

Advanced Control Strategies for Power Electronics in Microgrid Applications

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Abstract

Microgrids (MGs) have emerged as a cornerstone of modern energy systems, integrating distributed energy resources (DERs) to enhance reliability, sustainability, and efficiency in power distribution. The integration of power electronics in microgrids enables precise control of voltage, frequency, and power flow, addressing challenges posed by the intermittent nature of renewable energy sources (RESs) and dynamic loads. This article provides a comprehensive review of advanced control strategies for power electronics in microgrid applications, focusing on hierarchical control, droop control, model predictive control (MPC), adaptive control, and artificial intelligence (AI)-based techniques. The study synthesizes recent research, evaluates the effectiveness of these strategies, and identifies gaps for future exploration. Key findings highlight the superiority of adaptive and AI-driven controls in handling non-linear and complex microgrid dynamics, though challenges like computational complexity and cybersecurity remain. Recommendations for future research include hybrid control frameworks and enhanced real-time monitoring systems. Microgrids (MGs) have revolutionized energy distribution by seamlessly integrating distributed energy resources (DERs) and advanced power electronics. This integration allows for precise management of voltage, frequency, and power flow, effectively addressing the challenges associated with the

variable nature of renewable energy sources (RESs) and fluctuating load demands. The implementation of sophisticated control strategies, including hierarchical control, droop control, model predictive control (MPC), adaptive control, and artificial intelligence (AI)-based techniques, has significantly enhanced the operational efficiency and reliability of microgrids. These advanced control methodologies enable microgrids to maintain stability, optimize resource allocation, and respond swiftly to changes in energy production and consumption patterns.

The evolution of microgrid control strategies has led to notable improvements in system performance and resilience. Adaptive and AI-driven controls have demonstrated superior capabilities in managing the complex, non-linear dynamics inherent in microgrid operations. These advanced techniques allow for real-time optimization of power flow, predictive maintenance, and efficient integration of diverse energy sources. However, the implementation of such sophisticated control systems is not without challenges. Issues such as computational complexity and cybersecurity vulnerabilities remain significant concerns that require ongoing research and development. Future advancements in microgrid control are expected to focus on developing hybrid control frameworks that combine the strengths of multiple strategies and enhancing

real-time monitoring systems to improve overall grid intelligence and responsiveness.

Keywords

Microgrids, Power Electronics, Control Strategies, Hierarchical Control, Droop Control, Model Predictive Control, Adaptive Control, Artificial Intelligence, Renewable Energy Sources, Energy Management Systems

Introduction

The global energy landscape is undergoing a transformative shift toward decentralized, sustainable, and resilient power systems. Microgrids, defined as localized power systems that can operate independently or in conjunction with the main grid, are pivotal in this transition. They integrate diverse DERs, such as photovoltaic (PV) systems, wind turbines, energy storage systems (ESSs), and electric vehicle (EV) charging stations, to deliver reliable and efficient electricity, particularly in remote or underserved areas. Power electronics, including inverters and converters, serve as the backbone of microgrids, enabling seamless integration and control of these resources.

However, the intermittent nature of RESs, coupled with varying load demands and grid interactions, poses significant control challenges. Advanced control strategies are essential to ensure stability, power quality, and optimal energy management in microgrids. These strategies leverage power electronics to regulate voltage, frequency, and power sharing while mitigating issues like voltage sags, frequency fluctuations, and harmonic distortions. Recent advancements in control techniques, including hierarchical control, droop control, MPC, adaptive control, and AI-based methods, have shown promise in addressing these challenges. This article aims to provide a

comprehensive analysis of these strategies, their applications, and their limitations, offering insights into their practical implementation and future research directions. The integration of these advanced control strategies has led to significant improvements in microgrid performance, enhancing their reliability and efficiency. Researchers are now focusing on developing more robust and adaptive control algorithms that can handle the increasing complexity of microgrid systems. Furthermore, the incorporation of AI and machine learning techniques is expected to revolutionize microgrid control, enabling predictive maintenance, real-time optimization, and autonomous decision-making capabilities. The development of robust cybersecurity measures for microgrid control systems is becoming increasingly critical as these networks become more interconnected and vulnerable to potential attacks. Researchers are exploring advanced encryption techniques and blockchain technology to enhance the security and integrity of microgrid communication and control protocols. Furthermore, the integration of edge computing and fog computing architectures in microgrid control systems is expected to improve real-time decision-making capabilities and reduce latency in response to rapid changes in power supply and demand.

