

Applications of Power Electronics Technology in Smart Grids

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Abstract. With the Dual Carbon goals and the rapid construction of new power systems, smart grids have become a key enabler of energy transition. To integrate high shares of renewable energy, diverse loads, and rapidly changing grid conditions, power electronics technology has become a vital support for the safe, reliable, and efficient operation of smart grids through high-efficiency power conversion and precise control capabilities. Using the literature review method, this paper identifies the application scenarios of power electronics technology in smart grids. The study finds that the technology has been widely used in new energy grid connections, flexible power transmission, and power quality management. Research indicates that key technologies such as wide-bandgap devices and modular multilevel converters will be the primary focus in future development. The research further points out that smart grids currently face significant challenges in reliability, cost, standardization, and system stability, and provides guidance for future technological trends.

Keywords: Smart Grid, Renewable Energy Integration, Power Quality, Flexible Power Transmission

1. Introduction

With the acceleration of the low-carbon energy transition, renewable energy, particularly wind and photovoltaic power, is experiencing rapid development. However, the intermittency and variability of renewable energy in traditional power grids pose significant challenges to the security and stability of the grid. The smart grid is the main carrier of the new type of power system, and it can enable coordinated regulation of power sources, the power grid, and loads through information technology, automation, and digital technologies. Power electronics technology can be a critical link between renewable energy, energy storage systems, and the power grid. Power electronics technology primarily employs semiconductor switching devices to achieve efficient energy conversion and precise control. Existing research has demonstrated that it can improve energy conversion efficiency and enhance grid flexibility and controllability. In recent years, research and engineering applications related to grid-connected control, power flow regulation, and power quality management of power electronic devices have continued to deepen. With technological advancement, power electronics technology has also evolved from single-device control and optimization to system-level and intelligent approaches, achieving deep integration in the generation, transmission, transformation, distribution, and consumption stages. It also provides strong support for the efficient, stable, and economical operation of smart grids [1].

Against this background, the motivation of this study is to systematically review the typical application statuses of power electronics technology in smart grids and analyze the further development trends. The research adopts the literature review method, summarizing existing research outcomes and technological routes to extract key technological directions and common challenges. The study aims to provide a systematic theoretical foundation and technical guidance for subsequent research, promoting the further intelligent development of power electronics technology in smart grid applications.

2. Application of power electronics technology in smart grids

Power electronics technology has been widely used at all stages of smart grids, including generation, transmission, transformation, distribution, and consumption. This section focuses on three aspects: renewable energy integration, flexible transmission, and power quality management.

2.1. Renewable energy integration technology

Renewable energy alters the power flow characteristics of traditional distribution networks, and the voltage characteristics of these networks change significantly between steady-state and transient states, posing significant challenges for voltage control [2]. Power electronics technology offers rapid response and flexible control capabilities, making it an excellent solution for connecting new energy sources to the power grid. Renewable energy sources such as wind power and photovoltaic are typically connected to the grid through power electronic converters. Grid-connected inverters must not only achieve maximum power point tracking (MPPT), but also possess capabilities such as harmonic suppression, low voltage ride-through (LVRT), and fault isolation. Power electronics technology provides a fast-response control platform for renewable energy integration.

In the field of photovoltaic grid-connected inverter control, model predictive control (MPC), characterized by receding horizon optimization and constraint handling, has become a research hotspot in power electronics control [3]. MPC is a control strategy based on receding horizon optimization and feedback correction, and can be divided into continuous control set MPC (CCS-MPC) and finite control set MPC (FCS-MPC) [3]. Among them, FCS-MPC predicts the variation trends of controlled variables based on the system's mathematical model, constructs a cost function, and selects the optimal switching state to achieve multi-objective coordinated control, which has been validated in handling multiple objectives and constraints. However, the computational complexity of FCS-MPC increases rapidly with system scale, becoming a major bottleneck for engineering applications.

