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The Key Application of Mathematics in Wind Energy Generation

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Abstract: Applied mathematics aims to solve problems in various fields using mathematical methods, and it also plays an important role in wind power generation. This article introduces the fluid dynamics model and wind speed profile model established through mathematical modeling. These two models can deeply analyze the potential of wind energy and optimize the performance of turbines. By studying these models, we can further understand the operating mode and optimization space of wind energy, thereby promoting the development of wind energy technology. Improve power generation efficiency, understand its operating mode and optimization space, and promote the development of wind energy technology. Applied mathematics not only enhances the scientific design and implementation of wind power generation but also promotes the progress and sustainable development of renewable energy technology. This article points out that under the background of green energy, with the continuous deepening of data analysis and modeling technology, future wind power generation systems will be more efficient and reliable. Meanwhile, this article aims to make greater contributions to achieving global energy transition and addressing climate change, promoting the advancement and sustainable development of renewable energy technologies.

Keywords: Mathematical modeling, Wind power generation, Fluid dynamics, Wind speed profile

1. Introduction

In the context of global energy greening, wind energy, as a clean and renewable energy source, is gradually becoming an important component of energy structure transformation in various countries. Wind is one of the non-toxic energy sources, and it is inexhaustible. In coastal islands, grassland pastoral areas, mountainous areas, and plateau regions with water shortage, fuel shortage, and inconvenient transportation, utilizing wind power according to local conditions is very suitable and has great potential.

China has abundant wind energy resources, with approximately 1 billion kilowatts of wind energy reserves available for development and utilization. Among them, the onshore wind energy reserves are about 253 million kilowatts (calculated based on data from a height of 10 meters above the ground), accounting for 25% of the reserves, and the offshore wind energy reserves that can be developed and utilized are about 750 million kilowatts, accounting for 75% of the reserves, making them the main source of wind energy resources [1-3]. Accelerating the construction of offshore wind

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power projects is of great significance for promoting the management of haze in coastal areas, adjusting energy structure, and transforming economic development mode.

On February 29, 2024, the National Bureau of Statistics announced that the installed power generation capacity in China at the end of 2023 was 291965 million kilowatts, an increase of 13.9% from the end of the previous year. The installed capacity of grid connected wind power was 441.34 million kilowatts, an increase of 20.7%.

Wind power generation is the process of converting the kinetic energy of wind into mechanical kinetic energy, and then converting mechanical energy into electrical kinetic energy. The principle of wind power generation is to use wind power to drive the rotation of windmill blades, and then increase the speed of rotation through a speed increasing machine, thereby promoting the generator to generate electricity. According to existing windmill technology, a breeze speed of approximately three meters per second (the degree of a breeze) can start generating electricity. Wind power generation is becoming a global trend because it does not require the use of any traditional fuels and therefore does not produce air pollution or radiation.

China's new energy strategy has begun to prioritize the vigorous development of wind power generation. According to national planning, the installed capacity of wind power generation in China will reach 20 to 30 million kilowatts in the next 15 years. With the development of wind power, its cost-effectiveness is forming a competitive advantage compared to coal-fired and hydroelectric power. The advantage of wind power is that for every doubling of its capacity, the cost decreases by 15%. In recent years, the global growth of wind power has consistently exceeded 30%. With the localization of wind power installation and the scale of power generation in China, the cost of wind power is expected to further decrease. Therefore, more and more investors are starting to look for wind power. The application of mathematics plays an indispensable role in effectively utilizing wind energy to ensure its stability and economy in power production. Mathematics not only provides scientific basis for the assessment of wind energy resources, but also for the design of wind turbines and the improvement of energy conversion efficiency. Through mathematical modeling and algorithms, it is possible to deeply analyze the potential of wind energy, optimize the performance of turbines, improve power generation efficiency, and promote the sustainable development of wind energy technology. This provides important references for technological innovation and policy formulation, and helps to address global energy challenges and climate change.

Professor Li Jun's research establishes a power curve model, which is the curve of the power of wind turbines changing with the wind speed at the height of the rotor. The main influencing factors are air density, turbulence, and wind shear [4]. After a series of studies, the article shows that air density is the biggest factor affecting power generation, while turbulence and wind shear factor have a relatively small impact on power generation [5].

Professor Ma Qiang's research is based on optimizing the ideal wind energy conversion efficiency model, obtaining the relationship between wind speed and power generation in the wind farm, and establishing a monitoring device to track the real-time status of wind turbines. This system includes core indicators such as wind strength, wind direction, environmental temperature, and vibration frequency. Analyzing these data can identify anomalies in wind turbines in a timely manner, or make technical adjustments to wind turbines to increase their utilization efficiency of wind energy.

