International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 03 March-2026 | Impact Factor: 3.5

Microgrid: Challenges and Progress in Recent Years

A Comprehensive Review on Architecture, Control, Communication, and Future Directions

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How to Cite this Article:

Raut, P., Somankar, K., Thakur, K., Choudhari, K. & Tayde, K. (2026). Microgrid: Challenges and Progress in Recent Years. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(03). https://doi.org/10.55041/ijcope.v2i3.254

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Abstract

The global push toward decarbonized and resilient power systems has revived deep interest in microgrids (MGs) — localized grids that can operate either connected to the main utility or in autonomous islanded mode. This paper reviews the challenges and significant progress in microgrid technology over the past several years, focusing on architectures, power converter topologies, control and energy management strategies, communication technologies, and protection schemes. Drawing from peer-reviewed literature published between 2019 and 2024, this review identifies persistent gaps such as stability under high renewable penetration, cybersecurity vulnerabilities, and the need for standardized protection frameworks, while also documenting the rapid advances driven by artificial intelligence, IoT integration, and smart grid convergence. The paper is intended as a reference for researchers, engineers, and students working in the field of distributed energy systems.

Keywords: Microgrid, Renewable Energy Integration, Distributed Energy Resources, Power Converter, Droop Control, IoT, Energy Management System, Smart Grid, Islanded Operation

1. Introduction

The electricity grid as conceived in the twentieth century was designed around large, centralized power plants dispatching power unidirectionally to passive consumers. That model is under increasing strain. The rapid growth of distributed renewable energy sources (RES) — solar photovoltaic (PV), wind turbines, small-scale hydro — has fundamentally altered the generation landscape. Consumers are no longer purely passive; many now generate power locally, store it in batteries, and feed surplus back to the grid. This bidirectional flow creates new complexity in voltage regulation, frequency control, and protection coordination.

Microgrids offer a compelling architectural response to this complexity. A microgrid is a cluster of distributed energy resources (DERs), storage systems, and loads, all operating within a well-defined electrical boundary and controlled by a dedicated energy management system. Its defining capability is the ability to switch between two modes of operation: grid-connected mode, in which it exchanges power with the main utility, and islanded mode, in which it operates autonomously following a planned or unplanned disconnection from the grid.

Despite decades of research and numerous demonstration projects, microgrid technology still faces formidable challenges. Stability during mode transitions, cost-effective communication architectures, intelligent protection under variable fault currents, and the integration of intermittent RES with limited storage — all remain active research problems. At the same time, the pace of progress has accelerated considerably since 2019, driven by advances in power electronics, machine learning, and low-cost wireless communication.

This paper is organized as follows. Section 2 defines the problem context. Section 3 surveys recent literature. Sections 4 through 7 examine architectures, power converters, control strategies, and communication technologies respectively. Section 8 discusses ongoing challenges. Section 9 outlines future research directions, and Section 10 concludes.

2. Problem Statement

Despite their promise, microgrids face a set of persistent and interrelated challenges that have slowed widespread commercial deployment:

- Stability and Reliability: Microgrids, especially inverter-dominated systems, exhibit low inertia. This makes frequency and voltage vulnerable to rapid fluctuations when generation or load changes suddenly. Traditional synchronous machine-based stabilization mechanisms are absent or reduced.
- Protection Coordination: Conventional overcurrent protection was designed for unidirectional fault currents from a single grid source. In microgrids with multiple DER injection points, fault current magnitudes and directions change depending on the operating mode, rendering fixed-setting relays ineffective.
- Intermittency of Renewables: Solar and wind generation are inherently variable. Without adequate storage or demand-side flexibility, a microgrid dependent on these sources will experience generation shortfalls or surpluses, both of which threaten stable operation.
- Energy Management Complexity: Optimally scheduling generation, storage charge/discharge, and controllable loads in real time — while satisfying economic, environmental, and reliability constraints — is a computationally intensive problem, particularly under uncertainty.
- Communication Security: As microgrids rely on digital communication infrastructure for monitoring and control, they become targets for cyberattacks. Breaches can lead to incorrect control decisions, outages, or equipment damage.
- Standardization and Regulation: The absence of globally accepted standards for microgrid protection, control interfaces, and market participation creates barriers to investment and interoperability.
- Cost of Implementation: While component costs have fallen, the engineering cost of system integration, commissioning, and ongoing operation remains high, particularly for smaller or rural deployments.

