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Review Article

Powering up microgrids: A comprehensive review of innovative and intelligent protection approaches for enhanced reliability

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ABSTRACT

Microgrid protection schemes play a vital role in ensuring the reliability and efficiency of power distribution in urban and rural areas, especially as renewable distributed energy resources are increasingly integrated. This paper aims to provide a comprehensive analysis of existing microgrid protection schemes, discussing their advantages and limitations and highlighting key challenges and opportunities for future research. As microgrid systems become increasingly common, the management of power flow in small-community networks equipped with intelligent electronic devices, non-linear loads, and multiple distributed generation sources becomes more complicated. In order to address these challenges, coordination of protective schemes is required to prevent overload and damage to equipment. Firstly, the study discusses microgrid definitions and functional categories, highlighting their benefits and drawbacks. An analysis of microgrid protection literature includes adaptive protection systems as intelligent methods to address coordination challenges. Secondly, this review classifies microgrid protection techniques as modified, new knowledge-based and conventional schemes and provides a systematic analysis of optimization approaches. The study also examines the essential problems associated with the coordination of protective relays within microgrids. Finally, examining the current state of microgrid protection to identify the key research directions and opportunities for future development in this rapidly advancing field. The findings of this comprehensive analysis highlight the importance of effective microgrid protection in ensuring a stable and sustainable energy future.

Contents

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1. Introduction

As concerns about the environmental and climate impacts of fossil fuel-powered energy generation continue to grow, researchers have sought to identify cleaner alternatives. One such modern approach involves the use of Distributed Energy Resources (DERs) to generate electricity in a decentralized manner, close to the point of consumption (Basso et al., 2012). DERs include technologies such as renewable sources and fuel cells, due to their ability to alleviate the negative consequences of fossil fuels, these alternatives have garnered significant with a lot of focus in recent times. One proposed method for integrating the widespread adoption of DERs is through the use of microgrids (Basso et al., 2012; Association et al., 2003; Australia, 2005). A microgrid is described as a grouping of electrical loads, heat sources, energy storage devices, and parallel DERs that may function in either a grid or islanding mode. Normally, distributed energy resources in a microgrid operate in grid-connected mode. However, if there is a malfunction in the main grid, the microgrid can detach itself and change to an islanding mode of operation (Teodorescu et al., 2011; Crăciun et al., 2012; Preda et al., 2012). However, integrating microgrids into the existing electrical grid poses a unique set of challenges, particularly in terms of protection. Microgrids operate on different dispatch ability operational modes than traditional grids and require specialized protection schemes to ensure system stability and reliability. Indeed, traditional protection schemes have been widely used in electrical grids, but their application in microgrids has posed new challenges due to the unique characteristics of these systems. As a result, researchers have proposed modifications to these conventional protection schemes to make them suitable for microgrid applications. For example, traditional overcurrent protection schemes have been modified to include directional overcurrent protection in order to make the protection system more sensitive and selective. Similarly, traditional differential protection schemes have been modified to include adaptive protection algorithms that can account for the varying operating conditions of microgrids. Furthermore, researchers have proposed new protection schemes designed explicitly for microgrid applications, such as passive islanding detection schemes that rely on changes in system impedance to detect islanding. Additionally, active islanding detection approaches that introduce a modest disturbance into the system have been proposed, as well as hybrid protection schemes.

Table 1 presents and discusses the recent review works on microgrid protection areas. In general, Table 1 has shown a clear focus on addressing the challenges caused by DERs integration and the need for robust protection strategies. The trends and directions for new protection schemes are identified from these reviews by focusing on using different optimization and soft computing algorithms, modern intelligent techniques, and energy management controllers. While the review papers provide valuable insights into microgrid protection, there are some limitations to consider. In Table 1 reviews focus primarily on certain aspects of microgrid protection, such as optimization techniques or energy management strategies, potentially limiting a comprehensive overview of all protection challenges. In addition, the researchers address protection challenges and strategies that are specific to the grid model. The increasing importance of microgrids in contemporary power systems has led to a notable rise in research investigations focused on resolving the particular protection challenges associated with them. Robust protection techniques are significant due to the integration of multiple energy supplies and the necessity for dependable operation. Therefore, this study will comprehensively examine the key challenges related to microgrid protection, including fault detection, islanding detection, and protection coordination. In addition, this paper will provide a comprehensive examination of several power protection strategies that have been presented in existing studies. This research endeavours to provide readers

Table 1
Recent review papers on microgrid protection filed.

Ref. No	Year	Title of the review paper	Citation	Highlights
Beheshtaein et al. (2019)	2019	A Review on Microgrids Protection	143	The paper covers bidirectional fault current, fault detection and location methods, cybersecurity issues, and the need for an efficient circuit breaker for DC microgrids. It also provides a comprehensive review of the protection challenges in AC and DC microgrids and future trends in microgrid protection.
Sarangi et al. (2020)	2020	Distributed generation hybrid AC/DC microgrid protection: A critical review on issues, strategies, and future directions	62	This paper discusses the integration of distributed energy resources with conventional systems. It compares the efficiency of AC and DC microgrids and suggests a hybrid system with a theoretical efficiency of more than 90%. The paper also reviews the challenges for the protection of microgrid systems and provides a comprehensive review of the issues, strategies, and future directions for distributed generation hybrid AC/DC microgrid protection.
Meskin et al. (2020)	2020	Impact of distributed generation on the protection systems of distribution networks: analysis and remedies – review paper	34	The paper reviews the impact of distributed generation (DG) integration on protection systems and suggests methods to mitigate their impacts. The paper provides a comprehensive review of the issues, strategies, and future directions for DG integration.
Vegunta et al. (2021)	2021	AC Microgrid Protection System Design Challenges-A Practical Experience	24	The paper provides an overview of the impact of high penetration of DERs on the existing distribution systems. It discusses how microgrids can address some of these challenges, but also present their own set of protection design challenges. Reviews the current challenges with protecting microgrids and provides an overview of several commonly used protection strategies with their respective advantages and disadvantages in addressing those challenges based on the authors' experience.
Usama et al. (2021)	2021	A Comprehensive Review on Protection Strategies to Mitigate the Impact of Renewable Energy Sources on Interconnected Distribution Networks	41	This paper makes several contributions, including a comparative analysis of protection techniques to mitigate the impact of integrated resources in distribution networks (DN). It conducts a thorough comparison between classical and modified protection approaches, assessing their advantages, drawbacks, and implementation costs. The study underscores the significance of leveraging user-defined programmable relays in contemporary distribution networks. The paper provides recommendations for the application of robust user-defined relay characteristics to address protection challenges in both existing and future power systems.
Rezaei and Uddin (2021)	2021	State-of-the-Art Microgrid Power Protective Relaying and Coordination Techniques	2	This paper presents an analytical appraisal of state-of-the-art protection techniques to address problems associated with microgrid protection. It discusses the advantages and disadvantages of each protection technique, as well as proper selection of protective relays suitable for each protection zone. The paper also provides recommendations on protection procedures and effective techniques to resolve microgrid protection issues.

(*continued on next page*)

with significant insights into the intricacies of microgrid protection by the adoption of a complete and systematic methodology. Its objective is to contribute to the advancement of strong and efficient protection solutions inside microgrid systems.

1.1. Review methodology

This review paper aims to offer a comprehensive exploration of protection schemes for microgrid applications, encompassing both traditional modifications and novel proposals. Through an examination of the advantages, limitations, and practical implementation aspects of these schemes, readers will gain valuable insights into their effective deployment in microgrid systems. The critical challenges associated with microgrid protection, such as fault detection, islanding detection, and protection coordination, will be thoroughly discussed in this work. Furthermore, a detailed review of various power protection schemes proposed in the literature will be presented. By adopting a comprehensive and systematic approach, this review aims to equip readers with valuable knowledge to navigate the complexities of microgrid protection and contribute to the development of robust and efficient protection strategies in microgrid systems. This review paper employs a systematic approach to investigate the field of microgrid protection systems. The review paper is structured into four main sections, as illustrated in Fig. 1.

This work is meticulously structured into several key sections, comprising a defined objective and further specific subsections, as outlined below:

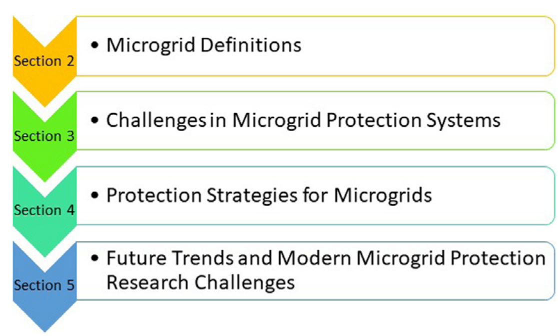

Fig. 1. The review paper structure for the microgrid protection systems.

- Microgrid Definitions.
  - Overview of microgrid definitions and functional classifications.
  - Examination of microgrid implementation.
- Challenges in Microgrid Protection Systems
  - Exploration of protection issues in Microgrid.
  - Discussion of coordination issues and the need for effective protective schemes.

Table 1 (*continued*).

Draz et al. (2021)	2021	Soft Computing Methods for Attaining the Protective Device Coordination Including Renewable Energies: Review and Prospective	11	Comprehensive review of optimization approaches for coordination of directional overcurrent relays (DOCRs) in systems with distributed generations (DGs). Discussion on challenges and use of metaheuristic and nature-inspired algorithms to address optimization problems.
Altaf et al. (2022)	2022	Microgrid Protection Challenges and Mitigation Approaches- A Comprehensive Review	20	Detailed review and comparative analysis of protection schemes for different microgrid architectures. Identification and discussion of challenges in microgrid protection implementation. Presentation of simulation studies highlighting microgrid protection challenges in various operation modes.
Ishaq et al. (2022)	2022	A review on recent developments in control and optimization of microgrids	41	In-depth literature review on control structures of microgrids (MGs) addressing stable operation of utility grids. Categorization of MGs based on criteria such as distributed energy resources (DERs) and control strategies for integrating renewable energy resources in MGs.
Gholami et al. (2022)	2022	State-of-the-art technologies for volt-var control to support the penetration of renewable energy into the smart distribution grids	5	Comprehensive review of current state-of-the-art technologies for volt-var control in distribution networks. Investigation of emerging volt-var technologies for distribution networks along with their advantages and disadvantages.
Ramli et al. (2022)	2022	The recent development of optimal DOCR protection strategies for sustainable power systems via computational intelligence techniques	1	Comprehensive overview of various optimization strategies for optimal directional overcurrent relay (DOCR) coordination in interconnected power grids. Evaluation of benefits, drawbacks, and future research trends for optimal DOCR coordination.
Hong and Pula (2022)	2022	Methods of photovoltaic fault detection and classification: A review	37	Review of various methods for detecting and classifying faults in photovoltaic systems (PVS).
Castro et al. (2023)	2023	Microgrid Applications and Technical Challenges-The Brazilian Status of Connection Standards and Operational Procedures	–	Analysis of norms, standards, and requirements for microgrid connection and operation in Brazil. Proposal of technical and operational requirements for microgrid projects. Discussion of critical points such as modes of operation, interoperability, connection structure, feasibility assessment, and operational issues.
Uzair et al. (2023)	2023	Challenges, advances, and future trends in AC microgrid protection: With a focus on intelligent learning methods	–	Critical review of AC microgrid protection methods. Analysis of recent protection approaches using modern intelligent techniques. Discussion of challenges in protecting microgrids against faults for different operation modes and dynamic network topologies.
Sheta et al. (2023)	2023	A comparative framework for AC–microgrid protection schemes: challenges, solutions, real applications, and future trends	–	Thorough evaluation of potential issues in network protection in AC-MGs. Comprehensive overview of MG structure and associated protection challenges, solutions, real applications, and future trends. Investigation of protection concerns in AC-MGs, including autorecloser deficiency, asynchronous reclosing, loss of coordination, and transformer winding connections.
Hamanah et al. (2023)	2023	AC Microgrid Protection Schemes: A Comprehensive Review	–	Comprehensive review of AC microgrid protection schemes. Examination of AC microgrid penetration into distribution network as part of a comprehensive review of protection systems. Understanding of microgrid interaction with and potential improvement of distribution network protection systems. Overview of standards to help developers connect distributed generations (DGs) to public distribution networks.
Shirkhani et al. (2023)	2023	A review on microgrid decentralized energy/voltage control structures and methods	1	Overview of different decentralized control methods for microgrids (MGs) based on recent research. Description of methods used in each study along with their results.
Allwyn et al. (2023)	2023	A comprehensive review on the energy management strategy of microgrids	2	Comprehensive review of energy management strategies for microgrids, including renewable energy resources, storage devices, non-renewable sources, and control devices. Review of techniques for optimal power sharing between components in microgrids, including forecasting methods, control strategies, and uncertainty considerations.

- Protection Strategies for Microgrids
  - Analysis of conventional, modified and knowledge-based protective schemes.
  - Overview of implementation adaptive protection techniques.
- Future Trends and Modern Microgrid Protection Research Challenges.
  - Design and Implement Microgrid System.
  - Examination of emerging trends for microgrid protection systems and identify the key research directions.

2. Microgrid definitions

2.1. Microgrid definitions and classifications

There have been several definitions and functional classification schemes proposed for microgrids in the literature (Teodorescu et al., 2011; Crăciun et al., 2012). Microgrids are defined by the Microgrid Exchange Group of the U.S. Department of Energy as "a collection of interconnected distributed energy resources and loads operating as a unified and controllable entity within clearly delineated electrical perimeters relative to the grid". By connecting or disconnecting from the main grid, a microgrid can operate in both operation modes, grid and islanding modes (Preda et al., 2012). Microgrids offer a number of advantages, such as delivering an uninterrupted power supply to customers with a high demand for dependable, high-quality electricity, which can result in cost savings through the use of heat and power systems.