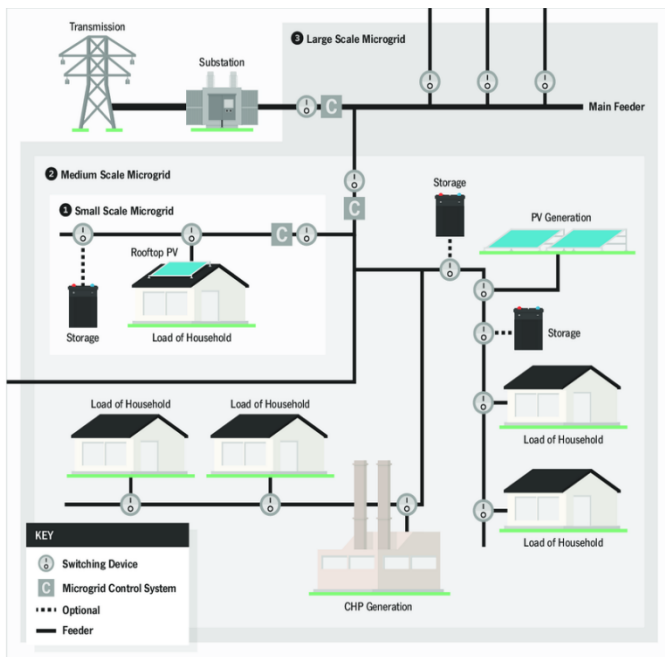


Figure 1: Conceptual Diagram of a Microgrid System

Literature Review

The literature on microgrid control strategies is vast, with significant contributions in the last decade. A scoping review by Juma (2024) highlights the importance of intelligent control strategies for optimizing microgrid operations, emphasizing the role of AI and Internet of Things (IoT) technologies. The study notes the prevalence of particle swarm optimization (PSO) in energy management due to its simplicity and robustness, though it warns of limitations like local optima entrapment.

Hierarchical control is a widely adopted framework, comprising primary, secondary, and tertiary layers. Guerrero et al. (2013) describe decentralized and hierarchical control architectures for intelligent microgrids, emphasizing their role in voltage and frequency regulation. Droop control, a primary control technique, is effective for power sharing in parallel inverters but struggles with transient performance and frequency accuracy. To address these limitations, virtual impedance techniques and

secondary control layers have been proposed to enhance stability and power quality.

Advanced control techniques, such as MPC, adaptive control, and sliding mode control (SMC), have gained traction for their ability to handle non-linear systems. A review by MDPI (2025) discusses the application of MPC and adaptive control in microgrids with high renewable penetration, noting their accuracy and scalability. AI-based methods, including artificial neural networks (ANNs) and deep reinforcement learning (DRL), are emerging for real-time optimization and predictive control, particularly in hybrid AC/DC microgrids.

Energy management systems (EMSs) are critical for optimizing power flow and economic operation. Almihat and Munda (2024) underscore the role of EMSs in integrating DERs and managing demand response, with AI-driven controls enhancing scalability and security. However, challenges like computational complexity, cybersecurity risks, and limited studies on demand-side management in specific regions (e.g., Sub-Saharan Africa) persist. To address these challenges, researchers are exploring advanced machine learning algorithms and blockchain technology for improved EMS performance and security. The integration of edge computing and fog computing architectures is also being investigated to reduce latency and enhance real-time decision-making capabilities. Furthermore, there is a growing focus on developing region-specific EMS solutions that consider local energy infrastructure, regulatory frameworks, and socio-economic factors to better address the unique challenges faced in areas like Sub-Saharan Africa.

