Advances in Power Systems Research

https://apsr.cultechpub.com/apsr

Cultech Publishing

Review

Resilient Microgrid Design for Disaster-Prone Regions: A Technical Review

Ahmad Ali*

Department of Computer Science, Abdul Wali Khan University, Mardan, Khyber Pakhtunkhwa, Pakistan

*Corresponding author: Ahmad Ali, a70685359@gmail.com

Abstract

Increasing frequency and intensity of natural disasters pose substantial risks to conventional centralized power systems, leading to prolonged outages, cascading failures, and severe socio-economic consequences. Resilient microgrids have emerged as a strategic infrastructure solution capable of enhancing energy security and operational continuity in disaster-prone regions. This review provides a comprehensive technical synthesis of resilient microgrid design principles, focusing on architectural configurations, distributed energy resource integration, advanced control methodologies, adaptive protection systems, resilience assessment frameworks, and optimization strategies. The study differentiates resilience from traditional reliability metrics and discusses quantitative approaches for evaluating performance degradation and recovery trajectories under extreme events. Alternating current, direct current and hybrid microgrid architectures are critically analyzed in the context of survivability, modularity, and fault tolerance. Advanced control techniques including grid-forming inverters, robust control, model predictive control, and AI-driven energy management systems are examined for their role in maintaining stability during islanded operation. Protection challenges in inverter-dominated systems are reviewed, highlighting adaptive relaying, solid-state breakers, and self-healing mechanisms. Probabilistic risk assessment and multi-objective optimization frameworks are presented for cost–resilience trade-off analysis. Real-world case studies from hurricane-, earthquake-, wildfire-, and flood-prone regions provide practical insights into deployment strategies and performance outcomes. Finally, emerging technologies such as digital twins, edge computing, and hydrogen-based storage are discussed alongside existing research gaps. Finally, emerging technologies such as digital twins, edge computing, and hydrogen-based storage are discussed alongside existing research gaps. The review highlights that the essence of resilient microgrids represents a paradigm shift from traditional fault-prevention approaches toward adaptive disturbance management and rapid recovery capabilities. Future resilient microgrid design will increasingly depend on ensuring stability in low-inertia inverter-dominated systems while enabling coordinated operation of distributed resources under extreme uncertainty conditions.

Keywords

Resilient microgrids, Survivability analysis, Extreme event modelling, Adaptive protection, Energy storage systems

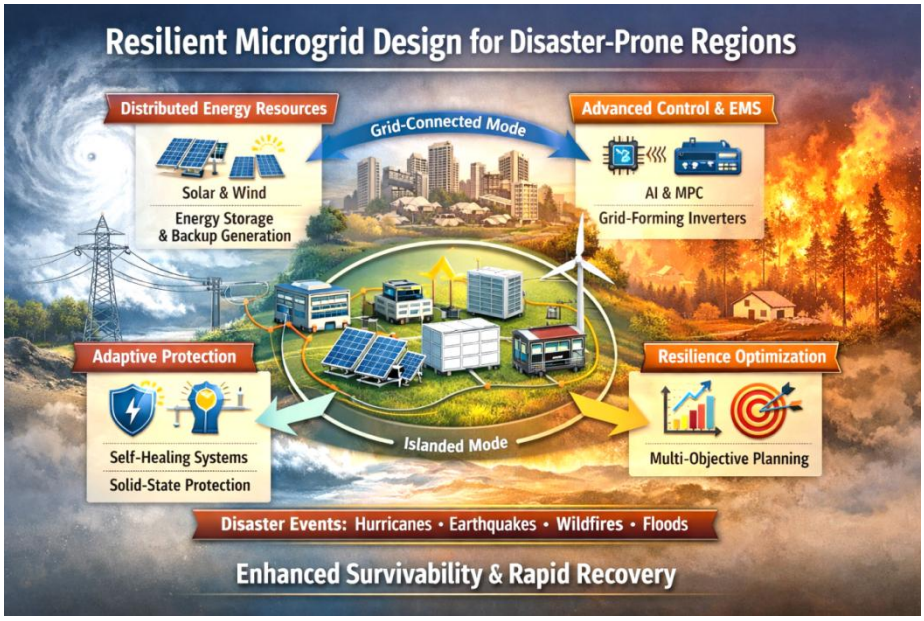
Article History

Received: 20 February 2026
Revised: 11 March 2026
Accepted: 19 May 2026
Available Online: 25 May 2026

Copyright

© 2026 by the authors. This article is published by the Cultech Publishing Sdn. Bhd. under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0): https://creativecommons.org/licenses/by/4.0

Graphical Abstract



1. Introduction

1.1 Background and Motivation

Power systems worldwide are undergoing a paradigm shift driven by decarbonization policies, technological advancement, electrification of critical sectors, and increasing exposure to extreme climate events [1]. Traditional centralized power grids, designed primarily for reliability under predictable disturbances, are increasingly vulnerable to high-impact, low-probability disasters such as hurricanes, earthquakes, floods, wildfires, and cyber-physical attacks. These events expose structural weaknesses in centralized infrastructure, leading to prolonged outages, cascading failures, and significant socio-economic losses. Microgrids have emerged as a technically viable and economically attractive solution to enhance energy resilience, particularly in disaster-prone regions. A microgrid is a localized cluster of loads and distributed energy resources (DERs) capable of operating in grid-connected or islanded modes. The ability to isolate from the main grid during disturbances and continue supplying critical loads makes microgrids uniquely suited for resilience enhancement [2].

The increasing frequency and severity of natural disasters have intensified the urgency of resilient microgrid design. Climate change projections indicate growing exposure of coastal, seismic, and wildfire-prone regions to infrastructure disruption. Hospitals, military installations, data centers, emergency shelters, and water treatment facilities require uninterrupted power supply even during catastrophic events [3]. Traditional backup systems such as diesel generators are insufficient due to fuel logistics constraints, single-point failure risks, and environmental concerns. Resilient microgrids integrate renewable generation, energy storage, advanced control systems, and adaptive protection to ensure survivability, rapid recovery, and sustained operation under extreme conditions. From an engineering perspective, resilience extends beyond simple redundancy. It involves structural hardening, intelligent operational strategies, rapid fault isolation, autonomous control, and adaptive reconfiguration [4]. The integration of inverter-based resources introduces new dynamic characteristics that demand revised stability and protection paradigms. Therefore, resilient microgrid design is a multidisciplinary problem involving power electronics, control theory, optimization, cybersecurity, risk assessment, and regulatory planning. This review synthesizes recent advancements in resilient microgrid design with emphasis on technical architecture, control strategies, protection mechanisms, resilience assessment frameworks, and future research directions. It aims to provide a systematic understanding of how microgrids can be engineered to withstand, absorb, and recover from extreme disruptions while maintaining economic viability [5].

1.2 Impact of Natural Disasters on Power Systems

Natural disasters impact power systems through both direct physical damage and indirect systemic disruptions. High winds and storm surges damage transmission towers and substations. Earthquakes compromise underground cables and transformer foundations. Flooding causes insulation breakdown and equipment corrosion. Wildfires lead to forced de-energization to prevent ignition. These events often trigger cascading outages due to the interconnected nature of bulk power systems [6]. The centralized topology of traditional grids amplifies vulnerability. Long transmission corridors create exposure to geographically correlated hazards. When a critical transmission line fails, power flows redistribute unpredictably, potentially overloading adjacent lines and initiating cascading failures. Restoration efforts are often slow because damaged infrastructure requires extensive repair, and accessibility may be limited by disaster conditions.

In disaster-prone regions, outage durations can extend from hours to weeks. Extended blackouts disrupt healthcare services, communication networks, fuel distribution systems, and financial operations. Economic losses are magnified by supply chain interruptions and reduced productivity. Moreover, vulnerable populations are disproportionately affected due to limited access to backup power. Microgrids mitigate these risks by decentralizing generation and reducing reliance on long transmission corridors. By embedding generation within load centers, microgrids reduce exposure to transmission-level failures. During a disturbance, intelligent controllers detect grid instability and initiate seamless islanding, allowing local resources to maintain service continuity. This localized autonomy prevents total service collapse and supports community-level resilience [7]. However, disasters also present challenges specific to microgrids. Renewable generation may be temporarily unavailable due to environmental conditions, communication networks may fail, and protection coordination may be compromised. Therefore, resilient microgrid design must consider extreme-event modeling, component hardening, communication redundancy, and adaptive control strategies.

