IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 2, 2022, accepted March 7, 2022, date of publication April 5, 2022, date of current version April 15, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3165011

Microgrid Protection Challenges and Mitigation Approaches–A Comprehensive Review

MUHAMMAD WASEEM ALTAF, (Graduate Student Member, IEEE), **MOHAMMAD TAUFIQUL ARIF**, (Member, IEEE), **SHAMA NAZ ISLAM**, (Member, IEEE), AND **MD. ENAMUL HAQUE**, (Senior Member, IEEE)

Renewable Energy and Electric Vehicle (REEV) Laboratory, Centre for Smart Power and Energy Research (cSPER), Deakin University, Geelong, VIC 3216, Australia.

Corresponding author: Muhammad Waseem Altaf (maltaf@deakin.edu.au)

ABSTRACT Microgrids gain popularity due to their economical and environmental benefits along with low power losses and smaller infrastructure. However, it has several operational challenges such as power quality, power system instability, reliability, and protection issues. Microgrid protection strategy is a prime issue for the reliable operation of the microgrid. The microgrid protection scheme must meet the essential conditions for grid-connected and islanded operational modes. This paper presents a comprehensive review and comparative analysis of protection schemes and their implementation challenges for different microgrid architectures with various operational requirements. The challenges associated with the implementation of microgrid protection schemes are identified and discussed in detail. Furthermore, various simulation studies have been conducted to demonstrate the microgrid protection challenges associated with different modes of operation. This paper presents key information to researchers and protection engineers to identify microgrid protection challenges and their mitigation approaches.

INDEX TERMS Microgrid protection, grid-connected mode, microgrid islanded mode, microgrid structure, microgrid protection challenges, critical analysis, solution approaches.

NOMENCLATURE

I_F	Total fault current.
$I_{F,Grid}$	Fault current contributed by the utility grid.
$I_{F,DER}$	Fault current contributed by the DER.
V_{TH}	Pre-fault voltage.
Z_{TH}	Thevenin's impedance.
Z_{Grid}	Utility grid impedance.
Z_{DER}	DER impedance.
Z_{T1}, Z_{T2}	Impedances of transmission line sections.

LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
DERs	Distributed Energy Resources
PV	Photovoltaic
PD	Protection Device
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling
IDT	Islanding Detection Technique
OC	Over Current
LOM	Loss of Mains
LV	Low Voltage
ANSI	American National Standards Institute
CB	Circuit Breaker
TT	French: terre-terre (Earthed neutral)
TN	(French: T=terre) terre-neutral (Exposed conductive parts connected to the neutral)
IT	French: isolé-terre (Isolated earthed neutral)
PSO	Particle Swarm Optimization
IEEE	Institute of Electrical and Electronics Engineers
AS/NZS	Australian/ New Zealand Standards

The associate editor coordinating the review of this manuscript and approving it for publication was Yang Li.

I. INTRODUCTION

The electricity demand is growing with time. Many new power plants have to be installed to fulfill the increasing electricity demand. The conventional fossil fuel based power plants have several drawbacks such as environmental pollution, lower system efficiency, high costs and power losses [1], [2]. Instead of a single large power source, several small-scale generators/ distributed generators such as PV, wind turbines, micro-hydro units are used in the distribution network. These micro-sources are environment friendly but intermittent in nature due to the use of renewable-based energy resources such as solar, wind, etc. These micro-sources and loads cluster is used as they are controllable to provide power to its nearby area which leads to the concept called a microgrid [3].

The term microgrid can be viewed as the cluster of distributed energy resources (DERs) and local loads along with a control and protection system within the specific electrical boundary. A microgrid is an efficient, low cost and resilient local power system consisting of DERs and supplies power to local loads with lower losses compared to traditional system with long transmission lines. From a utility perspective, a microgrid is a self-possessed element of the power system that may be dispatched with local loads without any transmission system. From the consumer perspective, it is a specially designed system that provides efficient, reliable, and stable power with the assistance of a power optimizer, local controller, and protection system [4].

Generally, microgrids have two types of operational modes; islanded mode and grid-connected mode. In grid-connected mode, the microgrid obtains power from the micro-energy resource as well as from the utility grid [6] but the major power supply source is micro energy resources which can be defined as DERs. Further, during the grid-connected mode, the utility grid has a responsibility to fulfill the demand of extra load within the microgrid and provide voltage and frequency stability, reliability to the microgrid functionality [5], [7]. While in islanded mode, micro energy resources are the only source of energy that fulfills the requirement of the load. In islanded mode, energy management is the key to meet load demand at peak and off-peak load time. At the peak demand time, the power balance is maintained by supplying power to essential loads only and in off-peak time excess energy is stored in the local storage.

The increasing penetration of DERs such as wind turbines, PV arrays, fuel cells, energy storage units, etc., integrates into the microgrid which acts as a cluster of interconnected DERs and electrical loads within a certain defined electrical jurisdiction. With appropriate control, the microgrid offers power factor correction, voltage and frequency regulation, and power quality. In addition to the benefits of microgrids such as economic and environmental benefits, low cost, less infrastructure, and low power losses [8], a microgrid faces a lot of operational and technical challenges such as system stability, voltage/frequency regulation, power quality and protection issues.

The protection of distribution network is primarily based on the level of fault current, and direction of current flow in a radial form of network. With the presence of DER, the direction of current flow and level of fault current can vary over time. Therefore the concept of protection of microgrid is different and more challenging than the traditional protection schemes. The main objective of a microgrid is to supply continuous and reliable power to consumers without using fossil fuel to reduce green gas emissions. The fault current level depends on the power generation sources, load location, and impedance [9]. These factors change during grid-connected and islanded modes. The fault current level is high during grid-connected mode as both utility grid and DERs are contributing to the fault and fault current is low during islanded mode as fault current is only contributed by the DERs. For example, any fault arises from the utility side and away from the microgrid, the utility side should be isolated and if the fault occurs within the microgrid, only the faulty part of the microgrid should be isolated [10] to protect the microgrid. As fault current varies with the DERs integration level and depends on the operational mode of the microgrid. The current protection system for microgrid should be modified according to the level of DERs integration and operational modes. As the renewable based energy sources are intermittent in nature, they introduce fluctuation in generated power and the fault current level changes according to the penetration level of energy sources [11].

The traditional protection scheme used for conventional power system depends on certain level of fault current and a single threshold setting is adequate for relay operation. However, it can may not operate properly and fails when fault current changes due to change in current due to intermittent generating sources or other disturbances [12]. Therefore, the conventional protection schemes which are designed for conventional network system is not suitable for a microgrid with DER due to the following reasons [13].

- Bidirectional Power flow
- Intermittencies in the renewable based microgrid
- At islanded mode faults current level is different
- Fault current level varies with the operational mode
- DER type, either it is directly fed or inverter fed

The traditional protection systems are only suitable for the unidirectional power flow and relays are made for specific fault levels. Fault level changes with the DERs integration level and operation modes. So, the traditional protection system is not suitable for microgrid protection [27].

For reliable operation of a microgrid in islanded and grid-connected mode, a suitable protection strategy is required. In this review article, we have classified microgrid protection structures, essential conditions in microgrid protection, microgrid protection challenges, critical analysis, and suggestions. Both AC and DC microgrid protection methods have been described in microgrid protection structures. Essential conditions in microgrid protections are discussed that include microgrid topology, microgrid type, DER type, relay type, fault type, earthing schemes, and various protection constraints. The DC and AC microgrid protection

TABLE 1. A comparison of recent review articles with this work related to the microgrid protection.

Ref. No.	MG-PS		EC in MGP							AC MG PC									DC MG PC	ST	CA	SR
	AC	DC	MGT	MGTy	DERTy	RTy	FTy	ES	PC	DFCM	FDGCM	FDIM	LOM	BOP	PD	FT	ReS	ARP				
[14]	√	√					√				√	√	√		√				√	√	√	
[8]	√	√	√	√															√	√		
[15]	√									√				√		√	√	√		√		
[9]										√										√		√
[13]	√		√							√										√		
[16]			√	√				√		√				√		√		√	√	√		
[17]		√					√												√	√		
[18]	√												√			√				√		
[19]	√								√	√										√		
[20]	√												√	√		√		√				
[10]	√																			√		
[21]	√																			√		
[22]											√	√								√		
[23]	√										√	√	√	√	√	√	√			√		
[24]	√	√			√	√							√	√	√	√	√	√		√		
[25]	√									√			√	√						√		
[26]		√	√	√		√	√	√							√				√	√	√	
This Work	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√

In Table 1, MG-PS = Microgrid structure, EC in MGP = Essential conditions in microgrid protection, AC MG PC = AC microgrid protection challenges, DC MG PC = DC microgrid protection challenges, ST = Solution Techniques, CA = Critical analysis, SR = Simulation results, MGT = Microgrid topology, MGTy = Microgrid type, DERTy = DER types, RTy = Relay type, FTy = Fault type, ES = Earthing schemes, PC = Protection constraints, DFCM = Dynamics in fault current magnitude, FDGCM = Faults during grid-connected mode, FDIM = Faults during islanded mode, LOM = Loss of mains, BOP = Blinding of protection, PD = Protection devices, FT = False tripping, ReS = Re-synchronisation, ARP = Auto recloser problems

challenges are analysed in detail in this paper. AC microgrid protection challenges include islanding (LOM or external fault), dynamics in fault current magnitude, blinding of protection, auto-recloser problems, switch selection, false tripping re-synchronization, and faults events during the grid-connected mode.

Simulation results demonstrating challenges of AC protection have also been discussed and analyzed. Grounding is one of the main challenges in DC microgrid protection which is being discussed in terms of DC ungrounded system, resistive grounding system, solidly grounded system, and lack of zero-crossing. Table 1, presents different mitigation approaches of microgrid protection as discussed in different literatures.

A comparison of this work with past review articles on the subject is presented in Table 1, which reveals that the area related to microgrid protection under investigation has not been covered in the existing literatures. For example, in [20], authors discuss different protection challenges for the power systems having high penetration of renewable energy resources. In [10], critical analysis for hybrid AC and DC microgrid has been presented. A review of different coordination schemes for the protection of microgrids has been presented in [21]. In [22], the authors analyze the impact of the failure of a communication system on microgrid protection schemes. Various issues and the available solutions related to the protection of AC microgrids have been described in [23]. In [24], [25], different solutions and the involvement of various factors for microgrid protection have been analyzed.

The main purpose of this paper is to highlight and investigate all microgrid protection-related problems as well as suitable solution approaches according to the DERs integration level, types of DERs are used and different microgrid configurations. The main contribution of this paper is as follows.

- Study the microgrid protection structure and requirement.
- Study the essential condition of the microgrid protection in terms of microgrid topology, microgrid type, DERs type, relay types, earthing requirements, and protection constraints such as selectivity, sensitivity, reliability, etc, of relays.

- Investigation of microgrid protection issues with mathematical modeling and simulation results
- The critical analysis and suitable solution approaches related to microgrid protection are discussed according to the protection issue.

The remaining paper is arranged as follows. In section II, microgrid structures have been discussed. Section III elaborates on the essential conditions in microgrid protection. Section IV discusses various microgrid protection challenges. Section V depicts the critical analysis and solution approaches related to microgrid protection. Finally, section VI concludes the review article and highlights some future research scope relating to the subject area under analysis.

II. MICROGRID STRUCTURE

The microgrid can be defined as a decentralized network of DERs units and loads that are situated within specific electrical boundaries. The microgrid can implement its operations in an islanded mode where it works independently without external control or in a large area grid-connected mode [16]. Microgrids are divided into two major groups: AC and DC microgrids based on their framework of operations. The detail of the AC and DC microgrid's structure is explained as follows.

A. AC STRUCTURE

In an AC microgrid, all DERs and AC loads are connected by using AC buses. The DERs which are generating DC power can be connected to AC buses by converters which are used for the conversion of power from DC to AC. The load is connected to the AC bus using a transformer that brings the required voltage level [14]. An uninterrupted power supply (UPS) system may be connected in which the battery is used to provide better service. LV AC bus is connected to the AC utility grid through transformers and CBs at the PCC. PDs (relays, CBs, fuses, and switches) are placed to protect DER, load side, power converters, and transformers [28]. AC microgrid system as shown in Figure 1. An AC microgrid can be a three or single-phase system and can be operated in utility grid-connected or islanded mode. In Figure 1, the AC microgrid is connected to the utility grid through PCC. The AC microgrid has DER, energy storage, and loads that are connected to the load. The PDs such as fuse, CBs, relays, etc; are placed at each DERs, energy storage, and each load. The key advantages of AC microgrids are given as [29], [30];

- The ability to integrate and operate with the utility grid or can work independently makes it versatile [31].
- It has a compatibility to supply the power to the AC equipment such as motor easily without any inverter needed for power conversion [32]
- A cheaper protection system is required for the AC microgrids
- Higher load is available for AC microgrid

The AC microgrid has some disadvantages which are given as follows [33];

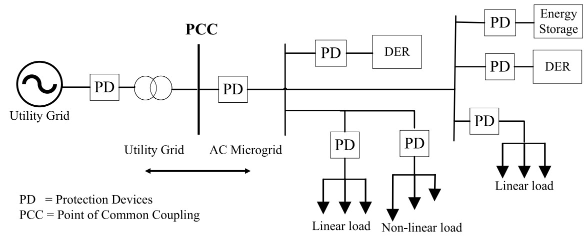

FIGURE 1. Typical AC microgrid.

- Expensive converters (such as DC to AC converter) are needed in AC microgrid when DERs are generating DC power output
- Low conversion efficiency due to loss of power during conversion
- Controllability difficulty due to factors of voltage regulation, frequency stability, and power unbalance
- Higher transmission losses

B. DC STRUCTURE

In DC microgrid DC source-based DERs like PV, fuel cells, energy storage, and DC load are directly connected to the DC buses through DC-DC converter if needed. AC source-based DERs like a wind turbine, micro-turbine, diesel generators can also be connected to DC buses through an AC-DC converter [34], [35]. DC microgrid structure is as shown in Figure 2. DC bus is connected to the utility grid through the transformer and power electronics converters at the PCC. Loads are connected to the DC bus through the converter if required. The bidirectional converter is required to maintain the voltage between the battery and the DC buses. DC source-based DERs are connected to the DC bus through the boost converter [36]. AC source-based DERs such as wind and micro-turbines are connected to DC bus via AC-DC converter. PDs (relays, CBs, fuses, and switches) are placed at each DERs, load, power converters, and transformer. DC loads such as mobiles, laptops, and a lot of other high-efficiency DC loads are utilizing DC power. DC microgrid bus may evade the use of power electronic conversion equipment for conversion of AC to DC power from the AC utility grid [37]. This decreases the losses during the conversion of power and transmission of energy and decreases the cost of operation.

DC microgrid has the following advantages [38]–[42]:

- Decrease the power loss during the conversion of power from AC-DC
- Decrease the cost of power electronics equipment due to fewer conversion stages
- No transmission losses as there are no transmission lines
- Simple control structure as there is no requirement for ancillary services

The DC microgrid has some disadvantages which are given as follows [43], [44];

- Inadequate power protection system for DC microgrids that can increase the risk factor, especially for sensitive DC loads

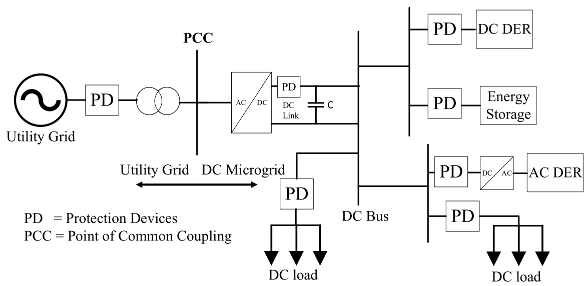

FIGURE 2. Typical DC microgrid.

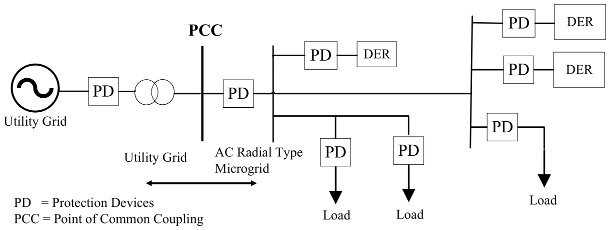

FIGURE 3. Radial/multi-bus type AC microgrid.

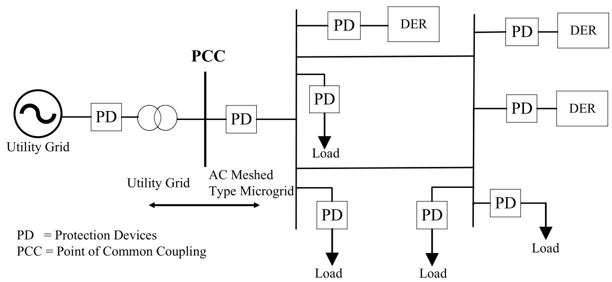

FIGURE 4. Ring type AC microgrid.

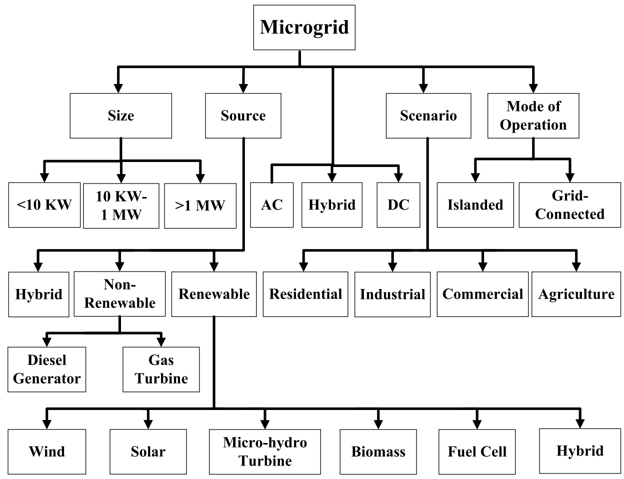

FIGURE 5. Microgrid classification.

- High initial infrastructure cost that creates hurdle in its implementation
- Less awareness about DC microgrids in the market
- Due to more number of AC loads, DC microgrid has low compatibility to feed AC loads

It is concluded from the above microgrid structure discussion that AC and DC microgrids have different structures due to the different nature of current flow with different pros and cons. So, both AC and DC microgrids have different types of protection challenges. In the next section, the essential condition in microgrid protection will be discussed. Essential conditions include microgrid topology, microgrid types, the influence of different types of DERs in the microgrid protection, fault types, relay types, and different protection constraints which will be discussed.

III. ESSENTIAL CONDITIONS IN MICROGRID PROTECTION

A. MICROGRID TOPOLOGY

Microgrid systems may either be a single bus, multi-bus, ring/mesh, looped or mixed [24]. Magnitude and direction of fault current and microgrid protection strategies depend on the topology of the microgrid, for example, fault current in loop structure distributes into two parallel lines. So, upstream feeder PDs monitor double fault current flowing from these two parallel lines in a loop structured microgrid. In article [45], a DC microgrid protection scheme is presented for the loop topology microgrid. Fault current is the same in downstream and upstream branches in mesh structured microgrid [46].

