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SURVEY

AC Microgrid Protection Schemes: A Comprehensive Review

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ABSTRACT The power grid infrastructure has evolved from a centralized to a distributed model utilizing renewable energy sources in the last few years. This trend is likely to continue, given the increasing demand for environmentally conscious energy solutions. Different types of microgrids include sustainable, non-sustainable, and distributed energy sources. As such, microgrids (MGs) are becoming increasingly popular in providing reliable and sustainable energy at a local level. Microgrids can be operated grid-connected and islanded to address the significant increase in electricity demand, storage, and transmission issues. The penetration of renewable energy sources has increased the importance of power electronics in microgrids. The benefits of microgrids are many, but their challenges are also many, especially when it comes to power distribution. This article examines AC microgrid penetration into the distribution network as part of a comprehensive review of protection systems. This review allows us to understand how microgrids will interact with and potentially improve the protection systems found in the distribution network. As a result of the expansion of a microgrid, changes in the distribution network's direction impact coordination and protection. The literature proposes a variety of solutions for power system protection. In conventional protection systems, relays are timed to transmit backup and primary information at different times. Several protection schemes have been proposed to improve the protection system when microgrids are present. DC/AC systems, communications infrastructures, rotating synchronous machines, and inverter-based distributed generation (IBDG) can all be classified as MGs. An overview of the standards is provided to help developers connect DGs to public distribution networks. Furthermore, a detailed explanation of the requirements is included to ensure successful integration. The overview and description of the standards and conditions should be carefully examined to ensure successful integration. Finally, conventional power systems are discussed with a view to future protection schemes.

INDEX TERMS Literature review, ac microgrid, protection schemes, distributed generation, renewable energy, greenhouse gas emission.

I. INTRODUCTION

The microgrid concept provides resilience and energy security by aggregating distributed energy resources - generation, storage, and loads. Microgrids offer energy security in extreme weather events, cyberattacks, and equipment failures. Microgrids protect energy security and offer resilience against natural and man-made disasters. This includes homes, industrial and commercial facilities, and military bases. As a result of increased energy demand and climate change threats,

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microgrids have been developed as a solution to these issues. By leveraging the power of microgrids, energy security can be maintained, and a greater level of resilience and protection can be achieved against various disasters, making it an ideal solution for home, commercial, industrial, and military applications. Furthermore, microgrids offer increased reliability, efficiency, and environmental sustainability, making them an attractive option for all facilities.

Due to power systems' complexity and challenges, protection system schemes have become increasingly significant. A large part of the reason for blackouts and cascading events is the malfunction of protective relays and miscoordination [1]. According to a report by the International Council on Large Electric Systems (CIGRE), 27% of bulk power system disturbances are caused by faulty tie protection systems [2]. Protection systems separate the fault from the healthy sections to prevent power supply interruptions, cascading failures, or blackouts. Proper coordination and maintenance of protective relays are essential to ensure reliability and reduce the risk of electrical disturbances. Therefore, it is paramount that tie protection systems be regularly tested and maintained to ensure optimal performance and prevent widespread power outages.

In grid operation, a microgrid can be defined as an interconnected group of Distributed Energy Resources (DERs) with clearly defined electrical boundaries. They can operate grid-connected and islanded based on their connection to the grid. Microgrid deployment has increased significantly in recent years. The global market for microgrids is expected to reach $40 billion by 2028, according to a survey conducted by Navigant Research [3]. As well as improving power quality and reducing carbon emissions, modern microgrids provide reliability, efficiency, and power security. However, they also pose many technical challenges that prevent their widespread adoption in the future. There is an urgent need to investigate sophisticated and state-of-the-art microgrids protection strategies and control systems. To ensure the long-term success of modern microgrids, it is essential to develop effective protection strategies and control systems that can help address the technical challenges faced by microgrids. To this end, exploring innovative approaches that can lead to reliable and secure microgrids is crucial.

Power system components, such as generation, transmission lines, and distribution, should be appropriately configured. So, with the growth of the power system, the protection challenges significantly increase. Based on the system backup protection technique, the authors investigated the ***generator*** protection system [4]. Two devices are utilized here, device 21 relay to measure the impedance and voltage-controlled or voltage-restraint time-overcurrent device (51V). This function provides back up protection when transmission system protective relays have not cleared system faults. As such, it is a crucial component of the power system, ensuring the safe operation of the grid. Directional overcurrent (DOC) and distance relays provide backup protection with the 21 and 51V protective functions [5]. Electricity is delivered from generation to customer via ***transmission lines***. Many faults have occurred as the transmission system expands and long lines are built. Distance protection is one of the most common methods of protecting transmission lines with different zones. As a result of voltage and current swings, power swings in a protection transmission system can cause the device distance relay's impedance to oscillate. Usually, unnecessary relay trips may occur when the power swing reaches the operating zone [6]. Several issues are related to parallel transmission systems, including mutual coupling, back-feeding, in-feeding, and a lack of discrimination between faulty and healthy lines. These issues affect distance protection, especially in faults near the far end bus [7], [8], [9]. Several solutions have addressed the protection of parallel transmission lines.

A wavelet transforms way is employed in references [10], [11], [12] to identify disturbances in the current signals, estimate the phasors of all signals, and achieve high-speed relaying to protect parallel transmission lines. The authors in [13] proposed adaptive distance protection in different operating conditions based on surrounding information. Flexible AC transmission systems (FACTS) have been shown in [14] and [15] to affect protective devices in the transmission line. Transmission lines with FACTS devices can transfer power but have serious problems protecting the distances between them [16] and [17]. But, the protective relays are influenced by the transformer inrush current. In [18], the authors proposed delaying the relay operation to prevent differential relays from maloperation. A differential relay with only harmonic restraint was presented in [19] for bus protection. As well as harmonic restraint or blocking, transformer differential relays use the methods described in [20]. This approach provides more reliable protection, as harmonics can be detected more accurately. Due to these methods, relay security is guaranteed for a very high percentage of inrush and overexcitation cases. Furthermore, relay settings can be adapted to different system conditions, allowing customized protection. Additionally, relays can be used to monitor the health of the system, providing information that can be used to identify potential issues before they cause damage. However, the operating current has a very low harmonic content, so this method is not useful.

In recent years, consumer diversification and technological advancements have changed the structure of ***distribution networks***. As a result, distribution network protection issues have increased, and protection systems have become more critical. As a result, high-impedance fault detection (HIF) is one of the most challenging aspects of a distribution network. Due to their low fault currents and high impedances, typical protection systems cannot detect HIFs in distribution feeders [21]. As a result of failing to detect HIFs, fire hazards may arise, and humans may be at risk [22], [23], [24]. The authors utilized a systematic method for detecting and classifying HIF features. HIF detection has also been proposed using a pattern recognition-based algorithm based on discrete wavelets [25]. Therefore, it is essential to develop a reliable and accurate method for detecting and classifying HIF features to reduce the risk of fire hazards and ensure the safety of humans. Moreover, a robust approach to HIF detection must be employed for reliable operation in various and dynamic scenarios.

There are two modes of operation for grid-connected and islanded sets of interconnected loads and DGs. Furthermore, energy delivery from power plants to consumers becomes more expensive due to improved system reliability and environmental benefits [26] and [27]. This, in turn, leads to higher electricity prices for consumers, further driving the need for renewable energy sources. There are several issues that microgrids face, including blinding zones, false tripping of protective relays, lowering fault levels, islanding, and automatic reclosing, which pose several challenges. These challenges can be addressed through careful design of the microgrid system, implementation of proper control strategies, and implementation of advanced fault analysis algorithms. Furthermore, improved communication between the microgrid and its components can help to prevent issues such as false tripping and islanding. Many studies have demonstrated these challenges [28], [29], [30], [31]. New solutions must be developed to overcome these challenges to ensure microgrids operate safely and reliably. Therefore, it is essential to develop new solutions to ensure microgrids operate safely, reliably, and cost-effectively for consumers.

A microgrid has many components, such as connection, protection, communication, DC/AC system, type of DG, etc. There are three types of microgrids, each of which has its operation mode. Among these are facility-based microgrids, remote microgrids, and utility-based microgrids [32]. A facility microgrid can operate intentionally or unintentionally in island mode, a remote microgrid can only operate in island mode, and a utility microgrid can only operate in grid-connected mode. As well as this, facility and utility microgrids offer utility connections instead of remote microgrids. That is primarily used in remote areas, islands, and large geographical areas to install remote microgrids. DGs [33] are classified as rotating synchronous machines or inverter-based DGs, depending on their inverter architecture. A short circuit current level is classified based on the difference between the AC/DC voltages in the short circuit. Remote microgrids cover a larger geographical area than facility and utility microgrids. Based on their connection with AC or DC buses, microgrids can be classified into three main categories AC, DC, and hybrid AC/DC [34]. AC and DC systems were also discussed regarding their advantages and disadvantages. AC systems were also discussed for their limitations regarding DG synchronization, power quality, and three-phase imbalance. DC systems have several advantages, including high efficiency, low voltage, and no need for inverters and transformers. Moreover, DC power is a reliable and efficient way to exploit renewable resources and supply DC loads. As a result of hybrid microgrids, AC and DC-based DGs can be directly integrated into the same distribution network without using multiple distribution networks.

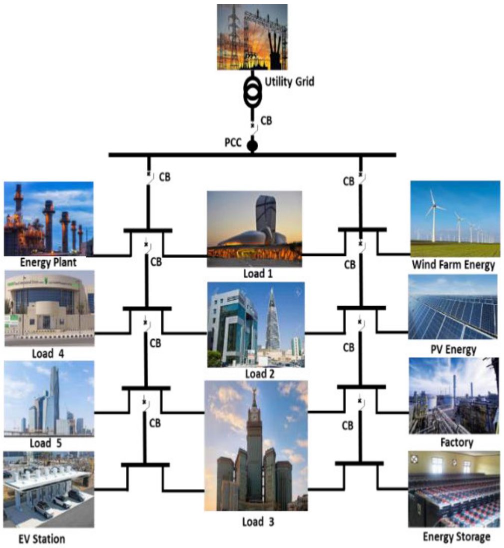

FIGURE 1. **Microgrid connected to the grid in a single-line diagram.**

In [35], fault current characteristics in AC and DC distribution systems were compared. The authors examined the differences among AC/DC protection schemes and discovered that the AC short circuit current has two zero-crossings in each period, along with a fault impedance and a high-rising-rate current. Using a simplified AC/DC hybrid microgrids model, the authors in [36] propose a fault analysis method. In this way, the characteristic system under fault conditions was analyzed using a mathematical model equivalent to simplification. Microgrids are typically connected to the grid via a point of common coupling (PCC), as shown in Figure 1. Figure 2 shows a hybrid structure with AC and DC microgrids. Furthermore, the proposed mathematical model was used to identify the fault-induced current-voltage characteristics in the AC/DC hybrid microgrid. In addition, the proposed mathematical model was used to gain insight into the fault-induced power transfer behavior of the AC/DC hybrid microgrid under different fault conditions.

