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Systematic Review of Microgrids Protection: Challenges, Methods, and Solutions

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Abstract*: Microgrids, pivotal in modern power systems, face unique protection challenges due to bidirectional power flows, dynamic topologies, and inverter-based resources (IBRs). This systematic review critically analyzes 55 peer-reviewed studies (2020-2024) to evaluate microgrid protection challenges, methods, and emerging solutions. We synthesize findings from IEEE Xplore, MDPI, Springer, Wiley, and Taylor & Francis databases using the PRISMA framework. Key challenges include bidirectional power flow (36% of studies), low fault currents (33%), and protection coordination failures (62%). Conventional methods like overcurrent and distance protection struggle with adaptability, while adaptive, communication-assisted, and intelligent strategies show promise but face complexity and cybersecurity risks. AI-driven methodologies achieve a fault-detection accuracy of 99.2%. However, they require substantial datasets and considerable computational resources. Resilience frameworks remain inadequately developed, with merely 10% of the literature addressing critical metrics such as reliability and recovery. This review underscores the imperative for hybrid solutions and the establishment of standardised resilience metrics. It also highlights the importance of validating findings in real-world contexts to ensure the practical application of theoretical progress. Future investigations should emphasise the importance of cybersecurity measures, the implementation of modular enhancements for legacy systems, and the development of explainable artificial intelligence to reconcile theoretical progress with practical application.

Keywords: Adaptive Protection, Conventional Protection, Intelligent Protection, Microgrid, Systematic Review.

Nomenclature:
KPIs: Key Performance Indicators
HIFs: High-Impedance Faults
DERs: Distributed Energy Resources
RES: Renewable Energy Sources
DOCP: Directional overcurrent protection
IBRs: Inverter-Based Resources
CTs: Current Transformers
DGs: Distributed Generators
MTD: Moving Target Defence
TCCs: Time-Current Curves
PMUs: Phasor Measurement Units
TCV: Time-Current-Voltage
ML: Machine Learning
AI: Artificial Intelligence
ANNs: Artificial Neural Networks
SVMs: Support Vector Machines
MAS: Multi-Agent Systems
PMUs: Phasor Measurement Units
TW: Travelling Wave
DSDRs: Dual-Setting Directional Reclosers
FRT: Fault Ride-Through
TCV: Time-Current-Voltage
ENS: Energy Not Served

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I. INTRODUCTION

Microgrids, including residential, commercial, and industrial variants, have revolutionized contemporary power systems by incorporating distributed energy resources (DERs), improving reliability, resilience, and sustainability. Unlike traditional centralized grids, these microgrids operate independently or in grid-connected modes, dynamically However, these unique operational characteristics create managing local generation, storage, and loads. significant protection challenges as conventional protection schemes struggle to handle bidirectional power flows, islanding transitions, and fluctuating short-circuit levels [1]. As microgrids expand, researchers must develop advanced protection strategies that ensure selectivity, reliability, and adaptability under varying grid conditions [2].

Over the past decade, researchers have proposed numerous microgrid protection methods, including adaptive protection, artificial intelligence (AI)-based approaches, and communication-assisted techniques [3], [4]. Despite this progress, no comprehensive study systematically compares the effectiveness, adaptability, and implementation complexity of these methods. In this systematic review, we critically examine the extant literature, categorise the principal challenges in protection, and evaluate the most viable solutions. Our methodical framework guarantees an impartial and transparent assessment of research outcomes, thereby assisting engineers and policymakers in making well-informed choices regarding prospective microgrid protection methodologies [5].

This systematic review aims to answer the following key questions:

- **Question 1:** What are the main challenges in microgrid protection, and how do they differ from conventional power system protection?

This question aims to identify and classify challenges in microgrid protection and to analyse the influence of renewable energy sources on fault detection, selectivity, and protection system coordination.

- **Question 2:** What are the most commonly used microgrid protection methods? How do they

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compare in performance, adaptability, and implementation complexity? How do they improve fault detection and system resilience?

This question aims to compare and evaluate traditional and modern protection approaches.

- **Question 3:** What are the recent advances in intelligent microgrid protection systems?

This question explores the role of AI, machine learning, and communication-based approaches in improving microgrid protection.

These three questions form the basis of the work, and every decision made during its development will aim to answer them successfully.

This review paper organizes its analysis into five distinct sections:

The first section introduces the paper.

The second section demonstrates the meticulous, systematic review method used to develop the review, ensuring the credibility and thoroughness of our research.

The third section shows the details of our analysis's results. It discusses the implications of the key findings for microgrid protection challenges, renewable energy integration, protection methods, and advances in intelligent protection. The fourth section summarizes the conclusions and suggests future research directions.

II. SYSTEMATIC REVIEW METHOD

A. Information Sources

This review gathered literature from five well-known databases:

- IEEE Xplore
- MDPI
- Taylor & Francis
- Springer
- Wiley

B. Search Strategy

The specific search terms employed included "Microgrid," "Isolated grid," "Distributed energy resources," "Protection," "Fault protection," "Relay coordination," "Challenges," "Methods," and "Solutions."

The query strings, which include combinations of key terms like "Microgrid," "Isolated grid," "Distributed energy resources," "Protection," "Fault protection," "Relay coordination," "Challenges," "Methods," and "Solutions," were designed to narrow down the search results to the most relevant papers.

A filter was applied to the initial search results, reducing the number of papers to a manageable level. The number of documents presented without this restriction is 2241.

We considered the following filters:

- This review used only peer-reviewed journal papers and rigorously verified and credible research while emphasizing microgrid protection studies. This targeted approach ensures that the review remains relevant and comprehensive, exploring both theoretical and applied aspects of microgrid protection through modeling, simulation, and practical case studies.
- This review used only papers published between 2020 and 2024, ensuring that the information in this study is up-to-date. By focusing on studies published over the past five years, the journal captures the latest advances and contemporary methodologies, reflecting the current state of research and technological progress.
- This review used only papers in English, a language considered the most common for scientific research. By focusing on English, we aimed to ensure the broadest accessibility and comprehensibility, as it is the predominant language of scientific communication, keeping our audience informed and knowledgeable.

The different tools employed to organize and evaluate the papers were:

- Mendeley Reference Manager: Eliminate duplicates, read, take notes, and organize papers throughout the process.
- Microsoft Excel: Arrange and evaluate data.

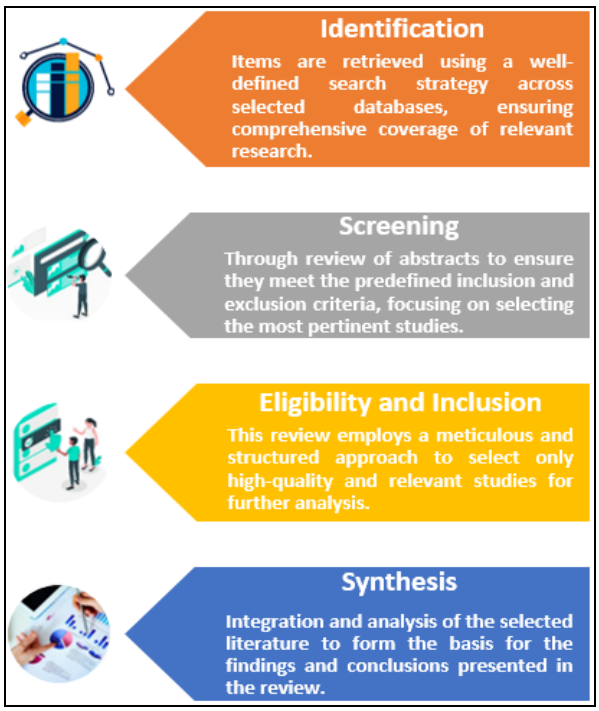
C. Selection Process

i. Prisma Methodology

This review employs the PRISMA 2020 Statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [5] to guide its literature selection process, minimizing potential biases and improving transparency. This systematic approach consists of four stages:

- Identification
- Screening
- Eligibility & Inclusion
- Synthesis

Figure 1 illustrates an overview of the PRISMA methodology.



[Fig.1: Literature Review Process Based on PRISMA Methodology]

ii. Identification Stage

In the Identification stage, we retrieved 347 items using the search strategy defined in the information sources subsection. We introduced a coding system

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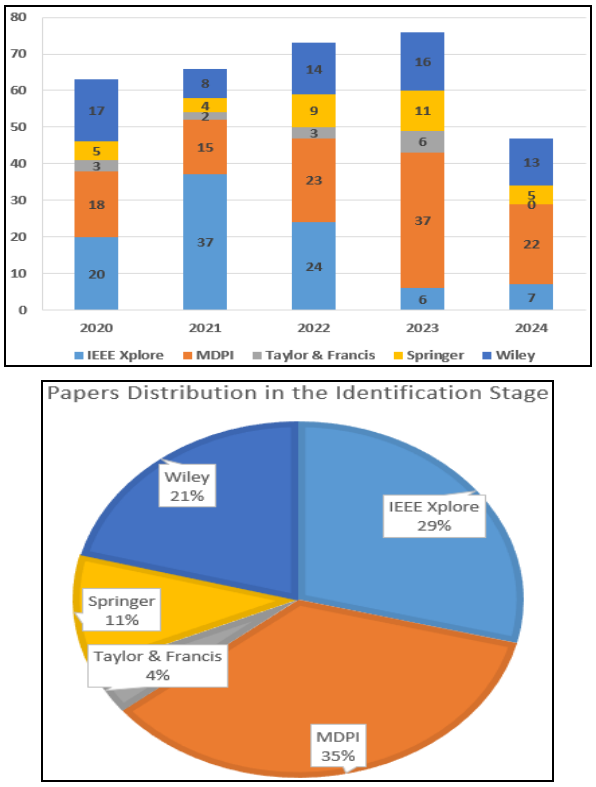
for each item according to the database consulted. Table I presents the identified extracted items.

Table I: The Coding System of the Extracted Items

Data Base	Coding System
IEEE Xplore	xxxx-IEEE
MDPI	xxxx-MDPI
Taylor & Francis	xxxx-Taylor
Springer	xxxx-Springer
Wiley	xxxx-Wiley

We significantly reduced the risk of redundant analysis and bias by diligently removing duplicate entries. With the aid of Mendeley Reference Manager, we identified and eradicated 22 duplicate records, resulting in a precise total of 325 unique items for our research.

