An Aerodynamic Characteristic Measurement Method for Fixed-Pitch Wind Turbine

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***Abstract*—Non-grid-connected wind power theory, which is defined as the optimized integration of grid-connected and stand-alone wind power generation forms, avoids the technical issue of integrating wind power into utilities, and creates a new solution to wind power generation. In order to describe the characteristic of the non-grid-connected wind power generation, this paper discusses a kind of power control strategy that suits the large-scale, non-grid-connected wind power system with electrochemistry loads. Then, with the help of LABVIEW, an experimental and testing platform is designed to meet the special requirement of the fixed-pitch wind turbine and high-energy -consuming simulated loads. The results of wind tunnel experiments verify the feasibility of the presented system and control strategy.**

***Keywords*—Wind turbine; DC/DC convertor; CP-λ curve; Power control**

I. INTRODUCTION

Wind power generation (WPG) technology, which shows the pioneering of renewable energy generation, has grown explosively in the past decades due to public support and the maturing of turbine techniques. In order to design an advanced generation system, how to promote the wind power generation performance is widely focused on. A wind turbine, as the key part of WPG system, not only impacts the wind turbine conversion efficiency, but also influences the safe operation. The design of controller for the fixed-pitch wind turbines is more difficult than the variable-pitch systems[1], and it is very necessary for studying the aerodynamic characteristics of wind turbines, which is an important precondition for safe operations in a WPG system. There are many literature studies on the theory and simulation analysis [2] [3], but it is difficult to test wind turbines in natural conditions. So, the research on the aerodynamic characteristics of fixed-pitch turbines in the wind tunnel is very necessary.

For the wind turbine characteristics testing, there are two feasible methods, that is theoretical calculation and experimental test respectively. The theoretical calculation method which is based on numerical simulation is commonly used and is convenient in the aerodynamic characteristics analyzing. However, the aerodynamic characteristic of fixed-pitch wind turbine becomes very complex when it is running under stall mode, and it's difficult to estimate the stall characteristics accurately with theoretical method. The experiment method which means the output power, rotational torque and axial thrust feature can be directly measured under a series of loads, in different wind and rotor speed. It is simple and common, but also disabled unless there is a closed-loop controller, when the turbine has been stalled.

In this paper, an improved method for fixed-pitch turbine testing is discussed. And experimental platform, which is composed by a fixed-pitch wind turbine, an electromagnetic doubly salient (DSEM) generator, a DC/DC converter, the computer testing control system and the loads, has been built according to the variable-speed, stall-regulated wind turbine testing targets without gearbox,. The purpose of this paper is to investigate the feasibility and reliability of this testing platform through the wind tunnel experiments.

II. POWER CHARACTERISTIC OF THE FIXED-PITCH WIND TURBINE

Fig.1 shows a typical C_P-λ curve of a fixed-pitch wind turbine. When the optimal tip-speed ratio λ_{opt} is reached, its corresponding value is C_{pmax}. It is determined by geometric structure of the turbine, and it is nonlinear.

The turbine is rotating steadily, when the tip-speed ratio λ is on the right of λ_{opt}, the CP is dropped in this stage. And when the λ is on the left of λ_{opt}, the turbine is stalled; it is difficult for testing aerodynamic characteristics, because of the turbulent separation on the turbine. So it is a challenging job for testing the C_P-λ relation curve accurately.

