The Role of Power Electronic Converters in Microgrid Technology: A Review of Challenges, Solutions, and Research Directions

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Abstract:

The paper is on the role of power electronic converters in microgrid technology: A review of challenges, solutions and research directions. The objective of the paper is to perform a comprehensive overview of the role of power electronic converters in microgrid technology, focusing on challenges, solutions, and research directions. Findings revealed that major challenges of power electronic converters integration in microgrid technology are voltage and frequency regulation issues, power quality issues, creative management and coordination challenges, and Integration of renewable energy sources. The solutions to these problems are advanced control algorithms such as Model Predictive Control (MPC); deployment of active power filters or harmonic compensators to reduce harmonic distortion and improve power quality; implement a centralized control system with centralized monitoring controllers to coordinate the operation of several converters and ensure consistent operation; and combining multiple renewable energy sources in a hybrid energy system to diversify generation sources and reduce the gap. The future research directions include, among others, advanced control strategies, grid-forming converters, wideband semiconductor, and cyber-security and Resilience. The paper concludes that the integration of power electronic converters into microgrid technology presents both opportunities and challenges. Although these converters play an important role in the efficient conversion, distribution and utilization of energy in microgrids, they face various technical and practical challenges. To mitigate these challenges, the implementation of advanced control strategies, grid-forming converters, etc., is inevitable.

Keywords: power electronic converters, microgrid technology, challenges, solutions, future research directions.

Introduction

In recent years, the integration of renewable energy sources (RES) into the power grid has witnessed a significant surge, driven by the global imperative to transition towards a sustainable energy future (Tang, Yang, & Blaabjerg, 2022). Microgrids, as decentralized and controllable power systems, have emerged as pivotal platforms for incorporating RES and enhancing grid resilience and sustainability (Iskender & Genc, 2020; Shahbazi & Khorsandi, 2017). At the heart of microgrid operation lie power electronic converters, which facilitate efficient energy conversion, distribution, and utilization (Ming, 2021). These converters play a crucial role in enabling various applications within microgrids, including renewable energy
integration, energy storage, and transportation electrification (Francés, Asensi, García, Prieto & Uceda, 2016).

The conventional approach to controlling power converters in microgrids has been through cascaded linear controllers. However, recent advancements have seen the emergence of advanced control methods as viable alternatives, offering enhanced dynamic performance and robustness (Dragicevic, Vazquez & Wheeler, 2020; Mandrile, Carpaneto & Bojoi 2021). These advanced control techniques hold promise in addressing the challenges associated with voltage and frequency regulation, power quality issues, and converter control coordination (Osorio, Saavedra-Montes, Ramos-Paja, HerreraMurcia & Bastidas Rodríguez, 2023; Naderi, Hosseini, Ghassem Zadeh, Mohammadi-Ivatloo, Vasquez, Guerrero, 2018). Moreover, they pave the way for optimizing converter operation in microgrid applications, thereby maximizing efficiency and reliability.

Despite the progress made in advancing control methodologies, several challenges persist in the effective integration of power electronic converters in microgrids. These challenges range from ensuring compatibility with grid codes and standards to addressing stability concerns arising from the variability of renewable energy sources (Meegahapola, Sguarezi, Bryant, Gu, Conde & Cunha, 2020). Furthermore, the selection and implementation of appropriate converters for diverse microgrid configurations remain non-trivial tasks (Galigekere & Kazimierczuk, 2021).

In light of these challenges, this review aims to provide a comprehensive overview of the role of power electronic converters in microgrid technology, focusing on challenges, solutions, and research directions. The review begins by elucidating the key functionalities of voltage source converters (VSCs) in microgrid systems, followed by an exploration of traditional control methods and their limitations. Subsequently, prominent advanced control techniques are critically examined, highlighting their implementation principles, advantages, and drawbacks. The review concludes with a discussion on promising research directions in the realm of advanced control for power electronic converters in microgrids.

By synthesizing existing literature and identifying gaps in current research, this review endeavors to offer valuable insights for researchers, engineers, and policymakers involved in the design, operation, and management of microgrid systems.

