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Developing Experimental Scenarios to Evaluate Dynamic Response Effectiveness of DFIG-Based Wind Power Generator

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ABSTRACT

This paper develops experimental scenarios to analyze the dynamic responses of a DFIG-based wind power system. The wind speed was suddenly varied at short intervals to evaluate the dynamic behavior of the output parameters of the DFIG system, therefore, four typical scenarios considered in this study include: maintaining a constant wind speed, increasing the wind speed from 5 m/s to 12 m/s, increasing the wind speed from 5 m/s to 18 m/s, and varying the wind speed according to a practical 24-hour profile. These scenarios are implemented using the DFIG-based wind power experimental system to evaluate key outputs such as torque, voltage, current, active power, reactive power, and pitch angle. The experimental results confirm the dynamic response performance of the DFIG-based wind power system. Furthermore, the sub-synchronous and super-synchronous operational modes of the system, as observed in the experimental scenarios, are studied and evaluated to enhance the operational performance of the DFIG-based wind power system.

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1. Introduction

Today, renewable energy sources are rapidly developing to meet the growing demand for energy. Among them, wind energy is a highly promising resource that is being increasingly harnessed [1]. In Vietnam, wind power projects are expected to grow significantly, as outlined in the Power Plan VIII. Research topics related to wind power systems continue to attract significant interest from both domestic and international researchers [2].

In the paper [3], the authors discuss the crucial role of wind energy, particularly the doubly fed induction generator (DFIG) in renewable energy systems. The paper focuses on modeling and controlling the DFIG-based wind turbine, as well as its response to practical disturbances. The authors emphasize that the DFIG wind turbine can effectively respond to disturbances due to its rapid and stable control. The voltage and frequency of the system are key factors in evaluating the impact of wind energy on the overall power grid, especially under transient fault conditions. Similarly, the authors in [4, 5] address the impact of variable-speed DFIG wind turbines on the dynamic response performance of power systems. Specifically, the paper analyzes factors such as frequency stability, transient stability, small-signal stability, and voltage stability. Additionally, the author discusses the ancillary services provided by the DFIG wind turbine to the grid, such as frequency control support and reactive power, along with methods for mitigating power oscillations in the system [6, 7]. In [8], the authors proposed a coordinated control strategy for DC-link voltage and crowbar to enhance low voltage ride-through capability in a partially-rated converter-based wind turbine with the energy storage system (ESS). The work [9] proposed an adaptive temporary frequency support strategy for DFIG-based wind turbines to enhance frequency stability under varying load disturbances. Two-variable admittance models for DFIG-based wind farms were developed in [10] for considering wake effects and single-input and dual-output characteristics, along with an improved stability analysis method to determine stable wind speed intervals under different series compensation levels. The work [11] studied the transient instability issue

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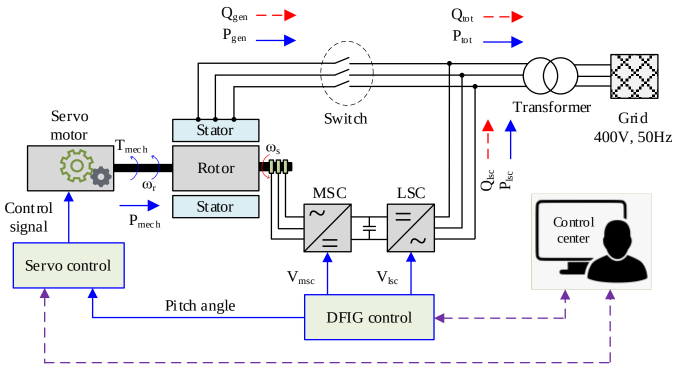
in DFIG-based wind turbines using Lyapunov's energy function and inverse trajectory method through hardware-in-the-loop experiments.

Based on the above analysis, this paper develops scenarios to evaluate the dynamic response of the DFIG-based wind power system through experiments. The main contributions of this paper include: analyzing the operational parameters of the DFIG wind generator under different wind speeds; assessing the dynamic response to sudden changes in wind speed over a short period; and constructing a 24-hour wind profile from practical data to evaluate the dynamic response performance of the DFIG wind generator. The remainder of this paper is organized as follows. Section 2 presents the structure of the DFIG wind power system used for the study, including the system's hardware and software components, as well as their technical specifications. The experimental results and analysis for evaluating the dynamic response of the DFIG wind power system under four scenarios are discussed in detail in Section 3. Finally, Section 4 provides some conclusions.

