Review of Networked Microgrid Protection

Architectures, Challenges, Solutions, and Future Trends

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A review of Networked Microgrid Protection: Architectures, Challenges, Solutions, and Future Trends

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***Abstract*—The design and selection of advanced protection schemes have become essential for the reliable and secure operation of networked microgrids. Various protection schemes that allow the correct operation of microgrids have been proposed for individual systems in different topologies and connections. Nevertheless, the protection schemes for networked microgrids are still in development, and further research is required to design and operate advanced protection in interconnected systems. The interconnection of these microgrids in different nodes with various interconnection technologies increases the fault occurrence and complicates the protection operation. This paper aims to point out the challenges in developing protection for networked microgrids, potential solutions, and research areas that need to be addressed for their development. First, this article presents a systematic analysis of the different microgrid clusters proposed since 2016, including several architectures of networked microgrids, operation modes, components, and utilization of renewable sources, which have not been widely explored in previous review papers. Second, the paper presents a discussion on the protection systems currently available for microgrid clusters, current challenges, and solutions that have been proposed for these systems. Finally, it discusses the trend of protection schemes in networked microgrids and presents some conclusions related to implementation.**

***Index Terms*—Smart grid, networked microgrid, multiple microgrids, microgrid cluster, protection schemes, adaptive protection, real-time simulation.**

I. INTRODUCTION

NETWORKED microgrids (NMGs) are a particular case of microgrid clusters (MGCs), where a group of microgrids (MGs) is close to each other and physically interconnected by nodes in DC or AC. They have different voltage levels and can exchange energy between them and with a distribution system [1]. NMGs optimize the use of energy resources, guarantee system reliability, improve power quality management [2] and resiliency [3], [4], introduce more flexibility [5]–[7], and enhance the electricity grid availability [8], [9]. Therefore, it is expected that NMGs will be the essential components of future smart grids [5], [6], [10].

The interconnection of these MGs in different nodes causes frequent changes in the network topology [9], increasing the network fault occurrence and complicating the operation of system protection and the network [11], [12]. Furthermore, the challenges in operating individual or single MGs also extended to NMGs. These challenges include power flow bi-directionality, short-circuit current variation, and integration of several distributed energy resources (DERs). In addition, protecting NMGs requires the interconnection of single MGs at different voltage levels, multiple nodes, and higher short-circuit currents in the interconnection mode.

Protection schemes are used for the safety and reliable operation of MGs. Currently, some protection schemes use different conventional protection techniques that ensure the operation of MGs in different fault zones without communication systems. Conventional protection schemes are inexpensive and simple to use; however, they are efficient only for specific topologies and types of faults because of the dynamics and changing characteristics of MGs [13]–[16]. Other protection schemes use relays with optimization techniques [17]–[19], hybrid tripping characteristics [20], communication systems [21]–[24], and adaptive algorithms [25]–[28]. Furthermore, other protection technologies have been used, such as micro-phasor measurement units and superconducting current limiters [29], [30]. However, none of these include protection schemes for NMGs.

Protection schemes for NMGs have been recently suggested in the literature, as those presented in [31], [32]. Protection schemes for NMGs have been used to detect internal and external faults [33]–[35]. Other protection schemes use advanced algorithms to identify the system topology, operating conditions, fault current level [36], centralized adaptive protection with overcurrent relays [37], and multi-functional relays with communication and integration of protection settings [38].

The existing literature also suggests different protection coordination methods. For example, the authors of [39] discussed a method that uses clusters to reduce the adjustment group number for the adaptive coordination of overcurrent relays (OCRs) using a k-means clustering method. Protection systems that employ this coordination method may be able to work independently of the control center operation, achieving decentralized protection. The authors of [40] studied a protection coordination scheme that

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uses numerical directional overcurrent relays (DOCRs) with single and dual settings. They formulated the coordination as an optimization problem solved by the interior point method. The tests showed this scheme is an effective protection coordination system for this type of NMG.

Using different protection schemes for single MGs in different operation modes is effective. However, more work needs to be done on the scalability and security of networks that integrate multiple MGs with different architectures and interconnection devices. A recent report addressed the future needs for the design of NMGs [41]. They emphasized the need to design protection systems that provide core criteria to assure the security and coordinated performance of the NMG. Therefore, a suitable protection scheme for these systems will translate into more significant benefits for the interconnected networks of the future.

This paper presents a comprehensive review of various architectures and topologies applied to NMGs and their corresponding protection schemes. We also discuss the challenges and solutions recently considered in the literature and provide suggestions for future work. The rest of this document is organized as follows: Section II introduces the concept of multiple microgrids and their operating architectures. Section III discusses the challenges to their protection and the proposed solutions. Section IV discusses future trends, and Section V provides some conclusions.

II. NETWORKED MICROGRID

There are three types of interconnected MGs: Multi microgrid (MMG), MGC, and NMG. In [42], the authors define an MMG as a "higher level structure, formed at the medium voltage (MV) level, consisting of several low voltage (LV) microgrids and distributed generator (DG) unit connected on adjacent MV feeders". In [43], the authors define an MGC as "two or more electrically coupled microgrids controlled and operated in a coordinated fashion". These structures can improve reliability, stability, and power quality because of the connection of several DGs to the distribution system [44]. The MGC can be conceived as a subsystem of an MMG, where several MG are electrically coupled to form a cluster; these clusters can also be connected with another cluster made up of several MGs. However, an NMG is a particular case of an MGC and is define as "Interoperable groups of multiple advanced microgrids that become an integral part of the electricity grid while providing enhanced resiliency through self-healing, aggregated ancillary services, and real-time communication" [45].

An NMG can also be defined as "a system that contains a connection of two or more microgrids with the ability to exchange energy with each other and with a distribution system" [9]. These systems form a cluster of interoperable and interconnected microgrids that can operate with fixed or dynamic boundaries [46]. Fixed-boundary NMGs allow interconnection under normal conditions and require disconnection from the main grid under fault situations. On the other hand, NMGs with dynamic boundaries can be connected to a distribution feeder through a different point of common coupling (PCC). They can change the electric boundaries dynamically and organize the DERs and loads through a boundary switch.

NMGs are also different from hybrid microgrids (HMGs). HMGs combine AC and DC configurations, while NMGs can bring together several HMGs. NMGs also have clear advantages in their operation and implementation. They reserve and share energy in critical conditions, lower the chances of a system collapse, minimize emergency load-shedding requirements, and enhance overall system reliability [47]. Their hierarchical architecture improves grid operation flexibility while reducing control complexity [48], and they strengthen their resiliency in local and regional areas [4], [48].

Despite all these advantages, protection coordination is more difficult when multiple MGs are interconnected in different nodes and topologies, increasing the fault occurrence. Before addressing these challenges and offering potential solutions for these protection impacts, we must assess what architecture and topologies we can discover and predict. Next, we provide details on the architecture and topologies of NMGs.

A. Architecture and Topologies

There are three basic NMG architectures: serial microgrids on a single feeder, parallel microgrids on a single feeder, and interconnected microgrids with multiple feeders [49]. However, it is possible to analyze these architectures according to their constitutional electric form: AC, DC, or hybrid; their voltage level classification: low voltage (LV), medium voltage (MV), or MV/LV hybrid; and their phase-sequence constitutional forms: single-phase or multi-phase [50]. In [51], the authors classified, identified, and analyzed the different multi-microgrid architectures. They classified the MMG according to the interconnection of MGs, electricity transmission, and interconnection technology. In addition, they compared the architectures, their costs, scalability, protection, reliability, stability, communications, and the different business models for their implementation. According to them [51], future work on NMGs should consider different architectures with any interface technology and use both technologies (AC and DC).

In 2021, the NMGs were classified according to network formation [52]. a) Star-connected: MGs can be connected to a common bus to form a star network, and all the MGs are connected to the main grid through the common bus. b) Ring-connected: MGs can be connected to comprise a ring and share power with their neighbors. These are typically used in LV residential networks. Moreover, c) mesh-connected: similar to ring-connected NMGs, but they have additional redundant lines to avoid main loop failures, and they are typically used in MV and HV power networks.

In Fig. 1, Fig. 2, and Fig. 3, we can see the typical architectures considering the network formation, constitutional electric form, and voltage grade classification. Fig. 1 shows the star or parallel AC NMG architecture, Fig. 2 shows the interconnected or meshed DC-NMG architecture, and Fig. 3 shows the ring hybrid-NMG architecture.

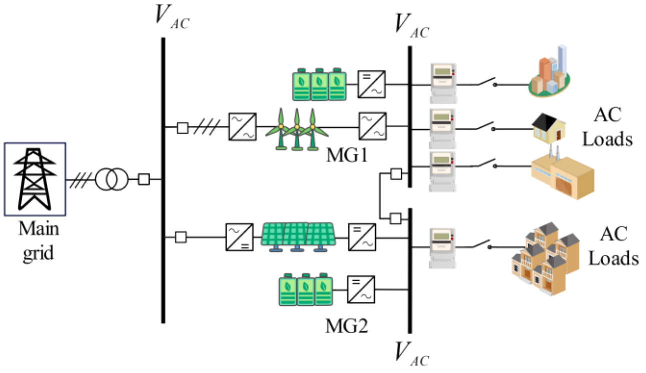

Fig. 1. Star or parallel AC NMG architecture.

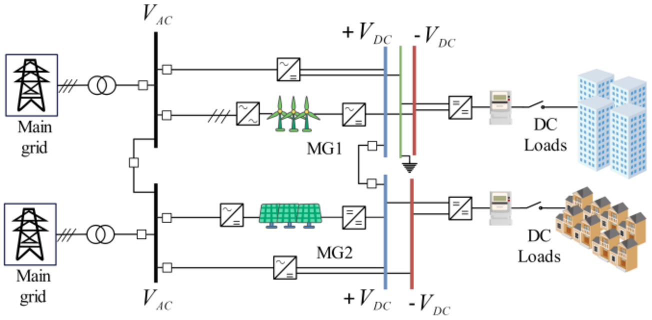

Fig. 2. Interconnected or meshed DC-NMG architecture.

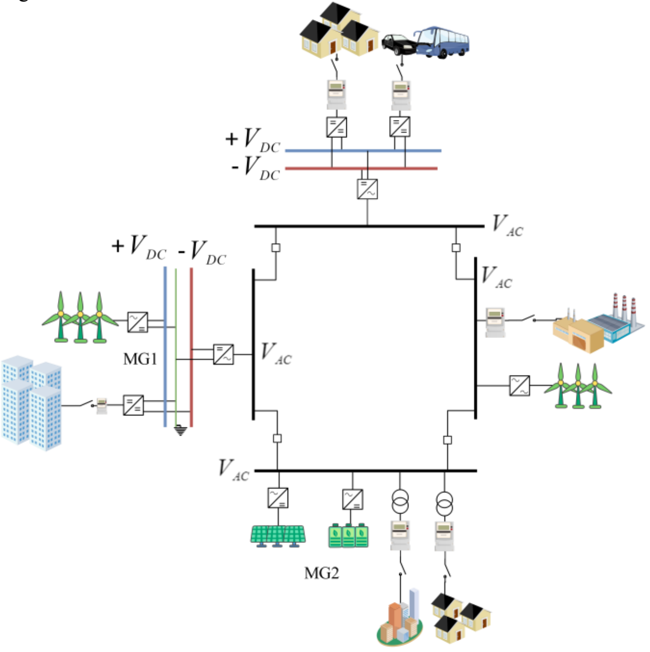

Fig. 3. Ring hybrid-NMG architecture.

Given these architectures, different topologies have been proposed. In [53], X. Zhou et al. proposed an autonomous coordination control strategy for an MG cluster structure. This MG cluster comprises AC and DC systems, multiple AC/DC converters, and DC converters. This cluster also includes a power exchange unit (PEU) and energy storage batteries, which are all connected to form an energy pool (EP). This model permits mutual power support among each MG, controls the voltage deviation, and improves the utilization of DERs.

A novel design for NMGs with hybrid AC/DC connections was presented in [54]. This model has a hybrid unit of common coupling (HUCC) for the NMG to achieve flexible integration and optimal use of DERs. In this design, four MGs were connected via AC lines to the distribution network and interconnected to each other via DC lines of the HUCC. This connection gives the structure higher control, asynchronous interconnection, major flexibility, fewer electromagnetic issues, and more DER integration capacity.

In 2019, the authors of [55] developed a simulation test system with a hybrid AC/DC microgrid in a grid-connected mode with a modified version of the IEEE-14 distribution model. Three different configurations are considered:

1) MG series configuration with a DC bus, where all the DER and loads are connected through converters.
2) MG-parallel configuration with an AC bus, where the generation system and loads are connected directly.
3) Switched configuration, in which DG or the distribution grid can supply the load, and the DC and AC MG are linked by two inverters.

This test system can be used to perform research on control strategies, test different protection schemes and isolated scenarios, and simulate the dynamics of the different sources. The authors indicated the need to develop real-time automated tools and use intelligent and adaptive protection in AC and DC.

In [56], S. Jena and N. P. Padhy presented a hierarchical distributed cooperative control strategy in a networked hybrid AC/DC microgrid cluster using a back-to-back converter. This model has sources, storage, and loads for each MG cluster. A back-to-back converter control (BTBC) is used to interconnect the AC and DC MGs. An interlinking converter (ILC) is used to exchange power between AC and DC MGs based on droop control. This structure can reduce AC/DC power conversion losses by providing different voltage levels for integrating the resources.

Furthermore, in 2020 [57], M. Cintuglu et al. created a framework for real-time implementation and experimental validation of the cyber-physical secured distributed state estimation (SDSE) for an NMG. The communication and interoperability architectures within each MG are established by IEC 61850 with DER data model extensions. Each MG service area has its own energy management system, protection relays, and DER controllers in this model. A supervisory controller for each DER assesses the connection status using an additional interface to IEDs through peer-to-peer (P2P) communications.

The communication between MGs is established using industrial grade 4G LTE routers, and the local measurement of data is collected from remote Terminal units (RTUs) and IEDs using IEC61850 GOOSE analog and breaker status messages. The model for this system was designed in MATLAB-Simulink/SimPowerSystem. In addition, the authors created a model of an NMG in a power-hardware in the loop configuration, physically representing the controllers, the electrical elements of the NMG, and the associated communication infrastructure.

In 2020, the authors in [58] explored the flexibility and resiliency of a multi-layer and multi-agent architecture to achieve P2P control of NMGs. This model is considered an

AC-NMG with multiple LV MGs, integrated into an MV network through LV/MV transformers. They also used a static transfer switch (STS) to isolate the NMG from the main grid. The communication system contains an upper-level communication network among MGs and a lower communication network among DGs within each MG. The results prove that the agents can work effectively in this environment and help to achieve the P2P architecture.

