Analysis of energy control system in wind farm

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Abstract. This article first introduces the structure and principle of two mainstream wind turbine models, analyses the different power generation principles and energy transfer structures of these two different wind turbines, and briefly introduces the network topology structure of wind power stations, as well as the direction of command data from the control end to the controlled end. Then, it introduces and analyses several widely used maximum power point tracking (MPPT) control algorithms and frequency control methods, summarizes and predicts these algorithms for single wind turbines, and lays the foundation for future research. Large-scale wind power and other new energy grid connection is one of the most effective solutions to address the world energy crisis. With continuous development of technology, more and more power electronic control components are being closely integrated with traditional power systems, and we are facing problems different from those in the past. We must change our thinking and work hard to address these issues.

Keywords: wind farm, energy control system, maximum power point tracking (MPPT).

1. Introduction

Energy is the cornerstone of human civilization. Only by using more and more energy can the national economy and human living standards be improved. However, traditional energy sources like fossil fuels such as oil and coal are not only non-renewable and unsustainable, but also emit a large amount of greenhouse gases and pollutants, such as carbon dioxide, sulfur dioxide, PM2.5, which seriously harm the environment and people's health, and have a great impact on our quality of life [1]. In recent years, the unstable situation in the Middle East, the frequent occurrence of wars, and the fluctuation of energy prices have also had a negative impact on the development of oil-importing countries around the world.

The increasingly severe environmental problems and energy crisis have received increasing attention and social concern from countries around the world. According to the Paris Agreement and the content of the Katowice Climate Conference in 2018, major countries in the world and other countries should control carbon emissions for the sake of protecting our common world, curbing climate deterioration, promoting sustainable development, and controlling carbon emissions. As a responsible major country, China should also make its own contribution to global climate security. China has proposed that by 2030, China aims to reduce its gross domestic product (GDP)-related CO_2 emissions by 60%-65% compared to 2005 levels, while also targeting to increase the share of non-fossil energy to approximately 20% of primary energy consumption. [2]. Other countries have also set targets for the use of new energy. Among them, wind resources, which do not consume other resources, do not produce additional products, and do not pollute the environment, are clean and renewable energy sources with large amounts of energy [3].

Currently, China's wind power development is in a period of rapid development. By the conclusion of 2018, China had amassed a cumulative grid-connected installed capacity of 210GW for wind power, constituting 32% of the total global installed capacity for wind energy. The new installed capacity is also among the top in the world. In 2019, wind power generation was 357.7 billion kW·h, with an accumulated growth of 7% [4]. The "Thirteenth Five-Year Plan for the Development of Renewable Energy" of China proposes that by the conclusion of 2020, China's total Installed capacity for wind energy generation will be ensured to exceed 210GW, and the wind power generation target for that year will reach 420 billion kW·h. Based on the aforementioned data, it is apparent that the wind power industry will exceed the goals of the "Thirteenth Five-Year Plan". Figure 1 shows the cumulative and new wind power installed capacity in China from 2008 to 2018 [5].

