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A Comprehensive Review on Protection Strategies to Mitigate the Impact of Renewable Energy Sources on Interconnected Distribution Networks

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ABSTRACT Technology advancement in the last few decades allows large penetration of renewable energy resources in the distribution network (DN). The integration of such resources has shown a substantial impact on DN through power loss reduction and improved network reliability. Besides this, the existing protection system has encountered coordination challenges due to the bidirectional power flow, different types and capacity of generation sources, and changes in fault levels due to network operating modes (grid-connected or islanded). Such conditions may cause the relays to malfunction and imperil the effectiveness of the existing protection scheme. Therefore, an efficient and robust protection coordination scheme is imperative to avoid network reliability and stability issues to the grid. This review paper presents a comparative analysis of various protection techniques implemented to alleviate the impact of integrated resources into DN. Moreover, a comparison of classical and modified protection approaches in terms of advantages, shortcomings, and implementation costs is presented. The prime objective of this study is to highlight the prominence of utilizing user-defined programmable relays for modern DNs. Moreover, recommendations are presented by considering the application of user-defined relay characteristics that can be proved as a robust protection scheme to cope with the protection challenges in existing and future power systems developments.

INDEX TERMS Distribution networks (DN), microgrids (MG), protection coordination scheme, renewable energy resources (RES), user-defined characteristics (UDC).

I. INTRODUCTION

Reduction in carbon emission policy all over the globe focused the research on the development and integration of renewable energy resources (RES). The increasing proliferation of distributed generation (DG) units is anticipated, which inevitably challenges the conventional operating principles of the power networks. With the high penetration of RES in distribution networks (DN), the bidirectional power flows and topology-dependent fault scenarios could affect the protection scheme, which endangers the maintenance personnel and result in maloperation of under-/over frequency and voltage relays. Due to this reason, IEEE standard 1547–2003 specifies to disconnect the RES units whenever any disturbance occurs on the electric grid [1], [2].

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Microgrids (MG) are introduced as one solution to mitigate the technical issues regarding the high penetration of DG units in the power networks. A MG is a small electrical power system area that embeds DG units and loads, which is connected to a grid at the point of common coupling (PCC) and can contribute power at the distribution voltage level, as illustrated in Fig. 1 [3]. The prime role of MG is to ensure an uninterrupted, reliable, and high-quality power supply for consumers. Furthermore, MGs bring significant economic benefits with the utilization of combined heat and power technology.

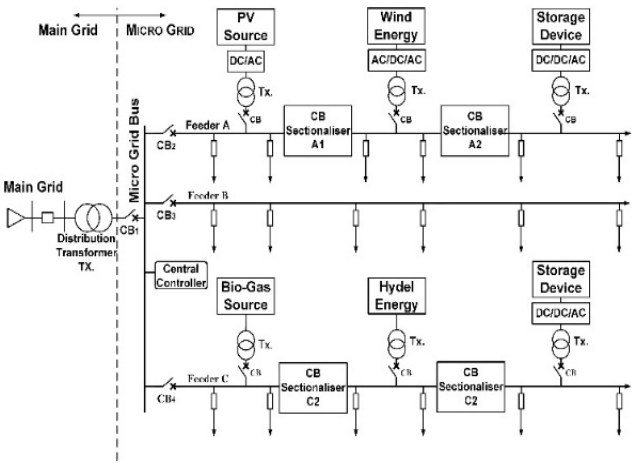

FIGURE 1. Typical structure of microgrid integration to the distribution network general structure.

Microgrids are a small-scale active power network that consists of renewable and non-conventional energy resources as well as different types of loads. MGs can operate in conjunction with the grid or can be independently operated (e.g., Islanded Mode). In a grid-connected mode, it can exchange power from both the utility side and from the distributed sources. It can also operate in islanded mode during power failure or fault at utility; in this scenario, MG expeditiously disconnects itself from the PCC by a static switch and independently feeds power to the priority loads [4], [5].

Regardless of MG advantages, other technical issues need to be focused related to MG protection and its entities. The existing DN protection is designed based on radial power flow with the highest fault level, thus the traditional protection scheme fails to detect a short circuit and coordination between the protective devices altered or completely lost. The miscoordination of protective devices occurs in the MGs containing a different type of RES units which ultimately increases the fault currents levels, changes the fault path due to the bidirectional power flows. Moreover, the loss of coordination occurs specifically in the MG interconnected with inverter-based DG units, these DGs during islanded mode limit the fault current which desensitizes the protection scheme [5]–[7]. Consequently, undesired relay tripping might occur that further degrades the reliability and selectivity of protection device coordination [8]. Therefore, the existing protection devices require modifications and improvement to address the challenges encountered by RES integration in the DN.

Various conventional and modified relaying schemes are available in the literature for the protection of integrated power networks. The authors in [9]–[13] summarize the various protection strategies and relay coordination methods based on additional components and modified relay characteristics to avoid reliability issues and ensure safe operation of the network, as summarized in Fig. 2. In recent years, some authors have proposed an alternative protection coordination approach based on the amendments in standard relaying characteristics [14]–[17]. Kiliçkiran *et al.* in [17] presented a comprehensive study on non-standard characteristics (NSC) to provide a reliable protection scheme for modern power networks. This study presents a promising solution to alleviate the protection coordination challenges for integrated DN at different operating scenarios. A similar analysis in [8] focused on the technical concerns required to alleviate the

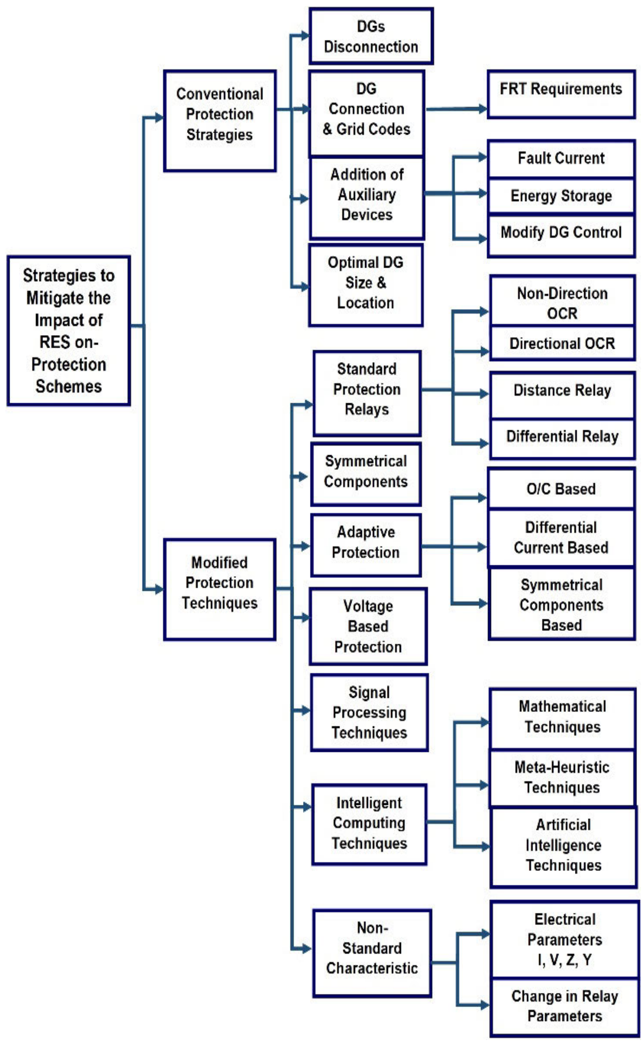

FIGURE 2. Protection coordination schemes for interconnected distribution networks.

impact of integrated DGs on protection performance. The study highlighted a list of general solutions to overcome protection issues related to integrated networks with specific operating topology or layout, in addition to presenting the recent techniques using different characteristics other than the standard ones. Therefore, the protection coordination study requires proper adjustment and settings of the relay parameters to avert the unintentional disconnection in the extensive integrated network.

Relay coordination is a highly constrained, nonlinear, and non-convex protection problem. Thus numerous solutions have been proposed based on conventional protection techniques [18]–[20], analytical methods [21], [22], optimization, and intelligent computing techniques [11], [23], [24] have been explored to solve the relay coordination problem. Although the proposed strategies contributed to obtaining optimal and robust overcurrent relay settings during dynamic network operating states. They are however lead to a more complex protection system and fail to provide effective protection against the faults originating after a change in grid topology, network reconfiguration, and multi-MGs operating in different zones after a permanent grid fault.

To address the research gap, this paper presents a comprehensive review of protection strategies to alleviate the impact of the high penetration of renewable energy resources into the DN. The remaining sections of this paper are structured as follows: Protection coordination challenges in integrated DN are presented in Section II. Section III discusses the review of possible solutions that have been proposed to mitigate the impact of various types of DGs connected to DNs. Section IV presents the recommendations to alleviate the protection challenges in the integrated DN and finally, Section V concludes this review paper.

II. PROTECTION COORDINATION CHALLENGES IN INTEGRATED DISTRIBUTION NETWORKS

The integration of MG into the DN has improved the grid reliability and resilience by utilizing the on-site generation of renewable resources ecologically and cost-effectively. However, the increased integration of distributed generations and novel topologies embedded in MG would impose a major challenge to the existing protection strategies. Some of the prominent protection challenges of integrated DNs are highlighted as follows:

A. CHANGE IN FAULT LEVELS

Conventionally, the protection scheme is designed based on the largest fault current and the type of network (transmission/distribution). However, such a protection scheme might not be able to protect the network integrated with different types and capacities of RES. The complication arises for the existing protection scheme to detect the fault in the presence of various types of RES-DGs when operating in Grid On/OFF modes [25]–[27]. Moreover, the high penetrated Synchronous DGs inject fault currents in the range of 5-6 times its rated current [6], [7], [28], which causes a considerable change in the fault levels. Whereas inverter-based DGs incorporated in MGs are unable to contribute adequate current towards the total fault current. It is due to the low thermal overload capability of inverters, limiting their maximum output fault current to about 1.1-3 times the rated current [10], [29], [30].

B. PROTECTION BLINDING

The injection of multi-type DGs on large scale results in the bidirectional current flow in the feeders, which has posed many protection issues, like the new fault current sources, which increases the fault levels and reduces the reach of relays. Moreover, the contribution of fault current by the grid varies with respect to the location and size of DG. Considering a network with a DG connection at Bus1 as shown in Fig. 3, when a fault occurs at the far end of the feeder Bus 2, the upstream relay R_1 underreaches the fault current owing to current division and change in Thevenin impedance. Thus, this phenomenon jeopardizes the relay sensitivity of the feeder relay R_1. This undesirable effect is termed as protection blinding. [31], [32].