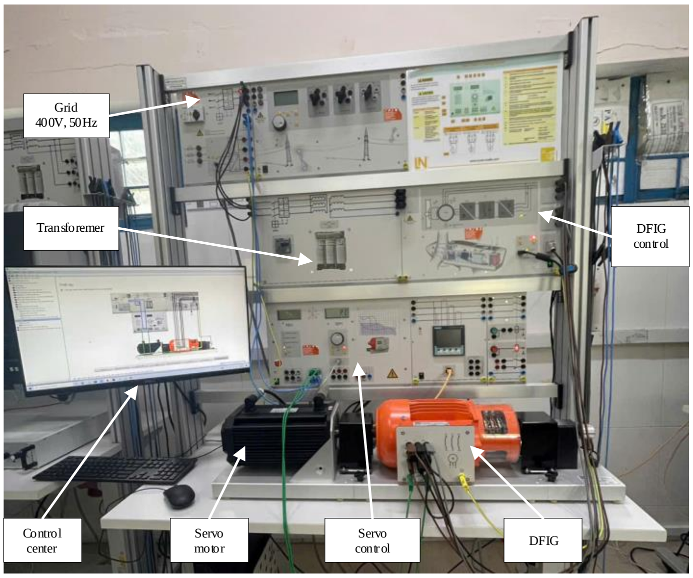
2. DFIG-Based Wind Power System

2.1. Hardware components

The DFIG-based wind power system includes components such as the DFIG wind generator, DFIG control, servo motor, servo control, grid power source, transformer, multifunctional power quality meter, etc. The schematic diagram and hardware components of the system are shown in Figure 1. The DFIG based wind turbine modelling and control strategies are presented in [5, 7], in which different rotor current control methods are investigated with the objective of eliminating the influence of the back electromotive force.



(a) Schematic Diagram of the DFIG System



(b) System Model

Figure 1. *DFIG system*

In Figure 1(a), the servo motor is used to simulate the wind input source, driving the rotor shaft of the DFIG. This motor is controlled by the Servo Control unit, which receives signals from the computer system representing the control center, where the user can set various wind speed scenarios. Some parameters such as mechanical torque, rotor speed, active power, and reactive power at different positions are clearly shown in the schematic diagram of Figure 1(a). These parameters will be investigated across various scenarios. The connection between the components in the schematic diagram of Figure 1(a) and the actual devices is also clearly demonstrated in the paper through annotations in the textbox in Figure 1(b). The specifications of these devices are provided in Table 1. This model allows us to study the DFIG-based wind power system using real-world data, helping us better understand the operational management process of wind power plants in practice [12].

Table 1. *Equipment specifications*

No.	Element	Specifications
1	Doubly-Fed Induction Generator (DFIG)	Rated voltage: U = 230/400 V Rated frequency: f = 50 Hz Rated power P = 1.0 kW Rated current: I = 3.5/2.0 A Rated rotor speed: n = 1500/1400 rpm Power factor: cosφ = 1.0/0.75
2	Servo motor	Rated power: P = 1,4 kW Rated voltage: U = 390 V Rated current: I = 3.3 A Rated rotor speed: n = 2000 rpm Power factor: cosφ = 0.75
3	Three-phase two-winding transformer	Primary voltage: U_1 = 400 V Secondary voltage: U_2 = 400 V Rated power: S = 1.0 kVA
4	Servo motor control	Voltage: U = 300 V Frequency: f = 50 Hz Power: S = 1.0 kVA
5	Resistance load	Load: P = 1.0 kW
6	Power quality meter	Siemens PAC4200

