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Research Review of Power Electronic Technology in Power Grid Stability Improvement

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Abstract: When renewable energy are connected to the power grid through power electronic technological (such as inverters), ensuring the stability of the power grid becomes a very valuable challenge. This is because power electronic converters usually encounter some problems when converting electrical energy, such as unstable voltage, the presence of high-frequency or low-frequency harmonics, islanding effect, leakage current, etc. To solve these problems and enhance the stability of power grids when new energy is connected, improvements can be made to the components and topological structure of power electronic modules, or more precise and comprehensive control strategies can be adopted. This paper outlines the topological structures and control strategies of inverters in photovoltaic grid-connected systems, including innovative topological structures, control algorithms, and analysis methods. It summarizes recent research achievements in improving grid stability through inverters, discovering several disadvantages and raising some possible development directions of inverters in the future.

Keywords: photovoltaic inverter, maximum power point tracking, harmonic distortion, LCL filter, islanding effect

1. Introduction

With the advancement of technology, the increase in population and the continuous exploitation of resources, global countries have gradually begun to realize the importance of environmental protection and are constantly seeking sustainable energy sources to replace widely used fossil fuels. Among these, solar energy is highly valued by researchers, and photovoltaic systems are being installed in large numbers globally. According to IRENA, an enormous decline in costs of solar PV panels and batteries is observed in the past years, with equipment price reductions of around 90% between 2010 and 2023 [1]. This trend is likely to continue due to technologies advances, the manufacturing techniques and growing economies of scale. In China, the photovoltaic industry is considered a national strategic emerging sector. Its rapid development has not only strengthened China's competitiveness in the global energy market but also generated numerous jobs in manufacturing, installation, and maintenance.

However, converting electricity generated by PV panels remains a critical challenge. Power electronic converters are required to transform the direct current (DC) produced by PV systems into the alternating current (AC) needed by power grids. This conversion enables seamless integration of solar energy into the electrical network. The most commonly used device for this conversion is the photovoltaic inverter. However, power electronic devices like PV inverters can affect grid stability,

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causing issues such as harmonic distortion, which degrades power quality and reduces conversion efficiency. Therefore, enhancing grid stability when integrating renewable energy is crucial. The most effective approach to achieving this is by improving power electronic equipment, particularly the electricity conversion module.

Extensive research has been conducted both domestically and internationally on improving the stability of renewable energy integration into power grids. This paper summarizes existing studies on enhancing power electronic systems, with a particular focus on photovoltaic inverters, from the perspectives of control strategies and topological structures.

2. Improvement of photovoltaic inverter

The body of literature on enhancing grid stability through power electronics technology is extensive, with a predominant focus on inverters, the core component in integrating renewable energy sources into power grids. In studies centered on renewable energy integration, photovoltaic (PV) inverters have been extensively examined, alongside research on the integration of other energy sources such as wind and nuclear power.

In analyzing the structural configurations of PV inverters, it is widely recognized that string inverters are more conducive to grid stability than centralized inverters. Literature [2] highlights that string inverters contribute to improved efficiency and cost reduction. Given that maximum power point tracking (MPPT) represents a fundamental technology in PV systems, numerous studies suggest that optimizing the control strategies and algorithms of MPPT can enhance the stability of energy injection into the grid. Meanwhile, research has consistently identified challenges associated with PV inverters, including harmonic distortion in power conversion, low stability in islanding systems, leakage current, and frequency fluctuations. They all adversely affect grid stability and power quality. Accordingly, various solutions have been proposed to address these challenges.