A. *The normal method for the wind turbine*

The normal method for the wind turbine is "Direct

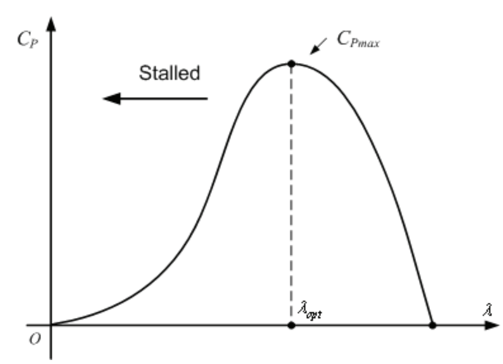


Fig.1 The curve of C_P and tip-speed ratio

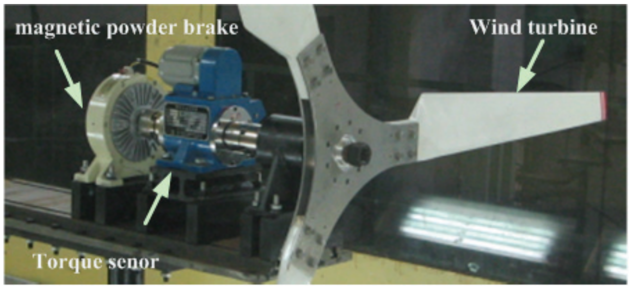


Fig.2 The experiment with “direct dynamometry” method

dynamometry,” which the most common method for testing of wind turbine due to its simplicity and reliability. The turbine is tested in the wind tunnel by a measure system that includes a wind tunnel balance for aerodynamic testing and a torque sensor. Usually, two forms can be used as the turbine testing loads, generator and brake respectively. The generator, acting as an electromechanical translation department, can be considered as the load of a wind turbine, while the brake dissipates the mechanical power in the form of heat. The rotator speed could be controlled by changing the mechanical load of the wind turbine.

In the first experiment, a magnetic powder brake was used as a mechanical brake on the load of the wind turbines. In this process, the mechanical energy was changed into heat. The testing system is shown in Fig.2. In the test, by fixing the brake torque, the test data was recorded when the transient process of the turbine is over. Through changing the excitation voltage of the magnetic powder brake, the static torque and speed of the wind turbine were tested when the turbine was running in the non-stall region (the operation points on right of CP-λ relation curve).

B. Limitations of the “direct dynamometry” method

In the deep-stall area of the fixed-pitch turbine, the “direct dynamometry” method has its limitations. The loads must be regulated rapidly to fit the changing torque of the wind turbine, to make the system work in a stable stage. The stability criterion of the changing torque is

$$\left.\frac{\partial T_m}{\partial n}\right|_{op} \geq \left.\frac{\partial T_b}{\partial n}\right|_{op} \qquad (1)$$

Where, T_m is turbine output torque;

T_b is brake torque as the equivalent load;

The turbine stalls when $\lambda<\lambda_{opt}$, and its rotator speed is unstable. There are two reasons:

C. The time-delay of magnetic powder brake is too long.

For testing the time-delay of the magnetic powder brake, a testing system was built, which includes a DC-motor. Keeping the DC-motor running smoothly, the step response time of braking torque was investigated by recording the motor armature current when steps change the excitation voltage of the magnetic powder brake.

As Fig.3 shows, the response time of the brake torque is more than 800ms until the DC-motor armature current is stable. It shows that the response of the magnetic powder brake is too slow to fit the loading system.

D. The controller of turbine speed is too slow.

The control diagram of the fixed-pitch wind turbine speed in the testing system is shown in Fig.4. Because the control cycle of the speed regulation is 1s, the rate of change of the mechanical brake load is too slow to fit the changing torque of the wind turbine, and the wind turbine is unstable in the deep-stall area.

Above, the simple test is based on the magnetic powder brake speed; a closed-loop system can't adapt to the wind turbines in testing the Cp. This measurement system is simple and commonly used but is weak for variable-speed, stall-regulated wind turbine testing. When the operating point is located on the left side of the CP-λ curve, the wind turbine is stalled, and it is difficult for testing the parameters because of the rotational speed is unstable. Therefore, a new system with special requirement is discussed:

1. The load of the wind turbine can be adjusted quickly
2. A control system with fast response is required.
3. The operation data could be recorded accurately and automatically.