3. Literature Survey

A substantial body of literature has emerged over the past five years addressing the challenges identified above. The table below summarizes key contributions that form the foundation of this review:

Research / Reference	Authors / Year	Key Contribution
Stability and control of microgrid architectures	Ahmed et al. (2020)	Comprehensive review of stability challenges and control architectures in both AC and hybrid AC/DC microgrids; identified feeder parameter sensitivity as a critical factor.
AI applications in microgrid EMS	Tajjour & Chandel (2023)	Surveyed artificial intelligence applications for energy management in solar microgrids; highlighted ANN and fuzzy logic as leading approaches.
Protection of microgrids with DERs	Alasali et al. (2023)	Reviewed intelligent protection approaches using directional overcurrent relays and adaptive relay coordination; proposed dual-setting schemes.
DC microgrid voltage control	Al-Ismail (2024)	Critical review of voltage balancing and power management strategies for DC microgrids, particularly bipolar bus topologies.
Hybrid AC/DC MG optimization	Hernandez-Mayoral et al. (2023)	Power quality issues and optimization strategies in hybrid microgrids; evaluated PSO, GA, and MPC-based controllers.
Stochastic energy management	Azarhooshang et al. (2021)	Two-stage stochastic day-ahead and real-time scheduling for microgrids with high renewable penetration and EVs; demonstrated 77$ cost reduction with collective storage.
Communication in smart microgrids	Reddy et al. (2022)	Broad survey of wired and wireless communication technologies for interoperable smart microgrids; compared PLC, ZigBee, Wi-Fi, LoRa, and NB-IoT.
IoT-based MG monitoring	Petrov et al. (2021)	Low-cost NB-IoT power quality monitoring system for microgrid deployments; demonstrated viability for resource-constrained rural installations.
Model predictive control for MGs	Shahzad et al. (2022)	Concise revisit of MPC strategies; identified nonlinear system behavior as the principal limitation of linear MPC formulations.
Autonomous microgrid planning	Naderi et al. (2024)	Techno-economic planning framework for fully renewable autonomous MGs with both single and hybrid energy storage; evaluated lifecycle costs.

Across these studies, several convergent themes are visible. First, the shift toward inverter-dominated microgrids has made control design more complex but also more flexible. Second, AI and machine learning — particularly reinforcement learning and neural networks — are emerging as the dominant approaches for energy management under uncertainty. Third, communication infrastructure is no longer a secondary concern; it is integral to both normal operation and cybersecurity. Finally, the protection challenge remains largely unsolved for microgrids that switch frequently between grid-connected and islanded modes.

4. Microgrid Architectures

4.1 DC Microgrids

DC microgrids have attracted growing interest because they eliminate the need for reactive power compensation and are naturally suited for DC sources (PV panels, fuel cells, batteries) and loads (LED lighting, EV chargers, data centers). Two bus configurations are common. The unipolar bus uses a single positive rail referenced to ground — simpler and lower cost. The bipolar bus adds a negative rail, providing a neutral point and allowing both higher-voltage transmission and lower-voltage distribution from the same infrastructure, significantly improving reliability and power capacity.

The primary technical challenge in DC microgrids is voltage regulation under variable loading and generation. Without the inherent frequency cue that AC systems provide, all coordination must be achieved through voltage droop and communication-based secondary control. Voltage imbalance in bipolar systems — where the positive and negative bus voltages drift away from symmetry — requires dedicated voltage-balancing converters or NPC-based topologies with built-in balancing capability.

4.2 AC Microgrids

AC microgrids mirror the structure of conventional distribution networks and are therefore the most common architecture for upgrading existing infrastructure. Voltage source inverters (VSIs) interface DERs to the AC bus and must collectively maintain frequency and voltage. In grid-connected mode, the main grid acts as an infinite bus, providing a stable frequency reference. In islanded mode, the VSIs themselves must establish and maintain the voltage and frequency reference — a fundamentally more demanding task.