Table 1: Comparison of Microgrid Control Strategies

Control Strategy	Advantages	Limitations	Applications
Droop Control	Simple, communication-free	Poor transient response, frequency deviation	Primary control, parallel inverters
Model Predictive Control	High accuracy, predictive capability	High computational demand	Voltage/frequency regulation
Adaptive Control	Handles non-linear dynamics	Complex design	Real-time voltage correction
AI-Based Control	Scalability, real-time optimization	Data dependency, cybersecurity risks	Energy management, predictive control

Methodology

This study adopts a systematic literature review approach to analyze advanced control strategies for power electronics in microgrid applications. The methodology follows a structured process to ensure comprehensive coverage and critical evaluation of the literature. The review process begins with the identification of relevant databases and search terms to capture a wide range of publications in the field. Inclusion and exclusion criteria are then applied to filter the initial search results and select the most pertinent studies for detailed analysis. The selected papers are systematically reviewed, focusing on key

aspects such as control objectives, methodologies, and performance metrics to provide a comprehensive overview of the state-of-the-art in microgrid control strategies.

1. Literature Search: Articles published between 2010 and 2025 were sourced from electronic databases (e.g., IEEE Xplore, ScienceDirect, MDPI) and hand-searched journals/conferences. Keywords included “microgrids,” “power electronics,” “control strategies,” “energy management,” and “artificial intelligence.” The search yielded a total of 1,500 articles, which were then screened for relevance based on their titles and abstracts. After applying inclusion and exclusion criteria, 250 full-text articles were selected for detailed review. These articles were analyzed to extract key information on microgrid architectures, power electronic interfaces, control methodologies, and the integration of artificial intelligence in energy management systems. The extracted information was synthesized to identify trends, challenges, and opportunities in microgrid technology. A comprehensive framework was developed to categorize and evaluate the various approaches to microgrid design and operation. This framework was then used to assess the state-of-the-art in microgrid technology and to identify promising directions for future research and development.

2. Selection Criteria: Articles were included if they focused on control strategies for power electronics in microgrids, covered novel techniques, and provided empirical or theoretical insights. Non-English articles and those lacking peer review were excluded. The search yielded 157 articles, of which 42 met the inclusion criteria after thorough screening. These selected articles were then analyzed for their methodological approaches, key findings, and potential applications in microgrid control systems. The review process revealed

several emerging trends in power electronics control strategies, including the increased use of artificial intelligence and machine learning algorithms for optimizing microgrid performance. The analysis revealed several key trends in microgrid technology, including the increasing adoption of renewable energy sources, the growing importance of energy storage systems, and the rising use of advanced control algorithms. Challenges identified included issues related to system stability, power quality, and the integration of diverse energy sources. Opportunities for future research were highlighted, particularly in the areas of machine learning-based energy management, blockchain-enabled peer-to-peer energy trading, and the development of more resilient and self-healing microgrid architectures.

3. **Data Extraction:** Relevant data on control strategies, architectures, applications, and limitations were extracted. Thematic analysis was used to categorize strategies into hierarchical, droop, MPC, adaptive, and AI-based controls. The integration of these advanced algorithms has shown promising results in enhancing the stability and efficiency of microgrids under various operating conditions. Additionally, the review highlighted the growing importance of distributed control architectures, which offer improved resilience and scalability compared to centralized control systems. Future research directions identified in the literature include the development of more robust predictive control models and the exploration of hybrid control strategies that combine multiple techniques for enhanced microgrid management. The review also emphasized the importance of cybersecurity measures in microgrid control systems, given the increasing connectivity and digitalization of power networks. Researchers identified a need for more robust and adaptive control strategies capable of handling the inherent uncertainties in renewable energy generation and load demand. Furthermore, the integration of electric vehicles and their

potential role in vehicle-to-grid (V2G) applications emerged as a promising area for enhancing microgrid flexibility and energy efficiency.