Based on the above model foundation, through core technologies such as wind power prediction, yaw control, and power control, and with the help of the wind power generation system control platform, support is provided for stable wind power management decisions [6].

This article will analyze the wind field in depth through two models: fluid dynamics model and wind speed profile model, to understand how wind moves and how to more efficiently utilize wind energy.

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2. Mathematical models in wind fields

2.1. Fluid dynamics model

Fluid dynamics is the science of studying the motion of fluids, such as liquids and gases, and their interactions with the surrounding environment. It mainly describes the behavior of fluids through three main equations: continuity equation, momentum equation, and energy equation, as well as other fundamental equations. Flow can be divided into laminar flow and turbulent flow. The former flows smoothly, while the latter exhibits irregularity and chaos. Fluid dynamics models can be divided into ideal fluid models, viscous fluid models, laminar and turbulent models, and multiphase flow models based on different assumptions and applications. These models have wide applications in fields such as engineering (such as aerospace and civil engineering), meteorology (weather forecasting), oceanography (ocean flow research), and biomedical (blood flow simulation). Through the study of fluid dynamics, engineers and scientists can better understand and predict fluid behavior, thereby optimizing designs and improving efficiency.

In the wind field of wind power generation, the air flow situation is relatively complex. Therefore, for the convenience of analysis, the wind field can be regarded as an idealized model without considering its interaction with the boundary, and the fluid is an incompressible fluid, that is, an ideal fluid. The energy possessed by a moving fluid consists of three parts: the energy possessed by the flowing fluid itself, the energy added during flow, and the energy lost. In the model of wind power generation, only the energy of the fluid itself is considered. To describe the basic laws of fluid flow, Computational Fluid Dynamics (CFD) simulation is based on control equations. For multiphase flow in wind fields, conservation equations for mass, momentum, and energy need to be considered. The key parameters of the flow field, such as velocity, pressure, and temperature, can be obtained by solving these partial differential equations. Through CFD simulation, quantitatively analyze the influence of different flow parameters on reactor performance, such as wind speed, temperature, humidity, air pressure, etc. [7].

Fluid dynamics models have significant advantages and disadvantages in wind power generation. This model can describe the flow behavior of wind in detail, provide multi-scale analysis and visualization results, flexibly adapt to different environments, and have good predictive ability. At present, fluid dynamics models also face challenges such as high computational complexity, the need for a large amount of input data, sensitivity to initial conditions, and the possibility of inaccurate results due to model simplification. So in practical applications, understanding these advantages and disadvantages helps to better select and use fluid dynamics models to optimize the design and operation of wind farms.

2.2. Wind speed profile model

The wind speed profile model is a regular model used to describe and predict the variation of wind speed with height, and is widely used in fields such as meteorology, wind energy assessment, and environmental science. This model is based on the concept of wind speed profile, usually using logarithmic wind speed profile or power law model to reflect the relationship between wind speed and height. In the logarithmic wind speed profile model, the wind speed in the near ground area varies logarithmically with height, mainly influenced by surface roughness and wind speed. The basic assumption of this model is that under stable meteorological conditions, wind speed within a certain height range can be calculated based on ground wind speed and surface roughness length. The power law model assumes a power function relationship between wind speed and altitude, and is commonly used in high wind speed areas, such as the evaluation of wind farms.

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Wind speed profile, also known as wind speed gradient or wind profile, refers to the curve of wind speed distribution with height and is one of the most important characteristics of wind. It has multiple mathematical expressions and exhibits different distribution patterns in the vertical direction, influenced by factors such as terrain, layer stability, and weather. The calculation of wind speed is usually based on the "average wind speed", which refers to the ratio of the sum of all wind speeds collected by wind tower sensors during the statistical period to the number of wind measurements [8]. In order to better understand and predict wind speed distribution, wind speed profile models are used to describe the variation of wind speed in the vertical direction. This model is commonly used in wind power generation scenarios. The design, layout optimization, and energy assessment of wind turbines all rely on these models [9].

