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Imitation of the characteristics of the wind turbine based on DC motor

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Abstract This paper analyzed the operating principles and power and torque characteristics of the wind turbine and the direct current motor (DC motor), and investigated the operating characteristics of the wind turbine compared to that of the DC motor. The torque imitation scheme, which has good performance and high feasibility, together with the whole wind turbine imitation system, was provided. The wind turbine imitation system includes not only a hardware platform composed of PC, data-collection board and thyristor-based velocity-regulator, but also monitor software of wind turbine imitation. The experimental results of different occasions verify the correctness and feasibility of the wind turbine imitation scheme proposed in this paper, which provided a valid idea for wind turbine imitation and investigation of wind power generation techniques in the laboratory.

Keywords wind turbine, DC motor, imitation, characteristics, wind power generation

1 Introduction

Wind energy is a kind of renewable blue source that produces no pollution. It is of great significance to resolve the energy crisis and the environment pollution throughout the world so that wind energy will be rapidly developed and widely applied in practice. This has made wind power a research focus of scholars in different countries [1–7]. In recent years,

with wind power technology having gained fast development, many advanced technologies proposed from the laboratory, such as variable blade control, variable speed constant frequency (VSCF) generation, direct-drive without gear box, etc., have been applied to actual spots [3]. The early investigation and research conducted in the laboratory could actively drive forward the development of wind power technology. With researchers exploring hard, more and more new technologies and theories would be presented and verified. Because there is no wind turbine (or wind plant) in most laboratories, it is important and practical to research how to simulate the characteristics of the wind turbine under laboratory conditions [8]. However, only a few documents have introduced the characteristics of the wind turbine and have given a deep analysis together with an actual scheme. Control for the generator and converter is mainly introduced in Ref. [9] where a doubly-fed induction generator (DFIG) is driven by a direct current motor (DC motor), which is used to imitate a wind turbine. However, imitation of the characteristics of the wind turbine was not discussed in detail. Although the rough control strategy of wind turbine imitation with electric motor has been presented in Ref. [10], the practical project and the imitation equations were not developed. In Ref. [11], the characteristics of the wind turbine at optimal operation are imitated through regulating the voltage of a DC motor, but the characteristics at no-optimal operation could not be imitated. With its simple principle and perfect performance, the DC motor is superior to any other devices for wind turbine imitation. To imitate the universal characteristics of the wind turbine, this paper firstly analyzed the operating principles and power and torque characteristics of the wind turbine in contrast to those of the DC motor. Next, a power imitation scheme and a torque imitation scheme were put forward and compared. The torque imitation scheme gains more research interest in this issue because of its relatively simple realization and high performance. The whole wind turbine imitation system, which includes hardware platform and monitor software, was created. Finally, imitation experiments for the characteristics of the wind turbine under different operating conditions were carried out. The experimental results verify the high feasibility and good

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performance of the wind turbine imitation scheme proposed in this paper. The scheme can be expected to lay the foundation of research for wind power techniques in the laboratory.

2 Characteristics comparison of a wind turbine with DC motor

To imitate the characteristics of the wind turbine, the essential differences of characteristics of the wind turbine and those of a DC motor should first be investigated according to their operating principles.

As is known by aerodynamics, the output mechanical power of a wind turbine can be calculated as follows [12]

$$P_o = \frac{\pi}{8} \rho D_w^2 v^3 C_p \quad (1)$$

where ρ is air density, D_w is the diameter of the turbine, v is the wind speed and C_p is the wind turbine's power coefficient.

C_p is important to denote wind turbine efficiency. It should be noted that the power coefficient is a function of the ratio between the turbine's angular velocity ω_w and the wind speed v . This ratio, called the tip speed ratio, denoted by λ , is given by

$$\lambda = \frac{D_w \omega_w}{2v} \quad (2)$$

A typical relationship between C_p and λ is shown in Fig. 1. It is clear from this figure that there is a value of λ , for which C_p is maximized so as to maximize the converting power for a given wind speed v . The λ , which is called the optimal tip speed ratio, can be denoted by λ_{opt} , and the corresponding C_p , called the optimal wind turbine's power coefficient, can be denoted by C_{pmax} . If λ is greater or less than λ_{opt} , turbine efficiency will degrade.