Microgrids are interconnected through power electronic converters, such as AC/DC and DC/AC converters. Depending on technical and economic evaluations, microgrids can operate in either grid-connected mode or islanding mode, which is controlled by a fast-switching isolator at the Point of Common Coupling (PCC). In the grid-connected mode, microgrids function as a typical arrangement when the main grid remains stable without any disturbances. On the other hand, in the islanding mode, microgrids can be intentionally activated to supply power to rural areas or military zones. Additionally, they can automatically respond to perturbations in the main grid, ensuring continuity of power supply during grid disruptions. In the realm of microgrids, a primary classification can be made based on the electrical power type, resulting in three main categories: AC, DC, and hybrid microgrids (Preda et al., 2012; Piesciorovsky et al., 2020).

- AC-microgrids facilitate the direct connection of facilities generating or consuming AC power to the main bus, streamlining the integration process. In contrast, DC/AC converters are essential for interfacing with DC installations, catering to the rise in DC renewable, HVDC systems, and rechargeable appliances such as electric vehicles.
- DC-microgrids, on the other hand, have emerged as a response to the growing adoption of DC-based technologies, offering specialized support for HVDC systems and various DC applications.
- To combine the strengths of both AC and DC systems, hybrid grids have been developed, providing enhanced flexibility for new installations through the use of power electronics. By minimizing multiple conversion processes (AC/DC and DC/AC), capital expenses are reduced, and overall efficiency is improved in these hybrid setups.

Microgrids take an important position as flexible subsystems inside the expected power networks of the future. Integrated within the distribution network, these microgrids have the capacity to operate in two modes: related to the main grid or in an isolated island mode, serving the energy needs of the local area. A variety of distributed generators, both renewable and non-renewable, are integrated into the system. The control component of microgrids plays a vital role in addressing the issues that arise from the increased integration of DGs. Microgrids have the ability to implement either centralized or decentralized control systems, depending on the specific duties performed at various control levels (Sheta et al., 2023; Shiles et al., 2017).

- Centralized approach: The main objective of this controller is to enhance the significance of the microgrid and optimize its general functioning. This is achieved by determining the optimal power stability for the microgrid, whether it involves importing or exporting energy from the upstream distribution system, while simultaneously optimizing local production and consumption capabilities. The decision-making process of this controller relies on several criteria such as the current electrical market pricing, the importance of grid protection, and the additional services required by the Distribution System Operator (DSO). The outcome is an improved operational situation, achieved by effectively managing the DGs and adjustable loads inside the microgrid through coordinated control. This control technique facilitates the disconnection of non-essential, adaptable loads in situations when it is beneficial to the economy.
- Decentralized approach: This controller is responsible for optimizing output, satisfying demand, maximizing grid export, and ensuring consistency with real-time market pricing. The present work investigates the operational characteristics of microgrid control systems.

Table 2
Comparison between centralized and decentralized microgrid controller.

Term	Centralized	Decentralized
Controller	High complexity	Lower complexity
Performance	Slow	Faster
Flexibility and reliability	Medium	High
Decision-making process	Slow	Faster

Table 2 offers a brief overview of the primary differences between centralized and decentralized microgrid systems, explaining their different control methodologies, decision-making processes, communication prerequisites, levels of resilience, and complications associated with implementation. The provided resource functions as a beneficial point of reference for understanding the different characteristics and factors related to each system design (Sheta et al., 2023; Piesciorovsky et al., 2020).

2.2. Microgrids implementation

This section provides a concise overview of real microgrid applications and projects. It highlights the grid operation, control and protection systems that have been actually implemented in these projects. In general, the majority of microgrid projects rely on DGs including solar, gas, wind, diesel, and thermal energy systems. This diversity reflects the various approaches taken by these projects to harness different renewable and conventional energy resources for their microgrid deployments. Table 3 presents the real applications of microgrid systems (Sheta et al., 2023; Piesciorovsky et al., 2020; Shiles et al., 2017; Hmad et al., 2023).

Santa Rita Jail and Borrego Springs projects are AC-type MGs with decentralized control operations. Santa Rita Jail, serves a university facility, while Borrego Springs caters to residential, commercial, and industrial applications. They use different distributed generation sources, with Santa Rita Jail integrating PV, diesel, and fuel cell DGs, while Borrego Springs utilizes diesel and PV DGs, as shown in Fig. 2. The Santa project is only operated under the Grid-connected (GC) mode, while the Borrego is manually operated with the Islanding mode (IM). Protection mechanisms also vary, with Santa Rita Jail utilizing OCR and Borrego Springs employing voltage-restrained OCRs. The Navy Yard and Fort Collins are microgrids with decentralized control operations. The Navy Yard serves AC residential applications, while Fort Collins is a hybrid microgrid serving residential applications. They have different distributed generation sources, with The Navy Yard integrating gas/diesel turbines, PV, and fuel cell DGs, while Fort Collins utilizes PV, microturbines, fuel cells, and diesel DGs. Fort Collins incorporates thermal storage as a storage system, while The Navy Yard utilizes a community solar and energy storage system. The Navy Yard operates exclusively in grid-connected mode, while Fort Collins can switch between grid-connected and islanding modes. Illinois Institute of Technologies and Colonias projects are AC-type MGs, with Illinois Institute of Technologies serving residential applications. They use different distributed generation sources, with Illinois Institute of Technologies integrating gas turbines, PV, wind, and diesel DGs, while Colonias utilizes PV, wind, and diesel DGs. Illinois Institute of Technologies employs a Follow battery as a storage system,

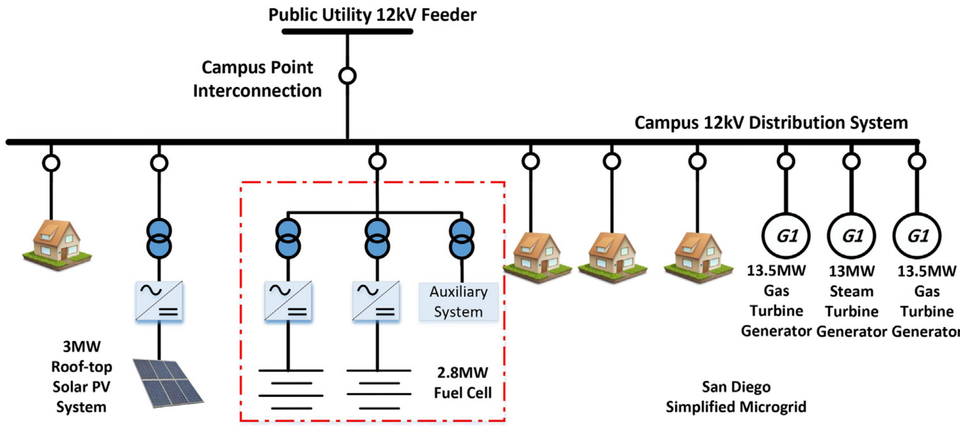

Fig. 2. San Diago microgrid.

Table 3
Implantation of real microgrid projects.

Project name	Area	Voltage level (kV)	MG type and size	Load application	DGs	Control operation	Operation	Protection
Santa Rita Jail	Dublin, California	12.47	AC (6.6 MVA)	University	PV, diesel, fuel cell	Decentralized	GC	OCR
Borrego Springs	San Diego County, California	12	AC (4.6 MVA)	Residential, commercial and industrial	Diesel, PV	Decentralized	GC	Voltage-restrained OCRs
The Navy Yard	Philadelphia	–	AC	Residential	Gas/diesel turbines, PV and fuel cell	Decentralized	GC	–
Fort Collins	Fort Collins, Colorado	–	Hybrid	Residential	PV, micro-turbines, fuel cells, diesel	Decentralized	GC and IM	–
Illinois Institute of Technologies	Chicago, Illinois	4.16	AC	Residential	Gas turbines, PV, wind, diesel	Decentralized	GC and IM	OCR and differential protection
Colonias	Texas	–	AC	–	PV, wind, diesel	Centralized	Grid-connected	–
University of Miami Testbed	Florida	–	DC	University	PV, fuel cell	Decentralized	GC and IM	–
Electric power board	Chattanooga	12.47	AC (1.3 MVA)	Residential	PV	Decentralized	GC	Fuse
Boston Bar–Canada	Canada	25	AC (3 MVA)	Residential	Hydropower	Decentralized	GC and IM	OCR
British Columbia Institute of Technology	Canada	12.47	AC (17.9 MVA)	Residential	–	Decentralized	GC and IM	Differential protection
Boralex Planned Islanding	Canada	25	AC (7 MVA)	Residential	–	Decentralized	GC and IM	OCR

while Colonias does not have any storage system in place (Shiles et al., 2017; Hmad et al., 2023). Colonias operates exclusively in grid-connected mode, while the Illinois project is operated under Grid-connected and islanding modes which have been protected by using a differential protection scheme. However, the implementation of microgrids introduced limited approaches to microgrid protection schemes (Antonova et al., 2012; Tailor and Osman, 2008). The conventional protection strategies implemented in microgrids were not been tested and evaluated over different fault scenarios and grid operation modes. In Canada, three main AC microgrid projects are implemented based on decentralized controllers for residential load. Fig. 3 presents the single-line diagram for Boston Bar–Canada project. In terms of employing protection systems, most of the implemented projects used OCR and differential protection, as presented in Table 3. However, the Electric power board project employed and used only fuse to protect the system in case of overcurrent and faults, while Borrego Springs project used an advanced scheme based on voltage-restrained overcurrent protection (Sheta et al., 2023; Piesciorovsky et al., 2020; Shiles et al., 2017; Hmad et al., 2023).

2.2.1. Microgrids protection constraints

The design and adaptation of power system protection depend on various factors such as the system configuration, whether it is a ring, radial, microgrid, or distributed energy resources (DER) system. These configurations dictate the specific requirements for

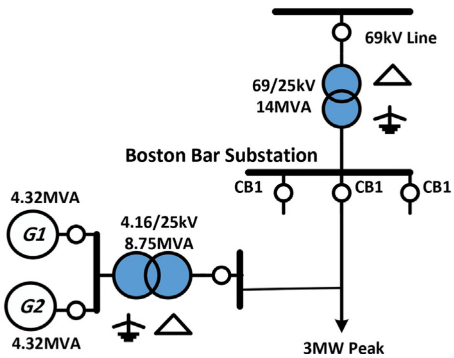

Fig. 3. Boston microgrid.

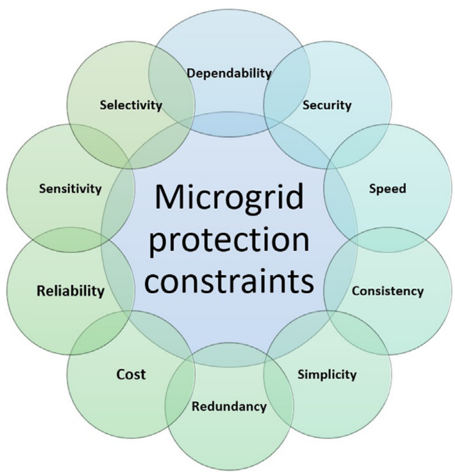

Fig. 4. Microgrids protection constraint terms.

protection relays. Key factors considered in this process include selectivity, sensitivity, reliability, operational speed, simplicity, redundancy, and consistency, as shown in Fig. 4 (Ishaq et al., 2022; Hussainand et al., 2020).

The selection of an appropriate protection scheme for a microgrid application involves careful consideration of various factors related to the protection requirements, as shown in Fig. 4, and the microgrid topology to ensure the reliability and safety of the system. Table 4 defines the key factors that have a vital influence in establishing the optimal protection method. Every consideration relates to different components of the microgrid, including its configuration, sources of generation, characteristics of faults, critical loads, operational modes, and other significant variables. Through careful analysis of these factors, designers and engineers specializing in microgrids can make sensible decisions that are compatible with the particular requirements and challenges faced within their specific microgrid framework (Hussainand et al., 2020; Alasali et al., 2021; Kumar and Zare, 2019).

3. Challenges in microgrid protection systems

3.1. Protection issues in microgrid

The integration of DERs into the Distribution Network (DN) has raised significant issues due to the radial design of these networks, especially in the context of Microgrid applications. Microgrids can independently operate or in conjunction with the utility, providing improved power quality and reliability to the connected loads, which makes designing high-performance

Table 4
Considerations for selecting microgrid protection scheme.

Consideration	Explanation
Configuration and Size	The microgrid's topology and size influence protection strategies.
Generation Type and Capacity	The type and capacity of DGs impact protection requirements.
Fault Characteristics	Understand fault current levels, impedance, and locations for selection.
Critical Loads and Equipment	Identify and safeguard critical loads and equipment.
Operational Modes	Different modes require specific protection coordination approaches.
System Stability	Rapid fault detection and isolation maintain overall system stability.
Protection Coordination	Coordinate protection devices to avoid unnecessary tripping.
Speed of Operation	Quick fault clearance can minimize equipment damage.
Cybersecurity	Ensure protection against unauthorized access or cyberattacks.
Cost and Complexity	Balance cost and complexity for a cost-effective solution.
Flexibility and Adaptability	Adapt to changes in configuration, generation mix, and demand.
Standards and Regulations	Comply with safety and performance standards and regulations.
Fault Ride-Through Capability	Handle faults and transients, especially in high-renewable microgrids.

protection systems a critical concern for microgrids. These protection methods are widely implemented and discussed in the existing literature (Soshinskaya et al., 2014; Choudhary et al., 2014; Al-Nasseri et al., 2006; González et al., 2012) . However, as distribution systems move away from radial designs and incorporate microgrid technology at high penetration levels, traditional protective schemes become inappropriate for modern DN interconnected to DERs. This is because the operating impacts of DGs in the DN require specialized protection schemes tailored to the unique characteristics of microgrids with high levels of variation for the directions of fault currents.

3.1.1. Variation in both the levels and directions of fault currents

Both the level and direction of fault currents in power networks have undergone significant changes as a result of the contribution of distributed energy supplies. The quantity of fault current is significantly affected by the DG technology adopted, which can be either converter-based or synchronous, as well as the size and position of the DG and the point of common coupling (PCC) (Papaspiliotopoulos et al., 2017a; Walling et al., 2008; Blaabjerg et al., 2017; Talebizadeh Sardari, 2018).

