

Promising Protection Scheme for Renewable Resources Connected Microgrid: A Systematic Review of an Adaptive Protection

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The integration of Distributed Generators (DGs) into distribution networks has experienced rapid growth in recent years due to their numerous advantages, forming microgrids that can function in either grid-connected or islanded modes. However, this increasing penetration of DGs presents several challenges to microgrid protection systems. Traditional protection methods struggle with issues such as dynamic fault current levels, bidirectional fault flows, protection blinding, and false tripping. To overcome these issues, researchers have proposed various solutions, with adaptive protection standing out as a promising approach. Numerous adaptive protection schemes have been introduced and thoroughly discussed in the literature, each offering unique benefits and limitations. This paper provides an in-depth review of these adaptive protection methods, outlining their strengths and weaknesses. The primary goal of this review is to inspire and encourage further research in adaptive protection systems for DG-integrated distribution networks, ultimately ensuring more reliable and efficient power distribution systems in the face of growing DG integration.

Keywords: Adaptive protection, Distributed generators, Microgrid, Power system protection, Renewable energy

Introduction

Conventional power plants, despite their undeniable contributions to electricity generation, carry a multitude of drawbacks that cast a shadow on their presence.^{1,2} Global warming, limited fossil fuel sources, and exorbitant construction costs stand as formidable adversaries to their sustained existence.³⁻⁵ Furthermore, as the physical distance between power plants and load centers widens, the losses incurred in transmission lines grow exponentially, exacerbating the inefficiencies of the system. In response to these pressing concerns, a paradigm shift has occurred, manifesting in the remarkable growth and utilization of DGs within distribution networks over the past few decades.⁶⁻⁸ DGs play a pivotal role by supplying ample power to meet local demand and serving as an auxiliary support to the main grid during^{9,10} times of high power withdrawal. This alleviates the need for extensive transmission infrastructure, while simultaneously enhancing the reliability and dependability of power systems.^{4,11} The emergence of DGs has ushered in a

new era, one where localized power generation and distribution flourish, empowering communities and reducing the burden on traditional power plants besides their economic feasibility.¹²

At the heart of this transformation lies the microgrid, an interconnected ensemble of DGs and loads that can function in both grid-connected and islanded modes.¹³ While a cornucopia of advantages presented by microgrid, it also poses unique challenges in terms of protection within power networks.^{4,14} The very essence of microgrid protection becomes a focal point¹⁵ demanding astute attention and innovative solutions to ensure the safe and efficient operation of these interconnected systems. Several critical issues emerge when delving into microgrid protection. Foremost among them is the dynamics surrounding fault current intensity, which necessitates careful monitoring and regulation to prevent potential disruptions and damages. The intricacy of microgrid protection is further exacerbated by protection blinding, a phenomenon that hinders the accurate detection of faults due to complex fault currents. Moreover, bidirectional fault current, an inherent characteristic of interconnected systems, requires specialized protection

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measures to effectively mitigate its impact. Lastly, false tripping, an occurrence that triggers protection devices unnecessarily, poses a challenge to the seamless operation of microgrids, calling for robust and intelligent protection schemes to minimize such disruptions.¹⁶ In summary, while DGs and microgrids have emerged as compelling alternatives to conventional power plants¹⁷ and centralized distribution systems, they bring forth a new set of protection challenges.¹⁸ These challenges encompass fault current intensity dynamics, protection blinding, bidirectional fault current and false tripping. Addressing these issues demands innovative approaches and meticulous study, enabling the realization of resilient and secure microgrid systems that harness the advantages of DG while safeguarding the integrity of power networks.

Researchers have suggested a variety of solutions to guarantee microgrid security. These include the voltage-based method¹⁹, Fault Current Limiter (FCL) method^{20,21}, distance measurement technique^{22–24}, Wide Area Monitoring (WAM) method²⁵, differential approach²⁶, and adaptive protection.^{3,13,16} The voltage-based method, while offering certain advantages, has limitations such as reduced sensitivity to high impedance faults and applicability only to specific microgrid configurations.¹⁹ On the other hand, the FCL method encounters difficulties in determining the optimum impedance value, particularly as the inflow of DGs increases, and may result in the miscoordination of directional over current Distance-based protection suffers from issues related to harmonics and transients, leading to inaccurate fault impedance measurement and inadequate sensitivity for short lines.^{22,23} In the WAM method, the Phasor Measurement Unit (PMU) approximates only the fundamental frequency components, thereby lacking information on harmonics and DC offset components. Additionally, problems can arise due to communication failures and delays.²⁵ Differential-based protection, while effective in many cases, can be susceptible to maloperation when confronted with unbalanced loads.²⁶

Considering the aforementioned challenges, adaptive protection emerges as a promising solution for microgrids. Adaptive protection schemes are designed to dynamically adjust their settings and configurations based on real-time system conditions and changes, offering enhanced adaptability and resilience. In the realm of adaptive protection systems, microprocessor-based relays play a pivotal role.¹³

In addition to their sophisticated computational capabilities, these relays allow protection settings to be dynamically adjusted in response to modifications in microgrid behavior and setup. By utilizing microprocessors, these relays can swiftly process and analyze real-time data, facilitating seamless communication and association between upstream and downstream relays within the microgrid. The adaptive nature of these relays allows for the continuous monitoring of system conditions, enabling them to adapt their settings to optimize protection performance. The microprocessor-based relays adapt their settings to the microgrid's design, such as the addition or removal of DGs or loads, in order to maintain the integrity and dependability of the protection system.

