Design of multi-energy fields coupling testing system of vertical axis wind power system

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Abstract. The conversion efficiency of wind energy is the focus of researches and concerns as one of the renewable energy. The present methods of enhancing the conversion efficiency are mostly improving the wind rotor structure, optimizing the generator parameters and energy storage controller and so on. Because the conversion process involves in energy conversion of multi-energy fields such as wind energy, mechanical energy and electrical energy, the coupling effect between them will influence the overall conversion efficiency. In this paper, using system integration analysis technology, a testing system based on multi-energy field coupling (MEFC) of vertical axis wind power system is proposed. When the maximum efficiency of wind rotor is satisfied, it can match to the generator function parameters according to the output performance of wind rotor. The voltage controller can transform the unstable electric power to the battery on the basis of optimizing the parameters such as charging times, charging voltage. Through the communication connection and regulation of the upper computer system (UCS), it can make the coupling parameters configure to an optimal state, and it improves the overall conversion efficiency. This method can test the whole wind turbine (WT) performance systematically and evaluate the design parameters effectively. It not only provides a testing method for system structure design and parameter optimization of wind rotor, generator and voltage controller, but also provides a new testing method for the whole performance optimization of vertical axis wind energy conversion system (WECS).

1. Introduction

The clean and renewable energy sources such as solar and wind energy are gaining importance due to their less influences to environmental. The rapidly increasing demand of electrical energy, the issues associated with limited reserves and the rising cost of fossil fuels such as oil, coal, and natural gas are also responsible for the growth and rise of renewable energy application [1]. Although the capacities of WT units have increased from a few tens of kW power capacity to multi-MW level over the past few decades, the conversion efficiency of WECS is also the focus of researches and concerns [2].

The WECS is mainly composed of wind rotor, generator, storage battery and voltage controller. Now more advanced generators, improved wind rotor, power converter systems and optimal control...
solutions have developed to enhance the conversion efficiency of wind energy, such as Darocy and so on used two-dimensional CFD simulation and parameter optimization for H style darrieus rotor turbulence aerodynamic modeling [3]. McTavish and so on proposed a new type of composite structure of vertical shaft wind turbines, and conducted two-dimensional steady and three-dimensional dynamic CFD simulation analysis [4]. Considering two different vertical shaft WT, Li yan team attempted to explore the torque, power characteristics and the influence of real parameters through performance simulation and wind tunnel experiment [5,6]. Aubree proposed a sensorless maximum power point tracking method for small wind power permanent magnet synchronous generator with dc load [7]. Qi ZY proposed an integrated power control method by involving the maximum power point tracking, load power tracking control, overspeed protection control and battery management optimization [8]. The method above are mostly by improving the wind rotor structure, optimizing the generator parameter and energy storage controller to enhance the conversion efficiency separately.

Though the conversion efficiency has improved in varying degree after using different methods, the effect is not particularly evident. While when different energy conversion occurs, such as wind rotors convert air kinetic energy into mechanical energy, generators convert mechanical energy into electrical energy, batteries convert electrical energy into chemical energy, the coupling effect between them will occur and influence the overall conversion efficiency. At present, the research of wind power MEFC technology is still in blank, therefore this research has a certain practical significance.

The purpose of this paper is to provide a MEFC testing method for the vertical axis WECS, the aim is to solve the existing technology question that can only test one part of the system separately. This method can test the whole WECS performance systematically, when the coupling parameters are allocated to an optimal state, it can improve the overall conversion efficiency of WECS.

2. Composition of MEFC system

The main WECS equipment designed in this paper includes the alternating current (AC) frequency converter, the open jet return flow wind tunnel, the vertical axis wind rotor, the permanent magnet generator, the storage battery and the load box. To keep it simple in following, these equipment are simplified as converter, wind tunnel, wind rotor, generator, battery and load respectively.

The testing and auxiliary equipment of MEFC system include the anemometer, disc coupling sensor, UCS, three-phase electric parameter tester, voltage controller, inverter and power management device. The composition block diagram of this system is shown in figure1.