Materials and Methods

This article is a review of the role of power electronic converters in microgrid technology focusing on the challenges, solutions and future directions. The article reviewed related literature to establish the role of power electronics converters, challenges, solutions and future research directions.

Review of Related Literature

Dragicevic, Vazquez and Wheeler (2020) investigate advanced control methods for power converters in distributed generation systems and microgrids. The authors emphasize the role of advanced controllers in improving dynamic performance and robustness. The paper reviews traditional linear controllers and compares them with model- and data-based advanced control methods.

In Tang, Yang, and Blaabjerg (2022), focusing on the integration of renewable energy sources in microgrids, highlight the significance of power electronics in the transition to sustainable energy. The authors discuss power conversion technologies, grid codes, and future trends in power semiconductor development and advanced control for wind and photovoltaic systems.

Moreover, Osorio, Saavedra-Montes, Ramos-Paja, HerreraMurcia and Bastidas Rodríguez (2023), presents an overview of power converters used in microgrids with non-conventional renewable energy sources and energy storage. The authors classify converters based on their applications and discuss advantages, disadvantages, and research gaps.
They identify a need for more studies on direct current microgrids.

In the same vein, Ming (2021), focusing on the fundamentals of power electronic converters in microgrids, introduces different converter topologies and discusses their design and control with wide-bandgap semiconductors. The author emphasizes the trade-offs between converter efficiency, power density, and cost.

According to Iskender and Genc (2020), investigating direct current (DC) microgrids, highlight the importance of power electronic converters in maintaining voltage regulation and controlling power flow direction. The authors discuss different converter types and their functions in DC microgrid systems.

Furthermore, Shahbazi and Khorsandi (2017) provide an overview of power electronics, emphasizing their role in converting electrical energy between different forms. The authors discuss power converter components, control units, and bidirectional power flow, highlighting their importance in various applications. Similarly, Francés, Asensi, García, Prieto and Uceda (2016), Focusing on DC microgrids, this study discusses the role of electronic power converters in enhancing system controllability. The authors emphasize the importance of converters in managing power flow, stability, and dynamic response in smart DC microgrids.

More so, Alayi, Zishan, Mohkam, Hoseinzadeh, Memon and Garcia (2021), investigating power management in microgrids integrated with renewable energy sources, propose a control configuration using back-to-back converters. The authors analyze different sustainability scenarios and demonstrate reliable network output power distribution.

In a related study, Meegahapola, Sguarezi, Bryant, Gu, Conde and Cunha, (2020) review power system stability issues arising from the integration of renewable energy sources interfaced with power electronic converters. The authors discuss stability challenges and improvement strategies, including synchronous inertia, reactive power reserve, and fault ride-through capabilities. Similarly, Galigekere and Kazimierczuk (2021) providing an overview of distributed generation and renewable energy sources, this study discusses the role of power electronics in wind, solar, and photovoltaic systems. The authors emphasize the importance of advanced power electronic systems for efficient energy conversion and smart energy management.

**Fundamentals of Power Electronic Converters in Microgrid Technology**

Microgrids, as an autonomous and controlled power system, rely on powerful electronic converters to control the flow of energy in the grid. Power converters act as a bridge between different energy sources, loads and storage systems, enabling efficient conversion, distribution and use of energy (Ming, 2021; LaCommare, Eto, Dunn & Sohn, 2018; Shen, Tan, Shuai, & Luo 2019). In this chapter, we explore the basics of power electronic conversion in microgrids, studying their types, functions, and operating principles.

**Power Electronic Converters: Types**

Power inverters used in microgrid applications include a variety of topologies to suit specific requirements and applications. Some commonly used converter types are:

**AC/DC Converters:** These converters help convert alternating current (AC) to direct current (DC), allowing renewable energy sources such as solar panels and wind turbines to be integrated into the microgrid (Francés, Asensi, García, Prieto & Uceda 2016; Lin, Eto, Johnson, Flicker, Lasseter, Villegas, Seo, Pierre & Ellis, 2020). Figure 1 is an example of an AC/DC converter. It takes AC supply and converts it to DC. Figure 2 shows the application of AC / DC converters in a microgrid.