While adaptive protection systems offer significant benefits, it is important to acknowledge and address their limitations. Several key limitations are associated with the implementation of adaptive protection.^{27,28}

- 1) Large memory storage: Adaptive protection systems require substantial memory storage to accommodate the settings for each relay. The quantity of storage needed in the microgrid broadens in correlation with the number of relays. This necessitates robust memory capacity to store and manage the relay settings effectively.
- 2) Updating all relay settings: Any minor changes in the power system configuration can trigger the need to update the settings of all protection relays within the microgrid. This procedure can take a while, especially in big and highly complex microgrid installations. Ensuring the timely and accurate update of all relay settings becomes a challenge, requiring efficient coordination and communication mechanisms.
- 3) Examination of microgrid configurations: Prior to the application of adaptive protection, it is essential to examine all practicable configurations of the microgrid. This investigation comprises assessing numerous potential operating scenarios and system architectures to identify the most appropriate settings for adaptive protection. This process can be laborious and demanding, requiring comprehensive analysis and consideration of multiple factors.
- 4) High communication costs: The implementation of adaptive protection necessitates robust communication infrastructure to enable efficient coordination and relay setting updates.²⁹ Establishing reliable and high-speed communication links between the relays within the microgrid incurs substantial costs.

Moreover, the maintenance and operation of such communication networks also require ongoing investments.

The planning as well as execution of adaptive protection for DGs connected distribution networks are still in a progressive phase. Although significant advancements have been made, there is ongoing research and exploration in this field. This paper sheds light on the diverse protection issues faced by microgrids and delves into the various approaches utilized for adaptive protection schemes. By examining the intricate dynamics and challenges inherent in microgrid protection, researchers have proposed and explored different strategies and techniques to enable adaptive protection. These approaches aim to enhance the responsiveness and adaptability of protection systems, ensuring efficient fault detection, discrimination, and response in the context of microgrids. Moreover, this paper offers recommendations and suggestions for future research endeavors in the development of adaptive protection for microgrids. These recommendations serve as a guiding light, inspiring scholars and practitioners to explore new avenues, address existing challenges, and advance the field of microgrid protection.

Need for Protection Improvement

In traditional radial distribution systems, the current flows in a unidirectional manner. However, as

the contribution of DGs increases in distribution networks, the system configuration evolves from radial to mesh, leading to bidirectional current flow.³⁰ This shift in the current flow direction introduces new challenges to microgrid protection. One significant challenge arises in the form of fault currents. The presence of various types and numbers of DGs, coupled with their dynamic characteristics, mode of operation, and changes in network configuration, affects the fault current behavior within the microgrid. Fault currents, which are abnormal electrical currents that occur during system faults, require careful monitoring and protection measures to guarantee dependable and the safe operation of the microgrid. The following subsections delve into different problems associated with the microgrid protection, shedding light on specific issues that need to be addressed.^{3,31,32}

Dynamics in Fault Current Intensity

In the modern distribution systems, the dynamics in fault current mainly depend on the kind of operation and types and penetration level of DGs.

Microgrid's Mode of Operation

Grid-connected and islanded are the two kinds of operation for a microgrid.^{13,33} The microgrid can operate in either kind, and the fault current varies depending on the kind, as illustrated in Fig. 1(a) and 1(b). The total fault current in the grid-connected

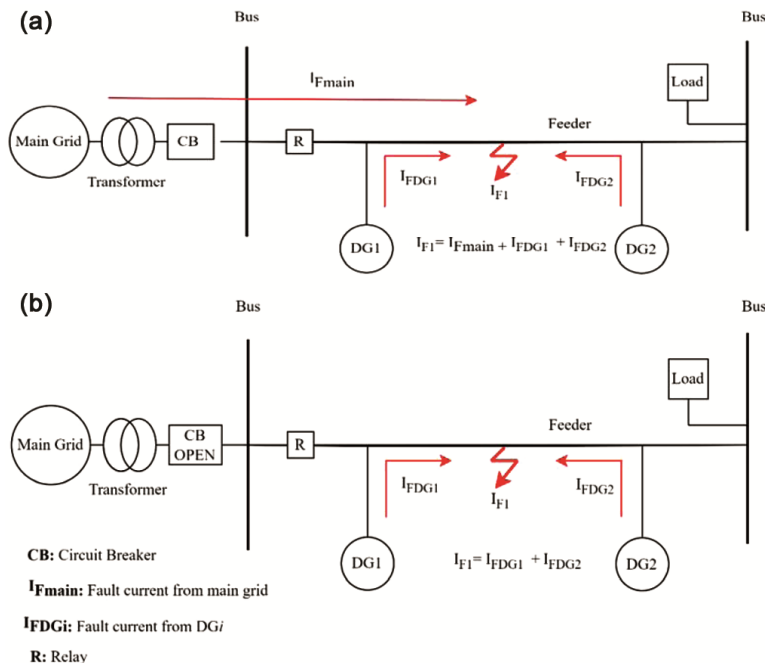


Fig. 1 — Dynamics in fault current intensity (a) Grid-connected mode, (b) Islanded mode

mode, which can be calculated as $I_{F1} = I_{Fmain1} + I_{FDG1} + I_{FDG2}$ is presented in Fig. 1(a). On the other hand, Fig. 1(b) shows the total fault current for the islanded mode, which is calculated as $I_{F2} = I_{FDG1} + I_{FDG2}$. It is apparent that the grid-connected mode's fault current value is substantially greater than the islanded mode's fault current value. Given the dynamics and varying levels of fault currents in these modes, it becomes exceedingly challenging to accurately calculate relay settings. The complexity arises from the need to consider the different fault current magnitudes and characteristics associated with grid-connected and islanded modes. Therefore, determining appropriate relay settings becomes a complex task, requiring careful analysis and consideration of the specific operating conditions and requirements of the microgrid.²⁸