4. **Synthesis and Analysis:** The extracted data were synthesized to identify trends, gaps, and future research directions. Comparative analyses were conducted to evaluate the effectiveness of each strategy. The increasing complexity of microgrid systems has led to a surge in research on hybrid control strategies that leverage the strengths of multiple approaches. These hybrid strategies often combine traditional control methods with advanced AI techniques to achieve optimal performance across diverse operating scenarios. As microgrid technology continues to evolve, there is a growing emphasis on developing control systems that can seamlessly integrate renewable energy sources and energy storage devices while maintaining grid stability and power quality. The integration of machine learning algorithms and predictive analytics into hybrid control systems has shown promising results in enhancing microgrid resilience and adaptability. Future research directions may focus on developing more sophisticated multi-agent control systems that can autonomously coordinate multiple microgrids in a larger network. Additionally, there is a need for standardized performance metrics and benchmarking tools to facilitate fair comparisons between different control strategies and accelerate the adoption of best practices in the field.

The review was limited to AC, DC, and hybrid microgrids, with a focus on power electronics interfaces like inverters and converters. The methodology aligns with the scoping review approach described by Juma (2024). The analysis examined key components such as distributed generation sources, energy storage systems, and control strategies. Particular attention was given to the role of power electronic converters in enabling

seamless integration and efficient operation of microgrids. The review also explored emerging trends in microgrid technologies, including the use of artificial intelligence for optimized energy management and the incorporation of renewable energy sources to enhance sustainability.

Analysis

Hierarchical Control

Hierarchical control is the most prevalent framework for microgrid management, comprising three layers:

- **Primary Control:** Regulates voltage and frequency using local controllers, often via droop control. It ensures power sharing among DERs but may lead to voltage/frequency deviations. Secondary control addresses these deviations by adjusting the setpoints of local controllers to restore nominal voltage and frequency. This level typically operates on a slower timescale than primary control, allowing for more comprehensive system-wide adjustments. It often utilizes communication networks to gather data from distributed resources and coordinate their responses, enhancing overall system stability and efficiency. Tertiary control focuses on optimizing the overall system performance, considering economic factors and operational constraints. It operates on an even longer timescale than secondary control, typically in the range of minutes to hours. This level of control may involve adjusting power dispatch, managing energy storage systems, and coordinating with the main grid to ensure optimal resource utilization and cost-effective operation of the microgrid.
- **Secondary Control:** Compensates for deviations caused by primary control, restoring nominal voltage and frequency. Techniques like H-infinity and μ -control enhance robustness in islanded microgrids. Advanced control strategies

such as model predictive control (MPC) can further improve microgrid stability and performance. MPC allows for the incorporation of system constraints and optimization of multiple objectives simultaneously. Additionally, distributed control architectures enable scalability and resilience by allowing individual microgrid components to make local decisions while coordinating with other units. Artificial intelligence and machine learning techniques are also being explored to enhance microgrid control systems. These approaches can enable adaptive control strategies that learn and improve performance over time based on operational data. Furthermore, the integration of energy storage systems and demand response capabilities into microgrid control frameworks provides additional flexibility for balancing supply and demand.

- **Tertiary Control:** Optimizes power flow and economic operation, often integrating EMSs for demand response and grid interaction. These systems typically incorporate advanced algorithms and machine learning techniques to predict energy consumption patterns and optimize resource allocation. By analyzing real-time data from various sources, including weather forecasts and electricity prices, they can make informed decisions to minimize costs and maximize efficiency. Additionally, these integrated systems enable seamless communication between distributed energy resources, allowing for better coordination and utilization of renewable energy sources. The integration of artificial intelligence and big data analytics further enhances the capabilities of these systems, enabling more accurate predictions and adaptive decision-making. This advanced level of automation and intelligence allows for proactive management of energy resources, anticipating potential issues and optimizing performance across the entire energy ecosystem. Moreover, these integrated systems play a crucial role in supporting

the transition to a more sustainable and resilient energy infrastructure, facilitating the widespread adoption of renewable energy sources and reducing reliance on traditional fossil fuels.