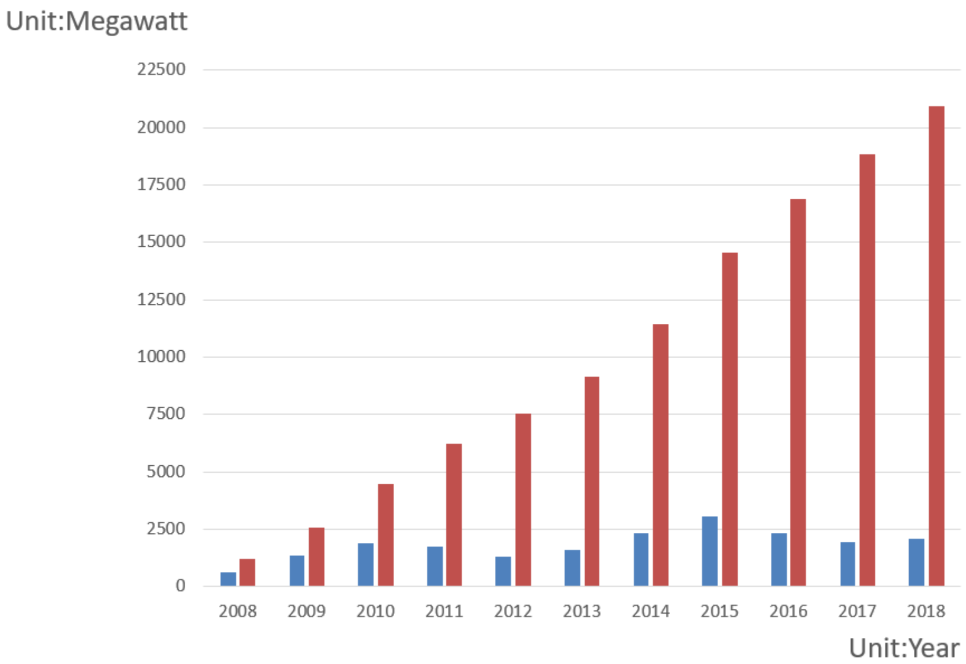

Figure 1. Statistical chart of new and total installed wind power capacity in China from 2008 to 2019.

Global experts are actively monitoring the progress of wind power technology, with particular emphasis on advancements in offshore wind turbines and wind turbines suitable for low wind velocity regions, which currently represent cutting-edge research domains, and the application scenarios for wind power will become more diverse. The informatization and capacity increase of wind dynamo will further reduce the cost of wind power and increase its market competitiveness. Cross-industry technology integration and transformation are injecting new impetus into the wind power energy industry. With the development and application of these technologies, the wind power industry will face key development opportunities. However, due to the instability and randomness of wind resources, there are large fluctuations in voltage. Therefore, it is necessary to use an energy control system in new energy stations to regulate the active power of the new energy station. By using an energy management system, stable and safe operation of the wind farm can be achieved.

In this paper, the fundamental of the wind power generation is introduced. Then, the key active power controls for enhancing the penetration level of wind power integration are comprehensively analyzed. Finally, the future research directions are given.

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2. Basics of wind power generation

2.1. Wind power generation system

Wind electric energy generation has the following characteristics: wind energy generation sites are usually installed in areas with high and stable wind speeds, which are often located in remote mountainous areas or near lakes far away from the load centers. Moreover, these areas are located at the end of the main grid, so the grid strength and protection configuration are weak. The output characteristics of wind turbines are greatly affected by wind speed, and the output power is fluctuating and random, resulting in large power fluctuations. Currently, wind energy units can be divided into two types based on their structure: doubly-fed asynchronous wind turbine and direct-drive synchronous wind power units.

2.1.1. Doubly-fed asynchronous generators. As shown in Figure 2, the energy transfer process of a doubly-fed asynchronous wind turbine begins with the wind driving the blades to rotate, and then the energy is transferred to the generator through a multi-stage gearbox. The generator transforms the kinetic energy of the rotational motion of the generator shaft into electrical energy, and then transmits the electrical energy to the grid through the stator of the generator. Doubly-fed asynchronous generators are currently the most widely used wind turbine generators. After being connected to the grid, they not only transmit electrical energy to the grid but also absorb reactive power from the grid. The difference is that the rotor side of the doubly-fed asynchronous generator is connected to the grid through a frequency converter, while the stator winding is directly connected to the grid. During operation, the current can be corrected by the frequency converter based on changes in wind velocity, thereby changing the generator's speed to adapt to the operating conditions. This can greatly improve the power generation efficiency and ensure safe and reliable operation.