Types and Penetration Levels of DGs

In faulty condition, inverter-based DG supplies a fault current of 1.5 to 2 times the rated full load current, while synchronous based DG supplies a fault current of 5 times the rated full load current.³⁴ Further, as the numbers of DGs, the fault current also increases. These all introduce new challenges to the existing protection systems.^{35,36}

Blinding of Protection

If the relay is struggles to sense a fault in its own zone, the problem of the blinding of protection will

occur. This issue is observed in DGs connected networks. Here, Fig. 2(a) shows I_{Fmain1} that is the fault current feed from the main grid when the DG is present. Whereas, I_{Fmain2} represents the fault current feed from the main grid as shown in Fig. 2(b), when the DG is absent. The DG will offer impedance to I_{Fmain1} , so its value is lowered compared to I_{Fmain2} . In the case where higher penetration of DGs is present, it is possible that the fault current feed from the main grid is underneath the pickup setting of the grid side relay (R). In this condition, the relay fails to sense fault current, and results in the blinding of protection.¹⁶

Bidirectional Fault Current

Penetration from the DGs not only changes the magnitude of the fault current but also alters its direction. For a fault at a bus, as shown in Fig. 3, both the DG and main grid will furnish the fault current. Now, If the DG contributed fault current value is greater than the relay pick up, the convectional non-directional relay will trip as it cannot discriminate that the fault current flows in the backward manner.

False Tripping and Lack of Coordination of Relays

As shown in Fig. 4, for fault location in feeder 2, the fault current involvement is from both the DG and main grid. The feeder 2 over current protection relay R2 should operate for the aforesaid fault. The Feeder1 protection over-current relay R1 should not operate. If

