Theory and Practice of Science and Technology
2025, VOL. 6, NO. 8, 153-158
DOI: 10.47297/taposatWSP2633-456928.20250608

Flexible Grid-Connected/Islanded Switching for Microgrids under Main Grid Faults

Yi Xiao

School of Electrical Engineering and Automation Tianjin University of Technology, Tianjin, 300387, China

ABSTRACT

With the acceleration of the energy transition and the continuous increase in the penetration of distributed generation, microgrids have become key carriers for integrating distributed energy resources. Consequently, the grid-connected/islanded switching technology is now a core element in ensuring grid resilience and power supply reliability. This paper systematically reviews the research status and development trends of flexible grid-connected/islanded switching technology for microgrids under main grid faults. It comprehensively analyzes the evolution paths, traditional control strategies, and intelligent collaborative methods. Traditional control techniques discussed include improvements in droop control, power compensation, phase pre-synchronization mechanisms, and communication protocol optimization schemes. Intelligent collaborative technologies examined encompass cutting-edge directions such as data-driven control, multi-agent collaborative decision-making, and deep reinforcement learning. Domestic and international case studies reveal the innovative value of PV-Storage-DC-Flexibility (PSDF) systems in practice, summarizing the performance advantages and switching processes of DC microgrid architectures. Research shows that adaptive control strategies can reduce transition processes to millisecond levels, and intelligent collaborative architectures significantly enhance renewable energy accommodation capacity. Finally, challenges such as the accuracy of multi-source data fusion, adaptability to complex fault scenarios, and the stability of hybrid systems are identified as future research priorities. This review provides theoretical references for building high-resilience smart grids.

KEYWORDS

Microgrid; Grid-connected/islanded switching; Main grid faults; Intelligent collaborative control; Droop control; PV-Storage-DC-Flexibility (PSDF)

1 Introduction

Against the backdrop of the global energy transition, microgrids have become critical carriers for integrating distributed renewable energy. Their ability to ensure power supply reliability and system resilience relies on seamless grid-connected/islanded switching capabilities. According to statistics from the International Energy Agency (IEA), the global installed capacity of microgrids exceeded 350 GW by the end of 2024. Among them, advanced microgrids capable of millisecond-level switching account for 35% of the total, representing a 20-percentage-point increase over the past five years. This growth trend highlights the central role of flexible switching technology in modern distribution grid architectures. Microgrid grid-connected/islanded switching technology refers to the control process through which a microgrid rapidly and smoothly disconnects from the main grid and transitions to islanded operation upon main grid faults, and subsequently achieves seamless reconnection upon grid recovery. This technology avoids potential load power interruptions inherent in traditional switching processes, significantly reduces fault propagation risks, and has become a key pillar in building resilient grids.

The development of microgrid switching technology can be divided into three stages. The early stage (2000-2010) primarily utilized passive detection methods based on local electrical measurements, which relied on voltage and frequency thresholds to determine islanding status. The switching times during this stage were slow, typically several seconds or more. The transition stage (2011-2020) saw the introduction of active perturbation detection and communication-assisted technologies. These innovations shortened switching times to hundreds of milliseconds, but problems such as power quality disturbances still existed. The current stage (2021-present) integrates intelligent prediction algorithms and multi-source collaborative control. This approach has achieved millisecond-level seamless switching and full-process optimized control. This evolution reflects a paradigm shift in microgrid control, from a single-response mechanism to system-wide collaboration.

Under main grid faults, microgrids face multiple technical challenges. At the instant of a fault, voltage and frequency fluctuations require detection systems to have high sensitivity and anti-interference capability. Furthermore, differences in the response of distributed power sources increase the complexity of control parameter tuning. Moreover, with the promotion of PV-Storage-DC-Flexibility (PSDF) systems—which integrate photovoltaic generation, storage, DC distribution, and flexible loads—the grid-connected/islanded switching of DC microgrids exhibits technical characteristics different from those of AC systems. Consequently, dedicated solutions need to be developed for DC microgrids.

This paper systematically reviews the technical challenges of intelligent collaboration systems, exploring traditional methods, innovative case studies, and future directions across six dimensions. Key innovations include proposing a hierarchical application architecture for intelligent collaborative technology and establishing a performance evaluation system for mode-switching control in DC microgrids. Furthermore, a virtual storage mechanism is refined to enhance stability during the switching process. A comparative analysis of domestic and international demonstration projects reveals the internal logic of technological evolution and summarizes practical experiences. The findings provide valuable theoretical references and practical guidance for subsequent research in this field.