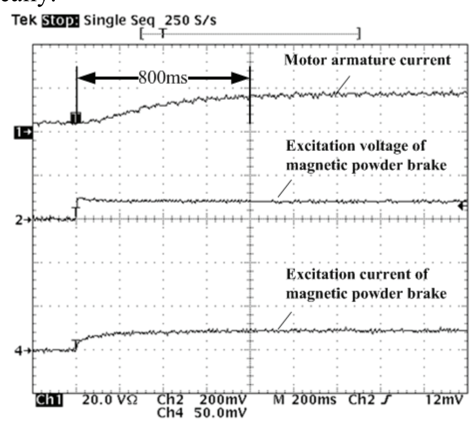


Fig.3 Testing for response time of the system load

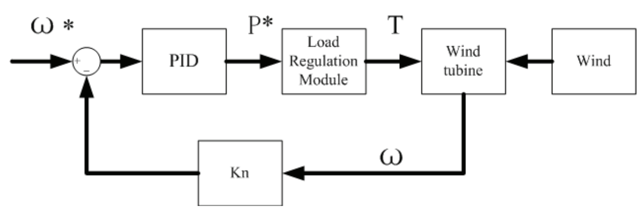


Fig.4 Control loop of the speed control system

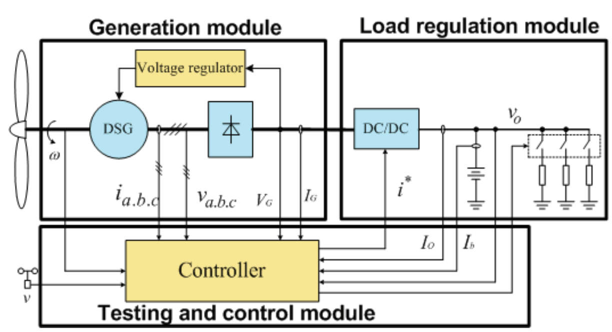


Fig.5 The experimental platform for the wind power system

III. A NEW PLATFORM FOR THE WIND TURBINE TESTING

A. The structure of the platform for wind turbine

As shown in Fig.5, A platform, which is composed of a fixed-pitch wind turbine, an electromagnetic doubly salient generator (DSEG), and a DC/DC converter, the computer testing control system and the loads, and is built according to the variable-speed, stall-regulated wind turbine testing targets.

A DC generator regulator for the excitation doubly salient generator is used in the DC generator system. In a certain speed range, through adjusting the exciter current, the DC generator output voltage is constant, and the output power of generation system can be changed by regulating the motor loads

In the testing system, a novel output power adjustable DC/DC converter is used as a load regulation operator, the power from the generator through the rectifier, and is transformed from high-voltage DC to 24V, then charges the batteries or consumption on the load resistance. Different from the first set of system, as the wind turbines load, the mechanical braking torque is improved by electromagnetic torque. DC/DC converter output power can be adjusted smoothly by changing the equivalent load of the generator quickly. So, the wind turbines' loads could be regulated quickly and smoothly.

A battery 65AH / 24V is connected into a DC/DC converter's output. The battery is considered as a buffer of the generation system, since it is in the process of regulating and balancing load resistance level. Because of the impacts of the current, the battery may be damaged when cutting load directly into 24V dc bus battery. For protecting the battery, the loading controller will cut the loads in or out of the generation system automatically, by judging if the battery is charging or discharging. Ten resistances were used in the load control module, each resistance is 280W, and the rated current is 10A.

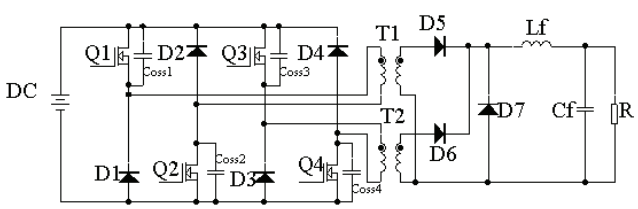


Fig.6 The topology of Interleaving Two-Transistor Forward

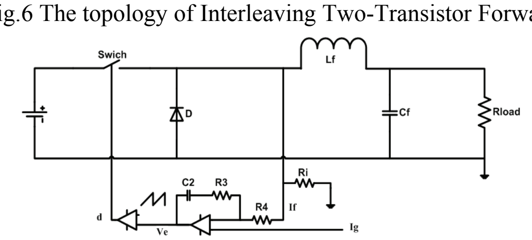
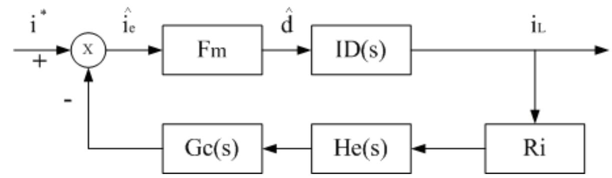