In 2021, the authors in [59] presented an autonomous and scalable energy management system architecture for NMGS using machine learning and cloud computing. The algorithm presented in this model solves the economic dispatch problem by considering the variable load and the power source changes.

In 2022, the authors in [60] presented a scalable and reconfigurable hybrid AC/DC MG clustering architecture with a corresponding decentralized control method to facilitate the networking of the hybrid AC/DC MG and to achieve flexible power coordination. This model comprises an energy network unit (ENU) that interfaces with the AC and DC sub-grids and the external power grid, forming the MMG.

In this design, only one common mainline is needed for AC power transfer in grid-connected mode and DC power transfer in island mode, which eliminates the complexity of the power networks and the line costs. This structure requires neither a master MG controller nor high-bandwidth communication links between the different controllers. This proposed architecture could improve the use of DERs and local energy consumption, achieving greater energy cluster compensation and consumption ratios and improving reliability.

Three different MGs are shown in Fig. 4's NMG structure: Village 1 (DC MG), Village 2 (Hybrid MG), and Village 3 (Hybrid MG). The AC node serves as the conduit connecting the hybrid MGs to the grid. Moreover, the DC Links connect the MGs to one another. The inclusion of a cluster of hybrid microgrids with a variety of generating sources (solar, wind, and batteries), as well as DC and AC loads, is a benefit of this topology. Similarly, it makes it possible to incorporate several transmission energy types into the same interconnection network and can decrease the losses in the distribution links using DC. The lack of standards and real-world implementation expertise that could specify the proper voltage level and operation management is one of this scheme's drawbacks. This is a schematic illustrative example, though, and it may be helpful to analyze it further to explain its advantages. For instance, it may serve as a test case to evaluate how the protection devices react to failures that happen internally and externally in various types of microgrids and in the distribution links, respectively.

Table I summarizes the topologies previously described.

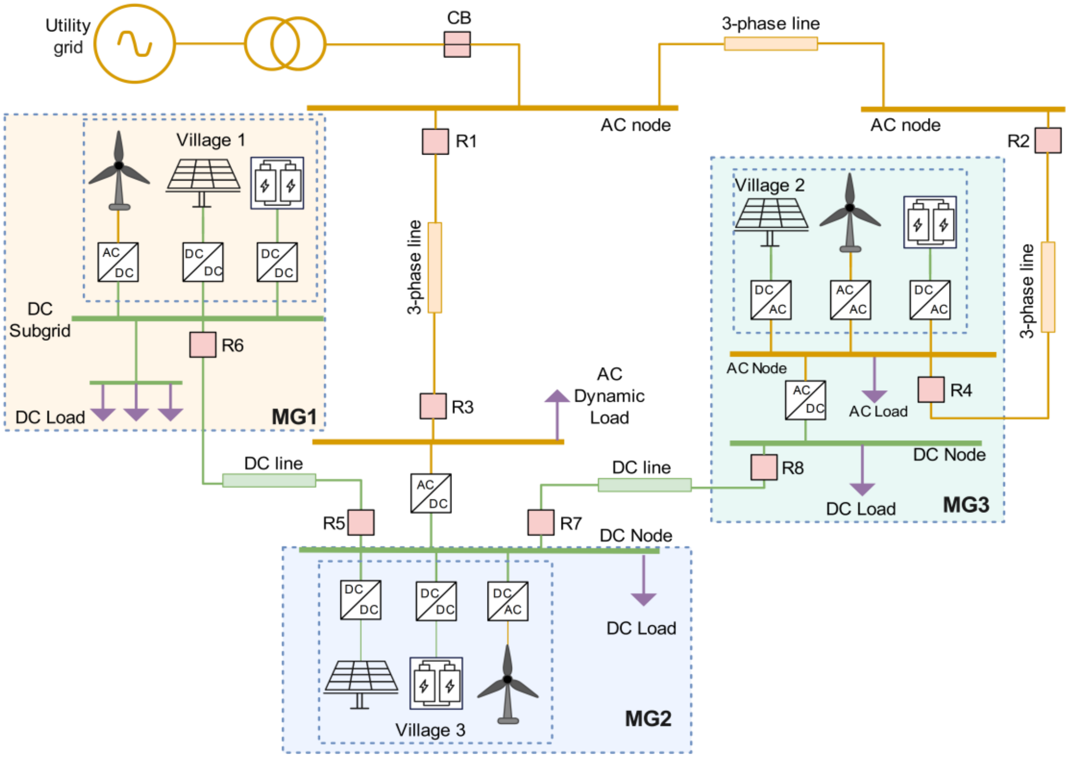

Fig. 4. Structure of the NMG.

TABLE I
SUMMARY OF THE NMG TOPOLOGIES

Topologies	Electric Transmission	Interconnection mode	Advantages	Reference
Meshed	Hybrid (AC/DC)	Interlinking converter.	Power support and Plug and Play.	[53]
Star	Hybrid (AC/DC)	Transformers/Power converters.	Higher control, Asynchronous Connection, Flexibility, and More DER integration capacity.	[54]

Star/Ring	Hybrid (AC/DC)	Transformers/Switches.	Benchmark for different studies in NMGS.	[55]
Star	Hybrid (AC/DC)	Interlinking converter.	Reduce Conversion losses, provide different voltage levels, and power sharing between clusters.	[56]
Ring	AC-NMG	Intelligent Electronics Device (IED)	Distribute implementation and physical model of NMGS in PHIL.	[57]
Star	AC-NMG	Transformers.	Peer-to-peer (P2P) control architecture, distributed and hierarchical network.	[58]
Star	Hybrid (AC/DC)	Transformers/Switches.	Cloud Computing Architecture Real-time energy management system.	[59]
Star	Hybrid (AC/DC)	Interlinking converter.	Decentralized control method, flexible power coordination AC/DC. Enhance system reliability and improve the use of local consumption of the network.	[60]

III. NMG PROTECTIONS: CHALLENGES, ADVANCED APPROACHES, AND SOLUTIONS

A. *Challenges*

There are still challenges associated with the protection of single MGs that have been addressed using different approaches, including intelligent algorithms, optimization, control techniques, communication systems, and intelligent equipment. The NMG complicates protection schemes because it must operate reliably for both the single MGs and the set of interconnected MGs, regardless of the type of topologies or architectures [61], [62]. In addition, they should be operating faster and with greater selectivity despite the diversity in the electrical transmission links (DC, AC, or AC/DC) and the interconnection technologies. Fig. 5 shows the general features that need to be considered for an NMG protection system.

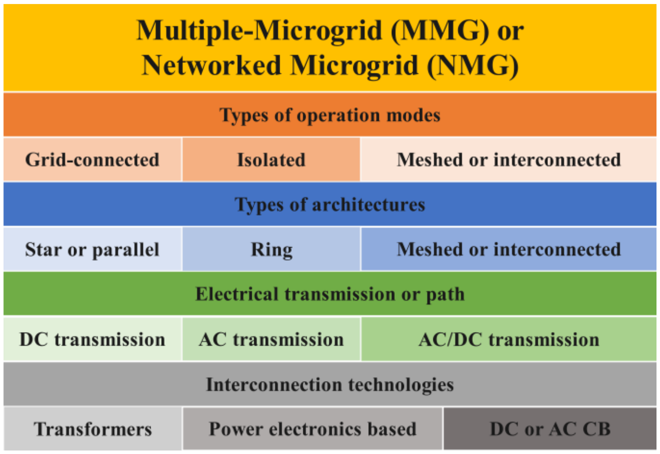

Fig. 5. General features of NMG's protections.

In NMGs, the fault current levels vary due to power flows from several MGs and DGs to the intermittency in the generation and the variable load demand [39]. It is also known that the fault currents in an NMG are higher than those in a single MG [63]. Therefore, it is challenging to design protection schemes that allow the interconnection of multiple networks immune to these changes [64].

The design process of NMGs and MGs could be complex [65]–[67]. The existing tools to design protection systems for NMGs are limited. There is no unanimity in the protection method used. The variability of size, distance, connections, sources, and location between MGs introduces many operational scenarios, independent variables, and protection schemes. The lack of a standard procedure for analyzing protections in NMGs also contributes to high implementation costs. While the DC-NMGs carry the issues of the single DCMG, like lack of phasor and frequency information, rapid fault rise, breaking DC arc, lack of standards, lack of design guidelines, and lack of practical experience [68]. The AC-NMGs need more comprehensive coordinated adaptive protection that can adjust the protection setting according to the operation mode [27].

The following section addresses the challenges of NMGs according to their interconnection system (operation mode), transmission type (direct current, alternating current, or hybrid), and interconnection technology (via inverters or transformers).

1) *Challenges According to the interconnection System*

Each MG that constitutes the interconnected system can have different DERs. That means each protection scheme is unique for each MG and configuration. The interconnections of these MGs require protection schemes that guarantee the isolation of the fault area and allow the supply of energy according to the type of interconnection or network formation. The bi-directionality of power flow, blinded protection, and unauthorized resynchronization are some challenges in NMGs.

The type of interconnection of the NMGs will play an essential role in the protection scheme. For example, in a star or parallel NMG, the operation of the system is similar to that of a traditional radial power system but with the added complexity of the bidirectional power flow. Therefore, the protection coordination is simpler and guarantees good selectivity. In addition, protection coordination is more complex for other interconnections of the NMGs and requires communications systems. For example, ring and mesh NMG architectures have several fault contribution paths and various short-circuit levels according to the topology, making it challenging to locate and isolate faults. Moreover, the complexity of their interconnections increases the implementation and operation costs.

The formation of the network in an NMG changes according to the operation modes [52]. The changes in the operation modes must be considered, and preplanning must be performed [1]. As a result, the design of a protection system (PS) is a challenging task as it must respond appropriately to faults in various topologies within the different scenarios [69], [70]. One issue is the variation in the short-circuit currents (SCC), which depends on the current configuration of the grid. For example, when the operation is in island mode, the magnitude of the SCC is too low [71], [72]. Another issue is related to the bidirectional power flows in the grid, where the operation of conventional protection schemes is not suitable, and the protections must be adjusted to the operating modes of the MGs [73]. Therefore, a communication or adaptive system is necessary to allow them to adjust to these changes.

One of the essential requirements to achieve a coordinated operation of NMGs with reliability, security, selectivity, and accuracy is to provide a proper protection coordination system [9], [40]. The protection coordination is also affected by unexpected changes in the network topology and the different power flow patterns [27], [46]. Different topologies are possible, and their frequent changes in the operation mode could impact the magnitude and direction of fault currents, causing the need to update the protection settings constantly. These continuous updates can cause some problems in protection coordination. Therefore, adaptive protection could be the best solution to these issues.

2) *Challenges According to the Electrical Transmission*

NMGs can be classified according to their transmission type as AC-NMG, DC-NMG, or hybrid-NMG. Next, we discuss the challenges according to operation: grid-connected, island, and multi-microgrid modes.

a) AC-NMG Challenges

For protecting AC-NMGs, the most notable challenges in the grid mode include:

(1) Faults tend to have high current levels, and arc flashes can be of considerable concern [74].

(2) Unwanted protection tripping can be caused by bidirectional power flows [75].

(3) Loss of mains between the main grid and the MGs [76].

(4) The protection equipment selection needs to consider a higher number of variables, such as the nature of the load, the variable fault current levels, different voltage magnitudes, and faster tripping ranges [76].

In the island mode, the most critical challenge is the low current contribution to the fault, which depends on the interconnection technology of the source and the number and type of distributed energy resources of each MG. Including different distributed generation sources in these systems causes substantial variation in fault current [77]. DGs can also cause problems such as blinding of protection, false tripping, and failed reclosing [37]. The penetration of synchronous DGs induces lower short-circuit currents that impact overcurrent relays and makes protection coordination difficult [78]. This limited short-circuit capacity will cause a notable drop in the fault current level of the MG [75]. Therefore, detecting the island mode operating condition is essential for correctly operating the protections [75].

The operation of traditional protection schemes fails in the multi-microgrid mode. The fault location and variable fault current characteristics are essential in developing an effective protection scheme in this operation mode. In the multi-microgrid mode, the fault current level is higher compared to a single microgrid or single grid-connected MGs [44]. The amplitude and the direction of the fault currents are constantly changing and can be quite different from each topology [1]. The variable fault current depends on the different control strategies of the inverter that interfaces each distributed generation [33], and whenever a fault occurs, disconnection of all DGs will make the operation of the MG impossible under the fault conditions [37]. Other challenges are the dynamic changes in topologies, unbalanced conditions, low voltage, low inertia, the detection of the NMG's points of connection, the high-cost technologies, the need for a highly reliable communication system, and the lack of standardization.

b) DC-NMG Challenges

For protecting DC-NMGs, the main challenges in grid mode are: i) the grounding issues, ii) the interruption of the current, and iii) the lack of natural zero-crossing current. In DC systems, grounding is necessary to detect faults. The issues in the grounding and the fault current amplitude reduction have a direct effect on the voltage sag and the value of the fault current [12], [68], [76]. The interruption of current in a DC system produces contact erosion of the circuit breaker (CB) and decreases the useful life of the equipment [71]. The lack of natural zero-crossing does not allow the AC-CB to extinguish the electric arc produced in the opening of an AC breaker [68], [79]. In a DC system, the rise in the fault current imposes a severe time limit on the fault interruption [68], and the uncertainties and varying topologies make the detection and diagnosis of the fault more complex due to the low fault current [80]–[82].

The challenges in the island mode are related to the change in fault current contribution and the detection of faults. Different fault characteristics, such as pole-to-pole and pole-to-ground faults, cause various fault current contributions. The location and characteristics of faults are critical in developing an effective protection scheme. In DC microgrids, fault detection is more complex because of the lack of frequency, phasor, and sequence components [81]. The relays must be set according to the fault current variations or consider an adaptive protection algorithm to solve this problem [83].

Locating the fault in a multi-microgrid mode is also a challenging task. The location of high impedance faults (HIF) and the accuracy of locating the faulty places in DC-NMG because of the distance between each DCMG and the use of underground cables could make quick system restoration and maintenance tasks more difficult after the faults [84], [85].

c) Hybrid-NMG Challenges

For protecting hybrid-NMGs in the grid-connected mode, the challenges are the following: i) the short response time of the DERs, ii) the unbalanced nature of the MG, iii) interlinking devices between the AC and DC nodes [55], and iv) location, modeling, and actions for the different faults for the hybrid systems. All of them need to be analyzed in an NMG [86].