Power flow in conventional distribution networks is a one-way street between the central substations and the distributed loads. The fault current magnitude is relatively high in such systems. The non-directional overcurrent relays (50/51) detect any overcurrent fault in any direction and trip the circuit, thus protecting the system from potential damage. Fuses, reclosers, and sectionalized relays provide additional protection to the distribution system by providing backup protection if the non-directional overcurrent relays fail [37]. This ensures that each device is triggered at the right time and that the current pickup settings are sufficient to coordinate the devices, allowing them to work together efficiently and safely. The time delays also help to ensure that the devices do not interfere with each other, allowing them to operate smoothly. Furthermore, the correct settings must

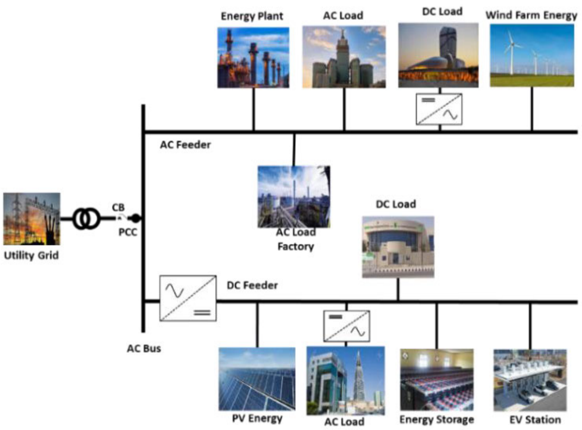

FIGURE 2. An AC/DC hybrid microgrid.

be programmed into the system to ensure reliable operation. Once faults have been cleared, a minimum number of distribution system faults will be isolated. These settings must be regularly monitored and adjusted to ensure the system runs optimally. In distribution networks, distributed generators disrupt radial structures and cause bidirectional fault currents. Besides, fault and non-fault currents continuously change magnitude and direction because of DGs' intermittent nature and changes in microgrid operation modes (grid-connected and islanded). Therefore, conventional protection schemes with fixed protection settings cannot satisfy protection requirements. Additionally, IBDGs are challenging in microgrids. Their control system has a limit of 1.5-2 pu (per unit) for IBDG fault current [38]. Overcurrent protection devices have difficulty handling islanded mode. Lack of stored kinetic energy causes low frequency and voltage rides in smart microgrids with high IBDG penetration. To prevent these issues from arising, it is necessary to incorporate energy storage systems into the microgrid [39]. Voltage and frequency protection of DGs make overtrips quickly when faults occur in islanded mode [40], [41]. DG integration and microgrid implementation pose new protection challenges to facilitate the widespread of microgrid concepts.

Microgrids distribute electricity efficiently from various generation plants and DGs. As a result of implementing microgrids, the primary goals of employing them in the power system are to use more renewable energy. In addition, they are to boost the power system's capacity to supply. Moreover, microgrids are capable of decreasing complete blackouts under peak shaving conditions. They can also reduce the time needed to restore a system damaged by a fault when it occurs. Besides, they provide an opportunity to involve individuals as part of the power system, such as consumers and electricity providers [42]. Furthermore, microgrids can offer advantages such as increased reliability and resiliency to the power system, ultimately leading to improved energy security. Moreover, microgrids can facilitate managing and distributing energy resources, thus enabling more efficient energy usage.

Several discussions have taken place on microgrid protection, each focusing on a different issue. An overview of microgrids and smart grids is presented in [35] based on current developments and future trends. The work discussed how to control generation and storage units within a microgrid, as well as how to transmit and monitor data. To ensure efficient operation, the study also proposed a communication framework to facilitate real-time information exchange between the units. According to [36], the authors evaluated AC and DC distribution systems, described DC and AC protection methods, and, finally, compared DC and AC protection methods. In [37], issues and approaches to microgrid protection are reviewed. Microgrid control, including centralized and decentralized control types, is discussed in detail. A review of different methodologies for adaptive protection for microgrid systems is presented in [43]. The authors in [44] reviewed microgrid system protection schemes and coordination techniques. A modified optimization algorithm was used to coordinate time-current discrimination in microgrids based on particle swarm optimization and a modified optimization algorithm. This modification improved the time-current discrimination accuracy, providing a more efficient microgrid system. A review of the power system and microgrid protection system was presented in [45]. Additionally, the author discussed future trends in protection systems and blind zones. Further, the authors examined the role of a supervisory control and data acquisition (SCADA) system for improved protection system coordination. The authors successfully achieved time-current discrimination in microgrids by incorporating particle swarm optimization and a modified optimization algorithm. Additionally, they discussed the potential benefits of a SCADA system and the challenges of blinding zones to better coordinate the microgrid protection system.

II. MICROGRID CONTRIBUTIONS TO GREENHOUSE EMISSIONS REDUCTION

Now microgrids have the opportunity to meet the challenges of climate change and contribute to carbon-free power distribution systems. As a result of microgrids, greenhouse gas emissions can be reduced by deploying more zero-emission electricity sources. It is possible to maintain a balance between renewable energy sources that are non-controllable, such as solar, and distributed, controllable energy sources, for example, natural gas-fueled combustion turbines, with a microgrid manager (e.g., local energy management). They can also be balanced by using energy storage and electric vehicle batteries.

In microgrids, the transition to net-zero begins. In fact, natural gas and diesel are the most common fuels used in today's microgrids, resulting in high greenhouse gas emissions. In microgrids, NetZero means replacing fossil-fueled generators with renewable energy sources. A new dispatchable generation technology is being developed that is 100% carbon-free and provides additional advantages, such as an energy and power source that is more reliable and sustainable.

A microgrid can be decarbonized by maximizing its renewable energy generation, managing storage and flexible loads to minimize their variability and intermittency, and introducing clean energy sources to balance out the variability and intermittency of renewable energy sources, including solar panels, wind turbines, hydrogen, and small modular reactors [46].

Net-Zero Microgrids are driven by the move away from fossil fuel reliance, clean power generation, and green distribution systems. The Net-Zero Microgrid could be a major step in greening the electricity sector. Microgrids could become increasingly green in the foreseeable future if they are deployed in large numbers. A major driver of zero-carbon microgrids is integrating distributed renewable generation into distribution networks and microgrids for resiliency [47]. Microgrid considerations have been identified by research and development projects, including advanced planning tools for managing complex owner structures, grid topologies, power flows, protection systems, local energy markets, tariff systems, and dynamic pricing structures, as well as smaller time steps for capturing renewable energy volatility, as much as improved controller functionality for managing microgrids that generate the maximum amount of renewable energy while generating the least amount of greenhouse gases. With the increasing spread of renewable energy, the protection system has become more difficult and faces many challenges. So, searching for protection schemes and standards to help developers connect DGs to public networks becomes imperative. In addition, discussing the various challenges and opportunities for microgrids should be made more efficient. To do this, implementing advanced protection schemes and standards is essential, along with determining the most efficient way to discuss the challenges and opportunities of microgrids. Therefore, to improve the integration of DGs with public networks, it is necessary to explore the advanced protection schemes and standards and find effective ways to discuss the various challenges and opportunities of microgrids.

III. AC MICROGRIDS AND DGs: PROBLEMS FACED

The lack of appropriate policies and regulatory frameworks in the Middle East and elsewhere makes isolated microgrid projects unattractive to private companies. To ensure the sustainability of the project, local actors should be responsible. This approach also involves collaboration between institutional and private actors. This methodology emphasizes the inclusion of the community in the planning and decision-making process while considering both the technological and socio-environmental aspects [48].

To set up a protected microgrid in a community, it is necessary to have an interdisciplinary team with expertise in the field. A community project certainly requires a technical solution, but it should also consider local power system realities and enhance local energy capabilities. Various professional fields should be involved in this effort (engineers, social workers, sociologists, geographers, etc.) from previous experiences in developing countries [49]. A technical protection type with social feasibility is the next step in assessing the microgrid's components on a technological, social, and environmental basis. Regarding technical protection, estimating electricity generation using historical data or direct measurements is necessary. Based on this information and considering the available technologies for protection, the design process evaluates the technical costs and benefits of the microgrid. To obtain a clear vision of the microgrid protection system, it is necessary to know the cost of the protection system required for setting up the microgrid [50], [51]. As part of participatory planning, the main focus should be on identifying relevant stakeholders, building community trust, and defining the views and narratives of community members.

Microgrids and DGs have numerous advantages from an environmental and economic standpoint, but they also negatively impact the power system. As far as the protection system is concerned, it is the effects of distributed sources that pose the most significant challenge. Distribution network structure and electrical parameters are altered by DG presence. Due to the radial structure of distribution networks, the protection system is designed based on that scheme. It is important to note that adding a DG to a distribution system changes the direction of its current and looping structure. Adding a DG can drastically alter the energy flow within a distribution system, thus requiring a detailed analysis before integration. Additionally, embedding a DG may change fault current levels [52]. As a result, protection coordination may be lost. Conventional protection schemes cannot adequately protect power systems. Additionally, distribution networks with a high penetration of DG are disconnected from the grid and connected directly to the DG. As such, the protection of these DG-connected distribution networks must be designed and implemented differently. To solve DG protection challenges, the authors in [53] proposed hardware-in-the-loop adaptive protection schemes (APS). A relay setting group is optimally calculated using online self-adjustment. A novel method for detecting faults with hardware-in-the-loops was presented in [54]. Various microgrid protection challenges and schemes are discussed in [55]. Microgrids should operate in both grid-connected and island modes, and their protection systems should enable quick microgrid disconnections from the grid. Microgrids are most successfully protected with adaptive protection systems based on digital relays and advanced communication.

The traditional configuration of distribution networks is radial, with power flowing from central substations to distributed loads. The fault current magnitude is relatively high compared to the maximum load current. Non-directional overcurrent relays (50/51) can protect the distribution system and fuses, reclosers, and sectionalizes. As a result, the distribution system will be isolated to the maximum extent possible after the fault has been cleared. Several distortions occur in the distribution network structure when distributed generators are integrated into it. Firstly, power distribution

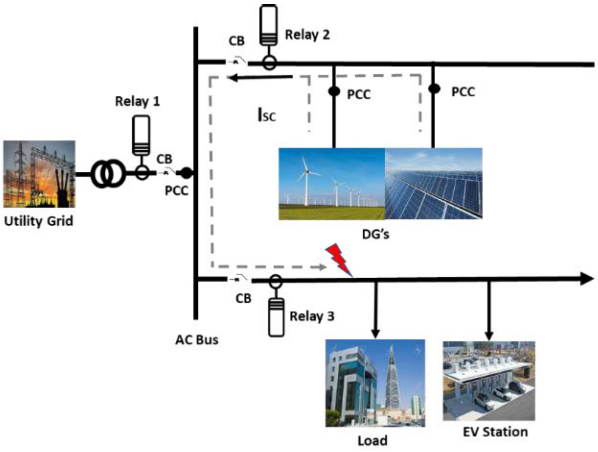

FIGURE 3. Distribution Feeder with Overcurrent Relays and DG (Sympathetic tripping).

is decentralized, and fault current is bidirectional. As a result, the fault current often flows in multiple directions and paths, which is not considered by conventional protection schemes. Secondly, as DGs are plug-and-play devices, their fault current magnitude constantly changes. Thirdly, distributed generation includes rotating machine distributed generation (RBDG) and an inverter. Fourthly, based IBDGs, which have different fault current characteristics. Due to their non-directional nature and fixed protection settings, most protection devices will lose their sensitivity or mis-coordinate relays, fuses, and automatic retracting schemes [35] and [56]. The next section will explain and elaborate on these issues.

