Voltage Stability Analysis of Power System Based on Wind Power Grid Connection Technology

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Abstract. With the widespread application of wind power grid connection technology, the issue of voltage stability in the power system is becoming increasingly prominent. The fluctuation output and wind speed changes of wind turbines pose significant challenges to the grid voltage, and how to improve voltage stability has become a key issue that urgently needs to be addressed in the power system. This article first briefly introduces two types of wind power generation system grid connection technologies and analyzes the categories and influencing factors of wind power generation voltage stability. Continuing to summarize the mainstream measures and methods for improving voltage stability during wind power grid connection, including increasing reactive power compensation, optimizing voltage control, and introducing energy storage technology, the basic principles and advantages and disadvantages of various methods are explained. Continuing with the previous methods, the solution to improve voltage stability is mainly to start with the control system and focus on reactive power. The issue of voltage stability under circuit faults can be addressed by improving the low-voltage ride-through capability. Finally, the prospects for the development of wind power grid connection technology were discussed.

Keywords: Wind Power Generation, Grid Connection Technology, Voltage Stability, Control System, Reactive Power

1 Introduction

The integration of wind power into the grid has promoted the vigorous development of a green and low-carbon economy. It refers to connecting wind turbines to the power grid, synchronizing the electricity generated by the generator with the grid, and delivering the electricity to the grid to meet the needs of the power system. Under the influence of factors such as low density and instability of wind energy, fluctuation of wind turbine output, and complexity of grid connection process, wind power grid connection will to some extent reduce the voltage stability of the power grid. The instability of grid voltage will reduce the quality and safety of power supply, affect the conversion power of wind power and the efficiency of grid operation, and cause multiple consequences such as equipment loss, resource waste, and personal and property losses.

Existing research has proposed various optimization measures and solutions to

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improve voltage stability. For example, Hu studied the frequency control and synchronization control strategies of doubly fed fans, compared the performance of their stability improvement strategies in parameter design, robustness, adaptability, and other aspects, and thus studied a comprehensive improvement method suitable for small and large disturbance stability of doubly fed fans in weak power grids [1, 2]. Sun verified that installing a 3Mvar reactive power compensation device at the wind power grid connection point can balance the reactive power demand in the power system by increasing reactive power compensation. Cao verified through simulation that energy storage connected to weak nodes in the power grid can effectively suppress voltage fluctuations, and enhance voltage stability, and the suppression effect of voltage connected to weak nodes is better than that connected to other nodes [3]. Although many solutions can solve the voltage stability problem caused by a certain part, some risks affect other links. At the same time, large-scale applications also need to consider factors such as economy, simplicity, and safety comprehensively, which will expose many problems and shortcomings.

Based on existing research, this article first classifies wind power grid connection technology and analyzes the types and main influencing factors of voltage stability. Then, based on the control system, the mainstream measures for controlling voltage stability and their advantages and disadvantages were summarized, and measures were supplemented under specific conditions of power grid faults. This article aims to provide guidance and suggestions for improving the efficiency and safety of wind power grid-connected applications in the future by summarizing solutions to wind power stability issues.

2 Wind Power Grid Connection Technology

2.1 Overview

Wind power grid connection technology is mainly divided into synchronous generator grid connection technology and asynchronous generator grid connection technology [4]. Synchronous generator grid connection technology is a grid connection method that connects wind power generation equipment with synchronous generators. Its principle is shown in Figure 1. This method requires the installation of a specialized excitation control system to keep the output voltage and frequency synchronized with the power grid. Its advantages lie in its reliability and stability, as well as the absence of complex power conversion steps, making it suitable for large-scale wind power plants. However, this technology requires high precision for the control system and has a large equipment volume.

The grid connection principle of asynchronous generator set grid connection technology is shown in Figure 2. It connects wind power generation equipment with asynchronous generators, uses reactive power provided by the power grid to establish a magnetic field, and achieves the output of electrical energy. This technology generally requires the installation of a static reactive power compensator to improve reactive power regulation, with a simple structure and low cost. However, the surge current during grid connection is relatively high, which can be improved by changing the grid connection method.

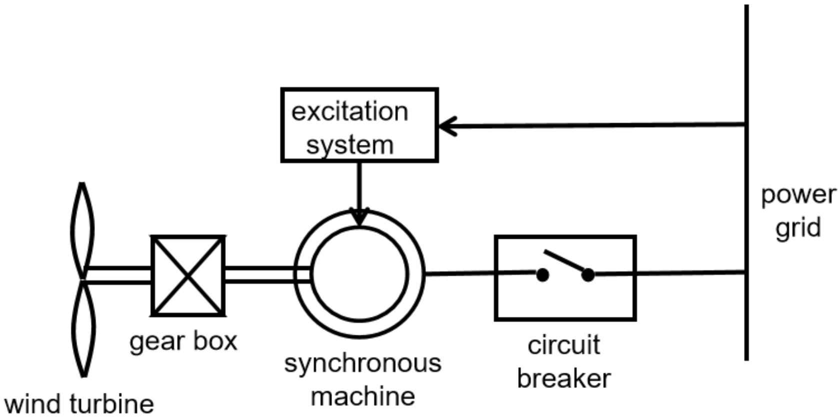

Fig. 1. Schematic diagram of the grid-connected system of the synchronous machine set [4]