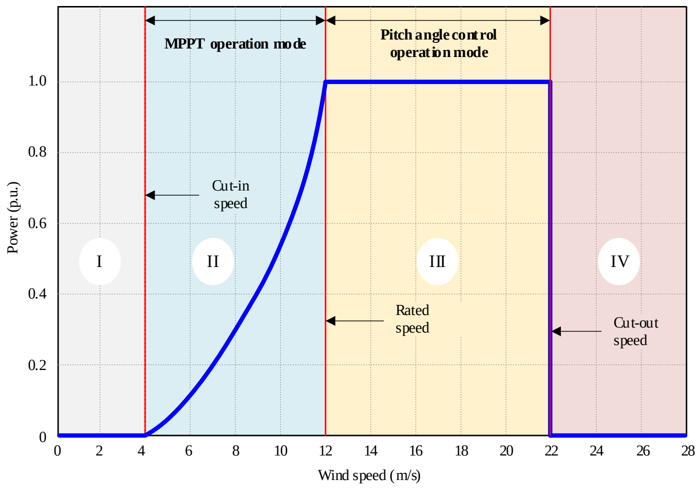


Figure 2. *Power-wind speed characteristics [10]*

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The turbine power characteristics as a function of wind speed are shown in Figure 2. Clearly, this characteristic curve has four regions corresponding to four different wind speed ranges [13, 14]. Region I represents the wind generator's operation in the DFIG system, where it cannot start at wind speeds from 0 to 4 m/s. Region II represents the operation of the DFIG wind generator under the Maximum Power Point Tracking (MPPT) mode for wind speeds ranging from 4 m/s to 12 m/s. Region III, which corresponds to wind speeds from 12 m/s to 22 m/s, is the region where the DFIG wind generator operates in the pitch angle control mode because the wind speed exceeds the rated speed. Region IV, with wind speeds greater than 22 m/s, forces the system to shut down completely. In this paper, the wind speed is set to fall within Regions II and III to investigate and evaluate the dynamic response of the DFIG when there are sudden changes in the wind speed input, facilitated by the central computer control system.

2.2. Software system

The Lucas-Nülle Labsoft software is a tool designed for researching in the field of electrical engineering, particularly in renewable energy applications such as wind power. For the DFIG system, the authors use it to control processes related to the operation of the wind turbine generator. The Control Center interface in the Lucas-Nülle LabSoft software is designed to provide users with an intuitive and efficient workspace for controlling and monitoring systems. The clear design makes it easy for both beginners and experienced users to operate. Users can use the control center interface to start or stop the machine and adjust its parameters. It displays parameters such as rotor speed, blade pitch angle, power, and voltage. The simulation area displays a 3D schematic diagram of the wind power system, helping users visualize how it works. It also has the capability to record graphs and export data, making it easier to create reports and compare experimental results [15].

3. Experimental Results and Discussion

Four wind speed profile scenarios at different levels were constructed to investigate and evaluate the dynamic response of the DFIG wind turbine generator. The data obtained from the experimental process, such as speed, torque, active power, reactive power, generator voltage, generator current, and blade pitch angle, were used to assess the dynamic response performance of the DFIG system.

3.1. Scenario 1: Maintaining a constant wind speed

In this scenario, the wind speed is set at constant values of 5, 10, 12, 15, and 18 m/s to investigate the operational parameters of the DFIG-based wind power system. The experimental results from the model are summarized and presented in Table 2. These represent the basic operating modes for studying the dynamic response of the DFIG-based wind power system when the wind speed changes abruptly from one value to another, as well as changes according to the typical 24-hour daily profile.

Table 2. *Operational parameters of the DFIG-based wind power system at different wind speeds*

Wind speed (m/s)	Rotor speed (rpm)	Pitch angle (degrees)	Torque (Nm)	P_{mech} (W)	P_{gen} (W)	P_{lsc} (W)	P_{tot} (W)
5	1014	0	1.0	102	46	-102	-56
10	1893	0	4.2	830	423	4	427
12	1903	0	5.5	1092	651	35	686
15	1906	15	5.9	1168	723	41	764
18	1905	24	5.8	1160	727	39	766

In addition, for the range of wind speeds varying from 0 to 18 m/s, the paper conducts experiments to assess the output parameters of the DFIG-based wind power system when the wind speed is maintained at each constant level. The results are presented in Figure 3. It is clear that when the wind speed reaches the minimum level of 4 m/s, the rotor speed begins to increase, along with other parameters such as mechanical power, stator power, and Line Side Converter (LSC), which also change because the DFIG has been connected to the grid at this point. However, at the wind speed of 4 m/s, the stator power is still lower than the power fed into the LSC converter, so the DFIG is still receiving power