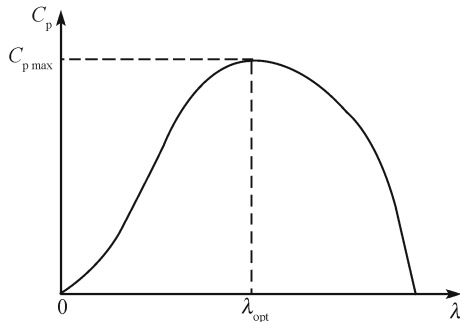


Fig. 1 C_p - λ curve of the wind-turbine

The power characteristics of the wind turbine at various wind speeds, which is shown in Fig. 2(a), can be obtained from Fig. 1 and Eq. (1). As seen in Fig. 2, the peak power for each wind speed occurs at the point where C_p is maximized.

The optimum power curve (P_{opt}) consists of those points. To maximize the converting power, it is therefore desirable for the generator to operate on this curve [12].

The conclusions for the fixed-pitch wind turbine traits are as follows:

1) under rated wind speed, the increase of wind speed for a given wind turbine's angular velocity will increase its output power, and vice versa;

2) as the wind turbine's angular velocity changes for a given wind speed, the output power would vary. One specific angular velocity, which is called the optimal angular velocity, can achieve the maximum output power;

3) the optimal angular velocity is unique for a given wind speed. As the wind speed changes, the optimal angular velocity would vary correspondingly.

The wind turbine's torque characteristics are shown in Fig. 2(b). Similarly, the optimal operation points of torque curves at different wind speeds form the optimum torque curve of the wind turbine, which is shown as T_{opt} . Operating on this curve, the wind turbine can capture the maximum wind power. The wind turbine's torque characteristics are in essence the same as those of the wind turbine's power; they only reflect the operation characteristics of the wind turbine from different point of views.

The maximum output power and the optimal torque of the wind turbine gained from Eqs. (1) and (2) are given by

$$\begin{cases} P_{max} = k_w \omega_w^3 \\ T_{opt} = k_w \omega_w^2 \end{cases} \quad (3)$$

where $k_w = 0.25 \rho S_w (D_w / \lambda_{opt})^3 C_{pmax}$.

From the equation above, it is obvious that the maximum output power is related to the cube of the turbine's angular velocity, and the optimal torque of the wind turbine is related to the square of the turbine's angular velocity.

The equivalent circuit of a separately excited DC motor is shown in Fig. 3, where R_a , R_f , L_a and L_f represent the resistance of armature winding, resistance of exciting coil, the inductance of armature winding, and the inductance of exciting coil, respectively. u_{dem} and i_{dem} are the terminal voltage of armature winding and the armature current, respectively. u_f and i_f are the terminal voltage of exciting coil and the exciting current, respectively. e_a is electromotive force of armature winding.

The steady-state mathematic model of the DC motor is given by Refs. [13–15]

$$\begin{cases} u_{dem} = i_{dem} R_a + e_a \\ e_a = C_e \phi \omega_m \\ T_{de} = C_t \phi i_{dem} \end{cases} \quad (4)$$

Where C_e and C_t are the electromotive force constant and torque constant, respectively, and $C_e = C_t$. ϕ is the main flux linkage. T_{de} is the electromagnetic torque. ω_m is the angular velocity.

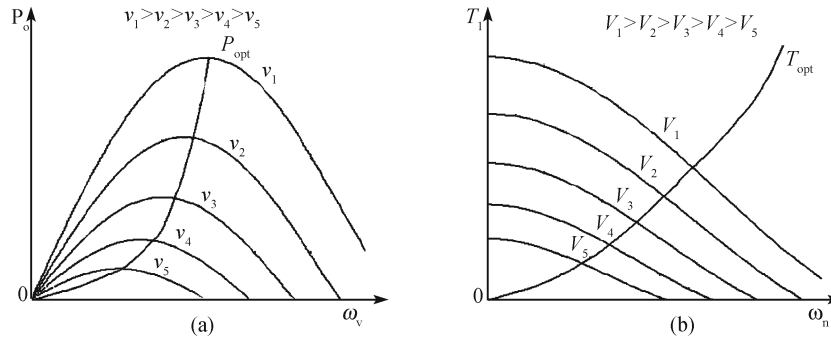


Fig. 2 The characteristics curve of the wind turbine
 (a) $P_o = f(v, \omega_n)$; (b) $T_1 = f(v, \omega_n)$