Figure 2 presents a comprehensive overview of the item distribution across the databases, providing a clear picture of our research scope: 94 items from IEEE Xplore, 115 items from MDPI, 14 items from Taylor & Francis, 34 items from Springer, and 68 items from Wiley.



[Fig.2: Statistics of the Papers Found in the Identification Stage]

iii. Screening Stage

In the Screening stage, we thoroughly reviewed the titles and abstracts to verify their relevance to the research objectives, using predefined inclusion and exclusion criteria. We carefully defined these criteria to ensure the selection of the most relevant and high-quality studies for protecting microgrids.

- **Inclusion Criterion (IC)**

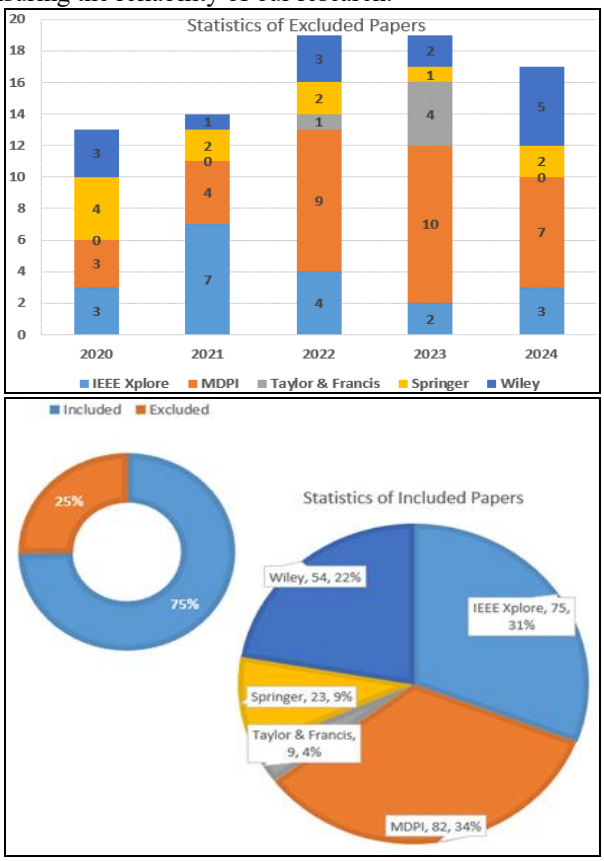
IC1: We included papers published between 2020 and 2024 in English-language journals focusing on protecting microgrids or power systems integrated with distributed generators.

- **Exclusion Criteria (EC)**

EC1: We exclude studies published before 2020 and documents such as editorials and conference papers. Our focus is on original contributions that provide new empirical findings or methodologies.

EC2: We exclude abstracts that show the study does not focus on a microgrid or power system with distributed generators.

EC3: We exclude review papers, reaffirming our commitment to only consider primary sources, thereby ensuring the reliability of our research.



[Fig.3: Screening Stage Process]

Figure 3 shows the Screening stage process, which resulted in the exclusion of 82 items (25% of the database's total) and the inclusion of 243 items (75% of the database's total). The included items appear across the databases as follows:

- 75 items from IEEE Xplore
- 82 items from MDPI
- 9 items from Taylor & Francis
- 23 items from Springer
- 54 items from Wiley

iv.Eligibility and Inclusion Stage

In the Eligibility and Inclusion stage, we assessed the full-text versions of the selected papers using predefined Key Performance Indicators (KPIs) to ensure relevance, quality, and contribution to our review objectives. We established a verification matrix, as summarized in Table II, to evaluate each study based on:

- The discussion of microgrid protection challenges.
- The impact of renewable energy.
- The protection methods.
- The advancements in intelligent protection systems.

A set of criteria guided us selection process. We

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prioritized studies that comprehensively identified protection challenges, classified protection techniques, analyzed performance metrics, and assessed adaptability in microgrid conditions. We also favoured papers that investigated the impact of renewable energy integration on protection reliability and selectivity. Furthermore, we evaluated studies on AI-based and communication-based protection methods for their contributions to system resilience. To ensure the highest methodological rigour, we considered citation count and the level of experimental validation. Each paper was assigned a total score, and only those that met the minimum threshold of 20 points out of 24 (85%) were included in our final dataset, ensuring the inclusion of highly relevant, high-quality studies.

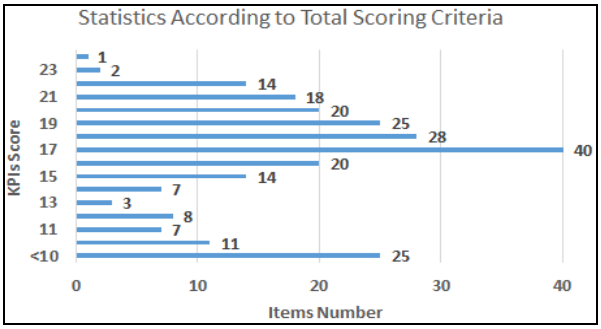
Table II: Verification Matrix

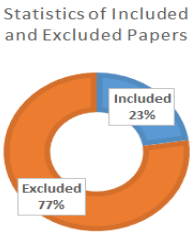
Category	Key Performance Indicators (KPIs)	Description	Scoring Criteria
Challenges in Microgrid Protection	CIS: Challenge Identification Score	Discusses microgrid-specific protection challenges	0 = No 1 = Brief Mention 2 = Detailed Discussion
	CCP: Comparison with Conventional Protection	Compares microgrid protection with conventional power system protection	0 = No 1 = General Mention 2 = In-depth Analysis
Impact of Renewable Energy on Protection	RIC: Renewable Integration Coverage	Evaluates the impact of renewable energy on microgrid protection	0 = No 1 = Brief Mention 2 = Detailed Impact Assessment
	RSA: Reliability & Selectivity Assessment	Analyzes how renewable energy affects protection system reliability and selectivity	0 = No 1 = Qualitative 2 = Quantitative (simulations/experiments)
Evaluation of Protection Methods	MCS: Method Classification Score	Categorizes protection methods	0 = No 1 = Some methods 2 = Comprehensive classification
	PMD: Performance Metrics Discussion	Evaluates methods based on detection speed, sensitivity, and false alarm rate.	0 = No 1 = Basic discussion 2 = Detailed numerical comparison
	ACA: Adaptability and Complexity Analysis	Assesses the adaptability of methods under different operating conditions	0 = No 1 = Basic mention 2 = Case study/simulation
Advances in Intelligent Protection	AIS: AI & ML Integration Score	Discusses AI, ML, or deep learning for microgrid protection	0 = No 1 = Mentioned 2 = Algorithm presented/tested
	CBP: Communication-Based Protection	Covers communication-based or adaptive protection schemes	0 = No 1 = Mentioned 2 = Analyzed in detail
	RI: Resilience Improvement	Shows how intelligent methods improve resilience during faults	0 = No 1 = Theoretical discussion 2 = Experimental/simulated proof
General Paper Quality Indicators	Experimentation Level (EL)	Level of validation	0 = Theoretical only 1 = Simulation-based 2 = Real-world validation
	Citation Count (CC)	Number of citations	0 = <10 1 = 10–50 2 = >50

We evaluated the 243 items from the Screening stage using the Table I criteria, resulting in 55 papers being included in this review. We used an MS Excel sheet to assess the documents and included those scoring 85% or higher (20 points out of 24).

Figure 4 illustrates the Eligibility and Inclusion stage results, which led to the exclusion of 188 items (77% of the database) and the inclusion of 55 items (23% of the database). The scoring distribution based on KPIs indicates that most included papers scored between 17 and 20 points. The included items with a score of 85% or higher (20 points out of 24) are distributed across the databases as follows:

- 37 items from IEEE Xplore
- 9 items from MDPI
- 0 items from Taylor & Francis
- 1 item from Springer
- 8 items from Wiley





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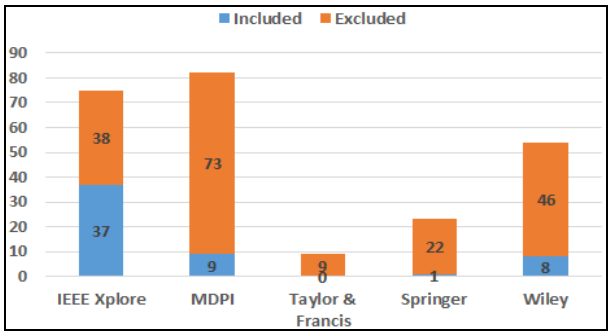
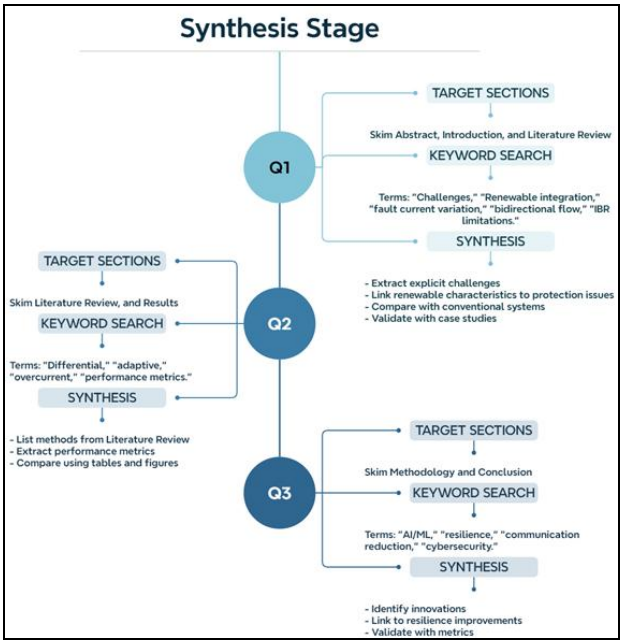


[Fig.4: Eligibility and Inclusion Stage]

v. Synthesis Stage

This stage aims to classify and interpret research contributions, and to identify significant trends and topics in microgrid protection. We combined synthesis methods with flowcharts for each research question to provide rigorous, reproducible answers. This method is consistent with the PRISMA systematic review guidelines, a framework known for its transparency and active synthesis, which reassures the reader of the reliability of our study. Figure 5 presents a flowchart outlining the systematic breakdown of how each question was synthesised.