1.3 Scope and Organization of the Review

This review focuses on technical aspects of resilient microgrid design for disaster-prone regions. It examines architectural configurations, distributed energy integration, control methodologies, protection mechanisms, resilience quantification metrics, optimization frameworks, and case-based insights [8].

Although several review studies have examined microgrid technologies and resilience enhancement strategies, many existing reviews primarily focus on economic optimization, distributed energy resource integration, or general reliability improvements in smart grids. Comprehensive technical reviews specifically addressing resilient microgrid design under extreme disaster conditions remain relatively limited. In particular, the complex challenges associated with multi-disaster coupling, dynamic system degradation, and multi-stage resilience response spanning prevention, absorption, recovery, and adaptation have not been systematically synthesized in the existing literature. Therefore, there remains a need for an integrated technical review that consolidates advancements in microgrid architecture, DERs, advanced control strategies, adaptive protection mechanisms, and resilience assessment frameworks within the context of disaster-prone environments. This review aims to address this gap by providing a comprehensive synthesis of resilient microgrid design principles and emerging research directions.

2. Concept of Power System Resilience

2.1 Definition of Resilience Versus Reliability

Reliability and resilience are often conflated but represent distinct performance attributes. Reliability traditionally measures the ability of a power system to deliver electricity under expected operating conditions and routine contingencies. It focuses on probabilistic adequacy and security, typically quantified through indices such as loss of load probability and system average interruption duration index. Resilience, by contrast, addresses system performance under extreme, high-impact disturbances beyond standard design contingencies [9]. It encompasses the capacity to anticipate, absorb, adapt to, and rapidly recover from disruptive events. While reliability aims to prevent outages through redundancy and preventive maintenance, resilience acknowledges that failures may occur and emphasizes minimizing consequences and recovery time. In microgrid contexts, resilience includes the ability to transition seamlessly into islanded operation, maintain frequency and voltage stability with limited inertia, prioritize critical loads, and restore full functionality after damage. Unlike reliability, resilience integrates physical robustness, operational flexibility, cyber-security, and adaptive learning mechanisms.

Mathematically, reliability is often represented using steady-state probabilistic models. Resilience requires time-dependent modeling capturing system degradation and recovery trajectories. A resilient microgrid maintains acceptable performance levels throughout the disturbance lifecycle rather than simply minimizing outage frequency [5].

2.2 Resilience Metrics and Performance Indices

Quantifying resilience is essential for engineering design and cost-benefit evaluation. Several resilience metrics have been proposed in the literature, typically based on performance-time curves. These curves represent system functionality over time, with performance degradation following a disturbance and gradual restoration during recovery. A commonly used metric is the resilience index defined as the normalized area under the performance curve during and after disruption. Higher area values correspond to improved resilience due to reduced performance loss and faster recovery. Additional indices include recovery time, robustness index, adaptability index, and service continuity ratio. In microgrids, resilience metrics may incorporate load criticality weighting, ensuring that essential services such as healthcare or emergency communication receive priority. Energy-not-served (ENS) during disasters is a key indicator. The integration of probabilistic hazard modeling enables risk-informed resilience quantification [10].

Advanced approaches use multi-criteria evaluation combining technical, economic, and environmental dimensions. For example, a resilience score may aggregate structural hardening measures, DER diversity, storage capacity, communication redundancy, and black start capability. Such composite indices support comparative analysis of design alternatives [11].

To provide a clearer comparison of resilience evaluation approaches, Table 1 summarizes commonly used resilience metrics applied in microgrid resilience assessment. The table compares metrics such as the resilience index, recovery time, robustness index, service continuity ratio, and ENS based on their evaluation principles, advantages, and limitations. This comparative framework highlights how different metrics capture complementary aspects of system performance during disturbance and recovery phases. In practice, resilient microgrid assessment often requires a combination of multiple indicators to accurately represent system robustness, adaptability, and restoration capability under extreme events.

Table 1. Comparative framework of commonly used resilience metrics in microgrid systems.

Resilience Metric	Definition / Principle	Advantages	Limitations	Relevance for Disaster-Prone Microgrids
Resilience Index	Measures the normalized area under the system performance–time curve during disturbance and recovery periods	Captures both degradation and recovery behavior	Requires accurate modeling of system performance over time	Widely used for overall resilience evaluation
Recovery Time	Time required for the system to restore normal or acceptable operational performance after a disturbance	Simple and intuitive metric	Does not reflect performance degradation during disturbance	Useful for evaluating restoration efficiency
Robustness Index	Indicates the ability of the system to withstand disturbances without significant performance loss	Highlights system strength during initial disturbance phase	Does not capture recovery capability	Important for infrastructure hardening analysis
Service Continuity Ratio	Ratio of supplied load to total demand during disruptive events	Reflects ability to maintain service for critical loads	May overlook system recovery dynamics	Suitable for evaluating critical load supply
ENS	Total amount of unmet energy demand during system disruption	Quantifies economic and operational impact of outages	Does not directly represent recovery speed	Common metric in reliability and resilience planning

2.3 Phases of Resilience: Prevention, Absorption, Recovery, and Adaptation

Resilience can be conceptualized as a lifecycle comprising four phases: prevention, absorption, recovery, and adaptation. Prevention involves system hardening, redundancy planning, and hazard forecasting to reduce vulnerability [12]. In microgrids, this includes underground cabling, elevated substations in flood zones, and robust inverter design. Absorption refers to the system's ability to maintain partial functionality during disturbance. Islanding capability, energy storage support, and real-time control contribute to absorption. During this phase, load shedding strategies prioritize critical infrastructure to prevent collapse. Recovery encompasses restoration of full service. Microgrids with autonomous black start capability and distributed resources recover more rapidly than centralized systems. Coordinated reconnection to the main grid requires synchronization and stability verification [13].

Adaptation represents long-term learning and system evolution following disasters. Data-driven assessment of performance informs future infrastructure upgrades and control strategy improvements. Adaptive microgrids incorporate predictive analytics to anticipate vulnerabilities and dynamically adjust operational parameters. Understanding these phases enables systematic engineering of resilient microgrids. Design decisions must consider not only steady-state efficiency but also dynamic survivability and restoration performance. Integrating physical infrastructure, intelligent control, and strategic planning produces microgrids capable of sustaining essential services under extreme conditions [14].

3. Microgrid Architecture for Resilience

3.1 Alternating Current (AC), Direct Current(DC), and Hybrid AC/DC Microgrids

Microgrid architecture significantly influences resilience performance under extreme disturbances. The selection between AC, DC, and hybrid AC/DC configurations affects protection coordination, control stability, fault behavior, and integration flexibility. Traditional AC microgrids align with legacy grid infrastructure and enable straightforward interconnection with utility systems [15]. AC architectures benefit from mature standards and protection schemes; however, they exhibit challenges when integrating high shares of inverter-based renewable resources. Reduced system inertia and increased reliance on power electronics may compromise transient stability during islanding transitions. Frequency deviations and voltage fluctuations become more pronounced in low-inertia environments, requiring sophisticated control strategies. DC microgrids eliminate reactive power flows and synchronization constraints. They provide improved efficiency for integrating photovoltaic (PV) systems, battery energy storage systems (BESS), electric vehicle charging stations, and data centers, which inherently operate on DC. DC architectures demonstrate enhanced controllability and simpler power flow management. Nevertheless, fault detection and interruption in DC systems remain technically challenging due to the absence of natural current zero-crossing, requiring fast-acting solid-state protection devices [16].