2 Traditional grid-connected/islanded switching control technologies

The ability to seamlessly transition from grid-connected to islanded mode during main grid faults, and to safely reconnect afterward, is paramount for microgrid power supply continuity and stability. Conventional grid-connected/islanded switching control strategies are hindered by critical limitations. Their lack of flexibility under fault conditions restricts the switching process, making it challenging to achieve the required goals of high speed, low impact, and high reliability [1].

2.1 Islanding detection reliability insufficient

The switching trigger is a critical link in the process. Traditional islanding detection methods for main grid faults exhibit significant defects. Passive detection methods, which rely on changes in voltage and frequency parameters at the Point of Common Coupling (PCC), possess an inherent Non-Detection Zone (NDZ). When the power generated within the microgrid closely matches the local load demand, the changes in PCC electrical quantities are minimal, leading to a high risk of detection failure. Theoretical analysis shows that under resistive load conditions, the NDZ range can reach a power mismatch of up to ±3% [2]. Active detection methods, such as Active Frequency Drift (AFD), can reduce the NDZ but require the continuous injection of disturbances. This introduces harmonic distortion and degrades power quality. In multi-inverter parallel scenarios, the superposition of disturbance signals can even cause system oscillation [3]. While communication-assisted methods can theoretically eliminate the NDZ, they rely on additional communication infrastructure. In complex grid topologies and fault scenarios, this introduces a risk of single-point failure and comes with high deployment costs. These defects in traditional methods can cause delays or misjudgments in identifying the islanding state, which directly affects the start timing and smoothness of subsequent switching control actions [4].

2.2 Mode switching impact suppression weak

Droop control serves as the core regulation method for islanded operation. However, the traditional approach faces an inherent trade-off: a high droop coefficient improves the power-sharing accuracy among multiple distributed generation units but exacerbates bus voltage drops. Conversely, a low droop coefficient helps stabilize voltage but significantly weakens current-sharing capability.

During the transition from grid-connected to islanded mode, traditional methods struggle to rapidly establish stable voltage and frequency references for the off-grid system. This difficulty often results in severe voltage dips exceeding 30% and frequency deviations beyond 2 Hz, triggering significant inrush currents.

The challenges are further compounded in AC/DC hybrid microgrids. Traditional bidirectional droop control, which links AC frequency (f) to DC voltage (Udc) regulation, lacks dynamic priority assignment. Under fault conditions and power fluctuations, this deficiency can lead to a cascading deterioration of system parameters. Studies indicate that to maintain stability under such conditions, the voltage fluctuation amplitude must often be reduced by up to 40% [5-7].

2.3 Reconnection synchronization accuracy speed contradiction

Safely reconnecting a microgrid to the main grid requires the elimination of phase differences between them. Traditional Phase-Locked Loop (PLL) technologies struggle to balance performance under adverse grid conditions. When grid voltage harmonic distortion (THD) exceeds 5%, PLLs can exhibit a dynamic response time longer than 100 ms and a phase tracking error greater than 5°, making accurate and fast synchronization challenging [8].

This is problematic given that international standards impose strict conditions for safety reclosing, typically requiring a phase difference of less than 5° and a frequency difference within 0.1 Hz [9]. With traditional synchronization technology, the process often exceeds 200 ms and generates impact currents as high as 20% to 30% of the rated value. These limitations make it difficult to meet the requirements for rapid power recovery [10].

2.4 Collaborative control communication real-time limitations

The collaborative operation of multiple internal equipment—such as power sources, storage units, and load controllers—during a microgrid switching process relies on low-latency communication. Traditional Ethernet, with its non-deterministic transmission delay (typically ranging from 10 ms to 100 ms [11]), cannot meet the stringent requirements for microsecond-level instruction synchronization that is critical for precise power quality (PQ) and voltage/frequency (V/f) control during mode switching [12].

High communication delays can cause key instructions—such as those for adjusting droop coefficients, activating power compensation, and triggering circuit breaker actions—to arrive out of synchronization. This desynchronization significantly increases the risk of transient events and instability during the switching process.

3 Intelligent collaborative control technologies

3.1 Data-driven control

Big data and artificial intelligence (AI) are reshaping microgrid switching paradigms through data-driven control technologies. The core advantage of this approach is its ability to achieve optimization in complex systems without relying on a precise mathematical model.