In the island and multi-microgrid modes of a hybrid NMG, the protections will need to consider the challenges of the presence of both DC and AC. A multicriteria protection strategy is needed, considering the concentration of high loads [50], the different short-circuit current contributions [87], [88], the lack of natural zero crossing currents, the severe magnitude of the fault current, and the standard gaps in protecting DCMGs [61], the different voltage levels, the uncertainties in the power sources, and the behavior of the energy demand [47].

3) Challenges According to the Interconnection Technology

Each MG in an NMG can be interconnected using various technologies, including power transformers, power converters, and AC or DC circuit breakers (CB) or switches [89]. Next, we discuss the challenges of each of these interconnection technologies.

The interconnection requirements for using power transformers are less restrictive, cheaper, and most frequently used in traditional power systems, and they use mature technology and have lower protection requirements. However, they do not have the high controllability to integrate a higher number of resources and are sensitive to short-circuit currents, voltage surges, and undervoltage events [51]. Power transformers can tolerate a fault between 2 and 5 seconds and are protected through fuses or relay protection devices. The high penetration of distributed sources and the expansion of interconnected MGs increases the level of system fault current and the nominal value of the transformers and the protection equipment [1]. On the other hand, the interconnection through power converters needs a faster response than the transformer during a fault condition and requires more accurate protection. This technology is sensitive to overloads and has high protection requirements [51].

Power converter or inverter-based MG sources in an NMG limits the fault current contribution of each DG source in a microgrid to only two to three times the maximum load current [90]. The inverter-based MG system in an NMG would also have to overcome reverse power flow and different fault current contributions according to the interconnection technology that makes the operation of the protection devices slow or unresponsive in a fault event under different operation modes. Moreover, the DG sources in these systems have rapid dynamics, unbalanced nature, low capacity of energy storage, lack of inertia, and short response time; all these need to be addressed using effective protection schemes [55].

Alternatively, the interconnection between MGs in an NMG could be done through switchgear, such as circuit breakers (CB), contactors, and switches [89]. The NMGs involve different architectures and multiple components that increase the possibility of fault occurrence, and a proper selection of interconnection switchgear will be needed. Furthermore, electrical transmission (AC-DC) plays an essential role in switchgear selection. A DC system requires a reliable and fast protection system to ensure fault clearance and maintain safety for the rest of the system [12], and traditional CB for DC faults has the drawback of slow operation.

Fig. 6 shows the main challenges discussed in the literature. All these difficulties demonstrate the need for more research into NMGs to implement them and lower their operating costs. Tables II, III, and IV summarize the challenges found in AC, DC, and Hybrid-NMGs, including references discussed in the literature.

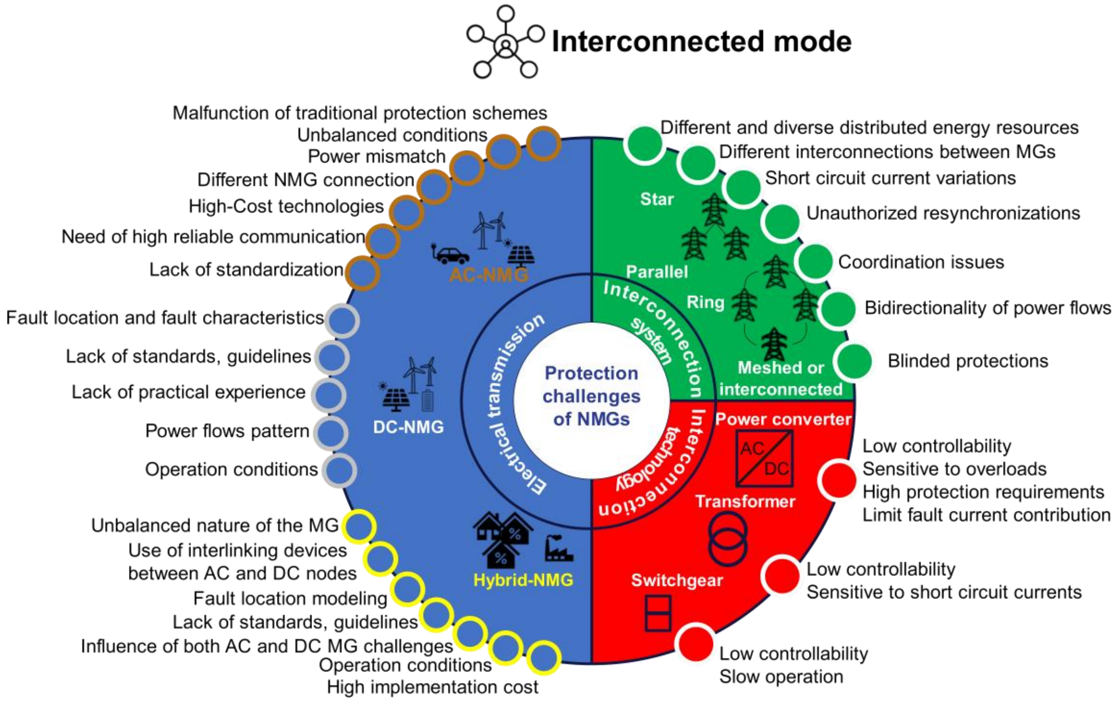

Fig. 6. Main challenges for protecting NMGs.

TABLE II
CHALLENGES IN AC-NMG PROTECTION

Operation modes	Challenges	References	Description/Consequences
Grid-connected	High-current levels.	[74]	Low source impedances and very high fault current availability. The faults need to be isolated from both sides. Arc flashes concerns.

	Selection of the protection equipment.	[76]	Proper selection considering fault current level, voltage magnitude operation, speed range, and nature of the load.
	Loss of mains.	[76]	Loss of direct connection between the utility grid and either the microgrid or the multi-microgrid.
Island	Low-fault current contribution.	[9], [75], [76], [90]	Changes in short circuit levels and the fault current contribution of inverter-based resources (IBRs). Slow operation or potential failure in the operation of the protection. Drop in MG fault level.
	Bidirectional power flows.	[75]	The paths of the power flows are bidirectional. Loss of protection coordination. requires different protection strategies.
Multi-microgrid	Malfunction of traditional protection schemes.	[76]	Reclosers and fusers may not provide sufficient protection coordination. Misoperation of protection relays. Bidirectional power flows.
	Unbalance conditions and power mismatch.	[75]	Imbalance between energy supply and demand, low inertia, and transition between different modes of operation.
	Detection of the NMG connection.	[72]	Dynamic Changes in the network topology. Several connection statuses of the PCC.
	High-cost technologies.	[75]	High cost of protective devices/technologies.
	Need for highly reliable communication.	[75]	Reliable communication links and fast processing units. Prior knowledge about MG.
	Lack of standardization.	[75]	The plug-and-play interaction of various components in the grids requires proper standardization regarding implementation.

TABLE III
CHALLENGES IN DC-NMG PROTECTION

Operation modes	Challenges	References	Description/Consequences
Grid-connected	High-current levels	[82]	The fault current levels exceed the nominal rating of the existing CB. Loss of coordination.
	Lack of phasor and frequency information.	[68]	Difficult to detect and locate faults.
	Rapid faults current increase.	[84]	Strict time limits for fault interruption. Damage in the cluster components
	Breaking the DC arc and interrupting the current.	[79], [83]	Contact erosion of CB. Decreased lifetime of the device. Fire hazards.
	Grounding issues.	[12], [68], [81]	Voltage sag and different values of the fault current. Difficult to detect the PG fault. Personal and equipment safety issues. Corrosion triggered by leakage current. Increase stress on different components. Lack of service reliability and continuity.
	Lack of natural zero-crossing current.	[79], [83]	Cannot eliminate the arc in the breaker opening. Expensive and slow solutions.
	Uncertainties and varying topologies in an NMG.	[83]	More complex fault detection. Changes in the direction of the fault.
Island	Fault current contribution	[68], [76]	Direction and nature of fault current. Variation in short circuit level.
	Fault detection.	[68],[80], [81], [82]	Low fault current. Unchanging in the current direction at fault inception angle. High uncertainties and varying topologies of microgrids. Rapid increase of the fault current.
Multi-microgrid mode	Fault location and fault characteristics.	[84]	Change in the amplitude and direction of fault currents. Variable fault current due to different control strategies of inverter interfaced generations.
	Lack of standards, guidelines, or practical experience.	[68], [76]	Lack of guidelines and well-defined protection standards. Lack of practical experience.
	Power flows pattern.	[81]	Circulating current may flow between the storage devices and VSC. Power oscillations of renewable sources. Power balance fluctuation.
	Operation conditions.	[81]	Reduced stability margins. High build-up current and peak magnitude. Need for a quick fault detection scheme.

TABLE IV
CHALLENGES IN HYBRID-NMG PROTECTION

Operation modes	Challenges	References	Description/Consequences
Grid-connected	Different fault current levels.	[71]	Variability of sources. Generation intermittency. Slow and failure in the operation of the protection.
	Variable load demand.	[71]	Unreliable operation. Load-shedding.
	NMG protection planning and design.	[65]	Many independent variables. Different sizes and types of connections of MG.
	Unbalanced nature of the MG.	[71]	Uncertainties in the power sources and the energy demand behavior.

Island and Multi-Microgrid	Use of interlinking devices between the AC and DC nodes.	[55]	Variability of distance location between MGs.
	Fault location, modeling.	[71]	Analysis and actions to take according to the type of fault. Low short circuit currents.
	lack of standards, guidelines, or practical experience.	[76]	Current solutions of single-MG have not been scaled to multiple microgrids. Lack of standard procedures.
	Influence of both AC and DC MG challenges.	[71]	High loads. Different contributions to the short-circuit current. Lack of natural zero crossing current. Severe magnitude of the fault current. Standard gaps in the protection of DC- NMGs.
	Operation conditions.	[86]	Different voltage levels. Variability of size. Variability of connections. Many operational scenarios.
	High implementation cost.	[88]	Need communication infrastructure.

B. Advanced Protection Approach and NMG Protection Solutions

Conventional protection schemes in NMG may cause transient incidents and loss of selectivity coordination [91]. On the other hand, communication-based protection schemes, such as adaptive and wide-area applications, are challenging to design or implement, have high implementation costs, and require secured communication systems and an extensive communication infrastructure [92]. Furthermore, protection schemes using intelligent computer approaches like artificial neural networks (ANN) or machine learning (ML) might experience latencies or data loss due to the high information processing speeds.

Advanced protection schemes for NMGS also require coordination strategies that optimize many variables, making protection coordination more complex. Nevertheless, advanced protection techniques are considered the best answer for NMGs. The following section discusses advanced protection methods and solutions suggested in the literature to address some of these issues.

1) Communication-based Protections

The fast, discerning, and dependable operation of MG protections is made possible by communication-assisted digital relays and communication protection schemes based on IEC 61850. These include the generic object-oriented substation events (GOOSE) message standard and the sample value messages (SVM). Unlike the first, the second makes network topology-based adjustment decisions [91].

The authors of [93] presented a protection that is “topology-agnostic, scalable, self-healing and cost-aware,” which works in the presence of high penetration of inverter-based resources (IBRs). This scheme protects both: grid-connected and island modes. The microgrid is divided into multiple zones separated by breakers, and the protection is designed using GOOSE messages with the IEC-61850 communication protocol. Zonal protection is designed for one zone, which sends GOOSE messages to trip the breakers and to identify the fault if there is a change in the current direction. This scheme also includes backup protection that could open or close other breakers to isolate the fault without affecting the operation of the whole area.

Next, we review two communication-based protection schemes, adaptive protections, and wide area protections.

a) Adaptive Protections

Adaptive protection is a set of steps or functions using communication protocols that allow changing protection settings according to the system requirements.

There are two types of adaptive protection: centralized and decentralized. Centralized adaptive protection incorporates all the information status of the DG units and circuit breaker status through centralized control, which is located at the point of common coupling (PCC). Under the status of the DG units, the protection equipment will update its settings to detect any faults. In decentralized adaptive protection, the decision-making and information analysis is done locally in the DG or IED units. This protection must detect changes in the system operation and modify the settings locally to respond and isolate the fault [94].

Adaptive protections are suitable for faults during island or grid-connected modes and can effectively address communication problems, low fault current, loss of coordination, and other problems according to the modification of the microgrid characteristics [95]. However, they need extensive communication infrastructure and may fail in looped MGs [92].

Due to the low fault current levels in the islanded mode, protection coordination in adaptive protection schemes is one of its challenges. This problem might be resolved with the help of AI and ML technologies [96]. The authors in [97] propose an online adaptive protection scheme by using fuzzy logic and Genetic Algorithm (GA). The GA resolves the network's coordination issue concerning its overcurrent relays, and the fuzzy logic rule determines the topology of the network and the best set of parameters for each topology. Using the benefits of AI, this security method makes use of synchronized information. The communication problems with this type of approach require further research.

In [37], the authors presented a new centralized adaptive overcurrent protection scheme with an inverse definite minimum time (IDMT) overcurrent relay for multi-microgrids to isolate the faulted section. The scheme has a central controller (CC) and an MG central controller (MGCC) that monitor the current levels at the PCC and the power flow directions from different DGs, establishing the thresholds for each relay. The results show that the proposed scheme allows faster tripping times compared with other studies and allows the operation of the healthy sections for different NMG topologies.

Most adaptive protections have been implemented in single MGs. It would be beneficial to consider using intelligent computer approaches such as the ANN-based, metaheuristic, or fuzzy and multi-agent approaches when implementing these to NMGs [72]. Additionally, adaptive protection for NMGs will need to include online relay coordination algorithms [75]. Adaptive protections indeed constitute good options for NMGs as they consider dynamic changes in the status of DGs and CBs for relay settings, operate faithfully in all conditions, and enhance the reliability of overcurrent protection in DC-MGs [98], [99]. Some examples of the implementation of adaptive protections are discussed next.

The authors in [100] considered an adaptive protection system using a neural network technique (convolution neural networks (CNN)) and a metaheuristic optimization algorithm (gorilla troops optimization (GOT)) to detect, classify, and locate the faults. The current and voltage measurements are transformed into images the protection system uses to evaluate the variation in the operation mode, topologies, load, and DG penetration. The authors show that integrating the CNN and GOT techniques effectively detects, classifies, and locates feeder faults in the proposed NMG model. In [36], three new protection algorithms were introduced to identify the system topology, the operation conditions, and the fault current level in an AC-MG. This adaptive protection was applied in active distribution networks with large penetration levels of inverter-based DERs.