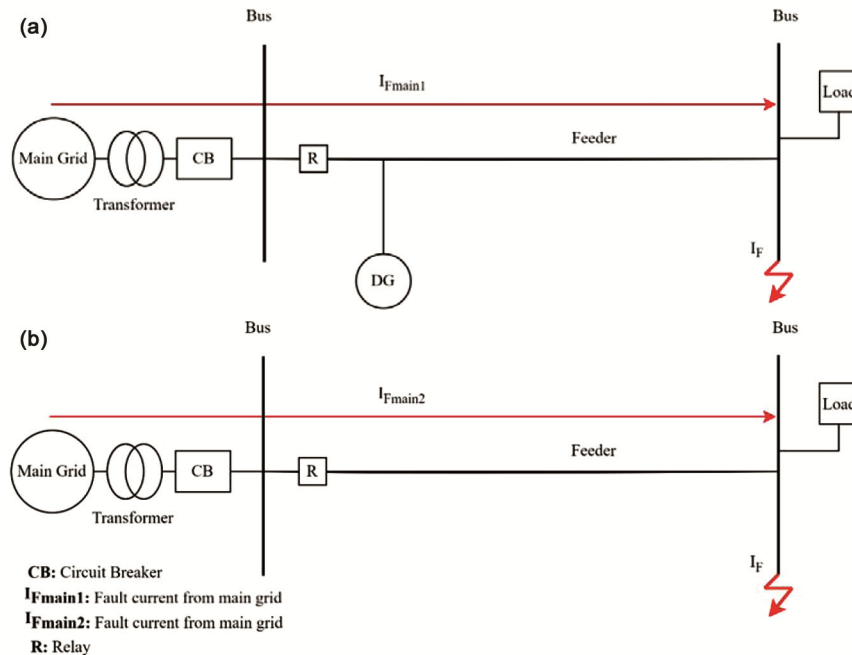


Fig. 2 — Blinding of protection (a) DG is present, (b) DG is absent

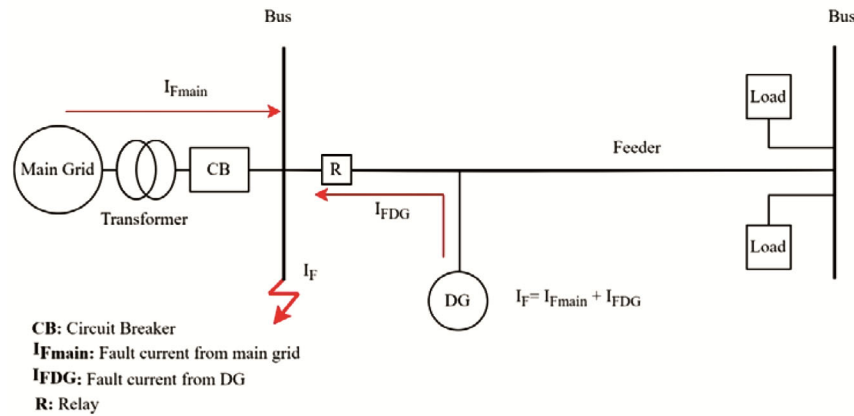


Fig. 3 — Bidirectional fault current

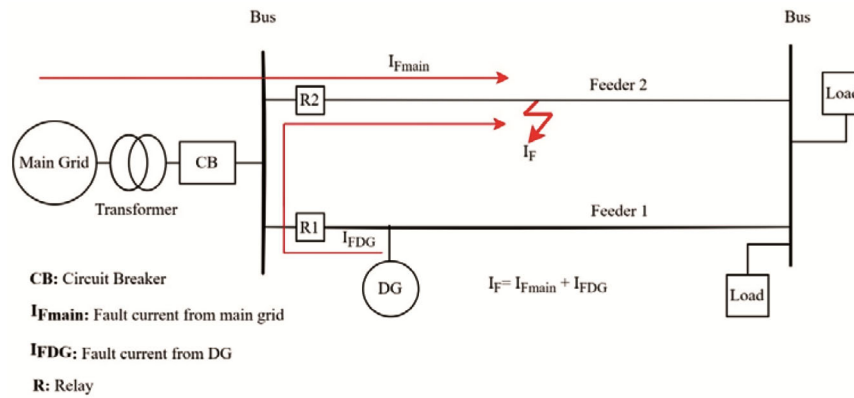


Fig. 4 — False tripping

the fault current I_{FDG} crosses the pickup setting of R1, it will operate fallaciously. This is known as false tripping. Here, the relay in the feeder operated because of a fault in an adjoining feeder.¹⁶

Fault Ride-Through (FRT)

DGs are expected to possess the competency for Low Voltage Fault Ride-Through (LVFRT). According to the established IEEE 1547 standard, it is required to disengage DGs from the power grid in the condition of a fault that results in a significant voltage drop near the power plant.³⁷ However, under the latest revision in grid code, it is crucial for DGs to remain connected during low-duration fault periods to ensure stable grid operation.³⁸ To maintain synchronism during faulty or abnormal conditions, DGs require support in the form of fault ride-through capability.³⁹ However, it should be noted that the fault ride-through phenomenon can impact the performance of relays, as the relays should refrain from operating during the fault ride-through period.

Different Adaptive Protection Schemes

Adaptive protection is not a new concept; earlier, it was also applied to conventional power systems.⁴⁰

Adaptive protection can be applied as centralized or decentralized.^{29, 41}

A centralized adaptive protection system has one key system known as the microgrid management system whose function is to constantly keep an eye on the microgrid configuration and update the protective component settings (Refer to Fig. 5). IEC 61850 communication standards are used between protective devices.^{42,43} The working position of the microgrid, either as a grid connected or islanded, is sent to protective equipment. Base on the status of microgrid, the protection equipment check the entity with the set values and accordingly releases a trip command.⁴⁴ Protection coordination is done in both offline and online modes.⁴⁵

Decentralized adaptive protection or multi agent systems have a set of distribution agents in relays, CBs, and DGs i.e., different devices of the network. They will operate in coordination and communicate through a communication infrastructure.⁴⁶

The adaptive protection methods maybe subdivided mainly into two parts: computational intelligence-based and other adaptive-based. The computational

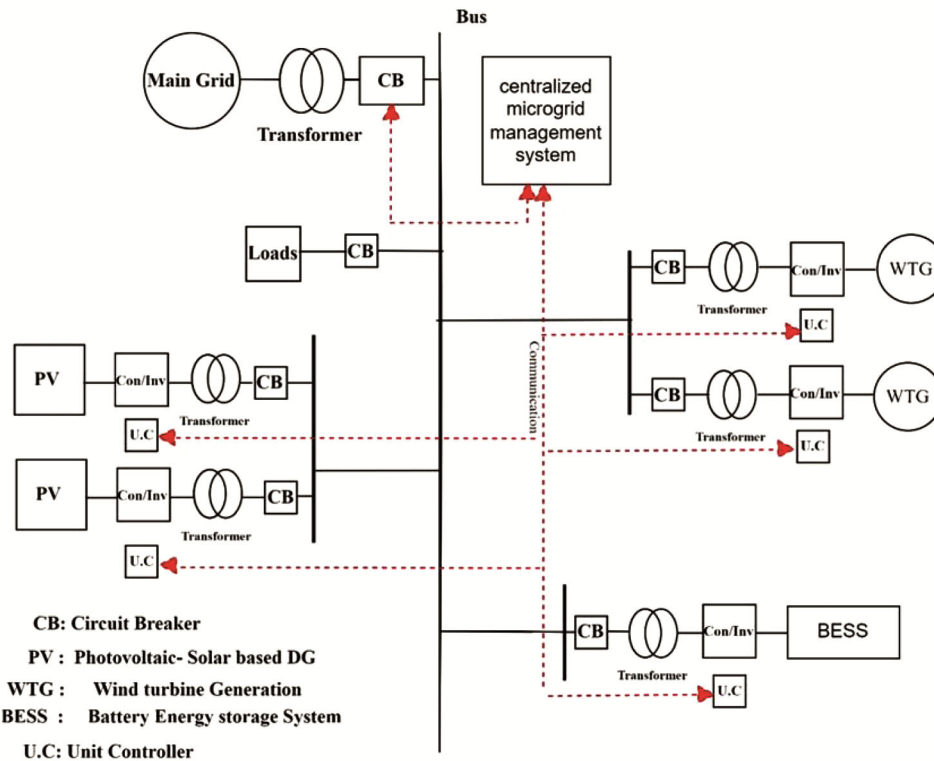


Fig. 5 — Generalized adaptive protection of microgrid

intelligence-based method covers Artificial Neural Network (ANN), Fuzzy Logic, Machine Learning, Metaheuristic, and Multi Agent System (MAS). Different researchers have suggested various methods and approaches for the adaptive protection of microgrids or DGs connected distribution systems.^{16,32,47}