Fig.7 The block diagram of current control strategy

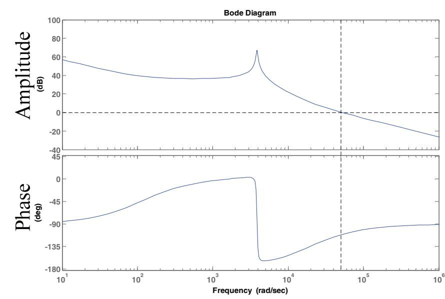
B. Adjustment methods of equivalent load

Wind turbine speed was controlled by the wind power output [10]. When the turbine is running, the rotational speed could be controlled by regulating the equivalent load of the wind generation system. Adjust smoothly through the quick equivalent load of generation systems, power increase or decrease of the output power, and the wind turbine speed can be controlled in a closed loop system.

An Interleaved Two-Transistor Forward convertor was used in the load regulation system, see Fig.6. Dynamic performance of DC/DC system is mainly assessed in the open loop cut-off frequency ω_c. The closed-loop system of a two-Transistor Forward convertor, which is equivalent to a BUCK converter [12], was shown in Fig. 7.



(a) Current loop control diagram



(b) Current loop frequency characteristics

Fig.8 Design of the current control loop

Due to the battery being connected at the convertor, the output voltage can be considered as a constant, so only a constant current loop should be designed, which is based on the state space average method for establishing the converter current control loop. The current loop model of the transfer function for Ti:

$$T_i = F_m \cdot ID(s) \cdot R_i \cdot H_e(s) \cdot G_s(s) \qquad (2)$$

Current loop control diagram was shown in Fig. 8 (a), including:

The comparator transfer function:

$$F_m = \frac{1}{2.4} \qquad (3)$$

Inductive current compared to duty cycle transfer function:

$$ID(s) = \frac{4.5e011\ s + 5e013}{67200\ s^2 + 7.5e006\ s + 1e012} \qquad (4)$$

Where, R_i: sampling resistance,

He (s) : sampling transfer function,

Gs (s) : compensation transfer function.

$$Gs(s) = \frac{51\ s + 1e006}{470\ s} \qquad (5)$$

Current loop frequency characteristics were shown in figure 8 (b), Angle margin gamma is 60 °, amplitude margin h is 144, open-loop cut-off frequency ω c = 20 kHz.

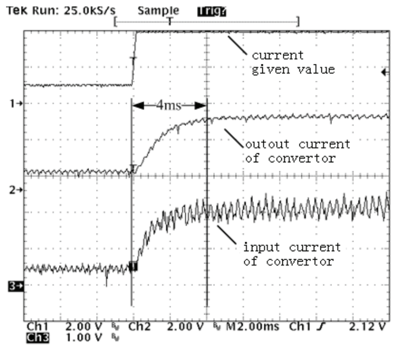


Fig.9 Response dynamic with current reference change

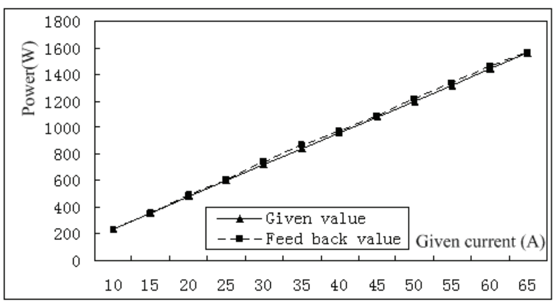


Fig.10 Control precision of the system load

TABLE I The System Parameters

Diameter	1.90 m	***Model***	NACA 0012
Wind speed	11 m/s	***Power***	2.0 kW
Rotate speed	100～1000rpm	***Swept area***	2.835m^2
Generator	DSEG	***Run mode***	SRG
Battery	24V/65AH	***Capacitance***	1000μF
Controller	NI-PXI-8106	***Software***	LabVIEW