Extensive studies have explored different strategies to mitigate these issues, focusing on aspects such as reactive power coordinated control, reactive current injection, and the implementation of LCL filters. Additionally, research has investigated different inverter topologies, including H-bridge structures and novel configurations such as current source inverters. Various control strategies, algorithms, and innovative topological structures have been proposed. For instance, as mentioned in Literature [3], the adjustment of reactive power is very important for the stability of grid voltage, especially under fault conditions. It is also pointed out that reactive power injection is crucial for improving the voltage distribution on busbars and feeder lines during short-term faults. Literature [4] notes that inverters generate supra-harmonics at frequencies exceeding the conventional harmonic range (2–150 kHz) during pulse-width modulation (PWM) control. The formation of these supra-harmonics is closely linked to the 16 kHz switching frequency of inverters. Other electrical devices, such as household appliances, also produce similar supra-harmonics within the same distribution network, leading to the superposition of these frequency components. Moreover, the study indicates that LCL filters can effectively attenuate the supra-harmonics induced by inverter switching frequencies.

2.1. Improvement of control strategies

Numerous studies aimed at enhancing control strategies primarily focus on reactive power regulation and reactive current injection, proposing various approaches to address these challenges from different perspectives. Literature [5] discusses the application of supercapacitors for current injection during photovoltaic array failures to sustain power flow within the inverte. Literature [2] provides a comprehensive review of advancements in model predictive control (MPC) technology and introduces an MPC-based maximum power point tracking (MPPT) method, along with reactive power injection strategies to maintain grid stability during voltage sags. Additionally, both Literature [3] and literature [6] highlight the implementation of droop control as a means of regulating reactive and active power to stabilize grid voltage and frequency.

After discussing specific advanced control strategies, we will then explore some topology optimization strategies that are also critical to improving the stability of grid-connected systems.

2.2. Improvement of topologies

In the enhancement of topological structures, significant research efforts have been dedicated to improving LCL filters, while some studies have explored novel inverter topologies.

Regarding LCL filters, Literature [4] highlights that optimizing the parameters of LCL filters capacitors and inductors can effectively mitigate super harmonic components. However, it also identifies a potential issue associated with LCL filters—namely, resonance at specific frequencies, which may result in increased current peaks. To address this challenge, the study proposes integrating a series resistor with the capacitor to suppress current peaks near the resonance frequency. While increasing the resistance effectively dampens resonance effects, it also leads to higher power losses, necessitating a trade-off between system stability and efficiency. Literature [7] introduces a super-spiral sliding mode control approach to enhance system robustness, effectively mitigating resonance effects, and implements an active damping strategy based on feedback control to eliminate resonance phenomena. Expanding on the active damping strategy. Literature [8] adopts a composite active damping approach to further enhance system stability, replacing the conventional proportional-resonance (PR) controller with a multi-frequency proportional resonance (MPR) controller to improve the system's anti-interference capability. Additionally, literature [9] explores a novel methodology by combining LCL filters with an active disturbance rejection control (ADRC) scheme, employing a two-level extended state observer (ESO) to estimate and compensate for system disturbances. To simplify controller design and system analysis, the study further utilizes Pade approximation to transform the complex dynamic model of the LCL filters into an approximated L-type filter model.

On new topologies such as H-bridge structure or current-source inverters, literature [10] mentions that by integrating multiple H-bridge units in series. They can achieve higher output voltages using lower-voltage components, thereby enhancing the flexibility and scalability of the system. Additionally, the CHB inverter significantly reduces total harmonic distortion (THD) and enhances overall power quality. However, Literature [11] notes that this topology generates common-mode voltage (CMV), potentially leading to leakage currents within the system. These leakage currents, which flow through the parasitic capacitance of photovoltaic panels, contribute to increased system losses and electromagnetic interference (EMI), thereby degrading power quality. To mitigate CMV, the study proposes integrating the inverter midpoint with the ground wire, effectively reducing leakage current by preventing excessive common-mode voltage generation. Additionally, the study introduces a two-phase DC-DC boost converter, which demonstrates higher efficiency and lower output voltage fluctuations compared to a conventional single-phase boost converter, particularly when operating at higher power levels. Regarding the issue of leakage current, literature [12] proposes a novel technique involving the integration of two clamping diodes to suppress leakage currents.