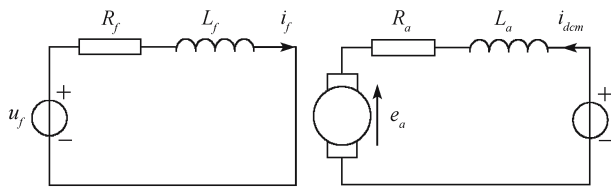


Fig. 3 The equivalent circuit of the separate excited DC motor

If various losses of the DC motor can be ignored, the electric power of the motor is equal to its mechanical output power as follows

$$P_{do} = T_{de}\omega_m \tag{5}$$

From Eqs. (4) and (5) it can be given that

$$P_{do} = \frac{C_e\phi}{R_a}(u_{dcm} - C_e\phi\omega_m)\omega_m \tag{6}$$

If armature reaction can be ignored and ϕ is constant, P_{do} is only related to u_{dcm} and ω_m , that is $P_{do} = f(u_{dcm}, \omega_m)$. And if u_{dcm} is a constant, then $P_{do} = f(\omega_m)$ is conic. As u_{dcm} varies continuously, there is a bunch of conics about P_{do} , which is shown in Fig. 4(a).

By ignoring various losses, the electromagnetic torque of the DC motor is equal to its mechanical output torque as follows:

$$T_{de} = \frac{C_t\phi}{R_a}(u_{dcm} - C_e\phi\omega_m) \tag{7}$$

As can be seen in this equation, T_{de} is also related to u_{dcm} and ω_m , that is $T_{de} = f(u_{dcm}, \omega_m)$. Suppose u_{dcm} is a constant, so the relationship between T_{de} and ω_m is linear. As u_{dcm} varies continuously, a bunch of beelines about T_{de} can be obtained, as shown in Fig. 4(b).

The conclusions contrasted the characteristics of the wind turbine (see in Fig. 2) with those of the DC motor (see in Fig. 4) as follows:

1) Both power characteristics and torque characteristics may be described by a bunch of curves with angular velocity as their abscissa. The change of v may give rise to a variety of wind turbine's power (torque) characteristics. Similarly, changing u_{dcm} can regulate the DC motor's power (torque) characteristics.

2) While v or u_{dcm} are constant, the output power of a wind turbine or a DC motor is directly related to their angular velocity. As a result, as their angular velocity changes, there is an optimal angular velocity at which the maximum output power can be attained. If angular velocity is greater or less

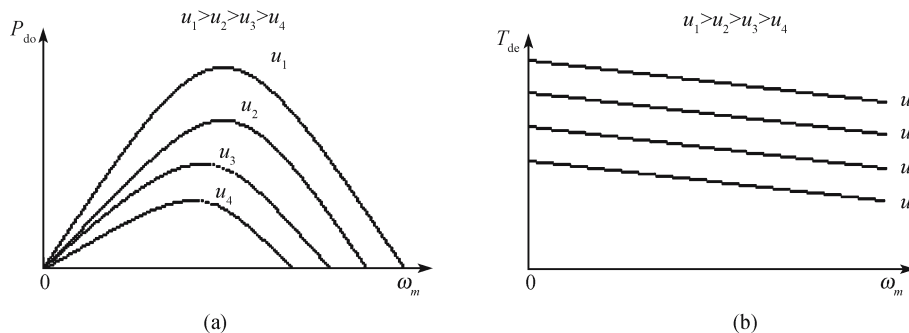


Fig. 4 The characteristics curve of the DC motor
 (a) $P_{do} = f(u, \omega_m)$; (b) $T_{de} = f(u, \omega_m)$

than the optimal angular velocity, output power would decrease. Therefore, there are optimal power curves for both wind turbines and DC motors.

3) There are different aspects between the characteristics of the wind turbine and those of a DC motor. For a given u_{dcm} , the power or torque of a motor is linear with its angular velocity or is related to its square, respectively. However, for a fixed v , the relationship between a wind turbine's power or torque and its angular velocity is relatively complex, because the relationship between C_p and λ cannot be directly expressed by parsing equation. The latter relationship can only be described by tabling method according to the parameters of an actual wind turbine.