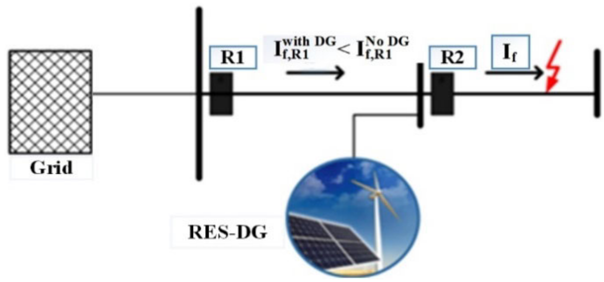

FIGURE 3. Protection blinding phenomenon in an integrated network.

C. NUISANCE TRIPPING

Nuisance or False tripping situation refers to an undesirable operation caused by the tripping of healthy feeder relay for the fault occurring at the adjacent feeder, due to the integrated RES. Fig.4 shows that if the fault occurs at an adjacent bus then the major portion of the fault is fed by the high penetrated DG, which ultimately increases the relay pickup current connected at the healthy feeder. Consequently, the relay R_2 trips earlier than the faulted feeder relay R_1 due to the DG back-feed on a fault incident.

D. UNINTENTIONAL ISLANDING

Unintentional islanding is another important consideration to maintain power system reliability. If the DGs connected in MG continue delivering the power to the load due to the fault at the grid (Loss of Mains). It may cause power imbalance, voltage, and frequency issues to the network if such unintentional islanding remains undetected. Therefore, it is desirable to activate the associated protection to avoid undesirable operations of MG during islanding mode [33], [34]. Moreover, it may cause the line in-charge life in danger who is attending the fault unknowingly that circuit is energized [35].

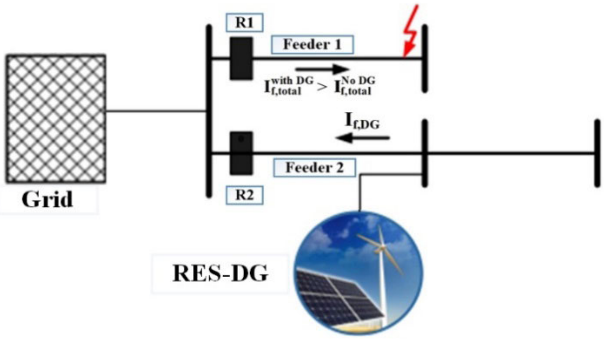

FIGURE 4. Nuisance tripping caused by integrated RES sources.

Other protection coordination problems include cascade failure of the protective devices due to loss of relay coordination, auto reclosure, and fuse coordination issues due to the fault currents injected by DGs which may damage the measuring equipment [5], [10], [26], [31]. To mitigate the aforesaid protection challenges related to the selectivity and sensitivity issues, a proper and reliable protection strategy need to be implemented for the stable operation of MG integrated with DNs.

III. RELAYING SCHEMES TO MITIGATE THE LOSS OF PROTECTION SETTINGS

In recent years, many literature reviews on protection challenges under bulk penetration of RES are published, and various techniques have been proposed to present an adequate protection strategy for MGs [9]–[11]. These studies summarize the various strategies proposed by the researchers to mitigate the protection issues in integrated DNs, as shown in Fig. 2.

A. CONVENTIONAL STRATEGIES BASED ON RES IMPACT AND TOPOLOGY CHANGES

This section discusses the mitigating strategies for the distribution protection system connected with DGs. The first approach is based on conventional strategies in which the protection settings remain intact to minimize the additional equipment cost and operational disruption due to reverse current flow.

1) DISCONNECTION OF DGS

A conventional approach is adopted to keep the protection settings intact to avoid unnecessary and unselective DG tripping. It minimizes the fault clearing time by disconnecting the DG zone once a fault is detected [36]. Generally, current practices are usually followed by Distribution Network Operators (DNO) and DG owners to decouple the DG once the fault is detected according to the IEEE 1547-2003 standard [37]. This practice usually applies to all types of DGs connected at the PCC up to 10MVA; the reason is to avoid the unnecessary tripping of healthy zones due to fault. Similarly, if a fault happens at the grid when connected with an inverter-based DG system. In that case, the standard specifies to disconnect the system within two seconds to protect the unintentional islanding. This could avoid the energization and operation of the remaining network connected at PCC according to the conditions as mentioned in German Standard VDE 0126-1-1 and Australian Standard 4777.3 [38], [39]. Most countries like the U.S., Canada also prefer to stop the power generation in a specified time duration and disconnect the DG under fault conditions at the grid as specified in their standards [40], [41]. However, these practices differ primarily in Europe [42], where DNOs allow the islanding operations, which contrasts developed countries' practices, as mentioned above, that cause reliability and safety problems due to present network topology and protection schemes.

2) DG CONNECTION AND FRT REQUIREMENTS

To maximize the DG usage in the network under different operating modes, the system operators have introduced the standardized grid codes where DG can supply power and energize healthy portions of DN during the fault condition. This enhances system reliability and ensures a stable and fast system restoration. According to the standard defined by South Africa for renewable power plants (RPP), the grid codes are applicable based on the magnitude of the voltages, category, and power rating of RPP, as illustrated in Fig. 5.

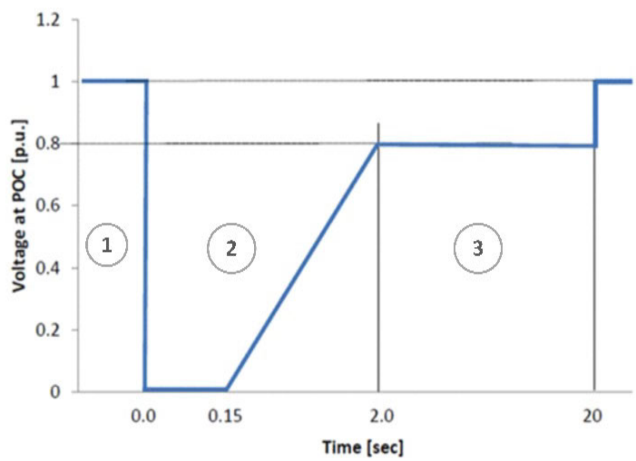

FIGURE 5. Fault current contribution in case of protection blinding.

Hence, the DGs are allowed with fault ride-through (FRT) techniques to avoid disconnection due to faults. Such FRT techniques support the grid and prevent the widespread loss of generation even at zero voltage dip for 0.15s measured at the point of common coupling (POC) as specified in Table 1 [43]. It also helps to control the damage in DN caused by the contribution of fault current due to high penetrated DGs [41].

The operation of DGs depends on the stability of system voltage & frequency; any sudden change or dip in the parameters may trip the protection device and fails to comply with the grid code requirement. FRT techniques discussed in [44]–[46] can avoid unnecessary disconnection of DGs and make them less sensitive to voltage dips and enable them to ride through for a short time. Moreover, the researchers have

TABLE 1. **Units for magnetic properties.**

Categories	Behaviour During Fault	Remarks
1	RPP must remain connected	The DGs must remain connected for the duration of 150ms; even the fault occurs at 0V.
2	RPP may disconnect	DG may disengage from DN, depending on the contract.
3	RPP must disconnect	Protection devices disengage the DG from DN

proposed a technique to detect the rate of rise of fault current in photovoltaic inverter-based DGs (PV-DG) and transform them "into dynamic reactive power compensator STATCOM (termed PV-STATCOM"). This conversion is suggested to comply with voltage and support the grid according to the grid code requirements [47]. Considering the benefits of FRT, several power supply companies and utility grids have standardized the requirements for different types of DG in their grid codes [41], [48]–[52]. Several FRT capability for a solar power plant is considered for various countries, as presented in Table 2.

TABLE 2. **Maximum time requirements for RPP disconnection.**

Country	Fault-Ride-Through Capability		
	Fault Duration (ms)	Voltage Drop Level	Post Fault Time Recovery (s)
Denmark	50	20%	1
UK	140	15%	1.2
South Africa	150	0%	2
Canada (Hydro-Quebec)	150	0%	0.18
Germany	150	0%	3
Malaysia	150	0%	5
Egypt	250	0%	10
Spain	500	20%	0.5
Ireland	600	50%	-

3) ADDITION OF AUXILIARY DEVICES

To alleviate the protection coordination failures in DN caused by high fault levels contributed by DGs, an auxiliary device such as fault current limiter (FCL) is connected in series to limit the fault current and improve FRT functionality of DGs. An ideal fault current limiter efficiently increases its impedance from low to maximum, which suppresses the fault current of DG so that proper coordination among relays could be maintained [53]. Another approach is given in [54], [55], which discusses the improved types of FCL (SR-FCL & CR-FCL) with modified control strategies. These are connected to the DC side of the double fed induction generator (DFIG) to limit the current injected by the rotor side converter during the faults. It improves the overall performance and achieves the maximum low voltage ride through (LVRT) capability of DFIG even at zero grid voltage. Thus far, many other strategies have been proposed for inverter-based DGs like passive "FCL (PFCL), superconducting FCL (SFCL), solid-state FCL (SSFCL), and controlled-based FCL" to meet the FRT code requirements [56].

During the Islanded mode, the inverter-based DGs do not inject enough fault current that can be sensed by existing overcurrent protection devices. Thus, the utilization of energy storage devices like flywheel, supercapacitors, and batteries has been proposed to overcome sensitivity issues [57]. Previously, in [58], [59], prototype fault current sources during transients have been proposed, including a storage device, a triggering circuit, and a switch-based charging module. Comparing to another device named a flywheel energy storage system was designed to act as a current source to increase the inverter currents. Similarly, the authors have proposed adding supercapacitors in the DC link of an inverter to get activated during abnormal conditions [60]. However, these fault current sources require a high initial cost.

Various methods have been investigated to mitigate the negative impacts caused by DGs towards conventional protection in DN. In [45], [61], a simple and reliable control method is proposed for inverter-based DGs to limit their output current based on terminal voltage. Mostly converter-based DGs are provided with voltage source converters (VSC), which are sensitive towards voltage dips and get trip failing to comply with the FRT requirement. This method does not compromise the existing protection scheme in DN without restricting DG utilization during normal conditions. Furthermore, in the literature [62], two VSC control types were provided for electronic-based converter VC-VSC and CC-VSC. Control strategies have been proposed to alleviate the impact of voltage dips and restrict the flow of real and reactive power within acceptable limits according to the grid requirement during fault conditions. The author has proposed in [63] that VC-VSC control is more acceptable for grid-connected and islanding operating scenarios than conventional current control. However, efficient control methods need to be introduced to respond to short circuits injected by various DG types to ensure continuous connectivity with grids.

4) OPTIMAL DG SIZING AND LOCATION

Another conventional practice to optimize the DG capacity and location without revising the existing protection devices. This approach could help the DNO decide to expand the network to permit the installation of new DGs or limit it. Furthermore, this approach could be efficient technically and economically compared to FRT techniques due to the high initial cost of FCL [64].