A. SYMPATHETIC TRIPPING

As a result of out-of-section faults, sympathetic tripping (False tripping) occurs undesirably on a protection relay. Sympathetic tripping can be caused by two types of distributed generation integration, overcurrent relay and DG interconnection relay sympathetic tripping. OCR operates in one direction in conventional distribution networks. In a radial feeder of a distribution network, the flow of fault current may change due to the high penetration of various sources. The non-directional OC relay trips the main feeder because it cannot detect the change in fault current direction but cannot determine the direction in which the fault current flows [57]. The interconnection protection relays on distributed generators provide over/under voltage and frequency protection. Faults on neighboring feeders may be cleared before the interconnection relay operates. In this case, the DG would be disconnected for a fault outside its protection zone. A false trip in the main feeder (DGs feeder) can be caused by a fault on the adjacent feeder, as illustrated in Figure 3. A fault on the adjacent feeder can operate the main feeder relay. To avoid sympathetic tripping in multi-loop systems in the presence of DG, it has been suggested that using DOC relays could be the most efficient solution.

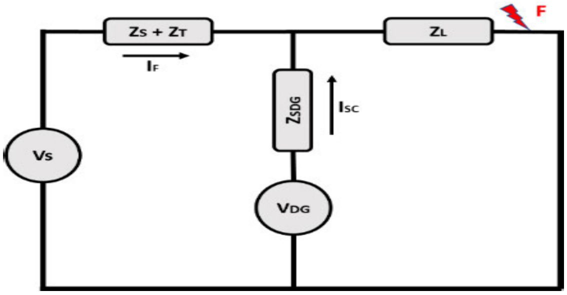

FIGURE 4. Typical distribution feeder's equivalent circuit.

B. REDUCTION OF RESPONSE TIME OR LOSS OF SENSITIVITY

In the microgrid configuration, especially in island mode, the response time is very fast, and the system inertia is very low. DG sources, especially reactive power, are unavailable, and there is a reason for this. This is because DG sources require more intricate technological know-how and resources to set up and operate than traditional power sources. Small disturbances in a system can cause catastrophic consequences if they are not detected promptly and accurately. To detect them efficiently and effectively, a protection system must be able to detect them on time [58]. The effect of DG integration on overcurrent relay sensitivity will be examined in Figure 3 with the estimation of a three-phase bolted fault (F). Figure 4 shows a distribution system that can be represented using the equivalent circuit. The utility voltage is represented by $\mathrm{V_S}$, and the DG voltage is represented by $\mathrm{V_{DG}}$. As a result, the equivalent impedances of the utility, transformer, DG, and distribution line are represented by $\mathrm{Z_S}$, $\mathrm{Z_T}$, $\mathrm{Z_{DG}}$, and $\mathrm{Z_L}$, respectively.

The three-phase fault current at F is expressed as follows if the DG is initially unavailable:

$$\boldsymbol{I_F} = \frac{\boldsymbol{V_s}}{\boldsymbol{Z_s + Z_T + Z_L}} \tag{1}$$

As a result of adding the DG, the fault current at F becomes:

$$\boldsymbol{I_F} = \frac{\boldsymbol{Z_L V_{DG} - (Z_{sDG} + Z_T + Z_L)\, V_s}}{\boldsymbol{(Z_s + Z_T)\, Z_{sDG} + (Z_{sDG} + Z_s + Z_T)\, Z_L}} \tag{2}$$

A utility source's fault current contribution can be written as follows:

$$\boldsymbol{I_L} = \frac{\boldsymbol{(Z_{sDG} + Z_s + Z_T)}}{\boldsymbol{Z_{sDG}}}\boldsymbol{I_F} + \frac{\boldsymbol{(V_{DG} - V_s)}}{\boldsymbol{Z_{sDG}}} \tag{3}$$

Therefore, the DG fault current contribution is as follows:

$$\boldsymbol{I_{SC} = I_F + I_L} \tag{4}$$

According to equation (3), adding DG can reduce power system disturbances and provide a more reliable power supply. Where DG can reduce energy consumption to a significant extent based on its type, size, and location, relay 1 will be delayed in tripping for faults at location F as a result of this reduction. Therefore, selectivity between Relay 1 and Relay 2, as shown in Figure 3, will be compromised. Fault currents that are less than the pick-up value of Relay 1 can prevent it from detecting the end-of-line fault at F. This is known as blinding of protection or underreach [37] and [59].

C. RECLOSING SCHEMES MISCOORDINATION AND FUSE PROBLEMS

Fuses and reclosers are the main protective devices that protect distribution systems against faults. Fuses protect the main feeders against permanent faults, while lateral feeders use reclosers to clear temporary faults. DGS can increase fault currents in distribution systems, which could result in the relay and fuse miscoordination and abnormal behavior [60], [61], [62]. Recloser performance can be affected by DGs in two ways: by reducing recloser sensitivity or by losing coordination between the fuse and recloser. Furthermore, DGs may influence recloser pick-up sensitivity [63]. The majority of faults in distribution systems are temporary [59]. Automatic rectifiers are often used to eliminate temporary faults without human intervention. Furthermore, a fuse-saving scheme coordinates reclosers with branch fuses. This is to prevent the fuse from blowing when there is a transient fault on the branch, called a fuse-saving strategy. This system ensures the line-recloser can quickly react to possible faults and interrupt the flow of electricity to the line, thus protecting the system from any damage, as shown in Figure 5. Suppose the DG in Figure 5 is initially unavailable. As shown in Figure 6. below, the fuse and recloser must be coordinated to function correctly. There are times when the recloser trips due to a temporary fault and reopens after a reasonable time between trips. The recloser trips using the slow curve during permanent faults for the fuse to clear the fault as quickly as possible. As well as providing backup protection the recloser can provide backup protection in case of fuse failure or when the fault is not on the fused branch. There are most likely to be 2-3 fast trips/delayed reclosing attempts conducted by the recloser before we switch to a slow curve. This procedure must be carried out to ensure the fault has been cleared. For a fuse saving scheme to work, both conditions must be met: (a) the fault current must pass through the fuse and the recloser, and (b) the fault current cannot exceed the value shown in Figure 6, (I_{fmin}, and I_{fmax}) [64]. As shown in Figure 5, adding a DG between the fuse and the recloser may cause coordination issues. For example, if there is a fault at F1, the fault current contribution is made up of both the fault currents contributed by the DG and the fault currents contributed by the recloser in the case of a fault at F_1.

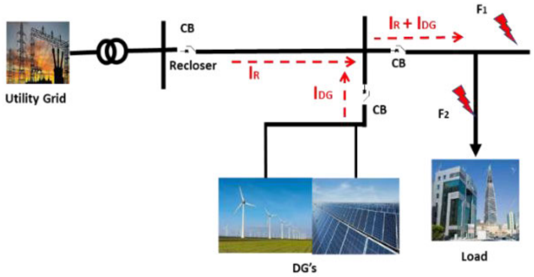

FIGURE 5. DG, fuse, and recloser on typical distribution feeder.

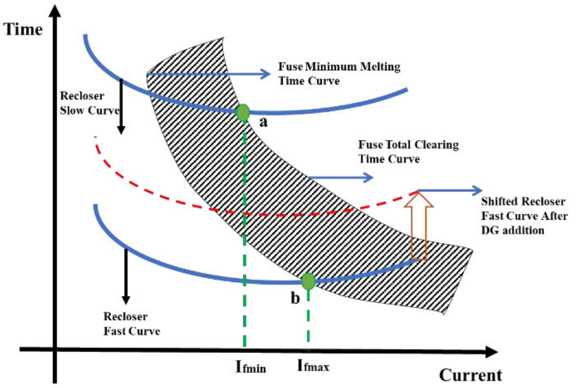

FIGURE 6. Mis-coordination of fuse recloser due to DG Addition current.

Contrary to that, the recloser will only be able to receive IR current, which means it will be either slower to operate or, worse, unable to detect faults. Due to this reason, automatic reclosing will no longer be allowed [65]. A fault at F_2 will cause the fuse to be able to see a higher current than the recloser since the fault current contribution from the DG will make the fuse see a higher current. Depending on the rating of the DG, the fuse fault current may exceed the I_{fmax}, as shown in Figure 6. There is a possibility that the fuse may be blown before the recloser trips, thus resulting in the fuse-saving scheme failing [64]. Due to this, the characteristics of the recloser are shifted above the minimum melting curve of the fuse. If the field arc is sustained due to the DG fault current, the recloser will trip before the fuse for F_2 is blown. During the reclosing deadtime, there may be a generator and load imbalance. This results in unsynchronized reclosing, which may damage the distribution network and the generator during the reclosing process [65]. Thus, adding DGs disrupts fuse saving, prevents automatic reclosing, and may cause unsynchronized closure.

D. EXCEEDING SHORT CIRCUIT LEVEL

Fault currents in the network are increased by distributed generation. Distribution equipment ratings and the power ratings of added DGs may exceed the short circuit levels of distribution equipment, such as switchgear and distribution lines. CT saturation may also occur with increased short-circuit levels. Changing equipment or installing fault current limiters may resolve these issues. Both cases will incur substantial additional costs [66], [67], [68].

A power system's short circuit current is vital in determining and protecting its equipment. A significant increase in short circuit current occurs when DGs are incorporated into the power system. DGs can operate in different modes and have different short circuit levels. A synchronous generator's fault level differs from an inverter-based generator's. DGs that use inverters have a maximum fault current that cannot be exceeded by two times the inverter's rated current [52], [69]. Inverter-based DGs produce less fault currents than synchronous machine-based DGs, which can generate four to ten times more fault currents. This makes inverter-based DGs ideal for applications where fault current levels are a priority [70]. Traditional protective devices such as OC relays and fuses display the variation of short circuit levels. DGs with inverters may cause protective devices to trip [52]. In addition, a grid-connected microgrid has a higher short-circuit level than an islanded microgrid [43]. Protective devices cannot detect short circuits by some DGs in island mode due to limited short-circuit capabilities. OC and distance relays, for example, can be affected by variations in the short circuit, especially indefinite periods. To limit fault current values, a Fault Current Limiter (FCL) is implemented [71]. Additionally, there are several approaches to mitigate the negative effects of DG on distribution network protection by using various methods [72]. For example, detecting and isolating DG immediately after a fault occurs. Additionally, limiting DG capacity, utilizing adaptive protection, adding additional circuit breakers and reclosers to the protection system, reconfiguring the distribution system, deploying distance and directional overcurrent relays, and installing FCL.

E. UNDETECTED ISLANDING PROBLEMS

Distribution networks with DERs can be isolated by disconnecting them from the main utility supplies. This allows them to be powered independently, allowing maximum flexibility and control. Consequently, the isolated network will continue to be energized by DERs. This isolation also prevents power disruptions from the main utility supply, ensuring a reliable energy supply within the isolated network. It is possible to create islands intentionally or unintentionally. Furthermore, intentional islanding is a deliberate decision by utilities or end users to disconnect from the grid, and use DERs to provide energy to the isolated network. This intentional islanding offers a reliable and cost-effective way to power remote and off-grid locations, which would otherwise be unable to access grid electricity. DGs, distribution company equipment, and customer equipment may be damaged if unintentional islanding is not detected [74], [75]. Further, maintenance personnel may be electrocuted. Islanding situations shall be detected quickly by the DGs, and they shall be notified accordingly to prevent unintentional islanding. As protective relays against islanding or as Loss of Main (LoM) relays, these devices are called anti-islanding relays. According to IEEE 1547 [76], intentional islanding occurs when local systems energize DGs. In parallel, they can be disconnected from the main system. Scheduled islanding helps operators to reduce the cost of electricity, prevent overloads on the grid, and keep the supply and demand of electricity balanced. Unscheduled islanding occurs when an unexpected event, such as a power outage or a fault in the grid, causes the area to become disconnected from other parts of the grid. This can cause an island to form to maintain the grid's stability. Planned intentional islands occur due to abnormal conditions at upstream distribution points. This features automatic disconnections from the grid when abnormal conditions are detected on the island due to installing the necessary detection and control devices [76].

