Exploration of Safety, Stability, and Power Quality Issues in New Energy Power Generation

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Abstract: The global energy structure's transition towards clean and low-carbon sources is driving the large-scale application of new energy power generation, such as wind and solar energy. However, the intermittent, fluctuating, and low-inertia characteristics of new energy power generation differ from the operational mechanisms of traditional power systems dominated by synchronous generators, leading to safety, stability, and power quality issues. This paper focuses on the core factors influencing the safety and stability of new energy power generation, discusses related power quality problems, identifies key contradictions in the current grid-connected operation of new energy, and proposes targeted solutions. It provides references for ensuring the reliable operation of power systems with a high proportion of new energy integration and supports the safe and efficient development of new energy power generation in the energy transition.

1. Introduction

Driven by the "dual carbon" goals, new energy power generation has become a crucial direction for optimizing China's energy structure, with the installed capacity of wind and photovoltaic power generation continuously increasing. Traditional power systems rely on the rotational inertia of synchronous generators to maintain frequency and voltage stability, featuring a mature operational mechanism and strong anti-disturbance capabilities. However, as the proportion of new energy power generation continues to rise, its inherent intermittency and low-inertia characteristics have become increasingly prominent, disrupting the power balance and stable operation mode of traditional power systems. Against this backdrop, conducting an in-depth analysis of the operational issues in power systems caused by new energy power generation, sorting out the influencing mechanisms, and exploring solutions are of great practical significance for promoting the sustainable and healthy development of new energy power generation and ensuring the safe and reliable power supply of power systems.

2. Core Factors Influencing the Safety and Stability of New Energy Power Generation

2.1 Inherent Intermittency and Fluctuation of New Energy Power Generation

The energy sources of new energy power generation directly depend on natural environmental conditions, making its output unstable and uncontrollable compared to traditional synchronous generators, and exhibiting significant intermittency and fluctuation characteristics. From the perspective of the energy conversion process, whether it is solar irradiance for photovoltaic power generation or wind speed for wind power generation, both change dynamically with natural conditions, resulting in continuous fluctuations in the actual output of new energy units. This fluctuation not only disrupts the long-standing power balance state of power systems but also poses challenges to the system's dispatch and operation modes. Traditional power systems operate on the core logic of "generation following load," achieving power balance by adjusting the output of synchronous generators. However, the instability of new energy output requires the system to continuously adjust reserve resources to cope with output fluctuations. If the adjustment capacity of reserve resources cannot match the fluctuation amplitude or if there is a delay in adjustment response, it will disrupt the original power balance of the system, leading to stability issues such as

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frequency deviations.

2.2 Low Inertia and Converter Control Characteristics of New Energy Units

Inertia is a key characteristic for maintaining the frequency stability of power systems. In traditional power systems, synchronous generators form inertia through the kinetic energy stored in their rotating components. When there is a power imbalance in the system, they can delay the rate of frequency change by releasing kinetic energy, buying time for the response of subsequent frequency regulation equipment and ensuring frequency stability. In contrast, the energy conversion and grid-connection processes of new energy units rely on power electronic converters. These units do not have rotating components and cannot form inertia similar to that of synchronous generators, making them typical low-inertia power sources. As the proportion of new energy units in the power system continues to increase, the total inertia of the system will continuously decline, weakening the system's ability to cope with power imbalances, accelerating the rate of frequency change, exceeding the tolerance range of traditional systems, and increasing the risk of frequency stability. Additionally, the control strategies of converters also have a significant impact on system stability. Currently, the control of new energy units mainly focuses on achieving maximum power output, prioritizing power generation efficiency. Their ability to regulate grid voltage is relatively weak, making it difficult to provide effective support when grid voltage fluctuates. In the event of a grid fault, converters may trigger protection mechanisms to cut off output to avoid damage to their own components, further exacerbating the power imbalance and voltage drop in the grid and causing severe impacts on the system's voltage stability[1].

2.3 Insufficient Synergy and Adaptation between New Energy Grid Connection and Traditional Power Systems

The design logic, grid structure, and dispatch mechanisms of traditional power systems are all built around the operational characteristics of synchronous generators. However, the operational characteristics of new energy power generation differ significantly from those of synchronous generators, leading to insufficient synergy and adaptation between large-scale new energy grid connection and traditional power systems at multiple levels. This issue has become an important factor exacerbating the safety and stability risks of the system. At the grid structure level, regions rich in new energy resources are often geographically separated from load centers. New energy power needs to be transmitted to load centers through long-distance transmission lines. However, long-distance transmission lines have low transient stability margins, and the fluctuations in new energy output can easily trigger power oscillations in the lines, increasing the risks of line overloading and power stability and threatening the safe operation of the transmission system. At the dispatch mechanism level, traditional dispatch modes are formulated based on deterministic generation plans, while new energy output has strong randomness, requiring probabilistic output forecasting for dispatch work. However, the current accuracy of new energy output forecasting still needs improvement, making it difficult for dispatch departments to precisely formulate power balance plans and effectively coordinate new energy output with load demand.