![Figure 1. The block diagram of MEFC testing system.](image)

In the wind tunnel there is a ventilator which speed can be controlled by the converter. There are three test-beds in the wind field of the wind tunnel outlet. The first test-bed is used to install the vertical axis wind rotor specimen, it equips an anemometer which is used to measure the wind speed.
The second test-bed is used to install the generator specimen which connects to the vertical axis wind rotor specimen, it equips an three-phase electric parameters monitoring device which is used to measure the output power of the generator specimen. Between the first test-bed and the second test-bed there is a torque sensor which is used to measure the torque of wind rotor specimen, here the torque sensor is a disc coupling sensor. The third test-bed is used to install the voltage controller specimen which can convert the three-phase alternating current from the generator specimen into the direct current, and it also equips an power management device which is used to measure the output power of voltage controller specimen. 

The UCS is used to collect and analyze the data from measuring instruments, the data acquisition unit of the UCS is used to keep communication connection to the anemometer, torque sensor, three-phase electric parameters monitor device and power management device. The output of torque sensor and three-phase electric parameters monitoring device all connect to the data acquisition unit through A/D conversion module. The output of voltage controller specimen connects to the battery, and the battery connects to load through the inverter.

The working process of this system is as follows. The size of the flow velocity of wind tunnel is controlled by the converter, when change the power frequency, the flow velocity is changed accordingly. The rotor specimen converts wind energy into mechanical energy. The torque sensor detects the performance parameters of wind rotor specimen, such as output rotational speed, torque, power and so on, and it converts those analog signals into digital signal through A/D module. Generator converts the mechanical energy into electrical energy, three-phased electric parameter tester detects the performance parameters of generator, such as the output current, voltage, power and so on, and converts those analog signals into digital signals through A/D module, then we can obtain the conversion efficiency characteristics of generator through the values detected by the torque sensor and three-phased electric parameter tester. The voltage controller specimen converts the unstable output from generator into the charging voltage and current of the battery. Through the analysis and calculation of the electricity parameters detected by power management device and the test values from three-phase electric parameter tester, we can obtain the efficiency characteristics of voltage controller specimens. The stored energy of battery is released through the load box. The UCS conducts the data collection for MEFC analysis.

3. The basic mode of MEFC

The performance parameters of MEFC testing system designed in this paper include the wind energy $E_W$, the output power $E_M$ of wind rotor, the output power $E_G$ of generator and the electricity power parameter $E_C$ of voltage controller. 

As shown in equation (1), the power of wind energy can be calculated according to the air density $\rho$, the swept area $A$ of the wind rotor and the wind speed $V$.

$$E_W = \frac{1}{2} \times \rho \times A \times V^3 \quad (1)$$

The output power of wind rotor $E_M$ can be calculated according to the rotor torque $T$ and rotor speed $n$ which are detected by the disc coupling sensor, as shown in equation (2).

$$E_M = \frac{2\pi}{60} \times T \times n \quad (2)$$

The output power of the generator $E_G$ can be calculated according to the single output voltage $U$ and current $I$ which are detected by the disc coupling sensor. When the load is the resistive, the computation formula of the generator output power $E_G$ is equation (3).

$$E_G = 3 \times U \times I \quad (3)$$

The conversion energy $E_C$ of the voltage controller can be calculated by the output voltage $U$ and current $I$ which are detected by the power management system.
In the WECS, the rotor transformed the wind energy into mechanical energy, the utilization of wind energy is $\eta_M$. The generator transformed the mechanical energy into the electric power, the utilization of generator is $\eta_G$. The working efficiency of the voltage controller is $\eta_C$. Those corresponding calculating formulas are as follows.

$$\eta_M = \frac{E_M}{E_W} \times 100\%$$ \hfill (5)

$$\eta_G = \frac{E_G}{E_M} \times 100\%$$ \hfill (6)

$$\eta_C = \frac{E_C}{E_G} \times 100\%$$ \hfill (7)

Here, the output parameters (rotor torque, rotational speed and power) of wind rotor are the coupling design parameters which are determined by the magnetic circuit calculation and structure of generator, while the wind rotor output parameters correspond to the maximum wind energy utilization rate which is captured by the wind energy utilization curve ($n$-$\eta_M$ characteristic curve of wind speed as shown in figure 2(a) [9]. The generator output parameters (voltage, current and power) are the input design parameters of voltage controller [10], while The generator output parameters correspond to the maximum efficiency which is obtained from the generator characteristic curve ($n$-$\eta_G$ characteristic curve of rotational speed as shown in figure 2(b). The MEFC testing method proposed in this paper can measure the comprehensive performance of WECS. The calculation formula of the overall efficiency of this system is equation (8).