DGs and interconnected loads can operate in on-grid and islanded modes in a microgrid [77]. IEEE standard 1547 requires DGs to be isolated during grid faults [78]. A significant benefit of islanded modes is that they allow energy to be provided to local loads to enhance system reliability. The operation of such a microgrid, both when it is connected to the grid and when it is isolated, is extremely complex and has to be protected and controlled. Moreover, careful consideration must be taken when designing the protection and control systems for islanded microgrids to ensure the system can respond quickly and accurately in any given scenario [79]. In islanded mode, overcurrent relays are insufficient to protect the microgrid as the main protection device [80]. In IEEE 1547-2018, the concept of "intentional islanding" is similar to that of a future microgrid. This is necessary because when a distributed generator island is formed, the DG will no longer be controlled by the utility and instead must be controlled by its power source. Islanding detection relays can detect when an island is formed, allowing the DG to take control and adjust the voltage and frequency. Islanding detection relays can also be used to safely disconnect the island when necessary to ensure that power quality is maintained and the system remains secure. To ensure the safety of consumers and the successful functioning of the grid, these fast and reliable islanding detection relays must be implemented. It is necessary to modify the protection settings to suit the island mode of operation to enable the protection relays.

To reduce the negative effects of DGs, several methods have been proposed. Several methods may help prevent power losses in DGs in a fault. This can be accomplished by changing or modifying the protection scheme, implementing FCL, limiting the DG's capacity, isolating the DG from the rest of the power system, and using an adaptive protection scheme. Additionally, by allowing sufficient time before reopening the faulted line or by implementing an islanding method, the consequences of the presence of DG can be effectively minimized. The next section will present and discuss overall protection schemes and their applications in detail.

IV. PROTECTION SCHEME OF AC MICROGRIDS AND THEIR APPLICATION

Extensive research has been conducted to protect microgrids and reduce DG integration impact. Here is an overview of fault protection solutions for AC microgrids and active distribution networks. According to the operating time, a traditional protective relay coordinates primary and backup protection [81], [82], [83]. Power system topologies and operational modes can change over time, but this scheme

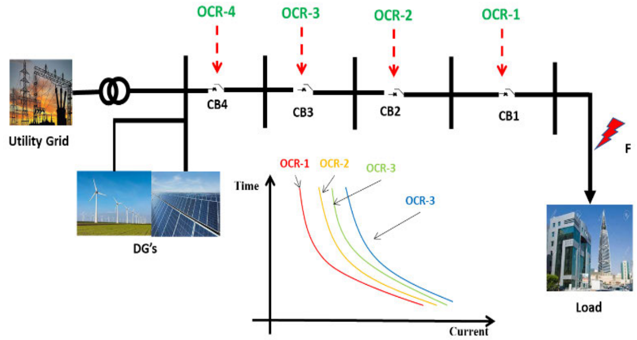

FIGURE 7. Traditional coordination of protective relays.

cannot be adapted [84]. DGs have altered the distribution network's structure and demand to accomplish this. In Figure 7, protective relays are shown in traditional coordination. Distribution network challenges are primarily related to changes like microgrids. Many schemes have been proposed for protecting distribution networks with high penetration rates of resources.

Several problems are associated with the distribution system in traditional distribution networks due to different distributed resources. These problems can lead to inefficiencies, delays, and increased organizational costs. Using DOC relays and changing relay settings can improve traditional distribution networks.

A. MODIFYING RELAY SETTINGS SCHEME

To ensure that the protective relay settings remain accurate in the event of changes to the topology of the power system, they must be revised. The relay cannot detect faults in blinding zones, but these zones can be covered by reducing the pickup current value and increasing the relay's sensitivity. This would allow the relay to detect faults in the zone, even when the fault cannot be detected directly. It is important to note that this should be done carefully, as the settings must remain within the limits of the protective relays. Changes in relay settings may cause problems in protection coordination. According to Reference [85], microgrid protection is achieved using low-voltage ride-through operation. Simulation results have corrected the protective relay setting values. An improved microgrid OC protective relay is presented in [86] that uses the compound of fault acceleration factor and the beetle antenna search method. This method has enhanced backup and primary relay coordination, and OC protection. DOC relays are proposed in [87] to protect DG feeders against sympathetic tripping due to nearby faults. Furthermore, the DOC relay prevents unwanted tripping in neighboring feeders [54]. Several protective relays are implemented particularly, and they can be activated simultaneously using modern digital and multifunctional protective relays.

B. VOLTAGE-BASED SCHEME

The voltage-based protection scheme is another way to protect microgrid systems [88]. As a backup protection scheme, the method utilizes the voltage gradient level in the power system during faults [89]. In Reference [88], voltage-based protection was combined with directional elements to develop a low-fault and low-voltage radial microgrids protection method. Several research works have described abc–dq transformations to detect voltage disturbances. A dq frame is created by converting the signals from an abc frame [90]. Then, a dq reference frame transforms the output voltages of micro-sources into DC quantities. When the grid faults cause disturbances at the micro-source output, the dq values are affected [91]. An abc-dq transformation of voltage waveforms was proposed by the authors of Reference [90] to detect faults in microgrids. It proposes a method that protects internal and external faults within a defined zone.

An island-based microgrid will be protected by voltage-based protection in a dq frame [91]. This scheme applies to both single-phase and three-phase generators. This provides users with a comprehensive system of protection and stability, ensuring an uninterrupted electricity supply. Additionally, it offers a cost-effective and resilient solution to help manage power fluctuations in remote areas. In this case, the magnitude of the voltage would be the same regardless of where the voltage is applied [92]. Additionally, the voltage drop in HIFs may not be sufficient. Under-voltage protection may not determine if the power system is overloaded or faulty [54].

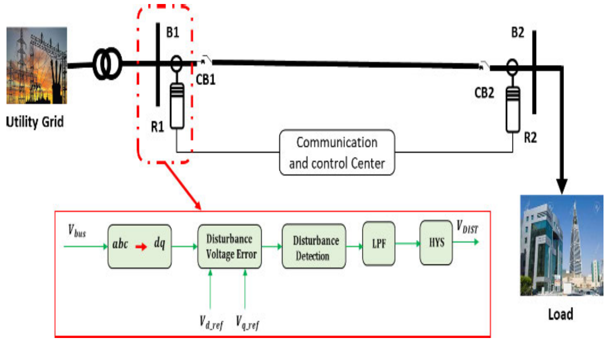

FIGURE 8. Schematic for voltage-based protection using communication.

Voltage signals are typically sent between relays via communication wires. Figure 8 illustrates the block diagram of the scheme, which consists of two steps to be implemented. The first step is to convert the supply voltage from an abc frame to a dq frame. As part of the next step, the disturbance signal (VDIST) is determined using disturbed dq values as input. Supply voltage deviation from a reference is called VDIST. A higher VDIST value means a higher disturbance. The disturbance signal indicates system disturbances. Low pass filters (LPF), hysteresis comparators, and upper and lower limiters are implemented to improve fault detection sensitivity. This scheme has the advantage of protecting both internal and external faults within any protected area. In contrast, high-impedance and symmetrical faults are ignored.

C. IMPEDANCE-BASED PROTECTION METHOD

Distance Relay or Impedance Relay is one type of relay that functions depending upon the distance of fault in the

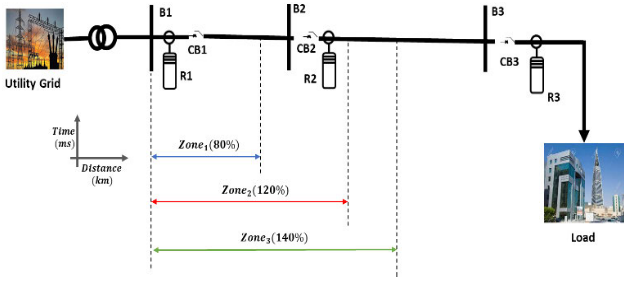

FIGURE 9. **The zones of distance protective relays.**

line. More specifically, the relay operates depending on the impedance between the fault point and the relay. A distribution network is protected by impedance-based protection when DGs are present. This type of protection is used to differentiate between faults and loads connected to the distribution network, ensuring the network remains stable [93]. Voltage and current at the relay point are used to measure the impedance of a line. Communication between relays is not usually required for distance protection [94]. Various admittance criteria were evaluated during faults with high resistance. To implement admittance-type protection, digital or analog techniques are used. Furthermore, resistor-grounded networks can benefit from admittance-based protection. A distance protection scheme was developed for island- and grid-connected microgrids [95]. Relays have the capability of clearing faults quickly, maintaining the stability of the system in an emergency. As a result, they are essential in power systems engineering to ensure a reliable and uninterrupted power supply.

Distance relay zones are shown in Figure 9. Distance relays usually cover three zones (zone 1, zone 2, and zone 3). A distance relay's zone 1 typically covers 80% of the protected line and operates without delay. In contrast, zone 2 and zone 3 are overreaching zones with a time delay. Distance relay zones 2 and 3 cover both protected lines plus 50% of the shortest adjacent lines. In addition to zone 1 and zone 2, zone 3 protects adjacent sections from unclear faults by serving as backup protection. Zone 3 serves as an additional layer of protection to ensure the safety of adjacent sections in the event of unclear faults [96].

Distance relays based on the wavelet transform (WT) method were studied for detecting faults [97]. A traveling wave protection technique can be successfully overcome using wavelet analysis for signal processing. Recently, a novel signal processing technique, the WT method, was developed based on the Fourier transform (FT) [98]. A dyadic wavelet transform was developed for transmission line protection [99]. The moving data window determines the discrete approximation factor of the dyadic wavelet transform with Haar wavelet for detecting transmission line faults. This approximation factor plays a vital role in assessing the accuracy of the fault diagnosis. An algorithm WT based on fault detection was presented based on transformation from the time domain into the time-frequency domain [100]. To approximate the decomposition of phase voltages and current samples, artificial neural networks (ANNs) were used. The ANNs also accurately predicted the relationship between phase voltages and current samples [101].

The autocorrelation of three-phase current envelopes was used to create a microgrid protection scheme using squaring and low-pass filtering techniques [102]. This approach enabled the successful protection of the microgrid from power disturbances and outages. It is designed to protect the systems from damage by detecting faults, sorting faults, identifying fault zones, classifying faults, and triggering them [103]. A hybrid method was proposed to detect ground faults located in blinding zones. Microgrids with ungrounded direct current voltages were modeled using discrete wavelet transforms. This method was successfully tested on a three-phase system and proved to be robust in overcoming the effects of noise, achieving fast and precise fault location. Two different methods were cited in References [104], [105], [106], [107]. According to the existing protocol, both single-ended and double-ended methods were implemented. A fault location was calculated without any special hardware/software in Reference [108]. An improved impedance-based fault location was implemented using a short-distributed line model [109]. Short circuit current levels change due to the high penetration of DGs. Consequently, the impedance of the power system is not the main cause of low fault current in microgrids.