Moreover, for current-source inverters, literature [13] presents a high step-up current-source inverter (CSI) tailored for grid-connected and islanded microgrids in photovoltaic applications. Simulation results indicate that this inverter leverages its inherent step-up capability to achieve high-voltage conversion without requiring a transformer. This topology facilitates efficient power conversion, maximizes output voltage, and reduces harmonic distortion, thereby enhancing overall system performance.

3. Outlook

Research on photovoltaic inverters and grid stability, both domestically and internationally, has been extensive and thorough. Various methods and control strategies for enhancing existing photovoltaic inverters have been explored, along with the development of new topologies and control algorithms. Different analytical approaches have been adopted to improve both inverters and grid systems.

From a more focused perspective, among the numerous enhancement strategies, relatively few address the issue of islanding effects. Notably, literature [14] discusses both active and passive methods for preventing islanding. These methods include monitoring the system's status at regular intervals to determine if it is in an islanding state, or using interference signals generated periodically by the inverter to ascertain its current status. Common active methods include the pulse current injection technique, output power change detection, active frequency offset method, and sliding mode frequency offset method. The technological requirements for these approaches have been mentioned previously. Similar to other strategies for improving grid stability, future research could focus on strengthening the ability to address multiple challenges simultaneously, potentially using a single solution to resolve multiple issues, thereby reducing costs. Additionally, research on current-source inverters tends to offer fewer insights into the inherent flaws and corresponding improvement measures for these inverters.

From a broader perspective, the majority of studies propose new solutions to challenges that hinder grid stability, while fewer studies examine the internal factors within the system that may influence its stability. Literature [6] and similar works point out that the X/R ratio in impedance impacts grid stability. A higher ratio enhances voltage control capabilities, while a lower ratio can lead to significant voltage and frequency fluctuations, prompting the suggestion of a more proactive Volt-VAR control strategy to improve voltage regulation.

Building on the previous discussion, one of the main challenges in enhancing stability is the issue of switching frequency. Instability or excessively high switching frequencies can introduce destabilizing factors, warranting further research in this area. Furthermore, literature [15] suggests that in the future, enhancing grid stability through photovoltaic inverters may shift from passive adaptation to active support of the grid, in conjunction with energy storage technologies to further bolster system stability. Currently, energy storage technologies are advancing rapidly and have made significant progress in various fields, particularly in the efficient utilization of renewable energy, power system stability, and electric vehicle applications. The future prospects of energy storage technology are broad and promising.

Moreover, the field of artificial intelligence has experienced unprecedented growth and offers vast potential for integration into the power electronics and power systems industries. Artificial intelligence can play an increasingly pivotal role in enhancing the stability of power grids through photovoltaic inverters. Future efforts could focus on improving the precision and efficiency of control algorithms, particularly through software solutions. For instance, enhancing maximum power point tracking (MPPT) algorithms—the core technology in photovoltaic systems—represents a promising application for improving the overall efficiency of the system.

4. Conclusion

This review provides a comprehensive summary of recent advancements in enhancing the stability of power grids when integrating renewable energy sources through power electronics technologies. The findings indicate that current research predominantly centers on the development of new control strategies and algorithms, structural optimization of traditional topologies, and the introduction of novel topological designs. Key challenges identified include harmonic distortion, leakage currents, frequency fluctuations, and islanding effects. Approaches to improve grid stability encompass

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reactive power control, parameter optimization, and the mitigation of defects in LCL inverters, as well as the enhancement of maximum power point tracking (MPPT) algorithms and control strategies.

Looking forward, future research directions are likely to focus on the regulation of switching frequencies, control of islanding effects, optimization of emerging topological structures, and the refinement of control algorithms incorporating advanced artificial intelligence techniques. Furthermore, there is a growing emphasis on the development of more efficient and robust power semiconductor devices, which are expected to play a pivotal role in advancing the performance and reliability of power electronics systems.

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