3.1.1 Adaptive bidirectional control

Bian et al [13]. proposed a machine learning-based framework for optimizing the timing of islanding detection. This framework utilizes a prediction model trained on historical data and dynamic programming to determine the optimal timing for active detection methods.

The optimization goals of this framework are to minimize the number of detections while maximizing the time coverage of accurate monitoring. A custom loss function is designed to guide the model's iteration towards these objectives. The process flow is illustrated in Figure 1.

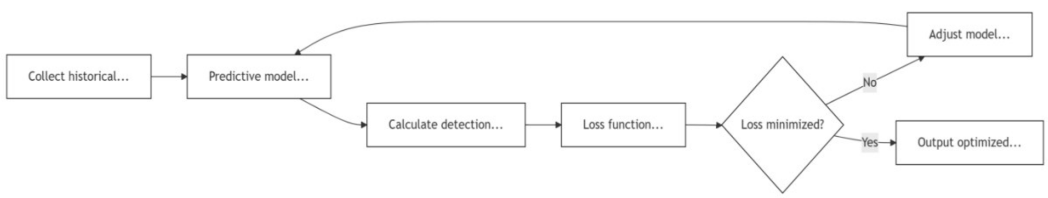

Figure 1 Process flow diagram

In practical applications, the proposed framework achieved a 45% reduction in the number of active detections compared to traditional methods while maintaining the same detection coverage. This leads to a significant reduction in computational resource consumption.

3.1.2 Full-dimensional state assessment

Sahani et al [14]. developed a hybrid framework that integrates the Holomorphic Embedding Power Flow Method (HEPFM) with an Extreme Learning Machine (ELM) to achieve real-time assessment of microgrids across all operational regimes. In this framework, the HEPFM provides high-precision power flow calculations, while the ELM rapidly generates contingency strategies. Their collaboration breaks the computational bottlenecks inherent in traditional methods.

This integrated solution supports operational assessment under three key scenarios: black-start, baseline operation, and generation interruption. It performs voltage and active power sensitivity analysis, vulnerability assessment, and can generate corrective strategies—including storage scheduling and load shedding—within milliseconds.

The framework was validated on a floating green microgrid. Test results demonstrated a dramatic reduction in emergency analysis time, from several minutes (using conventional approaches) to 800 milliseconds. This capability significantly improves the system's survivability during critical events.

3.2 Multi-agent collaborative decision-making

The Multi-Agent System (MAS) employs a distributed architecture to achieve equipment-level autonomy and system-level collaboration, effectively mitigating the single-point failure risk inherent in centralized control schemes.

A typical application of hierarchical agent collaboration in microgrid switching scenarios is demonstrated in the Schneider Electric Wuhan factory's Power Supply and Distribution Framework (PSDF) project. In this project, MAS coordinates photovoltaic (PV) units, storage systems, and flexible loads. Specifically, the PV agent is tasked with maximizing generation self-consumption; the storage agent dynamically adjusts charge and discharge thresholds; and the load agent manages priority-based classification and shedding.

This MAS architecture enabled the factory's distribution network to maintain power to critical loads for 4 hours during grid faults and achieved an annual carbon reduction of 577 tons.

It is noteworthy that implementing an MAS requires a unified communication protocol and information model. In this context, OPC UA over TSN has emerged as the mainstream solution to meet these requirements.

3.3 Deep reinforcement learning

3.3.1 Virtual storage mechanism

Traditional physical storage faces challenges of high cost and space limitations, making it difficult to deploy widely. Utilizing water systems as an energy form conversion medium provides an innovative capability for indirect energy storage. In this approach, surplus photovoltaic (PV) generation is used to start seawater desalination pumps, effectively converting and 'charging' electrical energy into water potential energy. During peak electricity demand periods, adjusting the pump power reduces grid load, achieving a 'discharge' of the stored energy.

A Deep Reinforcement Learning (DRL) agent was developed to optimize system operation through minute-level scheduling, with reward functions designed for profit, sustainability, and reliability.

The results show a significant performance improvement: renewable energy utilization increased from 26.7% to 40.1%, the proportion of diesel consumption was reduced by 9.3%, and a comprehensive performance score rose by 7.04%.