An impedance-based pilot protection method is studied in Reference [92]. An impedance-based protection scheme with communication support was proposed for microgrids with inverter dominance. The impedance and directional elements were installed on the relay feeder to detect faults. To design these protection elements [110], [111], the authors utilized and summarized the vast literature and extensive experience designing impedance and directional elements. To determine the location of faults, they used different pilot protection logic. An efficient protection method for DC microgrids has been proposed with high penetration of constant power loads [112]. The scheme uses first-order derivatives of fault current to exploit the fault location scheme strategy. Additionally, faults can be detected in DC microgrids based on pre-fault data, and high- and low-resistance faults can be located on constant power load lines. A remote input/output mirror bit, battery energy storage system inverters, and PCC breaker relays were used in reference [113] for synchronous islanding microgrid protection. In addition, an advanced protection system for microgrids was proposed in the study, providing a comprehensive solution for distributed energy resource islanding.

D. MODIFYING FCL SCHEME

A fault current limiter (FCL) is considered a serious candidate for installing in electrical grids to avoid short-circuit damage and the inevitable upgrade of the system equipment during short-circuits. Two types of FCLs are commonly used in power systems: non-superconductors and superconductors [114], [115], [116], [117], [118], [119]. An FCL that is non-superconducting is typically divided into three groups: a solid-state FCL (SSFCL), a hybrid FCL (HFCL), and a non-superconducting FCL [120]. Table 1 presents the classification of different types of FCLs. There are various applications of superconducting FCLs in the power network, including renewable power generation, distribution generation, transmission systems, distribution networks, etc. [118], [121]. Several branches of the power system have utilized non-superconducting types of FCLs to improve dynamic performance by limiting fault current [122], [123], [124], [125], [126]. Two types of superconducting FCLs are used in power systems: superconducting and non-superconducting FCLs. Table 1 compares these two types of FCLs. This table summarizes several technology and application aspects of FCLs.

E. HARMONIC CURRENT-BASED PROTECTION

Microgrid topologies have increased harmonic levels due to converter-based distributed generation. Two factors influence harmonics in power systems: the network topology and the source of harmonic interactions [149]. A communication-assisted protection scheme has been proposed using harmonic content in the output voltage of inverters as a protection technique for microgrids with inverter dominance. This communication-assisted protection scheme allows for improved microgrid protection while maintaining harmonic content in the output voltage of the inverters [150]. To identify the type of fault, monitoring the fundamental frequency amplitude and the Total Harmonic Distortion (THD) of all phases is necessary. This helps to diagnose the root of the problem and identify the optimal remedy. The sums of THD at each relay location are communicated to other relays to identify fault locations. A trip command is issued if local THD is higher than remote THD. In [151], an inverter-based DG protection strategy is proposed for islands with microgrids. During short circuit conditions, the inverter control system is modified in this manner. A certain amount of fifth harmonics is injected. An inverter's output is connected to a sliding window digital relay based on a fast Fourier transform that detects fifth harmonics. The proposed protection strategy can detect fault conditions quickly and accurately by injecting a fifth harmonic current into the grid. This will help to detect fault conditions.

The harmonics of the system can be controlled using modern relays that measure THD at the inverter terminals. By controlling the harmonics, the efficiency of the system can be improved significantly [150]. Electric power systems assess harmonic emission levels based on harmonic impedance. In reference [152], novel measurement and data selection techniques were presented based on complex least-square regression. In the method, two data selection methods are considered, which can be combined to cross-check the results of both methods, which are considered part of the method. The authors of [153] provide controls for inverter operation in different modes that determine each harmonic component of the microgrid. This scheme injects a current disturbance to measure the harmonic impedance. The harmonic injection strategy requires only one DG to activate the relay. This strategy can be used in various electrical systems, making it an ideal solution for remote and distributed installations. Due to this, the relays behave as directional relays. This scheme has the advantage that the resultant directional relays do not require a voltage transformer to detect fault direction. As a result, it is a cost-effective method of protecting microgrids.

F. ADAPTIVE PROTECTION SCHEME

In the 1980s, adaptive protection was introduced for transmission systems [154]. In response to external changes in the power system, the Adaptive Protection Scheme (APS) permits protection settings to change in real time. This allows power system operators to quickly and effectively respond to shifting conditions, ensuring the reliable operation of the entire grid. To identify changes in power system conditions, most adaptive protection systems must communicate with external entities; however, local measurements can be used to implement adaptive protection. Thus, adaptive protection can broadly be divided into: Local information-based APS and communication-based APS [154], [155], [156], [157]. In response to changes in power conditions, APS automatically adjusts protection functions and/or settings. This is done to ensure the safety and reliability of the power system by providing timely protection against any potential faults or overloads. The adjustments are made without manual intervention, meaning the system is constantly monitored and updated. Various relay input measurements, including voltage, current, and digital/analog values, are used to determine this. Microgrids can be protected effectively and at a low cost through APS, a low-cost solution that doesn't require any communication infrastructure. As a result, the failure only impacts the relay and does not affect any other relays. Additionally, APS has the added benefit of detecting any fault or disturbance in the microgrid in a timely manner and responding quickly to prevent any significant failures. A non-communication APS was proposed based on voltage-restrained overcurrent protection for islanded microgrids [158]. The scheme, however, considered only island-based systems and microgrids of a small scale. The authors in [154] proposed an adaptive inverse time OC scheme. Different microgrid configurations and operating scenarios were presented and studied based on the scheme settings. In References [156] and [159], the authors proposed algorithm detection techniques for islanded and grid-connected microgrids to identify microgrid mode of operation changes.

A relay's fault current and inverse time-tripping characteristics determine which relay has operated first and which DG is disconnected. These characteristics allow for the quick and

TABLE 1. Comparisons of classification and applications of different types of FCLs.

Type	Superconducting FCLs (SFCLs)	Non-Superconducting FCLs (NSFCLs)		
		Solid-state FCLs (SSFCLs)	Hybrid FCLs (HFCLs)	Other technologies
FCLs Classification [127], [128]	▪ Resistive ▪ Inductive ▪ Resonance-type ▪ DC Reactor ▪ Flux-Locked ▪ Bridge-type	▪ Switching Impedance ▪ Impedance-based ▪ Capacitor-based ▪ Multicell-type ▪ Bridge-type ▪ Resonance-type ▪ Magnetic turn-off	▪ Inductive ▪ Bridge-type	▪ Five-leg saturated core ▪ Low permeability ▪ Saturated Single-phase ▪ Pre-saturated Single-phase ▪ Permanent magnetic-based DC ▪ Electrodynamic ▪ Liquid metal ▪ positive temperature coefficient resistor ▪ Saturated Core
Fault detection and control systems [121], [129]	The majority of them do not require additional fault detection and control systems.	Almost all of them need additional fault detection and control circuits.		
Communication Interference [121], [130]	They interfere with communication between neighboring Line	Research articles have not reported any interference with communication lines.		
Size, cost, and losses [131]-[136]	Their size is large, and their weight is heavy. The superconducting nature of the required inductor and resistor makes its implantation costly. Furthermore, most SFCLs do not experience loss during normal operation, but inductive-type SFCLs do.	They are small in size and have less weight. Due to the non-superconducting nature of the required inductor and resistor, there is a savings in cost. Moreover, they have losses in the normal operation of the system.		
Topology complexity [123], [137]-[141]	The circuit topology of most of them is highly complex.	Most of them have simple structures.		
FCLs Applications	▪ Transmission Line [142]-[144] ▪ Distributed Generation [120], [145] ▪ Distribution Network [121], [146] ▪ Renewable Energy [129]	▪ Transmission Line [147] ▪ Distributed Generation [123], [124], [148] ▪ Distribution Network [122], [125] ▪ Renewable Energy [126]		

accurate identification of the source of the fault. However, the scheme is unable to identify when the DG is reconnected. Additionally, radial microgrids with rotating machines were considered. A radial microgrid's primary and backup overcurrent relays could be coordinated using an adaptive scheme based on sequence component quantities [160]. An adaptive fault current parameter determines the inverse time delay equation in this technique. This coordination scheme could improve the system's security and reliability during overloads and short circuits. It is, however, imperative to establish a communication system to keep the relay informed about available DGs and their status since the impact factor calculation depends on their type. It is, therefore, only possible to implement the method without communication if all DGs share the same type. Furthermore, it is essential to have a reliable communication channel to ensure that the network is aware of the types of DGs, as different types can significantly affect the calculation of the impact factor. An innovative method of non-intrusive load monitoring was described in [161] for detecting the operational status of loads in real-time without requiring communication. This load monitoring method promises accurate results with minimal effort and cost, helping to improve the efficiency of operations. The power flow sign and magnitude determined the fault direction algorithm. To adjust tripping thresholds as load conditions, change, relays must communicate with each other to determine the appropriate tripping action. In contrast, this scheme coordinates relays, not for adaptive protection.

The APS-based communication scheme consists of centralized and decentralized sections for adaptive protection. The centralized section includes a base station or central server that collects and processes data from the network. In contrast, the decentralized section includes decentralized nodes responsible for generating and transmitting data. The two sections work together to ensure the network is secure and reliable. Central Protection Units (CPUs) communicate with relays as part of the centralization approach. This allows the relay to be monitored for current, voltage, and other parameters and for the CPU to send commands to the relay to open or close the circuit. This centralization allows for better control over the operation of the system. Several communication protocols, including MODBUS, DNP3, and IEC 61850, can support this topology. A serial communication protocol, a bus-communication protocol, a power-line carrier transmission protocol, and an Ethernet transmission protocol can be used to implement this scheme [162]. The literature contains a wide variety of centralized adaptive protection techniques. In addition, distributed adaptive protection techniques have also been discussed in the literature. These methods differ significantly, including fault detection strategies, relay setting calculation (online or offline), and relay setting updating methods. Figure 10 shows an example of a centralized adaptive protection approach. DOC relays and communication capabilities are integrated into every CB. In this way, the CB can exchange information with the CPU using a primary-secondary scheme, where the CPU is the primary and the CBs are secondaries.

Operating scenarios for MGs are identified in advance as part of the offline setting calculation approach for APS. This means that the MG can be operated optimally without constantly analyzing the situation in real time. In this way, all possible operational and topological changes are considered for a more efficient and cost-effective operation of the MG. This includes MG mode, load status, CB status, and DG status. Artificial Bee colony optimization algorithm and non-linear programming optimization were used to optimize the relay coordination problem [53], [163]. Commercial optimization software (Baron) and open-source optimization software (I_{popt}) were employed to obtain the solutions. However, both methods could only operate in a grid-connected mode. A comprehensive central APS strategy for a medium voltage MG at Hailuoto Island is proposed [164]. For PCC protection, directional and non-directional OC relays are for main feeder relays, and zero sequence voltages are used for diesel generators. In addition to this, the auto-reclosing scheme is used for the main feed in grid-connected mode. The CPU uses IEC 61850-based protocol communication networks to monitor MG and DG units during online operation. In [165], the author proposed a centralized APS that used a protocol communication network IEC61850 to encompass generic substation events. To meet the protection requirement, this was studied offline. As a result, it was determined that the necessary steps could be taken to ensure the safety of all parties.

In References [38], [39], [75], [83], [166], [167], [168], and [169], the authors proposed a centralized APS with online setting calculation overcurrent protection strategy for MGs. To detect and locate faults, the central unit communicates with every relay in the system while operating online. In addition, it monitors the status of each DG, determines its capacity, and determines the capability of the DG to feed fault currents. A CPU estimates fault current contributions based on real-time information exchanged at each relay location. This ensures that the system can quickly detect and isolate a faulted section of the grid, restoring power to unaffected areas faster. In [75], the state estimation protection scheme is used for fault detection. Wind-turbine distribution systems with open and closed loops were proposed in [83]. The proposed systems offer power quality, reliability, and efficiency advantages. Furthermore, the CPU performs online short circuit analysis and protection setting calculations and monitors the connections between all CBs and DGs in the network [168]. The CPU calculates relay response time based on current and updated settings to update the protection settings. It compares the results with coordination rules, such as operating time limits and grading margins. This helps to ensure that the system is optimized for maximum efficiency and safety, as it prevents the overloaded power system from failing and protects the equipment from damage. This process, also known as system protection, is essential to any power system.