$$\eta = \eta_M \times \eta_G \times \eta_C$$ \hfill (8)

Here, $A$ is the state matrix which is determined by the structure parameters of WECS. $B$ is the input matrix which is determined by the controller parameters of energy transformation and storage system. $C$ is the output matrix which determined the output information $y$. $D$ is the direct transmission matrix which represents the error of the testing process.

$$x = (x_1, x_2, x_3, x_4)^T$$ is the state vector, $x_1$ and $x_2$ are the speed and output torque of wind wheel, $x_3$ and $x_4$ are the charging current and SOC of battery.

$$u = (u_1, u_2, u_3, u_4)^T$$ is the controlled variable, $u_1$ is the wind speed, $u_2$ is the charging voltage, $u_3$ and $u_4$ are the internal resistance and temperature of battery.

Figure 2. The characteristic curves-(a) is the wind rotor efficiency curve, (b) is the generator efficiency curve, (c) is the battery controller efficiency curve.

Through the characteristics of these parameters, we can get the coupling relationship between the properties which are used to coupling performance test. When design the whole coupling controller, we can use the following state equation to describe it.

$$\begin{cases}
\dot{x} = A(t)x + B(t)u \\
y = C(t)x + D(t)e
\end{cases}$$ \hfill (9)
According the control equation and the corresponding coupling theory, we can design the controller which we needs.

4. Component description and fundamental principle of testing system

As shown in figure 1, the converter 1 provides the variable AC frequency power source for ventilator of wind tunnel 2, the wind tunnel 2 provides wind field simulation parameters (uniform laminar flow velocity \( V \)) for MEFC testing. The wind rotor testing specimen 3 converts the wind energy into mechanical energy under the action of the wind speed \( V \), the generator specimen 4 converts the mechanical energy into electrical energy, the voltage controller specimen 5 makes the unstable electric energy into stable power source for battery 10. The electric energy stored in the battery 10 is absorbed by the load 8 after the inverter 11. The power management device refers to the battery management system.

The output characteristic of wind tunnel 2 is detected by the anemometer 9, the testing parameters (wind speed \( V \)) are transmitted to the data acquisition unit 14 through RS232C communication mode. The output characteristic parameters obtained from the disc coupling sensor 6 of the wind rotor specimen 3, such as the rotational speed \( n \), torque \( T \) and mechanical power \( E_M \) and so on, are transmitted into the data acquisition unit 14 through AD converter 13. The output characteristics of the generator specimen 4 are detected by three-phase electric parameter tester 7, its characteristic parameters including the voltage \( U \), current \( I \), electric power \( E_G \) and so on are transmitted into the data acquisition unit 14 through AD converter 13. Through the power management unit 12, the output characteristics of the voltage controller specimen 5 including the DC voltage and current parameters and so on are transmitted to the data acquisition unit 14 through RS232C communication mode. Data acquisition unit 14 completes the data analysis of MEFS performance parameters such as wind energy, mechanical energy, electric energy and so on, and it creates the coupling test report.

Figure 3 is the input and output characteristics calculation model of wind rotor specimen 3. The wind rotor swept area \( A \) can be ascertained according to the size of the diameter and height of the testing wind rotor. The input wind power \( E_W \) of the wind rotor test specimen 3 can be calculated by equation (1), while the output mechanical energy \( E_M \) can be calculated by the equation (2) with the parameters of the rotor torque \( T \) and rotor speed \( n \) which obtained from the disc coupling sensor 6. The wind energy utilization \( \eta_M \) which corresponds to the system input parameters under the condition of different frequencies and different wind speed can be derived from the equation (5), thus we can draw out the wind energy utilization curve \( (V-\eta_M) \) characteristic curve figure 2(a) of the vertical axis wind turbines specimen 3. The extreme value at the inflection point of the \( V-\eta_M \) characteristic curve is the maximum wind energy utilization rate value, its corresponding parameters including the rotor torque \( T \), rotational speed \( n \) and the power \( E_M \) are the coupling design parameters which are determined from the magnetic circuit calculation and structure of generator 4.