Figure 5 presents the Synthesis method used for questions 1 (Q1), 2 (Q2), and 3 (Q3).



[Fig.5: Synthesis Method]

III. RESULTS AND DISCUSSIONS

A. Challenges in Microgrid Protection and Differences from Conventional Systems

i. Novel Taxonomy of Challenges

The growing penetration of distributed energy resources (DERs) drives the rapid development of microgrids, which, in turn, introduce protection challenges that differ significantly from those in conventional power systems. In this review, we address the question, "What are the main challenges in microgrid protection, and how do they differ from conventional power system protection?" by synthesising insights from 55 papers ([6]-[60]). To identify dominant challenges, we implemented a bibliometric analysis. Table III presents a quantitative and thematic breakdown of challenges in microgrid protection and their differences from conventional grids.

Table III: Quantitative and Thematic Breakdown of Challenges in Microgrid

Challenge	Frequency	All Papers Addressing the Challenge
Bidirectional power flow	20 out of 55 papers 36%	[6], [10], [11], [14], [15], [17], [22], [24], [25], [30], [31], [40], [43], [48], [49], [50], [54], [57], [58], [59]
Low/limited fault currents	18 out of 55 papers 33%	[7], [10], [12], [13], [14], [20], [25], [27], [29], [30], [31], [36], [46], [49], [54], [55], [56], [60]
Fault current variability (grid-connected - islanded)	17 out of 55 papers 31%	[6], [12], [15], [22], [26], [28], [34], [38], [40], [43], [44], [47], [50], [51], [52], [55], [59]
Communication dependency	20 out of 55 papers 36%	[7], [8], [13], [25], [26], [29], [30], [31], [32], [33], [36], [37], [43], [44], [46], [48], [53], [54], [55], [57]
High-impedance fault (HIF) detection	9 out of 55 papers 16%	[13], [14], [15], [18], [23], [28], [40], [41], [56]
Sensitivity to noise	5 out of 55 papers 9%	[7], [13], [29], [41], [54]
Voltage/frequency instability	6 out of 55 papers 11%	[16], [26], [41], [49], [50], [53]
Inverter-based resource (IBR) limitations	17 out of 55 papers 31%	[7], [10], [12], [13], [19], [25], [27], [28], [30], [31], [44], [46], [49], [55], [56], [57], [60]
Protection blinding Miscoordination	34 out of 55 papers 62%	[6], [8], [10], [11], [15], [16], [17], [19], [21], [22], [23], [24], [25], [27], [28], [30], [31], [33], [34], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [53], [57], [58], [59], [60]

ii. Bidirectional Power Flow

Bidirectional power flow in microgrids complicates fault detection and relay coordination. Unlike conventional systems with unidirectional power flow, microgrids render traditional directional protection schemes ineffective and increase the risk of sympathetic tripping, as recloser-fuse coordination often fails under reverse-power-flow conditions.

iii. Variable and Low Fault Current Levels

Inverter-based microgrids limit fault currents to 1.2–2 p.u., far below the 5–10 p.u. range. typically generated by synchronous generators in conventional grids. This lower current range prevents traditional overcurrent relays from functioning reliably, particularly in islanded mode, and leaves high-impedance faults (HIFs) nearly undetectable. While the fluctuating nature of renewable energy sources (RES) reduces the sensitivity of conventional protection methods, potentially delaying fault clearance and raising misoperation risks, localised generation simultaneously strengthens resilience. For example, RES in islanded mode can supply backup power during grid disturbances, sustaining critical loads. Achieving this advantage, however, requires deploying advanced protection strategies that rapidly isolate faults and shorten outage durations.

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iv. Dynamic Topology and Operating Modes

Microgrids frequently switch between grid-connected and islanded modes, causing significant variations in fault current magnitudes and network configurations. In islanded mode, fault currents can drop to just 2–3 times the rated current, far lower than those observed when connected to the primary grid. These shifting operational states demand adaptive protection schemes that dynamically adjust relay settings in real time, unlike conventional systems, which rely on static topologies and fixed configurations.

v. Inverter-Based Microgrids Limitations

Inverter-based microgrids generate non-sinusoidal fault currents with harmonic distortions and controlled phase angles, complicating phasor estimation and relay coordination. Distance relays, for example, frequently misoperate when exposed to the atypical fault behaviours of inverter-based microgrids. Unlike synchronous machines, these microgrids cannot generate stable sinusoidal waveforms during faults. Furthermore, harmonics produced by inverters disrupt relay fault-detection algorithms, forcing engineers to integrate advanced filtering methods to improve accuracy.

vi.High-Impedance Faults (HIFs) and Sensitivity Issues

High-impedance faults produce low-magnitude currents that overlap with load currents, making fault detection in microgrids challenging. Under high renewable energy penetration, this "protection blindness" becomes more pronounced, as traditional overcurrent protection relies on the high fault currents typical of conventional systems.

vii.Communication and Synchronization Requirements

Advanced protection schemes rely on high-bandwidth communication networks for real-time coordination. This reliance exposes microgrids to risks such as delays, synchronization issues, and cyber-attacks like false-data injection that compromise relay operations, unlike the simpler, decentralized protection found in conventional systems.

viii. Protection Coordination Challenges

The intermittent output of RES and variable fault currents disrupts coordination among primary relays, backup devices, reclosers, and fuses. In microgrids, RES back-feed currents can trigger sympathetic tripping, disconnect healthy feeders and complicate fixed coordination strategies that work well in static, radial conventional networks.

ix. Grounding and Re-Synchronization Issues

During islanded operation, microgrids lose the primary grid's grounding reference, which complicates ground fault detection. Additionally, re-synchronization during grid reconnection introduces voltage and frequency deviations that force dynamic adjustments in relay settings to maintain system stability.

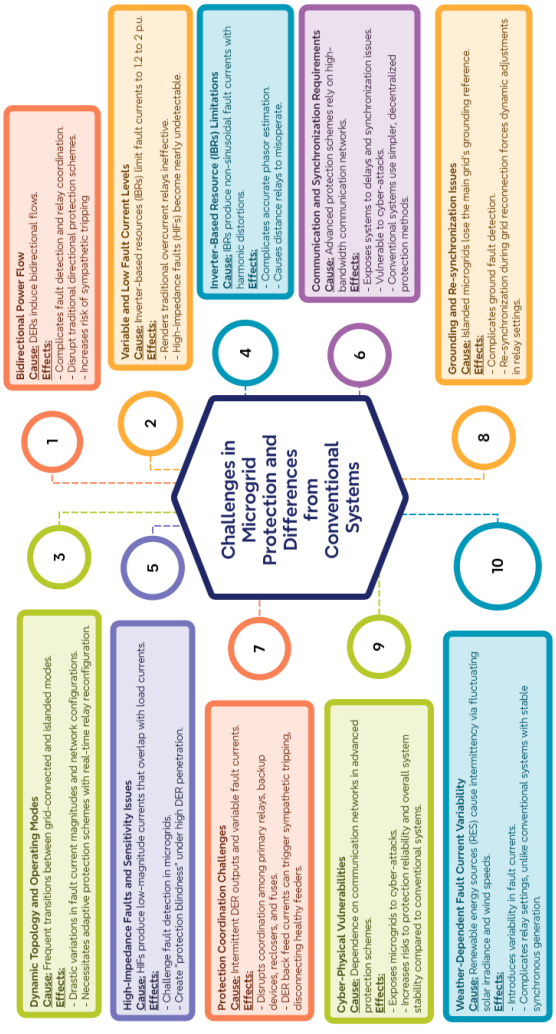
x. Cyber-Physical Vulnerabilities

Many studies emphasize that the integration of RES increases the reliance on sophisticated control strategies and robust communication networks. While these systems enable adaptive protection by continuously updating relay settings, they also introduce vulnerabilities related to communication delays and potential cyber threats, and expose microgrids to cyber-attacks such as false-data injection (FDI), which can disrupt relay coordination. These vulnerabilities pose significant risks to protection reliability and system stability, conventional systems, with simpler decentralized protection, face fewer such threats due to predictable fault behavior.

xi. Weather-Dependent Fault Current Variability

Renewable energy sources (RES) create intermittent fault currents because solar irradiance and wind speeds vary unpredictably. These weather-dependent variations complicate the coordination of protective relays, forcing engineers to adopt stochastic modelling to ensure reliable system operation. In contrast, conventional power systems rely on stable synchronous generation, which inherently avoids such unpredictability.

Figure 6 presents a comprehensive mind map outlining the key challenges in microgrid protection and highlighting how they differ from those in conventional power system protection.



[Fig.6: Mind Map of Key Challenges in Microgrid Protection]

Microgrid challenges are classified into four interconnected categories that reflect their technical, operational, economic, and regulatory dimensions.

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Table IV: Microgrid Challenges Categories

Category	Sub-Challenges	Key Papers
Technical	Bidirectional power flow	51 out of 55 papers 93%
	Low/inconsistent fault currents (IBR limitations)	
	Relay coordination failures	
	High-impedance fault (HIF) detection	
	Voltage/frequency instability	
Operational	Mode transitions (grid-connected ↔ islanded)	18 out of 55 papers 33%
	Dynamic topology changes	
	DG penetration variability	
	Communication latency/packet loss	
Economic	High cost of differential protection	5 out of 55 papers 9%
	Communication infrastructure expenses	
	Retrofitting legacy systems	
Regulatory	Lack of microgrid-specific standards	3 out of 55 papers 5%
	Inverter compliance issues	
	Cybersecurity mandates	

Tables III and IV show that most researchers focus primarily on technical challenges in modern power systems, with 93% of the papers exploring bidirectional issues. This substantial focus underscores engineers' need to revamp traditional systems to accommodate energy from distributed sources. The research also investigates issues such as low and inconsistent fault currents from inverter-based sources, relay coordination problems, difficulties in detecting high-impedance faults, and voltage and frequency stability issues. About 33% of the studies examine operational challenges, such as the intricacies of switching between grid-connected and islanded modes, changes in network layouts, variations in distributed generation, and communication delays or losses that can disrupt system control. Only 9% of the research addresses economic challenges, such as the high cost of differential protection, suggesting that cost issues and outdated system updates are not the primary focus. Finally, just 5% of the papers address regulatory challenges, highlighting the need to establish specific standards, improve inverter compliance, and strengthen cybersecurity to underpin new grid technologies.