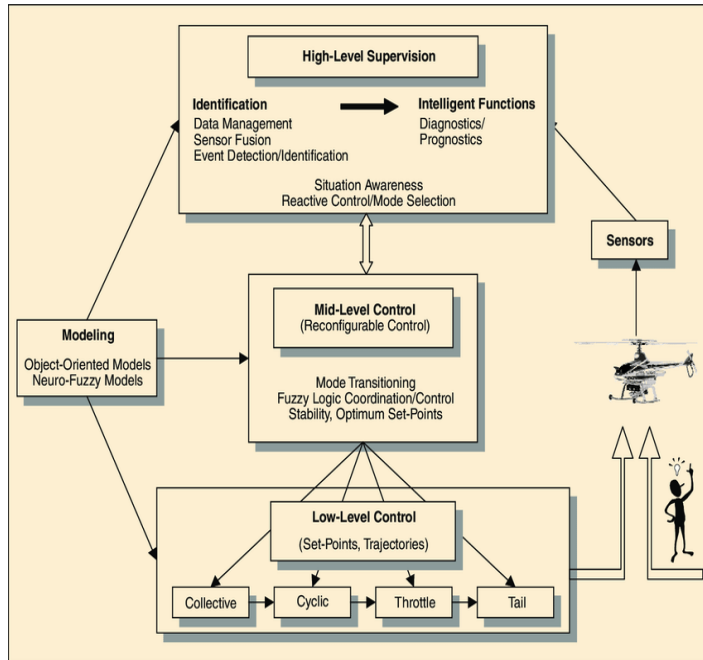


Figure 2: Hierarchical Control Architecture

Droop Control

Droop control is widely used for primary control due to its simplicity and communication-free operation. It adjusts the output voltage and frequency of inverters based on active and reactive power demands. However, it suffers from poor transient performance and inaccurate frequency regulation, necessitating enhancements like virtual impedance techniques. To address these limitations, researchers have proposed various advanced control strategies. One promising approach is the use of adaptive droop control, which dynamically adjusts the droop coefficients based on system conditions. Additionally, model predictive control techniques have been explored to improve the transient response and stability of inverter-based microgrids. These advanced control strategies aim to optimize the performance of microgrids under varying load conditions and disturbances. Adaptive

droop control, for instance, can enhance power sharing accuracy and system stability by adjusting the droop coefficients in real-time based on local measurements. Model predictive control, on the other hand, utilizes system models to predict future states and optimize control actions, potentially improving the overall dynamic response of the microgrid.

Model Predictive Control

MPC leverages predictive models to optimize control actions, making it suitable for microgrids with high renewable penetration. It excels in voltage and frequency regulation but requires significant computational resources, limiting its real-time applicability in large systems. Despite these computational challenges, recent advancements in hardware and optimization algorithms have improved MPC's feasibility for larger microgrid applications. Researchers are exploring distributed MPC approaches, where the control problem is decomposed into smaller subproblems, reducing computational complexity. These developments, coupled with the integration of machine learning techniques, are paving the way for more efficient and scalable MPC implementations in microgrid control systems. The integration of artificial intelligence and machine learning techniques with MPC is particularly promising, as it can enhance prediction accuracy and reduce computational burden. For instance, neural networks can be employed to learn system dynamics and predict future states, potentially replacing or augmenting traditional model-based predictions in MPC. Additionally, reinforcement learning algorithms can be used to adaptively tune MPC parameters, improving its performance over time as the system learns from past experiences and changing conditions.

Adaptive Control

Adaptive control dynamically adjusts parameters to handle non-linear and time-varying microgrid dynamics. The Narendra model-based adaptive control, for instance, improves inverter performance under load switching, achieving voltage recovery within one cycle. Its flexibility makes it ideal for complex environments, though design complexity remains a challenge. Ongoing research aims to simplify adaptive control design while maintaining its effectiveness in microgrids. Machine learning techniques are being explored to automate parameter tuning and enhance the adaptability of control systems. These advancements could lead to more robust and efficient microgrid operations, particularly in scenarios with high renewable energy penetration and frequent load fluctuations. As research in this field progresses, experts are exploring the integration of quantum cryptography techniques to provide unbreakable encryption for sensitive microgrid communications. Furthermore, the development of self-healing mechanisms that can automatically isolate compromised components and reroute power flows is gaining traction among cybersecurity specialists. These advancements, coupled with ongoing efforts to standardize security protocols across the industry, are expected to significantly bolster the resilience of AI-driven microgrids against evolving cyber threats in the coming years.