Computational Intelligence-based

ANN based

Zayandehroodi *et al.*⁴⁸ proposed a new adaptive protection system that combines the fault location with the protection relay coordination. A novel method was developed utilizing a two-stage neural function to autonomously detect faults. In the initial stage, the fault location is determined for each power source, followed by the identification of the specific faulty line in the subsequent stage. Upon locating the faulted line, a protection relay coordination strategy employing the backtracking algorithm is employed. Simulations incorporating four different fault types, including symmetrical and asymmetrical faults, were used to assess the suggested system, conducted in the Dig SILENT software. The output results demonstrate the potency of the proposed approach and its ability to achieve the desired coordination of protection relays. Lin *et al.*⁴⁹ have presented the an adaptive protection

system combined with machine learning technique. In this paper from a data mining perspective, the authors have analysed dubious components in microgrids by the Pearson correlation coefficient. After that, for the state recognition process, the hybrid approach of ANN and support vector machines is utilized. According to the state recognition, the protective relay settings and operating modes of the microgrid are revised by the adaptive reconfiguration.

Metaheuristic based

Shih *et al.*⁵⁰ presented adaptive directional over current relay (DOCR) harmonization by ant colony optimization (ACO). In this study, an adaptive protection coordination approach incorporating the resetting of DOCR and online coordination was developed. The obtained results were examined with the outcomes of the genetic algorithm (GA) analysis. The test results indicate that the ACO method exhibits favorable convergence in terms of operation time and demonstrates superior performance in selectivity and sensitivity.

Papaspiliotopoulos *et al.*⁵¹ proposed the adaptive protection in over current relays using an optimized coordination. The coordination problem of DOCR is addressed through the utilization of particle swarm

optimization linear programming (PSO-LP) and nonlinear interior-point optimization algorithms, which were formulated as a nonlinear programming optimization. The focus was on investigating symmetrical faults at the end of the transmission lines, while asymmetrical short circuits were not considered. Additionally, it was observed that as the number of buses increases, the results were slightly delayed.

Shih *et al.*⁵² introduced a novel adaptive protection system based on the differential evaluation algorithm. The system aims to mitigate the impact of DGs and enhance relay sensitivity. Centralized adaptive protection was implemented, with Supervisory Control and Data Acquisition System (SCADA) monitoring being utilized. The proposed system was evaluated using the IEEE 6-bus and 14-bus systems.

Fuzzy based

Nasir el Nailly *et al.*⁵³ conducted a study on an online adaptive fuzzy algorithm-based protection system. The algorithm proposed in their research considers the status of the Point of Common Coupling (PCC) and circuit breakers of DGs, as well as the load flow just prior to a fault occurrence. The method accounts for changes in the time-current characteristics of protective relays caused by modifications in the system topology. The study reveals that the selectivity of relays is affected when DGs are connected.

Kumar *et al.*⁵⁴ proposed an adaptive numerical protection method for a medium voltage distribution systems. Novel hybrid method is applied to reduce the tripping time of relays by optimizing its settings. Two algorithms are used. One is an optimization algorithm for the current setting and the second one is a heuristic algorithm for time setting in the adaptive fuzzy inference module (AFIM). The proposed system is simulated and tested in IEEE 14 bus test system.

The research conducted by Chaitanya *et al.*⁵⁵ focuses on the development of a fuzzy built communication-aided adaptive protection microgrid system. The aim of this system was not only to detect faults but also to classify the fault type and faulty phase. The researchers employed a separate rule-based adaptive fuzzy protection mechanism for this purpose. They simulated the standard microgrid model using MATLAB and SIMULINK and achieved a perfect response time. The results obtained from testing were applicable to both grid-connected and

islanded modes of the microgrid. One of the concerns mentioned is related to the fact that the system relies on communication, which introduces the possibility of cyber threats. Therefore, cyber security issues may need to be addressed before the scheme can be practically implemented.

Kar *et al.*⁵⁶ presents a microgrid protection system for fault determination and classification. The proposed system utilizes a fuzzy rule-based approach built on a decision tree. In this system, the authors extract differential features such as energy and entropy by collecting current samples from the end of the feeder immediately after a fault occurs. These samples are then processed using the s-transform, which allows for frequency domain analysis. The extracted features serve as inputs for constructing the decision fault classification tree. To make the final relay decision, fuzzy rules are employed, which are prepared based on fuzzy membership functions. These fuzzy rules help in mapping the extracted features to specific fault types or fault classes, thereby enabling effective fault classification. It provides a framework for fault determination and classification in microgrids. However, it is important to conduct further evaluation and testing to assess the performance and soundness of the suggested system under various fault situation and system configurations.