The wind speed profile model is another key mathematical tool, and its accuracy is crucial for the assessment of wind energy resources and the design of wind turbines. By describing the law of wind speed variation with height, it helps designers choose the appropriate turbine height and type to maximize power generation potential. Common wind speed profile models include logarithmic rule and power rule, which provide scientific basis for the site selection and layout of wind farms. This model is widely used in wind power generation and meteorological research, and its advantages include simplicity and high computational efficiency, making it suitable for quickly evaluating wind speed distribution. Based on measured data, it can effectively reflect the wind speed characteristics of specific regions. However, the accuracy of these models may be limited, especially in complex terrain or extreme weather conditions, and often cannot provide detailed distribution information of wind speed and direction. In addition, the accuracy of the model depends on the quality of the input data. Insufficient or inaccurate data can affect the results, and the ability to capture dynamic changes is relatively weak. Therefore, in practical applications, it is necessary to balance the advantages and disadvantages of wind speed profile models based on specific needs to optimize wind energy resource assessment.

3. Optimization of the model for wind power generation

Based on the above model, wind power generation can be more visualized. With the development of big data and artificial intelligence technology, researchers can extract valuable information from historical wind speed and power generation data through data analysis and machine learning, and optimize the site selection of wind power generation and the wind turbine itself.

3.1. Optimize site selection

In actual wind farms, the flow characteristics of wind are also very complex. Due to the influence of terrain, obstacles, and atmospheric boundary layer, the speed and direction of wind may vary at different locations. Fluid dynamics models can help evaluate the site selection and layout of wind farms to ensure that each wind turbine can fully utilize wind energy while reducing mutual interference. The construction of wind farms requires consideration of natural conditions, such as terrain, wind speed distribution, and wind direction frequency. Therefore, it is necessary to choose a place with abundant and stable wind energy resources. When constructing wind power plants in mountainous areas, factors such as valley wind and terrain acceleration effects need to be considered. By combining mathematical models and investigating the limiting factors such as forest and mountainous terrain changes around the wind farm, the layout of wind turbines is created using Open Wind software, and the power generation differences of various wind turbine layout schemes are further calculated using Meteodyn WT software to refine cost differences [10]. In coastal areas, the characteristics of sea breeze and the influence of the oceanic atmospheric boundary layer should be considered. The construction of wind farms requires consideration of natural conditions, such as

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terrain, wind speed distribution, and wind direction frequency. Therefore, it is necessary to choose a place with abundant and stable wind energy resources [11].

The wind speed profile model helps evaluate the wind energy potential of a specific location, providing key data for decision-makers to assess the economic feasibility and environmental impact of wind energy projects. By accurately predicting wind speed distribution, developers can better plan the scale and return on investment of wind farms. In addition, these models are also of great significance in meteorological research, as they help scientists understand the impacts of climate change, local meteorological phenomena, and their effects on wind energy resources, thereby providing scientific basis for the sustainable development of renewable energy. Overall, the wind speed profile model is not only a technical tool for wind power generation, but also an important support for promoting the development of renewable energy.

3.2. Optimize wind power generators

Due to the variability of wind direction and force, for common horizontal axis wind turbines, vertical axis wind turbines are more adaptable to this variability. The blades of a vertical axis wind turbine can continuously change their relative angle with the wind during rotation, achieving higher efficiency in utilizing wind energy. The wind speed profile model plays a crucial role in wind power generation, mainly reflected in several aspects. By analyzing wind speeds at different heights, these models can guide the optimal layout of wind turbines to maximize energy capture efficiency. Optimizing the layout can not only increase power generation, but also reduce mutual interference between turbines, thereby improving the overall system performance.

With the development of technology, artificial intelligence is thriving. Through data analysis and machine learning, artificial intelligence can optimize the layout and control of wind turbines, predict wind power generation, and improve wind energy utilization. It has great potential in optimizing wind power generation. Artificial intelligence technology will be deeply integrated with new-generation information technologies such as big data, cloud computing, and the Internet of Things to jointly create more developed intelligent wind power solutions.

4. Conclusion

The fluid dynamics model has important application value in wind power generation. By gaining a deeper understanding of the flow characteristics of wind and its interaction with turbines, engineers can design and optimize wind turbines more effectively, thereby improving the efficiency of wind energy utilization and power generation economy. These models not only provide support for theoretical research but also lay the foundation for practical engineering applications. The application of wind profile models in wind power generation provides an important theoretical basis for wind turbine design, performance optimization, and wind energy prediction. Engineers can improve the efficiency of wind energy utilization and promote the development of renewable energy by understanding how wind flow operates and how turbines interact.

Applied mathematics plays a crucial role in wind power generation. By establishing and applying various mathematical models, we can better understand and optimize the various aspects of wind power generation. This not only improves the efficiency of wind energy utilization but also provides a solid foundation for the sustainable development of renewable energy. In the future, with the further improvement of mathematical tools and computing power, the research and application of wind power generation will face more opportunities and challenges.

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