Hybrid AC/DC microgrids combine the advantages of both configurations. They incorporate AC buses for conventional loads and rotating machines while maintaining DC sub-networks for inverter-dominated resources. Bidirectional converters interconnect AC and DC segments, enabling flexible power exchange. Hybrid systems improve operational redundancy and allow selective isolation of faults within sub-networks, enhancing resilience. During disasters, the hybrid configuration supports sectionalized operation, reducing the propagation of disturbances [17]. From a resilience engineering perspective, architectural redundancy, electrical segmentation, and converter flexibility determine survivability. Hybrid architectures are increasingly recognized as optimal for disaster-prone regions due to their modularity and ability to maintain partial functionality even when one subsystem is compromised.

To provide a clearer technical comparison of microgrid architectures, Table 2 summarizes key characteristics of AC, DC, and hybrid AC/DC microgrids based on important engineering criteria including system efficiency, protection complexity, renewable integration capability, fault management, and operational flexibility. AC microgrids benefit from compatibility with existing power infrastructure and mature protection technologies, while DC microgrids offer improved efficiency and simplified integration of renewable energy sources and storage systems. Hybrid AC/DC architectures combine the strengths of both systems by enabling flexible interconnection between AC and DC subsystems through bidirectional converters. This hybrid configuration improves redundancy and fault isolation capabilities, making it particularly suitable for resilient microgrid deployment in disaster-prone regions.

Table 2. Technical comparison of AC, DC, and hybrid AC/DC microgrid architectures.

Architecture Type	Key Characteristics	Advantages	Challenges	Suitability for Resilient Microgrids
AC Microgrid	Uses alternating current distribution similar to conventional power grids	Compatible with existing infrastructure, mature protection systems	Lower efficiency for DC loads, reduced stability with high inverter penetration	Moderate resilience, widely deployed
DC Microgrid	Direct current distribution suitable for inverter-based resources	Higher efficiency, simplified renewable and storage integration	Complex fault detection and protection due to absence of current zero crossing	High efficiency and reliability for localized systems
Hybrid AC/DC Microgrid	Combines AC and DC subsystems interconnected through power converters	Flexible operation, improved redundancy, optimized integration of DERs	Increased system complexity and converter costs	Highly suitable for disaster-prone regions due to modularity and fault isolation capability

3.2 Grid-Connected and Islanded Operation Modes

Resilient microgrids must seamlessly transition between grid-connected and islanded modes. In grid-connected operation, the microgrid exchanges power with the main utility network and participates in ancillary services. During stable conditions, this mode optimizes economic dispatch and renewable integration. When a disturbance occurs, intelligent controllers detect abnormalities such as voltage sags, frequency excursions, or phase angle instability. A rapid disconnection mechanism isolates the microgrid to prevent cascading failures [18]. The transition must be executed within milliseconds to avoid load disruption. Islanded operation introduces challenges associated with maintaining frequency and voltage stability using local resources. Without the bulk grid's inertia and fault level support, inverter-based resources must emulate synchronous generator behavior through advanced control algorithms such as droop control and virtual synchronous machine strategies. Adequate energy storage capacity is critical to balance short-term fluctuations. Resilience-enhanced microgrids also incorporate reconnection protocols. Synchronization with the main grid requires phase, frequency, and voltage matching. Improper reconnection can cause equipment damage or destabilize the system. Therefore, adaptive synchronization schemes and predictive stability assessment are integral to resilient design [19].

3.3 Hierarchical Control Structures

Hierarchical control architectures are widely adopted in resilient microgrids to manage distributed resources effectively. The structure typically consists of primary, secondary, and tertiary control layers. Primary control operates at the local inverter level, ensuring immediate voltage and frequency stabilization through droop characteristics or virtual inertia emulation. It acts within milliseconds and does not rely heavily on communication networks, which may be compromised during disasters. Secondary control restores frequency and voltage deviations caused by primary droop control. It relies on limited communication infrastructure to coordinate multiple distributed generators. In disaster-prone regions, secondary control schemes must tolerate communication delays or partial network failure. Distributed consensus algorithms offer resilience by reducing reliance on centralized controllers. Tertiary control optimizes economic dispatch and power exchange with the utility grid. During disaster scenarios, tertiary control prioritizes resilience objectives rather than cost minimization. Critical load prioritization, energy rationing, and adaptive scheduling are implemented at this level. A resilient hierarchical architecture emphasizes decentralization. Fully centralized control may present a single point of failure. Distributed and peer-to-peer control mechanisms enhance survivability under communication disruptions [20].

3.4 Communication Infrastructure and Cyber-Physical Integration

Microgrids are inherently cyber-physical systems integrating electrical infrastructure with digital communication networks. Communication reliability becomes critical during disasters, as physical infrastructure damage may disrupt fiber or wireless networks. Resilient microgrid communication design includes redundancy, mesh networking, and edge computing. Distributed controllers capable of autonomous operation reduce dependency on centralized servers. Cybersecurity measures such as intrusion detection systems and encryption protect against coordinated cyber-attacks that may accompany physical disasters. Integration of real-time monitoring systems, including phasor measurement units (PMUs), enhances situational awareness. Wide-area measurement integration supports rapid fault isolation and dynamic stability assessment. A resilient microgrid architecture must therefore integrate electrical robustness with cyber redundancy. Failure in either domain can compromise overall system performance [21].

4. DERs in Resilient Microgrids

4.1 Solar PV and Wind Integration

Renewable energy sources constitute the backbone of sustainable resilient microgrids. Solar PV systems are particularly suitable for disaster-prone regions due to modularity, scalability, and minimal fuel dependency. However, their intermittency requires complementary storage solutions to ensure continuity during prolonged cloud cover or nighttime operation. Wind energy provides complementary generation profiles in certain geographic regions. However, extreme weather conditions such as hurricanes may necessitate turbine shutdown to prevent mechanical damage. Therefore, renewable integration strategies must consider structural reinforcement and adaptive operational thresholds. Advanced inverter technologies enable grid-forming capabilities, allowing renewable units to regulate voltage and frequency during islanded operation. Grid-following inverters are insufficient for resilience because they rely on external voltage references. Transitioning toward grid-forming inverter deployment significantly enhances microgrid survivability [22].

4.2 Energy Storage Systems

Energy storage is fundamental to resilient microgrid operation. BESS provide fast-response balancing, frequency regulation, and black start capability. Lithium-ion batteries dominate current deployments due to high energy density and declining costs. However, thermal management and fire safety are critical design considerations in disaster-prone environments. Alternative storage technologies such as flow batteries offer improved safety and scalability. Hydrogen-based storage provides long-duration backup suitable for extended outages [23]. Hybrid storage architectures combine high-power batteries with long-duration energy carriers to optimize cost and resilience. Sizing of storage systems requires probabilistic modeling of disaster scenarios. Oversizing increases cost, while undersizing compromises resilience. Multi-objective optimization approaches balance economic and resilience metrics.

4.3 Diesel and Backup Generation

Despite environmental concerns, diesel generators remain prevalent in resilient microgrids due to reliability and established technology. In disaster contexts where renewable output is uncertain, dispatchable backup generation ensures continuity. However, fuel supply logistics represent a vulnerability. Hybrid systems integrating diesel with renewables reduce fuel dependency while preserving reliability. Emerging alternatives include biofuel generators and microturbines. These technologies provide cleaner backup solutions and can operate continuously during prolonged disruptions [24].

4.4 Electric Vehicles and Vehicle-to-Grid Support

Electric vehicles represent distributed storage resources capable of enhancing resilience through vehicle-to-grid operation. Aggregated EV fleets can supply emergency power during outages. Bidirectional charging infrastructure enables energy exchange between vehicles and microgrid systems. However, vehicle-to-grid deployment requires advanced coordination algorithms and incentive mechanisms. Battery degradation and user mobility patterns must be considered in operational planning. In disaster scenarios, EV fleets located in evacuation zones may be unavailable, necessitating adaptive forecasting strategies (Figure 1).