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from the grid ($P_{tot} < 0$), indicating that the DFIG is operating in a sub-synchronous mode ($\omega_r < \omega_s$). The experiment continues similarly for the wind speed range from 4 m/s to 18 m/s. The results in Figure 3 clearly show that when the wind speed reaches 6 m/s, the LSC power remains negative ($P_{lsc} < 0$), but the stator power becomes greater than the power received by the LSC, so the DFIG exchanges to delivering power to the grid ($P_{tot} > 0$). When the wind speed reaches 10 m/s, the rotor speed reaches its rated value and stays at this level as the wind speed continues to increase up to 18 m/s. At this point, the LSC starts delivering power to the grid ($P_{lsc} > 0$), meaning both the stator and rotor are supplying power to the grid ($P_{tot} > 0$), indicating that the DFIG is operating in a super-synchronous mode ($\omega_r > \omega_s$). If the wind speed is further increased to 12.5 m/s, the DFIG continues to operate in the power delivery mode ($P_{tot} > 0$), but the control system will adjust the blade pitch angle to limit the mechanical power from exceeding the rated power, as shown in Figure 3(a).

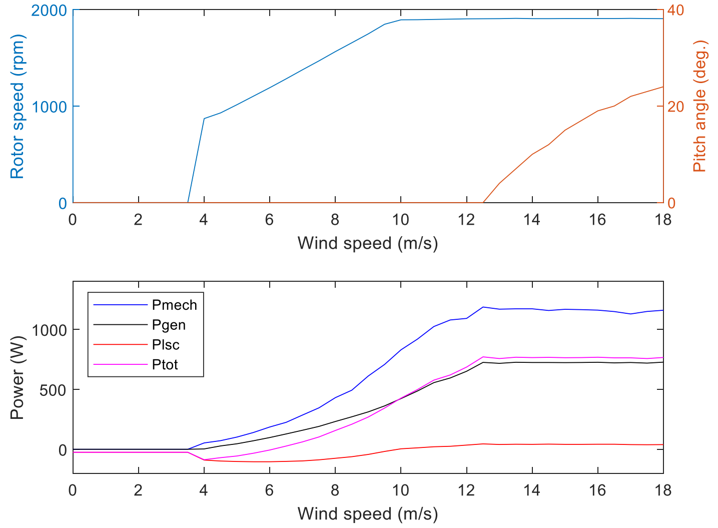

Figure 3. *(a) Rotor speed and pitch angle, (b) Parameters P_{gen}, P_{lsc}, P_{tot}, P_{mech}*

3.2. Scenario 2: Increasing wind speed from 5 m/s to 12 m/s

In this scenario, the wind turbine operates with a wind speed that increases from 5 m/s to the rated speed of 12 m/s, in order to evaluate the dynamic response of the DFIG-based wind power system. This process is set according to the wind speed profile over a period of time, initially starting at 5 m/s and gradually increasing to 12 m/s. Afterward, the wind speed returns to 5 m/s over the next 10 seconds. The wind speed profile for this scenario is shown in Figure 4(a).

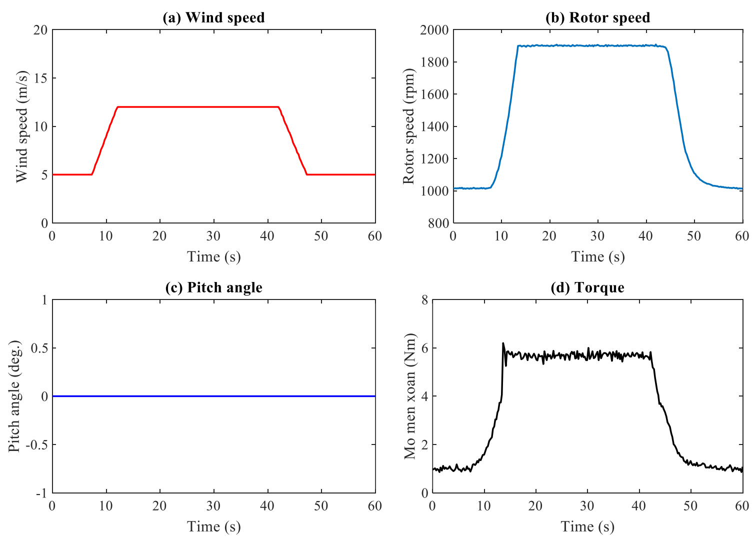

Figure 4. *Scenario 2: (a) Wind speed, (b) Rotor speed, (c) Blade pitch angle, (d) Torque*