B. Linking Challenges to Real-World Failures

While many studies rely on simulations, it's rare for a small subset of authors to bridge theoretical challenges with practical outcomes successfully. This exceptional approach validates theoretical models and underscores the urgent need to address these issues in real-world applications. With only 2% of studies (1 out of 55) directly correlating these challenges with documented real-world incidents, the significant gap between research and practical incident analysis becomes even more pronounced.

The Ukrainian Grid Attack (2015) serves as a stark reminder of the potential devastation of a synchronized and coordinated cyberattack. This incident compromised three Ukrainian regional electric power distribution companies, leading to power outages that affected approximately 225,000 customers for several hours. The exacerbation of cascading outages due to communication failures in adaptive protection [9] underscores the gravity of the situation.

U.S. Wind/Solar Cyberattacks (2019): A denial-of-service attack left grid operators temporarily blinded to several wind and solar farm generation sites in the U.S. Spoofed relay settings delayed fault clearing [9]. Case studies bridge theoretical research and practical implementation. Only 13% of studies (7/55) validate findings with real-world data.

C. Mapping Challenges to Microgrid Archetypes

The literature differentiates microgrid protection issues based on system architecture. Papers that explore centralized versus distributed configurations or compare grid-connected with islanded modes reveal that challenges vary significantly with system design. For instance, the unique challenges posed by low fault currents in inverter-based islanded microgrids and the more pressing issues created by communication delays in large, distributed networks highlight the field's complexity. Mapping these distinctions enables engineers to customize protection strategies for specific microgrid archetypes (Table V), ensuring solutions balance effectiveness and cost-efficiency.

Table V: Microgrid Archetypes

Archetype	Key Challenges	Key Papers
Grid-Connected	▪ Islanding detection and prevention ▪ Bidirectional power flow complicates fault current contributions ▪ Coordination between microgrid and central grid protection systems ▪ Dynamic network topology requiring adaptive settings Impact of cybersecurity vulnerabilities in communication-based schemes	33 out of 55 papers 60%
Islanded (IBR-Dominated)	▪ Reduced fault current levels and lack of external support ▪ Frequency and voltage regulation challenges ▪ Limited backup protection and inertia ▪ Adaptive protection schemes required for isolated operation Maintaining stability without a grid reference	16 out of 55 papers 29%
AC Microgrid	▪ Inverter-based resource behaviour reduces fault current levels ▪ Sensitivity issues with traditional overcurrent relays ▪ Coordination with legacy protection systems ▪ Variable fault contributions from renewable sources Necessity for adaptive and fast-acting protection schemes	6 out of 55 papers 11%
DC Microgrid	▪ Lack of natural current zero crossings, complicating arc fault detection ▪ Fast transient fault detection and isolation requirements ▪ Limited availability of standard protection devices ▪ Overvoltage and short-circuit protection challenges Rapid response needs for fault isolation	1 out of 55 papers 2%
Hybrid Microgrid	▪ Coordinating protection between AC and DC subsystems ▪ Bridging different voltage levels and fault characteristics ▪ Inconsistent fault propagation across domains ▪ Complex system integration and adaptive setting challenges Communication delays between the AC and DC protection layers	2 out of 55 papers 4%
Multi-Microgrid Clusters	▪ Complex inter-microgrid protection coordination ▪ Cascading fault propagation risks ▪ Communication and latency challenges across different microgrids ▪ Multi-layered protection settings requiring synchronization Ensuring consistency in adaptive protection schemes across a distributed network	3 out of 55 papers 5%

D. Resilience Scoring Framework

Resilience metrics are vital for assessing and enhancing

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microgrid reliability in the face of uncertainties such as component failures, extreme weather, or cyberattacks. Researchers and practitioners commonly emphasize the following key resilience metrics and concepts in the literature:

i. Reliability and Availability Metrics

- **Loss of Load Probability (LOLP):** is a practical metric that quantifies the probability of the available supply failing to meet the load demand during a specific period. This metric is not just a theoretical concept but a tool for assessing and improving the reliability of a microgrid in real-world scenarios.
- **Expected Energy Not Served (EENS):** estimates that the energy system fails to deliver critical loads during outages.
- **The System Average Interruption Frequency Index (SAIFI) and Duration Index (SAIDI):** These indices accurately assess the frequency and duration of power interruptions in the context of microgrids, making them highly relevant and applicable to energy systems and microgrid technology.

ii. Recovery and Restoration Metrics

- **Mean Time to Recovery (MTTR):** Measures the average time it takes for the microgrid to recover after a disruptive event.
- **Time to Resilience (TR):** Metric that may include restoration time and the time required to re-establish full operational functionality, including synchronization with the primary grid if needed.

iii. Robustness and Flexibility

- **Contingency Analysis (N-1, N-2, etc.):** The microgrid can sustain operation when one or more components fail.
- **Reserve Margin:** Extra capacity to meet demand during unexpected outages or load spikes.
- **Diversity of Energy Sources:** Mix and redundancy of generation resources can indicate resilience.

iv. Operational Resilience Metrics

- **Self-Healing Capabilities:** Measures how effectively a microgrid can automatically reconfigure or isolate faults to prevent cascading failures.
- **Cyber-Physical Resilience Indicators:** Metrics assessing the physical infrastructure and its cybersecurity.

v. Economic and Performance-Based Metrics

- **Cost of Resilience:** Evaluate the economic trade-offs involved in incorporating resilience measures.
- **Performance Degradation Under Stress:** Monitors how system performance degrades under stress conditions and how quickly it can return to optimal levels.

Only 6 (11%) of the 55 papers directly or indirectly address the crucial topic of resilience. This research is paramount in our field, as it provides valuable insights into the current resilience of energy systems.

Paper [19] focuses on self-healing capabilities and contingency handling as key resilience features. It validates these through dynamic reconfiguration and fault recovery in grid-connected and islanded modes. However, it does not address economic trade-offs, cyber-physical resilience, or formal reliability metrics (LOLP, SAIDI). The resilience framework is primarily technical, emphasizing protection logic, inverter stability, and automated reconfiguration.

Paper [32] addresses resilience through reliability metrics (PSuccess, LOutage), self-healing via agent negotiation and fault isolation, and contingency handling for multiple faults.

Paper [53] addresses robustness (via contingency handling and VSM optimization) and operational resilience (through priority-based load shedding). However, it lacks an explicit discussion of traditional resilience metrics such as LOLP, SAIDI, MTTR, and cyber-physical indicators. This could limit the research's applicability in real-world settings. The focus remains on technical performance (detection accuracy, voltage stability) rather than comprehensive resilience frameworks.

Paper [28] mentions "resilience" in the abstract and conclusion, linking the proposed strategy to improved grid resilience. The focus is on mitigating protection blindness via adaptive settings and fault-current limitation, thereby indirectly supporting resilience through improved fault management.

Paper [36] focuses on the design of protection schemes and low-cost communication for fault detection in inverter-dominated microgrids. In contrast, it enhances operational reliability and indirectly supports resilience (e.g., fast fault isolation and communication redundancy). The resilience-related terms mentioned ("reliability," "self-healing") are qualitative and not quantified.

Paper [45] addresses protection system optimization (adaptive relay coordination) to enhance reliability and speed. While it indirectly touches on robustness (via DG/topology variations) and operational adaptability, none of the resilience metrics are explicitly analyzed.

E. Protection Strategies in Microgrid

i. Novel Taxonomy of Strategies

Researchers have investigated a wide range of protection strategies to address microgrids' unique challenges. This review addresses the question, " What are the most commonly used microgrid protection methods? How do they compare in performance, adaptability, and implementation complexity, and how do they improve fault detection and system resilience?", " What are the recent advances in intelligent microgrid protection systems?" by synthesizing insights from 55 papers ([6]-[60]). We implemented a bibliometric analysis to identify dominant protection strategies. Table VI presents a quantitative and thematic breakdown of microgrid protection strategies.

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Table VI: Quantitative and Thematic Breakdown of Microgrid Protection Strategies

Protection Strategies	Frequency	All Papers Addressing Protection Strategies
Communication-Based Protection	11 out of 55 papers 20%	[8]-[14]-[30]-[35]-[39]-[44]-[47]-[48]-[56]
Differential Protection	6 out of 55 papers 11%	[9]-[23]-[24]-[32]
Inverter-Based Protection	7 out of 55 papers 13%	[16]-[18]-[19]-[25]-[34]-[36]-[39]
Adaptive Protection	14 out of 55 papers 25%	[11]-[28]-[30]-[32]-[35]-[38]-[41]-[45]-[58]
Directional Overcurrent Protection	5 out of 55 papers 9%	[24]-[32]-[40]
Distance (Impedance) Protection	4 out of 55 papers 7%	[32]-[52]-[53]-[54]
Overcurrent (OC) Protection	6 out of 55 papers 11%	[17]-[21]-[37]
Recloser and Fuse Protection	2 out of 55 papers 4%	[17]-[29]
Voltage-Based Protection	1 out of 55 papers 2%	
Frequency-Based Protection	2 out of 55 papers 4%	[22]
Intelligent Protection	7 out of 55 papers 13%	[55]
Travelling Wave-Based Protection	7 out of 55 papers 13%	[18]-[19]-[30]-[49]-[54]
Hybrid and Novel Schemes	5 out of 55 papers 9%	[20]-[26]-[40]-[46]

We classify microgrid protection strategies into six categories to provide a comprehensive understanding of how to tailor these strategies to address the dynamic challenges posed by microgrids, as discussed in the previous section. Table VII presents data from a taxonomy that provides a structured framework highlighting the evolution from conventional approaches to emerging, adaptive, and integrated solutions. This taxonomy plays a crucial role in this review paper by organizing existing research into clear, mutually exclusive categories and identifying gaps and opportunities for future work.