3. Power Quality Issues in New Energy Power Generation

3.1 Voltage Fluctuation and Flicker

The output characteristics of new energy power generation systems directly lead to voltage fluctuation and flicker issues when they are connected to the grid. Due to their dependence on natural conditions, the output of wind and photovoltaic power generation adjusts in real-time with changes in wind speed and light intensity. This dynamic change in output injects fluctuating power into the grid through the grid connection interface. When this fluctuating power flows through grid impedance, it causes instantaneous voltage changes at the grid connection point and surrounding areas, resulting in voltage fluctuations. Compared to traditional power generation methods, the fluctuation frequency of new energy output is higher, and the amplitude of changes is more difficult to predict. Especially in regions with a high proportion of new energy installed capacity, the superposition of output fluctuations from single or multiple new energy units will further amplify the range and intensity of voltage fluctuations.

Voltage flicker is the direct impact of voltage fluctuations on electrical equipment. When the frequency of voltage fluctuations falls within the range where the human eye is sensitive to changes in light intensity, it causes the light intensity of lighting equipment to change periodically, resulting in a flickering sensation in human vision. This issue not only affects the visual comfort of residents in daily life but also interferes with industrial production processes that require high power supply stability, such as precision manufacturing and electronic processing. It may lead to a decrease in the operating accuracy of production equipment, fluctuations in product quality, and even malfunctions of equipment, posing a threat to the continuity and stability of industrial production. At the same time, continuous voltage fluctuations will also accelerate the aging of power equipment, shorten the service life of transformers, motors, and other equipment, and increase the operation and maintenance costs of power systems.

3.2 Harmonic Pollution

The widespread application of power electronic converters in new energy power generation systems is the main cause of harmonic pollution. Whether it is pitch control in wind power, maximum power point tracking in photovoltaics, or the AC-DC conversion of new energy power before grid connection, all require the use of power electronic converters for energy conversion and control. During the operation of converters, they adjust the amplitude and frequency of output power through the periodic conduction and shutdown of switching devices. This process generates a large amount of non-sinusoidal current components, namely harmonic currents. When these harmonic currents are injected into the grid, they produce voltage drops across grid impedance, causing the grid voltage waveform to distort and form harmonic voltages, which in turn affect other equipment and loads in the grid[2].

3.3 Three-Phase Imbalance

The grid-connected operation of new energy power generation systems can easily lead to three-phase imbalance issues in the grid, which mainly stem from the single-unit operational characteristics and grid connection methods of new energy units. Some small new energy units often adopt single-phase grid connection methods, and the output of these units is only injected into one phase of the grid, directly disrupting the power balance among the three phases of the grid and causing deviations in the three-phase voltage and current. Even for large new energy power stations that adopt three-phase grid connection, factors such as slight differences in the element parameters of each phase within the units, uneven light distribution in photovoltaic arrays, or inconsistent output from wind turbines in wind farms can also lead to an imbalance in the three-phase power output by the power station, thereby affecting the three-phase balance state of the grid.

4. Optimization Strategies for Safety, Stability, and Power Quality Issues in New Energy Power Generation

4.1 Strengthening Inertia Support and Voltage Regulation Capabilities of New Energy Units

To address the issues of low inertia and weak voltage support in new energy units, it is necessary to optimize the unit control strategies from a technical perspective to enhance their support capabilities for the grid. On the one hand, virtual inertia control technology can be introduced into the control systems of new energy units to simulate the inertia characteristics of synchronous generators. This technology dynamically adjusts the unit output by detecting grid frequency changes, releasing or absorbing power during frequency fluctuations to delay the rate of frequency change and buy time for system frequency regulation, thereby compensating for the lack of inertia in new energy units themselves. During this process, droop control strategies should be combined to enable new energy units to have frequency response characteristics similar to those of synchronous generators, enhance their ability to participate in system frequency regulation, and improve the system's frequency stability level.

On the other hand, the voltage control logic of new energy units should be optimized to enhance their voltage regulation capabilities. A voltage support module should be added to the converter control strategy. When grid voltage fluctuates, priority should be given to ensuring voltage stability rather than just pursuing maximum power output. By real-time detection of the grid connection voltage, the converter's reactive power output is dynamically adjusted to quickly compensate for the reactive power deficit in the grid and suppress voltage fluctuations, thereby further enhancing the power station's support capabilities for the voltage of the surrounding grid and reducing the occurrence of voltage fluctuations and flicker issues.