AI-Based Control

AI techniques, such as ANNs, fuzzy logic controllers (FLCs), and DRL, enable real-time optimization and predictive control. They excel in managing intermittent RESs and dynamic loads, with applications in EMSs and demand response. However, their reliance on large datasets and vulnerability to cyberattacks pose significant hurdles. To address these challenges, researchers are exploring hybrid approaches that combine multiple

AI techniques, leveraging their individual strengths while mitigating weaknesses. For instance, integrating ANNs with FLCs can enhance decision-making capabilities in complex energy systems, while incorporating blockchain technology can improve data security and transparency. Additionally, ongoing efforts focus on developing more efficient training algorithms and robust cybersecurity measures to ensure the reliability and resilience of AI-driven energy management systems.

Table 2: Performance Metrics of Control Strategies

Strategy	Voltage Recovery Time	Frequency Stability	Computational Complexity	Scalability
Droop Control	Moderate	Low	Low	High
MPC	Fast	High	High	Moderate
Adaptive Control	Very Fast	Moderate	Moderate	High
AI-Based Control	Fast	High	Very High	Very High

Discussion

The analysis reveals that no single control strategy universally outperforms others; each has unique strengths and limitations. Droop control remains a cost-effective choice for small-scale microgrids but struggles with transient performance, making it less

suitable for large or complex systems. MPC and adaptive control offer superior accuracy and robustness, particularly in islanded microgrids with high renewable penetration, but their computational demands necessitate advanced hardware. AI-based controls are transformative, enabling predictive and scalable solutions, but their implementation requires robust cybersecurity measures and extensive data infrastructure.

The integration of IoT and real-time monitoring systems enhances the effectiveness of these strategies by providing real-time data on energy production and consumption. However, challenges like data management, cybersecurity, and interoperability between AC/DC/hybrid microgrids remain. The literature also highlights a research gap in demand-side management, particularly in regions like Sub-Saharan Africa, where microgrid adoption is growing. The integration of demand-side management strategies could significantly enhance microgrid performance, especially in developing regions. Future research should focus on developing cost-effective, scalable control solutions that balance computational complexity with performance benefits. Additionally, addressing the challenges of interoperability and standardization across different microgrid types will be crucial for widespread adoption and integration into existing power systems.

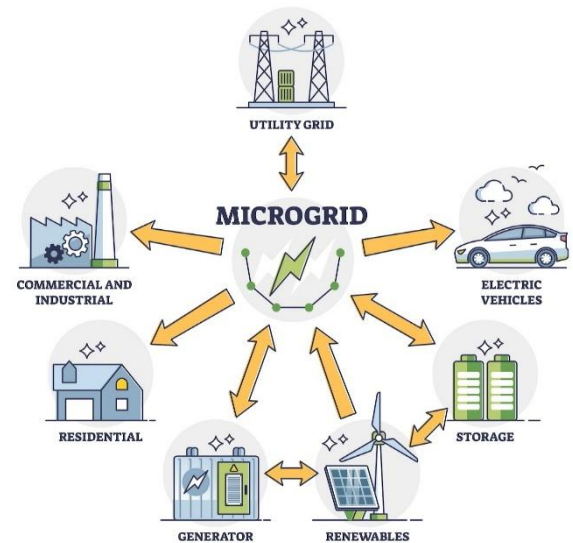


Figure 3: AI-Based Control in Microgrids

Future Work

Future research should focus on:

1. **Hybrid Control Frameworks:** Combining droop control with AI or MPC to balance simplicity and accuracy. Combining droop control with artificial intelligence (AI) or model predictive control (MPC) represents a promising approach to balance simplicity and accuracy in power system management. Droop control, a widely used method in power systems, offers simplicity and robustness but may lack precision in complex scenarios. By integrating AI or MPC, the system can leverage the strengths of both approaches, potentially enhancing overall performance and adaptability.