The authors in [101] used a machine learning technique, support vector machine (SVM), to estimate the circuit topology in an adaptive protection system. In this system, the IEDs first estimate the status of the circuit breaker and tie lines and then identify the circuit topology. The authors in [102] used a modified version of the original IEEE 13-node test system as a single MG. To identify the fault location and clearance, they used an adaptive protection center (APC), implemented with the Arduino AT Mega 2560 and connected to the internet with an Ethernet Shield: WIZnet W5100. In addition, they used a remote system via the Internet of things (IoT) to monitor the system status and load characteristics. This solution was used in individual MGs. However, it must be evaluated in NMGs or more extensive networks.

The authors in [103] considered a decentralized adaptive scheme using agent systems for MG protection coordination with uncertainties in its operation and its topologies. This protection strategy used an online decision-making process composed of a group of agents near the fault location to negotiate with one another the best protection coordination strategy in the event of multiple faults. The offline settings stored in the agent's memory were used for protection coordination. This approach is useful for various faults and does not necessitate using an offline database. This solution can also clear simultaneous faults, and it does so by utilizing a wide variety of agents. It should be interesting to apply these strategies to NMG and demonstrate them in an experimental model to evaluate its performance.

In [104], the authors implemented a framework for evaluating the impact of operational uncertainties on an MG centralized protection scheme, such as communication latency and the magnitude and duration of the fault current. Reliability indices, including the System Average Interruption Duration Index (SAIDI) and Expected Energy Not Provided (EENS), were obtained using a Monte Carlo simulation algorithm to assess the protection scheme's reliability. They employ a hybrid simulator framework that considers both MATLAB and the Java Agent Development (JADE) platform to evaluate the effectiveness of this approach. Real-time communication link performance was simulated in JADE, while the MG model was created in Matlab.

The authors in [27] developed a digital coordinate adaptive protection scheme for an AC microgrid. This method uses various digital protection devices (PD) with different protective modules. i) Directional over-current relays (DOCR) to protect the PCC and the feeders. ii) Differential current-based relays (DFRs) to protect the lines. iii) Communication-based and local trip commands to protect the DG units. Additionally, they used adaptive protection coordination involving both offline and online steps. In the offline stage, they adopted various settings for the protective modules. When doing the online calculation, they identified any system changes and executed a new set of settings for each protective device. As a result, under various fault scenarios, reliable, selective, and coordinated protection was created. The latter five have not been implemented in NMGs. However, they could potentially be extended to these.

b) Wide Area Protections

Wide-Area Protection Systems (WAPS) is an advanced protection strategy often used with conventional protection devices. These protections use phasor measurement units (PMUs) to detect and localize line faults in a shorter and more accurate time. They provide flexible relaying schemes, fewer load-shedding events, and well-coordinated control actions. This protection system can manage disturbances or outages and offer adaptive relaying in collaboration with local protective devices [105]. Integrating wide-area protections in an advanced system provides capabilities for monitoring and coordinating different protection devices and performing complex protection algorithms. This system also provides a high-speed wide-area communication network [106], [107]. A global cloud-based framework for a wide area is a solution for large deployments of smart devices and protection equipment in NMGs [108].

Next, we discuss protection schemes using intelligent computer approaches, coordination strategies with optimization techniques, and other tools or new devices used in NMGs.

2) Computer-based Intelligent Techniques

Digital relays have enabled more advanced protection systems that use machine learning tools and digital signal processing methods [69]. The most popular machine learning tools used in protection systems are support vector machines (SVM) and artificial neural networks (ANN). Applying these techniques for protecting NMGs provides fault detection in the island and grid-connected microgrid modes and decision-making about the changes in the protection settings according to the network topology.

A fault location method using SVMs for DC-NMGs was discussed in [84]. This method uses a current sensor located at one end of the faulty line. The fault and fault features are applied to the SVM to detect high-impedance faults (HIF). The results indicate that this method is more accurate than other methods for these types of faults. Furthermore, it has the advantage of being communication-free, which lowers costs and improves fault location accuracy. Future work with these methods should address applications in other topologies and architectures of the NMGs and use other variables, such as voltage waveforms.

3) Coordination Strategies with Optimization Techniques

The main goal of an optimization technique in protection coordination is to evaluate the best coordination and the best settings for the chosen protection strategy [109]. Additionally, with optimization techniques, protection can turn off generators and optimize energy usage [77]. Some optimization techniques used in NMGs include heuristic and metaheuristic algorithms such as particle swarm optimization (PSO) and grey wolf optimization (GWO) [110]. Other techniques are linear and quadratic programming [111] and multi-agent systems [52].

Different authors have examined various optimization strategies for microgrid protection coordination and adaptive protection. The authors in [110] used an optimization algorithm that imitates the hunting mechanism of gray wolves (GWO) to achieve the coordination of the DOCRs in an AC-MG. In [111], the authors proposed protection coordination for an adaptive relay with optimal settings, integrating two optimization methods: nonlinear programming (NLP) and PSO. In [112], the authors presented a coordination scheme for MGs that uses a rate of change of fundamental voltage (ROCOV) relay and the NLP optimization method. The proposed coordination scheme is not affected by the short-circuit currents variation or the network topology changes. The authors in [70] proposed an efficient protection coordination scheme for NMGs using numerical directional overcurrent relays (DOCRs) with single and dual settings. An interior-point algorithm was used to solve the protection coordination problem.

The authors in [75] reviewed reliable coordination strategies based on advanced optimization algorithms (AOA) for AC-MGs. Their review includes ant colony optimization (ACO), cuckoo optimization algorithm (COA), PSO, genetic algorithm (GA), and teaching learning-based optimization (TLBO).

Related work in NMGs is [113], where the authors used a stochastic programming model, the Bender decomposition, to design a strategy that examines in real-time the island mode of the NMGs. They also used a deterministic mathematical model, the analytical target cascading (ATC) model, to achieve a decentralized operation schedule for each MG and to detect the mismatches between the load and the power generation in the island operation mode. This combination results in a reliable NMG.

4) New Devices and Tools

A protection scheme for NMG using fault current limiters (FCL) was recently proposed [114]. The authors solved the operational problems of changes in the level and direction of the fault current and provided one set of directional overcurrent relay (DOCR) settings valid for the different operation modes in an NMG using FCL. This solution limits the excessive fault currents without requiring extra communication infrastructure. The protection coordination was formulated as an NLP problem and solved using a hybrid optimization approach with appropriate protection coordination time. They used this method both in series and parallel architectures and implemented HIL to validate the performance of the protection scheme. The use of this solution in different NMG structures, such as a hybrid NMG, must be validated. The adaptability and plug-and-play capabilities of the NMG must be assessed using these tools.

M. A. Yaqobi and colleagues in [12] used a bidirectional semiconductor breaker insulated-gate bipolar for isolated DC-NMGs. This circuit breaker can quickly interrupt the short-circuit current to maintain the DC-MG’s operation. The authors in [115] presented another solution combining control strategies with protection schemes for DC-NMGs. In this solution, voltage source converters (VSC) of DC/DC regulate the instantaneous power transfer and cancel the interactions between the interconnected DC microgrids. They used a protection scheme based on Fuzzy Inference Systems (FIS) for faster fault detection. This scheme requires high-speed communication and synchronization. It would be ideal for testing this solution in hybrid MMGs under different topologies.

The authors in [116] designed a microgrid testbed for protection and resiliency using a real-time digital simulator (RTDS) platform. They studied different protection schemes and communication delays for real-time operation and validated their performance using hardware in the loop (HIL). This testbed was performed in the IEEE 13-node distribution system, focusing on inverter modeling and inverter behavior during faults.

Another real-time HIL test of adaptive protection for AC-MGs was proposed in [117]. In this test, the authors evaluated the performance of an adaptive protection algorithm with a centralized control using GOOSE messages in a radial AC-MG. They found that Ethernet communication helped achieve fault detection, isolation, and adaptive settings. Fig. 7 and Fig. 8 present the evaluation of different solutions for protecting NMGs regarding reliability, selectivity, speed, sensitivity, economics, simplicity, and scalability.

We established a classification system based on each property's key characteristic. Reliability also includes dependability and security, and the key characteristics to consider for the NMG protection solution should be the capability to protect different models, the use of communication infrastructure, the computational burden, and cybersecurity. We chose two features for selectivity: fault detection, classification, and location capacity, and detection of internal and external faults; for speed, coordination optimization performance and sampling time; for sensitivity, the ability to protect the system in various operation modes and the fault detection for the smallest fault levels; for economics, the solution's investment cost; and for simplicity and scalability, the capability to be easily implemented. We used the findings and recommendations from the literature study to evaluate each of these items, assigning a score of 1 to the item with the lowest score and a score of 5 to the item with the highest score.

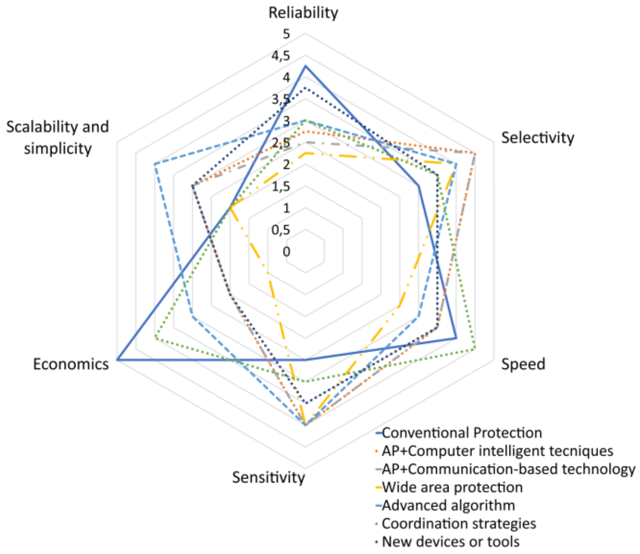

Fig. 7. Evaluation of solutions for AC-NMG protection.

We can see that while protection schemes based on communication and intelligent algorithms are scalable, selective, sensitive, and reliable, traditional schemes are cheap but not very scalable. As a result, when choosing a protection scheme for NMGs, these properties should be considered.

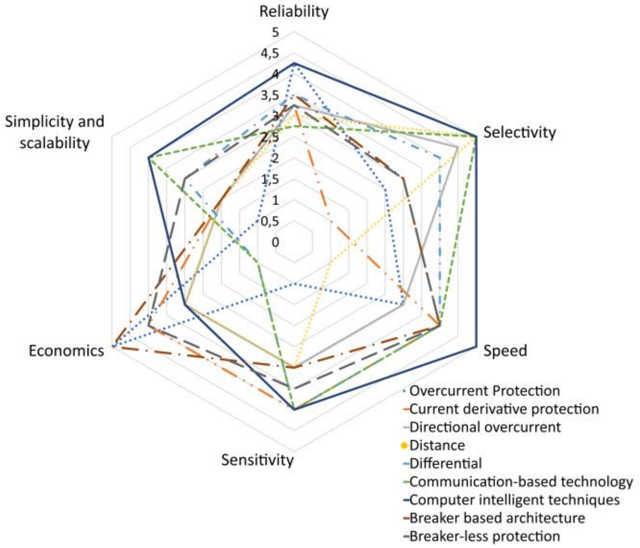

Fig. 8. Evaluation of solutions for DC-NMG protection.

Tables V, VI, and VII show important references for applying advanced protection strategies based on interface technologies AC, DC, and AC/DC NMG.

TABLE V
ADVANCE PROTECTION APPROACHES FOR AC-NMGS

Item	**Reference**
Conventional protection	[16], [33], [37], [63],[112], [118], [119]
Adaptive protection and Communication-based technology	[7], [23], [24],[27],[70],[78], [100],[101],[120],[121],[122], [123], [124],
Wide area protection	[107]
Advanced algorithm	[36],[125][126]
Coordination strategies with optimization techniques	[40],[127],[128]
New devices or tools	[114]

TABLE VI
ADVANCE PROTECTION APPROACHES FOR DC-NMGS

Item	**Reference**
Conventional Protection	[34]
Adaptive protection	[129]
Advanced algorithm	[130],[115],[84]
New devices or tools	[12],[131],[132]

TABLE VII
ADVANCE PROTECTION APPROACHES FOR AC/DC-NMGS

Item	**Reference**
Adaptive protection	[133]
Advanced algorithm	[19],[86],[134]
New devices or tools	[135]

C. Protection Standards

Currently, the protection of single MGs and interoperability of MGs are guided by national and international standards. The use of MGs has led to the continuous development of these standards. However, it is worth noting that there are no specific standards for protecting NMGs. However, it is critical to provide a sustainable, reliable, and safe energy market for NMGs, and to develop standards to improve protection-related NMGs' design, communications, and operations. Next, we discuss the current standards applied to the design, communication, and operation of protections for single MGs.

1) Protection-related Design Standards

There are two standards for the design of protections of MGs, the IEEE Std 2030.9-2019 and the IEC TS 62898-3-1:2020 [136]. A third standard, the IEEE P2030.12/D1.4, is still in draft. As stated above, no standards are developed for the design of multiple MG protections.

a) IEEE Std 2030.9- 2019 IEEE Recommended Practice for the Planning and Design of the Microgrid.

This guide provides a method for the internal design and external connection and best practices for implementing typical AC MV MG protections. This standard recommends and explains the type of protection used for the busbar and feeder on both the utility and the MG sides and the PCC, power source, and distribution transformer on the MG side. This standard does not consider the interconnection of multiple MGs and the possibility of having different operating topologies or various types of electrical transmission (AC-DC or hybrid).

b) IEC TS 62898-3-1:2020 Microgrids – Part 3.1: Technical Requirements – Protection and Dynamic Control.

This standard was developed by the International

Electrotechnical Commission (IEC) to cover the requirements for AC MG protections, specific protection systems, and dynamic control issues in MGs. This guide addresses the specific challenges for protecting the systems of non-isolated and isolated MGs. It introduces different approaches for short-circuit protections (overcurrent, directional overcurrent, distance, differential), system protections (under/over voltage protection, frequency protection), and communication-based protections (centralized protection systems) [137]. Extending this standard to the decentralized and advanced protections for interconnected MGs is a great opportunity.

c) P2030.12 Guide for the Design of Microgrid Protection Systems.

A standard draft was published on June 28, 2022, [138] and its final version is expected to be approved before December 2022. This standard will cover the design and selection of protective devices and the coordination between them for different operation modes (grid-connected and island modes and during the transition between modes). The standard includes communication-based protections (centralized and decentralized) and other protection types [136]. This guide does not consider the protection of NMGs, but extending it to this framework would be ideal.