From the experimental results shown in Figures 4 and 5, we can observe that as the wind speed increases, the rotor speed of the generator, blade pitch angle, torque, generator current, and power output also increase. Conversely, when the wind speed decreases, the rotor speed, torque, current, and power output of the generator decrease accordingly. The current through the converter decreases as the wind speed increases, while the voltage and reactive power remain nearly unchanged. When the wind speed reaches 12 m/s, the rotor speed reaches 1900 rpm and remains stable from the 10th second to the 45th second.

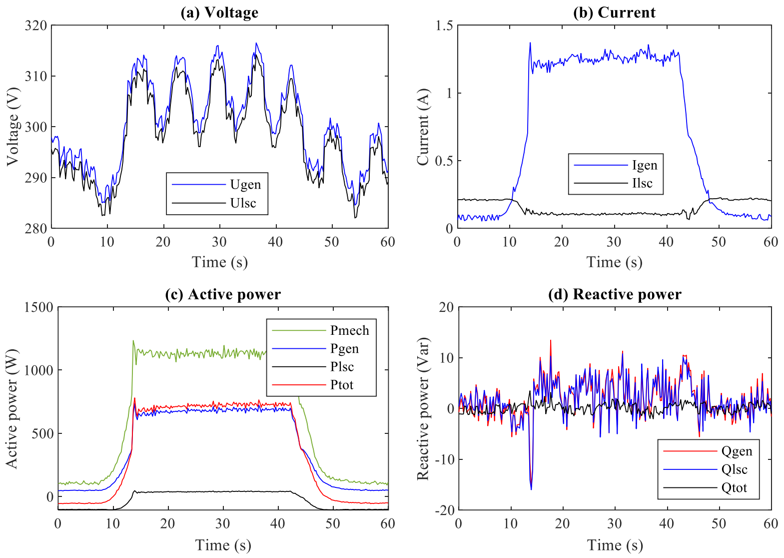

Figure 5. *Scenario 2: (a) Voltage, (b) Current, (c) Active power, (d) Reactive power*

Figure 5(c) shows the mechanical power and electrical power of the rotor and stator in the DFIG wind generator. P_{mech} is the mechanical power of the wind turbine, P_{gen} is the generated power on the stator side, P_{lsc} is the power output from the rotor through the converter, and P_{tot} is the total power generated from both the stator and the rotor through the LSC to the grid. The initial mechanical power is P_{mech} = 102 W, and it reaches its maximum value when the wind speed increases to 12 m/s, with P_{mech} = 1234 W at the 13th second, after which it stabilizes. The power changes in proportion to the wind speed. The maximum generated power by the stator is P_{gen} = 733 W, and the initial value is 47 W. From the figure, we can observe that the initial value represents the negative power from the rotor to the converter. This indicates that the DFIG generator is operating in the sub-synchronous mode, where power is being transferred back from the converter to the rotor. When the wind speed reaches 12 m/s, the power value is P_{lsc} = 32 W, indicating that the generator is operating in the super-synchronous mode, where power is transferred from the rotor to the LSC to the grid. P_{tot} represents the total electrical power from both the stator and rotor through the LSC. From these obtained results, at the time when the power reaches its maximum value at the 13th second, it can be calculated that about 40% of the mechanical power is lost during the conversion to electrical power. The voltage on the stator side does not change significantly, indicating that the active power and reactive power are controlled through the stator current I_{gen}. The current I_{lsc} on the rotor side to the converter decreases when switching from sub-synchronous to super-synchronous mode and increases when the opposite transition occurs.