Several load flow, dynamic programming, and optimization-based algorithms have been proposed to maximize the DG power utilization and meet the protection coordination constraints [65]–[67]. The work in [68] proposed an optimization method to calculate the maximum DG sizing by considering the protection settings as constraints to maintain the relay coordination in the DN. Moreover, network power losses and node voltage constraints have been considered to avoid unwanted impacts on the existing system. The results reveal that the allowable DG size was achieved by considering the protection coordination constraints and reduced line losses. If such constraints were avoided, there could be the possibility of utilizing maximum DG capacity; however, it may cause the failure of the entire protection scheme. Similarly, work in [69] proposed a methodology that decides the optimal location, sizing, and proper utilization of intermittent and dispatchable DGs. The author used two-stage optimization frameworks to reduce the long-term cost, including investment, operational & maintenance(O&M), and fuel cost of DGs connected in the MG. In [61], a multi-objective framework has been suggested to optimize the DG location and capacity limits to maintain the existing protection coordination in integrated DN. An optimization technique is implemented to solve the formulated problem by considering various network aspects, including protection coordination settings as a constraint. The proposed technique assigns optimal DG location in the network to achieve better penetration levels. However, in practical scenarios, any modification in network topology or change in protection devices and settings may reduce the DG capacity.

In 2016, Kumar *et al*. proposed an optimal implementation and sizing of RES based on techno-economic viability [70]. The scheme optimizes and controls the generation capacity of MG-RES and DG connected in the DN for both grid-connected and islanded modes of operation. The control scheme for RES optimally prioritized the critical load based on available generation to maintain the continuity of power supply. Moreover, to enhance the reliability and power utilization of MG-based RES, a PSO-based optimization approach has been implemented in [71] to find the optimal location of photovoltaic inverter-based DGs (PV-DG) connected in MG. The main goal is to minimize the network power losses by complying with radiality and voltage stability limits constraints. The overall results have improved the bus voltages in the MG and reduced the power losses of the network; however, the protection challenges that occurred due to the integration of generating sources must be considered accordingly.

This section has discussed the advantages and shortcomings of the conventional protection strategies implemented to mitigate the impact of integrated generating sources into DN. Table 1 summarizes the key features of current practices adopted to mitigate the protection challenges. To meet an existing protection requirement from an operational perspective, disconnecting the DGs or limiting their generating output is considered an economical and viable solution for DNO's. However, this affects the DG operational efficiency and reliability along with capital investment by the DG owners. Moreover, the FRT requirements are suggested to meet the protection challenges and utilize the maximum DG capacity for the network under different operating modes. This strategy can prevent the widespread loss of generation even at zero voltages for 0.15sec and ensures system recovery. Though, this technique requires additional control strategies to overcome protection failure during low-level faults. This approach injects high fault currents, which must be sensed by conventional overcurrent relays and alleviate the impact of voltage dips. Due to the growing concerns of RES into DN, such developed control strategies, e.g., FCL, energy storage devices, capacitor banks, etc., need resizing and relocations accordingly. Which ultimately increases their operational cost to meet the FRT grid requirements. Therefore, secure and reliable protection solutions need to be implemented to overcome the interconnected generation impacts.

B. MODIFIED PROTECTION COORDINATION STRATEGIES FOR INTERCONNECTED DISTRIBUTION NETWORKS

Another set of solutions have been proposed by researchers to solve the protection coordination issues in the integrated networks. This section discusses the modified protection coordination methods and strategies based on additional components and relays characteristics to avoid reliability issues and network stability on the grid. Table 5 highlights the key features, advantages, and shortcomings of the modified protection approaches implemented to the integrated network.

1) CONVENTIONAL PROTECTION RELAYS

Conventionally, a distribution network (DN) contains, e.g., fuses, reclosers, relays, and circuit breakers as protection devices. These protection devices are coordinated with each other to interrupt the unidirectional fault current that flows from the source end to the fault point. For distribution feeders, three protection relays are considered: (i) instantaneous OCR, (ii) definite time (DTOC), and (iii) inverse-time over current (IDMT). If the value of current magnitude exceeds a present value, in that case, the relays provided with instantaneous overcurrent characteristics send a trip signal instantly without any delay, whereas, for DTOC relays, they operate after a definite time, accordingly. Conventionally, IDMT OCR is the most utilized protection device in DN and coordinates with other relays in the network.

a: OVERCURRENT RELAY

Generally, non-directional overcurrent (NDOCR) protection is usually required for radial DN. However, DG integration has changed the direction of fault currents and jeopardize feeder protection due to bidirectional flow. For DN, relays are installed on each feeder to protect the faults in their respective zones, termed as primary protection of that line. If a primary relay fails to operate, it may cause a spread of fault current in the adjacent lines and create a catastrophic effect. Therefore, the primary relays are coordinated with another relay known as a backup relay. This backup relay coordinates with the primary relay and operates after a specific time interval termed as Coordination Time Interval (CTI) [72].

TABLE 3. Conventional protection techniques for composite generating sources connected with distribution network.

Protection Strategy	Main Feature	Advantages	Shortcomings	Implementation Cost	Communication Link
1. Disconnect DG from the network during a fault. [36, 37]	Disconnect the DG according to IEEE 1547-2003 standard to avoid tripping of Healthy Feeder	• Simple technique • Prevent unintentional Islanding and nuisance tripping of relays • No communication Link required • Avoid changes to existing protection settings	• Limits DG capacity and usage (underrated) • Load disruption in case of Islanding • Disconnection of DG each time may reduce the reliability of the system.	Economical	NO
2. FRT Techniques [46, 47]	DG remains connected by complying with grid codes. Prevents widespread loss of generation even at zero voltage for 0.15sec	• Ensures safe operation and fast system restoration • Help to support voltage recovery. • Protect DNO personnel from accident and injury	• Effects the network operation with a change in topology • High operational cost to meet the FRT requirement. • Difficulties in fault detection and isolation for inverter-based DGs	Expensive	No
3. Auxiliary Methods [53, 57, 61, 62]	Inject high fault currents abnormal condition, which must be sensed by conventional overcurrent relays and alleviate the impact of voltage dips	• FCLs significantly reduce the high fault injected by DGs. • The response of energy storage devices is fast and provides sufficient fault current and rapid grid voltage recovery.	• Recovery time of superconducting FCL is long. • FCL requires resizing and relocations with network and DG expansion • Difficult to control the fault current in modifying DG indirect control method	FCL: Reasonable ESS: Expensive Control Techniques: Expensive to meet FRT requirements	No
4. Optimal DG Sizing and Location. [68-70]	Optimal sizing to maximize the DG contribution and locations of incoming DGs. Minimize the network power losses, Improving voltage profile	• Maintain existing protection device settings • Protection device coordination based on local measurements • Stable operational against non-fault transients caused by induction motors starting current, load switching, etc.	• Efficient control strategy requires needs for inverter-based DGs • DG capacity gets limited according to its load consumption and unable to supply extra power to the utility grid. • Restricts the line current capability based on protection constraints.	Economical	No

Considering this, Fig. 6 explains the coordination of non-directional relays for a simple radial network containing two buses B_1 and B_2 provided with IEC standard 60255-3 normal inverse time-current characteristics, as shown in Fig. 7 [73]. A Line-to-ground (LG) fault is assumed at locations F_1 and F_2; the relay R_2 must sense it and sends the trip signal to its associated circuit breaker. Meanwhile, the backup relay R_1 must wait for a specific time interval, i.e. (T_{R2}+ CTI), to maintain the coordination with a primary relay. Therefore, to obtain a proper relay setting, the protection coordination is formulated as a highly constrained, non-convex, and non-linear optimization problem. According to standard IEC-60255-3 [73], the characteristics equation of time inverse overcurrent relay is given below:

$$T_{op} = \frac{A * TMS}{(PCS)^B - 1} \tag{1}$$

In Eq.(1), T_{op} is the relay operating time, TMS is the time multiplier setting; PCS is the pickup current setting that determines the fault current passing through the relay, whereas A and B are standard characteristics coefficients of inverse time overcurrent relay as specified in Table 4.

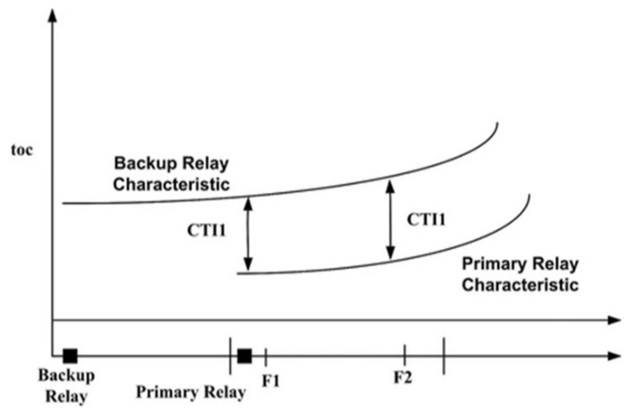

FIGURE 6. Coordination curve between a primary and backup relay.

The goal of the objective function (OF) is to achieve the minimum relay operating time while meeting the coordination constraints against various fault locations and different types of short circuit faults, namely phase to ground faults, phase to phase faults, and three-phase faults. The generalized

TABLE 4. IEC 60255 characteristics constants of idmt relays.