2) Protection-related Communication Standards

a) IEC 61850 – Communication Networks and Systems in Substations

The IEC 61850 is an international standard for communication in substations, which enables high-speed automated protection applications across different zones (process, field, and station) in a smart grid architecture model (SGAM). This standard integrates the protection, control, measurement, and monitoring functions of the smart grid architecture [139]. IEC 61850 covers all communication-related aspects inside substations for automation and protection. More recently, working groups in IEC TC57 have extended IEC 61850 to include DER for communication between both ends of line protection [140]. The common data model used in IEC 61850 promotes smooth communication among DERs and NMGs. As a result, adaptive and decentralized protections for NMGs could be easily implemented using this standard and the IEC 61850 standard [117].

b) Other Standards for Sub-Networks

In NMGs, it is necessary to identify the different subnetworks that form the communication architecture. Types of subnetworks include the Field Area Network, the neighborhood network, the inter-substation networks, the intra-substation networks, the wide area network, and the metropolitan area network. Standardized communication technologies are used within different subnetworks and between them for interoperability. Fig. 9 presents the mapping of a communication network and standardized communication technology in SGAM [141]. The yellow highlighted is the protection-related communication network in a microgrid and NMG. For the mapping details, please refer to [141].

3) Protection-related Operation Standards

Protection requirements are different depending on the operation modes. In island mode, the protection should disconnect the faulty portion of the microgrid with the minimum disruption to the loads, while in grid-connected mode, the protection should be coordinated with the utility network protection to minimize the network impact [142]. The protection of NMGs should also consider the impact on the interconnected MGs. Therefore, the standards for MG control, testing, application, and interconnection, such as the IEEE 2030.7-2017 and the IEEE 2030.8-2019 [143], could also be used to guide the implementation of the protection in MGs and NMGs [136].

IV. FUTURE TRENDS IN THE PROTECTION OF NMG

A. Communication Infrastructure

Interconnecting multiple microgrids will necessitate more reliable communication systems that allow communication between different protective devices [36], [71]. The types of interlinking devices can directly influence which type of protection scheme is more effective and suitable, but the interlinking devices must also be effectively protected [144], [145]. A high-speed communication architecture is also required to achieve fast, selective, secure, and reliable protections [92], [146], [147]. A cost-efficient communication framework [76] must be designed and implemented along with the protection infrastructure to create effective communication channels [88]. Accurate data transfer, proper energy utilization, and detection of the island mode operation, data traffic, and latency issues must also be considered in designing protections for NMGs [148].

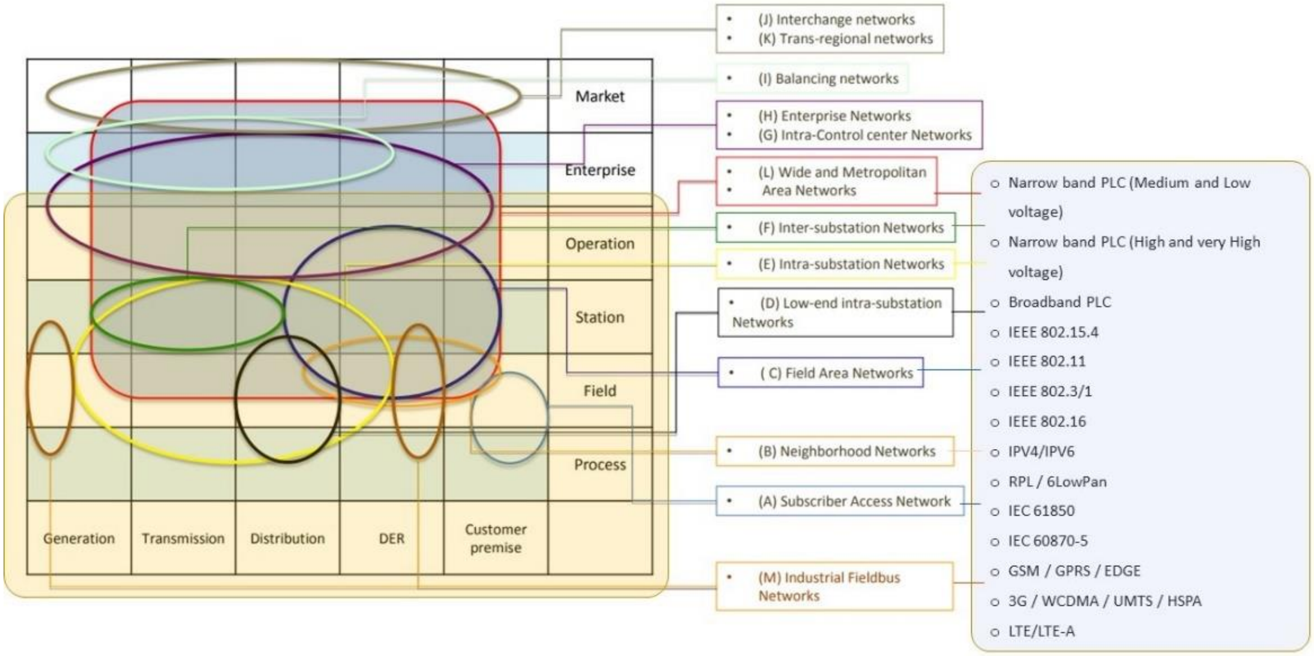

Fig. 9. Mapping of standardized communication technology in the protection-related communication network of NMG.

The development of communication infrastructure for protecting NMGs should consider mobile relays, evaluating communication delays, latency, and data loss between agents, and using 5G technologies. This will require more research before implementation. Implementing IoT-based protection schemes should help migrate from conventional protection strategies to modern protection frameworks. In addition, IoT-based support can be integrated into the protection devices of NMGs [102], [121], [149]. Field tests considering dynamic communication links, failures, and cyber-attacks should be implemented to improve interconnection and adaptive protections in NMGs [72].

B. *Fault Location*

The fault location and diagnosis in hybrid NMGs will require more investigation. Good references in the framework of non-NMGs are [80], [125], [134]. Research in this subject needs to explore the types of faults that occur at different locations, the fault direction identification, and the fault tolerance of the protections of the NMGs. Developing protection schemes for NMGs could consider advanced metering infrastructure (AMI) to collect information about faults or the status of the circuit breakers. Control strategies in protection applications should address the detection of internal faults, the operational behaviors of the DGs, and the interconnection and interaction among adjacent MGs. Moreover, research should be focused on developing innovative techniques to accelerate the detection of fault periods in inverted-based NMGs in island mode with or without communication systems.

C. *Protection Coordination*

Protection coordination methods and short-circuit calculations for different operation modes of the NMGs are additional areas that need further exploration. For the protection coordination of the NMGs, ideally, studies could consider adaptive protection schemes based on machine learning and optimization approaches based on mixed-characteristic curves of directional overcurrent relays. Convex optimization approaches could also be considered for determining a strict optimal point for the DOCR relays and their application to interconnected MGs with meshed topologies.

D. *Hierarchical Protection Strategies*

Protections that combine advanced control and protection techniques require a good communication infrastructure with specialized ride-through capabilities that make information about the system resources available online [46]. These protections could also consider using hierarchical protection strategies with balanced DER technologies and adaptive relay settings to address low-fault-current issues and improve fault detection in the presence of DERs.

E. *Adaptive Protection Schemes*

Dynamic changes in the operation modes of NMGs create the need to redesign the protection scheme. Changes in the topologies with different technologies make the protection structures and operations more complex. Adaptive protections are a suitable alternative for NMGs as they facilitate the effective integration of an MG into an existing main grid or multiple microgrids. However, it is still necessary to consider additional factors, like selectivity, sensitivity, reliability, cost-effectiveness, and efficient operation, before implementing these types of protections [150]. In addition, an adaptive protection design should be robust enough to deal with the system fault behavior in NMGs regardless of their structure.

Both real-time simulation tests and real-time operation of adaptive protections in NMGs need to be studied to determine their proper operation and performance. Real-time simulation tests should be conducted to study how the adaptive protection handles the dynamic variations in the source of the generation, e.g., wind and PV sources, and with the synchronous and induction motor loads. A real-time operation of an NMG using decentralized adaptive protection like a multi-agent system (MAS) could be an interesting application since this system should handle the changes in the operation modes and the dynamic interactions of the protection in interconnected microgrids [151]. Furthermore, future research should focus on studying the impact of communication failures on the performance of adaptive protections on real-time NMGs [52].

The study of advanced microgrid protection systems for NMGs should be prioritized. Studies should be focused on determining suitable decentralized protection schemes, how to increase their flexibility and modularity [126], and potentially, consider exploring the use of artificial intelligence (AI), deep learning (DL), and data mining applications [152], [153]. For example, the experience in [120] suggests that the application of AI and machine learning (ML) techniques in adaptive protection schemes will most likely improve the accuracy of estimating dynamic fault currents [126].

Adaptive decentralized protections have several qualities that make them good candidates for protecting more distributed interconnected networks. They are flexible and modular and can handle additional MGs and variable loads without changing the protection devices. Furthermore, they rely on a communication infrastructure that allows them to be more effective in the control and decision-making tasks. Adaptive protection can also use methods that divide the system into zones or clusters that allow them to match the available relay settings to the existing network topologies [144].

F. *Monitoring and Control Protection Schemes*

Monitoring devices is another area of interest. The research on using wide-area protection to build an adaptive monitoring protection system for NMGs remains in the early phase [75]. Adopting a SCADA system for data collection and using micro PMUs in centralized protection architectures in NMGs are appealing options to study [92]. On the other hand, studying close-loop wide area protection will provide opportunities for implementing decentralized adaptive protections. Furthermore, more work is needed on advanced sensors and faster communication networks [154].

Protections that use devices with fast-acting grounding, solid-state technology, and intelligent electronic devices should improve the operation of grids with dynamic topologies like NMGs. For example, solutions like intelligent all-in-one adaptive protections and control schemes that integrate all the required operations in an NMG could be developed.

G. *Real-Time Simulation Test*

Future work could consider a HIL testbed approach in protection schemes in NMGs. The study of protection schemes with different test capabilities for low and medium voltage networks in NMGs would require developing a specific HIL testbed with transit simulations for relays with non-standard curves with variable settings and under different setups and topologies [155]. Additionally, HIL testing of adaptive protections using real IEDs and IEC61850 communication could be another area of future study for their practical implementation. An example where HIL testing is used is [156]. For any NMG topology, it is critical to consider carrying over real-time simulations to estimate the time required to update signals to all the relays during a fault and to assess the relay coordination during a communication failure [157]. All these must be followed or complemented with field evaluation of adaptive protection schemes in NMGs with digital relays, communication capabilities, and supervisory software.

H. *NMG Protection Design*

It is also necessary to design a multicriteria protection plan that takes into consideration: 1) bidirectional and variable fault current, 2) power-export restrictions, 3) network structure and the type of topology of NMGs [158], 4) response time of the protection, and 5) the protection of the equipment from synchronization failures [154], 6) the impact of the regulatory environment and the ownership model of the NMG [159]. The design of NMGs' protection standards should include a multicriteria protection plan and consider addressing and proposing solutions to the issues or gaps in advanced protection systems. For example, existing gaps include the absence of standards for DC circuit breakers, fuses, and grounding equipment required for the reliable operation of a DC-NMG [160].

Fig. 10 shows the trends in NMG protection. VOYANT tools were used to create this figure.

Fig. 10. Trends of MG-Protection.

V. CONCLUSIONS

In this document, we reviewed different architectures and topologies of NMGs that have been discussed in the literature and that might be used to study networked protection systems. In addition, we reviewed the literature on advanced microgrid protection systems, as they offer the most suitable path to developing protections for NMGs. The review focused on pointing out the challenges present in developing protections for NMGs, potential solutions, and areas of research that need to be addressed for their development. We presented a comparative table that summarizes the challenges in protecting NMGS and a radar chart that assesses the proposed solutions and their advantages, taking selectivity, reliability, simplicity, economics, scalability, and speed criteria into consideration.

According to the reviewed literature, the main challenges faced in designing and operating protection systems for NMGs are the following. i) Location of faults in the presence of multiple connections and disconnections. ii) Existing gaps in developing and implementing fast and appropriate communication infrastructures. iii) Lack of standards for DC protections, which are needed to implement hybrid NMGs.

Future research should focus on carrying over tests that study the performance of protection schemes designed to handle dynamic topologies and communication failures. However, the implementation of NMGs also depends on the development of regulations and standards designed to guide users in the selection of appropriate protection schemes. Guides for the design of a protection scheme for NMGs should consider criteria like selectivity, modularity, flexibility, reliability, fastness, dynamic high-speed communications, accuracy, and cost-effectiveness. Furthermore, guides should include the design of hybrid protection schemes that combine the use of DC and AC.

The implementation and the operation of NMGs cannot happen unless reliable, secure, and economically reasonable protection systems are developed. Therefore, more research on implementing suitable protections schemes for NMGs is clearly needed.

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REFERENCES

[1] M. Moradi and A. Akbari Foroud, “Operation Management of Microgrid Clusters,” 2021. doi: 10.1007/978-3-030-59750-4_2.

[2] P. Roy Chowdhury, P. K. Sahu, S. Essakiappan, M. Manjrekar, K. Schneider, and S. Laval, “Power Quality and Stability in a Cluster of Microgrids with Coordinated Power and Energy Management,” in *2020 IEEE Industry Applications Society Annual Meeting, IAS 2020*, Oct. 2020. doi: 10.1109/IAS44978.2020.9334828.

[3] S. Chanda and A. K. Srivastava, “Defining and Enabling Resiliency of Electric Distribution Systems with Multiple Microgrids,” *IEEE Trans Smart Grid*, vol. 7, no. 6, pp. 2859–2868, Nov. 2016, doi: 10.1109/TSG.2016.2561303.

[4] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, “Networked Microgrids for Enhancing the Power System Resilience,” *Proceedings of the IEEE*, vol. 105, no. 7. Institute of Electrical and Electronics Engineers Inc., pp. 1289–1310, Jul. 01, 2017. doi: 10.1109/JPROC.2017.2685558.

[5] Z. Wang, B. Chen, J. Wang, and C. Chen, “Networked microgrids for self-healing power systems,” *IEEE Trans Smart Grid*, vol. 7, no. 1, pp. 310–319, Jan. 2016, doi: 10.1109/TSG.2015.2427513.

[6] D. T. Ton and M. A. Smith, “The U.S. Department of Energy’s Microgrid Initiative,” *Electricity Journal*, vol. 25, no. 8, pp. 84–94, Oct. 2012, doi: 10.1016/j.tej.2012.09.013.

[7] M. Higginson, M. Payne, K. Moses, P. Curtiss, and S. Costello, “North Bay Hydro Microgrid: Innovative Protection of a Complex System,” *IEEE Power and Energy Magazine*, vol. 19, no. 3, pp. 70–82, May 2021, doi: 10.1109/MPE.2021.3057954.