Multi Agent based

A MAS is a computational framework where multiple autonomous agents interact and collaborate with each other to solve a problem or achieve a common goal. In a MAS, each agent represents an individual entity with its own set of capabilities, knowledge, and decision-making abilities. One of the distinguishing characteristics of a multi-agent system is that the problem-solving is typically distributed among the agents rather than being solved in a centralized manner. Each agent can perceive its environment, make decisions, and take actions independently from its own local knowledge and interactions with other agents. Through communication and coordination, agents can share information, exchange messages, and cooperate to achieve their objectives. The distributed nature of a MAS allows for flexibility, scalability, and adaptability. Agents can work in parallel, exploring different solutions, and exchanging information to collectively find optimal or satisfactory solutions to complex problems.⁵⁷

Liu *et al.*³⁶ proposed a protection and control scheme for microgrids utilizing a MAS. The authors designed an adaptive protection and control algorithm by integrating the functionality of protection relays and DG controllers. The scheme takes into consideration the variations in DG integration and system topology and develops appropriate protection strategies accordingly. It assumes the availability of a well-developed communication system to facilitate coordination and information exchange among the agents. The authors emphasized the time-consuming nature of the operation, which may necessitate the usage of backup protection in the event of delays during main relay upgrading or fault occurrences. This consideration underscores the importance of maintaining reliability and timely response in the protection scheme. To validate their proposed scheme, the authors conducted testing using Hardware in a Loop (HIL) real-time testing system. This approach allows for realistic evaluation and verification of the scheme's performance under dynamic conditions.

Fernando reis *et al.*⁵⁸ propose a dual tactically supported relay agent system for adaptive protection of microgrids. The authors introduced two approaches, namely online and offline, to enhance the adaptability and reliability of the protection scheme. The online approach utilizes a fast-centralizing mechanism with the support of a communication system. It operates based on the actions recommended by expert systems. This real-time decision-making process allows for swift response and adaptation to changing conditions within the microgrid. However, the authors also acknowledge that in certain situations, delays or communication failures may occur, compromising the effectiveness of the online approach. To mitigate this risk, the offline approach serves as a backup protection mechanism. This offline approach likely involves predetermined rules or algorithms that can function independently of real-time communication. The incorporation of dual tactics in the proposed scheme offers a comprehensive solution to address both real-time and contingency scenarios.

Other Adaptive Methods

Hosseini *et al.*⁵⁹ presented a decision tree-based microgrid protection approach aimed at addressing uncertainties within microgrid systems. The authors examine uncertain indices by assessing the likelihood of successful strategies in resolving faults and load

outages. The decision tree framework is employed to construct an optimized set of strategies that account for uncertainties. This approach ensures that in the event of a failed strategy, the decision tree algorithm selects the best alternative strategy based on the identified uncertainty indices. By considering both successful strategies and communication features, the adaptive protection mechanism is chosen, eliminating the need for offline settings storage. Further validation and evaluation of this approach are necessary to assess its performance across different microgrid scenarios and to determine its effectiveness in improving the overall reliability and security of microgrids. Additionally, exploring potential real-world implementations and investigating the computational requirements of the decision tree-based approach would be valuable for future research in this domain.

Brahma *et al.*⁶⁰ presented an adaptive protection scheme specifically designed for distribution systems with a significant contribution from DGs. The proposed approach employs a zoned methodology, where zones are established to ensure a balanced distribution of generation and demand. Each zone is equipped with at least one frequency controlling DG to maintain system stability. Offline calculations are conducted to evaluate power flow and perform short-circuit analysis for various practical fault cases. Based on these analyses, the protection method identifies the optimal choice without being reliant on the location and size of DGs. This approach ensures robust and efficient protection regardless of the specific characteristics of the DGs involved. It is worth noting that the system's performance needs to be evaluated under conditions of low DG penetration to understand the scheme's effectiveness in different scenarios. Furthermore, the validity of fault detection relies heavily on the precision of the PMU used.

The research conducted by Sitharathan *et al.*⁶¹ focuses on the development of an adaptive protection system for microgrids with electronically coupled DGs. The proposed scheme is designed to provide effective protection in both operating modes of the microgrid. One notable quality of the scheme is the incorporation of auto reclosing facilities, which enhance system stability and enable fast recovery from faults. By automatically restoring power after a fault, the scheme contributes to maintaining a continuous power supply and minimizing downtime. Simulations to examine the performance of the proposed scheme were conducted using PSCAD/

EMTDC, a widely used software tool for power system analysis. The communication between the relays and DGs within the microgrid is facilitated through the microgrid communication medium. The scheme demonstrates reliable protection capabilities for low impedance faults, ensuring proper fault detection and mitigation. Additionally, it possesses ride-through capabilities, allowing for the tolerance of temporary faults and supporting continuous operation of the microgrid.

The study conducted by Ates *et al.*⁴³ proposes an adaptive relay coordination algorithm designed to achieve rapid fault isolation in distribution systems. The algorithm's effectiveness was tested on an IEEE 4-node distribution system. The adaptive relay coordination algorithm dynamically adjusts relay settings in response to changes in DG sources. By adapting the relay settings, the algorithm aims to enhance the fault isolation process, leading to faster fault detection and isolation. However, a notable limitation of this study is that the proposed method is applied and evaluated solely on a small four-bus system. The small-scale nature of the system may not fully capture the complexities and challenges present in larger distribution systems. Therefore, the effectiveness and performance of the algorithm in larger and more realistic systems remain uncertain. To further validate the algorithm's capabilities and assess its applicability in real-world scenarios, it would be valuable to test the proposed method on more extensive and diverse distribution systems. Evaluating its performance under various operating conditions and system configurations would provide a more comprehensive understanding of its strengths and limitations. Although the adaptive relay coordination algorithm presented here is promising in terms of achieving fast fault isolation, its limited application to a

small-scale system highlights the need for further investigation to ascertain its efficacy and scalability in more complex and large-scale distribution systems.