**Figure 3.** The energy transmission model of vertical axis wind rotor.

**Figure 4.** The energy transmission model of generator.
Figure 4 is the input and output characteristics calculation model of the generator 4, the input energy is the output mechanical energy $E_M$ of the wind rotor 3, while the output electrical energy $E_G$ can be derived from the equation (3) with the parameters of single-phase output voltage $U$ and current $I$ which detected from the three-phase intelligent electric parameters monitor 11. When the generator efficiency $\eta_G$ is calculated by equation (6), we can draw out the $n-\eta_G$ characteristic curve (Figure 2(b)) of generator 4. The extreme value at inflection point of the $n-\eta_G$ characteristic curve is the maximum power output value of the generator, its corresponding parameters including the voltage $U$, the current $I$ and electric power $E_G$ are the circuit design and performance simulation coupling parameters of voltage controller 5.

Figure 5 is the input and output characteristic calculation model of voltage controller 5, its input is the three phase unstable power source of generator 4, its output is the charging voltage and charging current of battery. Its input electric power is the output energy $E_G$ of voltage controller 5, while its output energy $E_C$ can be obtained from the equation (4) according to the output voltage $U$ and current $I$ which are detected by the power management system. Then through the equation (7) we can calculate the work efficiency $\eta_C$ of voltage controller 5.

![Figure 5](image)

**Figure 5.** The voltage controller model.

The comprehensive performance of the vertical axis WECS can be obtained from the overall efficiency of the testing system, while the overall efficiency can be calculated from equation (8) according to the results of MEFC test.

5. The implementation process of testing system

When the design of each part component completes, we can enter into the following testing steps.

**Step 1. Wind rotor test.** It tests the wind energy conversion efficiency of wind rotor by coupling sensor. The input detecting parameter is wind speed, through the wind speed it can calculate the wind energy. The output detecting parameter is torque and rotational speed which can calculate the mechanical kinetic energy.

This test can evaluate the wind rotor efficiency curve, at the same time it can make the start torque, rotating speed (corresponding to the wind speed at 10 m/s of the commonly used small-sized rotor) and the power corresponding to the rotating speed as the original design parameters of the generator. If there exists a larger difference between the best efficiency point of the wind rotor efficiency curve and the rotating speed, it needs to adjust the wind rotor geometry parameters to the best efficiency point. The equipments required here are the wind tunnel and rotor testbed, the test instruments needed are anemometer and coupling sensor. The coupling sensors is connected to the RS232C interface of the UCS, then the value of testing rotating speed, torque and power parameters can be transmitted into the UCS directly [11].

**Step 2. Generator test.** It tests the input parameters (torque, speed and power) of generator through coupling sensor and the output parameters (current, voltage and electric power) through three-phase integrated electric parameter tester. This test can evaluate the efficiency curve of the generator. The equipment required here are the converter, driving motor, generator specimen and resistive load. The test instruments needed are the coupling sensor and three-phase integrated electric parameter tester. This test can share the whole equipment with wind rotor test, also can build it respectively.
Step 3. Voltage controller test. It tests the input parameters (current, voltage) of the controller through three-phase integrated electric parameter tester and the output parameters (current, voltage and electric power) from the battery tester. This test can evaluate the efficiency curve of the voltage controller. Note that it requires to do this test cooperated with the generator test.

Step 4. Parameter analysis. This step needs to analysis the component performance of the wind rotor, generator and controller synthetically from a whole perspective of the system, and to evaluate the overall performance of the generator according to their respective efficiency curve, then improve the design parameters, and provide technical preparation for the whole system coupling test at last.

Step 5. Overall test. Assemble the wind rotor, generator, controller and battery to be a WT prototype, do the simulation experiment of this prototype in the wind tunnel testing site. The input detecting parameter is the wind speed, through wind speed we can work out the wind energy, the output detecting parameter is the electric power. This test can evaluate the efficiency curve of WECS, from the characteristic curve we can determine the best performance of the overall coupling system.

Note that only when the component performance analysis from step 1 to step 4 achieve to the optimal state, we can enter into system integration stage of step 5 effectively.