B. MICROGRID TYPE

Designing of secure protection system for the microgrid depends on the types of microgrid because the same protection scheme is not valid for all types of microgrids due to different load conditions, generation sources, and converters. Microgrids can be AC, DC, and hybrid depending on the DERs size, scenario, and operational mode. Different types of microgrids [47] are shown in Figure 5. The major challenge in microgrid protection is that the fault current level changes as the operational mode is changed from grid-connected to islanded mode. Another major problem is the minimum practical experience for the protection methods applied on the DC microgrid. PDs are available for both DC and AC systems but some of them are specially manufactured for DC systems, yet some of them may be used for AC systems. This factor should be kept in mind while designing protection schemes because DC and AC systems have different operational ratings [48].

C. DER TYPES

Traditional DERs are considered as large power-generating sources that are integrated into the same power grid. Now, DERs are considered as renewable energy resources i.e solar and wind which are interconnected in the microgrid. Some DERs are inverter-based DERs (IBDERs) which are mostly integrated into microgrids. These IBDERs are inverter-based fixed power controlled DERs and, frequency and voltage control inverter-based DERs [49]. Operations of traditional DERs and IBDERs are briefly discussed in this section.

1) TRADITIONAL DERs

Traditional DERs are mostly based on a synchronous machine that has high fault current input. The existence of this type of DERs in microgrids can interrupt the microgrid stability and protection coordination [50]. So their consequence should be studied carefully.

2) INVERTER BASED FIXED POWER CONTROLLED DERs

IBDERs are operating in the control mode of constant power. Reactive and real powers are shared with the rest of the microgrid or utility grid to control the frequency and voltage. It means that another source controls the frequency and voltage [51]. Hence, it may be assumed as a source of constant current that inserts power into the grid. A suitable algorithm is needed for proper synchronization of another source of real and reactive power [52]. High-level controllers like MPPT in PV cells and wind turbines may contribute to power-sharing [53] which are also known as voltage source grid-feeding inverters. These IBDERs have also an internal current-control-loop [51].

3) FREQUENCY AND VOLTAGE CONTROL-BASED IBDERs

Intermittent IBDERs frequency and voltage level fluctuated which is stabilized by incorporating optimal reserve power. By controlling the reserve power input, voltage and frequency level is maintained [54]. For voltage stability, the reactive power reserve is needed. Frequency instabilities occur due to low inertia and low power generation that is required due to intermittencies. At intermittencies, frequency level is maintained at the specified level, the active power reserve is required. Frequency instability due to low inertia is stabilized by reactive power reserve [55].

D. FAULT TYPE

The microgrid concept allows high integration of DERs without changing the design of a distributed system. In case of a fault in DERs and load, faulty parts can be isolated autonomously from the rest of the system. The microgrid will intentionally disconnect from the utility grid when its power quality falls under a specific standard [56]. When the microgrid is integrated with the utility grid and fault occurs at the utility grid, the microgrid is separated smoothly from the utility grid. The reconnection of microgrid with utility grid is made again when the fault is handled. Generally, during the grid-connected mode of microgrid, the DERs operate as constant power sources, which are controllable to insert the extra power into the network. In islanding mode, the DERs are responsible to fulfill the power demand of the local loads by maintaining the frequency and voltage within standard operating ranges.

The islanding is only done by suitable and fast IDT. The power flow is bidirectional when the microgrid is connected with the utility grid. When a fault occurs on the utility side then the microgrid is isolated from the utility grid [57], [58]. Then the relay on the PCC checks the active and reactive power balance to monitor the voltage and frequency whether these are in standard range or not. If frequency and voltage parameters are not within standard range then the relay sends a signal to the DER to disconnect the local loads to protect the equipment. These problems are due to steady-state or transient under or over voltage, power quality problems, short circuit level modification, false tripping, blinding of protection relay, and a lot of other reasons [18]. Different types of faults occur in the microgrid like high and low impedance faults, single and three-phase faults, short circuit faults, symmetrical and unsymmetrical faults, and voltage sags faults [24], [59]. The fault current level is high during grid-connected mode due to both utility grid and DERs are supplying to the fault point. On the other hand, in islanded mode, the fault current level is low because only DERs are supplied to the loads. So, it is necessary to use a suitable relay with different settings which should detect the fault during both grid-connected and islanded modes [15].

E. RELAY TYPE

As discussed earlier, the fault current level is different during both operational modes of microgrid and current flow is bidirectional. So, the use of a suitable relay according to the microgrid conditions would handle any type and level of fault current. Normally, different types of relays are applied in the protection of microgrid schemes. These are OC, voltage, differential, distance, and admittance relays [60].

1) OVER-CURRENT (OC) RELAY

OC relay is the most effective device used in the conventional distribution system. Due to the integration of DERs into the existing power system and two operational modes of microgrid like grid-connected and islanded change the level of short-circuit current considerably [61]. This problem creates confusion for the OC relays having conventional settings. So, it is necessary to reconfigure the OC relay with adaptive settings which cope with the changed fault current level and different working conditions [62]. This relay can also work with different saved settings for different scenarios either applied online or offline and this plan is explained in [63].

2) VOLTAGE RELAY

Over/under voltage, relays are used to protect PV type DERs in different voltage level networks. These relays settings are regulated according to the related standards that settings presented in [64].

3) DIFFERENTIAL RELAY

Differential relays are used in differential protection systems. Each differential relay has a set of five elements from which two differential elements are for zero and negative sequence current and three differential elements are for each phase. The phase elements are assigned to provide instant protection during high fault current. The remaining elements are responsible to protect the system during low fault unbalanced current which occurs in the feeder [65].

F. EARTHING SCHEMES

In an electrical system, an efficient earthing system is essential to decrease electrical hazards for preventing damage to electrical appliances from excessive current and increase human safety for preventing electric shocks. Earth grounding helps to save away the electrical charges from other unexpected sources such as a lightning strike. The earth grounding system can safely dissipate electricity from lightning [66]. The adapted earthing system decreases voltages and reduces electrical shocks. Furthermore, the return path is provided to leakage currents by the earthing system so that PDs can recognize and disconnect the fault [67]. Mostly, TN, IT and TT systems are three types of earthing configurations. These earthing configurations are distinct in connections of electrical appliances to earth and transformer neutral. In articles [67]–[69], authors described that the most suitable earthing configuration system is a TN system for microgrid applications. In this earthing configuration, the earth is connected to electrical appliances frame and transformer neutral. This system gives a high fault current through which PDs can recognize and disconnect the fault. The value of touch voltage will also be in the range which fulfills the safety margin by applying the TN system.

G. PROTECTION CONSTRAINTS

The power system protection depends on the system configuration like a ring, radial, microgrid, or DER system should fulfill the designing and adapting requirement for the protection relays. These requirements are selectivity, sensitivity, reliability, operational speed, simplicity, redundancy, and consistency [70], [71]. For example, if a fault occurs at the far point of the generator then fast protection is not needed because the fault current is not too much high due to high impedance in between fault point and generators. On the other hand, when a fault occurs to the generator, then fast protection is required due to high fault current to prevent the equipment from damage from high fault current. So, protection requirement is different according to the fault location, fault current level, and generation level. Some requirements are the responsibility of the manufacturer and others are the responsibility of the protection engineers. Deficiency of any requirements results in the protection system weaknesses [9], [26], [72]–[74].

1) SELECTIVITY

Selectivity is the competency of the relays to distinguish between fault zone and out fault zone.

2) SENSITIVITY

Selectivity is the reaction of the relay when a fault occurs in its protection zone.

3) RELIABILITY

Reliability is the major factor to test the protection system. Reliability depends upon the two important factors dependability and security which are responsible for the protection system whether it is reliable or not.

4) DEPENDABILITY

The relay should operate accurately when necessary to operate and should be designed to execute properly when itself undergoing a reasonable failure.

5) SECURITY

A power protection system should be designed as relays should not operate unnecessarily when it is not needed to operate on the no-fault condition, and reject all transients and other system events to avoid incorrect operation.

6) SPEED

The relay should operate as fast as possible on any fault to protect the equipment.

7) CONSISTENCY

The relay should restore its time and electrical properties.

8) SIMPLICITY

Minimum protected relays should be installed to protect equipment.

9) REDUNDANCY

A protection system should be installed as relays have a redundancy function. It means that every power system area has backup relay protection. Redundancy is the combination of two different protection principles for the protection of the same equipment such as differential and distance protection for the transmission lines.

10) COST

A protection system should have maximum protection at the lowest possible cost.

It is concluded from this section discussion that microgrid protection schemes should be according to the microgrid type, topology, DERs types, fault type. So, the integration of DERs into microgrid systems creates different types of protection challenges. In the next section, AC and DC microgrid protection challenges will be discussed due to the above-discussed protection essential conditions.

IV. MICROGRID PROTECTION CHALLENGES

A. AC MICROGRID PROTECTION CHALLENGES

As discussed earlier, the microgrid is a cluster of DERs and loads within a specific electrical boundary [3], [75]. DERs are based on renewable and non-renewable energy sources. The non-renewable-based DERs are providing constant power. But renewable-based DERs such as solar and wind are intermittent. These are relying on environmental conditions. Solar PV generation is based on the solar irradiation intensity. The solar irradiation intensity is not constant throughout the day. The irradiation intensity decreases in cloudy weather. So, it affects the overall solar PV-based DERs generation [76]. As well, wind turbine-based DER output power generation depends on the wind speed. As wind speed is not constant, the wind turbine-based DERs power generation is not constant [77]. Therefore, due to above mentioned intermittent nature of solar and wind-based DERs, the overall power generation of all DERs in the microgrid is not constant. Thus, these fluctuations in power generation disturbed the microgrid protection system as fault current varies which causes the mis-operation of relays.

On the other hand, the fault current depends on the position of DERs. Fault current is high near the DERs and low if the fault point is far from the DERs. The fault current depends on the total impedance between DERs and fault points. The total impedance varies depending on the distance between fault point and DERs generation. So, it is necessary to analyze the microgrid protection challenges related to the DERs integration level in grid-connected and islanded mode [78].

AC Microgrid protection challenges can be generally separated into two types; protection challenges when the grid-connected operational mode of microgrid and protection problems when the operational mode of a microgrid is islanded. In grid-connected operational mode, protection problems are associated with a response time of CB at the PCC of microgrid and utility grid, false tripping at isolation devices, re-synchronization as well as the speed of reconnection of microgrid with utility grid after the issue is resolved [14]. Response time of CBs or other PDs in the microgrid during grid-connected mode for events are also considered. In the islanded operational mode of microgrid, the response time of PDs for events in a microgrid depends upon the complications of the microgrid. The major interest in islanded operational mode is to reduce short-circuit current in which overcurrent (OC) protection relays response time is greater than required time [79], [80]. Different types of challenges of protection of microgrid with the integration of renewable energy resources are discussed in Figure 6. Though AC microgrids have many advantages, there are challenges involved in protecting AC microgrids that system engineers and researchers are trying to solve. To determine the safe and reliable performance of power system grid appropriate PDs along with the fast operation, better selectivity, flexibility, simplicity, novel setting opportunities, low cost should be chosen. More attention is required to sort out the protection problems of microgrids.

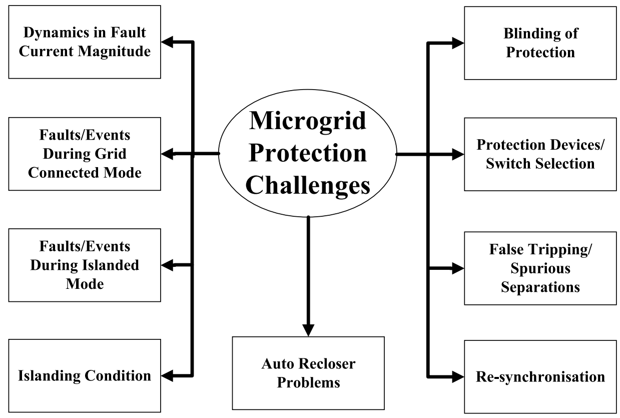

FIGURE 6. Challenges in microgrid protection.

1) DYNAMICS IN FAULT CURRENT MAGNITUDE

As discussed earlier, some renewable-based DERs are intermittent. The fault current contribution by that DERs is also intermittent. The fault current depends on the nature of DERs, size, and location of integration to the microgrid. The DER connection in the LV network shifts the fault level to a significant level generally in two primary operational modes that are grid-connected and islanded. In grid-connected operational mode, the fault current is significantly high due to both DERs and utility grid contribution within the microgrid which feeds the fault. But in islanded operational mode fault current is very low because low-powered DERs are the only source in a microgrid. Furthermore, the fault current feed by DER changes with respect to DER type. DER of synchronous type contributes fault current 5 times more than the rated current [81].

On the other hand, According to the ''National Renewable Energy Laboratory, USA'' report, the DER of inverter type contributes 1 to 2 times of rated current [25], [82] and ''rule of thumb'' applied for relay pickup value settings when DERs integration level is low. The fault current level significantly increased when DERs penetration level increased. So, relay pickup settings should be according to the DERs integration level. DERs of the renewable energy resources types are extremely intermittent. Therefore, that type of DERs only contributes fault current in ON condition. Hence the fault current magnitude observes changing depending upon the operational mode, DERs type, and number of DERs. Thus, it is hard to anticipate fault current exactly [83].

The main grid feeds short-circuit current to the faulty point during the grid-connected mode of operation. In distribution network the protection is performed by existing protection scheme but in islanding mode of operation DER units in the microgrids provide fault currents is very low as compared to the fault currents during grid-connected mode then the traditional PDs are not valid and there will be need of alternative solutions [10]. The reduction of fault current magnitude during islanding mode can be overcome by installing a supercapacitor or flywheel with power electronics converter-based DERs in the LV side of the busbar which raises the value of fault current. This can overcome the fault current magnitude issue in some manner. This technique requires a huge investment in installing, operating, and maintenance of that heavy capacity storage equipment [84].

A simulation model which is shown in Figure 7 is developed to analyze the underlying discussed challenge of dynamics in fault current magnitude. The synchronous-based DER is used in this simulation. Figure 8 represents the fault levels in the grid-connected and islanded mode of microgrid both at highlighted fault point 1 and fault point 2

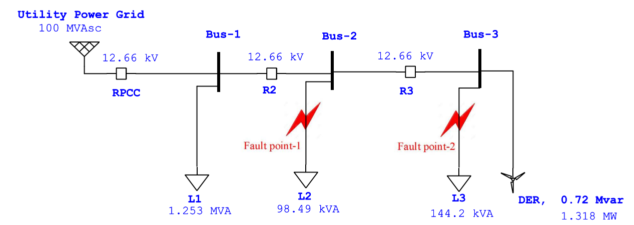

FIGURE 7. Test system used to investigate dynamics of fault current level.

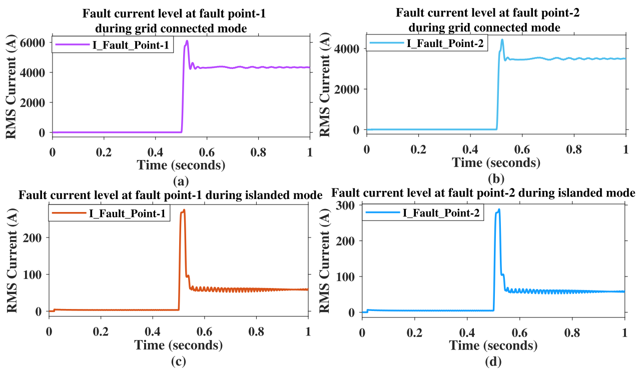

FIGURE 8. Fault current dynamics (a) RMS current level at fault point-1, and (b) RMS current level at fault point-2 during grid-connected mode, (c) RMS current level at fault point-1, and (d) RMS current level at fault point-2 during islanded mode.

in Figure 7. The fault current value is shown in Root mean square (RMS). Figures 8 (a,b) shows the fault current in grid-connected mode at fault point 1 and fault point 2 as shown in Figure 7. While, Figures 8 (c,d) shows the fault current during islanded mode at fault point 1 and fault point 2 as shown in Figure 7 during the grid-connected mode. The three-phase fault occurs at 0.5 seconds of simulation time. The microgrid is disconnected from the utility grid through the PCC at the RPCC CB as can be seen in Figure 7. It can be seen that fault current levels at both fault points 1 and 2 are high during grid-connected mode because both utility grid and DER are contributing to the fault. While fault current levels at both fault points 1 and 2 are low during islanded mode because only DER is contributing to the fault current. It can be seen that fault current level is high during grid-connected mode is greater than islanded mode at both fault points.

2) FAULTS/EVENTS DURING GRID-CONNECTED MODE

During grid-connected mode, when the fault occurs on the utility grid side, PDs of DERs should not trip before PCC PDs and DERs must keep operational activity during fault detection and tripping of PCC PDs. To recognize such a situation all DERs must have fault ride-through capacity [85]. When the fault occurs in the microgrid side during the grid-connected mode, the feeder/line protection must isolate the faulty part from the network as fast as possible. The action time of protecting devices depends upon the microgrid complexity, protection scheme used, and features of the microgrid. Some non-fault events occur in LV at PCC i.e open phases non-fault and voltage unbalance conditions which are hard to detect and may also create issues for micro sources and sensitive loads. So, some protection schemes should be developed to handle such situations [86]. On the other hand, when the fault occurs within the microgrid boundary during the grid-connected mode, then the microgrid internal protection system must operate and isolate the fault.

A simulation model is shown in Figure 7 which is designed to analyze the underlying discussed challenge of faults/events during the grid-connected mode. Figures 8(a,b) represents the fault levels in grid-connected at highlighted fault point 1 and fault point 2 in Figure 7. Figures 8 (a,b) clearly shows that fault current in grid-connected mode at fault point 1 is greater than the fault current at fault point 2 because the fault current depends on the load and impedance value at that fault point. The fault current level is always high if the fault occurs near the generation unit and low if the fault point is far from the generation unit as total impedance increases as distance increases which results in lower the fault current at the far fault point.

3) FAULTS/EVENTS DURING ISLANDED MODE

The sort of problems in microgrids operated during islanded mode become disparate from the grid-connected microgrid [87]. During the grid-connected operational mode of microgrid, the fault current has a high magnitude which is obtained from the utility-grid to trip traditional OC protection relays/devices. In contrast, microgrid operated in islanded mode has a fault current of almost 5 times the normal current is obtainable.

When a lot of power converter-based DERs are attached in a microgrid, then the fault current of 2-3 times the normal current is accessible, or much less fault current depends on the converter controller method [88], [89]. The traditional OC PDs/relays are normally fixed to run at 2 to 10 times the normal current. Thus, because of the decreasing the drastic fault current level, the current-time management of OC protection relays is disordered; instantaneous OC relays and traditional OC relays having highly inverse features such as the fuses are the most probably affected.

A network is shown in Figure 7 which is designed to analyze the underlying discussed challenge of faults/events during grid islanded mode. The microgrid is isolated from the utility grid through the PCC at the RPCC CB as can be seen in Figure 7 to make the islanded mode. Figures 8 (c,d) represents the fault levels during islanded mode at highlighted fault point 1 and fault point 2 in Figure 7. Figures 8 (c,d) clearly shows that fault current in islanded connected mode at fault point 2 is greater than the fault current at fault point 1 because the fault current depends on the load and impedance value at that fault point as discussed in faults/events during grid-connected mode part.