3 DC motor control in the wind turbine imitation

As is known from the analysis above, the power/torque characteristics of the wind turbine are found to be similar to those of a DC motor. The action of u_{dcm} for output power/torque of the DC motor is almost the same to the action of v for a wind turbine's output power/torque. If their differences are ignored, the simplest method to imitate the wind turbine can be obtained by varying u_{dcm} to emulate the change of the wind speed. However, this method only imitates the characteristics of the wind turbine partly, so it is not feasible for actual situations. Therefore, finding a more precise method is necessary.

Because a wind turbine is an energy conversion machine, the essence of wind turbine imitation based on the DC motor is to control the power/torque of the DC motor, but not to adjust its speed. This idea is shown in Fig. 5. The reference output power (torque) of a DC motor is calculated using the mathematic model of the imitated wind turbine, whose inputs are the present wind speed and the measured angular velocity. With the reference output power/torque as control instruction, the motor could operate in the way the wind turbine does. The model of the wind turbine obtained from its operation principle is shown in Fig. 6. The output of the wind turbine model can be power or torque according to the two different imitation schemes which are to be discussed consequently.

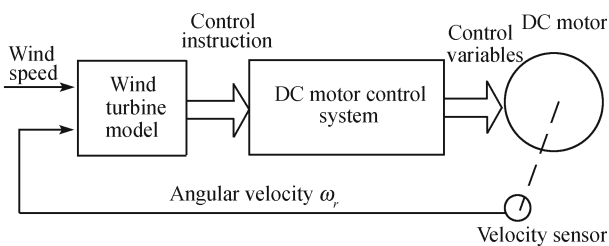


Fig. 5 The idea of wind turbine imitation using a DC motor

According to the different control objects of the DC motor, the emulation of the characteristics of the wind turbine could be classified into two schemes: the power imitation and

the torque imitation. The power imitation emulates the wind turbine's power characteristics by controlling the DC motor's power output. Similarly, the torque imitation emulates the wind turbine's torque characteristics by controlling the DC motor's torque output.

As is seen from Eq. (6), by controlling u_{dcm} , the output power P_{do} of the DC motor can be regulated. In the power imitation scheme, the control object is P_{do} and the control variable is u_{dcm} ; the latter is given by

$$u_{\text{dcm}} = \frac{1}{C_e \phi \omega_m} \left[P_{\text{do}} R_a + (C_e \phi \omega_m)^2 \right] \quad (8)$$

Obviously, not only the calculation of u_{dcm} requires speed measurement, but it can also be affected by speed measure errors. In addition, the voltage signal is highly sensitive and is easily disturbed. Therefore, the power imitation scheme has greater errors and is difficult to perform/implement.

As Eq. (4) describes, i_{dcm} is directly proportional to T_{de} , that is to say, the regulation of T_{de} can be realized conveniently by controlling i_{dcm} . Therefore, the torque characteristics of the wind turbine can be imitated by changing the i_{dcm} of the motor. In the torque imitation scheme, the control object is T_{de} and the control variable is i_{dcm} . With the advantages of easy implementation and high precision, this scheme will be studied in detail.

The torque imitation scheme based on linear PI loop controller is shown in Fig. 7. The control algorithm includes two parts: reference torque calculation and motor torque control. The reference torque is obtained from the wind turbine model using the emulated wind speed and the feedback angular velocity [16]. However, it should be noticeable that when calculating the reference torque, the feedback angular velocity should first be transformed into the angular velocity of the wind turbine in terms of the gear ratio between the turbine and generator, that is $\omega_w = \omega_m / N$.

4 Experiment for wind turbine imitation

A VSCF wind power generation experiment system based on the wind turbine imitation technique was built, as shown in Fig. 8. Supported by a digital signal processors (DSP)-based control system, the DFIG is running with VSCF generation [17,18]. As a generator-driven device, a DC motor is used for wind turbine imitation under the control of the wind turbine imitation system. A master computer was set up for the cooperation of the two systems.