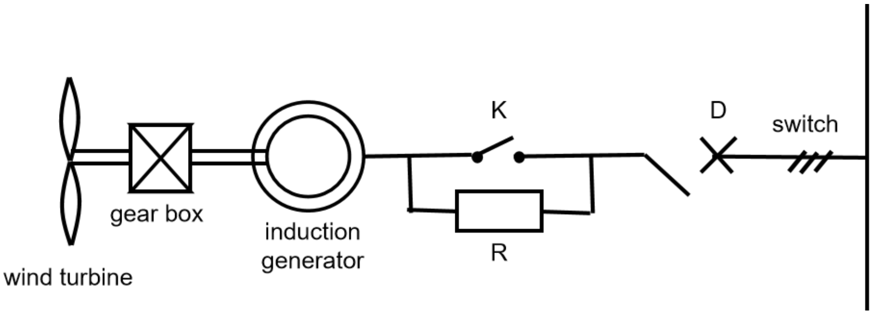

Fig. 2. Schematic diagram of grid-connected system of Asynchronous generator set [5]

2.2 Factors and classification affecting voltage stability

The factors that affect voltage stability mainly depend on the environment and the characteristics of the wind power system itself. Wind energy has obvious intermittent, low-density, and random characteristics, and changing wind speeds can cause fluctuations in voltage input and output. Meanwhile, factors such as the type of wind turbine, location and scale of grid connection, and wind farm capacity may exacerbate voltage fluctuations due to the integration of large-scale wind farms, especially in areas with unstable wind power. This makes wind power systems different from general power generation systems, requiring additional devices to improve voltage stability. Voltage stability can be divided into two categories: static and transient. The former is affected by wind speed and load fluctuations, while the latter is affected by wind power system faults.

3 Mainstream Measures to Improve Voltage Stability

3.1 Classification based on control systems

The existing research mainly proposes three mainstream measures for controlling voltage stability around control systems: increasing reactive power compensation, optimizing voltage control, and introducing energy storage technology.

When a short circuit fault occurs in the system, the voltage at the grid connection point and the outlet voltage of the fan will experience drastic changes Relying solely on the reactive power regulation capability of the wind farm itself is far from sufficient to meet the voltage stability of the system and the wind farm. Reliable reactive power compensation measures must be relied upon to improve the stability of the wind power grid-connected system. Because under the condition of constant apparent power output from the power grid, if all of this reactive power is provided by the grid, the output active power will decrease and the power factor will decrease. From an economic perspective, this situation not only leads to energy waste but also increases operating costs. Therefore, choosing reactive power compensation devices to replace the power grid in providing reactive power to inductive equipment is a conventional technical solution to solve this problem.

Existing research continuously designs and improves various reactive power compensation devices, and establishes models to evaluate and analyze their control voltage stability performance. Among them, the Static Synchronous Compensator (STATCOM) is widely used in the field of reactive power compensation due to its fast response speed, good stability, and continuous reactive power output. The principle is shown in Figure 3. Relevant studies have found that the reactive power compensated by STATCOM is determined by the angle between the output phase voltage of the device and the grid phase voltage [6].

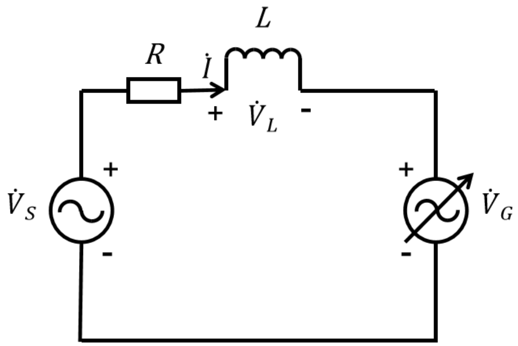

Fig. 3. STATCOM Single-equivalent circuit diagram [6]

Optimizing voltage control mainly refers to optimizing and controlling the secondary voltage. When wind power is connected to the regional power grid, specialized secondary voltage control equipment is installed to ensure that the reactive power of the regional power grid can be reasonably and effectively distributed and supplemented, achieving the goal of maintaining voltage stability in the power grid even when the power output of wind turbines changes [7]. According to Figure 4, the key link of secondary voltage control is to divide the power network into regions, with a focus on voltage stability within each region. Stable control is achieved by coordinating and allocating reactive power sources within each region [8]. Optimizing the secondary voltage control equipment can evenly distribute the reactive power output level of the generator, thereby significantly improving the instability of the system voltage caused by fluctuations in reactive power output.