4) ISLANDING CONDITION DETECTION

Islanding detection helps the smooth and safe transition of the grid-connected operational mode of the microgrid to the islanding mode [90]. Islanding is a state in which the

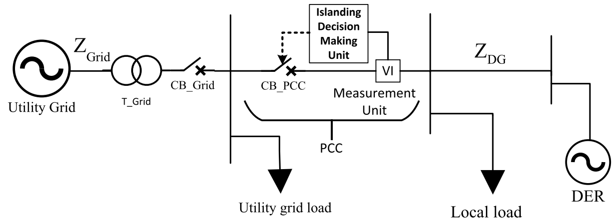

FIGURE 9. Schematic diagram of the test system for islanding condition detection.

microgrid is detached from the utility grid when any fault occurs on the utility grid side or LOM condition occurs [91]. The LOM is a condition when the utility grid supply is isolated and still the part of the utility load is connected with a microgrid. The schematic diagram of the islanding detection scenario is shown in Figure 9. On the left side of the PCC in Figure 9, the utility grid can be seen and on the right-hand side of the PCC, the microgrid is shown. The microgrid is connected to the utility grid through the PCC. The islanding detection relay is located at PCC. This IDT has a responsibility to detect the islanding condition when any fault occurs on the utility grid area or during the LOM of the mains condition. The relay senses the islanding condition and isolates the microgrid from the utility grid at the PCC [92], [93].

LOM (Islanding condition) concerns the separation of the utility grid from the microgrid, yet the microgrid remains coupled with a part of the load in a utility system. This is happened due to (i) utility grid fault (ii) CB associating with utility source having problem (iii) maintenance in power system. This effect leads to the instability of the microgrid [94]. When LOM (islanding condition) occurs then microgrid DERs start supplying to the external load that is outside the microgrid boundary through the PCC. Then DERs of the microgrid are designed to supply the power to the internal microgrid load. During LOM (islanding) conditions, microgrid DERs do not have enough capacity to feed power to an external load. The true challenge occurs when a microgrid with a small DER. In the event of LOM (islanding), the utility grid never controls frequency or voltage. So, it is necessary to detach the microgrid from the utility grid area through PCC as shown in Figure 9.

If the fault occurs on the utility grid side which is outside of the PCC and then DER remains supplied to the fault along with the utility grid [95]. During external fault (islanding) conditions, islanding detection should occur and the microgrid should be isolated from the utility grid area through PCC because fault current flowing in the reverse direction from the microgrid DER towards the fault point which is located at the utility grid area to protect the microgrid equipment [96], [97].

A system model is designed in Figure 10 which is used to study of islanding challenge. RPCC is the PCC in Figure 10. Simulation results are shown in Figure 11 (a) which highlights the effects of fault at utility grid side with

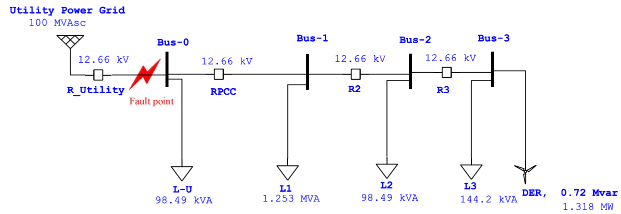

FIGURE 10. Test system for islanding condition detection.

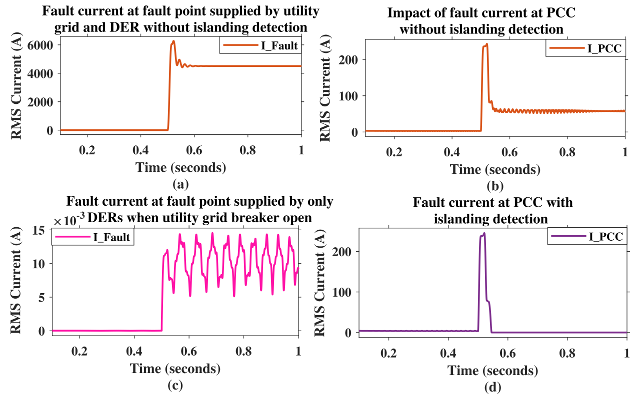

FIGURE 11. Current level at (a) fault point, and (b) PCC without IDT, (c) fault point during LOM, (d) PCC with IDT related to the network as shown in Figure 10.

and without islanding detection. The I_Fault is the fault current during fault at fault point in Figure 10. The simulation results clearly show that without islanding detection at PCC, the utility grid breaker opens on any fault that occurs on utility grid area, the DER still supplying the fault current to the fault point at utility side which may cause a dangerous situation for the utility personnel as can be seen in Figure 11 (c). With islanding detection of the utility grid area is isolated from the microgrid and current flow through PCC is zero as can be seen in Figure 11 (d) and prevent the reverse flow of current from microgrid to utility grid side through PCC.

However, the islanding situation can cause severe governance and operational challenges. Thus, islanding detection is the main provision for the secure operation of microgrids [7]. So, it is essential to recognize the islanding condition and isolate the microgrid from the utility grid area through the PCC within 2 seconds, according to the IEEE 1547 standard [98]. There are several types of IDTs such as active, passive, hybrid passive and active, intelligent classifiers based, communication-based, and signal processing based are available [91], [99]–[105].

5) BLINDING OF PROTECTION

In a conventional radial power system, the pickup value of the OC relay has been configured according to the total impedance value of the feeder. The pickup value of the OC relay is set in such a way that its value is always greater than feeder rated current and smaller than the lowest value of short-circuit current. With the integration of DER into this conventional radial power system, this power system act as a microgrid. Blinding of protection occurs

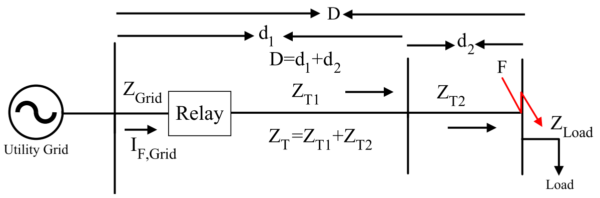

FIGURE 12. Test system without DER to investigate blinding protection.

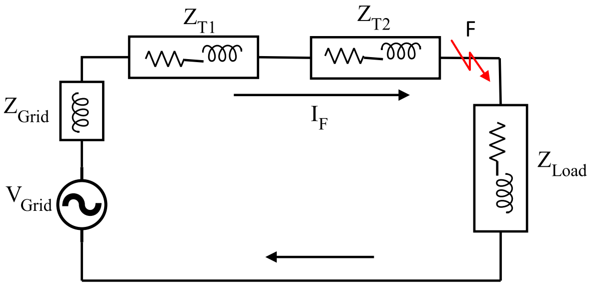

FIGURE 13. Equivalent impedance diagram without DER integration when no blinding of protection occurs.

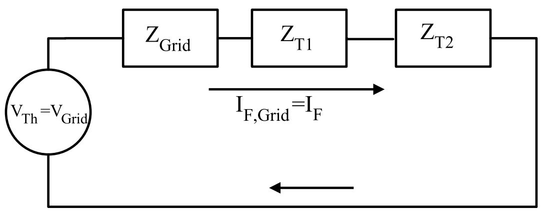

FIGURE 14. Simplified diagram of Figure 13 during fault.

when the integration of DER into this conventional power system due to the addition of DER impedance. Blinding of protection normally occurs only when the renewable energy resource is integrated in-between the utility grid and load [25], [106]–[108]. By increasing the impedance, the value of fault current decreases than the pickup value of the OC relay which is unable to sense the fault current.

To study of blinding of protection problem of a microgrid by creating two sets of networks. The first network is showing the fault current calculation study of the conventional power network and the second one shows the fault current study of the microgrid when DER integration occurs. First, we find the expression for fault current calculation for conventional power systems without integration of DER then find the expression for microgrid when DER integration occurs to study the blinding condition of protection of microgrid. Whenever a fault occurs at the far end of the conventional power system without DER integration is shown in Figure 12, then the OC relay operates and removes the fault due to high fault current flow.

To calculate the total fault current, the equivalent circuit diagram of the conventional power system without DER integration is shown in Figure 13. To calculate Thevenin's voltage V_{Th} and Thevenin's impedance V_{Th}, the Thevenin's-equivalent circuit diagram is shown in Figure 14. The fault is located as distance D, the peak fault

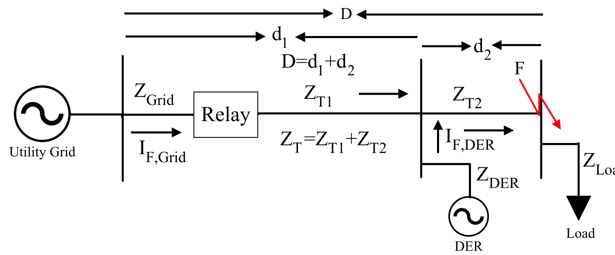

FIGURE 15. Test system with DER to investigate blinding protection.

current is calculated in each phase as an equation (1).

$$I_F = I_{F,Grid} = \frac{V_{Th}}{\sqrt{3}Z_{Th}} \tag{1}$$

where I_F is the total fault current, V_{Th} is pre-fault voltage and Z_{Th} is Thevenin's impedance.

Let Z_{Grid}, Z_{T1}, Z_{T2}, and Z_{Load} represent the impedance of the utility grid, transmission line sections, and load respectively. So equivalent impedance circuit diagram and equivalent Thevenin's circuit diagram of the system can be shown in Figures 13, 14 respectively. Thevenin's impedance can be calculated as an equation (2) [25].

$$Z_{Th} = Z_{Grid} + Z_{T1} + Z_{T2} \tag{2}$$

So we can find the total fault current by putting the value of Z_{Th} as an equation (3).

$$I_F = I_{F,Grid} = \frac{V_{Th}}{\sqrt{3}(Z_{Grid} + Z_{T1} + Z_{T2})} \tag{3}$$

When we integrate a DER to the conventional power system to make a microgrid then a DER supply power to the load and rated current value of the conventional power system also changed to the microgrid impedance due to the addition of a DER impedance. By the addition of impedance of a DER the fault current value decreases than pickup settings of OC relay in the microgrid system. When a fault arises at the ending of the feeder in the microgrid both the DER and utility grid supply to fault current. The Thevenin's impedance immediately provided at the fault point is raised in comparison to the conventional network because of the extra impedance provided by DER in the microgrid [25]. A low power (LV) DER is attached in the microgrid at distance d_1 from the utility grid as shown in Figure 15. The fault is located as distance D, the peak fault current is calculated in each phase as equation (4).

$$I_F = \frac{V_{Th}}{\sqrt{3}Z_{Th}} \tag{4}$$

where I_F is the total fault current, V_{Th} is pre-fault voltage and Z_{Th} is Thevenin's impedance.

Let Z_{Grid}, Z_{T1}, Z_{T2}, Z_{Load}, and Z_{Load} represent the impedance of the utility grid, transmission lines section, DER, and load of the microgrid respectively. So equivalent impedance circuit diagram and equivalent Thevenin's circuit diagram of the system can be shown in Figures 16, 17

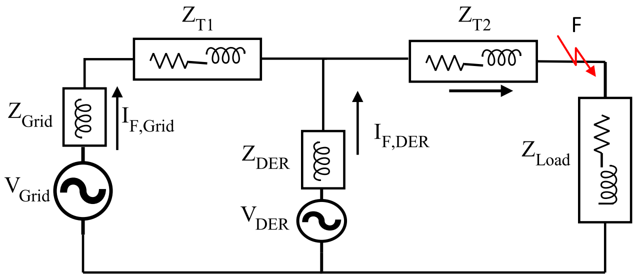

FIGURE 16. Equivalent impedance diagram with DER integration when blinding of protection occurs.

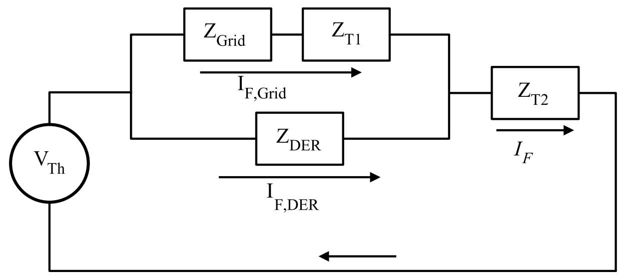

FIGURE 17. Simplified diagram of Figure 16 during fault.

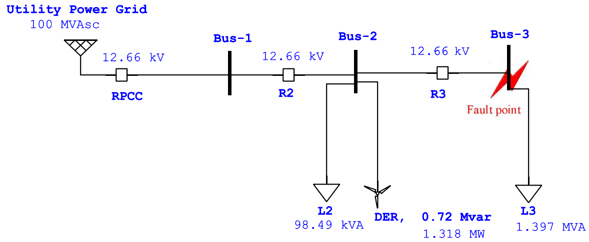

FIGURE 18. Test system for blinding of protection.

respectively. Thevenin's impedance can be calculated as an equation (5).

$$Z_{th} = \frac{(Z_{Grid} + Z_{T1})(Z_{DER})}{Z_{Grid} + Z_{T1} + Z_{DER}} + Z_{T2} \tag{5}$$

So, Thevenin's impedance provided at the fault point is raised because extra impedance is offered by DER in the microgrid. The contribution of fault current from DER in the microgrid is calculated as equation (6).

$$I_{F,DER} = \frac{Z_{Grid} + Z_{T1}}{Z_{Grid} + Z_{T1} + Z_{DER}}.I_F \tag{6}$$

The fault current contribution by the utility grid is calculated as an equation (7).

$$I_{F,Grid} = \frac{Z_{DER}}{Z_{Grid} + Z_{T1} + Z_{DER}}.I_F \tag{7}$$

The fault current is provided by the utility source is nonlinear with rating size and location of DER in the microgrid. On fault condition, synchronously based DER like small hydro turbine gives the 5 to 6 times of its rated value of current and inverter-based PV DER provide only 1.1 to 2 times of its rated value of current [20]. When a fault arises at the ending of the feeder in the microgrid, the DER impedance can be as large as the utility grid impedance. Therefore, the short circuit current is still below the feeder relay pickup current in the LV network that gets the relay to un-detect the fault. This problem caused the reduction of the protection zone and the relay failed to protect the whole protected feeder as a result this move malfunction the whole protection system [109]. The purpose of the above discussion is to study of blinding of the protection problem of a microgrid by creating two sets of networks. The first network is showing the fault current calculation study of the conventional power network and the second one shows the fault current study of the microgrid when DER integration occurs. It is concluded that the fault current contribution to the fault point depends on the total system impedance of the system either in a conventional power system or in a microgrid system.

A test system is designed in Figure 18 to verify the mathematical and theoretical concept of blinding of protection. The synchronous-based DER is considered in this simulation. A fault is created at Bus 3. I_F is the fault current at the fault point in Figure 18. Figure 19(a) shows the fault current level at the fault point shown in Figure 18 during conventional power system mode without DER integration. Figure 19(b) shows the fault current level at the fault point shown in Figure 18 during grid-connected microgrid mode when DER integration occurs. Figure 19(c) shows the fault current level at the fault point shown in Figure 18 during islanded microgrid mode when DER integration occurs. Figure 19 shows the effects of fault current level due to the incorporation of DER in the microgrid with the utility grid. Fault current level decreases sharply with the integration of DER in the microgrid due to impedance increases. This decrease in fault current is due to an increase in impedance which proves the underlying mathematical expression about blinding of protection. The current fault level is supplied by islanded microgrid when only DER is supplied to the fault point shown in Figure 19 which proves both theoretical and mathematical concepts of the challenge of the blinding of protection.

6) PROTECTION DEVICES(PDS)/SWITCH SELECTION

The selection of PDs depends on the requirement of operational speed, fault current availability, and voltage level; it can range from the conventional CB to fast speed solid state switch. As the switching speed of PDs depends on the system current and voltage specifications, the switching speed of PDs increases as the fault current level increases [38], [45].

The needed response speed by the PCC switch of microgrid depends upon the sensitivity of loads connected in microgrid [23]. Loss of microgrid stability occurs when a fault arises on the utility-grid area or inside the microgrid then a high-speed protection switch is required, especially when DERs are directly connected with microgrid which is highly responsive to voltage drop due to a fault and may imperil microgrid stability [110].

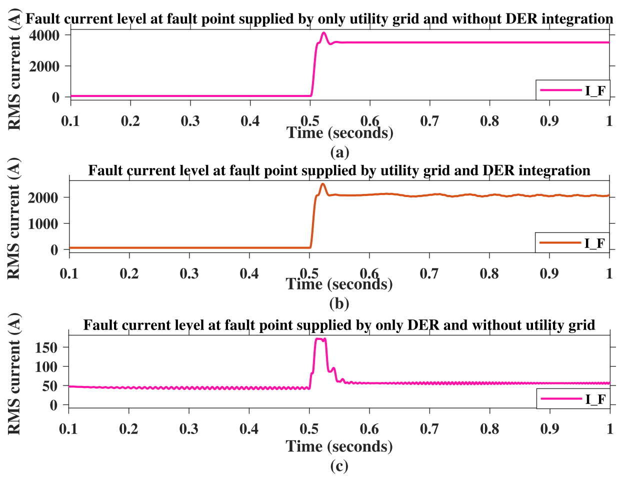

FIGURE 19. Fault current with blinding of protection related to the network as shown in Figure 18: (a) fault current level at fault point contributed by only utility-grid, (b) fault current at fault point contributed by both utility-grid and DER, (c) fault current at fault point contributed by only DER.

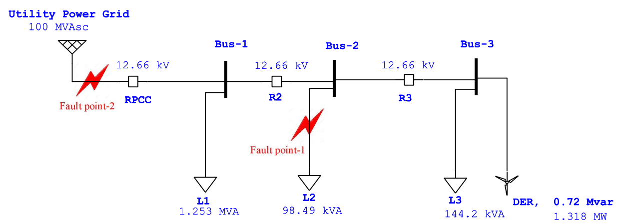

FIGURE 20. Test system for selection of protection devices.

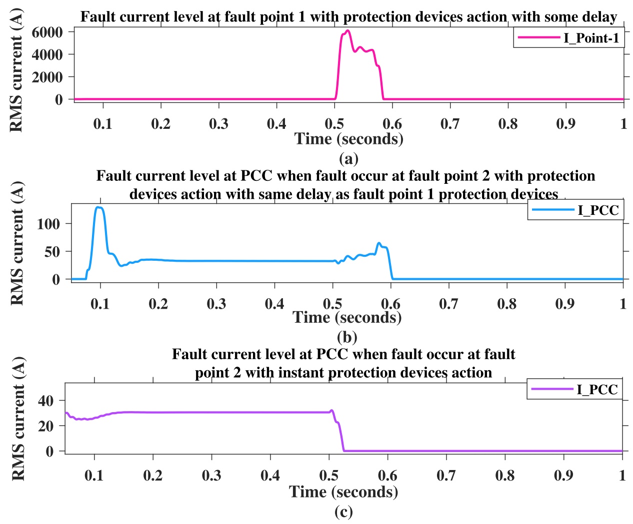

FIGURE 21. Fault current level with different protection devices related to the network as shown in Figure 20: (a) fault current level at fault point-1 with protection devices action with some delay, (b) fault current level at PCC when fault occurs at fault point-2 with same delay as fault point-1 protection devices, and (c) fault current level at PCC when fault occurs at fault point-2 without any delay of protection devices action.