The hardware platform for wind turbine imitation consists of a PC, data-collection board, and a thyristor-based velocity-regulator, which is shown in Fig. 9. In addition, the wind turbine monitor software has independently been developed, of which the main interface is shown in Fig. 10. With the aid of the monitor software, the PC acts as a control center of the wind turbine imitation system. The data-collection board has the ability to input or output analog/digital signals, which

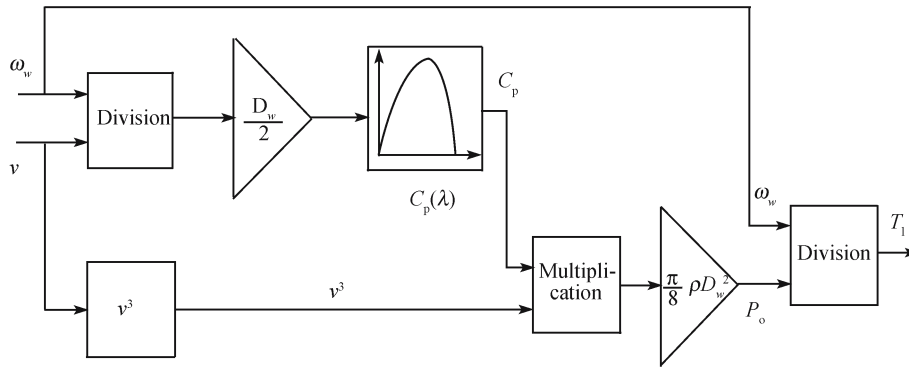


Fig. 6 The model of the wind turbine

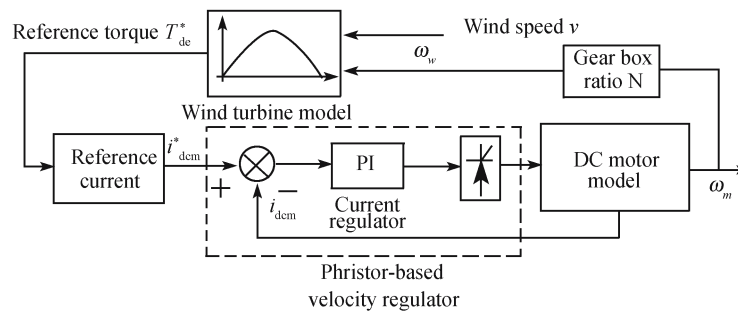


Fig. 7 The structure of the wind turbine imitation scheme

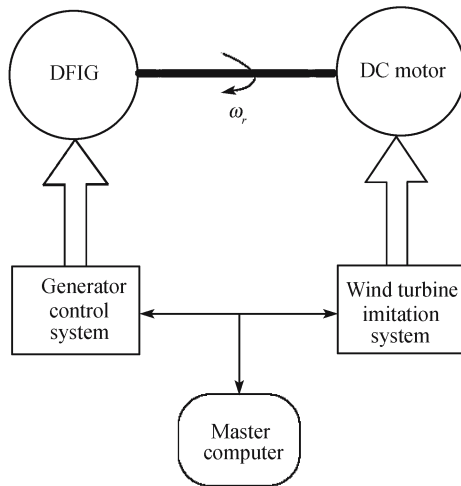


Fig. 8 The structure of the wind power generation experimental system

makes it possible for the board not only to feed back the operation parameters of the DC motor, but also to output the control signals to the thyristor-based velocity-regulator. The 3-phase bridge thyristor-based velocity-regulator [19,20], which is modified to control the armature current of the motor, acts as the motor driver.

Figures (11) and (12) show the experiment results for the wind turbine imitation at two kinds of representative situations. In the top graphic, the top curve describes the

change of the wind speed, and the one at the bottom describes the change of the angular velocity. The middle graphic and the bottom graphic illustrate the ideal output power of the wind turbine and the output power of the DC motor, which emulates the wind turbine respectively. The experiment results are shown in Fig. 11 when the turbine speed changes at a given wind velocity. In contrast, as the wind velocity linearly changes for a given turbine speed, the experiment results of the imitation system are shown in Fig. 12. The DC motor imitates the operation characteristics of the wind turbine well in both situations above.

Figure 13 describes the rotor/stator currents of DFIG in the course of imitation. Being the load of the motor, DFIG operates with variable output power and speed in this course. The change of stator current reflects the change of the generator output power when the grid voltage is constant, while the variable frequency of the rotor current reflects the change of the angular velocity.