**DC/AC converter:** A DC/AC converter, also known as an inverter, is required to convert DC power from a source or storage system into AC power suitable for loads connected to the grid (Iskender & Genc, 2020; Naderi, Hosseini, Zadeh, Mohammadi-Ivatloo, Savaghebi & Guerrero, 2019).
**DC/DC Converter:** This converter adjusts the voltage level to meet the output requirements of renewable energy sources or storage systems, loads or other energy storage devices (Francés, Asensi, García, Prieto & Uceda, 2016; Fabricio, Júnior, Jacobina & Corrêa, 2018). A DC-DC converter is an electrical circuit that reduces energy losses during transmission between different circuits, as well as a converter used to convert DC voltage (Alayi, Zishan, Mohkam, Hoseinzadeh, Memon & Garcia, 2021).

Figure 4 shows the application of the DC/DC converter in the DC microgrid. A DC/DC converter takes a dc voltage at one level and converts it to a dc voltage at the same level as the DC bus voltage.

**Bidirectional converters:** Bidirectional converters facilitate the flow of power in both directions, thus energy exchange between the microgrid and external systems or storage devices (Shahbazi & Khorsandi, 2017; Ni, Lyu, Yadav, Singh, Zheng, & Cao, 2020; Shen, Tan, Shuai, & Luo 2019). Buck/Boost is a bi-
A directional converter used to connect a subset of isolated DC/DC with equal but not identical voltage levels. Additional capacity is required at the same voltage level. Bidirectional power converters (BPCs) are devices that can support power between AC and DC subsystems, maintaining a dynamic power balance in the system. This converter can be used in parallel with other BPCs. Bidirectional converters are widely used in modern power systems, especially in charging electric vehicles (EV), renewable energy sources (PV, Wind, etc.) and ESS, as well as in microgrid applications, given the possibility of two-way power flow. In uninterruptible power supply (UPS) and aerospace (Osorio, Saavedra-Montes, Ramos-Paja, HerreraMurcia & Bastidas Rodriguez, 2023; Huang, Xiao, Wen, Wang & Zhang, 2019).

Functions of Power Electronic Converters

Power inverters in microgrids have several important functions, including:

1. Voltage and frequency regulation: Inverters regulate voltage and frequency in the microgrid to maintain grid stability and ensure compatibility with connected loads (Iskender & Genc, 2020).

2. Improving power quality: Generators improve power quality parameters such as voltage distortion and harmonic content, reducing the distortion of sensitive electronic equipment (Osorio, Saavedra-Montes, Ramos-Paja, HerreraMurcia & Bastidas Rodriguez, 2023; Naderi, Hosseini, Ghassem Zadeh, Mohammadi-Ivatloo, Vasquez, Guerrero, 2018).

3. Isolation and grid integration: Inverters provide isolation between different parts of the microgrid and facilitate seamless integration with external grids or renewable energy sources (Dragicevic, Vazquez & Wheeler, 2020; Mandrile, Carpaneto & Bojoi 2021).

4. Energy storage management: Inverters play an important role in managing energy storage systems, including charging, discharging and optimizing energy flow depending on demand and demand conditions (Francés, Asensi, García, Prieto & Uceda, 2016; Galigeke & Kazimierczuk, 2021; Sun, Zhao, Yang, Jia, Pei & Xu, 2020).

Figure 5. The Challenge of Power Electronic Converters in Microgrids
The operation of power electronic converters in microgrids is controlled by various control strategies and modulation techniques. Pulse width modulation (PWM) is commonly used to adjust the output voltage and current of the power supply to ensure smooth and efficient power transfer (Ming, 2021). In addition, advanced control techniques such as Model Predictive Control (MPC) and Sliding Mode Control (SMC) (Carmona, Marjanovic, Barnes & Green, 2020) offer enhanced dynamic performance and robustness, especially in grid-connected microgrid configurations (Dragicevic, Vazquez & Wheeler, 2020; LaCommare, Eto, Dunn & Sohn, 2018).