A decentralized adaptive protection system requires sub-areas to be organized into regions controlled by local controllers (LoC) [83]. An example of a decentralized adaptive protection scheme for microgrids is represented in Figure 10. Each relay communicates with other relays in this scheme and shares topological/operational information about microgrid and realties measurements [170]. However, each relay makes its own decision autonomously based on the communicated information. This scheme has the main advantage of not relying on a central unit, thereby eliminating single points of failure. The implementation of such a scheme, however, is more complicated, and advanced IEDs are required [171].

G. DIFFERENTIAL PROTECTION SCHEME

The differential protection scheme is among the most reliable for MGs in power systems when protecting transmission lines and transformers [172], [173]. This is because differential protection schemes compare current entering and leaving the component being protected, and a fault is only detected if the currents do not match. It provides fast and selective tripping of the faulted section while keeping the rest of the system in operation. This scheme is simple, cost-effective, and easy to implement. It is widely used in power systems. Based on the test method, the fault current varies regardless of whether there are MGs or variations in DG status. In addition, it offers high fault resistance and is highly selective. Typically, a differential protection scheme operates on the principle that the current entering a feeder must equal the current leaving it. To implement this, the secondary currents in the current transformers are compared at the terminals of the equipment that needs to be protected. This approach has maximum selectivity and operates only in internal fault cases. However, it requires reliable communication for instantaneous data transmission between the ends of the equipment to be protected [174]. This reliable communication allows the primary current transformer to be quickly informed of any internal faults, ensuring maximum selectivity and protective measures are taken as soon as possible. As shown in Figure 11, a microgrid can be protected differentially using copper pilot wire, fiber optic cables, microwaves, or other communication technologies. In accordance with ANSI/IEEE 87, as presented in [175], differential OC protection relays are used to protect sensitive equipment, such as generators, transformers, station buses, and transmission lines (ANSI/IEEE: 87G, 87T, 87GT, etc.). In addition, these differential protection relays operate by comparing the current between two points to detect overloads and faults in the microgrid. If a fault is detected, the protection relays isolate the faulted section from the system, improving protection and reliability.

This scheme generally has the best selectivity since it relies on communication between the beginning and the end of the protected line segment [93]. An adaptive wide-area current differential protection system was investigated in [176].

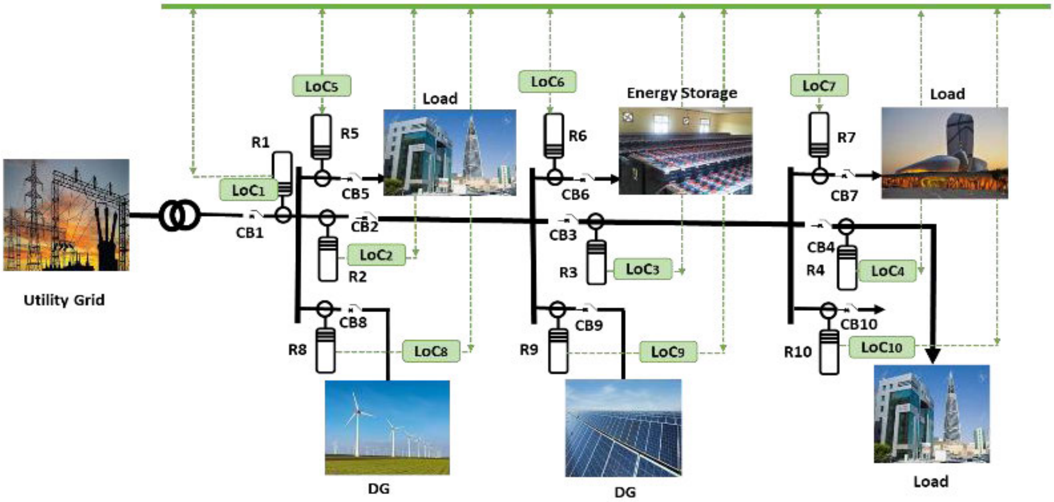

FIGURE 10. **Decentralized adaptive protection scheme.**

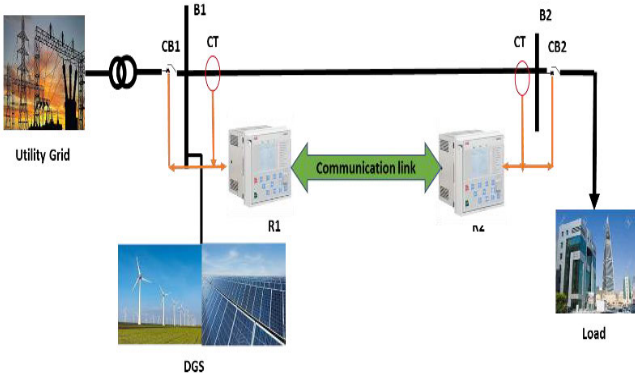

FIGURE 11. **Differential-based protection scheme.**

This method dynamically activates different protection zones within the power system. A digital relay was proposed to protect an MG in [52] and [54]. Based on the differential protection, HIFs and inverter-based MGs were utilized for low-fault currents.

A communication-assisted OC protection scheme was proposed for PV in DC MGs [177]. Differential protection was utilized as backup protection. DC MGs were implemented in both grid-connected and islanded modes by OC relays. In Reference [178], the authors present a protection scheme for the loop distribution system in the presence of DGs. The centralized protection scheme is based on the equivalent circuit of the distribution system and uses a control center with high-speed communication. This control center processes the signals from different protection relays to detect and isolate faults quickly and reliably. The proposed centralized protection scheme is designed to provide quick and reliable fault isolation and detection while supporting grid-connected and islanded modes.

As with any protection system, these schemes are incomplete and do not protect against all faults, such as upstream, line-to-line, and symmetrical faults. Other techniques must be used to identify faults, such as upstream, line-to-line, and line-to-line faults, if other faults are to be identified. However, these schemes protect faults that cannot be identified with other techniques, such as ground faults, overloads, short circuits, and unbalanced loads. In addition, the protection method needs a separate backup protection scheme to prevent possible communication failures. This redundancy significantly raises the protection system's cost, limiting its application in MGs. However, all previous proposals for directional overcurrent relays have assumed that they would be grid-connected and rotate due to their operation. This has posed a challenge for decentralized applications, as the relays must operate independently from the grid. Based on the available literature, a microgrid cannot be effectively configured using directional overcurrent relays alone in both modes of operation. Table 2 lists the advantages and drawbacks of MG protection as described in the literature. However, further research is needed to confirm the findings of these studies and to quantify the effectiveness of MGs protection. The classification of different items in the review is presented in Table 3. The presented classification is a helpful way to understand the various items in the review.

The real world employs a variety of different protection schemes today. In addition, Table 3 displays overall items in the literature on DGs and MGs protection, including the type of DGs, the protection scheme, protective relay, simulation situations (such as simulations of real networks or simulations of test cases), and their publication dates. This table comprehensively overviews the different protection schemes and protective relays used in DGs and MGs systems. It also details the simulation scenarios used to test the protection systems and the publication dates of the corresponding literature, providing a valuable reference for researchers in this field. The paper presents simulations and experimental results for some of the protection schemes in the table. Experimental and simulation results confirm that empirical results follow real-time conformity. Relays and DGs have completely similar protection schemes and types. However, the benefit of using a

TABLE 2. **Summary of advantages and drawbacks of microgrid protection schemes.**

Protection Scheme	Advantages	Drawbacks
A. Impedance-Based Protection Method	▪ Provides prompt protection. ▪ Coordinating and applying it is very easy. ▪ The settings are permanent, so there is no need to alter them. ▪ A generation of fault levels reduces the magnitude of fault current. ▪ Provides for the high-load lining.	▪ Non-directional since it operates on both sides of a line's fault. ▪ Non-directional since it operates on both sides of a line's fault. ▪ Influenced functionality by the resistance of a fault line's arc, whenever a defect occurs, an arc is formed. ▪ The capability of measuring fault resistance is limited. ▪ Power swings affect distance relay performance as the R-X plane covers a large area.
Differential protection	▪ Relatively simple. ▪ Capable of handling both radial and loop feeders' configurations. ▪ Highly sensitive and responsive.	▪ Problems during unbalance and transients. ▪ Requires reliable communication channels. ▪ A communication infrastructure could be expensive. ▪ Not sensitive to bidirectional flow. ▪ Affected by unbalanced loads or systems; ▪ Defects in the differential protection system may occur during the connection and disconnection of DG.
Overcurrent protection	▪ Easy to coordinate in mesh configurations. ▪ Able to sense both current directions	▪ Not cost-effective.
Harmonic based protection	▪ Used for inverter-based system ▪ does not require a voltage transformer ▪ Cost-effective	▪ Might fail to trip in several dynamic loads
Adaptive and pre-planned protection.	▪ Leverage adaptable settings of the protective relay. ▪ Online system	▪ Require reliable communication links and fast processing units. ▪ Require prior knowledge about microgrids.

real network for relays was apparent, as it allowed engineers to identify and mitigate potential issues with the protection scheme before it was implemented.

An overview of the standards and their scope is intended to provide developers with an understanding of what they must meet when connecting DGs to public distribution networks. There have only been a few recent developments in microgrid standards. To ensure that these standards meet the needs of all stakeholders, they must be regularly reviewed and updated as new technologies are adopted [217]. However, with the increasing demand for distributed generation sources, various standards are being created to ensure the reliable operation of these networks. With the newly established standards in place, developers are now able to develop DGs and public distribution networks that are reliable and efficient. To further ensure reliability, these standards must be regularly assessed and revised to accommodate new technology and innovations. This allows developers to develop DGs and public distribution networks that are both reliable and cost-effective. For each standard, TABLE 4 provides the following information: year, references, country, standard name identifier, title, and scope of application.

V. AC MICROGRIDS AND DGs: CHALLENGES AND OPPORTUNITIES

Integrating DG generally causes problems in protection, but when a microgrid is proposed, there are particular challenges. Grid-connected and island modes have sharply different fault current levels. The inertia of the island microgrid will depend on the number and type of DGs connected to it. As a result, current-based protection devices are challenged by IBDG fault current characteristics. As microgrids become more prevalent, the distribution network faces significant challenges. Protecting distribution networks with high penetration has been proposed in many ways. This section explains and elaborates on microgrid protection issues.

- ***Costly installation for the protection system in the MGs:*** Due to the complexity of MGs, distribution networks operate similarly to transmission networks. For this reason, sophisticated power interruption and blackout prevention schemes are necessary. Due to transmission systems' extensive reach, an expensive protection system is justifiable. With MGs, however, the need for protection systems is not as evident. This is due to the localized nature of MGs and their smaller size compared to transmission systems. As a result, protection systems for MGs may not be seen as a priority investment. Unlike the primary power grid, microgrids do not require complex protection schemes since failures are limited to a small area. This issue may restrict the future of MG acceptance unless cost-effective and realistic solutions are proposed. Therefore, it is essential to develop cost-effective and realistic power interruption and blackout prevention solutions to ensure the long-term success and adoption of microgrids. To do this, research should focus on developing strategies to reduce the impact of grid disturbances on microgrids and implementing technologies that allow for fast detection, identification, and isolation of faults.