Table VII: Microgrid Protection Categories

Category	Techniques	Key Papers
Conventional Protection	Overcurrent (OC) Protection Distance (Impedance) Protection Differential Protection Directional Overcurrent Protection Recloser and Fuse Protection	19 out of 55 papers 35%
Adaptive Protection	Adaptive Protection Voltage-Based Protection	14 out of 55 papers 25%
Communication-Assisted Protection	Communication-Based Protection	11 out of 55 papers 20%
Inverter/DER-Specific Protection	Inverter-Based protection	7 out of 55 papers 13%
Intelligent & Data-Driven Methods	Intelligent Protection Frequency-Based Protection Travelling Wave-Based Protection	14 out of 55 papers 25%
Hybrid/Integrated Systems	Hybrid and Novel Schemes	5 out of 55 papers 9%

The bibliometric analysis shows that researchers emphasise a diversified approach to protection strategies. Conventional protection techniques, including overcurrent relays, distance protection, differential protection, directional overcurrent protection, and recloser and fuse protection, appear in 35% (19 papers) of the literature, demonstrating continued reliance on established methods. Researchers also focus on adaptive and voltage-based protection, which accounts for 25% (14 papers), as they develop dynamic systems that swiftly respond to changing grid conditions. However, researchers increasingly emphasize communication-assisted protection in the literature, highlighting this approach in 20% (11 papers). This trend underscores the increasing importance of integrating real-time data exchange to improve system reliability. The literature also shows that inverter/DER-specific protection accounts for 13% (7 papers) and addresses the challenges associated with renewable energy integration. Meanwhile, intelligent and data-driven methods, including intelligent protection, frequency-based protection, and travelling-wave-based protection, account for 25% (14 papers) of the research, as investigators leverage innovative technologies to enhance resilience. Finally, researchers are exploring hybrid or integrated systems, as evidenced by 9% (5 papers) that present hybrid and novel schemes that blend traditional and innovative approaches to achieve robust protection.

ii. Conventional Methods

Traditional schemes developed for radial, centrally generated grids rely on fixed settings and simpler coordination methods.

iii. Overcurrent Protection (OCP)

Traditional overcurrent relays are widely used in conventional systems because they are cost-effective and straightforward. However, several studies highlight that OCP is less effective in microgrids. The low fault current levels, especially in islanded operation, and the bidirectional power flow often led to miscoordination and false tripping. While OCP has low implementation complexity, its performance and adaptability are limited in microgrids.

The adaptability of overcurrent protection (OCP) in microgrids, particularly its ability to handle bidirectional power flows and low fault currents inherent to inverter-based resources (IBRs), is a key aspect of this protection.

Implementing OCP in microgrids is a complex task that involves balancing cost-effectiveness with the need for adaptive settings to handle dynamic operating conditions.

The limitations of fixed relay settings pose a significant challenge for OCP, underscoring the need for more advanced, adaptable solutions in microgrids.

- False tripping due to bidirectional flows [11] proposes voltage-restrained relays (51V) to mitigate this.
- Limited sensitivity to high-impedance faults, addressed in [12] using Mahalanobis distance-based detection.

iv. Differential Protection

Differential relaying compares current measurements at both ends of a protected zone, providing high sensitivity and selectivity even under bidirectional conditions. This method excels at accurately isolating faults but typically requires robust communication infrastructure and synchronised measurement units, which increase costs and implementation complexity. Despite these challenges,

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differential protection remains a benchmark for performance.

- Achieves 99.97% accuracy in fault detection using EWT-LSTM models [47].
- Immune to external faults and load fluctuations (Paper [25] demonstrates 100% selectivity with harmonic injection).

The complexity of differential protection lies in the need for synchronised measurements and a high-speed communication infrastructure.

- Requires IEC 61850 protocols for real-time coordination (latency <2 ms in [26]).
- Costs escalate due to fibre-optic networks (24.54% increase over traditional methods [20]).

Despite its precision, differential protection faces cybersecurity and synchronisation challenges.

- Vulnerable to data spoofing (Paper [9] proposes Moving Target Defence (MTD) techniques).
- Synchronization errors degrade performance ([20, 35] use cosine similarity algorithms to reduce errors).

v. Distance (Impedance) Protection

Distance relays measure impedance to estimate fault location and are less dependent on absolute fault current levels. However, they are sensitive to the variable X/R ratios and bidirectional flows encountered in microgrids. These factors can compromise performance, particularly in distribution networks with short lines and multiple distributed generators (DGs). Variable X/R ratios can introduce errors in impedance measurements, while bidirectional flows can confuse the relay about the fault direction, leading to delayed or incorrect operation.

- Struggles with short-line applications (Paper [40] proposes the IIA scheme for IEEE 15-bus systems).
- Grid-forming inverters mimic synchronous behaviour, distorting impedance profiles (Paper [39] reports 4.4 Ω measurement errors).

Implementing distance protection in microgrids is a complex task that demands adaptive thresholds to account for the variability induced by Distributed Energy Resources (DERs). This feature is crucial for maintaining the protection scheme's reliability and effectiveness.

- Dynamic thresholds are essential (Paper [51] integrates SARIMA/ANFIS forecasting for adaptive impedance settings).
- Costs are moderate but higher than traditional OCP due to advanced relay logic.

Key challenges include sensitivity to fault resistance and inverter dynamics.

- Fails to detect high-impedance faults (HIFs >100) without supplemental methods (Paper [12] combines wavelet transforms with Mahalanobis distance).
- Variable X/R ratios in DER-rich networks reduce accuracy [39].

vi. Directional Overcurrent Protection (DOCP)

Directional overcurrent protection improves traditional overcurrent schemes by integrating directionality into fault detection. This method selectively triggers relay responses only when fault currents flow in predefined directions, enhancing precision in networks with complex or bidirectional power flows. While it mitigates key limitations of conventional overcurrent protection, its reliability in microgrids requires precise relay settings and a robust communication infrastructure to identify current direction under dynamic operating conditions accurately.

Directional overcurrent protection (DOCP) is a significant advancement in the field. It enhances traditional methods by incorporating directional sensitivity, making it a critical component for microgrids with bidirectional power flow from distributed energy resources (DERs).

- Resolves relay miscoordination caused by reverse power flow (Paper [11] uses voltage-restrained directional relays (51V) for grid-islanded transitions).
- Dual-setting DOCRs in Paper [33] reduce relay operating times by 44% while maintaining selectivity.

Implementing DOCP is not just about the protection scheme itself. It also requires a robust synchronization and communication infrastructure to ensure accurate directional fault detection. These elements are as crucial as the protection scheme itself.

- IEC 61850 GOOSE messaging [24] enables real-time coordination but introduces cybersecurity risks.
- Costs rise due to advanced relay logic and sensors (Paper [44] cites a 24% cost increase over non-directional relays).

DOCP faces limitations in low-inertia microgrids and scenarios with unsynchronized measurements.

- Unsynchronized current transformers (CTs) degrade accuracy (Paper [20] reports synchronization errors of 1.5 – 2.2 ms).
- Low fault currents in islanded mode may fall below relay pickup thresholds.

vii. Recloser and Fuse Protection

Reclosers and fuses—the cornerstone of protection against transient faults in network components—play a crucial role in microgrid design. Reclosers, with automatic service restoration after temporary faults, and fuses, which permanently isolate damaged sections, form the backbone of microgrid protection. However, successfully integrating these devices with the system's operational dynamics is paramount.

The built-in delays and mechanical limitations in fuses, coupled with a recloser's re-energization logic, directly influence network reliability and stability during fault conditions.

Reclosers and fuses are foundational components of radial microgrids, providing temporary fault mitigation and permanent isolation.

- Reclosers reduce outage durations by 60% in grid-connected mode [11].
- AI-optimized fuse-relay coordination in Paper [28] achieves zero miscoordination in simulations.

Coordinating reclosers and fuses demands precise time-current curves (TCCs) and adaptive settings for dynamic microgrids.

- Reclosers are costlier than fuses but offer automation benefits.

The primary challenges in coordinating reclosers and fuses are managing dynamic fault currents and preserving fuse durability in high-DER environments.

- Islanded operation

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invalidates pre-set TCCs (Paper [51] demonstrates a 54% reduction in total operating time with adaptive settings).

- Frequent recloser operations degrade fuse performance (Paper [22] observes a 20% shorter fuse lifespan in high-renewable systems).

Table VIII synthesizes each conventional protection strategy's strengths, weaknesses, and innovations.

Table VIII: Synthesizes of Conventional Protection Strategy

Strategy	Strengths	Weaknesses	Key Innovation	Microgrid Suitability
Overcurrent Protection	Low cost, simplicity	Bidirectional flow issues	Dual-setting DOCRs [33]	Moderate (with adaptations)
Differential Protection	High accuracy, selectivity	High cost, synchronization needs	Edge computing + AI [29]	High (for critical zones)
Distance Protection	Zonal fault localization	Sensitivity to X/R ratios	IIA scheme [40]	Low (unless hybridized)
Directional Overcurrent Protection	Bidirectional flow handling, high sensitivity	High implementation cost, synchronization dependency	Dual-setting DOCRs [33]	High (DER-rich, bidirectional systems)
Recloser and Fuse Protection	Cost-effective outage reduction, simplicity	Coordination complexity, fuse degradation	AI-optimized coordination [11]	Moderate (radial networks)

viii. Adaptive Protection Schemes

Adaptive methods play a crucial role in dynamically adjusting their settings based on real-time system conditions. This dynamic adjustment is of utmost importance in maintaining the reliable operation of dynamic microgrids.

ix. Adaptive protection

Adaptive protection dynamically adjusts relay settings based on real-time operating conditions. These systems can seamlessly transition settings between grid-connected and islanded modes to ensure optimal safety, even when renewable energy sources and DER integration introduce variability. While adaptive strategies deliver superior performance and flexibility, their implementation demands continuous monitoring systems, sophisticated algorithms, and dependable communication infrastructure to address inherent operational complexity.