Curve Type	A	B
Normal Inverse (IDMT)	0.14	0.02
Very Inverse (VIN)	13.5	1
Extremely Inverse (EI)	80	2
Long Inverse Standard Inverse (LI)	120	1

formulation of OF is given in Eq. (2).

$$OF = \min T = \sum_{j=1}^{K}\sum_{l=1}^{L}\left(\sum_{i=1}^{M}\left(t_{ijl}^{Primary} + \sum_{b=1}^{N} t_{ijl}^{Backup}\right)\right) \quad (2)$$

whereas T donates the total relays operating time, M symbolizes the total number of relays while 'i' is the relay indicator and N indicates the total number of backup relays corresponding to each primary relay. The subscript 'b' represents the backup relay, 'j' is the fault type identifier (L-G, L-L, LL-G, LLL) and 'l' represents the fault location. Moreover, for inverse time overcurrent relays, a set of time constraints, CTI is needed to ensure a safe operation and maintain coordination between primary and the backup relays as expressed in Eq. (3). The CTI value depends on the type of relay, relay error, circuit breaker time, and safety margins and is usually set between 0.2-0.5 seconds according to IEEE and industrial standards [14], [72]–[75].

$$t_{b_{ijl}} - t_{\mathrm{ijl}} \geq \mathrm{CTI} \quad \forall\ \mathrm{b, i, j, l} \quad (3)$$

$$\mathrm{t_{min}} < \mathrm{t}_i < \mathrm{t_{max}} \quad \forall i = 1,2,\ldots M \quad (4)$$

Here, t_{ijl} represents the primary operating time of i^{th} relay for the fault-type 'j' that occurred at location 'l', while $t_{b_{ijl}}$ denotes the backup operating time of the relay with respect to the primary relay 'i^{th}' for the same fault and location. Two other conventional relay constraints PCS & TMS are required to solve the non-linear formulation of relay coordination problem as given in Eq. (5) and (6). The PCS range of the relay is set between twice the max load current to the one-third of the minimum fault current, and the minimum and maximum bound of TMS for each relay are taken in the range between 0.05-1.1 [76], [77], respectively:

$$(2I_{Lmax})_{i\_\min} < \mathrm{PCS}_i < \left(\frac{1}{3}I_{fMinimum}\right)_{i\_\max} \quad \forall \mathrm{i} = 1, 2, \ldots M \quad (5)$$

$$\mathrm{TMS}_{i\_\min} < \mathrm{TMS}_i < \mathrm{TMS}_{i\_\max} \quad \forall i = 1, 2, \ldots M \quad (6)$$

To solve the protection coordination problem, various techniques are available in the literature to solve the protection coordination issues for integrated DN [10]. In [78], [79] classification techniques trial and error, curve fitting methods are implemented based on the location of DGs, which optimally adapts the recloser setting to maintain the coordination between fuse and recloser. These methods require many iterations and have a slow convergence rate to reach an optimal solution. Therefore, optimization techniques are

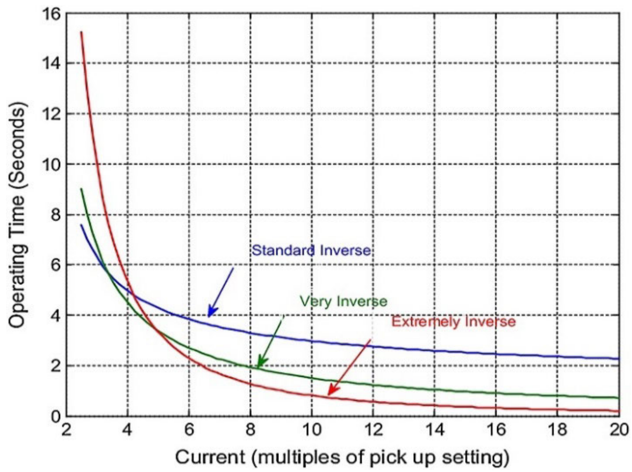

FIGURE 7. International Electrotechnical Commission (IEC) inverse-time characteristic curves Std [73].

proposed to solve the protection coordination issues instead of previous methods like analytical methods and graph theory techniques [80]. Such methods formulate the protection coordination problem as highly constrained and optimize the relay parameters to achieve minimum operating time to ensure proper coordination between relays. These techniques are quite useful for small penetrated DGs where fault levels do not vary much. However, due to the change in the direction of fault current normally fed by integrated generating sources, the protection setting needs to be revised to maintain the selectivity among relays.

b: DIRECTIONAL OVER CURRENT RELAY

The addition of DGs into the DN has changed the direction of fault currents, ultimately jeopardizing the feeder protection. Therefore, it is necessary to ensure that the relay installed in the grid can sense the fault current from any direction (i.e., upstream or downstream). A directional relay (DOCR) is designed to overcome the protection coordination issues due to bidirectional faults [74]. DOCR operates when the fault drives the power flow in a particular direction (forward direction). Fig.8 explains the robustness of DOCR provided at feeder 3 to protect the unnecessary tripping of healthy feeder due to the fault F_1 occurred at feeder 2. This relay has a quality to trip the fault in one direction that moves away from the bus. Therefore, these relays must coordinate to disconnect the affected portion of the grid in the shortest possible time. This can be done if the pickup setting current (PSC) and time setting multiplier (TMS) of the DOCR are set optimally. In this regard, various analytical and optimization methods have been implemented to mitigate relay coordination issues.

In [19], [22], the analytical approaches are proposed to identify the critical fault points in the system and obtain optimal relay settings. Another approach based on interior point iterative numerical algorithm was proposed in [21] to successfully obtain the protection coordination settings for primary and backup relays. As the analytical methods are known to be useful for radial DNs, but not effective for

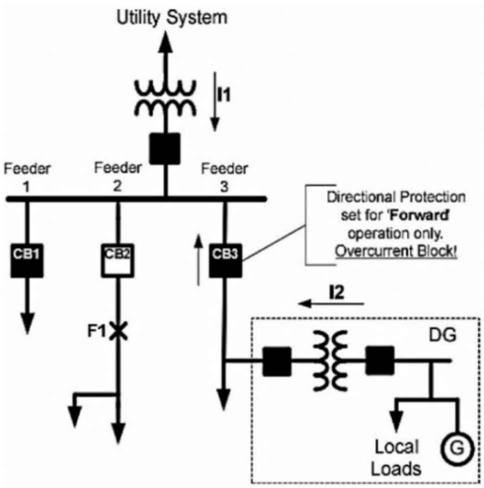

FIGURE 8. Configuration of DOCR to prevent nuisance tripping.

large meshed networks and require high computational time. Therefore, the relay settings need to be coordinated with the modifications in the network. Considering this fact, the author has proposed novel protection settings for relay considering future network planning [81]. The scheme can provide utility planners with a set of relay settings that remain valid for the various DG units to utilize their maximum capacity. The other protection approaches and formulation required to solve the relay coordination problems in the integrated networks are presented in [82]–[85].

For an extensive interconnected network, the authors in [86] have discussed the limitation of improper settings of DOCR that may cause the under-reach problem for varying the VARs of DGs. A unique solution using DOCR with an additional load encroachment function was proposed to detect far-end faults. The results showed that adding load encroachment control in the problem formulation ensures security over the full range of current directional angles without compromising the detection of faults on the collector end. Moreover, to avoid unintentional DG disconnection during the faults, the author has proposed a dual setting DOCR in a meshed DN [87]. This approach is utilizing the parameters of two inverse time characteristics, based on the direction of the fault. The results demonstrated that the proposed approach performed better as compared to the single directional O/C relay. However, utilizing the additional features may increase the cost of the relay.

Despite the advantages, the authors in [50], [55] highlighted the drawbacks of DOCR in terms of their cost, fault detection, and unwanted tripping. This scheme utilizes two DOCRs at each end of the line and requires two circuit breakers, two voltage and current transducers which may increase the cost of the protection equipment. Moreover, due to the thermal limit of inverters, the inverter-based DGs inject significantly less amount of current during a fault condition, which is less enough to be sensed by DOCR. Another drawback is the tripping of healthy feeders at the upstream feeder end due to the DGs provided with non-directional overcurrent relay (NDOCR) protection. Therefore, there must be a directional element associated with OC relays to cater to the forward direction faults and block the current fed by adjacent lines [88].

c: DISTANCE (IMPEDANCE/ADMITTANCE) PROTECTION RELAYS

As the name implies, distance relays are designed to respond to the impedance that occurs between relay location and reach of fault location. The fault is detected by measuring the apparent impedance seen by the relay using node voltage and the measured current at the relay point. The apparent impedance (Z_r) is compared with the impedance set value (Z_s) called reach point impedance. If Z_r is less than the Z_s, the fault is detected between the relay and the reach point. For the modern digital relays, three stepped distance protection is provided for double end-fed systems where the fault current is injected by multiple sources, as illustrated in Fig. 9. The key advantage of utilizing a distance protection scheme, the settings are not affected by the change in network topology, especially in the islanded mode of operation, because settings are mainly dependent on the measured impedance. Usually, distance relays are implemented for the protection of transmission networks (TN). However, this relay can be implemented to DN due to the natural directional property available in distance relays. A strategy is proposed for the DNs based on a distance relaying scheme that provides primary and backup protection of 11kV circuits [89]. A quadrilateral approach was suggested to mitigate the error of under reach and overreach errors for ring and radial circuits during the phase-to-earth faults.

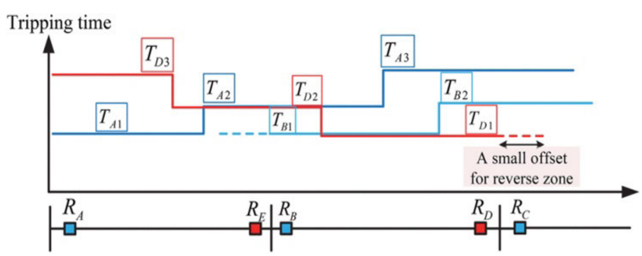

FIGURE 9. Distance protection scheme for bidirectional power flow in the system.

In comparison to conventional distance relays, which require default zones setting to issue a trip signal, the work proposed in [81] implements an adaptive protection scheme for highly penetrated DGs. The proposed schemes update the relay zones settings and impedance setpoints based on the network operating state. The robustness of the adaptive scheme makes the distance relay more sensitive and improves the selectivity and speed of the relay, as shown in Fig. 10. Another adaptive approach given in [90] discussed the failure of protection coordination for the low-level faults caused by the change in the network topology. An impedance-based protection technique is implemented to quickly detect and clear the temporary faults in the protection zone. The scheme

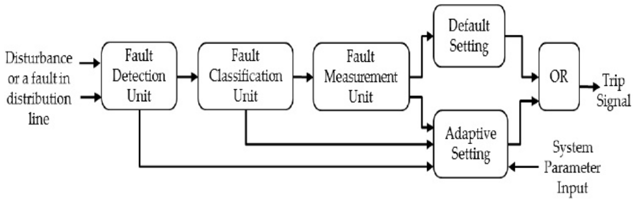

FIGURE 10. Adaptive protection scheme for distance relay.

adopts the modified zone and updates the reach of the relay with variation in the source impedance.

For bidirectional faults in DN, another type of distance relay is proposed in literature termed as admittance relay, as shown in Fig. 11. The operating characteristics show the boundary of $Z_{set,}$ and the ohmic setting of relay impedance Z_R is within the circle. It can be seen that the circle that passes through the origin activates the inherent directional relay property to discriminate against the faults that exist inside and outside of the zone. Considering the benefit of admittance relay, in literature [91]–[93], the authors proposed an idea to implement admittance relay for interconnected systems to improve the performance of MG protection during grid-connected and islanded scenarios. Therefore, in 2009, Dewadasa et al [92], [94] proposed incorporating admittance relay with IDMT relays to overcome the protection scenarios for low fault current in a standalone operation of MG. Another research conducted to protect feeders against three-phase fault occurs in radial MG connected to utility with back-to-back converters. As specified in [4] , the protection scheme overcomes the line protection difficulties cause by converters during fault and ensures low-level fault detections. The admittance relay incorporates inverse time characteristics based on measure the admittance of line to overcome the reach settings. The proposed scheme helps to control the converter voltages and limits the fault current in the affected phases accordingly. Furthermore, the proposed approach for admittance relay has provided improvements as compared to the impedance relays for DN. However, the relay's inverse time characteristic fails to comply with the safety margins and may disturb the selectivity and increase the tripping time of protection devices.