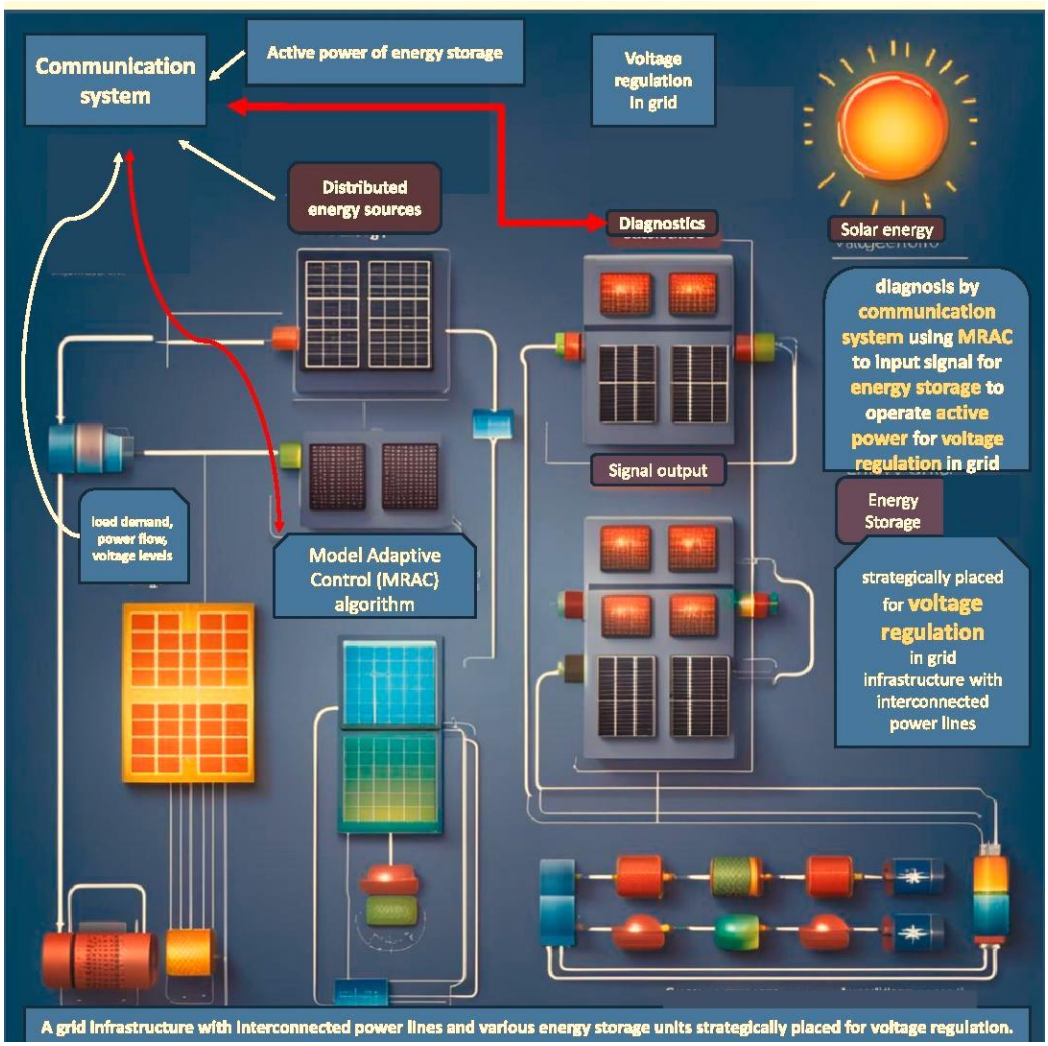


Figure 1. Achieving grid resilience through energy storage and model reference adaptive control for effective active power voltage regulation.

5. Control and Energy Management Strategies

Resilient microgrid operation under disaster conditions depends fundamentally on advanced control and energy management systems (EMS). Unlike conventional microgrids designed primarily for economic optimization, resilient microgrids must prioritize survivability, rapid stabilization, adaptive reconfiguration, and critical load continuity. Control strategies must remain functional even under partial communication failure, high renewable variability, and infrastructure damage [25].

While advanced control approaches such as model predictive control (MPC) offer significant advantages in economic dispatch and optimal resource scheduling under normal operating conditions, their resilience performance under extreme disaster scenarios requires careful consideration. MPC-based EMS typically rely on communication networks and centralized computational resources to obtain system-wide measurements and solve optimization problems in real time. During severe disturbances, however, communication infrastructure may be partially disrupted, limiting the effectiveness of centralized optimization-based control. In such situations, resilience-oriented microgrid design increasingly favors hybrid control architectures that combine predictive optimization with robust decentralized strategies. Local controllers based on droop control, virtual synchronous generator (VSG) operation, or other communication-independent mechanisms can maintain essential stability functions even when higher-level coordination is temporarily unavailable. This layered control philosophy reflects a fundamental shift from reliability-oriented optimization toward resilience-oriented survivability and autonomous operation during extreme events.

5.1 Adaptive and Robust Control Techniques

Adaptive control methodologies are designed to adjust system parameters dynamically in response to disturbances or topology changes. In disaster scenarios, network configurations may shift due to line faults, load shedding, or equipment isolation. Fixed-parameter controllers may fail to maintain stability under such variability. Robust control techniques address model uncertainties and parameter deviations. H-infinity control, sliding mode control, and robust

droop control frameworks are increasingly applied to inverter-dominated microgrids. These methods provide stability margins under uncertain load profiles and fluctuating renewable generation [26].

VSG control and grid-forming inverter strategies are critical in low-inertia environments. By emulating synchronous machine dynamics, VSG controllers enhance frequency stability during islanded operation. Their fast inertial response mitigates rate-of-change-of-frequency (RoCoF) excursions following sudden load changes. Distributed consensus-based control algorithms further enhance resilience by eliminating single points of failure. Instead of relying on a central controller, peer-to-peer communication allows decentralized frequency restoration and power sharing. Even if part of the communication network is compromised, local controllers maintain coordinated operation [27].

VSG control has emerged as a key technology for enhancing the resilience of inverter-dominated microgrids by emulating the inertial and damping characteristics of conventional synchronous generators. By providing virtual inertia, VSG controllers help mitigate rapid frequency deviations during disturbances and improve system stability during islanded operation. This capability is particularly valuable in low-inertia microgrids with high penetration of inverter-based renewable resources. However, several practical limitations must be considered when evaluating the resilience contribution of VSG control. The effectiveness of VSG operation depends strongly on appropriate parameter tuning, including virtual inertia and damping coefficients, which may need to adapt dynamically under extreme disturbances where the RoCoF can be significantly higher than under normal operating conditions. In addition, VSG functionality typically relies on energy storage systems to supply or absorb power during transient events. If storage capacity becomes constrained during prolonged disturbances, the ability of VSG controllers to provide sustained frequency support may be limited. Therefore, resilient microgrid design often requires coordinated integration of VSG control with adaptive energy management strategies and robust system-level planning to avoid introducing new operational vulnerabilities.

5.2 MPC for Resilience

MPC has emerged as a powerful tool for microgrid energy management due to its ability to optimize multi-variable systems under constraints. MPC predicts future system states using mathematical models and solves an optimization problem at each time step. In disaster-prone regions, MPC incorporates probabilistic forecasts of renewable generation and load demand under extreme conditions. It can schedule storage dispatch, prioritize critical loads, and manage generator ramping while respecting operational constraints such as battery state-of-charge limits. Robust MPC variants integrate uncertainty bounds into the optimization framework, ensuring feasible operation even when predictions deviate from actual conditions. Stochastic MPC formulations incorporate scenario-based modeling of disaster events, enabling risk-informed dispatch decisions. However, MPC requires computational resources and reliable communication infrastructure. Edge computing and distributed MPC implementations improve resilience by localizing computation and reducing dependence on centralized servers [28].