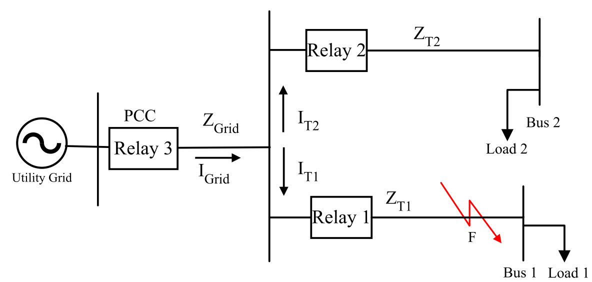

FIGURE 22. Test network to investigate false tripping under normal protection system operation.

To select the PDs, sizing of PDs should not depend only on voltage specifications and system current but also crucial to consider the operating estimations of two or more PDs such as the downstream PD should operate for a provided fault current while upstream protective should not operate according to the AS/NZS 3000:2018, clause 2.5.7.2.1 [111]. According to the AS/NZS 3000:2018 standard, the selection of PDs is essential in all power systems so that false tripping of the PDs can be minimized.

Figure 20 is a single line diagram that is used to analyze the importance of the selection of PDs for coordination among CBs/relays. RPCC is the PCC in Figure 20. In Figure 21, the fault current level when a fault occurs at fault point 1 and the PD acts after some delay. However, if the fault occurs at fault point 2 with the same relay delay settings as at fault point 1, then both the relays/breakers operate simultaneously. The fast PDs are needed to protect the system on a high fault current. The relay operation principle indicates that the relay closest to the fault should operate first. So, at fault point 2, the relay RPCC should operate first. The last simulation result of Figure 21 shows the instant operation of the relay at fault point 2. Thus, different PDs are needed at different locations of the system according to the expected fault current level. Further, it is also clear from the above-discussed results, the downstream switching devices are operated but upstream PDs are not operated.

7) FALSE TRIPPING/SPURIOUS SEPARATIONS

False trips may occur as a result of the PCC switching devices' failure to recognize whether the fault is inside the microgrid or on the utility grid area. Spurious separation occurs due to electromechanical relays and sophisticated microprocessor PDs which are operated based on the real-time frequency and voltage values at PCC. Currently, transfer trip is the only suitable method to dodge false tripping and fast tripping is produced at PCC breaker from breaker of utility substation [112], [113].

The utility and microgrid operations are lesser impacted due to false tripping as microgrids can recover their normal activity after isolation. The false tripping at PCC becomes costly because of decreasing the lifetime of PDs and after spurious separations at PCC, the maintenance cost is increased to recover the system. Furthermore, False tripping may also decrease the power quality in microgrid, unjustified outage of non-priority loads, and loss of profit due to over frequency operational period for exportation of microgrid [23].

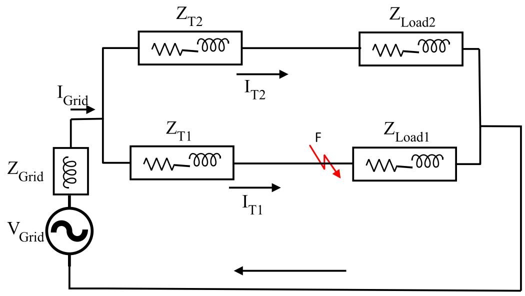

FIGURE 23. Equivalent impedance diagram of Figure 22.

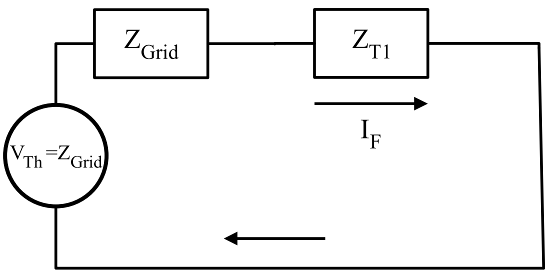

FIGURE 24. Simplified diagram of Figure 23 during fault.

When DERs are not connected to the utility grid and the utility grid feeding the consumers then no big protection issue is happened due to the current flow being directional to the load as shown in Figure 22 and relays operation is normal. When a lot of DERs are introduced in microgrid then during fault condition the bidirectional fault current flow on the lines/feeders of the power network. A DER is situated at bus 2 supplies the fault current to the fault which occurs at bus 1 load as shown in Figure 25, then in a certain case, the large share of fault current is supplied by a DER. An omnidirectional OC relay can neglect to provide the required protection of the power system during supplying from DER. During a fault, the relay$_2$ can be tripped in the reverse direction as relay$_1$ operated in the forwarding direction [109]. Relay$_1$ should trip for clearing the fault. But, due to the large fault current which depends on DER size and relay setting, the DER unit relay$_2$ can trip in the response of high current I_{DER} depending on the DER size and relay settings that would cut off bus 1 from the utility grid [46]. This problem occurs due to the use of omnidirectional OC relay which can fail to discriminate the direction of flow of fault current. This tripping action is called false tripping. Relay$_2$ operates in a secondary protective zone for faults [114]. In a large distributed power system, some relays observe greater fault levels than the pickup value of relay settings. So the total current which is available to DER feeder relay$_2$ exceeds from pickup value of current. Hence, Relay$_2$ tripped before the relay$_1$ which is associated with the faulted feeder that leads to the isolation of the major portion of the power network like bus 2. Thus the utility grid supplies I_{Grid} and the DER feeder provides I_{T2} to the faulty feeder. These false trippings are called sympathetic tripping [20].

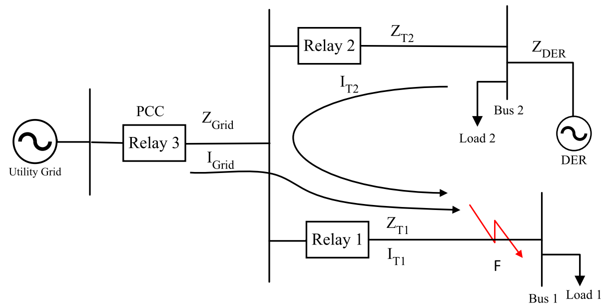

FIGURE 25. Test network with DER to investigate false tripping.

False tripping mostly occurs in distribution systems when DERs are involved to supply short-circuit current and while both relays (relay$_1$ and relay$_2$) do not have similar inverse time characteristics and have dissimilar values of pickup currents and time-dial settings [109]. The mathematical evaluation of fault current supplied by the utility grid. A can be seen in Figure 22, the three-phase fault happened at Bus 1, and assume that Z_{T1} is the impedance of feeder 1, Z_{Grid} is the impedance of the utility grid and V_{Th} is the voltage at fault. The total fault current contribution by utility grid in absence of DER is given as equation (8) and Z_{Th} of the network during a fault in the absence of DER at feeder 2 can be calculated as equation (9).

$$I_F = \frac{V_{Th}}{\sqrt{3}Z_{Th}} \tag{8}$$

$$Z_{Th} = Z_{Grid} + Z_{T1} \tag{9}$$

The mathematical evaluation of fault current contribution by the utility grid and a DER. A can be seen in Figure 25, the three-phase fault happened at Bus 1, and assume that Z_{T1} is the impedance of feeder 1, Z_{T2} is the impedance of feeder 2, Z_{Grid} is the impedance of utility grid, Z_{DER} is the impedance of DER and V_{Th} is the voltage at fault. The total fault current contribution by the utility grid in the presence of DER is given as equation (10) and Z_{Th} of the network during a fault with the presence of DER at feeder 2 can be calculated as equation (11).

$$I_F = \frac{V_{Th}}{\sqrt{3}Z_{Th}} \tag{10}$$

$$Z_{Th} = Z_{Grid} + (Z_{T1} \| Z_{T2} + Z_{DER}) \tag{11}$$

The false tripping results in unnecessary disconnection of healthy feeder 2 along with a DER as shown in Figure 25. The microgrid should clear the fault and make sure that the healthy feeder should remain in the operational state. This sympathetic tripping in the microgrid will lead to the significant unreliability of the power system [95], [115], [116].

To study the false tripping problem due to inverter-based DER of the microgrid, a protection model based on voltage calculation is developed and solutions are discussed to overcome the sympathetic tripping problem by changing the OC protection inverse time characteristics curves, protection settings, applying the suitable standards for the protection

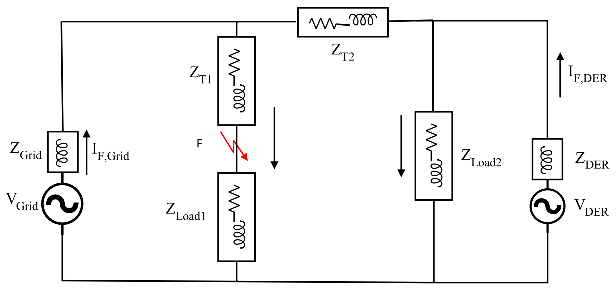

FIGURE 26. Equivalent impedance diagram of Figure 25.

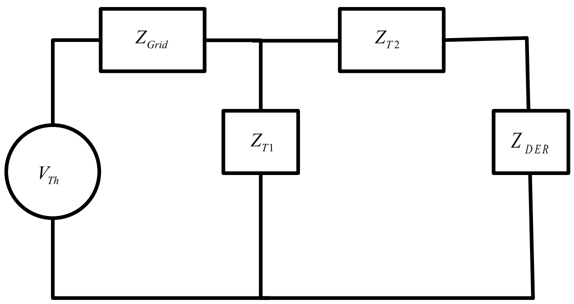

FIGURE 27. Simplified diagram of Figure 26 during fault.

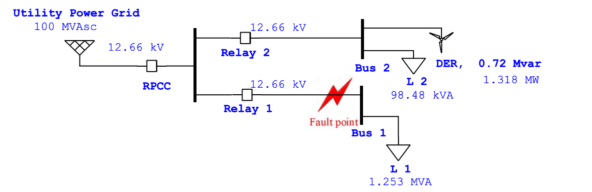

FIGURE 28. Test system to investigate false tripping problem.

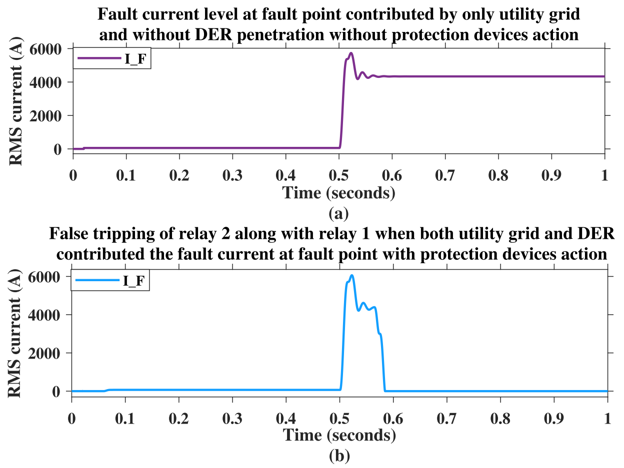

FIGURE 29. False tripping related to the network as shown in Figure 28: (a) fault current level at fault point contributed by only utility grid without protection devices action, and (b) false tripping of relay 2 along with relay 1 when both utility grid and DER contributed the fault current at fault point with protection devices action.

of microgrid and changing the relay settings but still it is a chance of arising a negative sequence during these actions. The sympathetic tripping can be reduced by using instantaneous protection of feeder but it is short time protection which is at the cost of disconnection of a large number of consumers. Still the downstream area of feeders where instantaneous protection is not working, the sympathetic tripping remains an overwhelming issue when secondary (backup) protection operates as shown in Figure 25.

Moreover, instantaneous protection is useful where the feeder is lengthy and fault level decreases prominently along the different protection zones, therefore instantaneous protection is not suitable for all feeders. For instance, sympathetic tripping can be reduced by using incremental solutions [117].

A test system in Figure 28 is used to verify the mathematical and theoretical concept of the false tripping problem of the microgrid. The synchronous-based DER is considered in this simulation. In the single line diagram which is shown in Figure 28, the microgrid is consists of two parallel feeders 1 and feeder 2. The load and DER are situated at bus 2 of feeder 2, while the only load is placed at bus 1 of feeder 1. The protection settings for both relays at bus 1 of feeder 1 and bus 2 of feeder 2 are the same and both are connected with the utility grid. The fault occurs at bus 1 load. In Figure 29 (a), the fault current level with only the utility grid is shown without the DER contribution. After integration of DER at bus 2, fault at bus 1 will also operate the relay at bus 2 along with the relay at bus 1 despite no fault occurring at bus 2 which proves the false tripping of bus due to the same settings as shown in Figure 29 (b). Bus 2 is unnecessarily disconnected from the system which should not be isolated on any fault on bus 1.

8) RE-SYNCHRONISATION

The accessibility of equipment for re-synchronization of a microgrid at PCC should be considered then microgrid can reconnect with the utility grid as long as the utility grid is fit to reconnect entire loads formerly disconnected during islanding. The process of reconnection and re-synchronization can either be automatic or manual and it can need a few seconds to a few minutes depending upon the characteristics of the system. Different types of re-synchronization schemes have also been discussed in [118], [119] and there are three major types of schemes: passive, active, and open transfer transition synchronization. Both passive and active synchronization schemes retain a high level of reliability as a comparison of the open transfer transition scheme. However, the active synchronization scheme is more uneconomical and complex.

Moreover, passive synchronization schemes are proposed applying capacitor banks switches and conventional synchro-check relay for a microgrid with both converter-based DERs and directly coupled. Since capacitor banks switches are used for balancing voltage after islanding of microgrid may consequence in slow re-synchronization. On the other hand, automatic re-synchronization schemes integrated via the central controller of microgrid using communication system is recommended for only complex microgrid system [120].

The design for re-synchronization of DER with the utility grid is shown in Figure 30. RPCC is the PCC in Figure 30. In Figure 31, the voltage level is less during the islanded

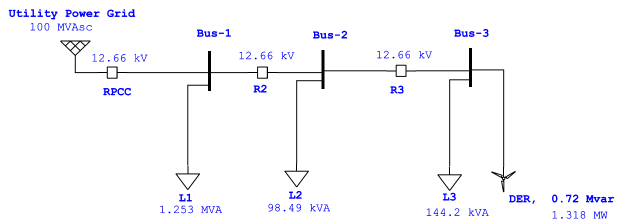

FIGURE 30. Test system with DER for the study of re-synchronisation problem.

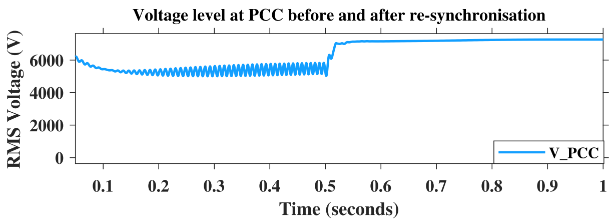

FIGURE 31. RMS voltage level at PCC before and after re-synchronisation.

mode. The microgrid is re-synchronized at time 0.2 with the utility grid through the PCC achieves the same voltage level after re-synchronization.

9) AUTO RECLOSER PROBLEMS

Auto recloser is a PD as the CB. In CB, once switching occurs, it does not come to the original state unless changed manually or by the control system. But in auto-recloser, once switching occurs, it comes to the original state automatically after pre-defined time by the auto-recloser control system action [121]. The schematic diagram of the auto-recloser problem is shown in Figure 32. For example, if the fault occurs in the system, the CB of the auto-recloser opens, then after some predefined interval, it again closed and checks whether the fault was removed or not. If the fault is removed then it continues to supply, otherwise, it trips again for a larger time than previous trips. It continues to return to its closed state after every trip and check for the fault is automatically removed or not. If the fault persists after a few auto-recloser trips, the auto-recloser turns to a permanently open state. The ANSI standard device number for the controller is 79 [122].

Auto-recloser is needed at the power system location where most of the faults are transient types caused by events like lightning strikes and arcing, and which removes automatically after a few-cycle and where less chance of permanent fault occupance. The advantage of using the auto-recloser is to increase the system stability and reduce the need for manpower that needs to visit the fault location to reset CB settings [123].

Without the contribution of DER, the distribution power system is radial. When a fault occurs, its downstream part is disconnected to remove the transient fault. When DER is connected with the existing distribution system to make the grid-connected microgrid. Then on fault condition on the distribution line, the fault is supplied by both the utility grid and the DER of the microgrid. Though the recloser isolates the utility grid, DER of the microgrid still feeds

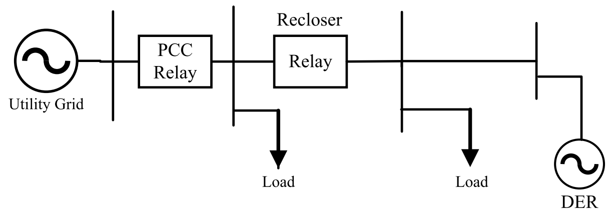

FIGURE 32. Test system with DER to investigate the auto recloser problems.

the fault, it will induce energization of the arc through the recloser and can transform the temporary fault to permanent fault [20], [24].

B. DC MICROGRID PROTECTION CHALLENGES

The term "DC microgrid" applies to a network of local power generation units and distribution to the DC load in the form of direct current [26], [124]. Despite various benefits offered by DC microgrid which are already discussed in DC structure section II-B, it has many protection challenges. Few of the challenges such as during islanded mode, inverter-based DER provides limited fault currents and incapability of the overcurrent relay having single-setting challenges in the DC microgrid protection system is same as discussed in AC microgrid protection challenges. Still, there are a few extra issues for the protection of DC microgrids like grounding scheme and lack of zero-crossing current [17], [125].