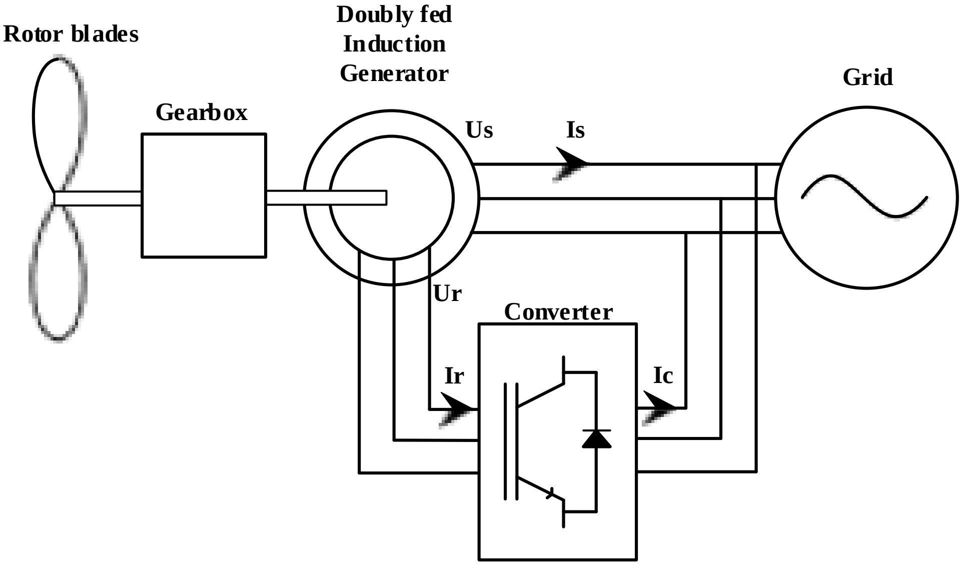

Figure 2. Doubly-fed asynchronous wind generator structure.

2.1.2. Permanent magnet direct-drive synchronous wind turbines. As shown in Figure 3, the direct drive permanent magnet synchronous generator is propelled by the power unit without any intermediate transmission components, and it operates via direct mechanical rotation. This wind turbine generator uses a multi-stage generator directly connected to the blades, reducing the gearbox structure and corresponding transmission devices in the process, greatly reducing construction and maintenance costs. This also makes the generator operate more stably, improving its reliability. When integrated into the grid, the direct-drive permanent magnet synchronous wind energy unit is connected through a full-power converter, with low voltage ride-through capability, making it friendly to the grid. This greatly increases the generator's power and is in line with the trend of larger wind turbine capacities.

For direct-drive permanent magnet synchronous wind dynamo, the blade pitch angle and power control can be adjusted to achieve maximum wind energy capture. Electrical energy is then rectified and inverted through a converter to match generator power and terminal voltage control, grid-side voltage, power factor, and direct current voltage control, achieving grid connection.

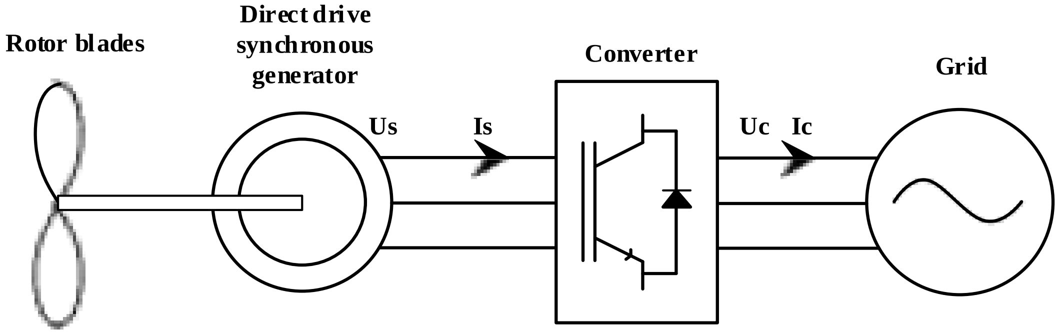

Figure 3. Direct drive synchronous wind turbine generator structure.

2.2. Network topology of wind farms

For a wind power plant, data monitoring and acquisition are crucial, which is why a SCADA system is commonly installed in power systems. Generally, the SCADA system of the plant monitors and controls the production control area, communicates with relay protection equipment and BCU equipment, and connects with the production II area (such as a wind turbine energy management platform) through a protocol conversion device and firewall. The PPC system receives signals from the main station, automatically calculates the target value, and sends it to the wind turbine energy management platform for real-time control.