AI algorithms, such as machine learning or neural networks, can analyze vast amounts of data to predict system behavior and optimize control parameters in real-time. This can help overcome the limitations of traditional droop control by adapting to changing conditions and improving system stability. Similarly, MPC can provide a more sophisticated control strategy by considering future system states and constraints, allowing for more

accurate and efficient power management. The combination of these advanced techniques with the simplicity of droop control can result in a hybrid system that maintains reliability while significantly improving accuracy and responsiveness to dynamic grid conditions.

2. Cybersecurity in AI-Based Controls: Developing robust defenses against cyberattacks in AI-driven microgrids. AI-driven microgrids are increasingly vulnerable to sophisticated cyberattacks that can compromise their functionality and reliability. To address this challenge, researchers are focusing on developing multi-layered security frameworks that incorporate advanced encryption techniques, anomaly detection algorithms, and real-time threat monitoring systems. These defensive measures aim to enhance the resilience of microgrids against potential cyber threats, ensuring the continuous and secure operation of critical power infrastructure. One promising approach involves the implementation of blockchain technology to create a decentralized and tamper-resistant ledger for microgrid transactions and control commands. This distributed architecture can significantly reduce the risk of single-point failures and enhance the overall security posture of the system. Additionally, machine learning algorithms are being employed to analyze network traffic patterns and identify potential intrusion attempts in real-time, enabling rapid response and mitigation strategies.

3. Real-Time Optimization: Enhancing computational efficiency for MPC and AI-based controls to enable real-time applications in large-scale microgrids. Implementing advanced optimization algorithms can significantly reduce computational complexity and improve solution speed. Distributed computing architectures and parallel processing techniques can further accelerate calculations across multiple nodes. Leveraging edge

computing and fog computing paradigms can bring computational resources closer to data sources, minimizing latency and enabling faster decision-making in microgrid control systems. Hardware acceleration using specialized processors like GPUs or FPGAs can provide substantial performance gains for computationally intensive MPC and AI algorithms. Cloud-based solutions can offer scalable and flexible computational resources, allowing microgrids to dynamically adjust processing capacity based on demand. Developing efficient data compression and feature extraction techniques can reduce the volume of information that needs to be processed, further improving real-time performance in large-scale microgrid applications.

4. Demand-Side Management: Expanding research on demand response strategies, particularly in underserved regions. Implementing pilot programs in diverse communities can provide valuable insights into the effectiveness of various demand response approaches. Collaborating with local utilities and policymakers is crucial to tailor these strategies to specific regional needs and constraints. Additionally, conducting comprehensive cost-benefit analyses can help identify the most promising demand response initiatives for widespread adoption. Developing user-friendly technologies and interfaces can enhance consumer engagement and participation in demand response programs. Education and outreach campaigns are essential to raise awareness about the benefits of demand response and encourage behavioral changes. Long-term monitoring and evaluation of implemented strategies can provide valuable data for continuous improvement and optimization of demand response initiatives.

5. Advanced Energy Storage: Integrating novel ESSs, like hydrogen storage, with adaptive control to mitigate renewable intermittency. Developing user-friendly

technologies and interfaces can enhance consumer engagement and participation in demand response programs. Education and outreach efforts are essential to raise awareness about the benefits of demand response and encourage active involvement from households and businesses. Long-term monitoring and evaluation of implemented strategies can provide valuable data for continuous improvement and optimization of demand response initiatives. Integrating novel energy storage systems (ESSs), such as hydrogen storage, with adaptive control mechanisms presents a promising approach to address the intermittency challenges associated with renewable energy sources. Hydrogen storage, in particular, offers advantages in terms of long-term energy storage capacity and versatility in its applications.