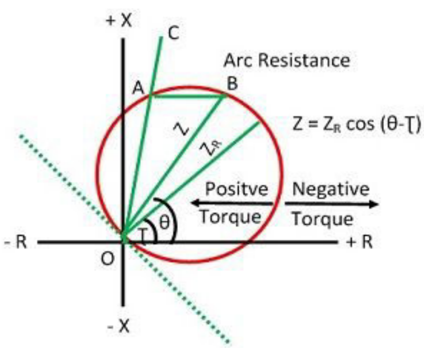

FIGURE 11. Operating characteristic of MHO relay.

d: DIFFERENTIAL PROTECTION SCHEME

This type of scheme normally protects the equipment by comparing the currents entering or leaving the defined zone. The relay operation based on the difference of current flow from the operating coil of the relay, as shown in Fig. 12. The significant advantage of implementing differential relay is the capability to detect bidirectional and high impedance faults. The zone settings are not affected by the change in fault levels due to changes in the network topology. Moreover, it provides high sensitivity and selectivity and acts against power swing and external faults [9], [95].

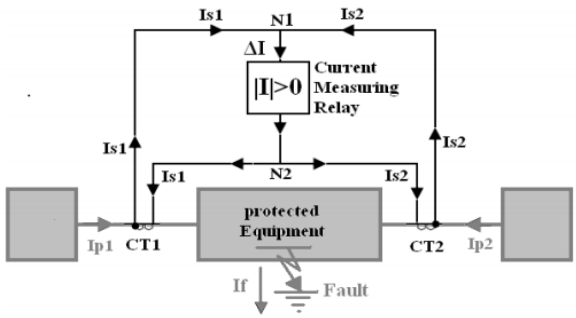

FIGURE 12. Differential Protection concept for bidirectional current flows.

As presented in [87], [88], various literature discusses the implementation of differential relay for interconnected networks. The scheme implemented in [96] provides efficient protection to the transmission network. The differential relay utilizes a communication link to measure and gather the required data to sense the fault occurrence. It sends a tripping signal accordingly to the CB to avoid nuisance tripping. Moreover, symmetrical components-based differential protection scheme proposed in [97] to determine the fault current and isolate the MG by a fast semiconductor switch. Another approach based on differential power fault detection has been proposed for detecting symmetrical components analysis during power swings [98]. The technique detects the difference of power by calculating the predicated and actual monitored voltage and current samples during a transient situation. A communication-assisted protection scheme was proposed in [99] to overcome the substantial variation of fault currents in the grid-connected and islanded operation mode. An algorithm is implemented to determine the current state of the network and calculate the restrain current for differential protection scheme to adjust the multi-terminal zone protection of the system. Many other approaches to differential protection schemes have been proposed in the literature [100] and found to be more reliable than conventional protection schemes. However, in the case of communication system failure, a backup protection scheme needs to be implemented to differentiate the currents that maintain the entire network reliability.

2) OVERCURRENT PROTECTION USING SYMMETRICAL PROTECTION

Such a protection scheme has been suggested to overcome the possibility of protection coordination failure for unbalanced faults, e.g., LG, LL, LLG in DN. In this approach, the unbalanced current components are split into three balanced components positive, negative, and zero sequence [97]. In [101], a negative sequence directional element protection based on microprocessor relays (MBR) to protect low voltage MGs was suggested. This method also implements neutral voltage protection to avoid the voltage rise at the ungrounded portion of the stepdown transformer. The scheme enabled the single-phase tripping for the faults that occur in the grid-connected and islanded operation of MG without need for any communication links among relays.

Similarly, a communication-assisted symmetrical components based differential relaying scheme was proposed for DNs and can locate both symmetrical and unsymmetrical faults. However, the low-bandwidth channel is required for the electrical data to be transferred using the communication medium. And any loss in the channel may cause undesirable effects on the system operation [102]. In smart DN, mostly protection coordination issues are raised because of low thermal limits imposed by semiconductor switches of electronically coupled DGs. Therefore, a solution is proposed for fault detecting and isolating control strategies for closed-loop MGs [103]. The proposed scheme incorporates the existing protection scheme without using a communication link and change in relay settings. According to the proposed scheme, each DG calculates the impedance of MG indirectly to identify the fault; if the measured impedance is less than the threshold value, the fault is detected. Moreover, the control scheme provided adjust the control of DG according to new droop characteristics. However, the extra cost is required for the energy storage system and supercapacitors to inject high fault current connected with the DC link. In 2017, Zhang *et al.* [95], [96] proposed the techniques to detect power direction by considering a spot network incorporating high penetrated RES. The method uses the positive and negative sequence current components to observe and compare the change in power direction for different fault types that occurs at different locations.

Additionally, a positive sequence-based pilot blocking approach for closed-loop networks is presented in 2018 [104], as shown in Fig. 13. The configuration consists of remote terminal units (RTU) installed in every Ring Network Cabinet (RNC) to monitor the current between the busbar of DN. The scheme analyzed the power direction and stimulated the value of (RTU) based on various short circuit fault current occurs at different locations. Thus, the Master station (MS) monitors the status of all RTUs, which are synchronized with each other, and makes the decision accordingly to recover the system. The symmetrical components-based protection methods are efficient and alleviate the protection issues caused by the reverse power flow in interconnected power networks. However, the need for strong communication links is mandatory for reliable operation, which may cost high and become difficult for real-time implementation.

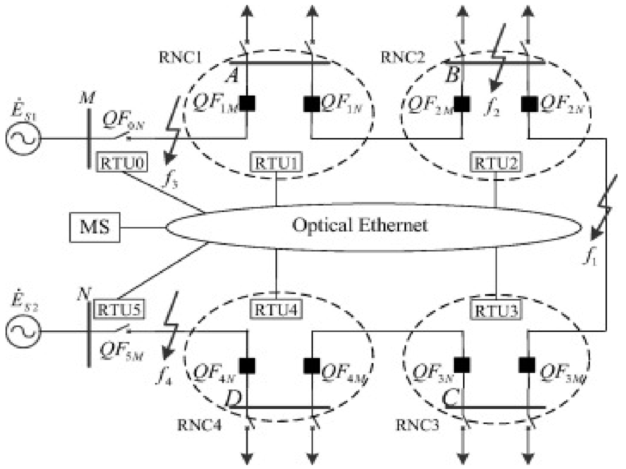

FIGURE 13. Symmetrical components-based protection scheme for the closed-looped distribution network.

3) ADAPTIVE PROTECTION SCHEMES

For conventional protection systems, technicians must be available on-site to reset the relay settings because of any network operational changes. For smart and modern DN, the workforce is not required since such systems are equipped with automation and online monitoring capabilities. Moreover, the conventional protection scheme for MG integrated with DN is subjected to selectivity and sensitivity issues during the fault in the standalone operation because of the change in fault level. Electro-mechanical and static relays, therefore, may not be suitable for the protection of interconnected MGs. Therefore, it is necessary to develop a relaying scheme to modify the relay settings using external signals. As the name implies, adaptive protection is an online protection scheme used to adapt both the relay settings and characteristics according to the system's current state, as given in Fig. 14. This section discusses the techniques proposed to make the protection scheme adaptive with intelligent devices and communication mediums.

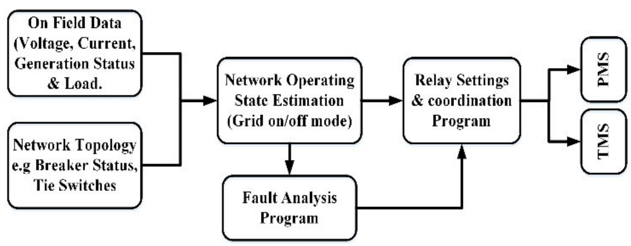

FIGURE 14. Configuration for Simple Adaptive Protection Scheme.

An adaptive protection scheme for DN was proposed in [105] to alleviate the effect of high penetrated DGs. The proposed scheme is efficient to adapt the protection coordination settings for any topological change in the network, and in case of permanent faults, the scheme ensures load recovery with minimum loss. However, the adaptive scheme fails to provide suitable protection for low-level faults; any failure in the downstream breaker sends the command to the main substation circuit breaker, ultimately shutting down the entire system. Further, a protection solution was proposed to improve the selectivity for the network reconfiguration system and islanded operation of distribution networks [106]. The scheme coordinates and communicates with the local control to detect the faults or observe any change in network condition based on local measurements. After that, the required changes for relay settings are sent to the central controller, updating the settings according to the current network state through communication links.

Antonova *et al*. 2012 in [42] recommended adaptive protection, in which each bus is provided with a DOCR through a communications system via the MG-central controller (MGCC). The offline study generates events and lookup tables by considering all the MG configurations. The MGCC monitors the network operating state and analyses the events and the lookup tables to coordinate the relay settings. The Intelligent protection device communicates with the CC during the fault scenario to adapt the relay settings by analyzing the fault type and location. However, the proposed strategy could not be effective for large MG configurations because of the excess memory used to store large amounts of offline data. Furthermore, this scheme fails to protect against high impedance faults (HIF) and dynamic load changes or network addition. In 2014, the work published in [107] developed an adaptive protection system for the MG installed on Hailuoto Island in Finland. This system used communication links to transmit the collected data from intelligent electronic devices (IED) to an MGCC for real-time analysis. The simulation work was carried out for several cases to evaluate the effectiveness of the proposed adaptive relay performance. The disadvantage of this strategy is the risk of a failure in the communication networks and the lack of DGs integration features.

Moreover, a detailed review of modified protection schemes discussed by the authors in [13] highlighted the key features and discussed the practices to adapt the relay settings using telecontrol and automation techniques. In recent years, adaptive strategies for digital relays in MG integrated networks utilize the MGCC and IED to adapt the settings in a short interval and improve the relay sensitivity and selectivity in their particular operating zones [108]. Furthermore, the development of reliable communications systems in smart DNs has been accelerated by the emergence of the standard IEC61850 communication protocol. This quickly shares the operating information among IED and MGCC, observes the DG status and any change in network configuration to take quick action, and devise the new relay settings accordingly [109].

In the literature, numerous adaptive strategies have been presented to update the protection settings based on network operating state. Considering this, the fault recovery schemes for MG has been discussed for the detection of permanent faults and network topologies such as network reconfiguration and grid switching [110]–[112]. The authors discussed the detailed literature review on developments and challenges for MG adaptive protection [13], [23], [113]. Despite the flexibility offered by adaptive protection, replacing all existing relays with the adaptive scheme is very costly. The most challenging part for DNO is maintaining safe and secure communication between each device when some new DGs are added. Although the industry has used IEC 61850 GOOSE messages, the main concern is that the costs are higher as all the devices owned by customers must be connected for metering purposes.