**Discussion**

**Challenges of Power Electronic Converters in Microgrid Technology**

Figure 5 shows the challenge of integrating power electronics converter in microgrids.

**Voltage and Frequency Regulation Issues**

Variability of renewable energy sources: Microgrids often incorporate renewable energy sources such as solar and wind, which shows product variability. This variability creates challenges for voltage and frequency regulation in microgrids, as sudden changes in power generation can cause voltage and frequency fluctuations.

Dynamic Load Changes: Changes in load demand in a microgrid can also affect voltage and frequency regulation. Rapid load changes can cause power electronic conversion responsible for regulating voltage and frequency, causing instability and circuit breakdown.

Island Operation: Microgrids are designed to operate in both grid-connected and island modes. During island operation, it becomes more difficult to maintain voltage and frequency within acceptable limits, because the microgrid must rely only on its internal sources without the support of external sources.

**Power Quality Issues**

Harmonic Distortion: Power electronic converters can introduce harmonic distortion into microgrid voltage and current waveforms, especially during transition periods. Harmonic distortion can reduce power quality, cause equipment failure and increase system losses.

Voltage surges and swelling: temporary voltage fluctuations such as sags and surges can occur due to sudden changes in load or faults in the microgrid. Power inverters must respond quickly to minimize these voltage fluctuations and maintain stable operation.

Voltage imbalance: An imbalance in the voltage distribution between the different phases of a microgrid can lead to inefficient operation and increased stress on the connected load. Power electronic converters play an important role in balancing voltage and ensuring balanced operation.

**Creative Management and Coordination Challenges**

Inverter interaction: In microgrids with several interconnected inverters, the coordination of individual inverter operations becomes important to avoid conflicts and instability. Issues such as voltage drop, phase synchronization, and current sharing must be carefully addressed by an effective control strategy.

Grid Code Compliance: Microgrids must comply with certain grid codes and standards to ensure compatibility with the grid. Generator control algorithms must be designed to meet these requirements, including frequency response, voltage regulation, and fault handling capabilities.

Communication and data exchange: Effective coordination between power electronics converters depends on timely communication and data exchange. Issues such as communication latency, data synchronization, and network reliability can affect the performance of the inverter control system.
Integration of Renewable Energy Sources

Intermittency and variability: The intermittent nature of renewable energy sources creates challenges for power grid converters to effectively integrate and manage the generation of renewable energy in a microgrid. The generator control algorithm must adapt to changing renewable energy output to maintain grid stability.

Incompatibilities: Different renewable energy sources, such as solar and wind, have different characteristics and operating modes. Integrating multiple renewable energy sources into a microgrid requires careful consideration of conversion measures, control strategies, and system design to ensure optimal compatibility and performance.

Grid support functions: To facilitate the seamless integration of renewable energy sources, power electronic converters in microgrids must provide important grid support functions such as voltage regulation, frequency control, and active power injection. However, designing a converter that can perform this cell support function while using more renewable energy poses technical challenges.

Solutions to the Challenges of Power Electronic Converters in Microgrid Technology

i. Apply advanced control algorithms such as Model Predictive Control (MPC) or Hierarchical Control to dynamically adjust converter operation based on actual grid conditions and load demand. It also integrates energy storage systems (ESS) such as batteries or supercapacitors to provide rapid power injection or absorption to accommodate voltage and frequency fluctuations. In addition, implement a distributed control scheme where multiple inverters adjust voltage and frequency together, improving system power and stability.

ii. Deploy active power filters or harmonic compensators to reduce harmonic distortion and improve power quality. Also, install a voltage regulator or static synchronous compensator (STATCOM) to maintain voltage stability and reduce voltage spikes and surges. Likewise, integrating power cooling systems such as uninterruptible power supply (UPS) to provide clean and stable power to sensitive loads, reducing the effects of voltage disturbances.

iii. Implement a centralized control system with centralized monitoring controllers to coordinate the operation of several converters and ensure consistent operation. Also, improve communication infrastructure and reliable and low-latency networks to facilitate data exchange and control coordination between converters. In addition, the design of converter control algorithms to meet cell codes and standards, including features such as cell control, voltage support, and fault tolerance.

iv. Combining multiple renewable energy sources in a hybrid energy system to diversify generation sources and reduce the gap. Develop predictive models to predict renewable energy production and apply predictive control strategies to proactively adjust converter performance based on forecasted data. Apply dynamic system configuration algorithm to adaptively change microgrid topology and control strategy in response to changing renewable energy generation patterns.