1) GROUNDING

In DC microgrid, the grounding design is a highly crucial issue because it eminently affects the overvoltage and short circuit transient current, and it affects its protection and fault detection capabilities [37], [126]–[129]. The DC power system grounding schemes can be separated into three configuration types, that are ungrounded, resistive, and solidly grounded method. These schemes are explained below in detail.

a: DC UNGROUNDED SYSTEM

The DC ungrounded power system has increased continuity in the power supply, which allows the power system to work for some time when a ground single-pole fault happens. This is also named a floating system, DC ungrounded grid significantly decreases leakage ground current along with corrosion level [130]. No device is required in this grounding scheme. It has a low implementation cost and it is simple technically. However, the ungrounded DC power system can usually function with ground single-pole fault. So, it is crucial to identify and limit this issue. This is due to the concern that a next-ground contact of the other pole may induce pole-to-pole fault and serious damage to the system. Hence, a ground single-pole fault location and detection in an ungrounded DC power system are complex because of low ground-fault current [131], [132]. An additional drawback of this scheme is that the existence of even minor leakage currents in the DC

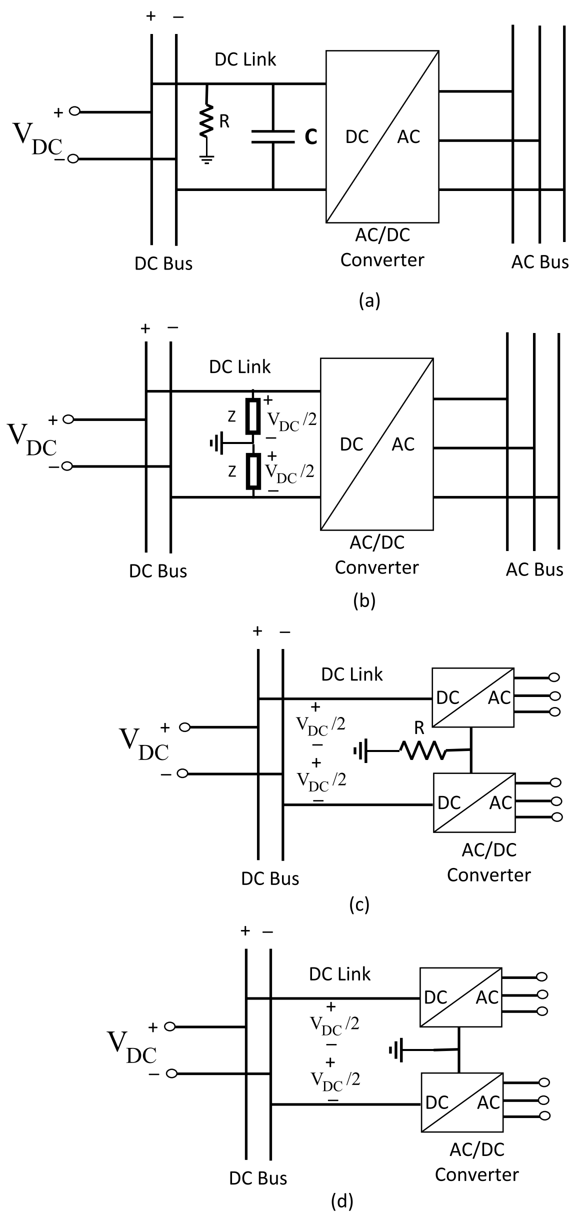

FIGURE 33. DC power system grounding schemes (a, b, c) DC power system resistive grounding schemes (d) DC power system solidly grounding scheme.

power system which do not have a path to the ground can lead to an uncertain DC offset because of DC bus has no DC reference points to balance the DC power [133].

b: RESISTIVE GROUNDING SYSTEM

In a resistive grounding DC power system, a resistor of a certain value is connected between any of the poles to the ground. Resistive grounding scheme for AC/DC power converter which is connected to DC bus as shown in Figure 33(a). Figure 33(b) shows the different configuration that has two impedances which is connected in series to DC bus whereas the central point is grounded. This grounding configuration is also named a virtually-grounded DC system because this scheme is mainly used in DC power systems in the absence of neutral points [128], [130]–[132], [134]–[136]. The size of the resistor increases as increases the possibility of system voltage unbalances.

Figure 33(c) shows the scheme of bipolar AC/DC power converter having neutral-point which are grounded through the resistor. The main advantage of this scheme is that during the ground single-pole fault, the system can operate and supply loads continuously due to having low fault current and small voltage transient. This system also reduces the disturbance for high voltage transient because of grounded single-pole fault [126]. Despite that, it is very difficult to evaluate and observe the low fault currents and as a consequence, loads of metal enclosures can be energized. So, safe operation for sensitive loads when pole-to-ground voltage changes need to be ensured when designing the resistive grounding system.

c: SOLIDLY GROUNDING SYSTEM

The ground-point is located electrically middle between positive and negative DC bus on the neutral point in the solidly-grounded bipolar DC power system. Figure 33(d) shows the solidly grounded configuration for the neutral-point-clamped inverter system. By comparing with different grounding schemes, this configuration induces high ground current and high DC-link voltage transient. Although, the fault could be detected easily and it could be cleared quickly by using the properly designed protective relay. The other advantage of this grounding scheme is that instruments and cables need insulation level by one-half of pole-to-pole DC voltage [37]. So, the system requires less space, weight, and lower cost. However, this grounding scheme in monopole DC system is practicable through the connection of the negative-pole to the ground directly, and it is suitable for a lot of applications due to safety and corrosion issues.

2) LACK OF ZERO-CROSSING CURRENT

CB operations in both AC power systems are led by AC CB mechanism, arc phenomenon, depending on the zero-crossing AC-current, make it possible to recognize the arc during half-cycle after tripping. But, the disruption of DC is the main problem because of the absence of the zero-crossing current in the DC power system which induces serious risk for workers' safety and also causes erosion in the CB which decreases the breaker lifetime [137], [138].

Nowadays, CBs and fuses are available commercially for the protection of DC power systems [10]. Fuses are used in the power system where the impedance is low which operates based on the thermal rating of the fuse wire, and thermal rating depends on the fuse impedance and current value flowing through the fuse. The fuse must be chosen based on the voltage and time-current rating of the system where it operates. It is used for both DC and AC power systems. Still, fuse development for the DC power systems demands a more precise calculation of the system time constant because it directly influences the fuse operation. Precisely, the metal wire of the fuse is melted quickly if the system time constant is under 2.5 ms but conversely, the melted time of fuse wire is increased if the system time constant is over than 6 ms and arc cannot be quenched rapidly [128]. Hence, melted time increases as the system time constant increases. Furthermore, DC system transient OCs may cause malfunction of the fuse. As a result, a fuse is not a good selection for DC-microgrid protection. Still, it may be utilized as a secondary PD.

The molded-case CB consists of contacts, a quenching chamber, and an electronic tripping device is an alternate option for disruption of fault current [139]. In a microgrid, some sources and loads are connected with the microgrid using power electronics devices. Such power electronics devices normally need line-to-ground or line-to-line filter capacitors. When DC fault occurs then the capacitors quickly discharge into fault-point and give rise to high peak current for a short-time period. Thus, required force to open the contacts completely may not be produced; especially, in an extremely inductive system contacts can weld each other during fault [140]. Therefore, a CB is not a perfect solution for disruption of fault current yet.

It is concluded from the above AC and DC protection challenges discussion that protection schemes for the microgrid should be designed according to the protection challenges. In the next section, different protection schemes will be discussed to handle these protection challenges.

V. CRITICAL ANALYSIS AND SOLUTION APPROACHES

Different protection challenges of microgrids have been discussed in the previous section. Different types of protection schemes were proposed in the literature to tackle these protection issues. Some of the protection schemes from literature, such as in article [9], authors expressed real-world experiences related to the microgrid design for protection systems, field experience, and implementation challenges. A comprehensive review is available in an article [10], for hybrid AC/DC microgrid protection. Different microgrid protection approaches are discussed with critical analysis and each approach of implementation challenges are also presented. In article [12], an adaptive protection scheme is proposed for the distributed system based on the fault current and variation of the load. Authors in articles [13], [115], developed a new microgrid protection approach and test for different types of protection challenges in terms of different types of DERs, microgrid configuration, bidirectional current flow, converter fault current level characteristics, and different relays fault levels.

In articles [26], [27], DC microgrid protection scheme is proposed in terms of different DC fault current levels, grounding schemes, fault detection methods, and also reviewed different control schemes for DC microgrid protection. AC, DC, and hybrid microgrids architecture along with related protection issues and solution approaches are discussed for both grid-connected and islanded operational modes of the microgrid [14], [112]. Microgrid structure and adaptive protection scheme are addressed for the protection of microgrid concerning different protection challenges [15]. Articles [16], [31], reviewed the different microgrid protection schemes in terms of different challenges such as low inertia, bidirectional power flow, the transition between operational modes, and absence of zero-crossing currents. In article [18], authors systematically reviewed the adaptive protection scheme for microgrid based on the communication system, and also present the future perspective of 5G wireless system in the microgrid to enable adaptive protection scheme. The innovative concept of a control and protection coordination scheme is presented for the DC microgrid [34]. DC microgrid protection challenges are analyzed in articles [38], [45], in terms of DC fault current levels, detection of fault methods, fault location, PDs, and grounding systems.

Articles [7], [63], proposed the dynamic adaptive protection for distributed systems for both grid-connected and islanded operation modes. AC microgrid protection challenges are analyzed in terms of fault classification, fault detection methods, fault location methods, and relay coordination [72], [141], [142]. Moreover, available protection methods are analyzed in terms of their advantages and disadvantages. The paper [78], presents the overview of protection in microgrid and power systems in terms of integration of DER. Article [104], presents a passive IDT for inverter-based microgrid which relies on synchrophasor measurements.

A review of protection challenges and solution approaches are discussed in articles [106], [142], [143]. Authors in [15], [107], presented an adaptive protection scheme for multi-microgrid systems for the grid-connected and islanded operational modes. A comprehensive protection scheme that is based on the digital relay is introduced for the protection of microgrids [144]. This proposed method comprises the protection of DERs, the PCC, and lines. In article [145], the authors presented a novel protection scheme for the radial microgrid using bi-directional overcurrent relays for backup protection. Renewable energy-based microgrid protection challenges and their solution approaches are discussed in [20], [146]. Phase-fault based protection scheme is introduced for reliable operation of the microgrid [147]. Fault current was analyzed in [148] to determine the overcurrent protection scheme for islanded and grid-connected operation modes of the microgrid.

A cognitive radio-based protection scheme is introduced for the protection of the smart grids [149]. Data mining and wavelet analysis-based protection scheme is introduced for the protection of microgrids [150]. A hierarchical protection scheme is introduced based on the multi-agents for the protection of the distributed system with high penetration of renewable-based DERs [151]. A non-pilot protection scheme is presented in an article [152], for the protection of inverter-based microgrids. The PSO optimal-based protection coordination method is introduced for the protection of radial distribution systems [153]. Article [154], introduced the parameter selection scheme for the economic configuration of CB and fault current limiter for meshed-type

TABLE 2. Protection schemes for the microgrid.

Protection Schemes& Methodology	Solutions of Challenge	Merits/Demerits
Adaptive Overcurrent protection: - Directional Overcurrent Relay [147], [159]–[164] - Overcurrent Relay [165]–[172] - Communication link [159] - Optimization Algorithms based [147], [160]–[165] - Microprocessor based relay [165] - Fault current limiter [161], [162] - Logic overcurrent and earth fault protection method [169]	- Faults/Events during grid-connected mode [147], [159], [167], [168], [170], [172] - Faults/Events during islanded mode [147], [159], [165], [167], [168], [170], [172] - Selection of PDs/switch [159] - Dynamics in fault current magnitude [147], [167], [168], [172] - Ati-Islanding Protection [168], [171] - False/sympathy tripping [163], [164], [169] - Un-balanced fault [170] - Loss of coordination [171]	Merits: -Suitable for both islanded and grid-connected modes of the microgrid operations -Overcurrent relays pickup settings are changed according to operational mode Demerits: -Different relays settings are required for different operational conditions -Essential to modified relays settings with respect to operational modes -Essential to recognize different microgrid configurations -Increase computational burden for big size microgrid -Communication link is needed -High operational cost -Centralized controller is needed
Differential protection: - Differential relay [170], [171], [173]–[178] - Data mining [174] - Fourier transform [174] - Hilbert–Huang transform [179], [180] - Time-frequency transform [181] - Multi-agent scheme [175] - Probabilistic method [182] - Differential relay [170]	- Fault/events during islanded mode [170], [173]–[178], [180], [181] - Fault/events during grid-connected mode [170], [173]–[176], [178], [180], [181] - False tripping [176], [182] - Un-balanced fault [170], [181] - High impedance fault [179]	Merits: - Suitable for both islanded and grid-connected modes of microgrid operations - It may suitable for all types of microgrids - Demerits: - Very expensive due to having a large number of relays - During connection/disconnection of DERs, it may cause some problems - A communication link is needed - Unable to protect the buses - Concerns due to transients and unbalanced load
Distance protection: - Ground relay [169], [183]	- False triping [169], [183]	Merits: - Suitable for microgrids having medium/long transmission lines Demerits: - It depends on the type of DERs installed and the configuration of the microgrid - Measurements problems due to fault resistance - Complexity due to the measurement of impedance in short transmission lines
Adaptive protection: - Adaptive protection relay [71], [184]–[186] - Alternative group settings [185] - Logic programming [185] - PSO algorithm [187] - OC relay [187], [188] - Auto-recloser [186] - Graph algorithm and fuzzy decision [189] - Hardware and programming based protection system [109] - Digital relays [190] - Fault current limiter [71]	- Fault/events during islanded mode [71], [184]–[186], [188], [190] - Fault/events during grid-connected mode [71], [185], [186], [188], [190] - Cyber security threats [185] - Low fault current [186], [187] - Blinding of protection [109] - Sympathetic tripping [109] - Auto-recloser problem [186]	Merits: - Suitable for both islanded and grid-connected mode of microgrid operations - Suitable for different microgrid types - Relays pickup settings are changed according to operational modes Demerits: - The size of the microgrid will increase due to expanding of protection structures for relay settings switchings - A communication link and the centralized controller is needed

TABLE 2. *(Continued.)* **Protection schemes for the microgrid.**

Directional protection: - Directional relay [170], [191]	Un-balanced fault [170] - Fault/events during islanded mode [170] - Fault/events during grid-connected mode [170]	Merits: - It is suitable for induction machine and inverter-based microgrid fault current - Un-suitable for different microgrid topologies
Microprocessor-based protection: - Microprocessor-based intelligent relay [172], [192]–[194] - Directional OC relay [172] - Fault current limiter [192]	- LOM [172] - Fault/events during islanded mode [172], [192], [193] - Fault/events during grid-connected mode [193]	Merits: - Suitable for both islanded and grid-connected modes of microgrid operations - Can work without communication link Demerits: - Does not reliable for medium voltage systems - A highly complex computer-based logic structure is required which take more time to compute the desired results
Under/over voltage protection scheme: - G83/2 under voltage relay [117] - Under voltage relay [145], [170], [195]–[197] - Over voltage relay [145], [170], [196]–[198] - LV ride through [170] - Rate of change of frequency relay [145], [196], [197], [199]	- False tripping [117], [195] - Fault/events during islanded mode [170] - Fault/events during grid-connected mode [170] - LOM [145], [196]–[199] - Re-synchronisation [198]	Merits: - Suitable for both islanded and grid-connected mode of microgrid operations Demerits: - Unable to detect high impedance faults - It may not suitable for microgrids having a different configuration - A communication link is needed
Digital protection: - Digital relay [144], [190], [200] - Communication system [200] - OC digital relay [201] - Artificial neural network-based relay [202]	- Fault/events during islanded mode [144] - Fault/events during grid-connected mode [144] - Ground fault [200] - LOM [202]	Merits: -Suitable for all microgrid components like feeders, inverter and conventional based DERs, PCC, and lines - It does not require adaptive protection and central controller Demerits: - Cost and computational time is increased due to requiring more calculations for different microgrid scenarios
Fault current limiter (FCL): Fault current limiter application [20]	Limit the fault current level	Merits: - Prevent the damage of power electronics equipment due to decrease of fault current Demerits: - Concerns related to locations of identification and sizing of FCL tuning parameters - It required a large size FCL when DERs integration increases which increased the total cost
Data-driven classifier [207]: - Naive Bayes and decision tree [203] - Random forest-based classifier [204] - Discrete wavelet transform [205] - PSO based optimal random forest classifier [206]	- Fault/events during islanded mode - Fault/events during grid-connected mode - Not suitable for loop-based microgrid	Merits: - Less dependency on communication link as it requires local measurements for implementation Demerits: - Less reliable in different types of microgrids - Data over-fitting problems can give unexpected results due to biased trained data set - Costly for small microgrid and have high algorithms complexity due to high computational burden

TABLE 2. ***(Continued.)*** **Protection schemes for the microgrid.**

Traveling wave-based protection scheme [207]: - Multi-end ultra-fast [208] - Mathematical morphology [208]	- Fault/events during islanded mode - Fault/events during grid-connected mode	Merits: - Fast detection of fault with high accuracy Demerits: - Not implementable for short distribution lines - High implementation cost
Reconfigurable DC grounding: Diode DC grounding scheme [10], [209]	DC grounding problems	Merits: - Suitable for all DC grounding problems - Suitable for utility personnel safety Demerits: - Corrosion can not be completely avoided in diode grounding system and it needed maintenance in routine
DC interruption: Current interruption by electromechanical switches [10], [210], [211]	Mitigate the lack of zero-crossing problem	Merits: - DC protection system split into several protection zones to isolate only faulty zone on any fault by making no-load switches to terminate the fault current Demerits: - The system is completely shut down after detection of fault due to continuous supply to the remaining network by converters which lead to re-energized the network which is not required - Limitation of CBs to sustain during maximum voltage and current - Problems to quench the arc which produced during CBs opening due to lack of zero-crossing current - Cost increased to buy a high current tackle CB

DC microgrid. Article [155], presents the stochastic-based energy management system and protection method for the reliable operation of the microgrid. The rate of change of voltage-based protection scheme and coordination scheme is introduced for the protection of the microgrid [156]. In [157], a new protection scheme is proposed for the internal faults of the multi-microgrids. The phase difference and bus admittances amplitude are used for the decision-making of this protection scheme. Further, voltage and current characteristics are analyzed considering faults at different locations of feeders of the multi-microgrids. An adaptive ROCOF based IDT is proposed to solve the islanding detection issue for different types of microgrid in an article [158].

Various protection schemes and their challenges, merits, and demerits are summarized in Table 2. In articles [147], [159]–[164], directional overcurrent based adaptive overcurrent protection is proposed to solve the faults/events during grid-connected and islanded operational modes of the microgrid, selection of PDs, dynamics in fault current magnitude, and false tripping problems of microgrid protection.

An overcurrent based adaptive protection scheme is proposed in articles [165]–[172], to solve the protection problems related to the faults/events during grid-connected and islanded operational modes, dynamics in fault current magnitude, islanding protection, false tripping, un-balanced faults, and loss of coordination problems of microgrid protection. A communication link-based adaptive overcurrent protection scheme is presented to solve the selection of PDs protection problem in the microgrid [159]. An optimization algorithm based adaptive overcurrent protection scheme is presented in articles [147], [160]–[165], to solve the protection problems related to the faults/events during grid-connected and islanded operational modes of the microgrid, dynamics in fault current magnitude, and false tripping problems of microgrid protection.

A microprocessor-based adaptive overcurrent protection is proposed to solve the protection problems related to the faults/events during grid-connected and islanded operational modes of the microgrid. Faults current limiter-based adaptive overcurrent protection method is presented in articles [161], [162], to solve the protection problems related to the faults/events during grid-connected and islanded operational modes of the microgrid. Logic overcurrent and earth fault protection methods are presented in an article [169], to solve the protection problem related to false tripping.

Differential protection based on differential relay [170], [171], [173]–[178], data mining, Fourier transform [174], Hilbert-Haung transform [179], [180], time-frequency transform [181], multi-agent scheme [175], and probabilistic method [182], is proposed to solve the microgrid protection issues related to faults/events during grid-connected and islanded operational modes of the microgrid, false tripping, un-balanced fault, and high impedance fault. The ground relay-based distance protection scheme is implemented in an article [169], [183] to solve protection problems related to false tripping.