3.3. Scenario 3: Increasing wind speed from 5 m/s to 18 m/s

In this scenario, the experiment will be conducted with wind speed changing from 5 m/s to 18 m/s over a period of 60 seconds. The initial wind speed is set at 5 m/s and increases to 18 m/s between the 10th and 20th second. It is then maintained at a constant speed of 18 m/s until the 40th second, after which it decreases to 5 m/s starting from the 50th second. In this scenario, the change in the pitch angle of the DFIG system will be observed more clearly.

Based on these obtained results, we observe a difference compared to Scenario 2, where the pitch angle changes when the wind speed reaches 18 m/s. The purpose of this change is to reduce the rotor speed and activate the braking system to decrease the shaft's rotational speed, thereby protecting the wind turbine system components when the wind speed is high. This is controlled by the wind speed and direction sensors. At the 17th second, the pitch angle begins to change as the wind speed exceeds 12 m/s. Therefore, in this scenario, we investigate the variation of parameters when the wind speed exceeds the stable threshold.

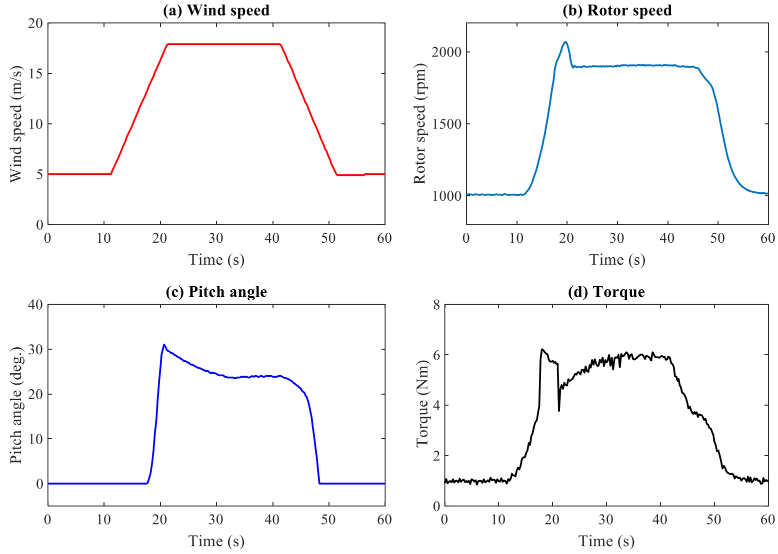

Figure 6. *Scenario 3: (a) Wind speed, (b) Rotor speed, (c) Pitch angle, (d) Torque*

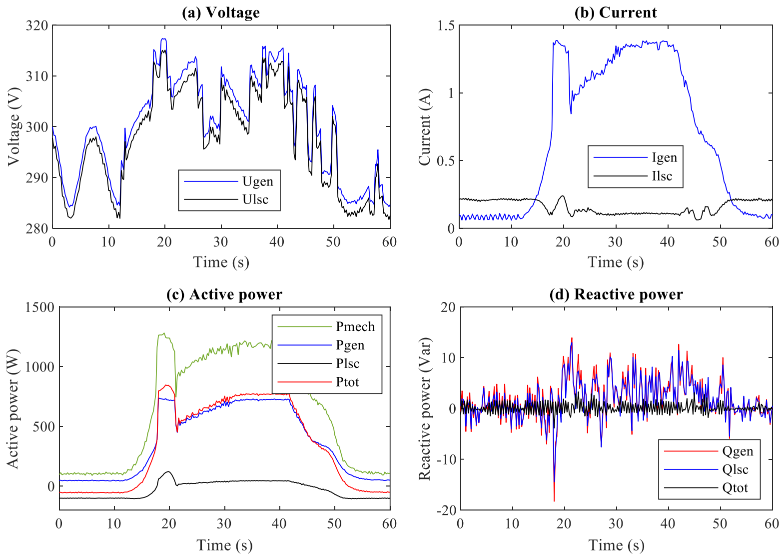

Figure 7. *Scenario 3: (a) Voltage, (b) Current, (c) Active power, (d) Reactive power*

First, there is no change in the stability of the voltage and reactive power generated from the stator and rotor to the converter. However, the generator speed, torque, stator current, active power, and total power exhibit noticeable changes. The rotor speed reaches a maximum of 2070 rpm when the wind speed reaches 18 m/s at the 19th second. At this point, the control system adjusts the rotor speed back to the rated value of 1900 rpm within approximately 2 seconds. For the wind speed sensor and the optimal operation of the turbine system, the system quickly intervenes to reduce the rotational speed by adjusting the pitch angle and activating the braking system to stabilize the generator, as shown in Figure 6(b).