Future Research Directions

In the future, some promising research areas can integrate the integration of electrical electronic conversion into microgrid technology:

1. Advanced control strategies: Continued research on advanced control algorithms such as artificial intelligence-based techniques (e.g., machine learning, neural networks) and distributed control techniques can improve the dynamic performance and efficiency of power inverters in microgrids.

2. Grid-forming converters: Investigate the development of grid-forming converters capable of autonomously determining the grid voltage and frequency, thereby enabling islanding and increasing microgrid resilience due to grid breakdown and blackouts.

3. Wideband Semiconductor: Research focused on exploring the potential of wideband semiconductor devices (e.g., silicon carbide, gallium nitride) can lead to the development of...
more efficient, compact, and reliable power electronic converters with high switching frequency and low losses.

4. Cyber Security and Resilience: Address cyber security threats and vulnerabilities related to power inverters and microgrid management systems to ensure the integrity, availability and resilience of microgrid operations due to cyber-attacks and malicious intrusions.

5. Standardization and interoperability: Develop standard communication protocols, interoperability standards, and test procedures, increasing system flexibility and scalability to facilitate seamless integration and interoperability between power electronic converters from different manufacturers.

6. Hybrid Energy System: Investigate the combination of different energy sources, including renewable energy sources, energy storage systems, and conventional generators, in a hybrid energy system to optimize energy management, improve grid stability, and maximize the use of renewable energy.

7. Smart Grid Integration: Exploring the incorporation of microgrid systems with broader smart grid initiatives, such as demand response programs, distributed energy resource management systems (DERMS), and real-time grid monitoring and control platforms, to enhance grid flexibility, reliability, and efficiency.

8. Resilient Microgrid Design: Learn key microgrid design principles and techniques to improve system resilience and survivability against weather events, natural disasters, and other disruptive events, providing uninterrupted energy supply to critical infrastructure and communities.

By focusing on this research area, the integration of power electronic converters into microgrid technology can continue to advance, leading to a sustainable and adaptive energy system capable of meeting future challenges. Collaboration between academia, industry, government agencies and other stakeholders is very important to drive innovation and accelerate the deployment of world-leading microgrid solutions.

Conclusion

In conclusion, the integration of power electronic converters into microgrid technology presents both opportunities and challenges. Although these converters play an important role in the efficient conversion, distribution and utilization of energy in microgrids, they face various technical and practical challenges. From voltage and frequency regulation to power quality issues and conversion control coordination, solving these challenges is essential to ensure reliable and sustainable operation of microgrid systems, especially with the rise of renewable energy sources.

Advanced control strategies such as model predictive control and hierarchical control offer promising solutions to the problems of voltage and frequency regulation and integration of energy storage systems. Active filters and voltage regulators help reduce power quality problems by providing a clean and stable power supply to connected loads. In addition, centralized control systems and advanced communication infrastructure facilitate efficient coordination between power electronic conversions, ensuring compliance with electrical codes and standards.

In addition, the development of hybrid energy systems, prediction models and dynamic system configuration algorithms are required to solve the problem of renewable energy source integration. This solution allows microgrid operators to harness renewable energy while maintaining grid stability and reliability.

Overall, by implementing innovative solutions and research advances in power electronic converter technology, microgrid systems can overcome challenges and realize their full potential in the operation of a sustainable, resilient and decentralized energy system of the future. Continued collaboration between researchers, industry stakeholders and policymakers is essential to drive innovation and accelerate the adoption of microgrid technology worldwide.
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Conflict of Interests

No conflict of interest.

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