2.2. Flexible transmission technology

Traditional HVDC based on LCC-HVDC faces challenges such as commutation failure and difficulty in multi-terminal networking, which leads to high costs for multi-point transmission [4]. Therefore, flexible transmission technology has emerged as a very effective solution. Flexible transmission technology is another core direction supported by power electronics technology for efficient smart grid operation. It mainly includes flexible AC transmission systems (FACTS) and voltage-source converter based HVDC (VSC-HVDC). Key implementations of VSC-HVDC include modular multilevel converter-based HVDC (MMC-HVDC) and diode rectifier-based HVDC (DR-HVDC); in addition, low-frequency AC transmission has also been explored as an alternative approach [5]. Among them, MMC-HVDC has become the mainstream technical route in many

power transmission fields, such as offshore wind grid integration, due to its modular structure and high-efficiency power transmission capabilities.

For the control requirements of converters in MMC-HVDC systems, finite control set model predictive control (FCS-MPC) has been verified as a feasible solution, as it can manage multi-variable problems and incorporate system constraints. It is regarded as a highly promising alternative for modular multilevel converters (MMC). FCS-MPC offers significant advantages in achieving high power levels and low harmonic distortion. However, as the number of output voltage levels and the length of prediction horizons increase, the computational burden of FCS-MPC also grows, limiting the overall performance of MMC systems [6]. Recently, studies have proposed novel methods to reduce computational complexity by screening and compressing the state space of FCS-MPC. Such approaches provide an efficient optimization pathway for the engineering application of FCS-MPC in large-scale flexible HVDC systems.

2.3. Power quality management

On the load and distribution sides of smart grids, issues such as reactive power fluctuations, harmonic pollution, and voltage sags frequently occur. These problems not only reduce power supply reliability but also affect the normal operation of equipment. Given the coexistence of multiple power quality issues, comprehensive control of voltage and current is required. The unified power quality conditioner (UPQC), as one of the most advanced power quality control devices, has attracted significant attention when combined with modular multilevel converter (MMC) technology [7]. MMC is composed of cascaded half-bridge or full-bridge submodules, offering advantages such as reduced switching frequency, near-sinusoidal output waveform, and suitability for higher voltage levels.

Existing studies have developed MMC-UPQC system models using the PSIM simulation platform and have designed separate control strategies for the series and shunt branches. Simulation results show that the MMC-UPQC topology and control strategy can effectively achieve comprehensive power quality compensation [7]. Compared with traditional power electronic devices such as static var compensator (SVC), static synchronous compensator (STATCOM), and active power filter (APF), which are limited to compensating reactive power or harmonics, MMC-UPQC achieves coordinated control of both voltage and current quality, providing more comprehensive protection for sensitive loads.

3. Development status of key power electronics technologies

To further enhance performance and functionality in renewable energy integration, flexible transmission, and power quality applications, ongoing breakthroughs in key power electronics technologies are essential. This section, therefore, explores the development status from three perspectives: devices, topologies, and systems.

3.1. Wide-bandgap semiconductor devices (SiC and GaN)

In power electronic converters, power semiconductor devices serve as the core foundation for energy conversion and control. Traditional silicon-based semiconductor devices are nearing their physical limits in high-frequency, high-voltage, and high-temperature applications. This limitation has become a major bottleneck for improving power density and efficiency.

Wide-bandgap semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN), offer superior properties. These include high breakdown electric field strength, high thermal conductivity, and high electron saturation velocity. Such advantages significantly increase power density and switching frequency. They also address the losses and thermal limitations of traditional silicon-based devices in high-power, high-frequency, and high-temperature scenarios [8]. By combining the modular structure of a full-bridge dual active bridge (DAB) converter with 3.3 kV SiC MOSFET devices, researchers have demonstrated that wide-bandgap devices can significantly improve operating efficiency in medium- and high-voltage isolated DC-DC conversion applications [9]. In addition, the integration of multilevel topologies with wide-bandgap devices has become another key research direction. Increasing the number of voltage levels on the primary and secondary sides of the transformer can improve output voltage quality and enhance conversion efficiency [9]. These high-efficiency, fault-tolerant multilevel converters based on wide-bandgap devices can also be combined with MMC-UPQC and other power quality control devices.