The current generated by the stator reaches a value of I_{gen} = 1.4 A when the wind speed is 18 m/s. It then suddenly drops to 0.9 A due to the influence of the system as the rotor speed is adjusted back to the stable level. After that, the current gradually returns to a stable state near 1.4 A and operates steadily. The active power depends on the current, so the active power value changes in a manner similar to the current, and it takes about 10 seconds, from the 20th second to the 30th second, for the generator system to return to a stable state, as shown in Figure 7. Comparing the results from this scenario with those from Scenario 2, we can observe the optimal performance of the turbine system and the dynamic response of the DFIG wind generator.

3.4. Scenario 4: Changing wind speed according to the 24-hour realistic wind profile

This scenario will experiment with the dynamic response of the DFIG wind turbine operating over a 24-hour period to establish the wind amplitude based on real data. Using the actual 24-hour wind profile, this study constructs a wind speed graph for a 24-minute period, where 1 minute is converted to 1 second, with each interval representing 30 minutes [16]. The maximum wind speed reaches 13.7 m/s at 7:30 AM, while the minimum wind speed is 6 m/s at 2:00 PM, and the average wind speed for the day is 9.2 m/s.

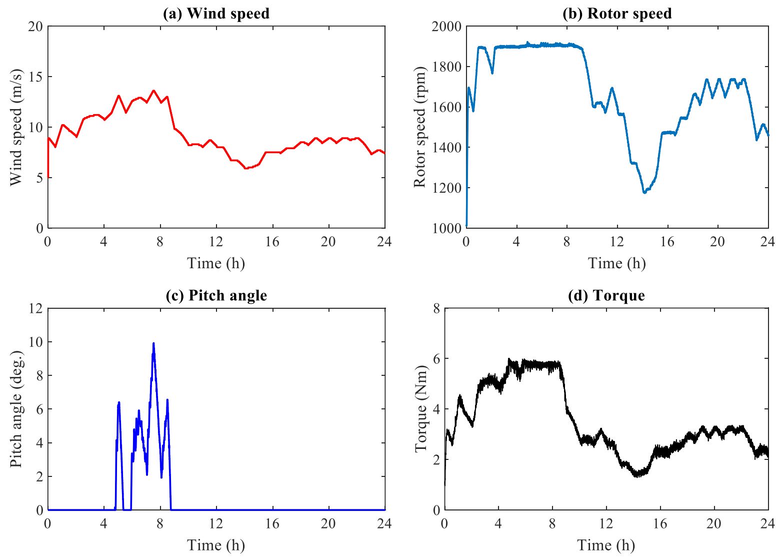

Figure 8. *Scenario 4: (a) Wind speed, (b) Rotor speed, (c) Blade pitch angle, (d) Torque*

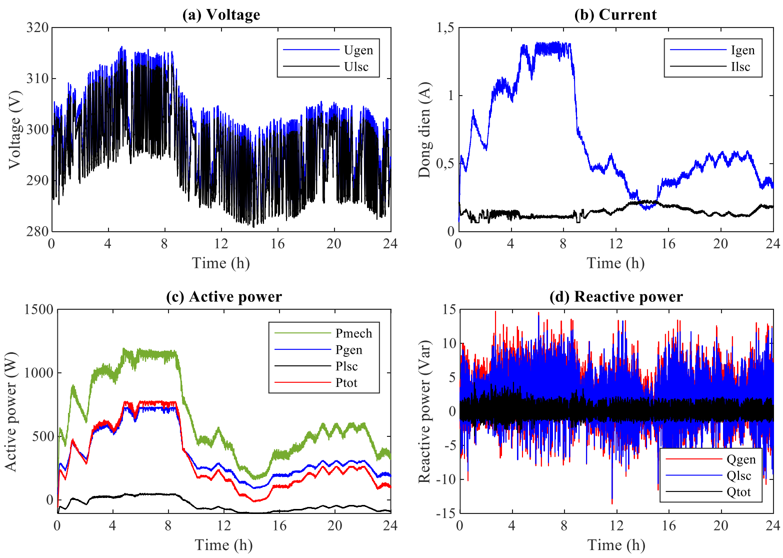

Figure 9. *Scenario 4: (a) Voltage, (b) Current, (c) Active power, (d) Reactive power*