Rising in the level of fault current: One of the major issues arising from integrating DG units into the DNs is the increase in fault current levels, which can lead to a decline in the overall performance of the protection system (Wippenbeck et al., 2015). TAs the fault current level rises, the ratings of circuit breakers (CBs) and power equipment, as well as the settings of protection relays, might become erroneous. This can result in a reduced breaking capacity of CBs, causing substantial impedance in short circuits at buses and switchgear in main substations (Hussain et al., 2010). In addition, the rise in minimum and maximum fault current levels complicates the design of the coordination scheme between the primary and backup protective relays in the DN. Therefore, protection setting values should be updated and existing equipment verified to sustain the system efficiency,

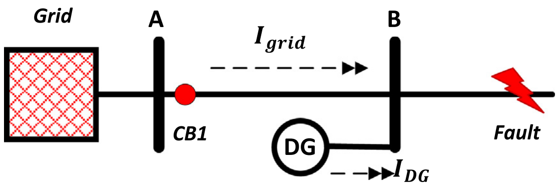

Fig. 5. Contribution of DG during fault conditions.

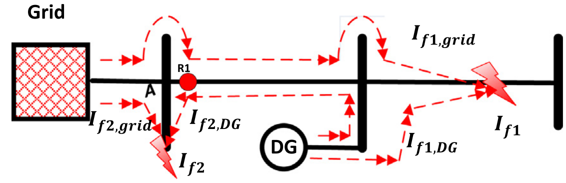

Fig. 6. Bi-directional impact due to DG penetration.

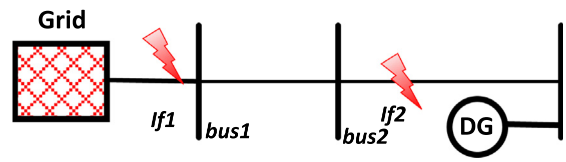

Fig. 7. Coordination failure caused by DG connections.

especially after any fluctuation in the grid, since short circuit variation can affect both reliability and safety. The fault current generated by distributed generating units (DGs) has a significant effect on the variation of short circuit levels. During the duration of the transient operation, the inverter-DG output current remains constant at the load current value (Glinka et al., 2017). During single-phase faults, the current contribution is larger than during three-phase faults, with IEEE-1547 requiring this current to be less than 100% of the DGs three-phase fault current. For the zero sequence, the DG acts as either a fixed impedance or a source of voltage, while for the positive sequence, it acts as an ideal current source. The significant induction machine current remains for a few cycles, resulting from the pre-fault voltage and transient reactance division (van der Walt et al., 2018; Nikkhajoei and Lasseter, 2007; Saint and Friedman, 2002). In DNs, it is often practical to ignore the contribution of fault current from DERs and induction machines, as their fault current is typically much less than that of motor loads. As a result, current-controlled inverter-based DERs can be considered as an insignificant short-circuit current source (Barker and De Mello, 2000). Despite this, it is necessary to reevaluate the fault impact of DERs owing to potential changes in their controls, which may seek to achieve other goals, such as functioning as a voltage source (Nassif, 2018). Synchronous generators need exciters and field-forcing circuits to withstand fault currents that may surpass their maximum load current. In such situations, it may become important to rely on distribution protection to detect and isolate problems in the DER plant (Zay et al., 2011; Kennedy et al., 2016).

Effects of fault currents reduction: When DERs are connected through electronic inverter interfaces, overcurrent protection systems may have difficulty recognizing fault currents, especially when they are very small. Photovoltaic and wound rotor induction generators are examples of DERs that can create such challenges. Additionally, wind turbine generators and doubly-fed induction generators are also common cases (Nassif, 2018; Kennedy et al., 2016). As shown in Fig. 5, If a problem develops downstream of the DER and its network current is insufficient to be detected by the CB at the end of the feeder, there is a possibility that the fault will not be identified and isolated. This may result in equipment damage or a threat to worker safety. To mitigate this, extra protection measures, such as directed overcurrent relays or fault current limiters, may be necessary. In such cases, DG can provide faster protection compared to the CB, and the DER may enter uncontrolled island operation after clearing the fault. Therefore, it is significant to consider the minimum fault current and re-examine the fault contribution of DERs in such scenarios.

The presence of DG can cause bi-directional flow of fault currents in power systems: In modern DNs with DG, the direction and level of power flow can change depending on whether the consumption is greater or less than the generation, as illustrated in Fig. 6 (Hussain et al., 2010). In DNs, the fault current can move in both directions along the line due to the radial nature of the network, where there is no unique forward path. This poses a challenge to traditional protective systems such as medium and fuses. One solution to this challenge is to use directional overcurrent relays (OCRs) as an alternative protective system, which has been found to be effective (Coffele et al., 2012).

3.2. Coordination issues in microgrids

Coordination between protection devices is achieved when two devices operate in basic backup mode during a fault occurrence, as defined in Wan et al. (2010). However, the contribution of protection devices may be lost due to changes in fault level or direction, which can be caused by DG integration in DN. Fig. 7 provides an example of this scenario, as described in Girgis and Brahma (2001). If a fault occurs at either Bus 1 or Bus 2, as seen in the diagram, the fault current coming from both buses will be identical. Consequently, the protection relay connected with the malfunction on Bus 1 will operate before the backup relay on Bus 2. If a problem occurs on Bus 2, the situation is inverted. Nonetheless, if one of the errors happens, the relays' coordination will be weakened (Girgis and Brahma, 2001). However, to avoid this case, a single curve of time-current setting should be used.

3.2.1. Protection blinding

The availability of DG units in the DN can change the fault current level and flow path, which in turn changes the main substation's contribution to fault occurrences in the traditional distribution grid. The relay reach is the distance that can be detected along the radial feeder by the overcurrent relays employed in the DN. Nonetheless, the integration of DG units might reduce the fault current contribution from the upstream grid and increase the possibility of having blinding zones. As the reach of the feeder relay decreases, this reduction might result in protective blindness or underreach (Dugan and Mcdermott, 2002; Zhou et al., 2010; Papaspiliotopoulos et al., 2016, 2014, 2017b; Saadat, 1999). Using directional Overcurrent Relays (OCRs) can be a viable solution to the problem of protection blinding or under-reach protection caused by the decrease in fault current contribution from the upstream grid as a result of the incorporation of DG units into the distribution network. Directional OCRs can give a higher level of protection than fuses or other medium-sized protective devices.

In Fig. 8, the issue of protection blinding is depicted with consideration given to a symmetrical fault that occurred at Bus A. The fault current in the power network with distributed generation (DG), denoted as $I_{f,sys}^{with,DG}$, is lower than that in the network without DG, denoted as $I_{f,sys}^{no,DG}$. However, the overall fault current level may increase due to the additional contribution of fault current from the DG units, represented as $I_{f,DG}$.

Various parameters, like the placement and capacity of DG units and the location of faults within the grid, need to be considered when determining the level of blinding protection. In

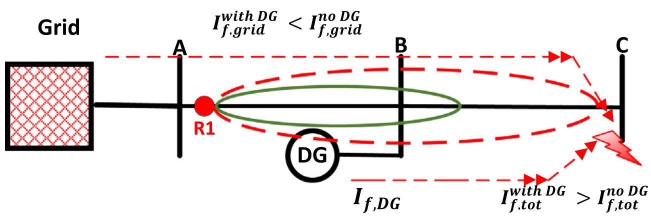

Fig. 8. Protection challenges and blinding points for grids with high DERs penetration.

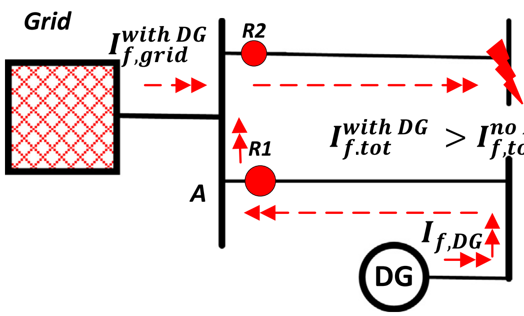

Fig. 9. Tripping cascades caused by distributed generation integration.

addition, the fault current and bus voltage may be analyzed using the superposition theorem to calculate the amount of protective blindness, assuming the system is carrying no load beyond the fault spot. By calculating the fault current before and after DG integration, the level of protective blinding may be ascertained.

$$I^{no\,DG}_{f,sys} = V_f/(Z_{sys} + Z_L) \tag{1}$$

$$I^{with\,DG}_{f,sys} = V_f/(Z_{sys}Z_{DG})/(Z_{sys} + Z_{DG}) + Z_L \tag{2}$$

where V_f is the bus voltage, Z_{sys} is the impedance at Bus A, Z_L is the impedance between Bus A and B, Z_{DG} is the impedance of DG1. Eqs. (1) and (2) shows that $I^{with\,DG}_{f,sys} > I^{no\,DG}_{f,sys}$, as follows:

$$I^{with\,DG}_{f,sys} = V_f/(Z_{sys}\left(\frac{Z_L}{Z_{DG}} + 1\right)Z_L) \tag{3}$$

$$I_{f,DG} = (V_f - Z_L I^{with\,DG}_{f,sys}/(Z_L + Z_{DG})) \tag{4}$$

By making a comparison between (1) and (3), thus, $I^{no\,DG}_{f,tot} > I^{with\,DG}_{f,tot}$. The impedances of both DG and distribution lines are proportional to the impedance of the upstream grid and can be expressed as $Z_{DG} = mZ_{sys}$, $Z_L = nZ_{sys}$.

3.2.2. Sympathetic tripping

In power system protection, an undesirable event called sympathetic tripping can occur due to the impact of feeder relays. This happens when DG feeds back power to a fault that occurs outside of its protection region, leading to a power cut in the entire network. This issue is commonly referred to as false tripping, and it can cause a variety of tripping problems. To illustrate this, Fig. 9 presents a schematic of the sympathetic tripping process. Specifically, in this example, Feeder 2 experiences a fault, and DG provides short-circuit current through the substation bus.

In power networks with a substantial degree of DG capacity, it is typical for circuit breaker R1 to trip before R2, which can lead to complications. The use of non-directional OCRs, exacerbates this issue. In DNs with classic integrated DG units, the problem of sympathetic tripping and the development of continuous short-circuit currents are more likely to occur. This issue develops when the feeder overcurrent relays have differing settings for their inverse-time pickup currents or times. For an appropriate evaluation of the effect of DG capacity and fault location, it is required to analyze the occurrence of sympathetic tripping. Fig. 9 shows a three-phase fault that occurs at bus 2 with Z_{L2}. This is the primary operating case without any integrated DG, where fault current can be calculated accordingly.

$$I^{no\,DG}_{f,sys} = V_f/(Z_{sys} + Z_{L2}) \tag{5}$$

where ($Z_{L1} \cong 0$) at the DG integrated near the substation and the overall fault current is:

$$I^{with\,DG}_{f,sys} = V_f/(Z_{L2} + (Z_{sys}Z_{DG}))/(Z_{sys} + Z_{DG}) \tag{6}$$

$$I^{with\,DG}_{f,sys} = V_f/(Z_{sys} + \left(1 + \frac{Z_{sys}}{Z_{DG}}\right)Z_{L2}) \tag{7}$$

$$I_{f,DG} = V_f/(Z_{DG} + \left(1 + \frac{Z_{DG}}{Z_{sys}}\right)Z_{L2}) \tag{8}$$

When a fault occurs near the substation, the resulting fault current tends to be high. Fig. 10 shows a 3D-r(m,n) plot diagram. $r \to 1$ is the result from $m \to 0$, this can happen when the impedance of the DG is relatively low. As a result, both circuit breakers R_1 and R_2 may trip simultaneously when a fault occurs at Bus 2, even if their tripping times were specifically chosen to be different. In cases where the time dial setting for one of the relays is shorter than the other, the chances of sympathetic tripping may increase, especially in systems with high DG capacity (Papaspiliotopoulos et al., 2017b).

In power systems with DG, it is essential to quickly identify and isolate faults within the system. This is significant during the early reclose interval, as allowing faults to continue flowing can result in delays in the arc and ultimately lead to permanent faults. This can result in power disconnections for customers, which should be reported promptly. Additionally, unbalanced active power fluctuations may occur during the reclosing time, which can cause generators to go out of synchronize. As noted in Barker and De Mello (2000), DG needs to recognize and isolate faults during the early reclose interval to prevent such issues from occurring.

4. Protection strategies for microgrids

This section examines the evolution of microgrid protection solutions that use DERs. Protection methods in distribution networks are generally built with unidirectional power flow in mind. However, the addition of DERs provides bidirectional power flows, necessitating a reevaluation of conventional microgrid safety strategies. Fig. 11 provides an overview of the main microgrid protection strategies: conventional, modified and knowledge-based protection schemes.

4.1. Conventional strategy for microgrid protection

In recent years, numerous techniques are proposed to alleviate the impact of DG on DN while also enabling larger DG units to coexist with service quality. These methods mainly involve adjusting the distribution system to accommodate the DG units. This section will examine different palliation strategies that have been suggested, falling under categories such as protection relay technologies and optimization protection relay settings. These methods, varying from basic to advanced, effectively address the unfavorable effects of DG on distribution systems. It should be emphasized that the choice of palliation strategy will depend on the specific attributes of the distribution system and the type of DG unit employed. In general, microgrid protection schemes utilize five types of relays, namely, overcurrent, distance, voltage, differential and admittance, as shown in Fig. 12.