3.2. Intelligent digital control technology

When distributed generation (DG) is connected to distribution networks through power electronic converters, it can actively regulate active and reactive power output, significantly influencing power flow and voltage characteristics. By injecting or absorbing reactive power, DG can provide voltage support for local nodes, improve power quality, reduce long-distance transmission demand, decrease losses, and enhance supply reliability [10].

However, the intermittency and variability of DG may introduce new disturbances. Therefore, designing appropriate control strategies for power electronic devices is essential for achieving optimal system operation and improving power quality. For example, Hajizadeh and Golkar developed an intelligent control strategy for fuel cell DG systems, in which a neural network-based controller was used to regulate active power output and maintain power quality under varying load and grid conditions [10]. The realization of intelligent control relies on accurate modeling of power electronic systems. By constructing device-level and system-level dynamic models, reliable foundations are provided for controller design, supporting functions such as self-diagnosis and self-optimization. On this basis, integrating artificial intelligence and big data analytics can further enhance the adaptability of control strategies.

3.3. System stability research

Renewable energy plays a crucial role in addressing energy crises and climate change. However, with the large-scale integration of renewable energy, the dynamic behavior of power systems has fundamentally changed, evolving from electromechanical dominance to complex interactions between grid and power electronic devices. This transition introduces wideband oscillations characterized by nonlinearity and strong coupling, with distinct spatiotemporal distribution, especially in interconnected grids, significantly increasing the difficulty of transient stability control [11].

Traditional transient stability analysis methods rely on nonlinear differential-algebraic equations, which lead to complex, time-consuming computations. AI-based methods can learn from historical data, extract useful features, and efficiently handle complex, nonlinear, dynamic problems, enabling fast and accurate stability assessment while overcoming the limitations of traditional methods [12].

4. Challenges

4.1. High computational complexity

Currently, in smart grids, advanced algorithms such as FCS-MPC are applied to large-scale systems, including modular multilevel converters and clusters of hundreds of grid-connected inverters. These algorithms need to traverse all possible switching state combinations in each control cycle and solve the cost function optimization problem in real time. As the system scales up, the number of switching states increases exponentially, leading to a sharp increase in the controller's computational burden and a significant increase in response delay. This delay not only affects the system's dynamic performance but may also cause control instability, making it difficult to meet the requirements of modern smart grids for both speed and stability.

4.2. High cost of wide-bandgap devices

Wide-bandgap semiconductor devices such as SiC and GaN involve complex material fabrication processes, and the corresponding packaging technologies and drive protection circuits are not yet mature. Furthermore, yield rates are low, and the failure mechanisms, aging characteristics, and fault protection schemes of wide-bandgap devices under long-term high-voltage and high-power conditions are not yet fully understood. This leads to high overall equipment investment costs and significant operation and maintenance risks, hindering their large-scale adoption in smart grids.

4.3. Insufficient system stability

With the large-scale growth of installed capacity of new energy sources such as wind power and photovoltaics, a large amount of new energy is being connected to the grid via power electronic converters, leading to a decrease in the proportion of traditional synchronous generators. Synchronous generators themselves possess rotational inertia, providing support to the grid. However, power electronic converters, with their fast response speed and limited overload capability, typically lack inertial response capabilities. When a short-circuit fault, large power fluctuation, or sudden load change occurs in the system, the system inertia decreases significantly. Due to their limited disturbance rejection capability, power electronic devices are prone to causing voltage instability and even cascading failures under such conditions.

4.4. Lack of standardization

Currently, power electronic devices such as grid-connected inverters and static synchronous compensators in smart grids lack unified industry standards in terms of topology, communication interfaces, control strategies, and protection logic. Different manufacturers employ various technical solutions, resulting in incompatible protocols, mismatched parameters, and inconsistent control objectives. In multi-device collaborative scenarios such as microgrids, flexible transmission, and power quality management, problems arise such as poor compatibility, complex commissioning, and difficulties in expansion. Specifically, system integration requires extensive protocol conversion and parameter debugging, necessitating the redesign of coordination logic. This lack of standardization not only increases the complexity and cost of engineering construction but also limits the openness and scalability of smart grids.