The design solution of the best efficiency point mentioned above is that through the analysis of the aerodynamic of wind rotor structure and the experimental test we can get the efficiency curve of wind rotor, according to the best efficiency point we can estimate the starting torque, rated speed and power of generator then we can design it, and make the best efficiency point of generator consistent with the wind rotor as far as possible. Because the influence factors are much more in practice, it is difficult to realize their optimal synchronously, at this time we needs the coupling test to verification it, to change the design parameters of the generator according to the test results and then to improve the structure and performance. As for the voltage controller, its low cost makes the adjustment easy relatively [12]. At last the final performance of WECS will needs the coupling test equipment proposed in this paper to detect.

It needs to firstly point out that the wind speed is a random variable, the wind tunnel is just a simulation test equipment only. The wind speed, as the input variable for theoretical calculation, its error can reach to 50%. Therefore, the commonly used method is CFD analysis combined with the experimental at present, the performance of the wind rotor depends on its geometry structure and shape, the big difference will exist in the output characteristics [13]. The test results of the single wind rotor provide the coupling design parameters for generator, its result still needs the overall coupling test to reach the overall optimal performance. Secondly, the wind field site selection and evaluation are the first link of wind power generation, its purpose is mainly to investigate the stability and sustainability of wind energy. For the WT structure and wind field, there is only a little relationship between them, for the outdoor WT, even though its rigidity and strength are satisfied (the limited wind speed required in Japan is 60 m/s, the British is 100 m/s, China has not clear regulation about this at present) [14], the safety is the first factor also need to consider. When the specific meteorological data is known, the range of the wind speed will be not restricted to the wind field. As for the rare and powerful storm, it must to take the stall control measures for the WT. At present, the main consideration is to choose the suitable size of the WT for the different wind field.

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References
[1] Dipesh K, Kalyan C 2016 A review of conventional and advanced MPPT algorithms for wind
energy systems Renewable and Sustainable Energy Reviews 55 957-70

[2] Tripathi S M, Tiwari A N and Deependra S 2015 Grid-integrated permanent magnet synchronous generator based wind energy conversion systems: A technology review Renewable and Sustainable Energy Reviews 51 1288-305

[3] Daroczy L, Janiga G, Petrasch K, Webner M and Thevenin D 2015 Comparative analysis of turbulence models for the aerodynamic simulation of H-Darrieus rotors Energy 90 680-90

[4] McTavish S, Feszty D and Sankar T 2012 Steady and rotating computational fluid dynamics simulations of a novel vertical axis wind turbine for small-scale power generation Renewable Energy 41 171-9

[5] Feng F, Li Y, Chen L X, Tian W Q and Zhang Y H 2014 The simulation and experimental research of combined vertical axis wind turbine aerodynamic characteristics Acta Energiae Solaris Sinica 35 855-60

[6] Ding G Q, Li Y, Wang S L, Xie W and Tian W Q 2013 The solidity impaction to the vertical axis wind turbine performance of wind tunnel test Renewable Energy Sources 31 58-62

[7] Aubree R, Auger F, Mace M and Loron L 2016 Design of an efficient small wind-energy conversion system with an adaptive sensorless MPPT strategy Renewable Energy 86 280-91

[8] Qi Z Y and Lin E 2012 Integrated power control for small wind power system J. Power Sources 217 322-8

[9] Aubree R, Auger F, Mace M and Loron L 2016 Design of an efficient small wind-energy conversion system with an adaptive sensorless MPPT strategy Renewable Energy 86 280-91

[10] Yang B, Jiang L, Wang L, Yao W and Wu Q H 2015 Nonlinear maximum power point tracking control and modal analysis of DFIG based wind turbine Int. Journal of Electrical Power & Energy Systems 74 429-36

[11] Qi Z Y and Lin E 2012 Integrated power control for small wind power system Journal of Power Sources 217 322-8

[12] Saeidi D, Sedaghat A, Alamdari P and Alemrjaji A A 2013 Aerodynamic design and economical evaluation of site specific small vertical axis wind turbine Applied Energy 101 765-75

[13] Almohammadi K M, Ingham D B, Ma L and Pourkashan M 2013 Computational fluid dynamics (CFD) mesh independency techniques for a straight blade vertical axis wind turbine Energy 58 483-93

[14] Beiter P 2015 2014 Renewable Energy Data Book (Washington: U. S. Department of Energy) 52-61