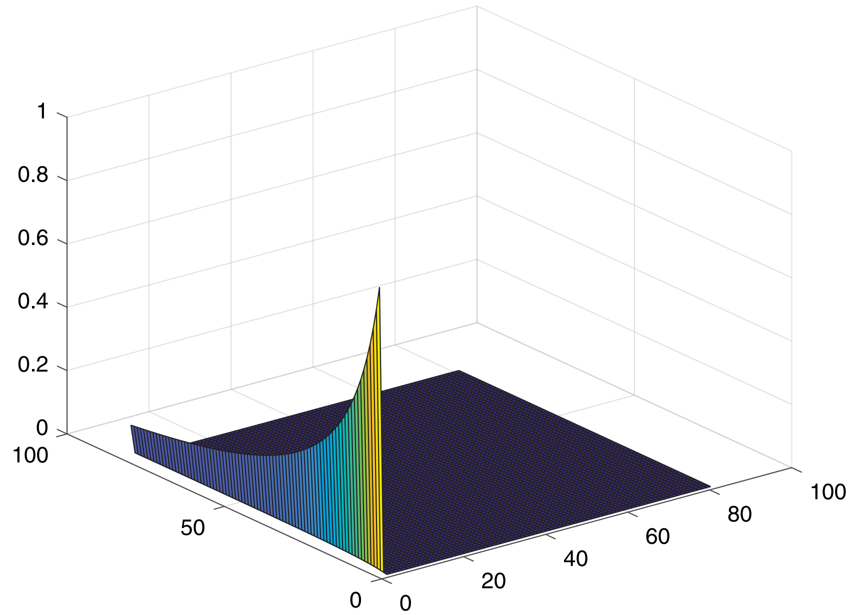

Fig. 10. 3D plot diagram for the fault levels.

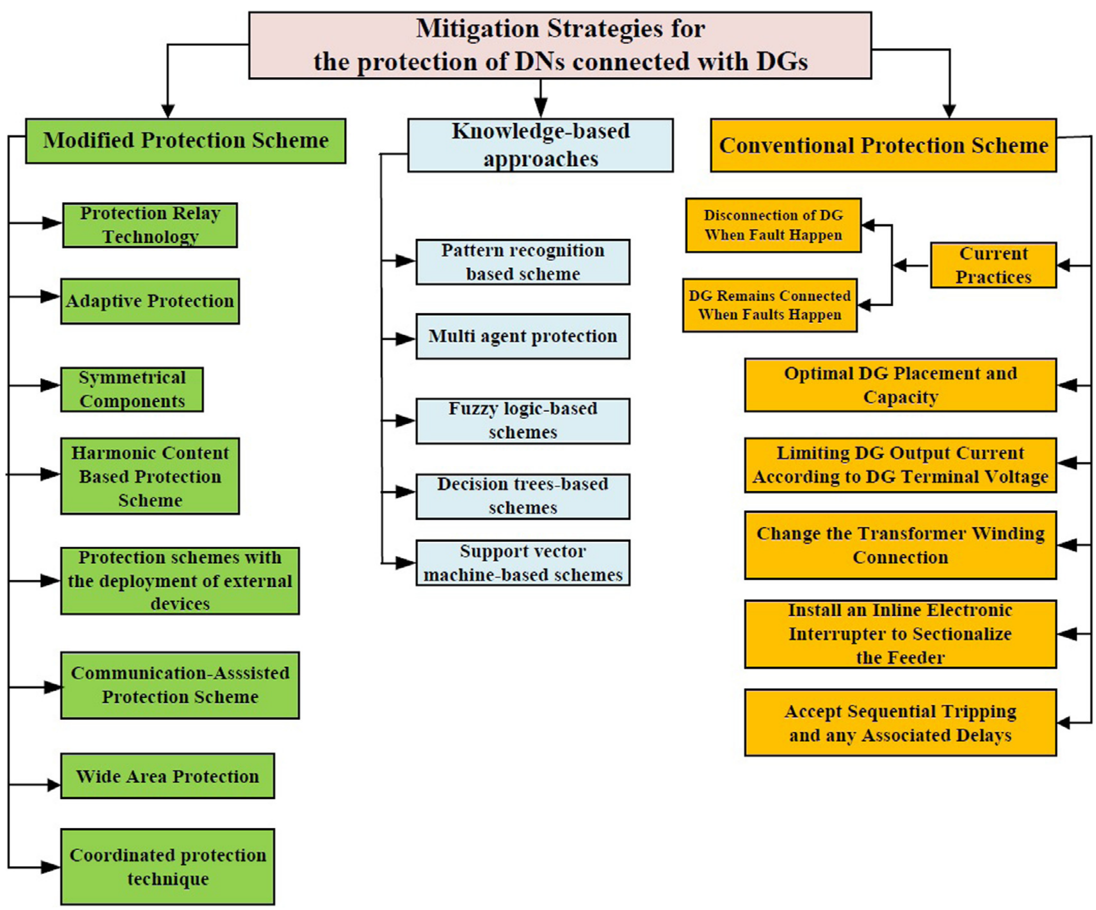

Fig. 11. Strategies to mitigate the impact of DGs on distribution networks (DNs) protection.

1. Overcurrent Relay
   OCR is widely acknowledged as one of the most effective safeguarding devices for conventional DNs. However, the addition of DGs and the operation of networks in both islanded and grid modes can substantially alter the networks short-circuit current, making it difficult for overcurrent relays to operate efficiently with conventional settings. Consequently, it is essential to restructure overcurrent relays in order to accommodate these shifting network conditions (Ustun et al., 2012).

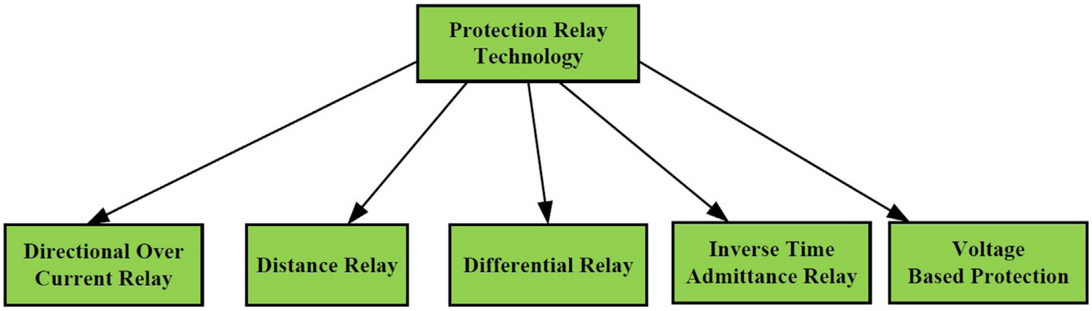

Fig. 12. Conventional protection relays for microgrid protection.

The parameters of overcurrent relays are dependent on the current malfunction conditions and fault current of the network. By reconfiguring the relays, various network situations can be accommodated, and the relay can choose an appropriate configuration based on the present network conditions. This strategy is applicable offline and online, as exemplified in Buque et al. (2012).

2. Distance Relay
Distance protection, which utilizes impedance or admittance measurements, effectively detects faults and performs trip actions in power systems. This protection scheme for distributed generation power systems (DPGS) in both grid-connected and islanded configurations was initially proposed by Dewadasa et al. (2009b) and Dewadasa (2010). Using a new admittance relay model, which possesses inverse time tripping characteristics, allows for the accurate identification of faults in this scheme. Distance protection has several advantages, primarily depending on the measured impedance. Using the extracted impedance, a new protection strategy with two procedures for primary and secondary protection was developed (Huang et al., 2014). The first procedure provides a time reference for data exchange to identify the occurrence of a defect. In addition, the latter has an inverse time characteristic for setting automatic, coordinated fallback protection. In Voima and Kauhaniemi (2014), the distance-protection method was utilized to safeguard medium-voltage DG systems (MV-DPGS) in both grid-connected and islanded modes. While the characteristics of distance protection may slightly differ in various operational modes when compared to conventional overcurrent protection, it still has its limitations. Intermediate in-feeds in the form of DGs located between the fault and the protection device may affect measurement accuracy, hence the performance of the system. Moreover, fault resistance can influence the measured impedance. Lastly, the precision of measurements can be impacted by transients, harmonics, and decaying DC currents.

3. Voltage-Based Protection
Using voltage source components, fault detection in power systems can accomplish low fault currents in the network. Potentially, the voltage source component values can be used to calculate various categories of defects (Brucoli and Green, 2007). Monitoring the output voltage of DG sources and employing Park and Clark transformations to convert the three-phase AC voltages into DC quantities is standard procedure (Al-Nasseri et al., 2006). The voltage signal from a given reference is computed using these DC values as the deviation of the disturbance signal. DC components may exhibit oscillations in the event of asymmetrical defects; therefore, these components are filtered using a notch filter. The references are subsequently compared to the filtered characteristics. In Hou and Hu (2009), a fault detection method based on elemental voltage components was proposed, which monitors the positive sequence and can detect symmetrical and asymmetrical faults in DGs. In Loix et al. (2009), a technique was introduced for distinguishing between three-phase, two-phase, and single-phase faults, which is particularly suitable for high-penetration DPGs in islanded operations. Although voltage-based protection schemes for DPGs are worth considering, they also have various challenges. The filtering process is time-intensive, and the detection results may differ depending on the type and magnitude of voltage during fault occurrence, impacting the scheme's effectiveness. Furthermore, non-fault events during islanded operations can cause voltage fluctuations, affecting the protection scheme's robustness, and making it more reliable in grid-connected mode.

4. Differential Relay
Current differential protection is a type of protection used in protective plans for power systems, as demonstrated in various studies such as (Sortomme et al., 2010; Zeineldin et al., 2006; Dewadasa et al., 2011b; Prasai et al., 2010; Pandeji and Pandya, 2015). The protection scheme of this type comprises five components in every relay, comprising of three-phase differential components for each phase, along with two supplementary components designed for negative and zero sequence currents. The phase components enable quick protection against high current faults, while the negative and zero sequence components provide more responsive protection against low current unbalanced faults that may emerge in feeders (Dewadasa et al., 2011b). This type of protection is particularly useful in distributed generation power systems (DPGS) as it can detect and isolate the faulted section quickly, minimizing the number of disconnected healthy sections and reducing the total interruption time. Additionally, current differential protection is suitable for various system configurations, such as radial, looped or meshed networks. Furthermore, this protection scheme is also beneficial for microgrids, a system of distributed generators, loads, and energy storage systems that can operate connected to the grid or as an islanded operation mode. Microgrids are becoming increasingly popular because they provide a reliable and sustainable power supply, especially in remote areas or during grid outages. The current differential protection scheme is suitable for protecting microgrids as it can detect and isolate the faulted section quickly, which is essential for maintaining the continuity of the power supply.

5. Admittance Relay
The inverse time admittance relay has been employed by several authors, including Majumder et al. (2011), Dewadasa et al. (2010, 2011c, 2009a,b), to measure the line admittance. Normalizing the admittance brings the inverse time to tripping characteristic to the forefront. The features

of the relay can be derived from the normalized admittance and can be illustrated as shown in Eq. (9):

$$t_p = \frac{A}{Y_r^{\rho} - 1} + k \tag{9}$$

In this equation, tripping time (t_p) is dependent on three constants, A, ρ, and k, as well as the normalized admittance measured by the relay (Y_r^{ρ}). As the fault point nears the relay location, the Y_r^{ρ} increases, resulting in a lower tripping time (Dewadasa et al., 2010).

4.1.1. Current practices

Typically, microgrids, Distribution Network Operators (DNOs) and DG system owners choose between two protection techniques to assure the safety and dependability of electricity systems. During a fault, the first technique includes disconnecting the DG from the network, but the second strategy allows the DG to stay connected if it complies with particular standards defined by international organizations such as the IEC and IEEE. The Grid Code, created by DNOs, sets these criteria and prioritizes consumers' power supply dependability. These protection measures are crucial for preserving the safety and dependability of the power system during failures.

- As per the IEEE 1547–2003, in case of a fault in the DN (Committee et al., 2009), an immediate disconnection of the DGs is required. The standard covers the compulsory interconnection criteria for all types of DG at the point of common coupling (PCC) with a capacity of up to 10 MVA. The disconnection is implemented to avoid the fault from affecting healthy zones (Basso et al., 2012; Roy and Pota, 2015). In addition to the above-specified standards, IEEE 1574 applies to photovoltaic power plants (PVPPs) with less than 10 MVA. The standard stipulates that in the case of an inadvertent islanding scenario in which the DG continues to energize a component of the DN through the PCC, the PV must detect the situation and halt power production for two seconds. This anti-islanding criterion is implemented to safeguard the functioning of the remainder of the network (Australia, 2005; Teodorescu et al., 2011; Crăciun et al., 2012).
- An alternative approach is to maintain the connection of DGs to the network during faults, known as fault ride-through (FRT) capability. This strategy allows DGs to continue supplying power to the grid during short-term disturbances and can protect the distribution network (DN) from additional fault currents from the DG. The use of FRT can also ensure the safety of personnel by avoiding the need for switching operations during faults.

  In order to prevent excessive disconnection of DDGs, various utility grid firms across the world have incorporated Fault Ride Through (FRT) provisions into grid regulations. These regulations are intended to promote the wider deployment of DGs and guarantee their stable and dependable connection to the electricity grid (Hernández et al., 2012). However, the requirements for FRT capability can vary among countries, as seen in studies such as (Rahmann et al., 2011; El Moursi et al., 2013; Yazdanpanahi et al., 2012). In these studies, the FRT capability of photovoltaic (PV) DGs was found to differ among various countries.

4.1.2. Optimal DG placement and capacity

The protection settings that minimize the incidence of loss of protection coordination in traditional networks, as reported in Naiem et al. (2012), must be taken into account in modern DNs that aim to recognize optimal penetration settings. The integration of DG into DNs is limited by the optimal sites and permissible capacity, as well as by the use of algorithms to find the optimal penetration levels and locations, such as the genetic algorithm (GA) used in Abdel-Ghany et al. (2015). The optimization approach must take into consideration the primary constraints of voltage level and protective device coordination. It is essential to highlight, however, that this approach is not exclusively a defensive measure. The loss of protection coordination may come from the capacity or disconnection of the DG which lead to a change in the fault levels. In addition, further optimization requirements, such as minimizing system losses and optimizing the voltage profile, may be applied, as explained by a number of experts in the area (Abdel-Ghany et al., 2015; Kennedy et al., 2016; HA et al., 2017; Hadjsaid et al., 1999; Hien et al., 2013; Hung et al., 2013).