5.3 AI-Based EMS

Artificial intelligence and machine learning techniques are increasingly integrated into microgrid EMS to enhance predictive and adaptive capabilities. Neural networks, reinforcement learning (RL), and deep learning architectures are applied for load forecasting, renewable generation prediction, and adaptive dispatch. RL-based controllers are particularly promising for disaster scenarios because they learn optimal policies through interaction with dynamic environments. RL agents can adapt to evolving system conditions without explicit model dependence. This adaptability is beneficial when system topology changes unexpectedly. Hybrid AI-physics models combine data-driven learning with physical constraints to ensure stability and interpretability [29]. AI-driven fault prediction enhances proactive intervention before system collapse. Despite their advantages, AI-based systems require robust cybersecurity measures and reliable training datasets. Model overfitting or adversarial attacks may compromise operational safety. Therefore, resilient AI integration requires explainability, redundancy, and fail-safe mechanisms.

5.4 Demand Response (DR) and Load Prioritization

DR plays a critical role in resilient microgrid operation. During disasters, supply constraints necessitate selective load shedding to preserve critical infrastructure. Intelligent load prioritization frameworks classify loads into essential, important, and non-critical categories. Automated DR schemes adjust consumption in response to frequency deviations or storage limitations [30]. Smart meters and IoT-enabled devices facilitate real-time load management. In extreme scenarios, microgrids may operate in survival mode, supplying only life-safety systems. Advanced optimization frameworks integrate DR with generation scheduling to minimize ENS while maintaining system stability (Table 3).

Table 3. Comparative analysis of control and energy management strategies in resilient microgrids.

Control Strategy	Core Principle	Advantages	Limitations	Suitability for Disaster Conditions
Droop Control	Local frequency-voltage droop characteristics	Simple, decentralized, communication-independent	Frequency deviation under heavy load changes	Suitable for primary stabilization
VSG	Emulates synchronous inertia	Improved transient stability, reduced RoCoF	Higher control complexity	Highly suitable for low-inertia islanded operation
MPC	Optimization-based predictive dispatch	Handles constraints, multi-variable optimization	Computational demand, communication reliance	Suitable with edge/distributed implementation
Robust Control (H∞, Sliding Mode)	Accounts for system uncertainties	High stability margin	Mathematical complexity	Highly suitable for uncertain disaster scenarios
RL-Based EMS	Adaptive policy learning	Self-learning, adaptable	Data requirements, cybersecurity concerns	Promising for adaptive resilience
Distributed Consensus Control	Peer-to-peer coordination	Eliminates single point of failure	Communication latency sensitivity	Highly suitable for resilient decentralized systems

From a comparative perspective, MPC and AI-based EMS offer complementary advantages for resilient microgrid operation. MPC provides a mathematically rigorous optimization framework capable of handling multiple operational constraints such as battery state-of-charge limits, generator ramp rates, and power balance requirements. Its predictive nature enables short-term scheduling of distributed resources under uncertain renewable generation conditions. However, MPC performance depends on accurate system modeling and may impose significant computational requirements, particularly in large-scale microgrids. In contrast, AI-based approaches such as RL and deep neural networks are capable of learning optimal operational policies from historical and real-time data without requiring explicit system models. These methods offer greater adaptability under rapidly changing system conditions but may require extensive training datasets and robust cybersecurity measures. In disaster scenarios where system topology and resource availability may change dynamically, hybrid control frameworks combining predictive optimization with data-driven learning are increasingly considered promising for enhancing microgrid resilience.

6. Protection and Fault Management in Disaster Conditions

Protection systems in resilient microgrids must address unique challenges posed by inverter-based generation, bidirectional power flow, and dynamic topology changes. Conventional overcurrent-based protection schemes designed for radial distribution networks are inadequate in microgrid environments [31].

Protection in inverter-dominated microgrids presents unique technical challenges due to the fundamentally different fault behavior of inverter-based DERs compared to traditional synchronous generators. Conventional protection schemes rely on high fault current levels to detect and isolate faults; however, power electronic inverters typically limit their fault current contribution to approximately 1.1-2.0 times the rated current in order to protect semiconductor devices. This reduced fault current magnitude makes traditional overcurrent relays less sensitive and may delay fault detection. Furthermore, bidirectional power flows and dynamic operating modes such as transitions between grid-connected and islanded operation complicate relay coordination and selectivity. To address these issues, advanced protection strategies are increasingly employed, including adaptive relay settings that adjust according to operating conditions, differential protection schemes capable of detecting internal faults with high selectivity, and impedance-based fault detection algorithms suitable for inverter-dominated networks. Additionally, the use of solid-state circuit breakers enables ultrafast fault isolation in both AC and DC micro-grids, improving system protection speed and minimizing equipment damage during extreme disturbances.

6.1 Adaptive Protection Schemes

Adaptive protection dynamically modifies relay settings based on system operating mode. During grid-connected operation, fault currents may be high due to utility contribution. In islanded mode, inverter-limited fault currents reduce sensitivity of overcurrent relays. Adaptive schemes incorporate real-time monitoring to adjust protection thresholds. Microprocessor-based relays and digital protection systems enable flexible configuration. Communication-assisted protection methods enhance selectivity. Differential protection schemes compare current measurements across network segments to detect internal faults rapidly [32]. However, communication failures during disasters necessitate fallback local protection mechanisms.

6.2 Fault Detection and Self-Healing Mechanisms

Resilient microgrids integrate self-healing capabilities that automatically isolate faults and restore unaffected sections. Fault detection methods include impedance-based algorithms, traveling wave detection, and AI-based anomaly detection. Self-healing involves automated sectionalizing switches and reconfiguration algorithms. By isolating

damaged segments, the microgrid preserves supply to critical loads. Fast-acting solid-state circuit breakers improve fault interruption speed, particularly in DC microgrids [33]. Wide-area monitoring systems support situational awareness, enabling coordinated response across distributed resources. Integration with distributed control systems enhances response speed.

Adaptive protection is considered the first stage in the resilience process, where rapid fault detection and precise location enable effective isolation of faulty components. The information obtained from adaptive protection supports the self-healing process by guiding network reconfiguration and restoring power to unaffected areas in an optimized manner. In large-scale outage scenarios, black start capability becomes essential for system recovery. Energy storage systems and DERs can provide initial power support to restart critical generators and stabilize microgrids, enabling the gradual restoration of the broader grid. This coordinated sequence demonstrates that adaptive protection, self-healing, and black start operate as complementary mechanisms within a unified resilience-oriented power system framework.

6.3 Black Start Capability and Restoration Planning

Black start capability is essential for microgrids operating independently after complete shutdown. Energy storage systems or small synchronous generators typically initiate restoration sequences. Restoration planning involves sequential energization of feeders, synchronization of distributed generators, and gradual load reconnection. Advanced optimization tools determine optimal restoration paths minimizing recovery time and system stress. Disaster-resilient microgrids incorporate automated restoration algorithms capable of operating without centralized supervision. This autonomy significantly reduces downtime compared to traditional grids (Table 4) [34].

Table 4. Protection and fault management techniques for resilient microgrids.

Protection Technique	Operating Principle	Advantages	Challenges	Disaster Resilience Level
Overcurrent Protection	Current magnitude threshold	Simple, cost-effective	Ineffective in low fault current inverter systems	Moderate
Differential Protection	Current comparison across zones	High selectivity and speed	Communication dependency	High with redundancy
Adaptive Relay Settings	Dynamic threshold adjustment	Mode-aware protection	Requires real-time monitoring	High
Impedance-Based Fault Detection	Impedance trajectory analysis	Effective for inverter systems	Parameter sensitivity	High
Solid-State Circuit Breakers	Fast electronic switching	Rapid fault isolation	High cost	Very High
Self-Healing Reconfiguration	Automated sectionalizing and rerouting	Minimizes outage area	Complex coordination	Very High
AI-Based Fault Detection	Data-driven anomaly identification	Early fault detection	Cybersecurity risks	Promising but emerging

7. Resilience Assessment and Optimization

Designing resilient microgrids for disaster-prone regions requires quantitative assessment frameworks capable of evaluating system robustness under extreme disturbances. Unlike conventional reliability analysis, resilience assessment must capture time-dependent degradation, recovery trajectories, and adaptive system behavior. Optimization techniques then utilize these metrics to identify cost-effective design configurations that balance survivability and economic feasibility.