4) VOLTAGE BASED PROTECTION SCHEME

For low voltage DN where the fault current is not sufficient, that could be detected by conventional overcurrent relays. Therefore, a voltage-based protection scheme was proposed in [114], [115] to monitor the DG output voltage and apply the Clark abc-dq transformation technique to obtain the dc quantities in the d-q reference frame. Thus, any disturbance at the output of micro-sources due to fault may disrupt d-q values. The approach then compared with the reference voltage signals to compute the disturbance in a voltage signal, as shown in Fig. 15. This disturbance is utilized to compute the fault and identify the faulty sections to protect the network against many faults. Another voltage-based protection using a positive sequence component is based on Park transformation to detect the symmetrical and unsymmetrical faults in MG without using a communication link [116]. Similarly, an approach suggested in [117] to monitor the voltage drop at the busbar to detect the fault occurrence in a network, and any change in the direction of power may indicate the location of fault for both the grid-connected and islanded mode of operation.

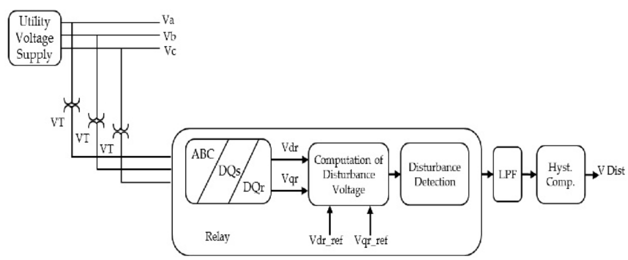

FIGURE 15. Voltage-based protection scheme for micro-sources equipped with power electronics interfaces.

The article proposed in [118] discussed an algorithm for voltage control on radial DN based on multi-agent systems, which mitigates the voltage deviation caused by the connection of DGs or dynamic load conditions. The distributed control is divided into several overlapping segments. Each segment is assigned to an agent that senses the voltage variables and exchanges the information between two adjacent segments. This approach formulates the reactive power compensation to restore the voltages and eliminate voltage deviation without any central controller intervention. The author in [119] proposed an algorithm to achieve its protection based on node voltage measurements when a fault occurs within a zone. The algorithm is based on modelling an approach that divides the DN into several overlapping protective areas. The overlapping function is logically achieved through peer-to-peer communication between intelligent agents in neighbouring zones. The body of knowledge and research in time-domain voltage measurements for protection currently appears to be limited specially to cope with limited short-circuit capacities of the converter-interfaced RES connected in MG based DN and this area needs further research.

Recently in [120], the author has proposed the new protection approach for MGs using synchronized voltage phasor measuring units (PMU). The relay algorithm exchanges the required information with IEDs located at neighbouring nodes and formulate its protective function by calculating the active power difference and sensitivity-based fault detection indices on the synchronized voltages within a specified protection zone. The proposed algorithm efficiently detects and identifies all types of faults for the grid-connected and islanded operation mode. Although the technique proposed is independent of change in network topology, the need for an efficient communication link is required to adapt the setting and calculate the active power difference for the reconfigured network after permanent faults in a standalone system.

5) SIGNAL PROCESSING TECHNIQUES

Another suitable protection strategy to mitigate the high penetration levels of RES integrated networks can be achieved by signal processing techniques. This technique detects the faults in the network by extracting the features of the fault index using voltage and current signals [121]. The studies presented in [13], [23], [122] discuss the protection challenges and strategies based on machine learning and signal processing techniques for RES and Inverter-based grid-connected systems. A work based on a multiscale representation of wavelets for fault detection and isolation is proposed in [123] by reducing harmonics, signal noise, and false alarms for an inverter-based PV source. Moreover, the authors in [124] have proposed a fast and adaptive relay mechanism implementing a fast and recursive discrete Fourier Transform (DFT) for an integrated radial DN. This algorithm provides optimal relay settings based on the network different operating conditions. More applications related to wavelet transforms and syntactic methods to detect and measuring the power system parameters are discussed in [125]–[127]. It can be deduced that the performance of these wavelet transforms studies can provide better performance for the identification of faults in the PV based integrated systems. However, their performance may be affected with the presence of noise. Therefore, a work in [128] introduced a fault recognition algorithm for PV-based integrated DN. The author has proposed a signal processing technique to identify the fault by Wigner distribution and Alienation index. The results show the effectiveness of fault identification at various locations and different fault types during the presence of noise. A recent adaptive protection approach based on Discrete Wavelet Transform-Differential Algorithm as shown in Fig. 16. to eliminate all noisy and unwanted signal issues and coordinate the relay settings [129]. However, a more efficient technique needs to be implemented for the hybrid RES integrated networks to verify the reliability of protective devices during fault scenarios based on the network new switching state. The summary of signal processing techniques is presented in Table 5.

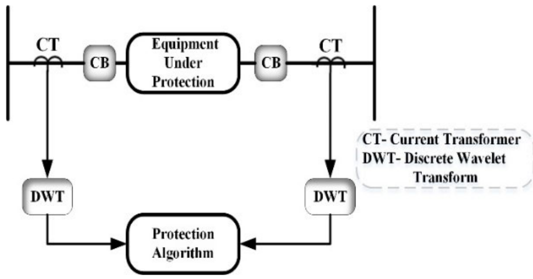

FIGURE 16. A protection approach using signal processing techniques [129].

6) MODIFIED PROTECTION COORDINATION STRATEGIES USING NSC

Many studies discussed above have highlighted the protection coordination challenges in MG based DN. Considering the challenges encountered by the classical protection scheme due to operational changes in interconnected networks, there is a need to adopt a new relay characteristic for the protection devices. With the advent of digital relays, a programmable microprocessor-based relay (MBR) can provide the potential change to the conventional protection approach. Moreover, competitive costs and reliable performance have increased the chance of micro-processing OCRs being used as a replacement for electro-mechanical OCRs [26], [130]. Therefore, the new user-defined characteristics (UDC) can be formed as an unconventional protection scheme to mitigate the coordination issues caused by integrated DGs into DN.

7) PROTECTION STRATEGY BASED ON ELECTRICAL PARAMETERS

The earlier study devised a formation of nonstandard characteristics using the pros of two standard curves. The author applied the Lagrange generalized optimization method with the Karush–Kuhn–Tucker conditions to reduce operating time [131]. A linear interpolation approach was devised for relays to construct a piece-wise linear characteristic and tabulate them with a minimum number of points. This characteristic removes drawbacks of the standard characteristics for unnecessary operating time for lower fault current and maintains constant CTI between primary and backup relays [132]. Such type of methods can only be applied where fault levels remain almost constant.

Another approach is related to overcome the coordination problems for industrial protection devices. The author has

TABLE 5. Modified protection coordination techniques implemented to DN integrated with microgrids.

Protection Technique	Main Feature	Advantages	Shortcomings	Implementation Cost	Communication Link
1. Overcurrent Relay (NDOCR) [78-80]	Trips the relay if the current exceeds a certain level	• Simple technique • Coordinated with relays based on current level detection	• Protection Blinding, and nuisance tripping • Selectivity issues due to bidirectional faults. • Unintentional islanding	Economical	NO
2. Directional Overcurrent relay (DOCR) [81, 86-88]	This relay trips for the fault in one direction that moves away from the bus	• Safe and reliable protection to meshed networks. • Able to detect bidirectional faults and contains good selectivity.	• Relay installation cost increases due to dual connection of, VT, CT, and CB required.	Expensive	NO
3. Distance Relays Impedance and Admittance relays [89, 92-94, 179]	The source impedance not changed with the integration of new sources and the reach of the relay remains unaffected by fault magnitude. Efficiently measures the fault admittance of line for low-level fault in the presence of inverter DGs	• Relay settings remain unaffected by the change in the network topology. • The response of energy storage devices is fast and provides sufficient fault current and rapid grid voltage recovery.	• High impedance fault effects. • Protection coordination difficulties against high resistance faults • Small range of parameter for relay characteristics	Reasonable	YES
4. Differential Relays [96-100]	Better performance for bidirectional and high impedance faults and not affected by the change in fault current level due to change in network topology	• High sensitivity and selectivity and act against power swing and for external faults • Able to protect radial and meshed feeder from the bidirectional flow.	• Error in measured current and communication delay affect the protection performance • Practical implementation cost very high	Expensive	YES
5. OCR using Symmetrical Components [101-104]	Unbalanced current components are split into three balanced components positive, negative, and zero	• Enables single-phase tripping for unbalanced faults • Incorporate with the existing protection scheme without changing the relay setting. • Suitable for protection against reverse power faults	• The bandwidth requires for electrical quantities data to be transferred using communication is low. • Loss of communication channel may cause undesirable effects on the system operation.	Expensive	YES
6. Adaptive Protection Schemes [107-112]	Modifies the relay settings based on system current state by using external signals and communication medium. Able to change the relay settings based on a change in network topology after fault restoration.	• Centralized protection system • with communications channels • Quick change in settings based on system topology • Can protect a practical system with real-time monitoring and implementation techniques	• Offline system and fault studies consume memory for the large meshed system. • Risk of failure due to communication networks and the lack of a DGs integration feature. • Chances of Cyber-attacks and security threats to communication infrastructure	Very Expensive	YES
7. Voltage based Protection [115, 116, 118, 120]	Utilizes sequence components to observe the terminal voltage disturbance especially during low-level faults	• Generate electrical signature when a fault occurs in the defined protection zone • Flexible technique in detecting the errors that effects the protection performance	• Selectivity using voltage alone for detection of permanent faults in a standalone system. • Involvement of voltage control increases the problem formulation complxity.	Expensive	YES
8. Signal Processing Techniques [124, 126-129]	• Fault diagnosis based on fault index by extracting the electrical parameters. • Signals transformation using wavelet domain and scaling energy	• Less computation burden than conventional overcurrent based Fourier Transform. • High Impedance Fault detection • Dependable and Secure	• Costly Scheme for intensive integrated networks and requires a communication link for long transmission lines. • Protection reliability issues for hybrid integrated	Expensive	YES