Adaptive protection systems thrive in microgrids by dynamically adjusting relay settings to align with real-time operating conditions, such as transitions between grid-connected and islanded modes or fluctuations in distributed energy resource (DER) output. These systems prioritise three core performance metrics: accurate fault detection, coordination speed, and the ability to adapt to unpredictable fault currents, ensuring reliable protection despite dynamic grid behaviour.

- **Grid-Islanded Transitions:** Paper [8] uses AI clustering to reduce relay setting groups by 63% during mode transitions in the IEEE 34-node feeder.
- **Fault Current Variability**: Paper [10] uses Time-Current-Voltage (TCV) relays in test microgrids to reduce total operation time by 44%.
- **Renewable Integration:** Metaheuristic algorithms (MPSO, GWO) in Paper [15] optimize directional overcurrent relays (DOCRs) in IEC networks, reducing computational costs by 32%.

Adaptive protection requires robust monitoring infrastructure, advanced algorithms, and reliable communication, increasing technical and financial complexity.

- Advanced monitoring infrastructure, such as Phasor measurement units (PMUs) and IoT sensors, plays a pivotal role in adaptive protection. These systems are essential for real-time data, as demonstrated in Paper [26], which reports round-trip delays of 48.3 ms.
- **Algorithm Overhead:** AI/ML models (ANN in Paper [6]) demand high computational resources, increasing relay costs by 18 – 25% [10]. These 'relay costs' refer to the additional expenses incurred due to the use of AI/ML models in adaptive protection systems. Understanding these costs is essential for budgeting and resource allocation in implementing adaptive protection systems.
- **Communication Networks:** IEC 61850 protocols are key to adaptive protection systems. They enable coordination but require specific infrastructure, such as fibre-optic or 5G, to function effectively [24]. Understanding the role and requirements of these protocols is crucial for successfully implementing adaptive protection systems.

Despite their advantages, adaptive schemes face synchronization errors, cybersecurity risks, and scalability limitations in large-scale microgrids.

- **Communication Latency:** Delays >130 μs degrade coordination accuracy [6].
- **Cybersecurity Vulnerabilities:** Paper [9] identifies spoofing risks in IEC 61850 GOOSE messaging.
- **Scalability:** AI models struggle with real-time processing in microgrids with>50 nodes.

x. Voltage-Based Protection

Voltage-based methods (such as undervoltage or overvoltage relaying) rely on changes in voltage to detect faults. While these methods are straightforward and inexpensive, their limitations become apparent when voltage drops occur uniformly across the network during faults. This lack of discrimination hampers their effectiveness, particularly in systems with low inertia, underscoring the need for alternative solutions.

Voltage-based protection uses undervoltage/overvoltage thresholds to detect faults. While low-cost and straightforward, its effectiveness is limited in microgrids with uniform voltage drops during faults or low-inertia conditions.

- **Simplicity:** Voltage-restrained overcurrent relays (51V) in Paper [11] reduce miscoordination by 40% in radial networks.
- **Hybrid Methods:** Paper [40] combines voltage and impedance measurements, achieving 95% accuracy in IEEE 15-bus systems.

While voltage-based methods are inexpensive to deploy, their lack of adaptability in dynamic microgrids is a pressing issue.

This highlights the need for more flexible and adaptive protection methods that can effectively respond to the changing conditions of modern power systems.

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- **Low-Cost Infrastructure**: Requires only voltage sensors (Paper [17] cites 60% lower costs than differential protection).
- **Fixed Thresholds:** Pre-set voltage limits fail during DER fluctuations [51].

Uniform voltage dips during faults, and inverter-dominated dynamics undermine selectivity and accuracy.

- **Low-Inertia Systems:** Grid-forming inverters distort voltage profiles, causing 4.4 Ω measurement errors. Paper [39].

Table IX synthesizes each adaptive protection strategy's strengths, weaknesses, and innovations.

Table IX: Synthesizes of Adaptive Protection Strategy

Strategy	Strengths	Weaknesses	Key Innovation	Microgrid Suitability
Adaptive Protection	Real-time adaptability, DER resilience	High complexity, cybersecurity risks	TCV relays [10]	High Dynamic DER environments
Voltage-Based Protection	Low cost, simplicity	Poor discrimination, low-inertia issues	Voltage Impedance Hybrids [40]	Low (unless hybridized)

xi. Communication-Assisted Protection

Modern protection strategies utilize high-speed communication networks and wide-area measurement systems to improve fault detection, coordination, and isolation. Protocols like IEC 61850 GOOSE enable rapid data exchange between protective devices in communication-based schemes, significantly accelerating fault detection and isolation while improving selectivity. However, these strategies require substantial infrastructure investment and depend heavily on the reliability of communication networks. While they achieve high performance and adaptability, they do so at the expense of higher infrastructure complexity.

Communication-assisted protection leverages high-speed data exchange and synchronised measurements to enhance fault detection, coordination, and isolation. These strategies are particularly effective in microgrids with distributed energy resources (DERs), where bidirectional power flows and variable fault currents complicate traditional methods.

- **Fault Isolation Speed:** IEC 61850 GOOSE messaging in Paper [24] reduces fault isolation times to 14 ms, compared to 50 – 100 ms in non-communicative schemes.
- **Selectivity Improvement**: Paper [19] demonstrates 100% fault discrimination in IEEE 123-node systems using synchronized phasor measurement units (PMUs).
- **Adaptive Coordination:** Multi-agent systems (MAS) in Paper [44] dynamically adjust relay settings, achieving zero miscoordination in 135-bus test systems.

Essential Robust Infrastructure: Communication-assisted schemes necessitate a robust infrastructure, including high-speed communication networks, synchronized sensors, and advanced protocols. This infrastructure is crucial and significantly increases technical and financial complexity.

- **Infrastructure Costs:** Fibre-optic networks and PMUs raise deployment costs by 30 – 40% compared to traditional methods [20].
- **Protocol Integration:** IEC 61850-9-2 process bus implementation in Paper [26] demands 48.3 ms round-trip delays for real-time coordination.

Despite their advantages, communication-assisted strategies are vulnerable to cybersecurity threats, prone to synchronisation errors, and dependent on network reliability.

- **Cybersecurity Risks:** A paper [9] identifies spoofing attacks on GOOSE messages, which cause 12% false tripping in simulated grids.
- **Synchronization Errors:** Unsynchronized PMUs in Paper [20] introduce 1.5 – 2.2 ms delays, leading to an 18% degradation in fault localization accuracy.
- Network reliability is not just a factor but a cornerstone of communication-assisted schemes.

xii. Intelligent and Data-Driven Methods

Emerging protection strategies leverage data analytics, artificial intelligence (AI), and machine learning (ML) to improve fault-detection accuracy, enable precise fault classification, and enhance overall system resilience. These adaptive methods excel in dynamic grid environments, enhancing protection coordination, particularly in microgrids where conventional methods often fall short.

xiii. Intelligent Protection

Recent research explores the use of artificial intelligence (AI) and machine learning (ML) for fault detection, classification, and location in power systems. AI-driven methods—such as neural networks, support vector machines, and decision trees—demonstrate high accuracy and adaptability across diverse fault scenarios. However, these approaches require large training datasets, robust data-acquisition systems, and significant computational resources, thereby increasing implementation complexity.

AI and ML techniques transform power system protection by enabling advanced fault detection, classification, and location estimation. Models like artificial neural networks (ANNs), support vector machines (SVMs), and deep learning frameworks adapt dynamically to shifting network topologies, intermittent renewable generation, and bidirectional power flows, making them ideal for microgrids. Despite their precision, challenges persist: reliance on vast training data, real-time processing demands, and high computational costs complicate scalability. Researchers are developing hybrid strategies that combine AI with conventional security measures to address this, balancing innovation with practicality.

Intelligent protection systems leverage AI and ML to improve fault-detection accuracy, classify complex nonlinear patterns (common in DER-rich microgrids), and bolster grid resilience. These systems excel in bidirectional power flows and variable generation environments, where traditional methods struggle.

- **High Accuracy:** Neural networks in Paper [15] achieve 99.2% fault

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classification accuracy in IEC microgrids.

- **Adaptability** is a key strength of Support Vector Machines (SVMs).
- **Speed:** Decision tree models in paper [56] detect faults within 1.5 ms, outperforming traditional relays by 80%. Intelligent methods demand robust data infrastructure, advanced algorithms, and substantial computational resources, thereby increasing costs and technical complexity.
- **Data Acquisition:** Paper [47] requires PMUs to sample at 10 kHz for training LSTM models, which raises sensor costs by 25%.
- **Computational Overhead:** Training ANN models in Paper [6] consumes 14 ms per cycle, necessitating edge computing resources.
- **Algorithm Tuning:** Metaheuristic optimization (GA in Paper [8]) adds 18 – 22% to deployment timelines.

Despite their potential, intelligent methods face data dependency, scalability issues, and cybersecurity risks.

- **Training Data Quality:** Poor data degrades ANN accuracy by 15% in field tests.
- **Real-Time Processing:** Edge devices struggle with ML inference in microgrids with>100 nodes.
- **Cybersecurity:** Adversarial attacks on ML models in Paper [9] cause 12% false positives.

xiv. Frequency-Based Protection

Frequency-based protection strategies exploit deviations in system frequency to detect and classify faults, particularly in microgrids with inverter-based resources. Modern frequency protection strategies integrate advanced signal processing techniques, such as Wavelet Transforms and the Hilbert-Huang Transform, to monitor and analyse real-time frequency variations. Unlike conventional frequency relays, these methods excel in islanded microgrids, where maintaining frequency stability is paramount. However, their performance depends heavily on the response speed of inverter-based generators and the dynamic behaviour of distributed energy resources (DERs), requiring adaptive tuning to ensure reliable operation.

Frequency-based protection detects faults by monitoring deviations in system frequency. It is particularly effective in islanded microgrids where frequency stability is critical.

- **Islanded Mode Sensitivity**: Paper [22] uses rate-of-change-of-frequency (ROCOF) relays to detect faults within 20 ms in IEEE 34-node systems.
- DER Integration, as detailed in Paper [39], impressively combines frequency and voltage thresholds to achieve a high % accuracy rate of 92% even during solar PV fluctuations.

Frequency-based methods require precise measurement tools and adaptive thresholds, which can complicate deployment in low-inertia systems.