5 Conclusion

This paper analyzed the operating principles and power and torque characteristics of the wind turbine and the DC motor. The torque imitation scheme proposed has good performance and is easy to carry out. Hardware platform and monitor software for the wind turbine imitation system were created. Eventually, the experiments of the imitation system were

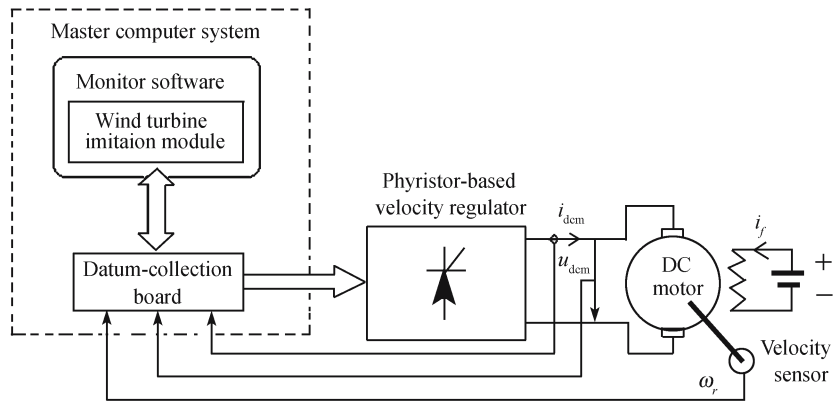


Fig. 9 Wind turbine imitation control system

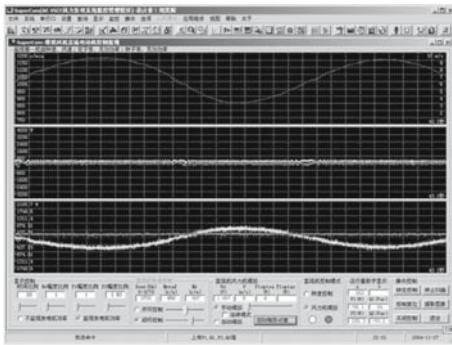


Fig. 10 The main interface of the wind turbine imitation monitor software

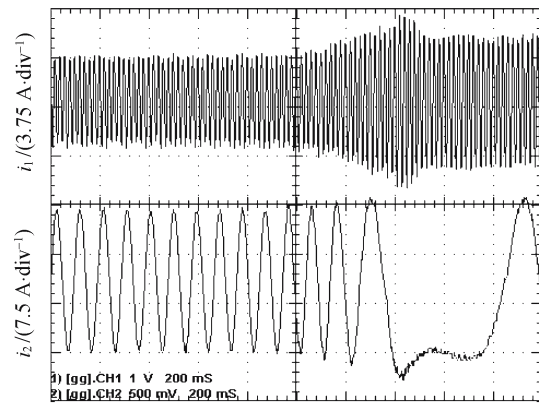


Fig. 13 Stator current and rotor current of generator in progress of wind turbine imitation

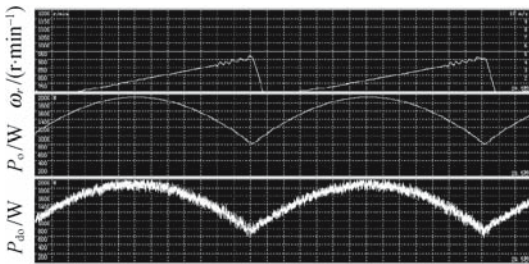


Fig. 11 Imitation experiment when wind speed keeps constant and motor velocity varies

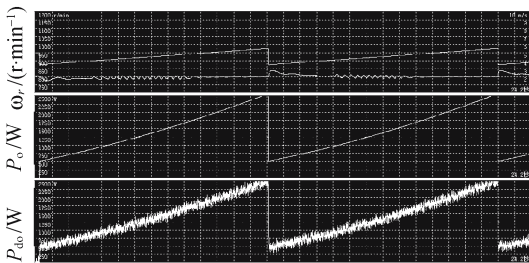


Fig. 12 Imitation experiment when wind speed varies and motor velocity keeps constant

performed in different situations, and the experimental results confirm the correctness and feasibility of the proposed imitation scheme. Not only does it provide a valid idea for

wind turbine imitation and investigation of wind power generation technique in the laboratory, but it also lays a foundation for an in-depth study of wind power.

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Appendix

Wind turbine imitation: blade radius: 4.3 m; rated power: 10 kW; the optimal wind coefficient: 0.43; tip-speed ratio: 9.

DC motor: rated power: 10 kW; rated speed: 1 500 r/m; rated voltage: 440 V; rated current: 39.3 A; excited-voltage: 220 V; excited-current: 2.74 A.

Thyristor-based velocity regulator: 3-phase full-bridge rectifier and smoothing reactor (100 mH / 15 A).

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