TABLE 5. *(Continued.)* **Modified protection coordination techniques implemented to DN integrated with microgrids.**

	coefficients.	Technique	resource to classify faults and requires long tripping times		
9. Modified Strategy using Non-Standard Relay Characteristics [133-137, 142] [143-147, 150]	• Fault current along with parameter relay constants to achieve the optimal relay settings • Optimizing all the relay parameters while maintaining the shape of the curve. • A voltage value is used as a multiplier to perceive a change in the node during fault	• Decrease in overall relay operating time • Optimized other relay parameters to achieve minimum operating time with proper coordination • User-defined relay features are less rigid than standard characteristics • Does not need communication infrastructure;	• Addition of extra parameters could make the protection problem more complex and increased the computational burden • Susceptible maloperation of relays because of dynamic network topological changes. • limited practical validation of user-defined characteristics to real networks	Moderate	YES
10. (a &b) Mathematical and Meta-Heuristic Techniques **[18, 153, 154, 157, 158, 160] [161-165, 167, 169, 171, 180]**	• Provides the primary and backup relay settings and maintains the CTI between relays. • Provide global optimal solution with fast convergence of objective function.	• The proposed approaches can solve specific optimization issues depending on their potential and features. • Applied to all operating conditions, independent to system configuration.	• Complexity to obtain optimal solutions because of highly constrained protection problem • Solution may take long processing time, cause non-convexity, and gets trap in local minima for large no of population sizes.	Economical	NO
10. (c) Artificial Intelligence Techniques [23, 173-178]	• Improve relay performance according to prevailing configuration of MG and train the data using AI Techniques. • Hybrid Methods ANFIS able to identify faulty zones based on symmetrical components	•Eliminates relay miscoordination errors using ANN • convenient to construct the relay characteristics according to pre-defined network topology, • Fast response time.	• Malfunctions the relay settings due to new operational changes, •Computation Complexity, and high burden due to large set of data training in AI methods. • Cost increase due to communication channels	Moderate	YES

proposed a curve fitting technique to set the parameters that vary with the fault current (I_f) [133]. The proposed characteristic equation, as given in Eq. (7) and (8), whereas the reduction in relay operating time with the change in function value can be observed in Fig. 17. The results showed that the UDC could be employed for industrial relays to alleviate the coordination issues with existing industrial protection devices. However, it must be noted that new constants must be adjusted for each specific case, and the generalization of the solution must be further investigated by providing a formula to address the protection challenges of power systems.

$$A\left(I_f\right) = A.e^{-\frac{I_f}{C}} \tag{7}$$

$$Top = \frac{A(I_f) * TMS}{(PCS)^B - 1} \tag{8}$$

.

To overcome the limitations of industrial OCR, the authors have devised a novel GA to enhance the industrial OCRs tripping characteristics and consider the maximum PCS of the industrial relays and formulated as a constraint to mitigate the technical issues embed by DG [134], [135]. Moreover, leveraging programmable relays benefits by devising a new characteristic equation to obtain an optimal protective relay solution. The researcher has modified the standard characteristic (SC) equation as given in Eq. (9) by adding

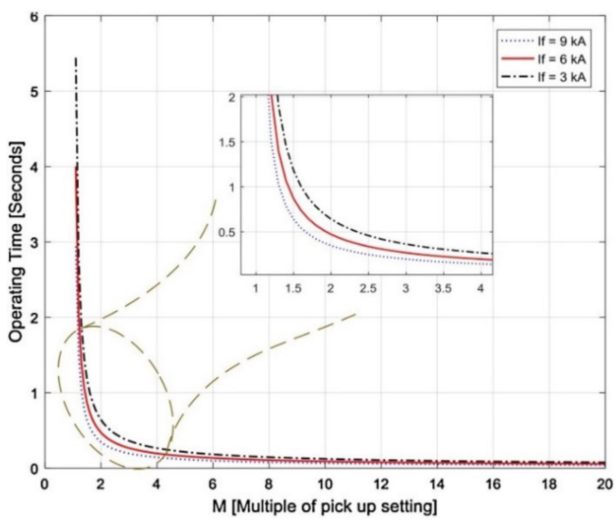

FIGURE 17. **Proposed tripping characteristic with the change in fault currents Soria, *et al.* [133]**

the bus voltage to mitigate the effects of DG using the DOCR relay [136].

$$Top = \left(\frac{1}{e^{(1-V_f)}}\right) \frac{A * TMS}{(PCS)^B - 1} \tag{9}$$

Furthermore, the same approach has been applied with a dual setting of DOCR for a transmission network, including a Wind Power Plant. This study aimed to provide fast fault isolation using the time current-voltage (TCV) tripping characteristics by considering the FRT capabilities of wind plants as defined by standard grid codes [137]. The benefit of an exponential term used in (4) accelerates the operation of OCR, the addition of node voltage usually affected during the fault, especially for PV-based distribution systems. Many other researchers have considered the addition of voltage in a characteristic equation to propose a more effective solution. Jamali *et al.* in [138]–[140] have improved the coordination between reclosure and downstream fuses by doing some amendments in a characteristic equation in terms of per unit voltage value and a constant "k" as given in Eq. (10). This scheme applies to modern reclosure embedded with microprocessor-based relays.

$$Top = \left(\frac{V_f}{e^{k*V_f)}}\right)\frac{A*TMS}{(PCS)^B-1} \tag{10}$$

Moreover, a similar approach in [141] utilizes the local measurements of fault voltage and current magnitude without any communication links. The addition of extra parameters and natural logarithm is considered to linearize the operation and improve voltage and current variations during the fault. But this leads to computational complexity and may trap in local solutions.

A robust protection scheme was proposed in [16] with two distinct characteristics for primary and backup protection. The fault voltage was added along with the time dial constant "A" to reduce the operating of the relay and maintain proper coordination. However, the relay coordination gets affected for the upstream faults by eliminating the TMS from the standard relay equation given in Eq. (11).

$$Top = \frac{\log\left(V_f+A\right)}{(PCS)^B-1}+C \tag{11}$$

Furthermore, an impedance and admittance-based characteristic has been proposed to mitigate the coordination issues from the integrated resources in the network. In [142], a new protection scheme for primary and backup relays was proposed considering measured impedance based on two procedures. Firstly, impedance-based differential protection was implemented to identify fault occurrence and provide sufficient time to exchange data. Then, the method is based on measured impedance incorporated with inverse time characteristics to obtain the optimal settings given in Eq. (12). The suggested approach provides efficient results and proper coordination for both grid-connected and isolated operation modes of MG.

$$T\text{op} = \frac{\mathrm{T_d}}{\left(\mathrm{m}^{\frac{\mathrm{ZL.min}}{\mathrm{Zm}}}\right)^{\alpha}-\beta} \tag{12}$$

As discussed earlier, Dewadasa *et al.* in [92] proposed a novel technique combined with a standard relay equation to provide a solution for low penetrated MG. Similarly, the authors in [4] have provided protection to converter-based DGs in MG. The scheme was efficient in providing the protection solution to MGs during dynamic operating modes. The scheme utilized the admittance parameters in the respective protection zones where the fault levels are low enough to be sensed by conventional relay settings. Therefore, the absolute value of admittance was added in a relay characteristic equation to improve the overall sensitivity, as given in Eq. (13). The proposed scheme did not include the TMS that may cause large operating times for the relay closer to the sources. Moreover, in this method, the identification of high impedance fault near the end of the defined zone can be a non-trivial task and careful measurement is required to calculate the admittance value due to shorter length of distribution lines than transmission lines.

$$Top = \frac{A}{Y_r^B-1}+C \tag{13}$$

The proposed approach demonstrated that admittance-based UDC could provide better results regardless of changes in source impedance. However, there are still limitations in implementing an admittance relay to sense low-level faults and dividing the lines into several zones may increase the computation burden and cause large operating time. More research needs to be investigated to implement the user-defined characteristic in a more efficient way to overcome the relay coordination issues in DN.

8) PROTECTION STRATEGY BY CHANGING RELAY CURVE PARAMETERS

Another approach has been discussed to construct the relay characteristic by manipulating the relay parameters without modifying the standard relay characteristics equation. Many studies have been conducted to change the relay parameters other than PMS and TMS setting to obtain a better solution. Considering the IEEE C37.112-1996 standard characteristics, the author has demonstrated an adjustable protection setting of IDMT relay by considering two short-circuit current maximum and minimum. The algorithm design a specific time curve for each relay, improving the coordination intervals without compromising the curve's shape [14]. In [15] protection coordination strategy was proposed to decrease the operating time of relays by considering the effects of DGs. The protection coordination problem was formulated as nonlinear programming, and the other relay parameters (A & B) values were chosen optimally in addition to (TMS and Ip) to achieve optimal coordination time for DOCR. The proposed technique was tested on meshed networks, and the results showed a significant reduction in overall operating time compared with conventional standard relays. Consdiering the benefits of user defined relay characteristics, the authors have proposed an efficient protection coordination strategy to obtain dual DOCR settings [143]. The results showed the robustness of implementing non-standard inverse-time characteristics to reduce the relays operating time in an interconnected DNs.

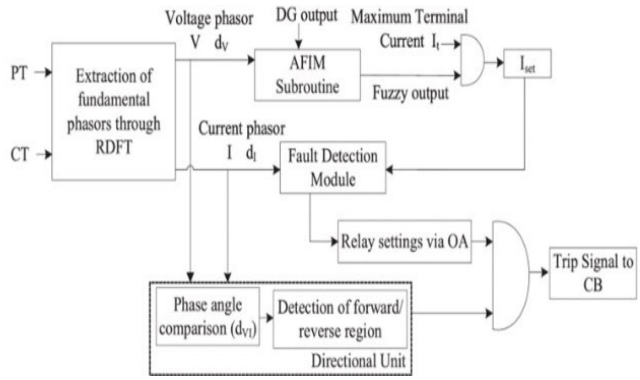

FIGURE 18. A Hybrid Protection Coordination Module using AI and Optimization Techniques [176].

Moreover, a combined characteristic-based protection approach using two different relays is proposed in [144]. In this strategy, the second zone of a transmission line is divided into two sections: the first section protects the main line beyond the first zone with delay time $T_{Z2,}$ and the second one protects 50% of the adjacent line with a time delay of T_{Z2}. Therefore, a new objective function was devised by combining the D& DOCR to overcome relays' operating time. This protection problem was formulated as NLP and solved by a hybrid optimization technique using (HGA_LP). The proposed new operating characteristics give better optimal settings for Distance and DOCR (D&DOCR) relays. Similarly, an approach used in [145] formulates the protection problem as a nonlinear problem (NLP) with five variables. The zone −2 setting of distance relays is made adaptive so that the minimum coordination time margin is maintained for a full reach of distance relays. The combined features of the zone-2 setting of distance relay and user-defined overcurrent relay provide better coordination between relays. To overcome N-1 contingency state conditions in sub-transmission lines, a communication-assisted coordination scheme with a dynamic objective function optimally determines the settings of D-DOCRs and operating time of the second zone of distance relay. However, due to the complex formulation of the problem, the solution may take a long computational time and trapped in local minima. Also, the connection of dual-type relays may increase the overall cost of the protection system [146].