Inverter-based AC microgrids are characterized by low inertia, since power electronics have no rotating mass to resist frequency deviations. This has motivated research into virtual inertia techniques, in which inverter controllers emulate the swing equation of a synchronous generator, providing a synthetic inertia response to frequency disturbances.

4.3 Hybrid AC/DC Microgrids

Hybrid microgrids contain both AC and DC buses, linked by interlinking converters (ILCs). This architecture is increasingly preferred because it accommodates the natural mix of AC sources (wind, diesel generators) and DC sources (PV, battery energy storage) without forcing unnecessary conversion stages. The ILC manages bidirectional power flow between the two buses and plays a critical role in stability: its control strategy must simultaneously support voltage and frequency on both buses while responding to disturbances on either side.

Case studies of hybrid shipboard microgrids demonstrate how this architecture eliminates dedicated rectifier stages for propulsion loads, improving overall efficiency. However, the control design is significantly more complex than for pure AC or DC systems, and feeder impedance parameters have been shown to have a disproportionate effect on dynamic performance.

5. Power Converter Topologies and Recent Progress

The power converter is the central enabling technology of a microgrid. It interfaces energy sources, storage devices, and loads to the common bus, and its control law largely determines system behavior. Recent years have seen significant progress across several converter categories.

5.1 Bidirectional DC-DC Converters

Bidirectional converters allow energy to flow in both directions between battery storage and the DC bus, enabling both charging and discharging within a single hardware unit. Three-leg interleaved designs distribute current across multiple inductors, reducing ripple and improving thermal performance. A persistent challenge is the response delay introduced when switching between charging and discharging modes — the inductor current must reverse, which introduces a dead-time during which bus voltage can deviate. Advanced multi-mode control strategies address this by pre-conditioning the current reference before the mode transition is commanded.

5.2 Voltage Source Inverters (VSI)

The VSI remains the dominant interface for connecting DERs to AC microgrids. Modern VSI designs incorporate LC output filters to attenuate switching harmonics and employ cascaded control loops — an inner current control loop for rapid response and an outer voltage/power control loop for steady-state accuracy. Grid-forming VSIs, capable of establishing the AC voltage waveform from scratch in islanded mode, have become a major research focus since around 2020. Unlike grid-following VSIs that require an existing grid reference, grid-forming controllers use virtual oscillator control or virtual synchronous machine (VSM) techniques to synthesize a stable voltage source.

5.3 Emerging Topologies

Several newer topologies have demonstrated advantages for specific microgrid applications. Switched-inductor boost inverters (SL-SBI) achieve higher voltage gain than conventional Z-source inverters in a more compact form, though they exhibit lower boost factors relative to the shoot-through duty cycle. Interleaved multi-input DC-DC converters allow PV arrays and battery banks to share a single conversion stage with multiple operating modes, significantly reducing component count and cost. Modular multilevel converters (MMC) are entering microgrid applications at medium-voltage levels, offering scalability and superior harmonic performance.

6. Control Strategies: Progress and Remaining Challenges

6.1 Primary Control — Droop-Based Methods

Droop control remains the most widely deployed primary control strategy for parallel-operated DERs. It achieves decentralized power sharing without explicit communication by creating a deliberate coupling between output power and frequency (P-f droop) or reactive power and voltage (Q-V droop). Recent improvements include virtual impedance techniques that compensate for line impedance mismatch between DERs, angle droop variants that reduce steady-state frequency deviation, and adaptive droop coefficients that adjust in real time based on DER state-of-charge or loading level.

Despite these advances, droop control inherently sacrifices steady-state accuracy for decentralization. It also performs poorly when feeder impedances are predominantly resistive — as is common in low-voltage distribution networks — because the P-f and Q-V coupling assumptions break down.

6.2 Secondary and Tertiary Control — Hierarchical Architecture

The standard hierarchical control architecture assigns distinct objectives to three levels. Primary control (fastest) handles immediate voltage/frequency stabilization via droop. Secondary control (slower) restores nominal frequency and voltage after primary control has introduced deviations. Tertiary control (slowest) optimizes power flow between the microgrid and the main grid for economic or environmental objectives. In fully autonomous microgrids, tertiary control manages DER dispatch scheduling based on forecast data.