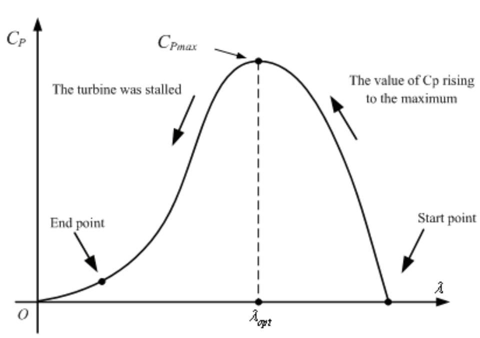


Fig.11 testing process for the wind blade

The experimental data of the output current regulation for the converter were shown in Fig. 9. The input current and output current response time is less than 5ms. For the large inertia of the wind turbine system, the response time meets the design requirements.

In order to ensure the accuracy of the load regulating system, which is based on the virtual instrument technology, the load adjusting precision of the generation system was evaluated. The value calculated and the value of feedback were shown in Fig. 10.

In summary, with the new load regulation module, the improved testing system for the variable-speed, stall-regulated wind turbine meets the challenge for the special system requirements mentioned above.

IV. The Experimental Method and Testing Results

A. Wind tunnel test method

The wind turbine is stalled when its operation point of C_P-λ relation curve is on the left of λ_{opt} ($\lambda>\lambda_{opt}$). For recording the testing data easily, the generation system must be loaded smoothly. In the second experiment, the turbine was released and worked in the fastest stage freely, and the generator output was increased to 500V by the excitation regulator. Then, the wind turbine speed was reduced; finally, the wind turbine was stalled, and its operation point of C_P-λ relation curve is on the right of λ_{opt} ($\lambda<\lambda_{opt}$).

Fig.12 The experiment in wind tunnel

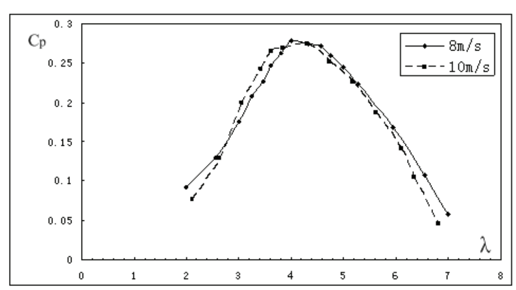


Fig.13 C_P-λ relation curves

In the experiment, the wind speed and output power can be tested, and the status of the C_P value for drawing C_P-λ relation curve could be calculated by (3) and (4) in different working conditions.

$$C_P = \frac{P}{0.5\rho S v^3} \quad (6)$$

$$\lambda = \frac{\omega R}{v} \quad (7)$$

B. Wind tunnel testing

The improved testing system platform was experimented with in the wind tunnel. The axial torque was tested by precision aerodynamic scale. The system parameters were shown in Table 1, and site layout was shown in Fig.12.

The C_P-λ relation curves in the wind speed of 8m/s and 10m/s are presented in Fig. 13. The experiment shows that two curves coincide well; the rotor of each working performance characteristic can be measured successfully in all the working stages by the new testing method

V. SUMMARY

According to the first wind tunnel experiments, the operating characteristics of a variable-speed, stall-regulated wind turbine was discussed. For the characteristic curve of Cp, an improved testing method was presented, which is composed of a fixed-pitch wind turbine, an electromagnetic doubly salient generator (DSEG), a DC/DC converter, the computer testing control system and the loads. Through the wind tunnel experiment, the new method of experiment has been proven as a powerful tool for variable-speed, stall-regulated wind turbine study.

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