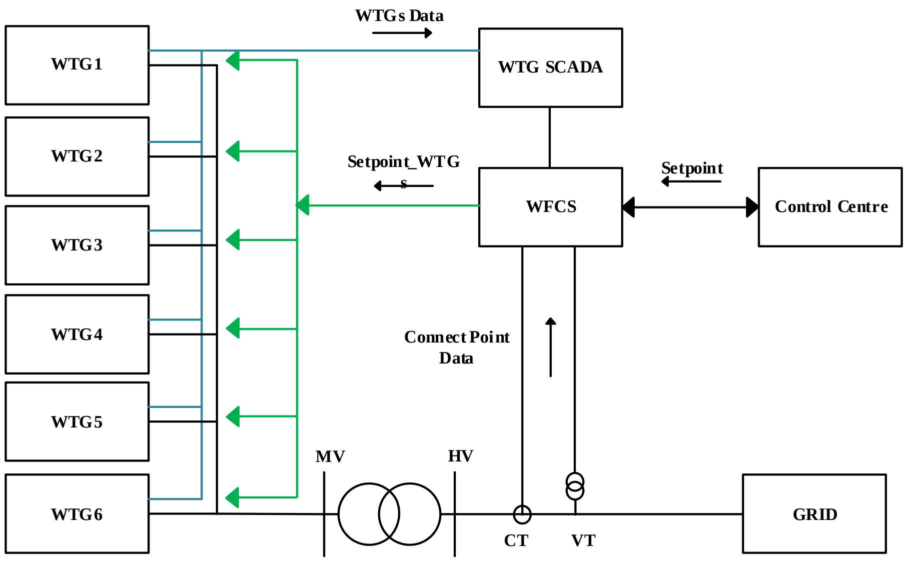

Figure 4. Network topology diagram of the energy control system of the wind farm.

3. Active power control of wind turbines

Currently, the energy control system for new energy power plants can be divided into two parts. One is active power control, which one approach to regulating wind power station's active power output and stabilizing the system frequency involves adjusting the active power output via a control mechanism. The second part is reactive power control, which can regulate the output of reactive power of wind

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energy park and control the system voltage and power factor by adjusting the reactive power. This paper mainly focuses on the active power control. The power generation state of wind turbines can be divided into free power generation and limited power generation. When wind turbines are in free power generation state, the rated wind speed becomes the main constraint. Below the rated wind speed, wind turbines will follow the maximum power point tracking (MPPT) strategy to produce the maximum energy power. Above the rated wind speed, the rated power will be set as the output target to maintain the wind turbine running at rated power. When wind turbines are in limited power generation mode, power reduction is mainly achieved through pitch control and torque control. Here, we mainly introduce the MPPT of wind turbines.

3.1. Maximum power point tracking

The maximum power point tracking (MPPT) is one common energy power control method for wind engines in wind farms. It mainly controls the output power of the aerogenerator by adjusting the rotational speed of the wind turbine. Wind energy generator can only output maximum mechanical power when operating at the optimal tip speed ratio [6]. The function and goal of MPPT is to find the maximum power point of the wind turbine output energy power to maximize the wind turbine output power. In the case of air current velocity changes, the wind power unit output power will also change, so it is necessary to continuously adjust the rotational speed of wind turbine to maintain the maximum output energy power. The interconnection between the active power and the rotational speed of wind power generation units is approximately shown in the characteristic curve as in Figure 5. The comparison between different MPPT methods is summarized in Table 1.

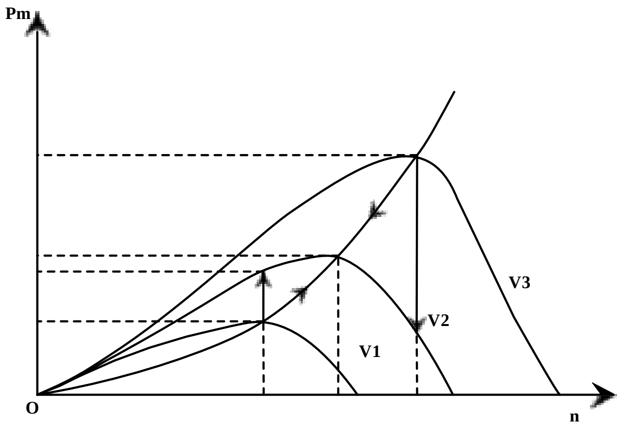

Figure 5. Speed-power curve of wind turbine.

In literature [7], the authors summarized several commonly used MPPT control strategies: tip speed ratio control, power signal feedback, hill-climbing search, and various other methods that are based on these three control methods. It can also be noted that there are several algorithms currently in use that require special attention:

The Perturb and Observe (P&O) algorithm: This algorithm is characterized by its ability to optimize the power of the aerogenerator without necessitating prior knowledge of wind speed or turbine characteristics. Instead, it employs a sophisticated methodology that involves analyzing the DC-side current and voltage to accurately track the optimal output power level. The method is relatively easy to implement, but due to the non-linearity of wind speed variations, the response speed of power output is slower when wind speed fluctuates rapidly [8].