The research conducted by Ustun *et al.*²⁷ introduces a centralized protection system for monitoring the status of a microgrid using a communication system. The aim was to update relay settings in response to variations in microgrid topologies. The microgrid is modeled with communication standards, specifically logical nodes in IEC 61850 and IEC 61850-7-420. In this system, a central protection unit is responsible for monitoring all parameters within the microgrid. Both DGs and relays are modeled with communication features, enabling the exchange of information. Based on the DGs' on/off status, current measurements, and fault current sharing status, the protection relay settings are updated using an interrupt algorithm. This adaptive approach ensures that the relay settings align with the dynamic changes in the microgrid. It is crucial that the total system's dependability could be compromised if the communication system malfunctions. The communication system serves as a critical link for updating relay settings and exchanging information among different components of the microgrid. Therefore, the reliability and robustness of the communication infrastructure become crucial factors for the effective operation of the proposed centralized protection system. Further research and analysis are necessary to assess the performance and resilience of the proposed system in real-world scenarios. Assessing the impact of communication failures and exploring strategies for fault tolerance and alternative communication paths would be valuable to enhance the reliability and dependability of the protection system.

The outcomes of various adaptive microgrid protection schemes are presented in Table 1,

Table 1 — Outcome of the review

Particular/reference	Contribution/Feature	Limitation
ANN based		
Two stage radial basis function neural network ⁴⁸	<ul style="list-style-type: none"> ● A two-stage radial basic function (RBFNN) is used for automatic fault location. ● The proposed calculated implementation time, less than 0.236s, meets the requirements of IEEE std.242-2001. 	<ul style="list-style-type: none"> ● Presence of sources other than a Diesel DG may affect the performance of proposed scheme. ● Various topologies of the microgrid need to be addressed.
Rule-based adaptive protection scheme integrated with machine-learning methodology ⁴⁹	<ul style="list-style-type: none"> ● Pearson correlation coefficient was utilized to analyze uncertain elements and fault measurement. ● A Hybrid ANN-SVM was implemented for state recognition. ● Modified Relay setting and operating mode based on state recognition. 	<ul style="list-style-type: none"> ● It requires a large amount of data for accurate information and to achieve brilliant system intelligence. ● There is a possibility of the implementing countermeasure in the case of inaccurate data.

(Contd.)

Table 1 — Outcome of the review — *Contd.*

Particular/reference	Contribution/Feature	Limitation
Metaheuristic method		
ACO ⁵⁰	<ul style="list-style-type: none"> ● Adaptive directional over current protection using ACO. ● The results are compared with the GA. 	<ul style="list-style-type: none"> ● Only phase fault coordination studied, ground fault coordination was omitted which need to be examined. ● The complexity increases in larger distribution systems, which can make it difficult to implement this method in real-world scenarios.
Hybrid PSO-LP approach ⁵¹	<ul style="list-style-type: none"> ● The coordination issue of directional over current relay is formulated as nonlinear programming. ● Two optimization methods PSO-LP and non-linear interior-point trust-region are utilized. ● The proposed scheme is tested in HIL test bed system. ● Different microgrid configuration been considered. 	<ul style="list-style-type: none"> ● While the proposed scheme can serve as a reference for future versatile and flexible systems, it may not be economically feasible to implement in a practical HIL distribution system.⁴⁷ ● Not all possible short circuit cases are included.
Differential evaluation algorithm ⁵²	<ul style="list-style-type: none"> ● DG impact mitigation on relay coordination and sensitivity is improved by differential evolution algorithm. 	<ul style="list-style-type: none"> ● Issues related to cyber attacks were not discussed.⁴⁷
Fuzzy method		
Adaptive Fuzzy logic ⁵³	<ul style="list-style-type: none"> ● An adaptive fuzzy algorithm based method was used to upgrade protective relay settings and optimize coordination when network configuration changes. 	<ul style="list-style-type: none"> ● Further studies are needed to examine the two-phase and earth fault protection, as well as the reaction of DG capacity on fault current levels.
Adaptive fuzzy inference module ⁵⁴	<ul style="list-style-type: none"> ● A numerical protection system has been developed, in which an adaptive fuzzy inference including an optimization algorithm and a heuristic algorithm is used for current and time settings calculation. 	<ul style="list-style-type: none"> ● The implementation of this scheme in practice poses a challenge.
Adaptive fuzzy inference system with central grid status communication unit ⁵⁵	<ul style="list-style-type: none"> ● An adaptive fuzzy inference system is developed with a centralized Communication arrangement which monitors PCC conditions to detect any changes in microgrid configuration and signals are sent to relays for updating their settings. ● The system response time is perfect. 	<ul style="list-style-type: none"> ● The concern of cyber security requires attention and must be addressed.
Decision tree built fuzzy rule ⁵⁶	<ul style="list-style-type: none"> ● A fuzzy rule-based technique utilizing a decision tree has been devised to protect microgrids in diverse configurations. 	<ul style="list-style-type: none"> ● The operational speed of the proposed scheme should be further optimized to facilitate online relaying.
Multi agent based		
MAS ³⁶	<ul style="list-style-type: none"> ● To accommodate variations in DG integration and system topology, adaptive multi-agent protection strategies have been devised. ● These strategies foster collaboration between protection relays and DG controllers, enhancing the overall effectiveness of the system. 	<ul style="list-style-type: none"> ● The proposed scheme achieves a fault clearing time of 1.11 seconds.
Dual online and offline ⁵⁸	<ul style="list-style-type: none"> ● The multi-agent strategy incorporates both online and offline approaches. ● The online approach utilizes a centralized communication infrastructure, enabling fast information exchange and efficient operation. ● Meanwhile, the offline approach serves as a backup mode in situations where communication delays or failures occur. 	<ul style="list-style-type: none"> ● The analysis focuses solely on single-phase to ground faults, while the performance with remaining faults still needs to be evaluated. ● The utilization of communication channels introduces the potential risk of cyber threats, necessitating careful consideration of cyber security measures.