4.2 Optimizing the Structure and Operation Dispatch of New Energy Grid Connection Systems

Improving the synergy and adaptation between new energy and traditional power systems from the perspectives of grid structure and dispatch mechanisms can reduce the impact of grid connection on system stability. In terms of grid structure optimization, in response to the separation of new energy resources and load centers, the coordinated development of distributed and centralized new energy should be promoted. Distributed photovoltaic and dispersed wind power projects should be deployed around load centers to reduce the demand for long-distance transmission and lower the risk of power fluctuations in transmission lines. For centralized new energy bases, the construction of supporting transmission channels should be strengthened, and flexible HVDC transmission technologies should be adopted to improve the transient stability margins and power regulation capabilities of the transmission system, suppress power oscillations in lines, and ensure the safety of long-distance transmission.

In terms of operation dispatch optimization, a flexible dispatch mechanism adapted to the randomness of new energy should be established. High-precision new energy output forecasting technologies should be introduced, combining meteorological data, historical operation data, and artificial intelligence algorithms to improve the accuracy of short-term and ultra-short-term output forecasting and provide a reliable basis for dispatch plan formulation. On this basis, a "new energy + energy storage" coordinated dispatch mode should be established, utilizing the charging and discharging characteristics of energy storage devices to smooth out new energy output fluctuations. Energy is stored during output peaks and released during output troughs to maintain system power balance. Additionally, dispatch rules should be improved to incorporate new energy units into the system's reserve resource system, clarify their technical standards and compensation mechanisms for participating in auxiliary services such as frequency and voltage regulation, and enhance the enthusiasm of new energy units to participate in system regulation, thereby compensating for the system's inertia and reactive power support deficits.

4.3 Strengthening Power Quality Monitoring and Harmonic Control

Effective control of power quality issues caused by new energy power generation can be achieved by constructing a full-chain monitoring system and implementing targeted control measures. In terms of harmonic control, a "source suppression + end treatment" dual strategy should be adopted. At the source suppression level, the topology structure and control algorithms of converters in new energy units should be optimized. Multi-level converters and pulse width modulation optimization technologies should be used to reduce the harmonic components generated during the operation of converters and fundamentally lower the source of harmonic pollution. At the end treatment level, according to the monitoring data, regions with severe harmonic pollution should be identified, and harmonic control devices such as active power filters and passive power filters should be configured accordingly. For new energy power stations, large-capacity active power filters should be centrally configured at the grid connection point to compensate for harmonic currents in the grid in real-time. For sensitive loads on the user side, small harmonic control devices should be installed at the load entrance to protect user electrical equipment from harmonic interference, forming a harmonic control system covering the entire process of power generation, transmission, and consumption[3].

4.4 Improving the Standard System for Safety, Stability, and Power Quality of New Energy Power Generation

Providing guarantees for the safe operation of new energy power generation systems from the perspective of standard specifications and clarifying technical requirements and management norms are essential. In terms of technical standard formulation, the grid connection technical requirements for new energy units should be refined, and stricter and more specific standard parameters should be formulated for key indicators such as frequency response, voltage regulation, inertia support, and harmonic suppression to ensure that units have sufficient system friendliness. By improving the design and construction standards for new energy power stations, the configuration requirements for energy storage equipment, reactive power compensation equipment, and monitoring equipment in power stations should be standardized, and the technical processes for equipment selection, installation, commissioning, and operation and maintenance should be clarified, ensuring the safe and stable operation and power quality level of power stations from the construction source. In terms of management standard improvement, operation and maintenance procedures for new energy power stations should be formulated to standardize work processes such as unit inspections, equipment maintenance, and fault handling, reducing safety, stability, and power quality issues caused by improper operation and maintenance. On this basis, a cross-departmental coordinated management mechanism should be established to strengthen communication and collaboration among grid enterprises, new energy power generation enterprises, and equipment manufacturing enterprises, forming a unified standard implementation and supervision system to promote the implementation of standards and provide institutional guarantees for the safe and efficient development of new energy power generation.

5. Conclusion

As the core force in the global clean energy transition, the safe and stable operation and power quality control of new energy power generation have always been key issues in promoting the large-scale development of the industry. Currently, new energy power generation still faces dual challenges of technological iteration and system adaptation in the process of high-proportion grid connection, and the practical effects of existing optimization strategies need further verification and adjustment based on the characteristics of different regional grids and the scale of new energy installations. In the future, with the deep integration of power electronics technology, energy storage technology, and artificial intelligence algorithms, the inertia simulation accuracy, output forecasting accuracy, and power quality control efficiency of new energy power generation systems are expected to be further improved, thereby promoting the continuous increase in the proportion of new energy power generation in the global energy structure and making it an important way to achieve carbon neutrality goals.

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