[8] L. Meng *et al.*, “Review on Control of DC Microgrids and Multiple Microgrid Clusters,” *IEEE J Emerg Sel Top Power Electron*, vol. 5, no. 3, pp. 928–948, 2017, doi: 10.1109/JESTPE.2017.2690219.

[9] M. N. Alam, S. Chakrabarti, and A. Ghosh, “Networked Microgrids: State-of-the-Art and Future Perspectives,” *IEEE Trans Industr Inform*, vol. 15, no. 3, pp. 1238–1250, Mar. 2019, doi: 10.1109/TII.2018.2881540.

[10] J. Wei, R. Roche, A. Koukam, and F. Lauri, “Decentralized coordination for mutual rescue in microgrid clusters,” *2018 IEEE International Energy Conference, ENERGYCON 2018*, pp. 1–6, 2018, doi: 10.1109/ENERGYCON.2018.8398769.

[11] M. N. Alam, S. Chakrabarti, and X. Liang, “A Benchmark Test System for Networked Microgrids,” *IEEE Trans Industr Inform*, vol. 16, no. 10, pp. 6217–6230, 2020, doi: 10.1109/TII.2020.2976893.

[12] M. A. Yaqobi, H. Matayoshi, M. S. S. Danish, M. E. Lotfy, A. M. Howlader, and S. Tomonobu, “Low-voltage solid-state DC breaker for fault protection applications in isolated DC microgrid cluster,” *Applied Sciences (Switzerland)*, vol. 9, no. 4, Feb. 2019, doi: 10.3390/app9040723.

[13] K. El Arroudi and G. Joos, “Performance of Interconnection Protection Based on Distance Relaying for Wind Power Distributed Generation.,” *IEEE Transactions on Power Delivery*, vol. 8977, no. c, pp. 1–1, 2017, doi: 10.1109/TPWRD.2017.2693292.

[14] A. Sinclair, D. Finney, D. Martin, and P. Sharma, “Distance protection in distribution systems: How it assists with integrating distributed resources,” *IEEE Trans Ind Appl*, vol. 50, no. 3, pp. 2186–2196, 2014, doi: 10.1109/TIA.2013.2288426.

[15] S. Beheshtaein, R. Cuzner, M. Savaghebi, and J. M. Guerrero, “Review on microgrids protection,” *IET Generation, Transmission and Distribution*, vol. 13, no. 6, pp. 743–759, 2019, doi: 10.1049/iet-gtd.2018.5212.

[16] A. K. Barnes and A. Mate, “Implementing Admittance Relaying for Microgrid Protection,” in *Conference Record - Industrial and Commercial Power Systems Technical Conference*, Apr. 2021, vol. 2021-April. doi: 10.1109/ICPS51807.2021.9416600.

[17] E. Dehghanpour, H. Kazemi Karegar, R. Kheirollahi, and T. Soleymani, “Optimal coordination of directional overcurrent relays in microgrids by using cuckoo-linear optimization algorithm and fault current limiter,” *IEEE Trans Smart Grid*, vol. 9, no. 2, pp. 1365–1375, 2018, doi: 10.1109/TSG.2016.2587725.

[18] P. Thararak and P. Jirapong, “Implementation of Optimal Protection Coordination for Microgrids with Distributed Generations Using Quaternary Protection Scheme,” *Journal of Electrical and Computer Engineering*, vol. 2020, 2020, doi: 10.1155/2020/2568652.

[19] M. Singh and P. Basak, “Conceptualization of adaptive relaying in protection of hybrid microgrid through analysis of open and short circuit faults based on q0 components of fault current,” in *15th International Conference on Developments in Power System Protection (DPSP 2020)*, 2020, pp. 6 pp.-6 pp. doi: 10.1049/cp.2020.0102.

[20] S. Chakraborty and S. Das, “Communication-less protection scheme for AC microgrids using hybrid tripping characteristic,” *Electric Power Systems Research*, vol. 187, Oct. 2020, doi: 10.1016/j.epsr.2020.106453.

[21] A. Hooshyar and R. Iravani, “A New Directional Element for Microgrid Protection,” *IEEE Trans Smart Grid*, vol. 3053, no. c, 2017, doi: 10.1109/TSG.2017.2727400.

[22] M. Monadi, M. A. Zamani, C. Koch-Ciobotaru, J. I. Candela, and P. Rodriguez, “A communication-assisted protection scheme for direct-current distribution networks,” *Energy*, vol. 109, pp. 578–591, 2016, doi: 10.1016/j.energy.2016.04.118.

[23] E. Sortomme, S. S. Venkata, and J. Mitra, “Microgrid protection using communication-assisted digital relays,” *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2789–2796, Oct. 2010, doi: 10.1109/TPWRD.2009.2035810.

[24] M. E. Elkhatib and A. Ellis, “Communication-assisted impedance-based microgrid protection scheme,” in *2017 IEEE Power & Energy Society General Meeting*, Jul. 2017, pp. 1–5. doi: 10.1109/PESGM.2017.8274206.

[25] H. F. Habib, T. Youssef, M. H. Cintuglu, and O. A. Mohammed, “Multi-Agent-Based Technique for Fault Location, Isolation, and

Service Restoration," *IEEE Trans Ind Appl*, vol. 53, no. 3, pp. 1841–1851, 2017, doi: 10.1109/TIA.2017.2671427.

[26] H. Lin, K. Sun, Z. H. Tan, C. Liu, J. M. Guerrero, and J. C. Vasquez, "Adaptive protection combined with machine learning for microgrids," *IET Generation, Transmission and Distribution*, vol. 13, no. 6, pp. 770–779, 2019, doi: 10.1049/iet-gtd.2018.6230.

[27] N. Hussain *et al.*, "Ac microgrids protection: A digital coordinated adaptive scheme," *Applied Sciences (Switzerland)*, vol. 11, no. 15, Aug. 2021, doi: 10.3390/app11157066.

[28] P. Chauhan, C. P. Gupta, and M. Tripathy, "A Novel Adaptive Protection Technique Based on Rate-of-Rise of Fault Current in DC Microgrid," *Electric Power Systems Research*, vol. 207, Jun. 2022, doi: 10.1016/j.epsr.2022.107832.

[29] M. P. Reddy and M. Manimozhi, "A review on microgrid protection using Superconducting Fault Current Limiter," *Journal of Green Engineering*, vol. 8, no. 2, pp. 89–124, 2018, doi: 10.13052/jge1904-4720.821.

[30] M. G. M. Zanjani, K. Mazlumi, and I. Kamwa, "Application of μPMUs for adaptive protection of overcurrent relays in microgrids," *IET Generation, Transmission and Distribution*, vol. 12, no. 18. pp. 4061–4069, 2018. doi: 10.1049/iet-gtd.2018.5898.

[31] F. Bandeiras, E. Pinheiro, M. Gomes, P. Coelho, and J. Fernandes, "Review of the cooperation and operation of microgrid clusters," *Renewable and Sustainable Energy Reviews*, vol. 133. Elsevier Ltd, Nov. 01, 2020. doi: 10.1016/j.rser.2020.110311.

[32] W. E. P. Sampath Ediriweera and N. W. A. Lidula, "Design and protection of microgrid clusters: A comprehensive review," *AIMS Energy*, vol. 10, no. 3, pp. 375–411, 2022, doi: 10.3934/energy.2022020.

[33] F. Zhang and L. Mu, "New protection scheme for internal fault of multi-microgrid," *Protection and Control of Modern Power Systems*, vol. 4, no. 1, 2019, doi: 10.1186/s41601-019-0127-3.

[34] N. Bayati, H. R. Baghaee, A. Hajizadeh, M. Soltani, and Z. Lin, "Mathematical morphology-based local fault detection in DC Microgrid clusters," *Electric Power Systems Research*, vol. 192, Mar. 2021, doi: 10.1016/j.epsr.2020.106981.

[35] M. M. Eissa and M. H. A. Awadalla, "Centralized protection scheme for smart grid integrated with multiple renewable resources using Internet of Energy," *Glob Transit*, vol. 1, pp. 50–60, 2019, doi: 10.1016/j.glt.2019.01.002.

[36] A. C. Adewole, A. D. Rajapakse, D. Ouellette, and P. Forsyth, "Protection of active distribution networks incorporating microgrids with multi-technology distributed energy resources," *Electric Power Systems Research*, vol. 202, Jan. 2022, doi: 10.1016/j.epsr.2021.107575.

[37] S. Gopalan, V. Sreeram, Y. Mishra, and H. Iu, "Protection Issues in Microgrids and Multi-microgrids," in *Handbook of Distributed Generation*, Cham: Springer International Publishing, 2017. doi: 10.1007/978-3-319-51343-0_16.

[38] A. M. Tsimtsios and V. C. Nikolaidis, "Towards Plug-and-Play Protection for Meshed Distribution Systems with DG," *IEEE Trans Smart Grid*, vol. 11, no. 3, pp. 1980–1995, 2020, doi: 10.1109/TSG.2019.2945694.

[39] M. Ojaghi and V. Mohammadi, "Use of Clustering to Reduce the Number of Different Setting Groups for Adaptive Coordination of Overcurrent Relays," *IEEE Transactions on Power Delivery*, vol. 33, no. 3. pp. 1204–1212, 2018. doi: 10.1109/TPWRD.2017.2749321.

[40] M. N. Alam, R. Gokaraju, and S. Chakrabarti, "Protection coordination for networked microgrids using single and dual setting overcurrent relays," *IET Generation, Transmission and Distribution*, vol. 14, no. 14, pp. 2818–2828, 2020, doi: 10.1049/iet-gtd.2019.0557.

[41] S. Hossain-McKenzie, M. J. Reno, J. Eddy, and K. P. Schneider, "Assessment of Existing Capabilities and Future Needs for Designing Networked Microgrids," 2019. [Online]. Available: https://classic.ntis.gov/help/order-methods/

[42] N. J. Gil and J. A. P. Lopes, "Hierarchical Frequency Control Scheme for Islanded Multi-Microgrids Operation," in *2007 IEEE Lausanne Power Tech*, Jul. 2007, pp. 473–478. doi: 10.1109/PCT.2007.4538363.

[43] S. Parhizi, H. Lotfi, A. Khodaei, and S. Bahramirad, "State of the art in research on microgrids: A review," *IEEE Access*, vol. 3. Institute of Electrical and Electronics Engineers Inc., pp. 890–925, Jun. 10, 2015. doi: 10.1109/ACCESS.2015.2443119.

[44] S. A. Gopalan, V. Sreeram, and H. H. C. Iu, "A review of coordination strategies and protection schemes for microgrids," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 222–228, 2014, doi: 10.1016/j.rser.2014.01.037.

[45] E. Trinklei *et al.*, "Scoping Study: Networked Microgrids," Albuquerque, NM, and Livermore, CA (United States), Oct. 2014. doi: 10.2172/1433071.

[46] B. Chen, J. Wang, X. Lu, C. Chen, and S. Zhao, "Networked Microgrids for Grid Resilience, Robustness, and Efficiency: A Review," *IEEE Transactions on Smart Grid*, vol. 12, no. 1. Institute of Electrical and Electronics Engineers Inc., pp. 18–32, Jan. 01, 2021. doi: 10.1109/TSG.2020.3010570.

[47] A. Alabdulwahab and M. Shahidehpour, "Microgrid networking for the monitoring, control and protection of modern power systems," *Electricity Journal*, vol. 29, no. 10, pp. 1–7, Dec. 2016, doi: 10.1016/j.tej.2016.11.012.

[48] J. Wang and X. Lu, "Sustainable and Resilient Distribution Systems with Networked Microgrids," *Proceedings of the IEEE*, vol. 108, no. 2, pp. 238–241, 2020, doi: 10.1109/JPROC.2019.2963605.

[49] G. Liu, M. R. Starke, B. Ollis, and Y. Xue, "Networked Microgrids Scoping Study," 2016. [Online]. Available: http://www.osti.gov/scitech/

[50] Z. Xu, P. Yang, C. Zheng, Y. Zhang, J. Peng, and Z. Zeng, "Analysis on the organization and Development of multi-microgrids," *Renewable and Sustainable Energy Reviews*, vol. 81. Elsevier Ltd, pp. 2204–2216, Jan. 01, 2018. doi: 10.1016/j.rser.2017.06.032.

[51] E. Bullich-Massagué, F. Díaz-González, M. Aragüés-Peñalba, F. Girbau-Llistuella, P. Olivella-Rosell, and A. Sumper, "Microgrid clustering architectures," *Appl Energy*, vol. 212, pp. 340–361, Feb. 2018, doi: 10.1016/j.apenergy.2017.12.048.

[52] M. Islam, F. Yang, and M. Amin, "Control and optimisation of networked microgrids: A review," *IET Renewable Power Generation*, vol. 15, no. 6. John Wiley and Sons Inc, pp. 1133–1148, Apr. 01, 2021. doi: 10.1049/rpg2.12111.

[53] X. Zhou *et al.*, "A microgrid cluster structure and its autonomous coordination control strategy," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2017, pp. 2332–2337. doi: 10.1109/IECON.2017.8216393.

[54] P. Wu, W. Huang, N. Tai, and S. Liang, "A novel design of architecture and control for multiple microgrids with hybrid AC/DC connection," *Appl Energy*, vol. 210, pp. 1002–1016, Jan. 2018, doi: 10.1016/j.apenergy.2017.07.023.

[55] L. Ortiz, R. Orizondo, A. Águila, J. W. González, G. J. López, and I. Isaac, "Hybrid AC/DC microgrid test system simulation: grid-connected mode," *Heliyon*, vol. 5, no. 12, Dec. 2019, doi: 10.1016/j.heliyon.2019.e02862.

[56] S. Jena and N. P. Padhy, "Distributed cooperative control for autonomous hybrid AC/DC microgrid clusters interconnected via back-to-back converter control," in *IEEE Power and Energy Society General Meeting*, Aug. 2020, vol. 2020-August. doi: 10.1109/PESGM41954.2020.9281505.

[57] M. Cintuglu, A. Kondabathini, and D. Ishchenko, "Real-Time Implementation of Secure Distributed State Estimation for Networked Microgrids," in *2020 IEEE 6th World Forum on Internet of Things (WF-IoT)*, Jun. 2020, pp. 1–6. doi: 10.1109/WF-IoT48130.2020.9221310.

[58] Y. Wang, T. L. Nguyen, Y. Xu, Q. T. Tran, and R. Caire, "Peer-to-Peer Control for Networked Microgrids: Multi-Layer and Multi-Agent Architecture Design," *IEEE Trans Smart Grid*, vol. 11, no. 6, pp. 4688–4699, Nov. 2020, doi: 10.1109/TSG.2020.3006883.