7.1 Probabilistic Risk Assessment Methods

Probabilistic risk assessment (PRA) integrates hazard modeling, system vulnerability analysis, and consequence evaluation. In disaster-prone regions, hazards such as hurricanes, earthquakes, floods, and wildfires are modeled using statistical distributions derived from historical data and climate projections. Monte Carlo simulation is widely applied to estimate system performance under numerous stochastic scenarios. Each scenario models different combinations of component failures, renewable variability, and load demand fluctuations. The resulting distribution of performance outcomes enables estimation of resilience metrics such as expected energy not served (EENS) during extreme events. Fragility curves are commonly used to represent component vulnerability as a function of hazard intensity. For example, transformer failure probability may increase with flood depth or seismic acceleration. Incorporating fragility curves into system-level simulations improves realism in resilience evaluation. Advanced PRA approaches integrate interdependency modeling between power, communication, and transportation systems. During disasters, failure in one infrastructure sector may propagate to others. Modeling such interdependencies is essential for comprehensive resilience assessment [35].

7.2 Scenario-Based Disaster Modeling

Scenario-based modeling evaluates system performance under specific representative disaster events. Unlike purely probabilistic approaches, scenario-based methods focus on realistic, high-impact cases such as a Category 4 hurricane striking a coastal community or a major seismic event affecting substation foundations. These models incorporate detailed spatial information, including geographic placement of DERs, feeders, substations, and critical loads. Geographic information systems (GIS) are frequently integrated with power flow simulations to analyze damage propagation [36]. Time-domain simulations assess system dynamic response during and after the disturbance. Transient stability, frequency excursions, and voltage regulation performance are evaluated under islanded conditions. Such analyses help identify critical design weaknesses and inform targeted infrastructure reinforcement. Scenario-based modeling also supports contingency planning by evaluating restoration timelines and resource allocation strategies (Figure 2).

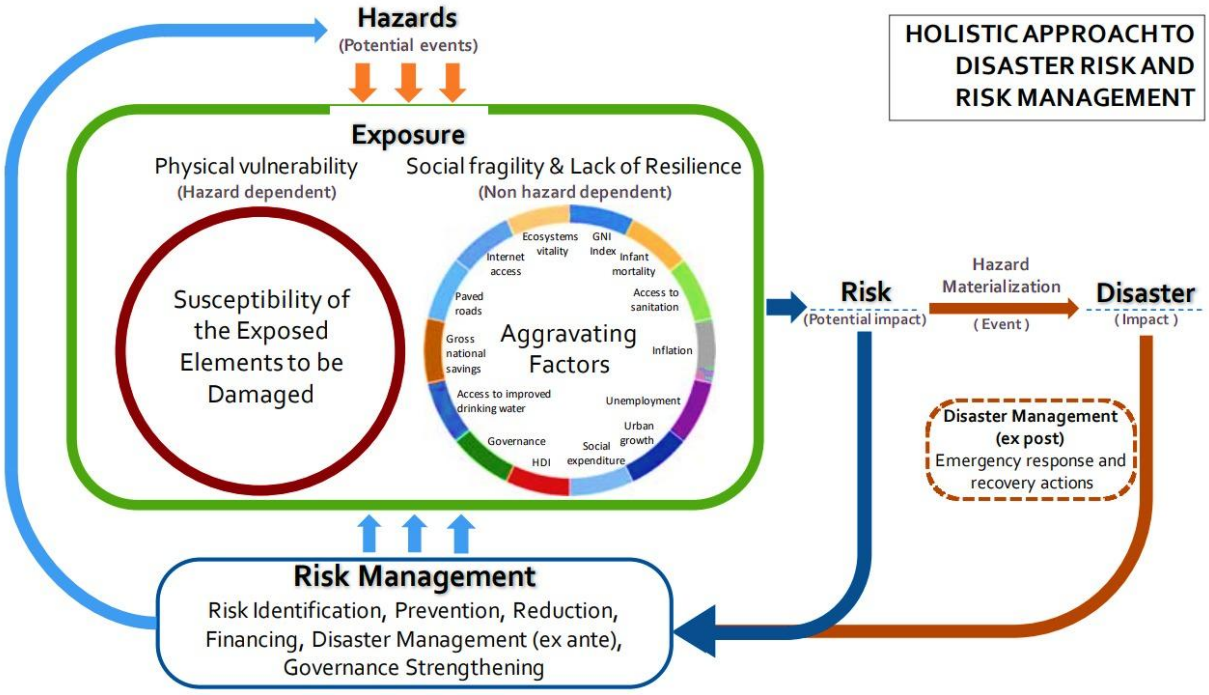


Figure 2. Dealing with uncertainty using PRA for decision-making.

In addition to conventional scenario modeling, it is important to consider the concept of deep uncertainty, where the probability distributions of future disturbances cannot be reliably estimated due to evolving factors such as climate change and increasingly complex cyber–physical interactions. Under such conditions, traditional probabilistic risk assessment and scenario analysis that rely heavily on historical data may face significant limitations. Future disasters may exhibit characteristics that are not captured by past observations, reducing the reliability of purely data-driven statistical models. To address this challenge, emerging decision-making frameworks such as Information Gap Decision Theory (Info-Gap) and robust decision-making methods have been proposed. These approaches focus on identifying strategies that maintain acceptable system performance across a wide range of uncertain conditions rather than relying on precise probability estimates. Integrating such methods into resilience-oriented scenario modeling can improve the adaptability and robustness of future power system planning and operation.

7.3 Multi-Objective Optimization for Resilient Design

Resilient microgrid design involves trade-offs among capital cost, operational cost, carbon emissions, and resilience performance. Multi-objective optimization frameworks are therefore widely employed. Common decision variables include DER capacity, storage size, network topology, protection configuration, and control strategy selection. Objectives typically include minimization of lifecycle cost and minimization of expected outage duration or energy not served. Evolutionary algorithms such as genetic algorithms (GA), particle swarm optimization (PSO), and non-dominated sorting genetic algorithm II (NSGA-II) are frequently used due to their ability to handle nonlinear, nonconvex design spaces. Robust optimization approaches incorporate uncertainty bounds for hazard intensity and renewable variability, ensuring feasible solutions under worst-case conditions. Stochastic programming formulations integrate scenario probabilities directly into the optimization objective. Recent research explores resilience-constrained optimization, where minimum resilience performance thresholds must be satisfied before cost minimization is considered. This approach reflects the critical importance of maintaining essential services during disaster [37].

7.4 Cost-Resilience Trade-Off Analysis

Resilience enhancement often increases upfront capital expenditure due to infrastructure hardening, additional storage, and advanced control systems. Therefore, cost-resilience trade-off analysis is essential to justify investment decisions. Marginal resilience benefit curves quantify the incremental improvement in resilience achieved per unit cost increase. These curves assist policymakers and planners in determining optimal investment levels. Lifecycle cost analysis includes capital cost, maintenance, fuel consumption, and expected outage-related losses. In disaster-prone regions, avoided outage costs can be substantial, particularly for hospitals, military bases, and data centers. Incorporating social cost metrics, such as public health impact and emergency service continuity, further strengthens the economic case for resilient microgrid deployment.

8. Case Studies from Disaster-Prone Regions

Real-world deployments provide practical insights into resilient microgrid design and performance.

8.1 Hurricane-Affected Regions

Following Hurricane Maria in Puerto Rico, extensive grid failure highlighted vulnerabilities of centralized transmission infrastructure. Subsequent deployment of community-scale microgrids incorporating solar PV and battery storage demonstrated improved local resilience. Grid-forming inverters enabled sustained islanded operation for critical facilities, reducing dependence on diesel fuel logistics. Similarly, microgrids installed in coastal regions of the United States have provided continuity to hospitals and emergency shelters during severe storms. These deployments emphasize the importance of underground cabling, elevated equipment placement, and robust energy storage integration [38].