4.1.3. Restricting output current of DG based on the voltage at DG terminal

The authors (Yazdanpanahi et al., 2012; Badran et al., 2017) proposed a way to handle the harmful impact of inverter-based DG on DN. In order to reduce DG failures and minimize the influence on fuse-recloser synchronization, their solution comprises limiting the output current of DG depending on the terminal voltage. Therefore managing non-fault disturbances, such as induction motor starting currents and load switching, has also been demonstrated to be possible using this method. Notably, the suggested technique is both cost-effective and simple to deploy, allowing for the best utilization of DG sizes inside the existing DN infrastructure without the need for changes.

4.1.4. Modify the connection of the transformer windings

The concept of replacing a transformer with a different winding connection to reduce the impact of zero-sequence fault from DERs or their step-up transformers on the transmission line is well-established by Working Group D3 (2004) and Pettigrew (2006). This approach may be practical in cases with significant zero-sequence apparent effects. Utilizing a DER transformer with a primary winding connection of Delta or undergrounded/high impedance grounded Wye is one method. By modifying the transformer winding connection, it is possible to restrict the passage of zero-sequence current back to the utility, hence decreasing investment costs if performed prior to procurement. As mentioned in the recommendations (ATCO Electric, 2002), however, this approach is not commonly used since it may need an effective ground source on the utility side of the connection. The construction of a grounding transformer at the PCC may be required for this strategy to be implemented, but it might potentially increase the system's susceptibility to transient overvoltage in the case of single-phase-to-ground problems. Therefore, this approach should be explored only as a last resort when other protective system choices are not viable.

4.1.5. Incorporate an inline electronic interrupter to facilitate feeder sectionalization

Integrating DER into DNs poses new challenges for protection system coordination. One potential solution to this issue is using a DER tap-off, which involves installing an online electronic interrupter at the PCC between the DER and the DN. This allows the protection scheme to only cover the area up to the newly installed interrupter, reducing the complexity of coordination and eliminating blind spots in the protection scheme. However, installing the interrupter upstream of the DER may result in a smaller potential islanded scenario, requiring additional anti-islanding protection measures and potentially increasing costs. Additionally, suppose the anti-islanding protection scheme involves using system disturbance elements such as Rate-Of-Change-Of-Frequency. In that case, it may lead to a smaller islanded network due to the imbalance between load demand level and generation (Nassif, 2018).

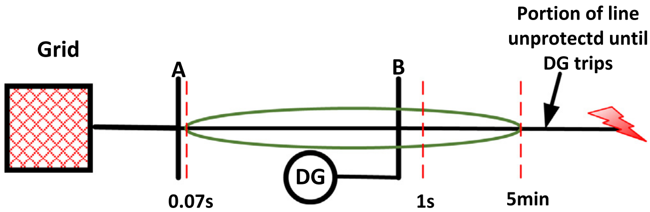

Fig. 13. Accept sequential tripping and any associated delays.

4.1.6. Tolerating sequential tripping and any resulting delays

In Fig. 13, the illustration depicts a scenario in which one portion of the distribution network experiences delayed cleansing while another becomes vulnerable due to a blind spot. When a distributed energy resource (DER) plays a role in the fault and fails to disconnect in a timely manner, this condition occurs. To prevent this, sequential tripping is implemented, which entails disconnecting the DER via an anti-islanding element or DER overcurrent relay prior to the substation relay detecting the fault. Thus, the fault-clearing period is significantly lengthened. As per the IEEE Standard, 1547 (Association et al., 2003), DERs are required to be disconnected from a formed island in 2 s, thus highlighting the importance of timely disconnection of DERs in avoiding such scenarios.

Integrating DER into DNs poses significant challenges to protecting these systems. One of the most significant concerns is the prospective formation of "blind spots" in the protection schemes, which can result in prolonged fault-clearing times and increased risks to both performance and compliance. This issue arises because the breaker status is typically joined with the DER. Consequently, if the fault is in a blind area, the relay will not trigger the feeder breaker. As a result, the DER may fail to isolate itself from the fault, and the utility remains an absolute dependency on the DER. One potential remedy for this issue is the use of sequential tripping, where the DER is tripped first, followed by the substation relay. This approach, however, carries the risk of prolonged fault-clearing times and increased safety risks. In addition, this circumstance raises concerns regarding the observance of performance standards, as there is no universal standard for clearance time in DN. Damage to distribution assets would result if the DER failed to isolate itself from the fault. Therefore, it is crucial to investigate and implement practical solutions to address this issue, as highlighted in studies such as ATCO Electric (2002) and AUC (2013).

4.2. Modified protection schemes for microgrid protection

Microgrids up to 66 kV in power system protection follow the same basic concepts used in medium-voltage distribution networks. However, there are certain distinctions in the types of protections utilized. As mentioned earlier, the typical conventional protection schemes include overcurrent, voltage, distance, and differential protection. Overcurrent protection employs current detectors and is activated when the current value surpasses a set point specified by a tripping device or relay. On the other hand, voltage protection utilizes voltage sensors and triggers when the voltage drops below a fixed set point. Using current and voltage sensors, distance protection monitors variations in impedance value based on fault current calculations. Current sensors are positioned at the extremities of the element to be protected (Ishaq et al., 2022; Hussainand et al., 2020). This protection mechanism responds to an increase in the current difference between the endpoints of the transmission line. While power system protection design principles are similar across microgrids with DERs, specific protection schemes can face various challenges that can impact their effectiveness. Studies have identified these issues as crucial to ensuring the safe and reliable operation of microgrids. During bidirectional power flow, overcurrent protection may incorrectly identify the faulty component, and it may suffer from extended tripping delays and low sensitivity at high fault impedances. High fault currents may also disrupt selectivity. Additionally, the configuration of the power grid and DER operation modes can affect voltage protection. In grid-connected modes, voltage protection may have reduced sensitivity and may not trip at significant fault impedance values. Distance protection schemes can suffer from insufficient sensitivity on short power transmission lines and faults with significant fault impedance. Integrating wind turbines into a microgrid can also cause challenges due to the varied nature and characteristics of individual turbines. Incorrect operation can occur if wind turbine resistance is assumed to be constant, and backup communication channels are necessary in case of damage to working channels (Alasali et al., 2021). Differential protection schemes have their unique challenges, including incorrect operation in unbalanced systems and faults with significant fault impedance. Backup communication channels are necessary in case of damage to working channels, which can increase project costs. Overall, these challenges must be considered when designing and implementing power system protections in microgrids to ensure effective and reliable operation (Alasali et al., 2021; Kumar and Zare, 2019). Therefore, the modified and Knowledge-based approaches are used to improve protection performance. The main modified protection schemes, as shown in Fig. 11, are discussed in this section.

4.2.1. Adaptive power protection schemes

Adaptive protection is a real-time process that adjusts the preferred protective response based on changing system conditions or requirements, as described in Kai-Hui and Ming-Chao (2011). This process involves monitoring the system by the protection system, and in the case of any alteration in the system topology or operation, new protection coordination is implemented. Implementing this procedure requires a thorough understanding of the system, as described in studies such as Islam and Gabbar (2012) and Oudalov and Fidigatti (2009). These studies have demonstrated that to implement adaptive production effectively; a robust monitoring and control system must detect changes in system conditions and respond accordingly. Additionally, it is crucial to have a thorough understanding of the protection coordination strategies and their impacts on the system.

- Employing directional and digital overcurrent relays.
- Utilizing group settings for digital overcurrent relays, which can be adjusted locally or remotely.
- Incorporating fast and reliable communication infrastructure following communication protocols like IEC61850.

Adaptive protection can be achieved through centralized and decentralized structures or multi-agent infrastructures, as demonstrated in Xiangjun et al. (2004). In both configurations, the microgrid's protective parameters must be updated in response to any network changes, whether in grid-connected or islanded mode. This can be accomplished offline or on the Internet. In offline mode, all configurations are stored offline in the memory of the agents. Then agents analyze the network status by utilizing local data or by sampling the communication infrastructure. This operation is performed online continuously and after every network change. An operator or agent uses associated settings to help information associated with the network change and use the related settings until the situation exists, as described in Oudalov and Fidigatti (2009). However, this method was examined by the authors of Conti (2009) and Conti and Nicotra (2009) for two

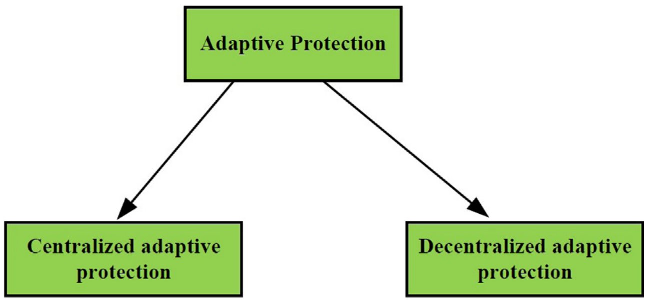

Fig. 14. The main adaptive protection approaches.

reasons. The authors contended that the adaptive method may not encompass all scenarios because of the dynamic nature of the network and that it does not take into account the possibility of concurrent faults. They further stated that this method necessitates the collection of a large amount of data due to the extensive range of conditions to be taken into consideration. Therefore, it is essential to consider the limitations of this method when implementing adaptive production in power systems. The adaptive protection scheme is mainly presented as centralized and decentralized approaches as shown in Fig. 14.

1. Centralized adaptive power protection scheme
This topology employs an Adaptive Supervisory and Remote Control Unit (ASRCU), which can communicate through a high-speed insecure communication infrastructure with distribution substation devices, such as relays, DGs, and circuit breakers. It can also send the necessary control and protection instructions to these devices while being cognizant of their condition as well as the state of the network as a whole, as illustrated by Oudalov and Fidigatti (2009). The ASRCU necessitates network information, including the number and name of buses, the number of DG units, the capacity on each bus, and the attributes of the power switches, as input data, as outlined in Islam and Gabbar (2012). To ensure the continuous adaptation of protective settings in microgrids, protective coordination is a crucial step, as highlighted in Abdelaziz et al. (2002). However, microgrid systems experience constant changes, which necessitates constant updating of protective settings. To address this issue, researchers such as Islam and Gabbar (2012), Oudalov and Fidigatti (2009), and Ustun et al. (2011) have proposed the use of an offline database to coordinate microgrid protection using the ASRCU topology. However, unlike these studies, a control signal is sent to the ASRCU when a DG connects or disconnects from the network. This signal triggers new calculations on the new line and sets the operational current of each relay based on the new situation.
2. Decentralized adaptive protection
The decentralized adaptive scheme, also known as multi-agent systems, has advantages such as greater speed, dependability, and scalability compared to central adaptive protection, as demonstrated in studies by Xiangjun et al. (2004) and Ren et al. (2012). The decentralized adaptive scheme is mainly a set of distributed agents located in different network devices, such as relays, circuit breakers (CBs), and distributed generators (DGs), which operate independently but can communicate through a communicative infrastructure. These agents can acquire local and wide-area data, as described in Xiangjun et al. (2004) and Ren et al. (2012). Generally, the features of the agent system include, as described in Zhao and Liu (2011), distributed decision-making, flexibility, robustness, and scalability. These characteristics make decentralized adaptive production an attractive solution for power system protection, especially for microgrids and other complex power systems. Agent-based systems in power system protection possess several key characteristics, such as Autonomy, sociability, reactivity, and pre-activeness:

- Autonomy is a key feature of agent-based systems in power system protection, as agents can operate independently without human intervention or interference from other agents. They can make decisions and take actions based on their local situations, which allows for a higher level of flexibility and robustness in the system. Autonomy is a critical feature for decentralized adaptive protection as it provides for distributed decision-making and enables the system to respond quickly to changes in system conditions. It also allows the system to operate without the need for constant human supervision, which can reduce the risk of human error and improve the system's overall reliability. Studies such as Zhao and Liu (2011) and Ren et al. (2012) have highlighted the importance of autonomy in designing and operating agent-based systems in power system protection.
- The term "sociability" refers to the capability of agents to swap information with each other through a communicative infrastructure.
- Reactivity refers to the ability of agents to detect changes in input data and respond accordingly.
- Pre-activeness denotes the ability of agents to react to input data in a manner that achieves their intended objectives as per their design.

To update agent settings, some studies have utilized an offline database. For example, in the studies presented in Khederzadeh (2012) and Dewadasa et al. (2011a), overcurrent relays were used as the only agents that are capable of making decisions based on local data. Hence, communicative links are not required in these studies. In this method, when the network's operational mode is determined, the relay retrieves the associated settings from its memory and uses them as the operating configuration. In Wan et al. (2008, 2006), overcurrent relays also decide on appropriate settings by taking into account local data and by communicating with other agents and according to data from their points of the network. Online calculation and decision-making, as opposed to offline collection and an offline database, also exist. For example, in the study presented in Ma et al. (2012), The adaptive setting was computed using the fault current from the steady-state network equivalent reduction. In this investigation, only overcurrent relays functioned autonomously, and communication infrastructure was not needed. In summary, various approaches have been proposed for updating agent settings in power system protection, and each approach has its advantages and limitations. The authors of Kato et al. (2005) proposed a microgrid protection scheme that utilizes multiple zones, each with its own set of agents communicating through a communicative infrastructure. These agents include a monitoring agent, a communicative agent, and a breaker agent. The monitoring agent is responsible for monitoring the magnitude and direction of current in each zone, while the communicative agent is responsible for transmitting this information to other zones. On the other hand, the

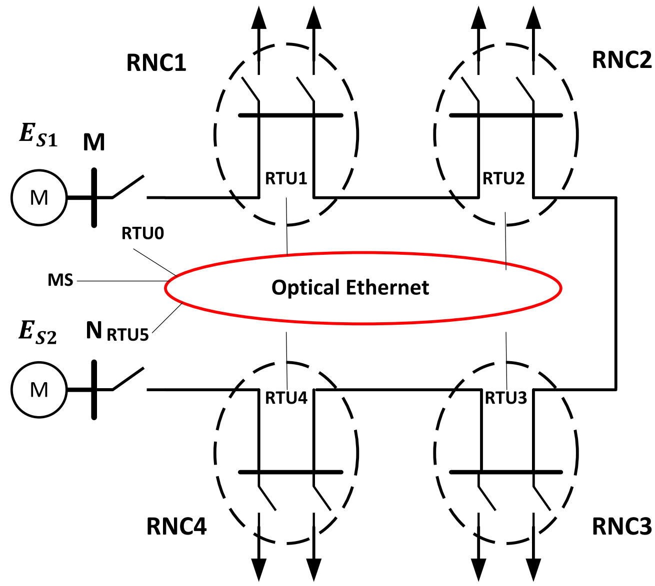

Fig. 15. A typical configuration of s closed-loop DN.

breaker agent sends tripping signals to the breakers in each zone. To facilitate agents' communication, binary codes represent the magnitude and direction of the current. If the magnitude and direction of the current remain constant, a zero code is sent to the other agents. Otherwise, a unit code is sent. Using these pre-assumed binary codes and logical circuits, the system can issue trip commands to the breakers. This approach has the advantage of being able to respond to changes in the microgrid in real-time, ensuring the reliability and stability of the power system.