Recent research has challenged the strict separation of these layers, arguing that faster communication networks enable tighter integration. Distributed secondary control schemes — in which each DER communicates only with its nearest neighbors in a sparse graph — have been demonstrated to achieve the same restoration objectives as centralized secondary control without a single point of failure.

6.3 AI and Data-Driven Control

Artificial intelligence has moved from a peripheral research interest to a central pillar of advanced microgrid control over the past five years. Model predictive control (MPC), which solves a finite-horizon optimization problem at each control step, has been widely adopted for energy management. However, MPC's reliance on accurate system models makes it vulnerable to model mismatch in highly nonlinear or uncertain operating conditions.

Reinforcement learning (RL) addresses this limitation by learning control policies directly from interaction with the microgrid environment, without requiring an explicit model. Deep RL agents have been demonstrated for voltage regulation, demand response, and multi-microgrid coordination. Adaptive neuro-fuzzy inference systems (ANFIS) combine the interpretability of fuzzy rules with the learning capability of neural networks and have been applied to droop parameter tuning and islanding detection. Multi-agent systems (MAS) distribute the intelligence across DER controllers, improving scalability and fault tolerance.

6.4 Energy Management Systems (EMS)

The EMS integrates forecasting, optimization, and dispatch into a unified decision framework. Classical approaches — linear programming (LP), mixed-integer programming (MIP), and dynamic programming (DP) — provide optimal solutions but scale poorly with system size and struggle with uncertainty. Stochastic programming explicitly models the probability distribution of uncertain inputs (solar irradiance, wind speed, load demand) and has been shown to reduce operational cost and unmet demand compared to deterministic approaches. Meta-heuristic methods such as genetic algorithms (GA) and particle swarm optimization (PSO) offer flexible multi-objective optimization but require careful parameter tuning to avoid premature convergence.

7. Communication Technologies

Reliable, low-latency communication is the nervous system of a smart microgrid. Unlike the power flow — governed by physics — the information flow can be engineered with significant freedom. The choice of communication technology involves trade-offs among range, data rate, latency, power consumption, and cost.

Technology	Standard	Range	Data Rate	Typical MG Use
ZigBee	IEEE 802.15.4 / 2.4 GHz	10–100 m	250 kbps	Sensor mesh, AMI
Wi-Fi	IEEE 802.11 / 2.4–5 GHz	50–150 m	Up to 1 Gbps	Local SCADA, dashboard
WiMAX	IEEE 802.16	Up to 50 km	Up to 70 Mbps	Wide-area MG clusters
LoRa	LoRa Alliance / Unlicensed	2–15 km	0.3–50 kbps	Remote monitoring, LPWAN
NB-IoT	3GPP / LTE bands	Up to 10 km	~200 kbps	Smart meters, rural MGs
PLC	IEEE 1901	Along power line	Up to 200 Mbps	Utility AMI, metering

Technology	Standard	Range	Data Rate	Typical MG Use
5G MEC	3GPP Release 15+	Cell coverage	Up to 20 Gbps	Latency-critical control

Security is an increasingly critical dimension of microgrid communication. Lightweight authenticated communication (LAC) protocols have been proposed specifically for smart meter to gateway data exchange, providing confidentiality and replay-attack resistance at low computational cost. The convergence of operational technology (OT) networks with information technology (IT) infrastructure introduces new attack surfaces, and recent surveys have documented successful demonstrations of false data injection attacks against droop-controlled microgrids.

8. Ongoing Challenges

8.1 Stability Under High Renewable Penetration

As the share of inverter-based DERs increases, the effective inertia of the microgrid decreases. Rate-of-change-of-frequency (RoCoF) and nadir depth during load steps or islanding events worsen accordingly. While virtual inertia and grid-forming inverters partially compensate, the interaction dynamics between multiple grid-forming inverters — particularly through the droop control coupling via the power network (IDCPN) — remain incompletely understood and are a source of low-frequency instability modes not present in synchronous machine-based systems.