[59] D. G. Rosero, N. L. Díaz, and C. L. Trujillo, "Cloud and machine learning experiments applied to the energy management in a microgrid cluster," *Appl Energy*, vol. 304, Dec. 2021, doi: 10.1016/j.apenergy.2021.117770.

[60] H. Yu, S. Niu, Z. Shao, and L. Jian, "A scalable and reconfigurable hybrid AC/DC microgrid clustering architecture with decentralized control for coordinated operation," *International Journal of Electrical Power and Energy Systems*, vol. 135, Feb. 2022, doi: 10.1016/j.ijepes.2021.107476.

[61] P. S. Prasad and A. M. Parimi, "Recent advancements in hybrid AC/DC microgrids," in *Microgrids*, Elsevier, 2022, pp. 227–246. doi: 10.1016/B978-0-323-85463-4.00004-6.

[62] S. Sarangi, B. K. Sahu, and P. K. Rout, "Review of distributed generator integrated AC microgrid protection: issues, strategies, and future trends," *International Journal of Energy Research*, vol. 45, no. 10. John Wiley and Sons Ltd, pp. 14117–14144, Aug. 01, 2021. doi: 10.1002/er.6689.

[63] S. A. Gopalan, V. Sreeram, H. H. C. Iu, Z. Xu, Z. Y. Dong, and K. P. Wong, "Fault analysis of an islanded Multi-microgrid," in *IEEE Power and Energy Society General Meeting*, 2012. doi: 10.1109/PESGM.2012.6344872.

[64] M. Sun and M. M. Ma, "The interconnection protection of the MV multiple microgrid," in *Advanced Materials Research*, 2014, vol. 860–863, pp. 1919–1924. doi: 10.4028/www.scientific.net/AMR.860-863.1919.

[65] H. Nagarajan, M. J. Reno, and S. Kundu, "Preliminary Design Process for Networked Microgrids Optimal Topology Design for Power System Stability View project," 2020. [Online]. Available: https://www.ntis.gov/about

[66] C. Cavalieri, V. Farias, and M. Kabalan, "Microgrid protection: A case study of a real-world industry-grade microgrid," in *2021 IEEE Kansas Power and Energy Conference, KPEC 2021*, 2021. doi: 10.1109/KPEC51835.2021.9446263.

[67] L. Hallemans, S. Ravyts, G. Govaerts, S. Fekriasl, P. van Tichelen, and J. Driesen, "A stepwise methodology for the design and evaluation of protection strategies in LVDC microgrids," *Appl Energy*, vol. 310, p. 118420, Mar. 2022, doi: 10.1016/j.apenergy.2021.118420.

[68] D. K. J. S. Jayamaha, N. W. A. Lidula, and A. D. Rajapakse, "Protection and grounding methods in DC microgrids: Comprehensive review and analysis," *Renewable and Sustainable Energy Reviews*, vol. 120. Elsevier Ltd, Mar. 01, 2020. doi: 10.1016/j.rser.2019.109631.

[69] D. Zheng *et al.*, "Protection of microgrids," in *Microgrid Protection and Control*, Elsevier, 2021. doi: 10.1016/B978-0-12-821189-2.00006-1.

[70] M. N. Alam, S. Chakrabarti, and A. K. Pradhan, "Protection of Networked Microgrids using Relays with Multiple Setting Groups," *IEEE Trans Industr Inform*, pp. 1–1, Oct. 2021, doi: 10.1109/tii.2021.3120151.

[71] S. Mirsaeidi, X. Dong, S. Shi, and D. Tzelepis, "Challenges, advances and future directions in protection of hybrid AC/DC microgrids," *IET Renewable Power Generation*, vol. 11, no. 12. Institution of Engineering and Technology, pp. 1495–1502, Oct. 18, 2017. doi: 10.1049/iet-rpg.2017.0079.

[72] G. Kaur, A. Prakash, and K. U. Rao, "A critical review of Microgrid adaptive protection techniques with distributed generation," *Renewable Energy Focus*, vol. 39. Elsevier Ltd, pp. 99–109, Dec. 01, 2021. doi: 10.1016/j.ref.2021.07.005.

[73] T. Patel, S. Brahma, J. Hernandez-Alvidrez, and M. J. Reno, "Adaptive Protection Scheme for a Real-World Microgrid with 100% Inverter-Based Resources," 2020.

[74] M. E. Ropp and M. J. Reno, "Influence of Inverter-Based Resources on Microgrid Protection: Part 2: Secondary Networks and Microgrid Protection," *IEEE Power and Energy Magazine*, vol. 19, no. 3, pp. 47–57, May 2021, doi: 10.1109/MPE.2021.3057952.

[75] B. Patnaik, M. Mishra, R. C. Bansal, and R. K. Jena, "AC microgrid protection – A review: Current and future prospective," *Appl Energy*, vol. 271, Aug. 2020, doi: 10.1016/j.apenergy.2020.115210.

[76] A. Dagar, P. Gupta, and V. Niranjan, "Microgrid protection: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 149. Elsevier Ltd, Oct. 01, 2021. doi: 10.1016/j.rser.2021.111401.

[77] S. G. Srivani, C. Suresha, K. N. S. v. Theertha, and D. Chandan, "Adaptive Protection Scheme for Renewable Integrated Microgrid—A Case Study," 2021. doi: 10.1007/978-981-15-7078-0_53.

[78] H. Bawayan and M. Younis, "Microgrid Protection through Adaptive Overcurrent Relay Coordination," *Electricity*, vol. 2, no. 4, pp. 524–553, Nov. 2021, doi: 10.3390/electricity2040031.

[79] P. Pan and R. K. Mandal, "Learning approach based DC arc fault location classification in DC microgrids," *Electric Power Systems Research*, vol. 208, Jul. 2022, doi: 10.1016/j.epsr.2022.107874.

[80] S. Jadidi, H. Badihi, and Y. Zhang, "Fault diagnosis in microgrids with integration of solar photovoltaic systems: A review," in *IFAC-PapersOnLine*, 2020, vol. 53, no. 2, pp. 12091–12096. doi: 10.1016/j.ifacol.2020.12.763.

[81] C. Srivastava and M. Tripathy, "DC microgrid protection issues and schemes: A critical review," *Renewable and Sustainable Energy Reviews*, vol. 151. Elsevier Ltd, Nov. 01, 2021. doi: 10.1016/j.rser.2021.111546.

[82] S. Beheshtaein, R. M. Cuzner, M. Forouzesh, M. Savaghebi, and J. M. Guerrero, "DC Microgrid Protection: A Comprehensive Review," *IEEE J Emerg Sel Top Power Electron*, pp. 1–1, Mar. 2019, doi: 10.1109/jestpe.2019.2904588.

[83] N. Bayati, A. Hajizadeh, and M. Soltani, "Protection in DC microgrids: A comparative review," *IET Smart Grid*, vol. 1, no. 3. Institution of Engineering and Technology, pp. 66–75, Oct. 01, 2018. doi: 10.1049/iet-stg.2018.0035.

[84] N. Bayati *et al.*, "Locating high-impedance faults in DC microgrid clusters using support vector machines," *Appl Energy*, vol. 308, Feb. 2022, doi: 10.1016/j.apenergy.2021.118338.

[85] N. Bayati, H. R. Baghaee, A. Hajizadeh, M. Soltani, Z. Lin, and M. Savaghebi, "Local Fault Location in Meshed DC Microgrids Based On Parameter Estimation Technique," *IEEE Syst J*, vol. 16, no. 1, pp. 1606–1615, Mar. 2022, doi: 10.1109/JSYST.2021.3107905.

[86] R. Mohanty and A. K. Pradhan, "Protection of DC and hybrid AC-DC microgrids with ring configuration," in *2017 7th International Conference on Power Systems (ICPS)*, Dec. 2017, pp. 607–612. doi: 10.1109/ICPES.2017.8387365.

[87] M. Vrtal, P. Toman, and J. Moravek, "CONTROL AND PROTECTION OF AC/DC HYBRID MICROGRIDS," in *CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution*, 2021, pp. 1510–1514. doi: 10.1049/icp.2021.1643.

[88] S. Sarangi, B. K. Sahu, and P. K. Rout, "Distributed generation hybrid AC/DC microgrid protection: A critical review on issues, strategies, and future directions," *International Journal of Energy Research*, vol. 44, no. 5. John Wiley and Sons Ltd, pp. 3347–3364, Apr. 01, 2020. doi: 10.1002/er.5128.

[89] E. Planas, J. Andreu, J. I. Gárate, I. Martínez De Alegría, and E. Ibarra, "AC and DC technology in microgrids: A review," *Renewable and Sustainable Energy Reviews*, vol. 43. Elsevier Ltd, pp. 726–749, 2015. doi: 10.1016/j.rser.2014.11.067.

[90] M. J. Reno, S. Brahma, A. Bidram, and M. E. Ropp, "Influence of Inverter-Based Resources on Microgrid Protection: Part 1: Microgrids in Radial Distribution Systems," *IEEE Power and Energy Magazine*, vol. 19, no. 3, pp. 36–46, May 2021, doi: 10.1109/MPE.2021.3057951.

[91] E. C. Piesciorovsky and B. Ollis, "Oak Ridge National Laboratory Literature Review: Methods for Microgrid Protection," 2019. [Online]. Available: www.osti.gov

[92] A. Chandra, G. K. Singh, and V. Pant, "Protection of AC microgrid integrated with renewable energy sources – A research review and future trends," *Electric Power Systems Research*, vol. 193. Elsevier Ltd, Apr. 01, 2021. doi: 10.1016/j.epsr.2021.107036.

[93] P. H. Gadde and S. M. Brahma, "Topology-Agnostic, Scalable, Self-Healing and Cost-Aware Protection of Microgrids," *IEEE Transactions on Power Delivery*, pp. 1–1, Nov. 2021, doi: 10.1109/tpwrd.2021.3128880.

[94] E. Gómez-Luna, J. E. Candelo, E. Marlés, J. M. Guardiola, and J. de la Cruz, "Impact of adaptive protections in electric microgrids, challenges and future trends," *Journal of Engineering Science and Technology Review*, vol. 12, no. 6, pp. 60–69, 2019, doi: 10.25103/jestr.126.08.

[95] M. W. Altaf, M. T. Arif, S. N. Islam, and Md. E. Haque, "Microgrid Protection Challenges and Mitigation Approaches- A Comprehensive Review," *IEEE Access*, pp. 1–1, 2022, doi: 10.1109/ACCESS.2022.3165011.

[96] G. Kaur, B. Moulik, and K. U. Rao, "Determining the optimum TMS and PS of overcurrent relays using the Firefly Algorithm for solving the relay coordination problem," in *Proceedings - 5th International Conference on Computing Methodologies and Communication, ICCMC 2021*, Apr. 2021, pp. 1011–1015. doi: 10.1109/ICCMC51019.2021.9418021.

[97] N. el Naily, S. M. Saad, T. Hussein, K. El-Arroudi, and F. A. Mohamed, "On-line adaptive protection scheme to overcome operational variability of DG in smart grid via fuzzy logic and

genetic algorithm," in *2018 9th International Renewable Energy Congress, IREC 2018*, May 2018, pp. 1–6. doi: 10.1109/IREC.2018.8362498.

[98] B. J. Brearley and R. R. Prabu, "A review on issues and approaches for microgrid protection," *Renewable and Sustainable Energy Reviews*, vol. 67. Elsevier Ltd, pp. 988–997, Jan. 01, 2017. doi: 10.1016/j.rser.2016.09.047.

[99] S. Faazila Fathima and L. Premalatha, "Protection Strategies for AC and DC Microgrid – A Review of Protection Methods Adopted in Recent Decade," *IETE J Res*, pp. 1–17, Oct. 2021, doi: 10.1080/03772063.2021.1990140.

[100] A. Y. Hatata, M. A. Essa, and B. E. Sedhom, "Adaptive Protection Scheme for FREEDM Microgrid Based on Convolutional Neural Network and Gorilla Troops Optimization Technique," *IEEE Access*, vol. 10, pp. 55583–55601, 2022, doi: 10.1109/ACCESS.2022.3177544.

[101] B. Poudel, D. R. Garcia, A. Bidram, M. J. Reno, and A. Summers, "Circuit Topology Estimation in an Adaptive Protection System," in *2020 52nd North American Power Symposium, NAPS 2020*, Apr. 2021. doi: 10.1109/NAPS50074.2021.9449636.

[102] O. V. G. Swathika and K. T. M. U. Hemapala, "IOT-Based Adaptive Protection of Microgrid," in *Proceedings of International Conference on Artificial Intelligence, Smart Grid and Smart City Applications*, Springer International Publishing, 2020, pp. 123–130. doi: 10.1007/978-3-030-24051-6_12.

[103] S. A. Hosseini, S. H. H. Sadeghi, and A. Nasiri, "Decentralized Adaptive Protection Coordination Based on Agents Social Activities for Microgrids With Topological and Operational Uncertainties," *IEEE Trans Ind Appl*, vol. 57, no. 1, pp. 702–713, Jan. 2021, doi: 10.1109/TIA.2020.3028351.

[104] A. M. Nakhaee, S. A. Hosseini, S. H. H. Sadeghi, and A. Nasiri, "A Framework for Assessing the Impact of Operational Uncertainties on the Reliability of Adaptive Microgrid Protection Schemes," *Arab J Sci Eng*, Oct. 2022, doi: 10.1007/s13369-022-07347-7.

[105] A. Zangeneh and M. Moradzadeh, "Self-healing: Definition, Requirements, Challenges and Methods," in *Microgrid Architectures, Control and Protection Methods*, 2020, pp. 509–525. doi: 10.1007/978-3-030-23723-3_21.

[106] F. Zhang, L. Mu, and W. Guo, "An Integrated Wide-Area Protection Scheme for Active Distribution Networks Based on Fault Components Principle," *IEEE Trans Smart Grid*, vol. 10, no. 1, pp. 392–402, Jan. 2019, doi: 10.1109/TSG.2017.2741060.

[107] T. S. Ustun, R. H. Khan, A. Hadbah, and A. Kalam, "An adaptive microgrid protection scheme based on a wide-area smart grid communications network," *2013 IEEE Latin-America Conference on Communications*, vol. 2013 IEEE, pp. 1–5, 2013, doi: 10.1109/LatinCom.2013.6759822.

[108] E. Harmon, U. Ozgur, M. H. Cintuglu, R. de Azevedo, K. Akkaya, and O. A. Mohammed, "The Internet of Microgrids: A Cloud-Based Framework for Wide Area Networked Microgrids," *IEEE Trans Industr Inform*, vol. 14, no. 3, pp. 1262–1274, 2018, doi: 10.1109/TII.2017.2785317.