4.2.2. Symmetrical components

The utilization of symmetrical current components is a prevalent technique employed by protection strategies to protect DNs. In a microgrid, Nikkhajoei et al. proposed a DN fault protection scheme for microgrids that accurately identifies fault scenarios by utilizing both zero and negative sequence current components (Nikkhajoei and Lasseter, 2006). Similarly, Xu et al. presented a positive sequence-based protection scheme for DNs with inverter-based distributed generation sources that effectively detect faults without requiring synchronous fault data measurements (Xu et al., 2016). The use of sequence current components in protection strategies has also been applied to protect DNs from power flow impacts. Zhang et al. introduced a strategy based on sequence current components that detect reverse power flow and identify DNs with high distributed generation penetration (Zhang et al., 2017). Zhang et al. presented a pilot protection approach based on the positive sequence fault component to safeguard meshed distribution networks (DNs) with distributed generation (Zhang et al., 2018). Fig. 15 displays a common configuration of remote thermal units (RTUs) that are installed in each ring network cabinet (RNC). These RTUs monitor the voltage and current flow between busbars, while the master station (MS) keeps track of all RTUs in the system and makes decisions on how to restore the system.

Due to the increasing penetration of DG in DNs, protection against reverse power flow is essential in this scheme. Despite the fact that symmetrical components-based protection strategies have been demonstrated to be effective, their real-time implementation could be enhanced by the need for robust communication connections. Furthermore, communication link failures can lead to disturbances in protection, resulting in high costs.

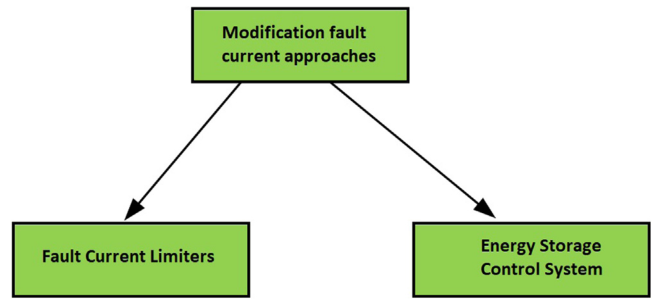

Fig. 16. The main modification fault current approaches.

4.2.3. Harmonic content based protection scheme

One approach to addressing these issues is the use of harmonic content-based protection schemes. Inverter-based renewable energy sources (RESs) are a significant source of voltage harmonic in microgrids. To mitigate total harmonic distortion (THD) in microgrid operations, a fast Fourier transform (FFT) can be implemented (Dash et al., 2007). Typically, this scheme consists of two stages: identification of the type of fault via computation of THD and differentiation of healthy zones from fault zones. If there is a deviation from the fundamental frequency, this strategy could be compromised (Dash et al., 2007; Al-Nasseri and Redfern, 2008), particularly when the size of the RES is not uniform or when the proportion of dynamic loads increases relative to static loads.

4.2.4. Power protection schemes based on deployment of external devices

Multiple protection strategies have prioritized coordination and defect detection. Modification of current levels is yet another essential aspect of mitigating the impact of DG connections to DN. DNs with DGs are typically operated in a grid-connected mode, but in the event of a disturbance, they seamlessly transition from grid mode to islanded mode. Consequently, changes in fault current levels are possible in both grid-connected and islanded modes, and it is a significant challenge to design appropriate protection mechanisms to ensure the secure operation of DNs from these disturbances. One solution to this problem is to adjust the failure level while switching from grid-connected to islanded operation. This can assist in mitigating the effects of DG connections on DNs and ensuring safe operation during disturbances. Modification of the fault current level is another important aspect in mitigating the impact of DG connections to DNs. Fault current limiters (FCLs) and energy-storing devices have been proposed by researchers to control the magnitude of fault currents, as shown in Fig. 16.

1. Fault Current Limiters

   - Traditional Fault Current Limiters (FCLs): FCLs are devices that are designed to prevent overcurrents by having a very small impedance close to zero during normal operation and an increasing impedance during fault conditions. They detect faults quickly and can endure fault currents until they are corrected. In Ustun et al. (2011), a central protection system was proposed for DNs and DGs that uses FCLs to estimate and isolate the fault. The proposed system uses Ethernet communication to update the relays' currents and detect the directions of fault currents in the system. To reduce the impact of DGs on DNs, resistive-type superconducting FCLs are used (Kalage et al., 2016). The installation of SFCLs has been found to reduce fault current contribution. The coordination of overcurrent relays in DNs utilizing FCLs was also reported in El-Khattam and Sidhu (2008), Elmitwally et al. (2015), Lee et al. (2008), Li et al. (2008) and Chen et al. (2014).

- Unidirectional Fault Current Limiters (UFCLs): UFCLs are devices that are installed at the tie point connecting the main grid downstream to the microgrid upstream of the network. Traditional FCLs can reduce the level of short circuits and bidirectional routes, but faults in the main network can still affect the downstream network due to a lack of coordination among protective devices connecting the two networks (Ghanbari and Farjah, 2013). Unidirectional FCLs can provide low impedance during typical operating conditions and high impedance in case of faults in the downstream network, thus reducing the impact of such faults on the microgrid (Ghanbari and Farjah, 2012; Saad et al., 2018).

2. Energy Storage Control System
The fault current value of DNs equipped with DGs is significantly reduced when operating in an isolated mode as opposed to when linked to the grid. As a result, overcurrent protection mechanisms may not be activated by the protection switches. Flywheels, batteries, or capacitors placed in the DN can raise the fault current to a level at which safety mechanisms can function normally, thereby mitigating this problem (Jayawarna and Barnes, 2009). To mitigate the impact of solar PV generation on the grid, Chen et al. (2017) proposed a coordinated protection strategy for DNs with DGs employing superconducting fault current limiters (SFCLs) and superconducting magnetic energy storage (SMES). The combined use of SFCLs and SMES resulted in the greatest overall performance with a reduced SMES capacity. Similarly, a protection scheme based on SFCLs and SMES was proposed in Guo et al. (2012) to mitigate the impact of wind turbine systems on grid-connected DNs.
Other DN protection schemes employing energy storage devices to alter the present fault level are described in Duggirala and Gundavarapu (2016), Ngamroo and Vachirasricirikul (2012) and Ngamroo and Karaipoom (2014). However, the high cost of energy storage devices is a significant barrier to the deployment of DN protection schemes that incorporate these devices. Therefore, when designing protection mechanisms for DNs with DGs, a cost–benefit analysis of energy storage devices must be considered.

4.2.5. Communication-assisted protection scheme

Researchers have proposed protection schemes for microgrids (MGs) that utilize communication networks to improve performance. These schemes use three categories of communication networks: centralized, decentralized, and distributed, with communication media including the internet, PLC, and wireless communication (Laverty et al., 2007). In Zamani et al. (2012), a protection scheme using microprocessor-based relays and directional elements was proposed for large, medium voltage MGs. This scheme utilized a communication medium to detect and isolate faulted zones in the MG, as depicted in Fig. 17. However, extensive communication networks are expensive and require technical features not present in current protection equipment (Elhaffar et al., 2015). Moreover, the design of communication-assisted protection schemes should take into account the cost–benefit analysis and the availability of communication infrastructure in the MG.

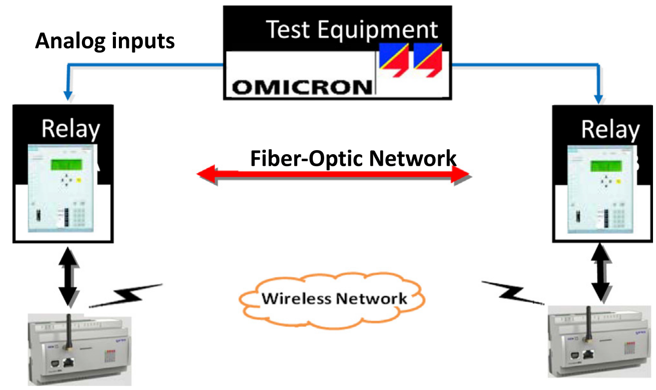

Fig. 17. Digital relays using communication medium.

4.2.6. Wide area protection

Researchers have proposed a method for obtaining system-wide information through the use of intelligent electronic devices (IEDs) to implement a wide-area protection system (Cai et al., 2004; Jian and Fu-quan, 2008; Cong et al., 2006). These IEDs are able to communicate with one another, enabling the implementation of pilot protection over a wide area, differential protection, and distance protection. A specific example of such a system can be found in Luo et al. (2012), where a wide-area protection system in intelligent DNs is presented, Using switching devices including overcurrent protection devices and fuses.

4.2.7. Coordinated protection techniques

Coordinating overcurrent relays (OCRs) is essential to detect and isolate faults in a power system network. The plug setting (PS) and time setting multiplier (TSM) are two primary factors that significantly affect OCR coordination. The PS, which ranges from 50 to 200% in increments of 25%, mainly relies on the minimum and maximum current level values. Numerous optimization methods and approaches have been proposed to ensure protection scheme security in interconnected microgrids, as shown in Fig. 18. These techniques aim to determine the best configuration for the protection schemes in the microgrid, as evidenced by several studies in Antonova et al. (2012). Traditionally, a combination of graphical and analytical approaches has been used to coordinate Directional Over-Current Relays (DOCRs). However, constrained optimization methods eliminate the need to determine breakpoints and simplify complex topological analysis programs.

- The main aim is to create a mathematical objective function representing the modern protection coordination problems at microgrid systems. Typically, researchers have framed the objective function using the total operation time of primary and backup relays. This formulation takes into consideration the selectivity and sensitivity constraints. Furthermore, the solving of the proposed objective function aims to find the optimal value of the time multiplier setting that minimizes the overall tripping time by solving the optimization problem. Recently, studies have demonstrated the effectiveness of employing different optimization solvers and algorithms, as presented in Table 5, compare to well-known algorithms such as particle Swarm Optimization (PSO) and Genetic Algorithm (GA) (Holderbaum et al., 2023a,b). Implementation of some of these algorithms is carried out using the Optimization Toolbox within MATLAB/SIMULINK. The selection of these new optimization algorithms facilitates the efficient implementation of new methodologies. These algorithms

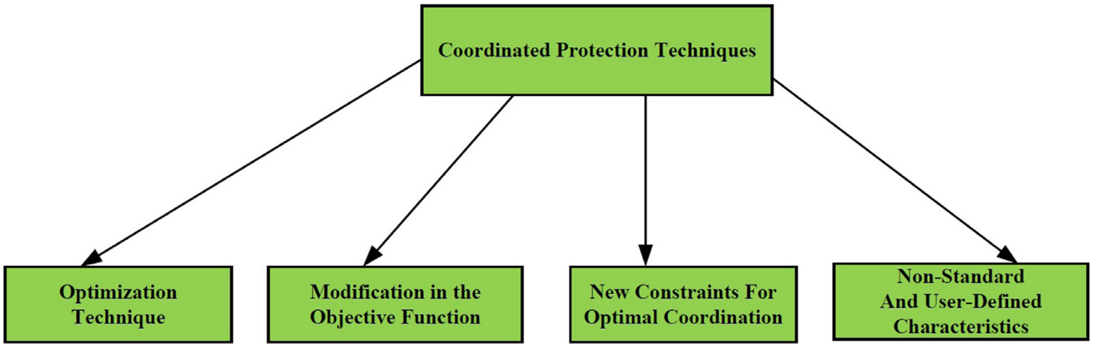

Fig. 18. The main modification fault current approaches.

Table 5
Optimization algorithms for microgrid protection.

Ref. No.	Year	Optimization algorithm	Scale of test network	Protection system
Srinivas and Shanti (2019)	2019	Improved Invasive Weed Optimization	IEEE 30 bus	OCR
El-Fergany and Hasanien (2019)	2019	Water Cycle Algorithm	IEEE 30 bus	OCR
Kida et al. (2020)	2020	Improved Simulated Annealing–Linear Programming Hybrid Algorithm	IEEE 30 bus	OCR
Sarwagya et al. (2020)	2020	Sine Cosine Algorithm	IEEE 30 bus	OCR
Ghotbi-Maleki et al. (2020)	2020	Mixed-Integer Linear Programming	IEEE 33 bus	OCR
Korashy et al. (2020)	2020	Improved Moth–Flame Optimization	IEEE 15 bus	OCR
Rizk-Allah and El-Fergany (2021)	2021	Hybrid Gradient-Based Optimizer	IEEE 30 bus	OCR
Muhammad et al. (2021)	2021	Hybrid Fractional Computing with Gravitational Search Strategy	IEEE 15 bus	OCR
Abdelhamid et al. (2022)	2022	Improved Seagull Optimization Algorithm	IEEE 14 bus	Distance and Directional OCR
Yu et al. (2022)	2022	Improved Gray Wolf Optimizer Algorithm	IEEE 15 bus	OCR
Merabet et al. (2023)	2023	Elite Marine Predators Algorithm	IEEE 15 bus	OCR
Assouak and Benabid (2023)	2023	Mixed-Integer Nonlinear Programming	IEEE 39	Distance and Directional OCR
Tripathi and Mallik (2023)	2023	Hybrid Genetic Algorithm-Non Linear Programming	IEEE 30	OCR

are recognized as promising tools for addressing intricate engineering problems. It is noteworthy that research involving the utilization of novel optimization algorithms for solving microgrid protection and coordination issues remains limited in the existing literature (Ishaq et al., 2022; Holderbaum et al., 2023c).