8.2 Black-Start and Islanding Transitions

The ability to restore power to an islanded microgrid following a complete shutdown — a black-start — requires one or more DERs to independently energize the network and allow other sources to synchronize against them. Designing control sequences that reliably sequence this process, coordinate DER output limits, and handle inrush currents remains an active research challenge. Equally demanding is the seamless transition: switching from grid-connected to islanded mode without interrupting load supply requires pre-synchronization and careful transient management that most existing systems do not achieve reliably.

8.3 Protection

Protection systems must detect and isolate faults within milliseconds, yet the fault current contributed by inverter-based DERs is typically limited to 1.2–2 times rated current — far less than the 10–20 times seen from synchronous generators. This makes conventional overcurrent relays ineffective. Adaptive protection schemes that update relay settings in real time based on network topology and operating mode have been demonstrated in research settings, but hardware implementations that can execute these updates within relay operating times are not yet widely commercially available.

8.4 Cybersecurity

The integration of digital communication and IoT devices into microgrid control creates a substantial cybersecurity attack surface. False data injection attacks can corrupt sensor measurements and mislead energy management decisions. Command injection attacks can cause inverters to deviate from their set points, potentially destabilizing the microgrid. Defending against these threats while preserving the low latency required for real-time control is a major open problem. Blockchain-based data integrity verification and anomaly-detection-based intrusion detection systems have been proposed but are not yet mature for production deployment.

8.5 Standardization

Despite numerous standards documents from bodies including IEEE (P2030 series), IEC (61850, 61968), and ISO, a cohesive and universally adopted framework for microgrid control interfaces, protection coordination, and market participation rules does not exist. Different regions have adopted different subsets of these standards, creating interoperability barriers when equipment from different vendors or different national markets must work together.

9. Future Scope

The trajectory of microgrid research and development points toward several high-impact directions:

- Widespread adoption of grid-forming inverters: As renewable penetration approaches 100% in some microgrids, grid-forming control will transition from a research curiosity to a necessity. Standardizing grid-forming requirements and testing procedures is an immediate priority.
- AI-native energy management: Reinforcement learning agents trained on digital twins of microgrid models are likely to replace rule-based EMS in high-complexity scenarios. Explainability and safety certification of these agents remain open challenges.
- Peer-to-peer (P2P) energy trading: Blockchain-enabled platforms that allow prosumers within a microgrid cluster to trade energy without a central clearing house could transform the economics of community energy systems.
- Integration with electric vehicle fleets: Vehicle-to-grid (V2G) technology enables EV batteries to act as distributed storage. Smart microgrid controllers that incorporate stochastic EV availability into real-time dispatch are an active research area.
- Quantum-resistant security protocols: As quantum computing matures, existing public-key cryptographic protocols used in microgrid communication will become vulnerable. Developing and standardizing post-quantum alternatives is a long-term but urgent task.
- Multi-microgrid coordination: Regional clusters of microgrids — each autonomous but able to exchange power — can provide mutual support during extreme events. Optimal coupling strategies and real-time coordination algorithms for these systems are still in early development.
- Predictive maintenance and digital twins: High-fidelity real-time simulation models (digital twins) synchronized with physical microgrid measurements can enable predictive maintenance, operator training, and contingency analysis without disrupting the live system.

10. Conclusion

Microgrids have evolved from a niche concept to a practical and increasingly indispensable component of the modern energy landscape. Over the past five years, significant technical progress has been made in power converter design, control theory, communication infrastructure, and energy management optimization. Grid-forming inverters, AI-driven EMS, and low-cost IoT communication have all moved meaningfully closer to production readiness.

At the same time, the challenges reviewed in this paper — stability under low-inertia conditions, adaptive protection coordination, cybersecurity, and the absence of unified standards — remain genuine barriers to the scale of deployment that the energy transition demands. Addressing them will require coordinated effort across hardware development, control theory, software engineering, regulatory policy, and international standards bodies.

The literature reviewed here, spanning architectures, converter topologies, control hierarchies, and communication technologies, makes clear that microgrid technology is not a single discipline but an intersection of many. Progress will continue to accelerate as these disciplines converge — and as the urgency of providing clean, reliable, and resilient electricity to the world's population makes microgrid deployment a global priority.

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