Figure 8 shows that the wind turbine's pitch angle changes between 6:00 and 8:30 AM as the wind speed exceeds 12 m/s, reaching a maximum power of 733 W, as shown in Figure 9. After 8:30 AM, the wind speed gradually decreases below 10 m/s, causing the blade pitch angle to return to its initial position. Consequently, the rotor speed, torque, stator current, and active power all change proportionally with the wind speed. The current through the rotor converter remains unchanged, and the active power on the rotor side converter operates in the super-synchronous mode from 6:00 AM to just after 8:30 AM. During the remaining time periods of the day, the active power is nearly negative, indicating that the generator operates in the sub-synchronous mode, with power being transmitted from the grid through the converter to the rotor. The average daily output power calculated from the data is 322 W.

From the experimental results of the four scenarios mentioned above, some analyses and evaluations can be drawn as follows:

Scenario 1 conducted an investigation into all operational parameters of the DFIG wind power system at each wind speed within the range of 0 m/s to 18 m/s in order to construct graphs of rotor speed, blade pitch angle, mechanical power, generator power, and LSC power. This clearly demonstrated the response of the DFIG at different wind speeds. This allows for an easy identification of the operating mode of the DFIG at each specific wind speed.

Scenario 2 involves a sudden increase in wind speed from 5 m/s to 12 m/s over a period of 5 seconds, while Scenario 3 increases the wind speed from 5 m/s to 18 m/s over a period of 10 seconds. The main purpose of both scenarios is to evaluate the changes in the output parameters of the DFIG when the wind speed fluctuates within a short period. It is clearly observed that in Scenario 3, there is a change in the blade pitch angle because when the wind speed reaches 18 m/s, it causes the rotor speed to exceed the rated speed. This also results in an increase in torque and power beyond the permissible limits. To ensure the safety of the DFIG wind generator, the control center sends a signal to adjust the blade pitch angle. This reduces the torque and power of the DFIG generator.

Scenario 4 is designed to construct a real 24-hour wind speed chart to analyze and assess the continuous changes in the output parameters of the DFIG generator throughout a typical day. This allows us to easily identify the time periods with strong wind speeds and those with weak wind speeds. The experimental model in this study has the potential for practical application, particularly in wind farms in Vietnam. With appropriate adjustments in scale and operational conditions, this control system can be implemented to optimize the performance of actual wind turbines. However, for large-scale deployment, additional factors such as climatic conditions, implementation costs, and integration capability with the existing power system need to be considered. Future research may focus on real-world testing on a larger-capacity system to provide a more detailed assessment of the system's efficiency and stability.

4. Conclusion

This paper has studied the dynamic response of the DFIG wind power system by analyzing and evaluating the experimental results. The scenarios were constructed based on theoretical and practical foundations in the operation of DFIG wind power plants. The data obtained from the scenarios showed the dynamic response of the DFIG wind power system when the turbine operates under different wind speed conditions. The input wind speed range was set up through simulation with a servo motor to rotate the rotor of the DFIG generator. The wind speed was varied abruptly within short intervals to study the dynamic response of the output parameters of the DFIG generator, such as blade pitch angle, voltage, current, power, etc. In addition, a scenario with an input wind speed over a 24-hour period of a typical day was also established to evaluate and analyze the dynamic response of the DFIG generator. The results demonstrate the DFIG system’s dynamic response. Furthermore, the research results contribute to identifying wind speed regions to select the appropriate operating mode for the DFIG wind turbine generator, while activating protective modes and automatically adjusting the blade pitch to enhance the operational efficiency of wind power plants in practice. The next research direction may be considered to evaluate the dynamic response of the DFIG generator to voltage sags or dips with varying magnitudes and durations.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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