(Contd.)

Table 1 — Outcome of the review — *Contd.*

Particular/reference	Contribution/Feature	Limitation
Other adaptive protection approaches		
Decision Tree ⁵⁹	<ul style="list-style-type: none"> •The proposed method employs a decision tree (DT) to generate an optimal composition of the scheme, ensuring that the most effective alternative is selected for each unsuccessful scheme based on uncertainty indices. •Offline setting storage requirement is less. 	<ul style="list-style-type: none"> •The proposed scheme was solely tested in a software environment. •It is crucial to take into account various microgrid topologies in order to comprehensively evaluate its effectiveness.
Zoned adaptive ⁶⁰	<ul style="list-style-type: none"> •An adaptive protection system is proposed for distribution systems with a significant contribution from DGs. •The power flow calculation is conducted offline, and short-circuit are performed to assess all faults. 	<ul style="list-style-type: none"> •When the penetration of DGs is low, the performance of the system is compromised.
Centralized adaptive protection ⁶¹	<ul style="list-style-type: none"> •The proposed adaptive scheme models electronically coupled Distributed Energy Resources (DER) for various fault scenarios and considers different modes of the microgrid. • Additionally, it incorporates a reclosing feature to facilitate faster recovery from faults. 	<ul style="list-style-type: none"> • The system was solely tested in a software environment.
Adaptive protection coordination ⁴³	<ul style="list-style-type: none"> •They proposed an adaptive relay coordination algorithm that offers rapid fault isolation. •The system was tested on the IEEE 4-bus distribution system. 	<ul style="list-style-type: none"> •The system was tested on a small-scale system.
Microgrid Central Protection unit(MCPU) ²⁷	<ul style="list-style-type: none"> •They developed a centralized protection system to monitor the status of the microgrid. When there are changes in the microgrid status, the system updates the relay settings accordingly. •The microgrid is modeled using communication standards such as IEC 61850 and IEC 61850-7-420 	<ul style="list-style-type: none"> •Reliability will be compromised in the event of a communication system failure.

highlighting the aforementioned research contributions and limitations.

Discussion and Further Planning

Microgrid protection is crucial in guaranteeing a stable and secure power supply for critical loads. It encompasses safeguarding DG sources, the PCC, lines, and loads. Traditionally, microgrid protection has focused on specific operating modes and topologies. However, with the emergence of adaptive protection schemes, a more flexible and robust approach can be embraced. An adaptive protection scheme for microgrids integrates the dynamic status of DGs into relay settings, effectively accommodating various operating modes and topologies. By adjusting relay settings based on the microgrid's current state, faults can be detected and isolated more efficiently, resulting in faster restoration times and improved power quality. However, it is important to carefully evaluate each adaptive protection method's merits and limitations before selecting the most suitable approach. While a significant amount of research on adaptive protection schemes for microgrids has been

conducted using software simulations and laboratory environments, it is essential to implement and test the most effective approach in real-world scenarios. Additionally, addressing issues such as cyber threats⁶² and communication failures⁶³ is crucial to safeguard the reliability and security of the protection scheme.

To ascertain high impedance faults (HIF) is a critical concern in distribution system protection. HIFs account for approximately 5–10% of overall system faults,⁴⁵ and their limited current flow can pose challenges for conventional protection systems, potentially leading to detection failures. While most research on adaptive protection of microgrids and distribution systems focuses on short-circuit faults, incorporating HIF detection is necessary to achieve comprehensive protection for the microgrid. Overall, an adaptive protection scheme demonstrates long-term benefits, including reduced outage time and improved power quality. However, it may involve higher costs due to the utilization of advanced digital relays and sensors. As the deployment of microgrids continues to grow, additional research is warranted to

develop and enhance adaptive protection schemes that can meet the evolving needs of the power system.

Conclusions

This review focuses on key challenges in microgrid protection, including the dynamics of fault current intensity, bidirectional fault currents, protection blinding, false tripping, and fault ride-through, all of which negatively impact relay performance. The review concludes the following:

- An adaptive protection system is best for microgrids. This system incorporates DG dynamic statuses, supports several operating modes, and adapts to microgrid topologies, improving fault detection and isolation.
- Further research is necessary to address the limitations of the proposed adaptive protection methods.
- The majority of studies are simulated, with few using real microgrids. Communication failures and cyber security threats must be addressed to improve protection methods.

This comprehensive analysis of adaptable protection schemes provides useful insights into their development trends, supported by pertinent research references. It also provides vital information for future researchers on developing more efficient and dependable adaptive protection systems.

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