An adaptive protection scheme is proposed in articles [71], [184]–[186], to solve the faults/events during grid-connected and islanded operational modes, cyber security threats, and auto-recloser protection problems. Alternative group settings and logic programming-based adaptive protection scheme is proposed in an article [185], to solve the faults/events during grid-connected and islanded operational modes and cyber security threats. PSO, overcurrent relay, and autorecloser-based adaptive protection scheme is presented in articles [186]–[188] respectively, to solve the low fault current, faults/events during grid-connected and islanded operational modes of the microgrid. Graph algorithm and fuzzy decision [189], hardware and programming based protection system [109], digital relays [190] and fault current limiter [71], based adaptive protection schemes are proposed to solve the false tripping, faults/events during grid-connected and islanded operational modes of the microgrid.

Directional relay-based directional protection scheme [170], [191], is proposed to solve the unbalanced fault, faults/events during grid-connected and islanded operational modes of the microgrid. Microprocessor-based intelligent relay, directional overcurrent relay and fault current limiter-based microprocessor-based protection schemes are presented [172], [192]–[194] to solve the LOM, faults/events during grid-connected and islanded operational modes of the microgrid. G 83/2 under voltage relay, over-voltage relay, LV ride through, and rate of change of frequency relay-based under/over voltage protection scheme is presented in [117], [145], [170], [195]–[199] to solve the false tripping, LOM, re-synchronization, faults/events during grid-connected and islanded operational modes of the microgrid. Digital relay, communication system, overcurrent digital relay, and artificial neural network-based digital protection are proposed [144], [190], [200]–[202] to solve the LOM, ground fault, faults/events during grid-connected and islanded operational modes of the microgrid.

Fault current limiter-based protection scheme is proposed to limit the fault current level [20]. Naive Bayes and decision tree [203], random forest-based classifier [204], discrete wavelet transform [205], and PSO based optimal random forest classifier [206], a data-driven classifier based protection scheme [207], are used to solve the faults/events during grid-connected and islanded operational modes of the microgrid. A multi-end ultra-fast and mathematical morphology-based traveling wave-based protection scheme [208] is proposed to solve the faults/events during grid-connected and islanded operational modes of the microgrid. Diode DC grounding-based reconfigurable DC grounding scheme is proposed to solve the DC ground problems for the DC microgrid [10], [209]. DC interruption is proposed [10], [210], [211] which is based on the current interruption by electro-mechanical switches to mitigate the lack of zero-crossing problem for the DC microgrid.

Some protection schemes are useful for both grid-connected and islanded modes but at the same time they have some demerits, e.g., they require the communication link and centralized controller. Some protection schemes rely on a microprocessor, optimization techniques, and intelligent classifiers to solve the different protection challenges of the microgrid. Finally, from the above discussion, all of these schemes are not useful to cover all types of microgrid protection challenges due to the limitations like topology, size of microgrid, communication link, centralized controller, bidirectional flow of current, modified fault current level due to change in operational modes, relays settings, computational cost and time, location of relays. Therefore, it is clear that the adaptive protection scheme is more useful if it reduces its dependence on the communication link, centralized controller, microgrid topology, and computational cost [212].

In contrast, the biggest issue in the DC microgrid is the quenching of arc produced during opening of DC CB due to lack of zero-crossing current. The DC microgrid protection issue can be tackled by connecting a high resistance dump load with the DC CB to quench the arc produced during the opening of the DC CB. In a nutshell, no single protection scheme can overcome all microgrid protection challenges because one protection scheme is covering one protection challenge but at the same time, it is unable to cover other protection challenges. So, it demands more research on the microgrid protection scheme which should be capable to cover all microgrid protection challenges. This paper summarises most of the microgrid protection challenges and listed solutions from current research which can be a key resource for designing advanced protection schemes for all the challenges.

VI. CONCLUSION

This paper presents microgrid structures, essential conditions of microgrid protection, and different types of protection challenges in the microgrid. It also critically analyzed different types of solution approaches to explore various protection issues. It is found that prior knowledge of essential conditions is important while designing a protection system for the microgrid. The essential conditions listed below are found from extensive literature survey.

- Microgrid topology: Protection schemes work differently for both AC and DC microgrids due to the different nature of current and voltage waveform.
- Fault type: Type of fault is very important while designing a secure protection scheme for the microgrid whether it is symmetrical or unsymmetrical fault.
- Relay type and earthing systems: The selection of relay and earthing schemes also play an important role while designing the protection scheme.
- Protection constraints: Protection requirement is different according to the fault type, fault location, fault level, and source or generator type and level.

The critical analysis of different protection schemes and their solution approaches are also discussed with respect to different protection issues, microgrid topology, size of microgrid, and different operational modes. Different microgrid protection challenges can be mitigated by using different protection techniques. Each of these techniques is discussed in detail with merits and demerits. The solution approaches are also explored to address the challenges.

- Adaptive protection schemes are suitable for faults/ events during islanded and grid-connected modes, with dynamic fault current magnitude and islanding protection. It is also effective to address cyber security threats, low fault current, blinding of protection, auto-recloser problem, false tripping, and loss of coordination problems.
- Differential protection schemes are suitable for faults/events during islanded and grid-connected modes, false tripping, un-balanced fault, and high impedance fault.
- A distance protection scheme can be used to solve the false tripping problem of the microgrid.
- A directional protection scheme can be suitable for the mitigation of un-balanced fault and faults during grid-connected and islanded modes.
- A microprocessor-based and digital protection schemes can be suitable for the mitigation of LOM issues and faults during grid-connected and islanded modes.
- Under/over voltage protection scheme can be suitable for mitigation of false tripping, LOM, re-synchronization issues, and faults during grid-connected and islanded modes.
- Fault current limiter can be used to limit the fault current level. Data-driven classifiers and traveling wave-based protection schemes can be suitable for the mitigation of faults during grid-connected and islanded modes.
- A reconfigurable DC grounding-based protection scheme is useful to overcome the DC grounding issues. DC interruption protection scheme is suitable to mitigate the lack of zero-crossing problems in DC microgrid.

The generic protection scheme for all types of AC or DC microgrids is not suitable to handle all types of microgrid protection issues. Therefore, it is necessary to design the proper protection scheme based on the microgrid type, size, structure configuration, installation location, operational modes, etc., and necessary modification is needed when any of the above circumstances change the microgrid characteristics. The adaptive protection scheme has the capability to modify the approach based on condition and it reduces dependence on the communication link, centralized controller, and microgrid topology. DC microgrid protection challenges can be reduced by using a high resistance dump load with the DC CB to quench the arc produced during DC protection devices action. This paper provided these key information to researchers and engineers which will help to investigate further to address challenges of microgrid protection and their solutions.

REFERENCES

[1] S. Lotfifard, J. Faiz, and M. Kezunovic, "Detection of symmetrical faults by distance relays during power swings," *IEEE Trans. Power Del.*, vol. 25, no. 1, pp. 81–87, Jan. 2010.

[2] J. A. Rohten, J. J. Silva, J. A. Muñoz, F. A. Villarroel, D. N. Dewar, M. E. Rivera, and J. R. Espinoza, "A simple self-tuning resonant control approach for power converters connected to micro-grids with distorted voltage conditions," *IEEE Access*, vol. 8, pp. 216018–216028, 2020.

[3] M. N. Naz, M. I. Mushtaq, M. Naeem, M. Iqbal, M. W. Altaf, and M. Haneef, "Multicriteria decision making for resource management in renewable energy assisted microgrids," *Renew. Sustain. Energy Rev.*, vol. 71, pp. 323–341, May 2017.

[4] H. J. Laaksonen, "Protection principles for future microgrids," *IEEE Trans. Power Electron.*, vol. 25, no. 12, pp. 2910–2918, Dec. 2010.

[5] X. Li, Z. Li, L. Guo, J. Zhu, Y. Wang, and C. Wang, "Enhanced dynamic stability control for low-inertia hybrid AC/DC microgrid with distributed energy storage systems," *IEEE Access*, vol. 7, pp. 91234–91242, 2019.

[6] D. J. Narang and M. Ingram, "Highlights of IEEE Standard 1547-2018," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/PR-5D00-75105, 2019.

[7] M. W. Altaf, M. T. Arif, S. Saha, S. N. Islam, M. E. Haque, and A. Oo, "Renewable energy integration challenge on power system protection and its mitigation for reliable operation," in *Proc. 46th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2020, pp. 1917–1922.

[8] O. Azeem, M. Ali, G. Abbas, M. Uzair, A. Qahmash, A. Algarni, and M. R. Hussain, "A comprehensive review on integration challenges, optimization techniques and control strategies of hybrid AC/DC microgrid," *Appl. Sci.*, vol. 11, no. 14, p. 6242, Jul. 2021.

[9] S. C. Vegunta, M. J. Higginson, Y. E. Kenarangui, G. T. Li, D. W. Zabel, M. Tasdighi, and A. Shadman, "AC microgrid protection system design challenges—A practical experience," *Energies*, vol. 14, no. 7, p. 2016, Apr. 2021.

[10] S. Mirsaeidi, X. Dong, and D. M. Said, "Towards hybrid AC/DC microgrids: Critical analysis and classification of protection strategies," *Renew. Sustain. Energy Rev.*, vol. 90, pp. 97–103, Jul. 2018.

[11] M. N. Naz, S. Imtiaz, M. K. L. Bhatti, W. Q. Awan, M. Siddique, and A. Riaz, "Dynamic stability improvement of decentralized wind farms by effective distribution static compensator," *J. Mod. Power Syst. Clean Energy*, vol. 9, no. 3, pp. 516–525, 2021.

[12] A. Shobole, M. Baysal, M. Wadi, and M. R. Tur, "An adaptive protection technique for smart distribution network," *Elektronika ir Elektrotechnika*, vol. 26, no. 4, pp. 46–56, Aug. 2020.

[13] X. Zhang and S. P. Azad, "A review of the protection of microgrids with converter-based resources," in *Proc. CIGRE Canada Conf. Expo*, 2020, pp. 1–8.

[14] A. Dagar, P. Gupta, and V. Niranjan, "Microgrid protection: A comprehensive review," *Renew. Sustain. Energy Rev.*, vol. 149, Oct. 2021, Art. no. 111401.

[15] P. H. A. Barra, D. V. Coury, and R. A. S. Fernandes, "A survey on adaptive protection of microgrids and distribution systems with distributed generators," *Renew. Sustain. Energy Rev.*, vol. 118, Feb. 2020, Art. no. 109524.

[16] 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," *Int. J. Energy Res.*, vol. 44, no. 5, pp. 3347–3364, Apr. 2020.

[17] Z. Ali, Y. Terriche, S. Z. Abbas, M. A. Hassan, M. Sadiq, C.-L. Su, and J. M. Guerrero, "Fault management in DC microgrids: A review of challenges, countermeasures, and future research trends," *IEEE Access*, vol. 9, pp. 128032–128054, 2021.

[18] T. Senarathna and K. U. Hemapala, "Review of adaptive protection methods for microgrids," *AIMS Energy*, vol. 7, no. 5, pp. 557–578, 2019.

[19] D. Gutierrez-Rojas, P. H. J. Nardelli, G. Mendes, and P. Popovski, "Review of the state of the art on adaptive protection for microgrids based on communications," *IEEE Trans. Ind. Informat.*, vol. 17, no. 3, pp. 1539–1552, Mar. 2021.

[20] V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, and S. G. Srivani, "Protection challenges under bulk penetration of renewable energy resources in power systems: A review," *CSEE J. Power Energy Syst.*, vol. 3, no. 4, pp. 365–379, Dec. 2017.

[21] I. Almutairy, "A review of coordination strategies and techniques for overcoming challenges to microgrid protection," in *Proc. Saudi Arabia Smart Grid (SASG)*, 2016, pp. 1–4.

[22] H. F. Habib, C. R. Lashway, and O. A. Mohammed, "A review of communication failure impacts on adaptive microgrid protection schemes and the use of energy storage as a contingency," *IEEE Trans. Ind. Appl.*, vol. 54, no. 2, pp. 1194–1207, Mar./Apr. 2018.

[23] A. A. Memon and K. Kauhaniemi, "A critical review of AC microgrid protection issues and available solutions," *Electr. Power Syst. Res.*, vol. 129, pp. 23–31, Dec. 2015.

[24] S. A. Hosseini, H. A. Abyaneh, S. H. H. Sadeghi, F. Razavi, and A. Nasiri, "An overview of microgrid protection methods and the factors involved," *Renew. Sustain. Energy Rev.*, vol. 64, pp. 174–186, Oct. 2016.

[25] B. J. Brearley and R. R. Prabu, "A review on issues and approaches for microgrid protection," *Renew. Sustain. Energy Rev.*, vol. 67, no. 1, pp. 988–997, 2017.

[26] S. Sarangi, B. K. Sahu, and P. K. Rout, "A comprehensive review of distribution generation integrated DC microgrid protection: Issues, strategies, and future direction," *Int. J. Energy Res.*, vol. 45, no. 4, pp. 5006–5031, Mar. 2021.

[27] R. Sahu, P. K. Panigrahi, and D. K. Lal, "Control and protection of hybrid smart-grid power system: A review," in *Proc. IEEE Int. Symp. Sustain. Energy, Signal Process. Cyber Secur. (iSSSC)*, Dec. 2020, pp. 1–6.

[28] A. Shukla, M. Yadav, and N. Singh, "Design and control of DC/AC microgrid with H-bridge multi-level inverter for unbalance loading," in *Proc. Int. Conf. Adv. Electron., Elect. Comput. Intell. (ICAEEC)*, 2019, pp. 1–14.

[29] H. A. Alsiraji and J. M. Guerrero, "A new hybrid virtual synchronous machine control structure combined with voltage source converters in islanded AC microgrids," *Electr. Power Syst. Res.*, vol. 193, Apr. 2021, Art. no. 106976.

[30] J. Singh, S. Singh, K. Verma, A. Iqbal, and B. Kumar, "Recent control techniques and management of AC microgrids: A critical review on issues, strategies, and future trends," *Int. Trans. Electr. Energy Syst.*, vol. 31, no. 11, p. e13035, Nov. 2021.

[31] 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, Art. no. 115210.

[32] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B.-M. Hodge, and B. Hannegan, "Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy," *IEEE Power Energy Mag.*, vol. 15, no. 2, pp. 61–73, Mar. 2017.

[33] E. Planas, J. Andreu, J. I. Gárate, I. M. de Alegría, and E. Ibarra, "AC and DC technology in microgrids: A review," *Renew. Sustain. Energy Rev.*, vol. 43, pp. 726–749, Mar. 2015.

[34] L. Zhang, N. Tai, W. Huang, J. Liu, and Y. Wang, "A review on protection of DC microgrids," *J. Mod. Power Syst. Clean Energy*, vol. 6, no. 6, pp. 1113–1127, 2018.

[35] H. Nian and L. Kong, "Transient modeling and analysis of VSC based DC microgrid during short circuit fault," *IEEE Access*, vol. 7, pp. 170604–170614, 2019.

[36] G. C. Bakos, "Distributed power generation: A case study of small scale PV power plant in Greece," *Appl. Energy*, vol. 86, no. 9, pp. 1757–1766, Sep. 2009.

[37] M. Farhadi and O. A. Mohammed, "Protection of multi-terminal and distributed DC systems: Design challenges and techniques," *Electr. Power Syst. Res.*, vol. 143, pp. 715–727, Feb. 2017.

[38] S. Beheshtaein, R. M. Cuzner, M. Forouzesh, M. Savaghebi, and J. M. Guerrero, "DC microgrid protection: A comprehensive review," *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, Mar. 12, 2019, doi: 10.1109/JESTPE.2019.2904588.

[39] M. M. Savrun, "Z-source converter integrated DC electric spring for power quality improvement in DC microgrid," *Eng. Sci. Technol., Int. J.*, vol. 24, no. 6, pp. 1408–1414, Dec. 2021.

[40] N. V. Kurdkandi and T. Nouri, "Analysis of an efficient interleaved ultra-large gain DC–DC converter for DC microgrid applications," *IET Power Electron.*, vol. 13, no. 10, pp. 2008–2018, 2020.

[41] J. Mohammadi and F. B. Ajaei, "Adaptive time delay strategy for reliable load shedding in the direct-current microgrid," *IEEE Access*, vol. 8, pp. 114509–114518, 2020.

[42] J. Mohammadi and F. B. Ajaei, "Adaptive voltage-based load shedding scheme for the DC microgrid," *IEEE Access*, vol. 7, pp. 106002–106010, 2019.

[43] I. Navoni, M. Longo, and M. Brenna, "Bidirectional solid-state circuit breakers for DC microgrid applications," in *Proc. IEEE Int. Conf. Environ. Electr. Eng., IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Europe)*, Sep. 2021, pp. 1–6.

[44] F. S. Al-Ismail, "DC microgrid planning, operation, and control: A comprehensive review," *IEEE Access*, vol. 9, pp. 36154–36172, 2021.

[45] S. Augustine, J. E. Quiroz, M. J. Reno, and S. Brahma, "DC microgrid protection: Review and challenges," Sandia Nat. Lab., Albuquerque, NM, USA, Tech. Rep. SAND2018-8853, 2018.

[46] L. Che, M. E. Khodayar, and M. Shahidehpour, "Adaptive protection system for microgrids: Protection practices of a functional microgrid system," *IEEE Electrific. Mag.*, vol. 2, no. 1, pp. 66–80, Mar. 2014.

[47] Z. Shuai, Y. Sun, Z. J. Shen, W. Tian, C. Tu, Y. Li, and X. Yin, "Microgrid stability: Classification and a review," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 167–179, May 2016.

[48] E. Hossain, E. Kabalci, R. Bayindir, and R. Perez, "Microgrid testbeds around the world: State of art," *Energy Convers. Manage.*, vol. 86, pp. 132–153, Oct. 2014.

[49] T. Yang, L. Zhang, L. Zhen, Y. Liu, Q. Song, and W. Tang, "Fast microgrids formation of distribution network with high penetration of DERs considering reliability," *Energy*, vol. 236, Dec. 2021, Art. no. 121524.

[50] A. Zamani, T. Sidhu, and A. Yazdani, "A strategy for protection coordination in radial distribution networks with distributed generators," in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, pp. 1–8.

[51] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of power converters in AC microgrids," *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4734–4749, Dec. 2012.

[52] C. Cho, J.-H. Jeon, J.-Y. Kim, S. Kwon, K. Park, and S. Kim, "Active synchronizing control of a microgrid," *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3707–3719, Dec. 2011.

[53] Y.-H. Ji, D.-Y. Jung, J.-G. Kim, J.-H. Kim, T.-W. Lee, and C.-Y. Won, "A real maximum power point tracking method for mismatching compensation in PV array under partially shaded conditions," *IEEE Trans. Power Electron.*, vol. 26, no. 4, pp. 1001–1009, Apr. 2011.

[54] S. F. Zarei, H. Mokhtari, and F. Blaabjerg, "Fault detection and protection strategy for islanded inverter-based microgrids," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 1, pp. 472–484, Feb. 2021.

[55] A. Yazdaninejadi, A. Hamidi, S. Golshannavaz, F. Aminifar, and S. Teimourzadeh, "Impact of inverter-based DERs integration on protection, control, operation, and planning of electrical distribution grids," *Electr. J.*, vol. 32, no. 6, pp. 43–56, Jul. 2019.

[56] A. A. Salam, A. Mohamed, and M. A. Hannan, "Technical challenges on microgrids," *ARPN J. Eng. Appl. Sci.*, vol. 3, no. 6, pp. 64–69, 2008.