- **Sensor Costs:** High-precision frequency relays cost 30% more than traditional OCRs.
- **Threshold Tuning:** Paper [51] uses SARIMA forecasting to adjust ROCOF limits dynamically, adding 15% computational load.

Frequency-based strategies struggle with noise, DER-induced volatility, and a lack of discrimination during system-wide disturbances.

- **Noise Sensitivity**: Paper [41] reports 8 – 12% false trips due to harmonic distortions in wind farms.
- **Low-Inertia Systems:** Paper [39] observes 3 – 5 Hz/s ROCOF errors in inverter-dominated microgrids.

xv. Travelling Wave-Based Protection

Travelling wave methods can detect faults extremely quickly by analysing high-frequency transient signals. Although they offer excellent speed and sensitivity, they are often impractical for microgrids due to short line lengths and the need for high sampling frequencies. Their high implementation complexity usually restricts their use to high-voltage transmission systems rather than low-voltage microgrids.

Travelling wave (TW) protection methods detect faults by capturing and analysing high-frequency transient signals generated during fault initiation. These methods enable ultrafast fault detection and pinpoint fault location, positioning them as ideal solutions for transmission networks where speed and accuracy are critical. However, the application of microgrids is challenging due to short line lengths, high-impedance network characteristics, and the need for high sampling rates for accurate detection. Despite these limitations, advancements in signal processing, such as wavelet-based feature extraction and machine-learning-assisted classification, have opened new possibilities for integrating travelling-wave techniques into microgrid protection frameworks.

Travelling wave (TW) protection detects faults by analysing high-frequency transient signals, offering ultra-fast response times that are ideal for transmission systems.

- **Speed:** TW methods in Paper [42] isolate faults within 0.5 ms in high-voltage lines.
- **Sensitivity:** Detects faults with 1 – 5 Ω resistance in Paper [13], surpassing impedance-based methods. Implementing TW protection in a microgrid is not simple. It demands high-sampling-rate sensors and advanced signal processing, significantly increasing the cost and complexity. This awareness of the investment required is crucial for effective planning and decision-making.
- **Sampling Rates:** Paper [13] requires 1 MHz sampling (vs. 10 kHz in traditional methods), increasing costs by 40%.
- **Signal Processing**: Wavelet transforms add 22% computational overhead.

Short line lengths, noise, and equipment costs limit the applicability of TW in microgrids.

- **Short Lines:** TW signals attenuate rapidly in microgrids <5 km [52].
- **Noise Interference:** Paper [42] reports 15 – 20% signal distortion from inverter switching.

Table X synthesises the strengths, weaknesses, and innovations of each Intelligent & Data-Driven strategy:

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Table X: Synthesizes of Intelligent & Data-Driven Protection Strategy

Strategy	Strengths	Weaknesses	Key Innovation	Microgrid Suitability
Intelligent Protection	High accuracy, adaptability	Data dependency, high costs	ANN/SVM hybrid models	High (DER-rich systems)
Frequency-Based Protection	Islanded mode sensitivity	Noise sensitivity, DER volatility	ROCOF + voltage hybrids	Moderate (islanded systems)
Travelling Wave Protection	Ultra-fast fault detection	High cost, short-line limitations	Wavelet-based noise filtering	Low (transmission systems)

xvi. Hybrid/Integrated Systems

Protection schemes that combine several approaches into an integrated framework to enhance reliability, flexibility, and cybersecurity across modes.

Researchers have proposed innovative protection strategies, including cosine-similarity-based methods, harmonic analysis techniques, dual-setting directional reclosers (DSDRs), and adaptive schemes that combine traditional approaches. These strategies, integrating harmonic current injection or leveraging time-domain energy features, demonstrate promising potential by balancing performance with manageable complexity while maintaining adaptability across diverse microgrid configurations. These hybrid solutions aim to address the shortcomings of conventional protection methods and ensure adaptability to evolving grid conditions, thereby minimising reliance on high-speed communication infrastructure.

Hybrid protection schemes combine multiple protection techniques within a unified framework and play a crucial role in improving system reliability and strengthening cybersecurity. By strategically combining traditional and intelligent protection approaches, these methods compensate for the weaknesses of individual schemes while leveraging their strengths. This integrated approach is particularly valuable for microgrid applications, where diverse and dynamic operating conditions demand robust protection solutions.

Recent research has introduced innovative hybrid strategies, including cosine similarity-based protection, harmonic-based fault detection, dual-setting directional reclosers (DSDRs), and adaptive multi-criteria protection schemes. For instance, methods that incorporate harmonic current injection or leverage time-domain energy features have demonstrated the ability to detect faults while maintaining moderate computational complexity accurately. These techniques balance precision, implementation feasibility, and resilience in the face of evolving grid conditions.

Hybrid protection systems demonstrate their adaptability by reducing reliance on high-speed communication infrastructure and employing decentralized decision-making algorithms that process local measurements. This decentralized approach is especially valuable in microgrids, where delays or cybersecurity risks often compromise centralized protection schemes. Moreover, these systems dynamically recalibrate protection settings based on real-time grid conditions, improving fault discrimination and reducing the risk of false tripping.

Hybrid protection systems combine multiple strategies such as traditional relays, AI-driven algorithms, and advanced communication protocols to overcome the shortcomings of standalone protection methods. These systems boost reliability, adaptability, and cybersecurity by combining complementary strengths: pairing the rapid response of travelling-wave techniques with the stability of impedance-based methods, or integrating the straightforward design of voltage-based schemes with the analytical accuracy of AI.

- **Cosine Similarity-Based Protection**: Paper [20] achieves 11.3 – 15 ms operation times and tolerates fault resistances up to 120 Ω in wind farm microgrids.
- **Harmonic Injection Techniques:** Paper [31] uses synthetic harmonic injection to decouple protection from fault ride-through (FRT) requirements, achieving 100% selectivity in CIGRE benchmark systems.
- **Dual-Setting Directional Reclosers (DSDRs):** Paper [22] reduces relay miscoordination by 62% in IEEE 34-node feeders during grid-islanded transitions. Hybrid systems balance moderate complexity by combining existing infrastructure with targeted innovations. They avoid the extreme costs of fully AI-driven or communication-dependent schemes, but they require careful integration of hardware, algorithms, and protocols.
- **Moderate Costs:** Paper [25] combines POTT (permissive overreach transfer trip) and DZI (directional zone interlock) schemes, increasing costs by 15 – 20% compared to traditional methods.
- **Algorithm Integration**: Hybrid ANN + wavelet models in Paper [12] demand 10 kHz sampling rates and edge computing resources.
- **Hardware Synergy:** Paper [33] uses dual-setting DOCRs with existing IEC 61850 infrastructure, minimizing retrofitting costs. Hybrid systems face interoperability issues, synchronization demands, and balancing trade-offs between component strategies.
- **Interoperability:** Paper [20] reports 8 – 12% performance degradation when integrating cosine similarity with legacy relays.
- **Synchronization:** Unsynchronized harmonic injection in Paper [31] causes 5 – 7% false trips during DER fluctuations.

xvii. Inverter/DER-Specific Protection

Protection techniques must address the unique behaviour of inverter-based distributed energy resources (DERs), which typically generate low fault currents. Protection schemes must account for variable fault characteristics, bidirectional power flows, and the dynamic behaviour of distributed generation in microgrids. Using only conventional methods often leads to relay miscoordination and unreliable operation, while purely AI-driven or communication-based strategies risk introducing excessive complexity and cybersecurity weaknesses. Hybrid and integrated protection frameworks resolve these issues by combining multiple methodologies and leveraging their complementary strengths to create resilient, adaptive fault-detection systems.

Due to their current-limiting control strategies, inverter-based distributed energy resources (DERs)

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produce low fault currents, rendering conventional protection schemes ineffective. Inverter/DER-specific protection techniques address this by leveraging adaptive thresholds, virtual impedance injection, and advanced fault detection algorithms tailored to inverter dynamics.

- **Low Fault Current Mitigation:** Paper [39] uses grid-forming inverter control to emulate synchronous generator behaviour, increasing fault currents by 1.8 and enabling traditional relays to operate reliably.
- **Adaptive Thresholds:** As detailed in Paper [22], the use of dual-setting directional reclosers (DSDRs) is a key part of adaptive thresholds. These reclosers dynamically adjust pickup currents during grid-islanded transitions, reducing miscoordination by 62%. Implementing DER-specific protection requires modifications to inverter firmware, the use of advanced sensors, and coordination with legacy systems. While these methods avoid complete infrastructure overhauls, they demand precise integration with DER control logic.
- **Inverter Firmware Updates:** Paper [26] retrofits inverters with fault current boosting algorithms, increasing deployment costs by 18 – 22%.
- **Sensor Requirements:** High-resolution current sensors (0.1% accuracy) in Paper [51] add 12 – 15% to system costs.
- **Communication Needs:** Paper [33] integrates IEC 61850 GOOSE messaging with DER controllers, introducing 14 ms latency for real-time coordination. Inverter-specific protection faces limitations from DER control strategies, synchronization requirements, and interoperability with legacy protection devices.
- **Inverter Current Limiting:** Paper [39] reports fault currents as low as 1.2× rated current, below traditional relay pickup thresholds.

xviii. Comparative Analysis

A summary of the comparison among these methods is presented below:

xix. Performance

Advanced protection methods, including differential schemes, adaptive relays, and communication-assisted strategies, outperform conventional approaches in fault detection accuracy and response speed.

- Differential protection, with its remarkable precision, isolates faults with an impressive 99.97% accuracy [47]. This level of reliability is a testament to its effectiveness in fault detection.
- IEC 61850 GOOSE messaging enables communication-assisted systems to clear faults in 14 ms. Paper [24].
- Adaptive schemes like Time-Current-Voltage (TCV) relays cut total operation times by 44% in dynamic microgrids, Paper [10].

Intelligent methods further elevate performance through real-time analytics: neural networks classify faults with 99.2% accuracy [15], though their effectiveness hinges on high-quality training data, as poor datasets degrade accuracy by 15%.