Hill-Climbing algorithm: This algorithm continuously changes the wind turbine speed to search for the maximum power point near the energy power point. The Hill-Climbing algorithm has high efficiency but is also prone to getting stuck in local optimal solutions, making it difficult to reach global optimal solutions [9].

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Fractional Short-Circuit Current (FSC) algorithm: This algorithm determines the maximum power point by measuring the generator voltage at a fixed current. Compared to other algorithms, the FSC algorithm has higher robustness and better adaptability for rapidly changing and low power output situations. However, its algorithm complexity is higher [10].

Table 1. Comparison of several algorithms of MPPT.

Algorithm name	Advantage	Shortcoming
Perturb and Observe (P&O) Algorithm	Don't require wind speed information and power characteristics of wind turbines, so it is simple to implement	When the wind speed fluctuates rapidly, the response speed of the power is slow
Hill-Climbing Algorithm	High efficiency and fast response	It is difficult to achieve the global optimal solution
Fractional Short-Circuit Current (FSC) algorithm	It has good adaptability to the conditions of rapid changes in wind speed and low output power	high complexity

3.2. P-Frequency control

In power systems, the frequency of the grid is a crucial parameter. When the grid load increases, the frequency reduces and vice versa. Therefore, the goal of P-Freq control is to balance the working power output of wind turbines with the load power required by the grid by controlling the rotor velocity of wind turbines, thereby maintaining the stability of the grid frequency. Currently, there are two main ways to study how wind turbines affect the grid frequency [11]: one is to change the rotor velocity of wind turbines to adjust the frequency, and the other is to stabilize the system frequency by using energy storage devices or mechanisms to absorb and release active power.

Different P-Freq control algorithms can be selected to achieve better control effects depending on the specific power grid environment and wind speed variation. For changing the system frequency by changing the rotor speed of wind turbines, commonly used P-Freq control algorithms include Model Predictive Control (MPC) and Proportional-Integral (PI) control.

The PI control-based P-Freq control algorithm achieves power control by controlling the rotor speed of wind turbines through proportional and integral control. This algorithm has a fast response speed and can instantly control the output power of wind turbines. However, it has overshoot phenomena and may cause system instability.

The MPC algorithm predicts the power output of wind turbines for a certain period of time by establishing mathematical models of wind turbines and wind models and adjusts the rotor speed accordingly [12]. This algorithm can predict the effect of future wind flow rate changes and control the output power of wind turbines more accurately. However, it requires higher computational power and more complex modeling processes. Reference [13] found a second-order nonlinear model for wind turbines based on blade element momentum theory (BEM) and the first principle of power transmission system modeling, which can precisely control the power and frequency.

Currently, there is also a wind power system that incorporates energy storage systems. When the load changes occur, the energy storage system provides or absorbs power in a timely manner to respond to the changes in load power, thereby maintaining system frequency stability. In references [14] and [15], the authors used modeling and simulation to find that due to its fast response speed, the frequency control of the entire wind farm is more stable with the addition of energy storage systems compared to wind farms without them. Reference [16] found that energy storage systems can effectively maintain power stability after the inertia energy of the rotor participates in frequency regulation, preventing secondary power fluctuations.

4. Outlook and development

Currently, the main active power control methods used in wind turbines include the following points. In terms of maximum power point operation, the Perturb and Observe (P&O) algorithm is the simplest, but it has problems in cases of large wind speed fluctuations. The Fractional Short-Circuit Current (FSC) algorithm can adapt to various complex scenarios, but the algorithm is more complex, and the response is slower. However, with the rapid development of computer computing power and AI technology, this technology will continue to be optimized and attain pervasive usage in the future.

In terms of frequency control, the P-Freq control algorithm based on the proportional-integral (PI) controller can quickly adjust the frequency, which is currently the most commonly used method. However, over-adjustment phenomenon cannot be avoided. The model predictive control (MPC) algorithm can smoothly control the system frequency and plays a significant character in the safe operation of the power grid. However, this technology requires support from large data on the local wind field and can only form a relatively accurate predictive model after a period of time. The most effective way for wind power systems to connect to energy storage systems is through technology. Currently, the capacity of power grid energy storage systems continues to increase, and they play an increasingly positive role in ensuring the safe and stable operation of new energy power stations. With the development of material technology in the future, the capacity of energy storage systems can also become larger and larger, as a supporting system for wind power-energy storage systems to connect to the grid.

