strategy is proposed for the higher wind speed in the II area of wind turbine. The method can improve wind shear effect on blades under the condition that output power is basically the same. In the islanding mode, the goal of controlling the stability of the output power is achieved, which ensures the safe operation of power grid.

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