[57] M. W. Altaf, M. T. Arif, S. Saha, S. Islam, M. E. Haque, and A. Oo, "Sensitivity analysis and performance ranking of different passive power system parameters for islanding detection," in *Proc. Australas. Univ. Power Eng. Conf. (AUPEC)*, 2020, pp. 1–6.

[58] A. A. Eladl, M. A. Saeed, B. E. Sedhom, and J. M. Guerrero, "IoT technology-based protection scheme for MT-HVDC transmission grids with restoration algorithm using support vector machine," *IEEE Access*, vol. 9, pp. 86268–86284, 2021.

[59] S. Parhizi, H. Lotfi, A. Khodaei, and S. Bahramirad, "State of the art in research on microgrids: A review," *IEEE Access*, vol. 3, pp. 890–925, 2015.

[60] B. Gergič and D. Hercog, "Design and implementation of a measurement system for high-speed testing of electromechanical relays," *Measurement*, vol. 135, pp. 112–121, Mar. 2019.

[61] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renew. Sustain. Energy Rev.*, vol. 24, pp. 387–405, Aug. 2013.

[62] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Modeling of a centralized microgrid protection system and distributed energy resources according to IEC 61850-7-420," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1560–1567, Aug. 2012.

[63] R. Jain, D. L. Lubkeman, and S. M. Lukic, "Dynamic adaptive protection for distribution systems in grid-connected and islanded modes," *IEEE Trans. Power Del.*, vol. 34, no. 1, pp. 281–289, 2018.

[64] J. C. Hernández, J. De la Cruz, and B. Ogayar, "Electrical protection for the grid-interconnection of photovoltaic-distributed generation," *Electr. Power Syst. Res.*, vol. 89, pp. 85–99, Aug. 2012.

[65] S. Jena and B. R. Bhalja, "A new differential protection scheme for busbar using teager energy operator," in *Proc. 8th Int. Conf. Power Syst. (ICPS)*, Dec. 2019, pp. 1–6.

[66] G. K. Srinivasan and M. Sahayam, "Microgrid: Structures, curb methods, standards and challenges," *J. Electr. Eng.*, vol. 20, no. 1, p. 9, 2020.

[67] R. M. Kamel, A. Chaouachi, and K. Nagasaka, "Design and testing of three earthing systems for micro-grid protection during the islanding mode," *Smart Grid Renew. Energy*, vol. 1, no. 3, p. 132, 2010.

[68] B. Li, Y. Li, and T. Ma, "Research on earthing schemes in LV microgrids," in *Proc. Int. Conf. Adv. Power Syst. Autom. Protection*, Oct. 2011, pp. 1003–1007.

[69] R. M. Kamel, A. Chaouachi, and K. Nagasaka, "Comparison the performances of three earthing systems for micro-grid protection during the grid connected mode," *Smart Grid Renew. Energy*, vol. 2, no. 3, p. 206, 2011.

[70] M. A. M. M. Esreraig, *Developing Protection Systems for Microgrids*. East Lansing, MI, USA: Michigan State Univ., Dept. Elect. Eng., 2012.

[71] L. Tao and C. Schwaegerl, "Advanced architectures and control concepts for more microgrids," Eur. Project, Eur. Commission Sixth Framework Programme RTD, Tech. Rep. SES6-019864, 2009.

[72] 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, p. 2149, May 2020.

[73] F. Alasali, N. El-Naily, E. Zarour, and S. M. Saad, "Highly sensitive and fast microgrid protection using optimal coordination scheme and nonstandard tripping characteristics," *Int. J. Electr. Power Energy Syst.*, vol. 128, Jun. 2021, Art. no. 106756.

[74] D. Kumar and F. Zare, "A comprehensive review of maritime microgrids: System architectures, energy efficiency, power quality, and regulations," *IEEE Access*, vol. 7, pp. 67249–67277, 2019.

[75] S. Zhang, M. Pu, B. Wang, and B. Dong, "A privacy protection scheme of microgrid direct electricity transaction based on consortium blockchain and continuous double auction," *IEEE Access*, vol. 7, pp. 151746–151753, 2019.

[76] Y. Wang, A. O. Rousis, and G. Strbac, "On microgrids and resilience: A comprehensive review on modeling and operational strategies," *Renew. Sustain. Energy Rev.*, vol. 134, Dec. 2020, Art. no. 110313.

[77] M. Tamoor, M. A. B. Tahir, and M. A. Zaka, "Energy management system for integration of different renewable energy system into microgrids," *Int. J.*, vol. 10, no. 2, pp. 1–28, 2021.

[78] J. S. Farkhani, M. Zareein, A. Najafi, R. Melicio, and E. M. Rodrigues, "The power system and microgrid protection—A review," *Appl. Sci.*, vol. 10, no. 22, p. 8271, 2020.

[79] S. Chowdhury and P. Crossley, *Microgrids and Active Distribution Networks*. London, U.K.: The Institution of Engineering and Technology, 2009.

[80] R. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromsom, A. S. Meliopoulous, R. Yinger, and J. Eto, "Integration of distributed energy resources. The CERTS Microgrid Concept," Lawrence Berkeley Nat. Lab., Berkeley, CA, USA, Tech. Rep. LBNL-50829, 2002.

[81] S. Baloch and M. S. Muhammad, "An intelligent data mining-based fault detection and classification strategy for microgrid," *IEEE Access*, vol. 9, pp. 22470–22479, 2021.

[82] J. Keller and B. Kroposki, "Understanding fault characteristics of inverter-based distributed energy resources," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-550-46698, 2010.

[83] P. P. Barker and R. W. de Mello, "Determining the impact of distributed generation on power systems. I. Radial distribution systems," in *Proc. Power Eng. Soc. Summer Meeting*, vol. 3, Jul. 2000, pp. 1645–1656.

[84] P. Gupta, R. S. Bhatia, and D. K. Jain, "Adaptive protection schemes for the microgrid in a smart grid scenario: Technical challenges," in *Proc. IEEE Innov. Smart Grid Technol.-Asia (ISGT Asia)*, Nov. 2013, pp. 1–5.

[85] S. Voima, K. Kauhaniemi, and H. Laaksonen, "Novel protection approach for MV microgrid," in *Proc. 21st Int. Conf. Electr. Distrib.*, no. 430, 2011, pp. 1–4.

[86] X. Xie, W. Xu, C. Huang, and X. Fan, "New islanding detection method with adaptively threshold for microgrid," *Electr. Power Syst. Res.*, vol. 195, Jun. 2021, Art. no. 107167.

[87] H. Lee, G.-S. Byeon, J.-H. Jeon, A. Hussain, H.-M. Kim, A. O. Rousis, and G. Strbac, "An energy management system with optimum reserve power procurement function for microgrid resilience improvement," *IEEE Access*, vol. 7, pp. 42577–42585, 2019.

[88] H. Laaksonen and K. Kauhaniemi, "Fault type and location detection in islanded microgrid with different control methods based converters," in *Proc. 19th Int. Conf. Electr. Distrib. (CIRED)*, Vienna, Austria, 2007, pp. 1–5.

[89] T. Loix, T. Wijnhoven, and G. Deconinck, "Protection of microgrids with a high penetration of inverter-coupled energy sources," in *Proc. CIGRE/IEEE PES Joint Symp. Integr. Wide-Scale Renew. Resour. Into Power Del. Syst.*, Jul. 2009, pp. 1–6.

[90] S. Biswas, M. K. Singh, and V. A. Centeno, "Chance-constrained optimal distribution network partitioning to enhance power grid resilience," *IEEE Access*, vol. 9, pp. 42169–42181, 2021.

[91] M. Seyedi, S. A. Taher, B. Ganji, and J. Guerrero, "A hybrid islanding detection method based on the rates of changes in voltage and active power for the multi-inverter systems," *IEEE Trans. Smart Grid*, vol. 12, no. 4, pp. 2800–2811, Jul. 2021.

[92] U. Markovic, D. Chrysostomou, P. Aristidou, and G. Hug, "Impact of inverter-based generation on islanding detection schemes in distribution networks," *Electr. Power Syst. Res.*, vol. 190, Jan. 2021, Art. no. 106610.

[93] K. P. Schneider, S. Laval, J. Hansen, R. B. Melton, L. Ponder, L. Fox, J. Hart, J. Hambrick, M. Buckner, M. Baggu, and K. Prabakar, "A distributed power system control architecture for improved distribution system resiliency," *IEEE Access*, vol. 7, pp. 9957–9970, 2019.

[94] M. L. Ong'ondo, N. G. Nyauma, and M. J. Saulo, "Modeling and simulation of solar photovoltaic renewable energy sources power generation system for MGs and loss of mains detection," *Multidisciplinary J. Tech. Univ. Mombasa*, vol. 1, no. 1, pp. 37–44, Nov. 2020.

[95] B. Hussain, S. Sharkh, S. Hussain, and M. Abusara, "Integration of distributed generation into the grid: Protection challenges and solutions," in *Proc. 10th IET Int. Conf. Develop. Power Syst. Protection (DPSP)*, 2010, pp. 1–5.

[96] D. M. Laverty, R. J. Best, and D. J. Morrow, "Loss-of-mains protection system by application of phasor measurement unit technology with experimentally assessed threshold settings," *IET Gener. Transmiss. Distrib.*, vol. 9, no. 2, pp. 146–153, Jan. 2015.

[97] A. Arif, K. Imran, Q. Cui, and Y. Weng, "Islanding detection for inverter-based distributed generation using unsupervised anomaly detection," *IEEE Access*, vol. 9, pp. 90947–90963, 2021.

[98] D. G. Photovoltaics and E. Storage, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces*, IEEE Standard 1547-2018, 2018.

[99] C. R. Reddy, B. S. Goud, B. N. Reddy, M. Pratyusha, C. V. V. Kumar, and R. Rekha, "Review of islanding detection parameters in smart grids," in *Proc. 8th Int. Conf. Smart Grid (icSmartGrid)*, Jun. 2020, pp. 78–89.

[100] M. A. Dawoud, D. K. Ibrahim, M. I. Gilany, and A. El'gharably, "A proposed passive islanding detection approach for improving protection systems," *Int. J. Renew. Energy Res.*, vol. 10, no. 4, pp. 1940–1950, Dec. 2020.

[101] K. Naraghipour, K. Ahmed, and C. Booth, "A comprehensive review of islanding detection methods for distribution systems," in *Proc. 9th Int. Conf. Renew. Energy Res. Appl. (ICRERA)*, Sep. 2020, pp. 428–433.

[102] H. Abdi, A. Rostami, and N. Rezaei, "A novel passive islanding detection scheme for synchronous-type DG using load angle and mechanical power parameters," *Electr. Power Syst. Res.*, vol. 192, Mar. 2021, Art. no. 106968.

[103] M. Babakmehr, F. Harirchi, P. Dehghanian, and J. H. Enslin, "Artificial intelligence-based cyber–physical events classification for islanding detection in power inverters," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 5, pp. 5282–5293, Oct. 2021.

[104] M. Karimi, M. Farshad, Q. Hong, H. Laaksonen, and K. Kauhaniemi, "An islanding detection technique for inverter-based distributed generation in microgrids," *Energies*, vol. 14, no. 1, p. 130, Dec. 2020.

[105] M.-S. Kim, R. Haider, G.-J. Cho, C.-H. Kim, C.-Y. Won, and J.-S. Chai, "Comprehensive review of islanding detection methods for distributed generation systems," *Energies*, vol. 12, no. 5, p. 837, Mar. 2019.

[106] 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 *Proc. IEEE Madrid PowerTech*, Jun. 2021, pp. 1–6.

[107] M. W. Altaf, M. T. Arif, S. Saha, S. N. Islam, M. E. Haque, and A. Oo, "Effective protection scheme for reliable operation of multi-microgrid," in *Proc. IEEE Int. Conf. Power Electron., Drives Energy Syst. (PEDES)*, Dec. 2020, pp. 1–6.

[108] D. Lagos, V. Papaspiliotopoulos, G. Korres, and N. Hatziargyriou, "Microgrid protection against internal faults: Challenges in islanded and interconnected operation," *IEEE Power Energy Mag.*, vol. 19, no. 3, pp. 20–35, May 2021.

[109] V. Papaspiliotopoulos, V. Kleftakis, P. Kotsampopoulos, G. Korres, and N. Hatziargyriou, "Hardware-in-the-loop simulation for protection blinding and sympathetic tripping in distribution grids with high penetration of distributed generation," in *Proc. MedPower*, 2014, pp. 1–6.
[110] H. Laaksonen, K. Kauhaniemi, and S. Voima, "Protection system for future LV microgrids," in *Proc. CIRED 21st Int. Conf. Elect. Distrib.*, 2011, pp. 1–4.
[111] *AS/NZS 3000:2018*. Accessed: Jan. 2022. [Online]. Available: https://www.gses.com.au/protection-coordination-of-circuit-breakers/
[112] V. Patel and V. Patel, "A comprehensive review: AC & DC microgrid protection," in *Proc. 21st Nat. Power Syst. Conf. (NPSC)*, Dec. 2020, pp. 1–6.
[113] M. Usama, H. Mokhlis, M. Moghavvemi, N. N. Mansor, M. A. Alotaibi, M. A. Muhammad, and A. A. Bajwa, "A comprehensive review on protection strategies to mitigate the impact of renewable energy sources on interconnected distribution networks," *IEEE Access*, vol. 9, pp. 35740–35765, 2021.
[114] P. A. Kumar, J. Shankar, and Y. Nagaraju, "Protection issues in micro grid," *Int. J. Appl. Control Electr. Electron. Eng.*, vol. 1, pp. 19–30, 2013.
[115] A. Hartono, "Microgrid safety and protection strategies," M.S. thesis, Dept. Elect. Eng. Electromagn. Eng., Roy. Inst. Technol., Stockholm, Sweden, 2018.
[116] N. K. Choudhary, S. R. Mohanty, and R. K. Singh, "A review on microgrid protection," in *Proc. Int. Electr. Eng. Congr. (iEECON)*, Mar. 2014, pp. 1–4.
[117] K. I. Jennett, C. D. Booth, F. Coffele, and A. J. Roscoe, "Investigation of the sympathetic tripping problem in power systems with large penetrations of distributed generation," *IET Gener., Transmiss. Distrib.*, vol. 9, no. 4, pp. 379–385, Mar. 2015.
[118] N. W. A. Lidula and A. D. Rajapakse, "Voltage balancing and synchronization of microgrids with highly unbalanced loads," *Renew. Sustain. Energy Rev.*, vol. 31, pp. 907–920, Mar. 2014.
[119] N. P. Gupta and P. Paliwal, "Regulation of hybrid micro grid under transient operations," *Int. J. Power Electron.*, vol. 13, no. 1, pp. 83–111, 2021.
[120] N. P. Gupta and P. Paliwal, "Novel droop integrated technique for regulation of islanded and grid connected hybrid microgrid," *Int. J. Power Energy Convers.*, vol. 12, no. 2, pp. 89–114, 2021.
[121] A. B. Nassif and A. Electric, "A protection and grounding strategy for integrating inverter-based distributed energy resources in an isolated microgrid," *CPSS Trans. Power Electron. Appl.*, vol. 5, no. 3, pp. 242–250, Sep. 2020.
[122] (2017). *Auto-Recloser*. [Online]. Available: https://megger.com/electrical-tester/september-2017-(1)/auto-recloser-whys-and-wherefores
[123] G. Kaur, A. Prakash, and K. U. Rao, "A critical review of microgrid adaptive protection techniques with distributed generation," *Renew. Energy Focus*, vol. 39, pp. 99–109, Dec. 2021.
[124] N. Bayati, H. R. Baghaee, A. Hajizadeh, and M. Soltani, "A fuse saving scheme for DC microgrids with high penetration of renewable energy resources," *IEEE Access*, vol. 8, pp. 137407–137417, 2020.
[125] S. Kim, G. Ulissi, S.-N. Kim, and D. Dujic, "Protection coordination for reliable marine DC power distribution networks," *IEEE Access*, vol. 8, pp. 222813–222823, 2020.
[126] Y. Wang, Z. Yu, J. He, S. Chen, R. Zeng, and B. Zhang, "Performance of shipboard medium-voltage DC system of various grounding modes under monopole ground fault," *IEEE Trans. Ind. Appl.*, vol. 51, no. 6, pp. 5002–5009, Nov./Dec. 2015.
[127] S.-L. Chen, S-C. Hsu, C.-T. Tseng, K.-H. Yan, H.-Y. Chou, and T.-M. Too, "Analysis of rail potential and stray current for Taipei Metro," *IEEE Trans. Veh. Technol.*, vol. 55, no. 1, pp. 67–75, Jan. 2006.
[128] D. Salomonsson, L. Söder, and A. Sannino, "Protection of low-voltage DC microgrids," *IEEE Trans. Power Del.*, vol. 24, no. 3, pp. 1045–1053, Jul. 2009.
[129] D. Kumar, F. Zare, and A. Ghosh, "DC microgrid technology: System architectures, AC grid interfaces, grounding schemes, power quality, communication networks, applications, and standardizations aspects," *IEEE Access*, vol. 5, pp. 12230–12256, 2017.
[130] I. Cotton, C. Charalambous, P. Aylott, and P. Ernst, "Stray current control in DC mass transit systems," *IEEE Trans. Veh. Technol.*, vol. 54, no. 2, pp. 722–730, Mar. 2005.
[131] D. J. Love and N. Hashemi, "Considerations for ground fault protection in medium-voltage industrial and cogeneration systems," *IEEE Trans. Ind. Appl.*, vol. 24, no. 4, pp. 548–553, Jul. 1988.
[132] J.-D. Park, "Ground fault detection and location for ungrounded DC traction power systems," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5667–5676, Dec. 2015.
[133] Y. Khersonsky *et al.*, *Recommended Practice for 1 to 35 kV Medium Voltage DC Power Systems on Ships*. Piscataway, NJ, USA: IEEE, 2010.
[134] W. Leterme, P. Tielens, S. De Boeck, and D. Van Hertem, "Overview of grounding and configuration options for meshed HVDC grids," *IEEE Trans. Power Del.*, vol. 29, no. 6, pp. 2467–2475, Dec. 2014.
[135] S. L. Blond, R. Bertho, D. V. Coury, and J. C. M. Vieira, "Design of protection schemes for multi-terminal HVDC systems," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 965–974, Apr. 2016.
[136] A. Nejadpak, A. Sarikhani, and O. A. Mohammed, "Analysis of radiated EMI and noise propagation in three-phase inverter system operating under different switching patterns," *IEEE Trans. Magn.*, vol. 49, no. 5, pp. 2213–2216, May 2013.
[137] J.-D. Park, J. Candelaria, L. Ma, and K. Dunn, "DC ring-bus microgrid fault protection and identification of fault location," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2574–2584, Oct. 2013.
[138] C. Yuan, M. A. Haj-Ahmed, and M. S. Illindala, "Protection strategies for medium-voltage direct-current microgrid at a remote area mine site," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 2846–2853, Jul./Aug. 2015.
[139] Y. Liu, D. Chen, H. Yuan, and Z. Ma, "Research of dynamic optimization for the cam design structure of MCCB," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 6, no. 3, pp. 390–399, Mar. 2016.
[140] H. Sun, M. Rong, Z. Chen, C. Hou, and Y. Sun, "Investigation on the arc phenomenon of air DC circuit breaker," *IEEE Trans. Plasma Sci.*, vol. 42, no. 10, pp. 2706–2707, Oct. 2014.
[141] O. V. G. Swathika and S. Hemamalini, "Review on microgrid and its protection strategies," *Int. J. Renew. Energy Res.*, vol. 6, no. 4, pp. 1574–1587, Jan. 2016.
[142] A. Khademlahashy, L. Li, J. Every, and J. Zhu, "A review on protection issues in micro-grids embedded with distribution generations," in *Proc. 12th IEEE Conf. Ind. Electron. Appl. (ICIEA)*, Jun. 2017, pp. 913–918.
[143] X. Kang, C. E. Nuworklo, B. S. Tekpeti, and M. Kheshti, "Protection of micro-grid systems: A comprehensive survey," *J. Eng.*, vol. 2017, no. 13, pp. 1515–1518, 2017.
[144] S. F. Zarei and M. Parniani, "A comprehensive digital protection scheme for low-voltage microgrids with inverter-based and conventional distributed generations," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 441–452, Feb. 2017.
[145] D. Pilaquinga and M. Pozo, "Novel protection schema for a radial microgrid system," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf.-Latin Amer. (ISGT Latin America)*, Sep. 2017, pp. 1–6.
[146] M. Elkhatib, A. Ellis, M. Biswal, S. Brahma, and S. Ranade, "Protection of renewable-dominated microgrids: Challenges and potential solutions," Sandia Nat. Lab., Albuquerque, NM, USA, Tech. Rep. SAND2016-11210, 2016.
[147] A. Sharma and B. K. Panigrahi, "Phase fault protection scheme for reliable operation of microgrids," *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2646–2655, May/Jun. 2018.
[148] U. Maqbool and U. A. Khan, "Fault current analysis for grid-connected and islanded microgrid modes," in *Proc. 13th Int. Conf. Emerg. Technol. (ICET)*, Dec. 2017, pp. 1–5.
[149] M. A. Hajahmed, M. Hawa, L. A. Shamlawi, S. Alnaser, Y. Alsmadi, and D. Abualnadi, "Cognitive radio_based backup protection scheme for smart grid applications," *IEEE Access*, vol. 8, pp. 71866–71879, 2020.
[150] S. Baloch, S. S. Samsani, and M. S. Muhammad, "Fault protection in microgrid using wavelet multiresolution analysis and data mining," *IEEE Access*, vol. 9, pp. 86382–86391, 2021.
[151] E. Abbaspour, B. Fani, I. Sadeghkhani, and H. H. Alhelou, "Multi-agent system-based hierarchical protection scheme for distribution networks with high penetration of electronically-coupled DGs," *IEEE Access*, vol. 9, pp. 102998–103018, 2021.
[152] H. Lahiji, F. B. Ajaei, and R. E. Boudreau, "Non-pilot protection of the Inverter- dominated microgrid," *IEEE Access*, vol. 7, pp. 142190–142202, 2019.
[153] M. Usama, M. Moghavvemi, H. Mokhlis, N. N. Mansor, H. Farooq, and A. Pourdaryaei, "Optimal protection coordination scheme for radial distribution network considering ON/OFF-grid," *IEEE Access*, vol. 9, pp. 34921–34937, 2021.
[154] L. Kong and H. Nian, "Parameters selection method of circuit breaker and fault current limiter in mesh-type DC microgrid," *IEEE Access*, vol. 9, pp. 35514–35523, 2021.