- Numerous studies have been conducted in the literature to address the challenging problem of coordinating overcurrent relays (OCRs) in power systems. To improve the effectiveness of the objective function of the OCR coordination problem, various modifications have been recommended by several authors. For instance, Alam et al. (2016) suggested modifications to the objective function for coordinating directional OCRs. Dual settings have been proposed by Zeineldin et al. (2015) and YazdaniNejadi et al. (2018) for optimal coordination of DOCRs in multi-looped DNs. Additionally, new time-current–voltage characteristics have been proposed by other authors for IEEE 14 and IEEE 30 bus systems (Saleh et al., 2016), as well as optimal coordination of directional OCRs for near-end faults (Birla et al., 2006) and detection of multiple fault locations (Saleh et al., 2015b).
- In addition to modifying the objective function, many authors have proposed new constraints for the optimal coordination of OCRs. For example, Purwar et al. (2017) introduced a novel constraint considering the variable operational status of a distributed system with distributed generation (DG). Other constraints have been proposed for fault current direction, transient stability (Aghdam et al., 2017), and OCR coordination with distance protection scheme (Damchi et al., 2016; Singh et al., 2016). Some authors have also proposed constraints that consider N-1 contingency, Fault Ride Through Requirements for Transmission Level Interconnected Wind Parks (Saleh et al., 2015a), and different network topologies (Noghabi et al., 2009).
- Many authors have proposed non-standard and user-defined characteristics in the literature to improve the coordination of OCRs. For instance, instead of using a phase over-current element for DN protection, Elneweihi et al. (1993) recommended using a negative-sequence element. Thermal models for rotating machines have also been enhanced (Zocholl et al., 1984; Swift et al., 2001), and double-inverse over-current relays have been proposed to improve the stability of DG operation (Aghdam et al., 2018). Other authors have suggested user-defined characteristics to obtain new values for standard inverse OCR (Salazar et al., 2015; Sharaf et al., 2015; Kılıçkıran et al., 2018) and enhance the coordination of distance protection schemes (Singh et al., 2018; Castillo et al., 2018). Furthermore, metaheuristic optimization algorithms such as gravitational search algorithms have been employed by some authors to coordinate OCRs using user-defined characteristics (Chawla et al., 2018). To evaluate the performance of different objective functions, several authors have used the IEEE 30-bus system (Shah et al., 2017) and considered all types of short-circuit contributions in the optimization of OCR coordination problems (Ehrenberger and Švec, 2017).

4.3. Knowledge-based approaches

A significant shift has occurred with integrating artificial intelligence (AI) and machine learning (ML) into the protection strategies of Microgrid. These innovative methodologies, demonstrated by artificial neural networks (ANNs), fuzzy logic (FL), genetic algorithms (GAs), decision trees (DTs), support vector machines (SVMs), the Random Forest technique (RF), and the Naive Bayes algorithm, have gained importance in protecting Microgrids against the complicated challenges posed by microgrid complexities and data uncertainties. The foundation of these AI-infused solutions is a wide range of data components. Included in these are extensive system measurements that cover factors like as voltage, current, frequency, and power. This section offers brief explanations of select methodologies, and their quintessential features are shown in Table 6, providing an overview of the methods of the investigation (Holderbaum et al., 2023a,b).

4.3.1. Artificial neural network-based schemes

An effective method for identifying and classifying faults in Microgrids has been proposed in Yu et al. (2017). This approach combines discrete Wavelet Transform (WT) with deep neural networks to process the system currents and extract corresponding evaluation metrics. These metrics are then utilized as inputs to the neural networks, which are responsible for detecting, classifying, and locating the faults with remarkable precision. In another study, Lin et al. (2019) proposes an adaptive protection scheme for microgrids by integrating Artificial Neural Network (ANN) and Support Vector Machine (SVM) models. The overcurrent and distance relays are upgraded with the help of the ANN model, which validates the occurrence of faults. Once faults are confirmed, the SVM model is used to pinpoint the fault location and update the relay settings accordingly. Moreover, Baghaee et al. (2019) introduces a protection scheme for autonomous microgrids that utilizes ANN and Total Magnetic Field (TMF) values. This approach identifies the fault based on TMF values and then categorizes the nature of the fault using ANN. This method provides an efficient and reliable protection scheme for autonomous MGs. In Lin et al. (2019), an adaptive protection scheme is suggested for microgrids using a combination of ANN and SVM models. The overcurrent and distance relays are upgraded with the help of the ANN model, which validates the occurrence of faults. The SVM model is then used to pinpoint the fault and update the relay settings (Baghaee et al., 2019).

4.3.2. Fuzzy logic-based schemes

The first scheme to be suggested is an intelligent Fuzzy logic-based protection scheme proposed in Chaitanya et al. (2018). This scheme uses the phase angle of positive-sequence current and Fuzzy logic to determine the operating mode of microgrids. The scheme then uses both fundamental and zero-sequence currents as inputs to a fuzzy model to identify and classify the fault in the MG. The second scheme relaying scheme is proposed in Kar and Samantaray (2015). This scheme integrates DTs and FL to detect and classify faults in microgrids. The scheme uses the S-transform to extract distinct parameters from one cycle of the fault current, which are then used to train the DT. The outputs of the DT are then used as inputs to the fuzzy model for the final fault decision. The scheme proposed in Castillo and Melin (2014) employs a type-2 Fuzzy logic (T2FL) to address data uncertainties and provide a reliable protection scheme. The scheme pre-processes voltage and current signals to provide inputs to the T2FL module, which contains two T2FL subsystems. One subsystem is used for detecting and classifying faults, while the other is used for identifying the fault direction concerning the relay. The use of fuzzy logic in all three schemes relaxes the crisp logic of DTs and addresses data uncertainties. Fuzzy logic allows for a more flexible and robust protection scheme that can handle different fault scenarios in microgrids. The importance of those schemes comes from the significance of fault detection and classification in microgrids due to the decentralized architecture of microgrids, which impacts the functioning patterns of the entire system, including control strategy, energy management philosophy, and protection scheme.

4.3.3. Support vector machine-based schemes

The primary goal of Support Vector Machines (SVM) is to optimize the margin between different classes. This approach is widely utilized in power systems, where fault-related attributes or classes are captured while voltage and current signals are processed. These attributes are then used to train the SVM classifier to identify abnormalities and faults. In a study (Mishra and Rout, 2018), the Hilbert–Huang Transform (HHT) is utilized to gather fault-distinguishing characteristics such as standard deviation, change in energy, mean, median, and others. These characteristics are then used to train the SVM model to detect fault occurrences. Another study (Manohar and Koley, 2017) utilizes the Wavelet Transform (WT) for feature extraction. Voltage and current samples are wavelet-transformed to generate training data for the SVM-based protection strategy. Overall, SVM-based protection strategies are highly effective in identifying faults in power systems by analyzing voltage and current signals and extracting fault-related characteristics using HHT or WT.

4.3.4. Multi agent protection

The traditional overcurrent protection in distribution systems utilizes autonomous devices that base their decisions on local measurements and configurations. However, with the integration of DGs, local measurements are no longer predetermined, and the relevant parameters need to be adjusted to accommodate the current system conditions. To address this issue, adaptive protection strategies have been proposed that rely on a central device monitoring the system state through wide-area measurements. Nevertheless, these centralized systems are susceptible to a single point of failure. Another approach to tackle this issue is multi-agent protection. Instead, using "agent" relays and peer-to-peer communications, fault location can be determined and detected in a distributed architecture (Wan et al., 2010). This multi-agent system can avoid or mitigate communicative and other types of failures (He et al., 2016). In the context of power networks, the term "agent" refers to an intelligent electronic device (IED) that is capable of taking autonomous action at its location and exchanging information with other agents (Brearley and Prabu, 2017). Agents can adjust relay settings to ensure proper discrimination under various operating conditions by using data such as the locations and capacities of DGs, the status of circuit breakers, and measured system variables (Habib et al., 2017). The method proposed in Habib et al. (2017) employs phase angles measured at multiple points to generate fault detection coefficients that can trigger a trip based on established criteria. Other agent-based approaches also calculate coefficients that represent the expected normal and abnormal current flows at each bus bar for various fault types. Coefficients are utilized in multi-agent protection methods to modify relay settings by analyzing measured system variables, circuit breaker status, and DG locations and capacities. However, if the network topology or DG penetration changes, these coefficients must be recalculated, which could result in significant computing and communication overheads. Fig. 15 depicts a standard configuration of remote thermal units (RTUs) in a ring network cabinet (RNC) that observes voltage and current flow between bus bars. The master station (MS) monitors all RTUs in the system and makes decisions on steps to recover the system.

Table 6
A comparison for the main knowledge-based approaches.

Protection scheme	Advantages	Disadvantages
Artificial Neural Network-based schemes	Wavelet transform (WT) and neural networks have been found to significantly improve fault accuracy. The combination of artificial neural networks (ANN) and support vector machines (SVM) has been found to provide a high level of accuracy in the validation of faults. The employment of a TMF-based method enhances the process of defect detection.	The process of complex integration may need the allocation of resources. The use of ANN-SVM necessitates comprehensive and thorough training. The susceptibility of the TMF to external influences.
Fuzzy logic-based schemes	FL-based scheme employs phase angle and FL for mode determination. An integrated DT-FL scheme helps to achieve more accurate fault classification. T2FL scheme addresses data uncertainties for reliable protection.	Complex integration of multiple techniques may require substantial computation. Fuzzy logic adoption could demand comprehensive training and tuning efforts. The importance of fault detection in decentralized microgrids impacts the entire system functioning.
Support vector machine-based schemes	SVM optimizes class margin for effective fault identification. SVM leverages fault-related attributes in power systems. SVM captures distinguishing characteristics for fault detection.	SVM implementation may require parameter tuning. Hybrid SVM processing could introduce computational complexity. SVM's effectiveness depends on accurate feature extraction.

4.3.5. Innovative relay

Two studies, namely Lai et al. (2015) and Miveh et al. (2012), suggest new microprocessor relays. The relay presented in Lai et al. (2015) can only protect the microgrid in islanded mode, while the relay proposed in Miveh et al. (2012) can only protect the microgrid in normal mode. The innovative directional relay in Miveh et al. (2012) utilizes the symmetrical components of the microgrid to detect faults. To identify symmetrical faults, the negative sequence of current is employed, along with both the negative sequence of current and voltage for locating such faults. The relay compares the line impedance's negative sequence, represented as Z2, with two symmetrical fault thresholds: the forward threshold (Z2F) and the reverse threshold (Z2R). The relay can identify forward faults when Z2 is below Z2F and reverse faults when Z2 is above Z2R. Asymmetrical faults are detected similarly, but with the relay settings based on Z1F and Z1R, as described in Miveh et al. (2012).

4.4. Overview of implementation adaptive protection techniques

In the study conducted by Piesciorovsky and, a comprehensive review of both conventional and nonconventional protection schemes was carried out for microgrid projects in North America. Conventional protection schemes were categorized according to the guidelines specified in the IEEE Standard C37.2–2008, while nonconventional schemes encompassed those not covered by this standard (Sheta et al., 2023; Piesciorovsky et al., 2020). The analysis aimed to gain insights into the existing protection strategies employed in microgrid projects within the region. Fig. 19 illustrates the application of conventional protection schemes in different microgrid projects, with a focus on current and voltage limits, represented by overcurrent and voltage protection systems. The overcurrent protection schemes covered 46% of the traditional protection system implemented in these microgrid projects. While the voltage protection systems achieved 32% of the implemented protection systems (Shiles et al., 2017; Hmad et al., 2023).

Fig. 20 displays the implementation of nonconventional protection schemes in real North American microgrid projects (Shiles et al., 2017; Hmad et al., 2023). Among these schemes, the adaptive protection scheme emerged as the most prevalent approach by 64%. This adaptive scheme showcased the capability to accurately detect whether the microgrid was operating in grid-connected or islanded mode. All other nonconventional protection schemes employed in the microgrids by 36% including voltage-restrained overcurrent protection scheme and Symmetrical components system, were used explicitly during the islanded modes (Piesciorovsky et al., 2020; Shiles et al., 2017; Hmad et al., 2023).

5. Future trends and modern microgrid protection research challenges

This section explores the dynamic field of microgrid protection, providing insight into the elements that are driving its development. The examination of microgrid protection is organized into two discrete subsections, each focusing on key aspects that will influence its future trajectory. Firstly, the challenges and implementation complexities of the microgrid protection system are discussed. In addition, this subsection discusses the main standards for designing and implementing protection schemes. Then, a comprehensive overview of advancing microgrid protection is discussed to identify gaps, limitations, and areas ripe for innovation. These investigations aim to highlight the leading-edge trends and technologies set of microgrid protection. Together, these subsections lay out a comprehensive road map for navigating the future of microgrid protection. By delving into strategic research directions and emerging trends and showing the ongoing transformation of microgrid protection into robust protection schemes.