TABLE 3. Microgrid protection schemes categorized in the literature.

Protection Schemes	Refs.	DG Presence	Protective Method with Relay type	Simulation / Experimental	Year
Modifying DOC Relay	[64]	Distribution network integrated with DGs	Recloser with directional element	Simulation	2010
	[88]	Synchronous Machine Based Inverter	A microprocessor-based relays for low-voltage microgrids	Simulation (PSCAD/EMTDC)	2011
	[179]	Biomass microgrid	Directional phase and ground over current	Simulation	2014
	[80]	Inverter Based	A communication-assisted strategy implementable with microprocessor-based relays	Simulation (PSCAD/EMTDC)	2012
	[180]	Meshed distribution systems with DG	Inverse time overcurrent relays	Simulation	2015
	[181]	Meshed distribution systems with DG	New time-current-voltage tripping for directional overcurrent relays	Simulation	2015
	[182]	Meshed distribution systems with DG	Dual setting directional overcurrent relays	Simulation	2015
	[183]	Microgrids with the grid-connected and islanded capability	Optimally setting directional overcurrent relays using the genetic algorithm	Simulation	2013
	[184]	MGs with the grid-connected and islanded capability	Optimal coordination of directional overcurrent relays based Cuckoo optimization algorithm	Simulation	2018
	[185]	Islanded Microgrid	A novel concept of using the central energy storage system (flywheel inverter)	Simulation (PSCAD)	2007
Modifying and Installing FCL	[71]	DGs	Implementation of FCL to locally limit the DG fault current without altering the original relay settings	Simulation	2008
	[186]	DGs	Hybrid type FCL connected in series	Simulation	2011
	[187]	looped microgrid	Simple overcurrent relays	Simulation and Experimental	2016
Harmonic based Protection	[150]	Inverter Based Islanded MGs	Total harmonic distortion (THD) monitoring relays based, intelligent device manager	Simulation	2008
	[159]	Inverter Based	Harmonic and Current Based	Simulation	2012
	[149]	Inverter Based	Harmonic based IDM	Experimental	2014
	[192]	Inverter Based Meshed MGs with DGs	Activate harmonic-based relays	Simulation	2018
	[193]	Islanded Microgrid	Harmonic footprint of short-circuit fault	Simulation and experimental	2018
	[194]	Islanded Microgrids with DGs	Synthetic harmonic current pattern injection	Simulation (PSCAD/EMTDC)	2020
	[195]	Islanded Microgrids	Utilize a third harmonic voltage generated by the Inverter-interfaced distributed generators.	Simulation	2021
	[196]	Islanded Microgrids with DGs	employing harmonic current injection capability of IBDGs to design a novel harmonic DOCR	Simulation (PSCAD/EMTDC)	2021
	[197]	Islanded Microgrid	Active protection scheme was suitable for microgrids with multiple	Simulation (PSCAD/EMTDC)	2021
	[198]	Without DG	Dead zone in the grounding electrode line of UHVDC transmission system was utilized	Simulation	2022
	[191]	Inverter Based	A harmonic injection-based distance protection method without revising the controller structure	Simulation (PSCAD)/ Experimental	2023
Adaptive Protection Scheme	[62]	DGs	Adaptive Real Fuse and Recloser	Experimental	2014
	[107]	Inverter Based	DOC	Simulation	2014
	[52]	DGs	Current	Simulation	2015
	[200]	SM and Inverter-Based	Adaptive OC	Simulation	2015
	[201]	SM and Inverter Based	Adaptive DOC	Simulation	2015
	[202]	SM Based	Adaptive OC	Simulation	2017
	[199]	Islanded microgrid	An autonomous control algorithm developed for the supercapacitors	Simulation	2017
	[203]	DGs	Adaptive DOC	Simulation	2018
	[204]	SM and Inverter Based	Adaptive Current and	Real	2019
	[205]	Inverter Based	Adaptive DOC	Simulation	2020
	[113]	Inverter Based	Adaptive IDM	Experimental	2020
	[178]	DGs	Adaptive Current Based	Simulation	2020
	[206]	SM and Inverter Based	Adaptive Current and Differential	Simulation	2020
	[207]	DG	Adaptive DOC	Simulation	2020
	[208]	Isolated MGs	An adaptive differential feature-based protection	Experimental	2020

TABLE 3. ***(Continued.)*** **Microgrid protection schemes categorized in the literature.**

	[209]	DGs	Decentralized adaptive protection Coordination using agents social activities	Simulation/ Experimental	2021
	[210]	DGs	A scheme used to handle DOCRs coordination problem in 7-bus and IEEE 33-bus MGs	Simulation	2021
	[211]	Inverter Based with offshore wind farms (WFs)	An adaptive droop-based hierarchical optimal voltage control was applied	MATLAB/Simulink	2021
	[212]	Inverter-Based DGs	The selectivity problem of OCR was discussed in depth	Experimental	2021
	[213]	DGs	A scheme for the future renewable electric energy delivery and management system used based on the convolution neural network	Simulation	2022
	[214]	DGs	Improved the scheme based on combined Centralized/Decentralized communications	Simulation/ Experimental	2022
Differential Protection Scheme	[54]	Solar energy and Wind Turbine	Differential Based Communication-assisted Digital Relays	Experimental	2009
	[52]	Inverter Based	Differential Based Sequence Component	Simulation	2013
	[215]	DGs/Wind Farms	Novel pilot protection based on cosine similarity	Simulation/ Experimental	2022
	[216]	Without DGs	Evaluating differential element performance, analysis of transformer inrush current, internal faults, external faults, and overexcitation conditions.	Simulation	2022

- ***Getting faster trips:*** The distribution network is typically connected to a robust grid. This resilient grid enables efficient electricity transmission throughout the network. Due to high fault current contribution and inertia, grid-connected systems have stable voltage/frequency. Riding through faults in DGs is more convenient than in islanded mode since overcurrent devices can quickly clear faults. In islanded mode, both a protection and a control system face challenges due to the absence of the main grid. However, in DG operation, the control system has the advantage of being unaffected by grid-related disturbances, thus making the operation more reliable. Short circuit power and system inertia are reduced as a result. A sharp drop in the short circuit level occurs when the main grid is absent. As a result, the speed requirement cannot be met with conventional protection methods, such as inverse time overcurrent. Effective fast protection methods must be developed to address this issue so the fault can be cleared before the DGs' frequency and voltage protection kicks in. Protection methods should be able to adapt to the current level regardless of it. To withstand long periods, DG FRT capability needs to be improved. These two approaches will enhance the microgrid's reliability and stability. Additionally, these improvements should be robust and account for contingencies, such as short-circuits and other abnormal events, to ensure the microgrid's reliable functioning further. To guarantee the microgrid's overall resilience and performance, protection methods should be developed to respond to any changes in the system. At the same time, DG FRT should be enhanced to allow for a greater functioning capacity.
- ***Grounding the transformer DGs in islanded mode:*** Interfacing transformers are usually used to connect distributed energy resources to the primary grid, so the grounding method of these transformers is significant. The microgrid will be islanded when utilities' grounding support for microgrids is disconnected. Transformers and DGs will ground the system primarily under these conditions. DGs and interfacing transformers must ground the microgrid effectively in islanded mode to prevent dangerous overvoltages. It is, therefore, necessary to consider a suitable interconnection transformer. To mitigate potential safety risks, selecting a transformer with an appropriate grounding connection between the microgrid and the utility is essential. The grounding connection should be carefully assessed, ensuring that the transformer is suitable to provide a safe and secure interconnection between the microgrid and the utility, thereby mitigating potential safety risks.
- ***Fault currents sensitivity before and during faults:*** The nature of renewable energy-based DGs, as well as microgrids, load shedding, feeder tripping, and changes in network design from radial to looped, results in abrupt changes in feeder currents and short circuit levels at the relay site, all of which result in sudden changes in magnitude and direction. These changes can lead to instability in the overall system, requiring timely and accurate relay protection and coordination. The fixed protection settings of overcurrent-based protection schemes cannot meet all operational requirements. These challenges are considered when developing MGs. MGs are designed to provide more precise and flexible protection schemes to ensure system stability, allowing

TABLE 4. Year, reference, country, name, title, and scope of standards.

Year	Ref.	Country	Standard ID	Title	Scope of Application
2000	[218]	International	IEEE 929	Recommended Practice for Utility Interface of PV Systems	PV ≤10 kW
2006	[219]	China	GB-T 20046	Photovoltaic (PV) systems. Characteristics of the utility interface	PV ≤10 kVA at low-voltage grid distribution
2009	[220]	Australia	IEC 61850	The Application-View Model of the International Standard IEC 61850	Logical Node application-view data model of the standard
2010	[221]	USA	UL 1741	Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources	DER connected to electric power systems
2010	[222]	Germany	BDEW	Generating Plants Connected to the Medium-Voltage Network	Generating Plants at MV and LV
2011	[223]	Germany	VDE-AR-N 4105	Power generation systems connected to the low-voltage distribution network. Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks	Power generation systems ≤100 kVA connected to low voltage
2011	[224]	Australia	IEC 61850 / IEC 61850-7-420	Distributed Energy Resources object modeling	Diesel Generators, PV, Fuel Cells, Combined Heat, and Power
2011	[225]	USA	IEC/IEEE/PAS 63547	Interconnecting distributed resources with electric power systems	DER ≤10 MVA
2011	[226]	International	UNE/EN/IEC 62109	Safety of power converters for use in photovoltaic power systems Part 2: Particular requirements for inverter	PV at ≤1000 V
2012	[174]	Australia	EC61850/IEC 61850-7-420	Distributed energy resource modeling in a centralized microgrid.	Two inverter-interfaced DGs and a diesel generator DG is used to set the frequency and voltage under islanded conditions.
2012	[227]	China	GB-T 19964	Technical requirements for connecting photovoltaic power station to power system	PV connected at HV, MV, and LV
2012	[228]	UK	G 83	Recommendations for the Connection of Type Tested Small-scale Embedded Generators (Up to 16A per Phase) in Parallel with Low-Voltage Distribution Systems	Small-Scale embedded Generators ≤16 A per phase at low-voltage distribution networks 230/400 V
2013	[229]	Spain	UNE 206007-1	Requirements for connecting to the power system. Part 1: Grid-connected inverters	Inverters connected to the public distribution network
2013	[230]	Europe	EN 50438	Requirements for micro-generating plants to be connected in parallel with public low-voltage distribution networks	Micro-generating plants ≤16 A per phase at public LV distribution networks 230/400 V
2014	[231]	India	Gazette of India Part III-Sec.4	Technical Standards for Connectivity of the Distributed Generation Resources	DER connected to the electricity system
2015	[232]	UK	G-59	Recommendations for the connection of generating plant to the distribution systems of licensed distribution network operators	Generating plants < 17 kW per phase or < 50 kW in three phases at the distribution system
2016	[233]	Australia / New Zealand	AS 4777-2	Grid connection of energy systems via inverters Part 2: Inverter requirements	Inverters at low voltage
2016	[234]	Australia / New Zealand	AS 4777-1	Grid connection of energy systems via inverters Part 1: Installation requirements	Inverters ≤200 kVA at Low voltage
2016	[235]	International	IEC 61850-7-420	Interoperability and interchangeability for microgrid protection systems	Relays and DGs modeled with communication modules
2017	[236]	International	IEC 62898-1	Microgrids—Part 1: Guidelines for microgrid projects planning and specification	AC electrical systems with loads and DER connected at LV or MV.
2017	[237]	International	IEEE P2030.8	Testing of Microgrid Controllers	Testing procedures of the different functions of the microgrid controller
2018	[238]	International	IEEE 1547	Standard for Interconnecting Distributed Resources with Electric Power Systems	DER at primary or secondary distribution voltage
2018	[239]	Ecuador	ARCONEL 003	Photovoltaic microgeneration for self-supply of final consumers of electric energy	PV systems ≤100 kW at LV or MV and, temporarily, ≤300 kW for residential use or ≤500 kW for commercial/industrial use
2018	[240]	International	IEC 62898-2	Microgrids—Part 2: Guidelines for operation	AC electrical systems with loads and DER connected at LV or MV
2019	[241]	Europe	CLC/TC 50549-1	Requirements for generating plants to be connected in parallel with distribution networks—Part 1: Connection to a LV distribution network—Generating plants up to and including Type B	Generating plants up to and including Type B at the LV network