In contrast, conventional overcurrent (OCP) and voltage-based protection struggle with slower detection (50–100 ms) and reduced sensitivity in DER-rich environments. Voltage-based methods, for instance, often misidentify faults during system-wide voltage dips, triggering false trips in 5–8% of cases within low-inertia microgrids.

xx. Adaptability

Adaptive and intelligent protection schemes demonstrate superior capability to manage microgrid dynamics, including topology shifts, DER integration, and transitions between grid-connected and islanded modes.

- Adaptive systems like dual-setting directional reclosers (DSDRs) automatically reconfigure relay settings during operational mode changes, significantly reducing the occurrence of miscoordination incidents, which are instances where protective devices fail to coordinate their operations, by 62% [22].
- AI/ML-driven methods utilize reinforcement learning to optimize directional overcurrent relays (DOCRs) in real-time, trimming computational expenses by 32% in IEC-standard networks [15].
- Communication-assisted strategies paired with resilient networks achieve complete adaptability, and phasor measurement units (PMUs) deliver 100% selectivity in IEEE 123-node test systems [19], though latency exceeding 130 µs compromises coordination [6].

In contrast, conventional approaches like overcurrent (OCP) and basic distance protection have significant limitations. They lack inherent flexibility, necessitating manual recalibration for DER compatibility. Fixed thresholds in traditional overcurrent relays, for example, are unable to detect low-magnitude fault currents (<1.5× rated current) in inverter-heavy systems [39]. This highlights the need for change and innovation in microgrid protection schemes.

xxi. Implementation Complexity

Microgrid protection strategies face a clear trade-off between performance/adaptability and implementation complexity. Conventional methods like overcurrent (OCP) and voltage-based protection offer simplicity and cost efficiency. Electromechanical relays, for instance, cost 60% less than AI-driven alternatives [17]. However, their limited effectiveness in modern grid environments severely restricts their practicality.

Advanced approaches such as differential protection and communication-assisted schemes require sophisticated infrastructure, which increases deployment costs by 30–40% [20]. At the same time, IEC 61850 protocols introduce latency (48.3 ms) that hampers real-time coordination, which is crucial for synchronising protection actions across the microgrid [26]. Intelligent methods further amplify complexity, requiring high-resolution phasor measurement unit (PMU) data (10 kHz sampling for LSTM model training [47]) and edge computing resources for real-time analytics.

Hybrid strategies balance these extremes by merging complementary techniques with manageable complexity.

- Harmonic-impedance hybrid schemes, with their complete selectivity and minimal reliance on communication networks, instil confidence in their practicality and effectiveness [31].

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- Dual-setting directional overcurrent relays (DOCRs) integrate smoothly with existing infrastructure, capping retrofitting costs at 15 – 20% [33].

These solutions represent a pragmatic compromise, enhancing protection performance without overwhelming infrastructure demands.

xxii.Reliability and Resilience

Reliability describes a system's capacity for fault-free operation under normal conditions, while resilience quantifies its ability to recover from disruptions. Conventional protection methods deliver high reliability in static grids but falter in DER-dominated microgrids, where they cannot adapt to inherent power fluctuations [39]. Communication-assisted schemes rapidly isolate faults but risk prolonged downtime (up to 62%) during network outages.

Adaptive and intelligent methods counter these limitations by embedding self-healing algorithms that sustain 95% uptime even during cyberattacks. Hybrid systems further enhance resilience; harmonic injection, for example, decouples protection functions from continuous communication dependency. DER-specific techniques, such as virtual impedance approaches, add robustness by emulating synchronous generator responses during faults, thereby improving system recovery.

xxiii. Scalability and Interoperability

Scalability measures a method's ability to scale to larger, more complex systems, while interoperability ensures compatibility with legacy infrastructure. Conventional methods often exhibit poor scalability in DER-rich grids due to their fixed configurations [33]. In contrast, intelligent methods demonstrate strong scalability potential; federated learning, though underexplored in this field, could decentralize AI training and enhance adaptability across distributed microgrids. Hybrid systems further boost interoperability through modular frameworks that enable incremental upgrades and seamless integration with legacy systems [25]. Emerging 5G wireless protocols, while not yet widely studied in this context, could also scale communication-assisted schemes, particularly benefiting rural microgrid applications.

xxiv. Cybersecurity Considerations

Cybersecurity is critical, as protection schemes must be robust against a range of cyber threats. Communication-assisted protection methods are particularly prone to spoofing and data injection attacks, with studies reporting up to 12% of false trips [9]. Intelligent methods are also vulnerable to adversarial machine learning attacks, posing significant risks in environments where data integrity is paramount. Conventional methods, while low risk from a cyber perspective due to their analogue nature, are not adaptable to DER fluctuations. Integrating quantum-resistant encryption and Moving Target Defence (MTD) techniques is critical to future-proof adaptive and communication-assisted systems, a unique insight highlighted by recent research.

xxv. Cost and Economic Feasibility

Cost-effectiveness and economic feasibility are essential when considering large-scale microgrid deployment. Conventional overcurrent protection is noted for its low initial and operational costs but offers limited returns in DER-rich grids. Adaptive protection methods incur moderate initial costs; however, their high ROI in industrial applications can justify the high maintenance cost associated with AI components. While offering ultra-fast fault isolation, communication-assisted systems incur high initial and operational costs due to network maintenance, making them better suited to urban environments. Hybrid systems strike a balance between moderate expenses, making them the most economically viable option for mixed-topology networks. Cost-benefit analyses in the Paper support these insights [20] and operational expenditure studies in Paper [26].

xxvi. Real-World Validation

Field validation is crucial for assessing the practical viability of protection strategies. Studies show that conventional methods validate in approximately 70% of cases, yet they often underperform in DER scenarios [39]. Advanced techniques such as adaptive, intelligent, and hybrid systems have undergone real-world testing in only 9–15% of cases—for instance, successful trials in Inner Mongolia wind farms [35]. Hybrid systems have shown 100% selectivity in CIGRE benchmark field tests [25]. A significant gap persists in standardising cross-study comparisons, underscoring the need for unified validation frameworks.

xxvii. Future Prospects and Recommendations

Several future directions can help bridge the gap between laboratory innovation and widespread microgrid deployment. There is a pressing need to integrate sustainability metrics into protection strategies, linking relay coordination directly to carbon reduction and improved energy efficiency (e.g., reduced Energy Not Served, ENS). Modular upgrades, such as retrofitting legacy relays with plug-and-play AI and communication modules, offer a practical pathway for enhancing existing systems [33]. However, developing Explainable AI is not just another step but a critical one in building industry trust through transparent decision-making processes. Additionally, establishing IEEE/IEC guidelines for AI model benchmarking and hybrid system interoperability will be vital in standardising protection solutions. Finally, cybersecurity must evolve by adopting quantum-resistant encryption and advanced Moving Target Defence techniques to safeguard microgrid operations against emerging threats.

xxviii. Improvements in Fault Detection and System Resilience

- **Collectively, these recent advances contribute to the following improvements:** Faster and More Accurate Fault Detection: AI/ML and advanced signal processing play pivotal roles in achieving quicker, more accurate fault detection. These technologies enable intelligent protection systems to detect faults in sub-cycle times (less than 16 ms), a significant improvement over conventional method.
- **Enhanced Adaptability:** Adaptive schemes and hybrid approaches are instrumental in maintaining high sensitivity and selectivity. These approaches allow protection settings to

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be dynamically adjusted to the microgrid's current operating mode and DER configuration, ensuring Enhanced Adaptability even under variable conditions.

- **Increased System Resilience:** The ability to seamlessly transition between grid-connected and islanded modes is a key factor in enhancing microgrids' resilience. This feature, along with communication-based and decentralized architectures and fault ride-through capabilities provided by intelligent relays, helps prevent cascading failures and minimize power outages.
- **Robustness to Communication Failures:** Several proposed schemes reduce dependency on high-bandwidth communication by employing local measurement techniques or redundant communication channels, ensuring continued protection even when communication links are compromised.

IV. CONCLUSION

This systematic review synthesises advancements, challenges, and gaps in microgrid protection, drawing on 55 contemporary studies. The review highlights that bidirectional power flows, variable fault currents, and dynamic topologies render conventional protection methods inadequate. It also emphasizes that while adaptive schemes, communication-assisted strategies, and AI-driven techniques show promise, they introduce complexity, cybersecurity vulnerabilities, and scalability limitations. The review suggests hybrid systems, combining traditional and intelligent methods, could offer a pragmatic balance, but interoperability and cost barriers remain.

A. Research Gaps and Future Directions

- **Resilience Metrics:** Only 10% of studies address resilience holistically. Future work must integrate standardized metrics (SAIDI, MTTR) with DER-specific contingencies and cyber-physical interactions.
- **Real-World Validation:** With only 13% of studies validating findings experimentally, the need for field trials in diverse microgrid archetypes (DC, hybrid) becomes even more critical. These trials are essential to assess scalability and reliability in practical settings.
- **Cybersecurity:** Communication-assisted and AI methods remain vulnerable to spoofing and adversarial attacks. Quantum-resistant encryption and Moving Target Defence (MTD) frameworks require urgent exploration.
- **Sustainability Integration:** Protection strategies must align with decarbonization goals. Optimizing relay coordination to minimize Energy Not Served (ENS) and enhance grid efficiency can make significant strides in sustainability.
- **Legacy System Upgrades:** Modular retrofitting of electromechanical relays with AI modules and 5G communication could enable cost-effective transitions to adaptive protection.
- **Standardization:** The absence of unified guidelines for AI benchmarking, hybrid system interoperability, and DER-grid synchronization underscores the need for IEEE/IEC-led initiatives.

B. Areas for Improvement

- **Adaptive Thresholds:** Develop dynamic relay settings using real-time DER forecasting to mitigate protection blinding.
- **Explainable AI:** Enhance trust in intelligent methods through transparent decision-making models.
- **Cost-Benefit Frameworks:** Evaluate the economic viability of hybrid systems in rural versus urban microgrids.
- **Decentralized Architectures:** Reduce communication dependency via federated learning and edge computing for distributed networks.

By addressing these gaps, future research can accelerate the transition from theoretical innovation to resilient, scalable microgrid protection systems, ensuring reliable integration of renewable energy into modern grids.

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