8.2 Earthquake-Prone Areas

In seismic regions such as Japan and California, microgrids have been implemented to support critical infrastructure. Earthquake-resistant mounting systems and flexible cable connections enhance survivability. After the 2011 Tōhoku earthquake, distributed generation systems demonstrated faster recovery compared to centralized infrastructure. Lessons learned include the necessity of autonomous control and black start capability [39].

8.3 Wildfire and Flood-Prone Regions

Wildfires increasingly cause preemptive grid de-energization to prevent ignition. Microgrids provide local continuity during such public safety power shutoffs. Battery-backed solar systems in California have sustained critical loads during extended outages. In flood-prone regions, elevated substations and waterproof enclosures reduce equipment vulnerability. Hybrid microgrids combining solar, storage, and dispatchable backup ensure prolonged operation even when access routes are compromised. Case studies consistently highlight the importance of decentralized control, diversified energy resources, storage redundancy, and automated restoration. Communication redundancy and cybersecurity resilience are equally critical.

To enhance the practical implications of the case studies, key design insights are extracted from each disaster scenario. Rather than only describing events, the analysis highlights the underlying resilience strategies demonstrated in practice. For example, hurricane-related cases emphasize the effectiveness of underground distribution lines, energy storage systems, and grid-forming inverters in maintaining power supply for coastal communities under severe wind and flooding conditions. Similarly, wildfire-related cases illustrate the role of microgrids as “island lifelines” during preventive grid shutdowns, ensuring continuity of power supply for critical facilities and communities. Based on these observations, a synthesis table is introduced to summarize the relationship between disaster types, key resilience requirements, and suitable technology combinations, providing a structured reference for microgrid design and resilience planning across different hazard environments (Table 5).

Table 5. Mapping of disaster types, resilience needs, and recommended technology combinations.

Disaster Type	Critical Resilience Needs	Recommended Technology Combinations
Hurricanes/Storms	Structural robustness, sustained islanded operation, frequency stability	Underground cabling + Energy Storage Systems + Grid-Forming inverters
Wildfires	Continuous power during planned grid shutdowns, local autonomy	Microgrid islanding capability + Local DERs + Advanced EMS
Earthquakes	Rapid fault isolation and system reconfiguration	Adaptive protection + Self-healing network architecture + Distributed generation
Floods	Infrastructure protection and rapid recovery	Elevated equipment design + Modular microgrids + Mobile energy storage
Extreme cold/heat events	Load flexibility and resource adequacy	DR + AI-based EMS + Hybrid renewable-storage systems

9. Policy, Regulatory, and Economic Considerations

Technical feasibility alone does not guarantee successful deployment. Regulatory frameworks must support microgrid interconnection, islanding rights, and tariff structures that incentivize resilience investment. Performance-based regulation models increasingly recognize resilience as a measurable utility objective. Incentive mechanisms such as resilience credits or disaster mitigation grants accelerate adoption. Standardization of grid codes for inverter-based resources ensures compatibility and stability. Harmonized standards simplify deployment and improve interoperability.

10. Emerging Technologies and Future Research Directions

Emerging technologies are reshaping resilient microgrid design. Digital twin platforms enable real-time simulation and predictive analysis of system behavior under evolving conditions. Edge computing enhances decentralized intelligence, reducing latency and vulnerability. Blockchain-based energy trading platforms support peer-to-peer resilience markets. Artificial intelligence continues to advance predictive maintenance, anomaly detection, and adaptive control. Hydrogen-based storage and long-duration battery technologies offer improved resilience against prolonged outages. Integration of advanced materials improves structural hardening of infrastructure components. Future research must address interoperability of grid-forming inverters, standardization of resilience metrics, and scalable cyber-physical security frameworks [40].

11. Challenges and Research Gaps

Despite significant progress, several challenges remain. Quantitative resilience metrics lack universal standardization, complicating comparative evaluation. Protection coordination in inverter-dominated systems remains technically complex. Cybersecurity threats targeting microgrid control systems pose escalating risks. Interdependency modeling between infrastructure sectors requires further refinement. Economic valuation of resilience benefits remains uncertain, particularly for community-scale projects. Policymakers require robust cost-benefit models to justify large-scale investments.

To better guide future research, the key challenges in resilient microgrid development can be prioritized into several critical areas. First, the lack of standardized resilience metrics remains a major limitation, as inconsistent evaluation frameworks hinder comparative assessment of microgrid designs across different studies. Second, protection coordination in inverter-dominated systems requires further investigation due to limited fault current levels and complex dynamic behavior of power electronic converters. Third, cyber-physical security has become increasingly important as microgrids rely heavily on communication networks and digital control systems that may be vulnerable to cyber-attacks during disaster events. Fourth, the integration of advanced control strategies including artificial intelligence and distributed optimization requires further validation under real-world operational conditions to ensure reliability and stability. Finally, comprehensive economic assessment models are needed to accurately quantify the long-term benefits of resilience investments, including avoided outage costs and societal impacts. Addressing these prioritized research gaps will play a crucial role in advancing resilient microgrid technologies and facilitating their large-scale deployment in disaster-prone regions.

12. Conclusion

Resilient microgrids represent a transformative solution for disaster-prone regions facing increasing climate-related and extreme-event disruptions. Through decentralized architecture, advanced control strategies, adaptive protection mechanisms, and robust optimization frameworks, microgrids enhance survivability and accelerate recovery. Engineering resilience requires integrated consideration of physical infrastructure, cyber systems, DERs, and regulatory frameworks. While technological advancements have significantly improved feasibility, continued research is necessary to standardize metrics, refine protection schemes, and enhance economic justification. As climate variability intensifies, resilient microgrid deployment will transition from optional enhancement to essential infrastructure strategy, ensuring continuity of critical services and strengthening societal preparedness against future disasters.

Acknowledgements

The author thanks Abdul Wali Khan University.

Ethics Statement

Not applicable.

Data Availability Statement

All Data are available in the published manuscript.

Author Contributions

Ahmad Ali have design, analyse and write the full manuscript.

Conflict of Interest

The author declares no conflict of interest.

Generative AI Statement

The author declares that no Gen AI was used in the creation of this manuscript.

References

[1] Shaukat N, Islam MR, Rahman MM, Khan B, Ullah B, Ali SM, et al. Decentralized, democratized, and decarbonized future electric power distribution grids: A survey on the paradigm shift from the conventional power system to micro grid structures. IEEE Access, 2023, 11, 60957-60987. DOI: 10.1109/ACCESS.2023.3284031

[2] Bajwa AA, Mokhlis H, Mekhilef S, Mubin M. Enhancing power system resilience leveraging microgrids: A review. Journal of Renewable and Sustainable Energy, 2019, 11(3), 035503. DOI: 10.1063/1.5066264

[3] Schlegelmilch J, Carlin E. Catastrophic incentives: Why our approaches to disasters keep falling short. Columbia University Press, 2023.

[4] Karthikeyan B, Kumar P, Karthikeyan P, Soufiene BO, Elngar A, Dhanaselvam PS, et al. Adaptive artificial intelligence for intelligent fault detection and correction in sensor systems. Adaptive AI in Sensor Informatics. Elsevier, 2026, 133-152.

[5] Hamidieh M, Ghassemi M. Microgrids and resilience: A review. IEEE Access, 2022, 10, 106059-106080. DOI: 10.1109/ACCESS.2022.3211511

[6] Vahedi S, Zhao J, Pierre B, Lei F, Anagnostou E, He K, et al. Wildfire and power grid nexus in a changing climate. Nature Reviews Electrical Engineering, 2025, 2(4), 225-243. DOI: 10.1038/s44287-025-00150-0

[7] Adhikari B. Power distribution system reliability and resiliency against extreme events. Saskatoon: University of Saskatchewan, 2022.