[109] A. J. Aghbolaghi, N. M. Tabatabaei, M. K. Azad, M. Tarantash, and N. S. Boushehri, "Microgrid Planning and Modeling," in *Microgrid Architectures, Control and Protection Methods*, 2020, pp. 21–46. doi: 10.1007/978-3-030-23723-3_2.

[110] A. C. Enríquez, Y. G. Cardoso, and J. T. Martínez, "Microgrid Protection," in *Microgrids (Advances in Operation, Control, and Protection)* , 2021, pp. 437–487. doi: 10.1007/978-3-030-59750-4_17.

[111] V. A. Papaspiliotopoulos, G. N. Korres, and N. D. Hatziargyriou, "Protection coordination in modern distribution grids integrating optimization techniques with adaptive relay setting," in *2015 IEEE Eindhoven PowerTech, PowerTech 2015*, Aug. 2015. doi: 10.1109/PTC.2015.7232558.

[112] M. A. Dawoud, D. K. Ibrahim, M. I. Gilany, and A. El'Gharably, "Robust Coordination Scheme for Microgrids Protection Based on the Rate of Change of Voltage," *IEEE Access*, pp. 1–1, 2021, doi: 10.1109/ACCESS.2021.3128999.

[113] H. Safari Fesagandis, M. Jalali, K. Zare, and M. Abapour, "Decentralized strategy for real-time outages management and scheduling of networked microgrids," *International Journal of Electrical Power and Energy Systems*, vol. 133, Dec. 2021, doi: 10.1016/j.ijepes.2021.107271.

[114] P. Naveen and P. Jena, "A Robust Protection Scheme for Multi-Microgrids Using Fault Current Limiter," *IEEE Trans Ind Appl*, pp. 1–1, 2022, doi: 10.1109/TIA.2022.3178687.

[115] A. Abdali, R. Noroozian, and K. Mazlumi, "Simultaneous control and protection schemes for DC multi microgrids systems," *International Journal of Electrical Power and Energy Systems*, vol. 104, pp. 230–245, Jan. 2019, doi: 10.1016/j.ijepes.2018.06.054.

[116] T. Patel, P. Gadde, S. Brahma, J. Hernandez-Alvidrez, and M. J. Reno, "Real-time Microgrid Test Bed for Protection and Resiliency Studies," in *2020 52nd North American Power Symposium, NAPS 2020*, Apr. 2021. doi: 10.1109/NAPS50074.2021.9449730.

[117] A. A. Memon and K. Kauhaniemi, "Real-Time Hardware-in-the-Loop Testing of IEC 61850 GOOSE-Based Logically Selective Adaptive Protection of AC Microgrid," *IEEE Access*, vol. 9, pp. 154612–154639, 2021, doi: 10.1109/ACCESS.2021.3128370.

[118] P. H. A. Barra, V. A. Lacerda, R. A. S. Fernandes, and D. v. Coury, "A hardware-in-the-loop testbed for microgrid protection considering non-standard curves," *Electric Power Systems Research*, vol. 196, Jul. 2021, doi: 10.1016/j.epsr.2021.107242.

[119] S. Paladhi, Q. Hong, and C. D. Booth, "Adaptive distance protection for multi-terminal lines connecting converter-interfaced renewable energy sources," in *16th International Conference on Developments in Power System Protection (DPSP 2022)*, 2022, pp. 31–35. doi: 10.1049/icp.2022.0907.

[120] M. Manohar, E. Koley, and S. Ghosh, "Microgrid protection against high impedance faults with robustness to harmonic intrusion and weather intermittency," *IET Renewable Power Generation*, vol. 15, no. 11, pp. 2325–2339, Aug. 2021, doi: 10.1049/rpg2.12167.

[121] O. M. Machidon, C. Stanca, P. Ogrutan, C. Gerigan, and L. Aciu, "Power-system protection device with IoT-based support for integration in smart environments," *PLoS One*, vol. 13, no. 12, Dec. 2018, doi: 10.1371/journal.pone.0208168.

[122] P. Kumar, V. Kumar, and R. Pratap, "RT-HIL verification of FPGA-based communication-assisted adaptive relay for microgrid protection," *Electrical Engineering*, 2021, doi: 10.1007/s00202-021-01387-2.

[123] S. Gopalan, V. Sreeram, H. Iu, and Y. Mishra, "A flexible protection scheme for an islanded Multi-Microgrid," in *2013 4th IEEE/PES Innovative Smart Grid Technologies Europe, ISGT Europe 2013*, 2013. doi: 10.1109/ISGTEurope.2013.6695358.

[124] M. W. Altaf, M. T. Arif, S. Saha, S. N. Islam, M. E. Haque, and A. M. T. Oo, "Effective protection scheme for reliable operation of multi-microgrid," in *9th IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2020*, Dec. 2020. doi: 10.1109/PEDES49360.2020.9379723.

[125] M. Ahmadipour, M. M. Othman, R. Bo, Z. Salam, H. M. Ridha, and K. Hasan, "A novel microgrid fault detection and classification method using maximal overlap discrete wavelet packet transform and an augmented Lagrangian particle swarm optimization-support vector machine," *Energy Reports*, vol. 8, pp. 4854–4870, Nov. 2022, doi: 10.1016/j.egyr.2022.03.174.

[126] A. Ananth, P. Mohan Babu, and C. Vaithilingam, "Estimation of Dynamic Fault Currents of Microgrids Using Generalized Regression Neural Network," in *Advances in Computational Intelligence and Communication Technology. Lecture Notes in Networks and Systems*, vol. 399, Springer, Singapore, 2022, pp. 139–146. doi: 10.1007/978-981-16-9756-2_13.

[127] M. N. Alam, A. Sallem, and N. Masmoudi, "Protection coordination using mixed characteristics of directional overcurrent relays in interconnected power distribution networks," in *6th IEEE International Energy Conference, ENERGYCon 2020*, Sep. 2020, pp. 761–766. doi: 10.1109/ENERGYCon48941.2020.9236488.

[128] R. Tiwari, R. K. Singh, and N. K. Choudhary, "Coordination of dual setting overcurrent relays in microgrid with optimally determined relay characteristics for dual operating modes," *Protection and Control of Modern Power Systems*, vol. 7, no. 1, Dec. 2022, doi: 10.1186/s41601-022-00226-1.

[129] M. Monadi, C. Gavriluta, A. Luna, J. I. Candela, and P. Rodriguez, "Centralized Protection Strategy for Medium Voltage DC Microgrids," *IEEE Transactions on Power Delivery*, vol. 32,

no. 1, pp. 430–440, Feb. 2017, doi: 10.1109/TPWRD.2016.2600278.

[130] K. Anjaiah, P. K. Dash, and M. Sahani, “A new protection scheme for PV-wind based DC-ring microgrid by using modified multifractal detrended fluctuation analysis,” *Protection and Control of Modern Power Systems*, vol. 7, no. 1, p. 8, Dec. 2022, doi: 10.1186/s41601-022-00232-3.

[131] D. K. J. S. Jayamaha, K. K. M. Siu, C. N. M. Ho, and A. D. Rajapakse, “Design and Development of Modular Hybrid DC Breaker Scheme for DC Distribution Systems,” Nov. 2021, pp. 5920–5926. doi: 10.1109/ecce47101.2021.9595192.

[132] S. Nandakumar, I. Venkata Raghavendra, C. N. Muhammed Ajmal, S. N. Banavath, and K. Rajashekara, “A Modular Bidirectional Solid State DC Circuit Breaker for LV and MVDC Grid Applications,” *IEEE J Emerg Sel Top Power Electron*, pp. 1–1, May 2022, doi: 10.1109/jestpe.2022.3177248.

[133] M. Singh, “A q component-based adaptive protection coordination optimisation using overcurrent relays in coordination with fuses for hybrid microgrid,” *IET Generation, Transmission & Distribution*, vol. 15, no. 14, pp. 2061–2074, Jul. 2021, doi: 10.1049/gtd2.12156.

[134] Y. Liu, Y. Gu, D. Yang, and J. Wang, “Fault Identification and Relay Protection of Hybrid Microgrid Using Blockchain and Machine Learning,” *IETE J Res*, pp. 1–11, Mar. 2022, doi: 10.1080/03772063.2022.2050307.

[135] A. G. Rameshrao, E. Koley, and S. Ghosh, “An optimal sensor location based protection scheme for DER-integrated hybrid AC/DC microgrid with reduced communication delay,” *Sustainable Energy, Grids and Networks*, vol. 30, Jun. 2022, doi: 10.1016/j.segan.2022.100680.

[136] W. Bower and T. Key, “Status of Microgrid Protection and Related Standards and Codes: Protection Supports Integration,” *IEEE Power and Energy Magazine*, vol. 19, no. 3, pp. 83–92, May 2021, doi: 10.1109/MPE.2021.3057975.

[137] International Electrotechnical Commission (IEC), “Microgrids - Part 3-1: Technical requirements - Protection and dynamic control,” 2020

[138] IEEE Draft Guide for the Design of Microgrid Protection Systems -, *IEEE P2030.12/D1.4*. 202AD.

[139] B. Kasztenny, J. Whatley, E. A. Udren, Burger John, Finney Dale, and Adamiak Mark, “IEC61850-Practical-Application-Primer-for-Protection-Engeneers,” Atlanta, May 2006.

[140] I. Mesmaeker, C. Brunner, and K.-P. Brand, “How to use IEC 61850 in protection and automation,” Switzerland, Oct. 2005.

[141] J. Bruinenberg *et al.*, “CEN-CENELEC-ETSI Smart Grid Co-ordination Group Smart Grid Reference Architecture,” 2012.

[142] J. Ekanayake, “Protection of Microgrids,” in *Microgrids and Local Energy Systems*, IntechOpen, 2021. doi: 10.5772/intechopen.99149.

[143] IEEE STANDARDS ASSOCIATION, *2030.8-2018 - IEEE Standard for the Testing of Microgrid Controllers*, IEEE. New York: IEEE, 2018.

[144] N. Hussain, M. Nasir, J. C. Vasquez, and J. M. Guerrero, “Recent developments and challenges on AC microgrids fault detection and protection systems-a review,” *Energies*, vol. 13, no. 9. MDPI AG, May 01, 2020. doi: 10.3390/en13092149.

[145] A. Mohamed, S. R. B. Vanteddu, and O. Mohammed, “Protection of bi-directional AC-DC/DC-AC converter in hybrid AC/DC microgrids,” in *Conference Proceedings - IEEE SOUTHEASTCON*, 2012. doi: 10.1109/SECon.2012.6196958.

[146] S. P. Rosado and S. K. Khadem, “Development of Community Grid: Review of Technical Issues and Challenges,” *IEEE Trans Ind Appl*, vol. 55, no. 2, pp. 1171–1179, Mar. 2019, doi: 10.1109/TIA.2018.2883010.

[147] I. Serban, S. Cespedes, C. Marinescu, C. A. Azurdia-Meza, J. S. Gomez, and D. S. Hueichapan, “Communication requirements in microgrids: A practical survey,” *IEEE Access*, vol. 8, pp. 47694–47712, 2020, doi: 10.1109/ACCESS.2020.2977928.

[148] A. Srivastava, R. Mohanty, M. A. F. Ghazvini, L. A. Tuan, D. Steen, and O. Carlson, “A Review on Challenges and Solutions in Microgrid Protection,” in *2021 IEEE Madrid PowerTech*, Jun. 2021, pp. 1–6. doi: 10.1109/PowerTech46648.2021.9495090.

[149] V. Almonacid and L. Franck, “Extending the coverage of the internet of things with low-cost nanosatellite networks,” *Acta Astronaut*, vol. 138, pp. 95–101, Sep. 2017, doi: 10.1016/j.actaastro.2017.05.030.

[150] S. Paul, N. Maity, S. Sinha, S. Basu, S. Mondal, and R. Porel, “A Comprehensive Review of the Available Microgrid Protection Schemes and Their Challenges,” 2021. doi: 10.1007/978-981-33-4604-8_45.

[151] H. E. Keshta, A. A. Ali, E. M. Saied, and F. M. Bendary, “Real-time operation of multi-micro-grids using a multi-agent system,” *Energy*, vol. 174, pp. 576–590, May 2019, doi: 10.1016/j.energy.2019.02.145.

[152] H. Khalid and A. Shobole, “Existing Developments in Adaptive Smart Grid Protection: A Review,” *Electric Power Systems Research*, vol. 191. Elsevier Ltd, Feb. 01, 2021. doi: 10.1016/j.epsr.2020.106901.

[153] V. Shanmugapriya, S. Vidyasagar, and K. Vijayakumar, “Recent Developments in AC and DC Microgrids: Systematic Evaluation of Protection Schemes,” *International Journal of Renewable Energy Research*, Dec. 2021, doi: 10.20508/ijrer.v11i4.12377.g8338.

[154] J. Reilly and S. S. M. Venkata, “Microgrid Protection: Its complexities & Requirements,” *IEEE Power and Energy Magazine*, vol. 19, no. 3. Institute of Electrical and Electronics Engineers Inc., pp. 14–19, May 01, 2021. doi: 10.1109/MPE.2021.3057949.

[155] Z. Cheng, E. A. Udren, J. Holbach, D. Hart, M. J. Reno, and M. Ropp, “SANDIA REPORT Low Voltage Network Protection Utility Workshop-Summary and Next Steps,” 2022. [Online]. Available: https://classic.ntis.gov/help/order-methods/

[156] A. A. Memon and K. Kauhaniemi, “An adaptive protection for radial AC microgrid using IEC 61850 communication standard: Algorithm proposal using offline simulations,” *Energies (Basel)*, vol. 13, no. 20, Oct. 2020, doi: 10.3390/en13205316.

[157] V. Farias, C. Cavalieri, and M. Kabalan, “Microgrid Protection Testing Using a Relay-Hardware-in-the-Loop Testbed,” in *2021 North American Power Symposium (NAPS)*, Nov. 2021, pp. 1–6. doi: 10.1109/NAPS52732.2021.9654656.

[158] H. A. B. M.-I. N. H. Amjad Anvari-Moghaddam, *Microgrids*. Cham: Springer International Publishing, 2021. doi: 10.1007/978-3-030-59750-4.

[159] F. Flores-Espino, J. Giraldez Miner, and A. Pratt, “Networked Microgrid Optimal Design and Operations Tool: Regulatory and Business Environment Study,” Golden, CO (United States), May 2020. doi: 10.2172/1659812.

[160] T. Wu, Z. Wang, C. Fang, and S. Liu, “Research on current limiting solid state circuit breaker for DC microgrid,” *Electric Power Systems Research*, vol. 209, p. 107950, Aug. 2022, doi: 10.1016/j.epsr.2022.107950.

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