Notably, during training, the DRL agent spontaneously learned a 'time-mismatch' strategy. Unlike traditional heuristic methods that blindly pursue immediate renewable utilization—often leading to depleted batteries by the morning—the DRL agent learned to actively reserve 60% of the battery capacity in anticipation of the afternoon period, which combines both high PV generation and high demand. This strategic foresight significantly enhances the system's resilience and efficiency.

3.3.2 Switching process optimization

Microgrid switching control based on Deep Reinforcement Learning (DRL) enables the acquisition of highly adaptive switching strategies. The core mechanism defines the state space through key real-time operational parameters such as voltage, frequency deviation, load rate, state of charge (SOC) of storage, and renewable energy output. The action space comprises executable controller decisions, including droop coefficient adjustment, power command issuance, mode switching, and timing selection. The reward function is designed to optimize switching performance, incorporating the integral of voltage deviation, switching time, and current amplitude impact. Simulations demonstrate that the DRL-trained controller significantly outperforms traditional controllers under random fault scenarios—maintaining stable system transition even amid drastic fluctuations in photovoltaic output.

3.4 Blockchain enabled trust mechanism

The significant increase in distributed energy participation across different operators has made trust issues a key bottleneck in multi-microgrid collaborative grid-connected and islanded switching. To address this core challenge, blockchain technology is introduced, aiming to build a decentralized trust foundation through distributed ledger and smart contract mechanisms. The core mechanisms involve on-chain storage of key switch states and control commands, ensuring transparency and non-tampering of the operation process. Smart contracts automatically and reliably execute predefined collaborative switching protocols, eliminating the risks of human intervention and trust concerns. Token incentive mechanisms are designed to reward units that provide auxiliary services during the collaborative switching process, promoting active participation.

Experimental projects verify that the decentralized trust mechanism significantly improves collaborative efficiency: the collaborative switching delay time is reduced from the original 30 seconds to 5 seconds, and trust-related deficiencies and disputes are reduced by 90%. However, the current throughput limitations of blockchain technology (<1000 TPS) hinder the large-scale application of this mechanism in complex microgrid clusters, representing a major technical barrier.

4 System architecture innovation application practices

4.1 DC microgrid architecture

Compared to AC systems, DC microgrids omit the AC/DC conversion switching process and exhibit significant performance advantages, as summarized in Table 1. The reliability of DC networking is verified in the "Dingheng 19" chemical tanker project, implemented by Danfoss Drives. (Un: nominal voltage; In: rated current)

Table 1 Comparison of switching performance between dc and ac microgrids

Performance Indicator	DC Microgrid	AC Microgrid	Improvement
Switching Time	20-50ms	80-150ms	above 60%
Voltage Fluctuation	±5% Un	±10% Un	halved
Impact Current	<1.2 In	1.5-2.0 In	40% reduce
Control Complexity	Low (single voltage variable)	High (frequency/phase/voltage)	60% simplified
Renewable Compatibility	High (naturally matches DC sources)	Medium (requires inversion)	Significant improvement

Maintaining bus voltage stability is the core objective of DC microgrid switching control. To achieve this goal, key implementation points from Chen Qinze's power compensation and droop coefficient attenuation strategy must be effectively integrated in engineering practice. These points include: configuring supercapacitor groups to provide rapid power support and buffer transient power gaps during switching; adopting Solid-State Circuit Breakers (SSCB) technology to achieve microsecond-level ultra-fast breaking and efficient fault isolation, thereby ensuring system safety; and performing real-time monitoring and analysis based on the rate of change of bus voltage (RoCoV) to accurately predict system operational status and provide advance information for control decisions.

The world's first DC grid-powered intelligent chemical tanker, "Dingheng 19", has adopted an advanced propulsion solution from Danfoss Drives that effectively incorporates these engineering concepts. Actual operational data verify its excellent performance: during switching processes, voltage and power disturbances are controlled within 5%, and the high efficiency of the DC architecture reduces overall energy consumption by 15% compared to traditional AC systems. The successful implementation of this project provides valuable engineering demonstration and experience accumulation for applying DC microgrid technology in demanding maritime and industrial power scenarios.

4.2 PSDF system

PV-Storage-DC-Flexibility (PSDF) systems, which build internal DC distribution networks within buildings, efficiently integrate photovoltaic generation, storage devices, DC loads, and adjustable resources. They have emerged as a core technological pathway for achieving zero-carbon building targets. The Schneider Electric Wuhan base demonstration project has successfully implemented this approach, with a system architecture that encompasses several key components. The energy source consists of 300 kW rooftop photovoltaics, while energy storage and regulation are handled by a 1 MWh lithium-flow battery hybrid storage system. A 750 V DC bus serves as the backbone for energy transmission, supporting diversified loads including 120 kW charging stations, LED lighting, and variable-frequency air conditioning. The system integrates flexible load resources accounting for 30% of the total load.