In addition, the safe and stable operation of wind turbines is also one of the conditions for ensuring that wind turbines maintain the maximum active power output. Therefore, more and more scholars are researching how to detect and eliminate wind turbine faults as soon as possible. For gearboxes with a higher failure rate in doubly-fed wind turbines, sound sensors can be added to collect the sound during gearbox operation and compare it with the sound of normal operation in a large database to determine whether there is a fault. Additionally, the working hours and fatigue of wind turbines can be analyzed in real-time using neural networks to ensure that wind turbines are always in an appropriate working state.

5. Conclusion

In this paper, we first introduced the two main types of wind aerogenerators currently in use, the doubly-fed asynchronous wind turbines and the direct-drive synchronous generator, and analysed the advantages and disadvantages of the two types. We then briefly introduced the network framework of energy control in wind farms, where the control master station sets the target value and sends it to each wind turbine through the energy management system after analysing and calculating the target value. In the operation of wind farms, active power control is a key technology for safe, stable, and controllable operation. By summarizing the real power control algorithm for a single wind turbine and looking forward to future research, this paper laid the foundation for future studies.

References

[1] Zhang Zhaoli. Economic Analysis of Sulfur Dioxide Pollution in China-Based on the Environmental Kuznets Curve and Trade Perspective[D]. Shanghai Jiao Tong University, Shanghai, 2012.
[2] Shi Lei. The New Progress of the Transparency Mechanism of the "Paris Agreement" and China's Practice [J]. Law and Society, 2019(36):107-108.
[3] Gao Yaokui, Wu Ruipeng, Liang Peng, Li Dingqiang. The advantages and problems of wind power generation [J]. China New Communications, 2013, 15(20): 34.
[4] National Bureau of Statistics. Statistical Bulletin of the People's Republic of China on National Economic and Social Development in 2019 [N]. China Information News, 2020-03-02(002).
[5] Statistical Report on China's Wind Power Lifting Capacity in 2018 [J]. Wind Energy, 2019 (04): 56-67.
[6] Wu Feng. Research on Optimal Control Strategy for Power Tracking of Large Wind Turbines

[D]. North China Electric Power University, 2017.
[7] Ma Tenghao. Research on MPPT control strategy for small wind turbines [D]. Beijing Jiaotong University, Beijing,2010.
[8] Ratna Ika Putri, Margo Pujiantara, Ardyono Priyadi, Toshifumi Ise, Mauridhi Hery Purnomo. Maximum power extraction improvement using sensorless controller based on adaptive perturb and observe algorithm for PMSG wind turbine application[J]. IET Applications 1, 2 Power Electrics 12(4).
[9] Mitchell M, Holland J, Forrest S. When will a genetic algorithm outperform hill climbing[J]. Advances in neural information processing systems, 1993, 6.
[10] Sher Hadeed Ahmed, Murtaza Ali Faisal, Noman Abdullah, Addoweesh Khaled E., Al Haddad Kamal, Chiaberge Marcello. A New Sensorless Hybrid MPPT Algorithm Based on Fractional Short-Circuit Current Measurement and P&O MPPT[J]. IEEE Transactions on Sustainable Energy, 2015, 6(4).
[11] Yuan-Kang W, Guan-Liang L, Quoc D P. A Review of Frequency Regulation of DFIG-based Wind Farms[C]//IET Conference Proceedings. The Institution of Engineering & Technology, 2018.
[12] Jain A, Schildbach G, Fagiano L, et al. On the design and tuning of linear model predictive control for wind turbines[J]. Renewable Energy, 2015, 80: 664-673.
[13] Mirzaei M, Poulsen N K, Niemann H H. Robust model predictive control of a wind turbine[C]//2012 American Control Conference (ACC). IEEE, 2012: 4393-4398.
[14] Ma Yulu. Wind-storage combined operation participates in power grid primary frequency regulation optimization control technology [D]. Shandong University of Technology, 2022
[15] Dong Tianxiang, Zhai Baoyu, Li Xing, Yang Qiufan, Lin Yujun, Chen Xia, Wen Jinyu. Optimal Control Strategy for Wind Storage Combined System Participating in Frequency Response [J]. Power Grid Technology, 2022, 46(10):
[16] Wang Xiao. Research on key issues such as wind power system operation control and frequency regulation [D]. Northeastern University, 2018.