Therefore, future efforts should focus on further introducing artificial intelligence optimization algorithms to reduce the computational burden of control algorithms, promoting the mass production

and topology optimization of wide-bandgap devices to lower costs and improve reliability, constructing intelligent transient stability assessment and coordinated control systems, and unifying industry standards.

5. Conclusion

This paper systematically reviews the application scenarios and key technologies of power electronics technology in smart grids. It highlights the important roles of power electronics in renewable energy integration, flexible transmission, and power quality management. Key technologies such as modular multilevel converters, wide-bandgap semiconductors, and AI-based algorithms are rapidly advancing, providing strong support for smart grid advancement. However, challenges such as reduced system inertia, high cost of wide-bandgap devices, and lack of standardization remain significant.

This study has certain limitations, as it is based solely on existing literature and lacks experimental validation. Future research should focus on AI-integrated control, high-efficiency fault-tolerant topologies, and coordinated system stability to further enhance the performance of power electronics technology in smart grids.

References

- [1] Wang, L., & Danzenbasang. (2025). Application discussion of advanced power electronic technology in smart grid. *China Strategic Emerging Industry*, (08), 26-28.
- [2] Li, Y., Tian, X., Liu, C., Su, Y., Li, L., Zhang, L., ... & Li, J. (2017, November). Study on voltage control in distribution network with renewable energy integration. In *2017 IEEE Conference on Energy Internet and Energy System Integration (EI2)* (pp. 1-5). IEEE.
- [3] Geng, T., Peng, B. Y., Xin, Y. L., et al. (2026). Application of improved model predictive control based on bi-objective cost function in T-type three-level grid-connected inverter. *Power Electronics*, 60(03), 52-60.
- [4] Chai, X., Liang, X., & Zeng, R. (2006, June). Flexible compact AC transmission system-a new mode for large-capacity and long-distance power transmission. In *2006 IEEE Power Engineering Society General Meeting* (pp. 6-pp). IEEE.
- [5] Yang, W. T., Zhang, Y., Guo, X., & Bao, M. L. (2026). Research on coordinated control strategy for offshore wind power transmission via integrated sea-land flexible DC system. *Power Capacitor and Reactive Power Compensation*, (2), 1-11.
- [6] Wang, K., Yang, X., Chen, S., & Park, K.-B. (2023). FCS-MPC based dual-module ANN controller for three-level converter. *2023 11th International Conference on Power Electronics and ECCE Asia (ICPE 2023-ECCE Asia)*, Jeju Island, Republic of Korea, 1861-1866.
- [7] Xu, Y., Zhan, X., Yang, C., et al. (2026). Research on modular device and its control strategy for comprehensive power quality control. *Automation & Instrumentation*, (02), 232-236.
- [8] Zhang, J. W., Wang, S., Shi, S., et al. (2026). Junction temperature measurement technology for wide bandgap high-power electronic devices. *Acta Physica Sinica*, 1-76.
- [9] Gandomi, A. A., Parsa, L., Dargahi, V., & Corzine, K. (2020, October). Fault tolerant isolated dual active DC-DC converter using WBG devices. In *2020 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 418-423). IEEE.
- [10] Hajizadeh, A., & Golkar, M. A. (2007). Intelligent control of fuel cell distributed generation systems. *2007 International Conference on Intelligent Systems Applications to Power Systems*, Kaohsiung, Taiwan, 1-7.
- [11] Liu, Y. L., Chen, L., & Xie, X. R. (2026). Research progress and prospect of wide-band oscillation analysis and control technology for new power system. *Electric Power Automation Equipment*, 1-16. <https://doi.org/10.16081/j.epae.202604007>
- [12] Liu, S. K., Ai, D., Hu, P., Zhang, L., Cao, J., & Liu, Y. Y. (2026). Research on transient stability preventive control of new energy power system based on deep learning. *Journal of Electrical Engineering*, 1-13.