[155] L. Tightiz and H. Yang, "Resilience microgrid as power system integrity protection scheme element with reinforcement learning based management," *IEEE Access*, vol. 9, pp. 83963–83975, 2021.

[156] 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*, vol. 9, pp. 156283–156296, 2021.

[157] F. Zhang and L. Mu, "New protection scheme for internal fault of multi-microgrid," *Protection Control Mod. Power Syst.*, vol. 4, no. 1, pp. 1–12, Dec. 2019.

[158] M. W. Altaf, M. T. Arif, S. Saha, S. N. Islam, M. E. Haque, and A. M. T. Oo, "Effective ROCOF-based islanding detection technique for different types of microgrid," *IEEE Trans. Ind. Appl.*, vol. 58, no. 2, pp. 1809–1821, Apr. 2022.

[159] H. M. Sharaf, H. H. Zeineldin, and E. El-Saadany, "Protection coordination for microgrids with grid-connected and islanded capabilities using communication assisted dual setting directional overcurrent relays," *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 143–151, Jan. 2018.

[160] A. K. Sahoo, "Protection of microgrid through coordinated directional over-current relays," in *Proc. IEEE Global Humanitarian Technol. Conf.-South Asia Satell. (GHTC-SAS)*, Sep. 2014, pp. 129–134.

[161] E. Dehghanpour, H. K. 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, Mar. 2018.

[162] A. Ahmarinejad, S. M. Hasanpour, M. Babaei, and M. Tabrizian, "Optimal overcurrent relays coordination in microgrid using cuckoo algorithm," *Energy Proc.*, vol. 100, pp. 280–286, Nov. 2016.

[163] D. Birla, R. P. Maheshwari, and H. O. Gupta, "An approach to tackle the threat of sympathy trips in directional overcurrent relay coordination," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 851–858, Apr. 2007.

[164] D. Birla, R. P. Maheshwari, and H. O. Gupta, "A new nonlinear directional overcurrent relay coordination technique, and banes and boons of near-end faults based approach," *IEEE Trans. Power Del.*, vol. 21, no. 3, pp. 1176–1182, Jul. 2006.

[165] X. Pei, Z. Chen, S. Wang, and Y. Kang, "Overcurrent protection for inverter-based distributed generation system," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Sep. 2015, pp. 2328–2332.

[166] E. C. Piesciorovsky and N. N. Schulz, "Fuse relay adaptive overcurrent protection scheme for microgrid with distributed generators," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 2, pp. 540–549, Jan. 2017.

[167] Z. Kailun, D. S. Kumar, D. Srinivasan, and A. Sharma, "An adaptive overcurrent protection scheme for microgrids based on real time digital simulation," in *Proc. IEEE Innov. Smart Grid Technol.-Asia (ISGT-Asia)*, Dec. 2017, pp. 1–6.

[168] R. R. Ferreira, P. J. Colorado, A. P. Grilo, J. C. Teixeira, and R. C. Santos, "Method for identification of grid operating conditions for adaptive overcurrent protection during intentional islanding operation," *Int. J. Electr. Power Energy Syst.*, vol. 105, pp. 632–641, Feb. 2019.

[169] H. Sabra, D. K. Ibrahim, and M. Gilany, "Field experience with sympathetic tripping in distribution networks: Problems and solutions," *J. Eng.*, vol. 2018, no. 15, pp. 1181–1185, Oct. 2018.

[170] X. Liu, M. Shahidehpour, Z. Li, X. Liu, Y. Cao, and W. Tian, "Protection scheme for loop-based microgrids," *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1340–1349, May 2017.

[171] C. Yuan, K. Lai, M. S. Illindala, M. A. Haj-Ahmed, and A. S. Khalsa, "Multilayered protection strategy for developing community microgrids in village distribution systems," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 495–503, Feb. 2017.

[172] K. Lai, M. S. Illindala, and M. A. Haj-Ahmed, "Comprehensive protection strategy for an islanded microgrid using intelligent relays," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Oct. 2015, pp. 1–11.

[173] M. Dewadasa, A. Ghosh, and G. Ledwich, "Protection of microgrids using differential relays," in *Proc. 21st Australas. Univ. Power Eng. Conf. (AUPEC)*, 2011, pp. 1–6.

[174] S. Kar, S. R. Samantaray, and M. D. Zadeh, "Data-mining model based intelligent differential microgrid protection scheme," *IEEE Syst. J.*, vol. 11, no. 2, pp. 1161–1169, Jun. 2017.

[175] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Differential protection of microgrids with central protection unit support," in *Proc. IEEE Tencon-Spring*, Apr. 2013, pp. 15–19.

[176] T. S. Aghdam, H. K. Karegar, and H. H. Zeineldin, "Variable tripping time differential protection for microgrids considering DG stability," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2407–2415, May 2019.

[177] A. Soleimanisardoo, H. K. Karegar, and H. H. Zeineldin, "Differential frequency protection scheme based on off-nominal frequency injections for inverter-based islanded microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 2107–2114, Mar. 2019.

[178] C. Louw, C. Buque, and S. Chowdhury, "Modelling and simulation of an adaptive differential current protection scheme for a solar PV microgrid," in *Proc. 3rd Renew. Power Gener. Conf. (RPG)*. Edison, NJ, USA: IET, 2014, pp. 1–7.

[179] S. Tian, Y. C. Sun, and L. Zhou, "Microgrid protection using Hilbert-Huang transform based differential energy scheme," *Power Syst. Protection Control*, vol. 46, no. 11, pp. 55–61, 2018.

[180] A. Gururani, S. R. Mohanty, and J. C. Mohanta, "Microgrid protection using Hilbert–Huang transform based-differential scheme," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 15, pp. 3707–3716, 2007.

[181] S. Kar and S. R. Samantaray, "Time-frequency transform-based differential scheme for microgrid protection," *IET Gener., Transmiss. Distrib.*, vol. 8, no. 2, pp. 310–320, 2014.

[182] M. Li, M. Ni, Y. Li, Y. Tang, and Y. Wu, "False-tirp probability model for the current differential protection considering power grid operation state and communication delay," in *Proc. 5th Int. Conf. Electr. Utility Deregulation Restructuring Power Technol. (DRPT)*, Nov. 2015, pp. 2512–2516.

[183] O. P. Dahal, S. M. Brahma, S. J. Ranade, and R. J. Malahowski, "Investigation of various options to avoid false tripping of a primary distribution feeder: Part II—Solution techniques," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–8.

[184] J. Dines, "Investigation into the protection of microgrids using adaptive relays," Ph.D. dissertation, Murdoch Univ., Perth, WA, Australia, 2016.

[185] H. Laaksonen, D. Ishchenko, and A. Oudalov, "Adaptive protection and microgrid control design for Hailuoto island," *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1486–1493, May 2014.

[186] R. Sitharthan, M. Geethanjali, and T. Karpaga Senthil Pandy, "Adaptive protection scheme for smart microgrid with electronically coupled distributed generations," *Alexandria Eng. J.*, vol. 55, no. 3, pp. 2539–2550, Sep. 2016.

[187] A. I. Atteya, A. M. El Zonkoly, and H. A. Ashour, "Optimal relay coordination of an adaptive protection scheme using modified PSO algorithm," in *Proc. 19th Int. Middle East Power Syst. Conf. (MEPCON)*, Dec. 2017, pp. 689–694.

[188] T. S. Ustun, C. Ozansoy, and A. Ustun, "Fault current coefficient and time delay assignment for microgrid protection system with central protection unit," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 598–606, May 2013.

[189] O. G. Swathika, S. Angalaeswari, V. A. Krishnan, K. Jamuna, and J. F. Daya, "Fuzzy decision and graph algorithms aided adaptive protection of microgrid," *Energy Proc.*, vol. 117, pp. 1078–1084, Jun. 2017.

[190] A. Oudalov and A. Fidigatti, "Adaptive network protection in microgrids," *Int. J. Distrib. Energy Resour.*, vol. 5, no. 3, pp. 201–226, 2009.

[191] S. Gottwalt, J. Gärttner, H. Schmeck, and C. Weinhardt, "Modeling and valuation of residential demand flexibility for renewable energy integration," *IEEE Trans. Smart Grid*, vol. 8, no. 6, pp. 2565–2574, Mar. 2016.

[192] Z. Chen, X. Pei, M. Yang, L. Peng, and P. Shi, "A novel protection scheme for Inverter- interfaced microgrid (IIM) operated in islanded mode," *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 7684–7697, Sep. 2018.

[193] M. A. Zamani, T. S. Sidhu, and A. Yazdani, "A protection strategy and microprocessor-based relay for low-voltage microgrids," *IEEE Trans. Power Del.*, vol. 26, no. 3, pp. 1873–1883, Jul. 2011.

[194] M. Khederzadeh, "Integration of renewables into the distribution grid needs new software tools for coordination of protective relays," in *Proc. CIRED Workshop, Integr. Renew. Into Distrib. Grid*, 2012, pp. 1–4.

[195] K. Jennett, C. Booth, and M. Lee, "Analysis of the sympathetic tripping problem for networks with high penetrations of distributed generation," in *Proc. Int. Conf. Adv. Power Syst. Autom. Protection (APAP)*, Oct. 2011, pp. 384–389.

[196] R. Ndou, J. Fadiran, S. Chowdhury, and S. Chowdhury, "Performance comparison of voltage and frequency based loss of grid protection schemes for microgrids," in *Proc. Power Energy Soc. Gen. Meeting (PES)*, 2013, pp. 1–5.

[197] A. Gangat, C. Buque, and S. Chowdhury, "Performance evaluation of ROCOF based loss of grid scheme for microgrid islanding prevention for different grid fault types near point of common coupling," in *Proc. 49th Int. Universities Power Eng. Conf. (UPEC)*, Sep. 2014, pp. 1–6.

[198] W. C. Edwards, S. Manson, and J. Vico, "Microgrid islanding and grid restoration with off-the-shelf utility protection equipment," in *Proc. IEEE Canada Int. Humanitarian Technol. Conf. (IHTC)*, Jul. 2017, pp. 188–192.
[199] S. Raza, H. Mokhlis, H. Arof, J. A. Laghari, and H. Mohamad, "A sensitivity analysis of different power system parameters on islanding detection," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 461–470, Apr. 2016.
[200] K.-Y. Lien, S.-L. Chen, D. M. Bui, and W.-X. Zhao, "A fast computing algorithm for microgrid fault protection system using communication-assisted digital relays and initially experimental results," in *Proc. 7th Int. Conf. Inf. Autom. Sustainability (ICIAfS)*, Dec. 2014, pp. 1–8.
[201] H. C. Kiliçkiran, İ. Şengör, H. Akdemir, B. Kekezoğlu, O. Erdinç, and N. G. Paterakis, "Power system protection with digital overcurrent relays: A review of non-standard characteristics," *Electr. Power Syst. Res.*, vol. 164, pp. 89–102, Nov. 2018.
[202] J. Lucas, *Power System Analysis: Faults*, document EE423, 2005.
[203] E. Casagrande, W. L. Woon, H. H. Zeineldin, and N. H. Kan'an, "Data mining approach to fault detection for isolated inverter-based microgrids," *IET Gener., Transmiss. Distrib.*, vol. 7, no. 7, pp. 745–754, Jul. 2013.
[204] E. Casagrande, W. L. Woon, H. H. Zeineldin, and D. Svetinovic, "A differential sequence component protection scheme for microgrids with inverter-based distributed generators," *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 29–37, Jan. 2014.
[205] Y.-Y. Hong and M. T. A. M. Cabatac, "Fault detection, classification, and location by static switch in microgrids using wavelet transform and taguchi-based artificial neural network," *IEEE Syst. J.*, vol. 14, no. 2, pp. 2725–2735, Jun. 2020.
[206] M. Manohar, E. Koley, and S. Ghosh, "Microgrid protection under weather uncertainty using joint probabilistic modeling of solar irradiance and wind speed," *Comput. Electr. Eng.*, vol. 86, Sep. 2020, Art. no. 106684.
[207] D. A. Gadanayak, "Protection algorithms of microgrids with inverter interfaced distributed generation units—A review," *Electr. Power Syst. Res.*, vol. 192, Mar. 2021, Art. no. 106986.
[208] X. Li, A. Dyśko, and G. M. Burt, "Traveling wave-based protection scheme for inverter-dominated microgrid using mathematical morphology," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2211–2218, Sep. 2014.
[209] C.-H. Lee and C.-J. Lu, "Assessment of grounding schemes on rail potential and stray currents in a DC transit system," *IEEE Trans. Power Del.*, vol. 21, no. 4, pp. 1941–1947, Oct. 2006.
[210] K. A. Corzine and R. W. Ashton, "A new Z-source DC circuit breaker," *IEEE Trans. Power Electron.*, vol. 27, no. 6, pp. 2796–2804, Dec. 2012.
[211] C. Meyer, S. Schröder, and R. W. De Doncker, "Solid-state circuit breakers and current limiters for medium-voltage systems having distributed power systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1333–1340, Sep. 2004.
[212] 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.

MUHAMMAD WASEEM ALTAF (Graduate Student Member, IEEE) received the B.Sc. degree in electrical engineering from the University of the Punjab, Lahore, Pakistan, in 2014, and the M.S. degree in electrical engineering from COMSATS University, Islamabad, Wah Campus, Pakistan, in 2017. He is currently pursuing the Ph.D. degree in electrical engineering with Deakin University, Australia. Then, he joined the Sharif Engineering College, University of Engineering and Technology, Lahore, as a Lecturer, from 2017 to 2018. He has been also an IEEE Industry Applications Society (IAS) Member, since 2018. His research interests include renewable energy resources, microgrids, distributed power generation, power system control, and protection.

MOHAMMAD TAUFIQUL ARIF (Member, IEEE) received the bachelor's degree in electrical engineering from UET, Lahore, Pakistan, in 1999, the master's degree in media communication engineering from Hanyang University, South Korea, in 2006, and the Ph.D. degree in electrical engineering from CQUniversity, Australia, in 2013. He is currently working as a Lecturer with Deakin University, Australia. He has published over 45 peer-reviewed journals and conference papers. His research interests include renewable energy, energy storage, electric vehicle, their impact assessment & integration into the grid, energy efficiency, energy management, and power system protection for the grid and microgrid applications. He is a member of Engineers Australia, IEEE Power & Energy Society (PES), and IEEE Industry Applications Society (IAS).

SHAMA NAZ ISLAM (Member, IEEE) received the Ph.D. degree from Australian National University, in 2015. She is currently a Senior Lecturer in electrical engineering with Deakin University. She is a leading Researcher in the area of smart grid communication, IoT for smart energy applications, energy management, and smart grid data analytics. She has successfully attracted internal grants worth of $250,000 and external grant of 1.4 million AUD over the last five years along with other investigators with Deakin University. She has been awarded Victoria Fellowship 2019 for her contributions in scientific innovations in Victoria, Australia. She has been accredited as a fellow of U.K.-based Higher Education Academy, in 2021.

MD. ENAMUL HAQUE (Senior Member, IEEE) received the B.Eng. degree in electrical and electronic engineering from the Bangladesh Institute of Technology (BIT), Rajshahi, Bangladesh, in 1995, the M.Eng. degree in electrical engineering from the University Technology Malaysia (UTM), Malaysia, in 1998, and the Ph.D. degree in electrical engineering from the University of New South Wales (UNSW), Sydney, Australia, in 2003. He is currently working as a Senior Lecturer with the School of Engineering, Deakin University, Australia. He is the current IEEE Industry Applications Society (IAS) Technical Chapters Area Chair, R10 Southeast Asia, Australia, and Pacific and the Chair of IEEE Power & Energy Society Victorian Chapter, Australia. His research interests include control of power electronic converters for renewable energy (wind, solar PV) systems, battery/supercapacitor energy storage systems, electric vehicle, motor drives, microgrid, and cyber security in microgrid/smart grid.