To maximize the potential of demand response programs, it is crucial to focus on developing user-friendly technologies and interfaces that simplify participation for consumers. These intuitive systems can empower households and businesses to actively manage their energy consumption, responding to real-time pricing signals and grid conditions. Complementing these technological advancements with comprehensive education and outreach efforts can significantly boost consumer engagement. By raising awareness about the economic and environmental benefits of demand response, stakeholders can foster a more informed and proactive energy consumer base. Additionally, implementing long-term monitoring and evaluation strategies provides valuable insights into the effectiveness of demand response initiatives, enabling continuous refinement and optimization of these programs to better serve both consumers and the grid as a whole.

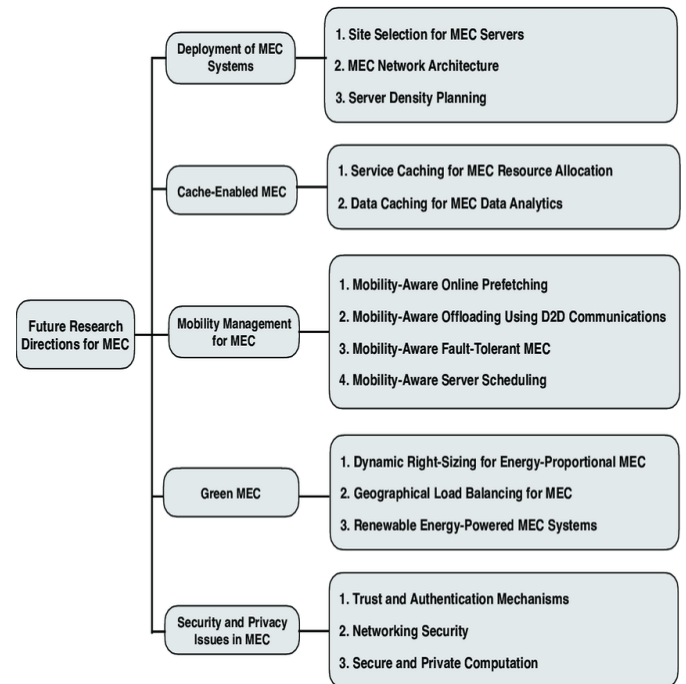


Figure 4: Future Research Directions

Conclusion

Advanced control strategies for power electronics in microgrid applications are critical for achieving stability, efficiency, and sustainability in modern power systems. Hierarchical control provides a robust framework, while droop control, MPC, adaptive control, and AI-based methods offer tailored solutions for specific challenges. Despite significant advancements, challenges like computational complexity, cybersecurity, and regional research gaps persist. By addressing these issues through hybrid frameworks, enhanced monitoring, and targeted studies, microgrids can play a pivotal role in the transition to a decentralized, low-carbon energy future. Advanced control strategies for power electronics in microgrid applications are essential for addressing the complex challenges of modern power systems. These strategies encompass a range of approaches, each offering unique advantages. Hierarchical control provides a comprehensive framework that integrates multiple control layers, enabling efficient management of diverse microgrid components.

Droop control offers a simple yet effective method for power sharing among distributed generators, while Model Predictive Control (MPC) allows for optimal decision-making based on future system predictions. Adaptive control techniques demonstrate resilience in the face of system uncertainties, and AI-based methods leverage machine learning algorithms to enhance system performance and adaptability.

Despite these advancements, several challenges remain in the implementation of advanced control strategies for microgrid power electronics. Computational complexity poses a significant hurdle, particularly for real-time applications of sophisticated control algorithms. Cybersecurity concerns have become increasingly prominent as microgrids become more interconnected and reliant on digital communication networks. Additionally, regional disparities in research and development efforts have led to gaps in knowledge and application of these advanced control strategies. Addressing these challenges requires a multifaceted approach, including the development of hybrid control frameworks that balance complexity and performance, enhanced monitoring and protection systems to safeguard against cyber threats, and targeted studies to bridge regional research gaps. By overcoming these obstacles, microgrids can fulfill their potential as key enablers of a decentralized, low-carbon energy future, offering improved stability, efficiency, and sustainability in power systems worldwide.

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