The demonstration project exhibits significant innovation in flexible grid-connected/islanded switching. It establishes a hierarchical control system comprising local, regional, and central layers: local control achieves μs-level rapid response; regional coordination completes ms-level decision optimization; and central optimization performs min-level global scheduling. The system implements a load-shedding strategy based on priority classification, distinguishing between uninterruptible (PO level), short-time delay interruptible (P1 level), and interruptible (P2 level) loads. It also incorporates innovative coordination strategies such as photovoltaic generation curtailment and adjusted storage discharge commands to ensure stability during mode transitions.

These innovative designs enable the efficient operation of the project, which successfully achieves a 100% green power supply for charging facilities and reduces annual carbon dioxide emissions by 577 tons. Recognized as one of the "Top Ten PSDF Engineering Practice Cases" in the industry, the project fully demonstrates the important value of PSDF systems in promoting building energy transition and supporting carbon neutrality goals.

4.3 Marine DC microgrid

The stringent operational conditions in marine environments impose particularly high requirements on the safety and reliability of electrical systems, with standards far exceeding those for land-based applications. Danfoss Drives possesses mature shipboard DC power distribution technology and has proposed a "Landing Plan" to extend this technological system to terrestrial scenarios. Its core advantages include high-reliability design, certified by the DNV-GL classification society, which ensures continuous operation under extreme conditions; a compact structure achieving a power density of 48 kW/m^3, 2.1 times that of traditional AC systems; and intelligent fault-tolerant control with redundant busbar architecture that maintains 90% of power output even in case of a single-point failure.

To support the migration of this technology, the Danfoss Suzhou Application Development Center has established a ship DC microgrid laboratory. Key research focuses on solving challenges such as salt-fog environments through composite insulation coating protection (salt spray test >1000 hours), anti-vibration and impact mechanical structures simulating Level 9 sea conditions, and multi-thruster power coordination algorithms with dynamic response times <50 ms. By 2025, the Danfoss Haiyan Phase II project will implement the "Landing Plan" as a land-based demonstration, adopting the same intelligent DC microgrid solution. Drawing on empirical results from marine applications, the DC system reduces AC/DC conversion losses by 12–18%. Combined with photovoltaic and storage optimization scheduling, a 20% improvement in energy efficiency is anticipated. The solid-state circuit breakers enable fault isolation within 5 μs, and the intelligent fault-tolerant design suppresses voltage fluctuations within ±5%, improving system stability by 35–40% compared to traditional systems. These data are consistent with the actual 38.7% stability improvement observed in Schneider Wuhan's PSDF project, corroborating the industry case performance.

5 Conclusion

This review has systematically examined the advancements in flexible grid-connected/islanded switching technologies for microgrids under main grid faults, highlighting both traditional control strategies and intelligent collaborative methods. While conventional approaches—such as improved droop control, phase pre-synchronization, and optimized communication protocols—have contributed significantly to switching performance, the integration of data-driven, multi-agent, and deep reinforcement learning technologies has led to substantial improvements in adaptability, speed, and reliability. Key findings confirm the superior performance of DC microgrid architectures in terms of switching speed, voltage stability, and compatibility with renewable sources, establishing them as ideal solutions for applications in high-end manufacturing, green buildings, and marine power systems. Furthermore, PSDF (PV-Storage-DC-Flexibility) systems have proven to be effective frameworks for integrating distributed energy resources, with real-world demonstrations validating their capability to achieve seamless source-grid-load-storage coordination. Innovations in deep reinforcement learning also offer promising paradigms for multi-energy coordination, particularly in resource-limited settings.

Despite these advancements, several challenges remain. Future research should prioritize enhancing multi-source data fusion techniques, improving adaptability to complex and concurrent faults, and addressing stability issues in hybrid AC/DC systems. Emerging fields such as digital twins, quantum computing applications in grid optimization, and cross-domain collaborative control represent critical frontier directions. As global "dual-carbon" goals continue to evolve, further innovation in flexible switching technologies will be essential to constructing resilient, efficient, and sustainable power systems, ultimately supporting the transition toward a cleaner and more reliable energy future.

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