[8] Iyaniwura AA, Mayaki CS. Artificial Intelligence-enabled smart grid systems for real-time load forecasting, fault detection, renewable energy integration and optimization. Global Journal of Engineering and Technology Advances, 2025, 24(03), 191-208. DOI: 10.30574/gjeta.2025.24.3.0272

[9] Nam Y, Yang Y. Hotel performance under extreme weather: A contingency perspective on organizational resilience. Journal of Sustainable Tourism, 2026, 1-21. DOI: 10.1080/09669582.2026.2614549

[10] Anderson Jr WW. Resilience assessment of islanded renewable energy microgrids. Monterey, CA: Naval Postgraduate School, 2020.

[11] Rafy MF, Srivastava AK, Neto F, Biasi, J. Communication technologies for DER-centric power distribution systems: A comparative analysis and cyber-resilience guidelines. IEEE Access, 2024, 12, 80549-80558. DOI: 10.1109/ACCESS.2024.3408164

[12] Martin-Breen P, Anderies JM. Resilience: A literature review. Brighton: IDS, 2011.

[13] Konar S, Srivastava AK. MPC-based black start and restoration for resilient DER-rich electric distribution system. IEEE Access, 2023, 11, 69177-69189. DOI: 10.1109/ACCESS.2023.3292254

[14] Wu T, Wang J. Artificial intelligence for operation and control: The case of microgrids. The Electricity Journal, 2021, 34(1), 106890. DOI: 10.1016/j.tej.2020.106890

[15] Dawn S, Ramakrishna A, Ramesh M, Das SS, Rao KD, Islam MM, et al. Integration of renewable energy in microgrids and smart grids in deregulated power systems: a comparative exploration. Advanced Energy and Sustainability Research, 2024, 5(10), 2400088. DOI: 10.1002/aesr.202400088

[16] Ouaida R, Berthou M, Tournier D, Depalma JF. State of art of current and future technologies in current limiting devices. 2015 IEEE First International Conference on DC Microgrids. IEEE, 2015, 175-180. DOI: 10.1109/ICDCM.2015.7152034

[17] Li C, Ding L, Fang Q. Dynamic simulation of the probable propagation of a disaster in an engineering system using a scenario-based hybrid network model. IEEE Transactions on Engineering Management, 2022, 71, 1490-1503. DOI: 10.1109/TEM.2022.3157528

[18] Salama M, El-Dakhakhni W, Tait M. Systemic risk mitigation strategy for power grid cascade failures using constrained spectral clustering. International Journal of Critical Infrastructure Protection, 2023, 42, 100622. DOI: 10.1016/j.ijcip.2023.100622

[19] Rajak MK, Pudur R. Multiobjective adaptive predictive virtual synchronous generator control strategy for grid stability and renewable integration. Scientific Reports, 2025, 15(1), 9241. DOI: 10.1038/s41598-025-93721-y

[20] Benkler Y. Peer production of survivable critical infrastructures. The law and economics of cybersecurity, 2005, 73-114.

[21] Mishra S, Anderson K, Miller B, Boyer K, Warren A. Microgrid resilience: A holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies. Applied Energy, 2020, 264, 114726. DOI: 10.1016/j.apenergy.2020.114726

[22] Hossain MI, Anonto HZ, Shufian A, Pathik BB, Mannan MA, Rashid A, et al. Enhancing microgrid resilience through integrated grid-forming and grid-following inverter strategies for solar PV battery control and fault ride-through. Scientific Reports, 2025, 15(1), 40078. DOI: 10.1038/s41598-025-18767-4

[23] Eltohamy MS, Aldawsari MS, Raouf A, Youssef H, Ahmed I, Alsenani TR, et al. Enhancing electric grid flexibility for the integration of variable renewable energy: Challenges, Innovations, and Future Directions. IEEE Access, 2026. DOI: 10.1109/ACCESS.2026.3660837

[24] Khanna A, Nalluri S. Sustainable backup and recovery practices in cybersecurity. International Conference of Global

Innovations and Solutions. Cham: Springer Nature Switzerland, 2025, 610-625. DOI: 10.1007/978-3-032-02853-2_43
[25] Habib HF, Lashway CR, Mohammed OA. A review of communication failure impacts on adaptive microgrid protection schemes and the use of energy storage as a contingency. IEEE Transactions on Industry Applications, 2017, 54(2), 1194-1207. DOI: 10.1109/TIA.2017.2776858
[26] Pierrou G, Wang X. The effect of the uncertainty of load and renewable generation on the dynamic voltage stability margin. 2019 IEEE PES Innovative Smart Grid Technologies Europe. IEEE, 2019, 1-5. DOI: 10.1109/ISGTEurope.2019.8905575
[27] Stankovic JA, Abdelzaher TE, Lu C, Sha L, Hou JC. Real-time communication and coordination in embedded sensor networks. Proceedings of the IEEE, 2003, 91(7), 1002-1022. DOI: 10.1109/JPROC.2003.814620
[28] Dai Y, Li M, Zhang K, Shi Y. Robust and resilient distributed MPC for cyber-physical systems against DoS attacks. IEEE Transactions on Industrial Cyber-Physical Systems, 2023, 1, 44-55. DOI: 10.1109/TICPS.2023.3283229
[29] Hu G. Hybrid AI-physics approach for thermo-hydro-mechanical coupled processes in geological systems. 2025. DOI: 10.21203/rs.3.rs-7963302/v1
[30] Samad T, Koch E, Stluka P. Automated demand response for smart buildings and microgrids: The state of the practice and research challenges. Proceedings of the IEEE, 2016, 104(4), 726-744. DOI: 10.1109/JPROC.2016.2520639
[31] Sarangi S, Sahu BK, Rout PK. A comprehensive review of distribution generation integrated DC microgrid protection: issues, strategies, and future direction. International journal of energy research, 2021, 45(4), 5006-5031. DOI: 10.1002/er.6245
[32] Li W, Tan Y, Li Y, Cao Y, Chen C, Zhang M. A new differential backup protection strategy for smart distribution networks: A fast and reliable approach. IEEE Access, 2019, 7, 38135-38145. DOI: 10.1109/ACCESS.2019.2905604
[33] Shen ZJ. Ultrafast solid-state circuit breakers: Protecting converter-based ac and dc microgrids against short circuit faults [Technology Leaders]. IEEE Electrification Magazine, 2016, 4(2), 72-70. DOI: 10.1109/MELE.2016.2544058
[34] Shittu MA, Shittu H, Akintayo TA, Opara IS. IoT enabled microgrid and bess integration in ADMS: A framework for climate resilient grid operation. 2025 IEEE Symposium on Wireless Technology & Applications. IEEE, 2025, 1-9. DOI: 10.1109/ISWTA68114.2025.11330023
[35] Mao Q, Li N. Assessment of the impact of interdependencies on the resilience of networked critical infrastructure systems. Natural hazards, 2018, 93(1), 315-337. DOI: 10.1007/s11069-018-3302-3
[36] Rehman N, Mufti M, Gupta N. Power flow analysis in a distribution system penetrated with renewable energy sources: A review. International Journal of Ambient Energy, 2024, 45(1), 2305701. DOI: 10.1080/01430750.2024.2305701
[37] Gülpinar N, Rustem B, Žaković S. Stochastic optimization and worst-case decisions. Cooperative Systems: Control and Optimization. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, 317-338. DOI: 10.1007/978-3-540-48271-0_19
[38] Aghmadi A, Mohammed OA. Energy storage systems: technologies and high-power applications. Batteries, 2024, 10(4), 141. DOI: 10.3390/batteries10040141
[39] Gorshkov A, Kossobokov V, Soloviev A. Recognition of earthquake-prone areas. Nonlinear dynamics of the lithosphere and earthquake prediction. Berlin, Heidelberg: Springer Berlin Heidelberg, 2003, 239-310. DOI: 10.1007/978-3-662-05298-3_6
[40] Liu C, Ye J, Fang G, Wang D, Zhou L, Emadi A. Resilience framework for power electronic systems against cyber-physical attacks: A review. IEEE Open Journal of Power Electronics, 2024, 6, 28-55. DOI: 10.1109/OJPEL.2024.3512452