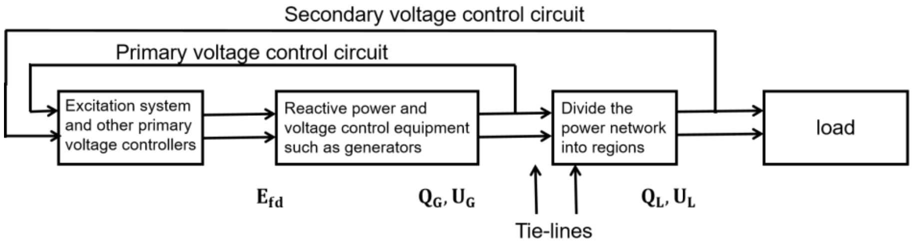

Fig. 4 Schematic diagram of the secondary voltage control circuit [8]

Wind farms can use energy storage technology to quickly exchange power with the system, control voltage drops, reduce voltage fluctuations, and thus improve power quality [9]. Energy storage technology can be divided into mechanical energy storage technology, electromagnetic energy storage technology, electrochemical energy storage technology, and thermal energy storage technology. The energy storage process is mainly divided into energy storage and energy release, which can compensate for the intermittency and volatility during wind power generation, thereby ensuring the stability of wind power output and the quality of electrical energy [10]. Energy storage technology can improve the ability of the power system to absorb wind energy through controllable bidirectional energy throughput, and its suppression effect on voltage fluctuations is related to the location of its access nodes [3].

3.2 Analysis of the advantages and disadvantages of different technologies and improvement plans

In summary, the above measures mainly start from the control system and focus on researching voltage stability around reactive power. To solve the reactive power voltage problem of partial wind power grid connection by increasing reactive power compensation, allocating reactive power output reasonably, and controlling the discharge of reactive power, to achieve the goal of voltage stability. However, there is relatively little research on the combined effects of comprehensive measures, and there are limitations in the experimental environment, simplification of model establishment, and difficulty in achieving large-scale applications. The specific advantages and disadvantages are analyzed in Table 1.

To address the drawbacks of adding reactive power compensation measures, it is possible to plan, calculate, and refine algorithms to solve reactive power capacity-related issues before adding reactive power compensation devices as an improvement solution [11, 12]. At the same time, by improving and perfecting the control partition method, the weak aspects of optimizing voltage control can be addressed. Reasonable use of energy storage control strategies can effectively improve the efficiency of energy storage systems, while also showing a direct relationship between economy and energy storage capacity, thus better applying energy storage technology to stable voltage [13].

Table 1 Analysis of the advantages and disadvantages of mainstream measures based on control system classification

	Increase reactive power compensation.	Optimize voltage control	Introducing energy storage technology
advantages	An effective supply of reactive power can reduce the impact of changes in reactive power and lower losses [14]	Balancing computational efficiency and economic benefits, Overcoming the locality and dispersion of input, Effective stable voltage [8]	Rapid response and adjustment, While maintaining a power balance. Can enhance the wind power consumption capacity of the system [14]
Disadvantages	Reactive power compensation device. The carbon emissions are relatively high. There is a high possibility of over-compensation or under-compensation [11, 12]	Not suitable for large-scale applications. There are many factors to consider in the calculation, The process is complex [8]	High requirements for battery technology, High cost

4 Supplementary Measures Based on Power Grid Faults

Power system failures in wind farms can lead to significant voltage drops. Although wind turbines can activate self-protection functions to reduce damage, they require low-voltage ride-through capabilities to continue operating. Therefore, improving the low-voltage ride-through capability of the power grid can achieve the effect of improving voltage stability by reducing the voltage impact caused by power grid faults. Control of existing low-voltage ride-through technology

There are two main solutions: improving control strategies and adding protective circuits [15]. Optimizing the control system in terms of reactive power compensation and energy storage, applying crowbar protection circuits, and the combined effect of the two can all improve the low-voltage ride-through capability of doubly fed wind farms when the grid voltage drops [16, 17]. The Crowbar circuit works by preventing overcurrent damage to the frequency converter and cooperating with the frequency converter to operate during the duration of the fault, thereby achieving the output of reactive power to the grid by the doubly fed power generation system during the fault period and providing support for the grid voltage [18].

5 Conclusion

With the continuous promotion of the dual carbon target, wind power grid connection will become the trend in the field of wind power generation. With the large-scale application of wind power grid connection technology, solving voltage stability problems has become a top priority, and research progress in related fields will be related to the quality and safety guarantee level of power grid supply.

This article starts with wind power grid connection technology and summarizes the mainstream measures for improving voltage stability in existing research. They are respectively increasing reactive power compensation, optimizing voltage control, introducing energy storage technology, and analyzing that the main entry point is the control system. Optimizing its compensation for reactive power, output allocation, and throughput control can alleviate voltage fluctuations caused by wind power characteristics. Furthermore, it should be noted that enhancing the low-voltage ride-through capability can increase voltage stability and operational safety under grid fault conditions. Taking into account various measures, the issue of voltage stability ultimately returns to the compensation and balance of reactive power. Optimizing various control systems is an effective measure, while also considering the introduction and optimization of protection circuits and comprehensive application solutions to address voltage fluctuations caused by different factors. This has good reference significance for improving the voltage stability of wind power grid connections in the future.

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