TABLE 4. ***(Continued.)*** **Year, reference, country, name, title, and scope of standards.**

2019	[242]	Italy	CEI 0-21	Reference technical rules for the connection of active and passive users to the LV electrical Utilities	Active and Passive Users at distribution systems < 1 kV (LV)
2020	[208]	Australia	IEC-61850 and IEEE 13-node-based isolated MG.	Real-Time Adaptive Differential Feature-Based Protection Scheme for Isolated Microgrids Using Edge Computing	480 V line–line voltage, 50 Hz, three-phase balanced system (diesel generator, solar power, distribution lines, and two load banks)
2020	[243]	USA	IEC 61850 Protocol	Hardware in the Loop Testing of a Protection Scheme for Microgrid using RTDS	Two ac generators of 7.5 KVA, 60 HZ, 208 V
2020	[244]	International	IEC 62898-3-1	Microgrids—Part 3: Technical requirements - Protection and dynamic control	AC electrical systems with loads and DER connected at LV or MV
2020	[245]	USA	IEC 61850 GOOSE	Controller Hardware-in-the-Loop Testing for Seamless Transition of an MG Between Island and Grid-Connected Modes	MG in grid-connected mode and the inverter output at 0.0 MVA
2021	[246]	USA	IEC 61850	Performance Testing and Assessment of Protection Scheme Using Real-Time Hardware-in-the-Loop	Two ac generators of 7.5 KVA, 60 HZ, 208 V
2021	[247]	Europe	IEC 61850 GOOSE/ IEC 61499	Real-Time Hardware-in-the-Loop Testing of Logically Selective Adaptive Protection of AC Microgrid	0.5 MW wind turbine generators and a 1.5 MW diesel generator for a peak load of 1144 kW

TABLE 5. **The summary challenges for microgrids and DGs protection schemes.**

Scheme Type	Challenges
Overcurrent Protection Relay	▪ Non-Directional OC ▪ Network Challenges between the grid-connected and islanded mode ▪ Variable fault current level during grid connected mode islanded ▪ Increase fault current DC offset contributed by the renewable energy source
Distance Protection Relay	▪ Network Challenges between the grid-connected and islanded mode ▪ Increase fault current DC offset contributed by the renewable energy source ▪ The infeed current effects on the distance protection due to the penetration of the renewable energy source
Differential Protection Relay	▪ Dependent on communication channels ▪ Communication delay ▪ Increase fault current DC offset contributed by the renewable energy source
Fault Detection	▪ Low fault current ▪ The high impedance fault current coupled with low frequency harmonic and noise ▪ The high impedance fault exhibits random phenomena ▪ The high impedance fault attributes are influenced by the network configurations, and the natural environment condition

the necessary coordination of protection devices in all operating scenarios. Thus, MGs are designed to provide superior protection with precise and flexible settings, allowing for reliable coordination of protection devices in all operating conditions.

- ***Fault current characteristics of IBDGs:*** In conventional protection relays, faults are assumed to be caused by rotating DGs as far as overcurrent, distance, and directional elements are concerned. In contrast, IBDG fault current characteristics are determined by its control system and are significantly different from that of RBDGs. Because most fault currents originate from the primary grid, these characteristics may not be observable in grid-connected mode. However, these characteristics cannot be ignored in islanded mode with multiple IBDG sources. IBDGs impact the performance of protection systems and create the following challenges: ***(1) An overcurrent relay's sensitivity:*** During a fault, the IBDG behaves as a current source, in contrast to rotating-based DGs that behave as voltage sources. To protect the power electronic switches installed in the inverters, the maximum fault current is usually limited to around two times the rated current by the inverter control system. It is possible that the fault current contribution from IBDG may exceed the rating of a distribution line due to its fault current contribution. Thus, it is impossible or challenging to detect overcurrents. Because inverse time overcurrent relays are less likely to damage equipment due to their low magnitude, their operation may be slowed down or blinded due to the low magnitude of fault currents. Although it is still dangerous and must be cleared out for safety reasons. ***(2) Ground-fault voltage support:*** Under unbalanced faults, the IBDG voltage characteristic depends on the design of the control system. The grid code requires IBDGs to balance the inverter's fault contribution using current-controlled voltage sources. In this scenario, there will only be a positive sequence of contributions, which makes fault detection harder. Inverters may also overvoltage healthy phases because of their fast voltage control. This may cause sympathetic tripping of DGs and/or impact protection sensitivity. To avoid this, IBDGs should be designed with an overvoltage protection system to limit the voltage rise of healthy phases. ***(3) Directional element malfunctions:*** Due to some current characteristics of IBDG faults and in certain conditions, conventional directional elements may mis-operation. This can lead to false tripping of the relay, thus causing a power system fault. Special directional elements must be used to detect IBDG faults to reduce this risk. These elements should be combined with other protection elements to ensure reliable and safe operation. Therefore, it is necessary to carefully analyze how directional elements can be applied to the microgrids that IBDG dominates. ***Operation modes with multiple controls:*** the IBDG's behavior during a fault depends on the inverter's voltage or current control mode. Current IBDGs have poor control over their output voltage and depend on the grid they are connected to. Current-controlled IBDGs in islanded mode are vulnerable to voltage drops during grid absence, depending on another source's strength. Voltage-controlled IBDGs can regulate their voltage more easily in islanded mode but cannot control their current very well. This makes them unsuitable for use in larger microgrids. Additionally, they are limited to a low power rating, which further restricts their usage. As a result, they are vulnerable to overcurrent faults. Voltage-controlled IBDGs have a different protection requirement than current-controlled IBDGs; hence, adaptive protection may be needed when the inverters are operated in multiple control modes. In practice, microgrids contain several IBDG sources, each with fault characteristics and a control system. The interconnection of these sources can provide the microgrid with reliability and resiliency, making it possible to reduce outages and maintain continuity of service. A microgrid also allows for greater control and flexibility of energy sources, allowing an optimal balance between cost and performance. Protection system engineers often struggle to understand fault current behavior because IBDG manufacturers rarely share detailed information about their control systems. Therefore, microgrids can provide a more reliable and cost-effective alternative by allowing engineers to control the fault-current behavior of their distributed generation systems precisely. The Summary Challenges for AC Microgrids and DGs Protection schemes are presented in **Table 5**. This lack of information creates a challenge for protection system engineers, who must design systems that can effectively respond to the various fault characteristics of each IBDG source. This means that protection system design must be tailored to the unique characteristics of each IBDG source, requiring engineers to develop a thorough understanding of the specific requirements and characteristics of their IBDG source.

VI. FUTURE TRENDS IN PROTECTION SYSTEMS

Research gaps are highlighted along with future directions to help guide researchers. These future directions should guide what areas need further exploration to make significant advances in the field. Digital relays, communication capabilities, and supervisory software are part of the adaptive protection schemes discussed in this review. Microgrids in island mode may also be controlled and protected using PMUs and communication platforms. PMUs and IDMs will be used to communicate with modern digital protective relays to provide adaptive and intelligent protection in the future. Future protection designs, particularly in microgrids, must consider the time delay of communication links. In addition, developing adaptive systems that can be integrated with digital communication platforms increases the risk of cyberattacks. This technology provides hackers access to confidential data and the ability to control digital systems. As a result, businesses must protect themselves from these threats and ensure their systems are secure. The security of the protection system must be sufficiently high to prevent blackouts in the event of cyberattacks. Therefore, it is essential to develop robust cybersecurity strategies to counteract the risks posed by digital communication platforms and protect the confidential data of businesses from malicious hackers. To ensure the security of future protection systems, secure networks, and protocols must be implemented to prevent cyberattacks. As a result, cybersecurity needs to be further investigated. Future experiments should examine fault detection in a microgrid based on inverters and in islanded mode with and without a communication system. In terms of future research, the following topics are suggested:

- In the future, other directional comparison schemes, such as directional comparison blocking/unblocking and permissive underreaching transfer trip schemes, can be explored.
- It is possible to investigate protection solutions for distribution networks with very short lines and a large number of feeders and laterals.
- In distribution systems, automatic reclosing and fuse-saving schemes may be applied to the proposed methodology.
- The MV synchronous generators contribute relatively high fault current in islanded mode. In this way, it is possible to detect faults and, with the help of overcurrent protection, ensure enough sensitivity in its islanded mode and provide fault isolation. As a result, microgrids that are dominated by inverters have a more significant challenge in this scenario. In a future study, researchers will examine how directional comparison-based protection can be applied to microgrids dominated by in-line generators for distributed generation. Distance protection based on directional comparison schemes can be used for microgrids with inverter-based DG.

VII. CONCLUSION

A review of power systems and AC microgrid protection was presented in this paper. Protection systems must be reviewed to integrate distributed generation technologies into protection systems. Furthermore, protection systems must be continually adapted to ensure reliable power delivery and safe grid operations. The presence of a microgrid complicates power system protection. Besides, this study addresses the challenges and solutions associated with these issues. In blinding zones, it has been proposed to change the protective relay settings and replace the relays optimally to improve the relay performance. To ensure the desired level of performance, the proposed changes should be implemented carefully. As a result of the use of DOC relays, false tripping occurs in the presence of DGs. In the event of a fault, isolating distributed energy resources from the grid is essential to avoid further damage. Proper coordination between the protective relays and the distributed energy resources must be established to prevent false tripping. Moreover, the protection and control of a microgrid are complicated when it is islanded. There is also an impact on the recloser/fuse and short circuit level when a microgrid is present.

Moreover, several protection schemes have been proposed for the power system in the presence of a microgrid to prevent changes in its topology. Inverter-based microgrids in island mode have been investigated using a variety of protection schemes. Communications were the most common method used to protect microgrids on islands. However, modern protection schemes also rely on using distributed control systems, which are more reliable and efficient. It is expected that based on PMU measurements and intelligent protection systems, wide-area protection based on PMU measurements can resolve several future smart grid protection and control issues. Additionally, using artificial intelligence algorithms for fault diagnosis and wide-area protection could provide enhanced accuracy and effectiveness for the protection of microgrids. Through a microgrid with wide-area protection, we can protect the power system when needed, including the time it takes to collect, process, analyze, and trigger commands. This is especially important in the face of rapidly evolving changes in the modern power grid, which require faster responses to protect the overall system. This would improve system reliability, reduce downtime, and fasten grid restoration.

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