5.1. Design and implement microgrid system

Multiple studies offer a variety of perspectives on microgrid difficulties and implementation complexities, as discussed in Sections 1 and 2. These findings provide a basis for the development of informed strategies, policy recommendations, and future directions for resilient and sustainable energy systems. The current state of research in Rhili et al. (2017), Chatterjee et al. (2018) emphasizes the significance of including microgrid integration into the broader energy matrix from a strategic perspective. Strategic recommendations and methodological frameworks form the basis for conducting a comprehensive examination of the complex dynamics related to grid operators, the enhancement of operational flexibility, environmental considerations, prospective advancements in design, market collaborations, and the validation of test frameworks (Chatterjee et al., 2018; Chkioua et al., 2018). These elements, as discussed in Rhili et al. (2017), Chatterjee et al. (2018), are crucial for the effective deployment of microgrids. A recurring theme is the essential nature of microgrids and the concept of operational flexibility become a prominent paradigm, which requires the creation of control systems that actively monitor consumption patterns in real time. These systems

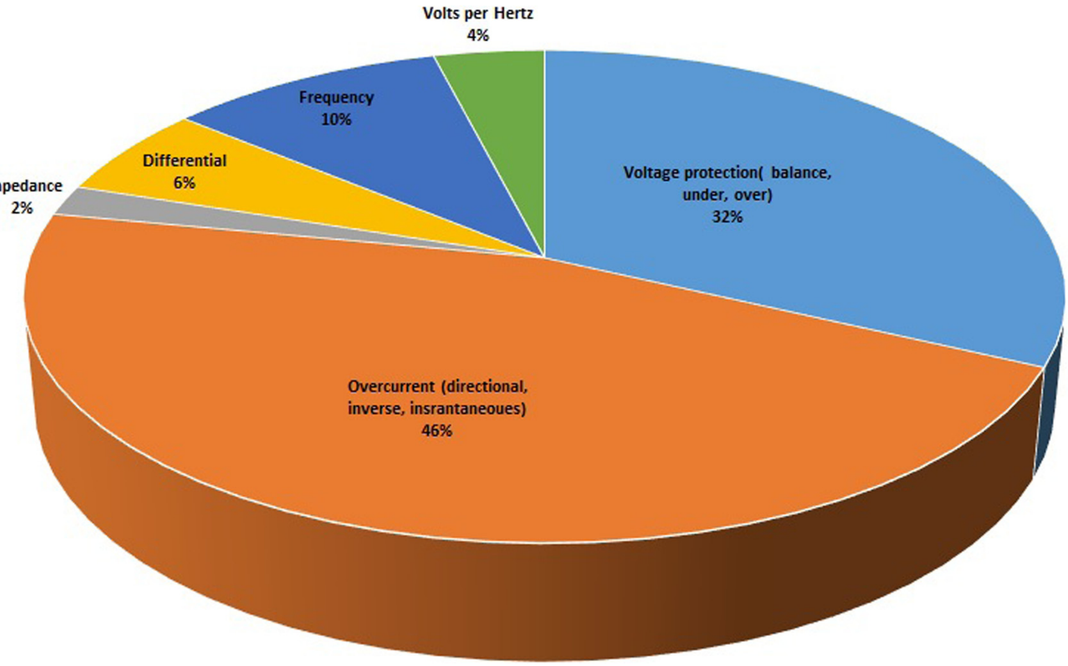

Fig. 19. The conventional implemented protection systems in microgrid projects.

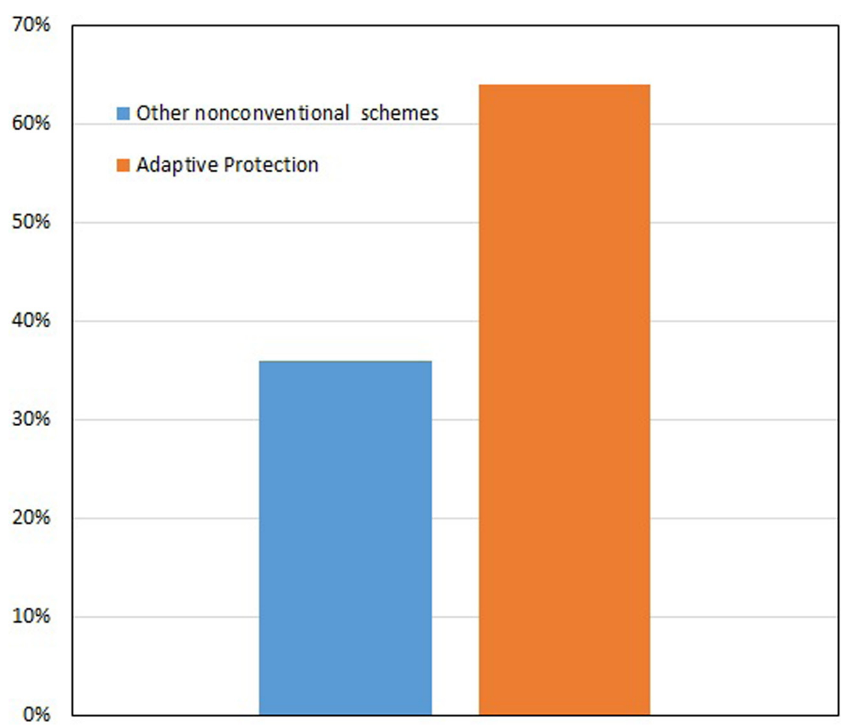

Fig. 20. The nonconventional implemented protection systems in microgrid projects.

enable adaptive reactions to changes in energy and protection systems for the microgrid. In addition, the concept of environmental sustainability is widely recognized and supported to take into account, as demonstrated by the implementation of various policies designed to reduce greenhouse gas emissions. Nowadays, research and development programs and grid operators take center stage in driving innovation at the implantation of microgrids and modern protection schemes. The establishment of expansive test facilities serves as validation data and results, affirming the feasibility and efficiency of microgrid concepts (Chkioua et al., 2018). Therefore, the literature incorporates a road map for the integration of resilient, sustainable microgrid deployments. Strategic recommendations, methodological frameworks, and interconnection standards converge to propel the energy landscape forward. The multifaceted exploration ensures the emergence of microgrids as foundational keystones balanced to redefine the energy sector in future. The technical complexities of electric power system integration with DGs, coupled with the harmonization of international standards. IEEE, IEC, and DIN/VDE (DKE) standards safety, quality, and electromagnetic, reflecting the global commitment to fostering a sustainable energy future. There are specific standards and specifications, which are commonly used,

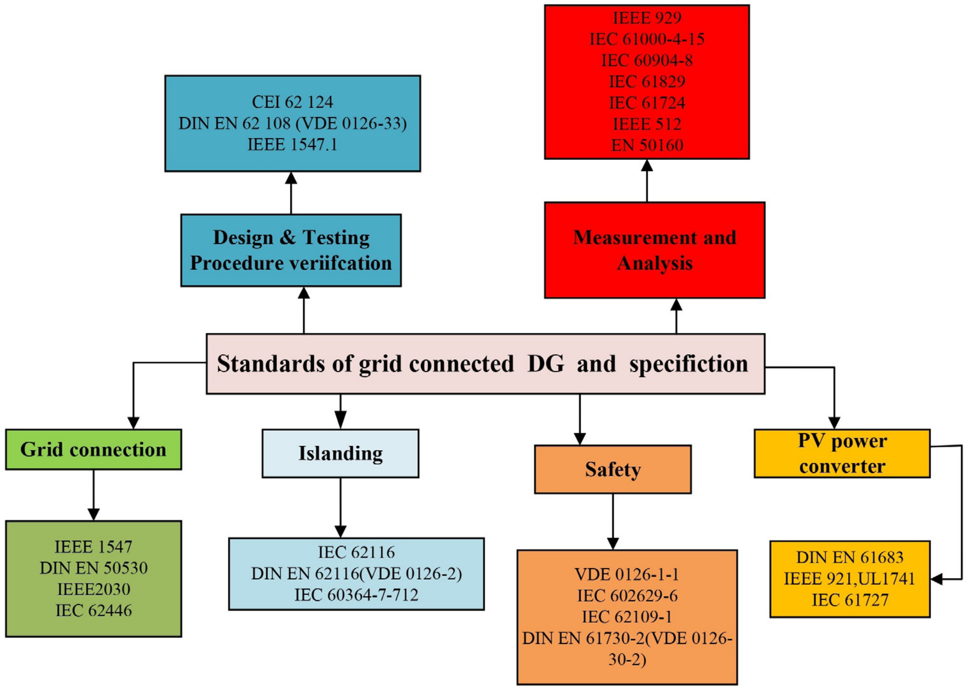

Fig. 21. The microgrid standards.

for implementing grid-connected DG systems and microgrid protection schemes, as shown in Fig. 21 (Chatterjee et al., 2018; Chkioua et al., 2018). These standards, governing the integration of electric power systems and DGs, contain multiple resources—photovoltaic arrays, microturbines, and more. The incorporation of both national and international standards increases the robustness of the proposed methodologies. IEEE 1547–2003, IEEE C37.95–1989, IEEE 929–2000, IEEE 242–2001, G59/1 Recommendation, and IEEE 519–1992 form complex criteria, for reliable microgrid implementation approach.

5.2. Examination of emerging trends for microgrid protection system and identify the key research

In the continually changing field of microgrid protection, it is crucial to conduct a comprehensive investigation into new trends and key areas of study in order to enhance the resilience and efficiency of these systems. This section explores the current state of microgrid protection, focusing on areas of significant progress and innovation. This section aims to provide scientists and engineers with valuable insights that will facilitate the advancement of microgrid protection systems, leading to improved dependability and flexibility. This will be achieved through the analysis of significant microgrid protection problems, as discussed in Sections 1 and 2, and the identification of potential development strategies. The scope of the research encompasses several factors that are crucial for the effective deployment of microgrids. This investigation introduces many key areas that necessitate comprehensive examination and potential research areas:

- Advance protection of Microgrids with DGs: the exploration of the complexities of microgrids that are mostly powered by Inverter-Interfaced Distributed Generators (IIDGs) is a noteworthy avenue for academic investigation. These systems demonstrate non-linearity in their impedance characteristics and display transient behaviors when fault events occur. Additional research is important in order to comprehensively understand and enhance protection solutions inside this particular framework.
- DG Sizing allocation with Fault Ride-Through behavior: the careful examination of fault ride-through behavior is essential for studying the allocation and sizing of DGs. The examination of the effects of various forms of DG on the performance and reliability of the grid continues to be an area of great potential for investigation. This field of study provides opportunities to optimize and improve the functioning of microgrids.
- Enhanced Fault Location Techniques for AC Microgrids: the current research problem lies in the development of more accurate and cost-effective techniques for fault localization inside AC microgrids. Advancements within this particular field would serve to improve the overall efficacy of microgrid protection systems.
- Cybersecurity Challenges in Modern Microgrids: as microgrids progressively depend on communication and Internet of Things (IoT) devices for advanced protection and management, the vulnerabilities associated with cybersecurity are increased. The power network stability is at risk by the prospect of cyberattacks. The development of robust and resilient protection measures to mitigate these risks is of the highest priority.
- Decentralized Backup Protection: the development of decentralized backup protection solutions is necessary in order to ensure the dependability of microgrid protection systems. These methodologies would play a crucial role in identifying defects in both operational modes of microgrids, even in situations where there are communication or main protection failures.
- Real-Time Validation of Proposed Techniques: in order to determine the effectiveness of several suggested protection solutions, it is necessary to conduct real-time experimental research. The availability of such validation would offer actual proof regarding the efficacy of these strategies in practical situations.
- Integrated Control and Protection Schemes: the incorporation of control and protection mechanisms has significant opportunities for improving the dependability and effectiveness of microgrid protection systems. The exploration of

the potential synergistic effects of these two aspects shows promise for enhancing operational efficiency.
- Cloud Computing Adoption in Microgrid Protection: the utilization of cloud computing for the purposes of enhancing processing capabilities and storage in places with limited resources provides a range of potential advantages and challenges. Although the utilization of such technology has advantages in terms of cost-efficiency and the availability of data, it also gives rise to apprehensions regarding cybersecurity and the management of data in developing adaptive protection schemes.

Conclusion

In conclusion, this review paper has provided a comprehensive overview of highly reliable microgrid protection approaches, including innovative and practical intelligent solutions. In recent years, a substantial number of advancements in the discipline have addressed the requirements of modern distribution networks. Many researchers have proposed novel techniques to overcome overcurrent coordination problems and to achieve optimal protection settings. However, despite the attention given to standard overcurrent coordination schemes, there is still a notable need for research on the use of communication-based schemes that can minimize the tripping time of overcurrent relays.

The design and implementation of protection schemes in microgrids require a thorough understanding of the functions and features provided by modern, intelligent, protective devices. This includes planning and investigation, the practical implementation and customization of data sets within the devices, proper use of information reports, operational simulation scenarios considering network topology, and finally, the requirements of end-users and presumes. Moreover, it necessitates the adept utilization of information reports, the simulation of operational scenarios with respect to network topology, and the alignment with end-user needs and presumptions. The implementation of reliable microgrid protection mechanisms is of the greatest importance in maintaining the reliability and adaptability of microgrids in the face of constantly changing loads, faults and the nature of DGs. The evaluation has examined an extensive variety of protective strategies and intelligent solutions, showing encouraging results. However, it is clear that further study is necessary in order to optimize their performance, improve their scalability and study different protection relays instead of focusing on OCR.

The design and adaption issues in the dynamic field of microgrid protection are complex. Protection relays have varied requirements that are determined by several circumstances, such as the microgrid design. These criteria may include the type of system, such as a ring, radial, microgrid, or DER system. Factors such as selectivity, sensitivity, dependability, operating speed, simplicity, redundancy, and consistency are crucial in influencing the decision-making process for selecting protective relays. Given the dynamic nature of microgrid protection, it is crucial to conduct a thorough investigation into new trends and key research areas. This is necessary to enhance the resilience and effectiveness of these complex systems.

CRediT authorship contribution statement

Feras Alasali: Participated in designing the control models, Drafting the article or revising it critically for important intellectual content. **Saad M. Saad:** Participated in designing the control models, Drafting the article or revising it critically for important intellectual content. **Abdelaziz Salah Saidi:** Participated in designing the control models, Drafting the article or revising it critically for important intellectual content. **Awni Itradat:** Participated in designing the control models, Drafting the article or revising it critically for important intellectual content. **William Holderbaum:** Participated in designing the control models, Drafting the article or revising it critically for important intellectual content. **Naser El-Naily:** Participated in designing the control models, Drafting the article or revising it critically for important intellectual content. **Fatima F. Elkuwafi:** Participated in designing the control models, Drafting the article or revising it critically for important intellectual content.

Declaration of competing interest

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere and the authors declare no conflict of interest. We also confirm that all authors have participated in drafting the article or revising it critically for important intellectual content; approval of the final version.

Data availability

No data was used for the research described in the article.

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