The discussed approaches have considered all the relay constants as variables and gained better results. However, this may increase the calculation burden and trap in local solutions to provide optimal relay settings. Therefore, instead of increasing the number of constants, a proposed optimum setting of DOCRs by considering different characteristic curves to protect AC MGs for different operation modes. In this approach, the third parameter of standard curve selection added along with the relay setting variable PS and TMS [147]. The proposed scheme selects the protection characteristic based on minimum operating time. However, this strategy may fail by changing the type of DG, which contributes to low fault currents and takes longer relay operating time. Another approach proposed in [148] presents a new coordination strategy for multisource meshed DN, which allows the users to define arbitrary TCC. A new objective function was formulated as an NLP problem and obtained by adding a new time constraint as a penalty factor and optimize the variables TMS, Ip & auxiliary variable T_{off} by PSO algorithm.

A work presented in [149] proposed a protection scheme for an ungrounded power network where the fault current is low and cannot be detected by an ordinary relay (51N). A UDC is formed by combining two conventional IEC characteristic features to minimize the total relay operating time for the lower fault currents. This scheme helps to overcome the unnecessary fuse blow and maintains the selectivity between relay-fuse pairs. Other ideas are available in the literature on developing the new characteristic curve by adding a scaling factor to overcome the relay coordination complexity for the far end faults [150]. The proposed protection strategy reduces the total relay operating time in grid-connected and islanding operating modes. However, a difficulty arises in relays selectivity with the change in network topology and reconfiguration with respect to future planning. Moreover, additional parameters may increase the complexity of objective function, and the probability of an infeasible solution will be generated. Hence, the process of updating these infeasible solutions may converge to local optima. Some features of user-defined standard characteristics to alleviate the impact of DGs and possible changes in the network that causes the coordination problems are summarized in Table 5.

9) PROTECTION COORDINATION STRATEGIES USING INTELLIGENT COMPUTING TECHNIQUES

This section discusses the intelligent computation techniques to solve the protection coordination issues in interconnected DN. The protection coordination is nonlinear, non-convex, and highly constrained problem due to its dynamic operation characteristics. Various intelligent optimization algorithms have been implemented to coordinate the primary and back-up relays to solve the protection coordination problem (PCP) [151], [152]. The PCP can be formulated as Linear Programming (LP), Non- Linear Programming (NLP), and Mixed Integer Non-Linear Programming (MINLP) which are solved by intelligent algorithms based on mathematical techniques, Intelligent optimization techniques, and Artificial Intelligence (AI) Networks techniques. Moreover, Fig. 19 illustrating a general structure to obtain an optimal relay setting using intelligent computing techniques in Active Distribution Networks.

a: MATHEMATICAL OPTIMIZATION TECHNIQUES

To solve relay coordination issues and eliminate the convergence gap to reach a global optimization solution. Thus, researchers have formulated such a problem as an optimization problem and implemented mathematical techniques to optimize DOCR settings. The author used the LP techniques to solve the protection coordination issue and considered the definite time of backup relay to obtain optimal settings for

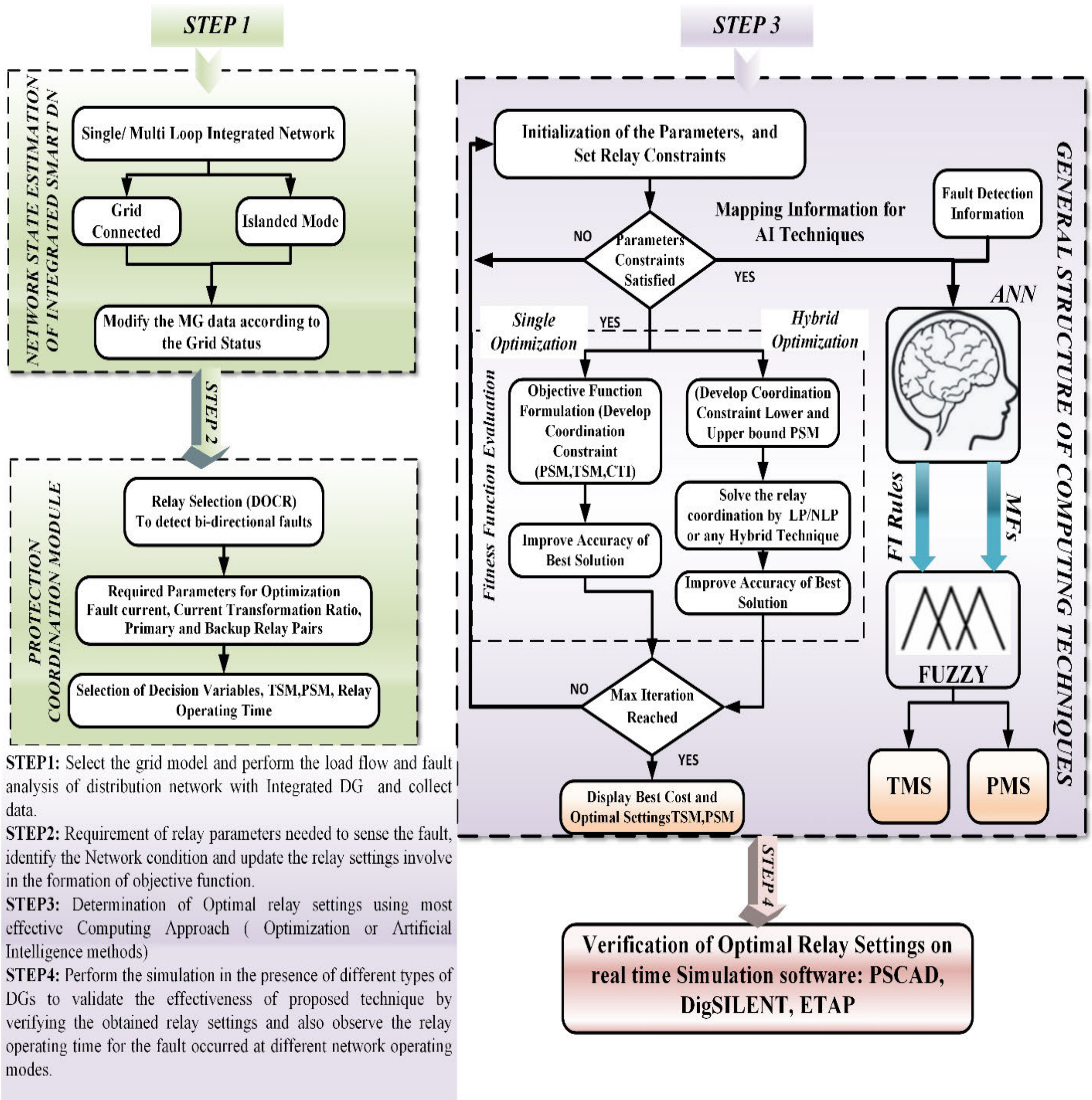

FIGURE 19. A general structure to obtain optimal relay settings using intelligent computing techniques in active distribution networks.

the relay [18]. Commonly, the authors preferred to use LP techniques to obtain the optimal TMS to achieve selectivity between relays. Simplex, dual simplex, two-phase simplex, trial and error method, and deterministic techniques have been reported in the literature to solve the coordination issue in the presence of DGs [81], [153], [154]. Several other LP-based optimization methods are discussed in the literature by considering the pickup as a pre-set value to obtain the minimal solution of relays and verified the selectivity by considering network uncertainties [83], [155]. Generally, in LP methods, the constraints develop for current settings may fail to give the optimal solution for TMS values and may cause higher relay operating times.

The other research methods, as mentioned in [156], have formulated the protection problem as NLP and implemented general Algebraic modeling, sequential quadratic programming (SQP), and Randomly search programming techniques to find the optimal solution for relay settings. In the SQP technique, PCP is formulated as nonlinear by considering the fault constraint as a part of the objective function, which does not affect the optimal coordination settings [157]. Another work proposed in [87] proposed dual settings of DOCRs to obtain optimal settings. The Primary and backup relays on each line coordinated with each other and capable of protecting both forward and reverse fault direction with different relay settings.

In [158], the author has proposed an optimization algorithm by appropriately designing the objective function according to the current system configuration and validated the results by SIMPoruchy 2.1 simulation. The scheme adopts the DOCR settings incorporated with IDMT characteristics. Similarly, the author proposed another mathematical algorithm in [159] using the Modified Electromagnetic Field Optimization (MEFO) algorithm. The protection problem was formulated as NLP to solve the DOCR optimal coordination problem using MEFO. The results demonstrate that the MEFO technique is a useful and reliable tool for DOCR coordination and comparatively better than several well-known optimization techniques. NLP techniques are implemented to formulate the PCP as high constrained and consider both pickup current and TMS as continuous variables that show compatibility with the nature of digital relays [160]. However, due to complex formulation, NLP may take a long processing time, cause the non-convex solution, and trap local minima. To obtain better solutions, the authors have proposed many other intelligent computational techniques for interconnected systems to solve the coordination issues for DOCR in more efficient ways [12], [23].

b: META-HEURISTIC OPTIMIZATION TECHNIQUES

The main advantage of using heuristic and meta-heuristic algorithms; they have a wider search space to create a number of populations and generations to find a global optimum solution. Many optimization techniques have been proposed in [11], [12] literature to optimize the relay coordination settings. An author has proposed an optimization technique to solve the PCP for DOCR and incorporate FCL for the MGs dynamic operating modes [27]. The relay coordination problem was formulated as NLP and solved by the genetic algorithm (GA) with a constraint handling penalty factor method. The constraints of FCL added along with the other protection settings TMS and PS to obtain the optimal values needed to achieve relay coordination.

Similarly, to obtain an optimal relay setting, an adaptive protection scheme using GA was proposed in [161] to test the relay performance for the multiloop system. Moreover, the researcher proposed a popular technique particle swarm optimization (PSO), to obtain the optimal and exact solution for the relay coordination settings. Another approach based on a modified PSO (MPSO) algorithm was presented in [162] to solve the relay coordination in the meshed network. The results obtained by the modified PSO algorithm were compared by the original PSO algorithm, which was initially used to optimize the relay settings as an unconstrained coordination problem. Another approach based on MPSO was utilized to obtain a better solution for large meshed networks with high penetrated DGs [163]. The obtained results showed better performance than deterministic methods to find optimal PCS and TMS for DOCR and also providing better selectivity and minimizing the relay operating time under different network topologies.

Many other metaheuristic methods have been applied in DN to solve the coordination problem of relays caused due to different DG penetration levels, fault types, and locations. Ant Lion Optimizer in [164] proposed to produce the optimal setting of DOCR to minimize the total relay operating time. In [165], enhanced differential evolution (HDE) algorithms able to produce the lowest standard deviations for the high constraint DOCR problem, and [20] used a teaching learning-based optimization (TLBO) algorithm to determine backup relays for every primary relay by employing LINKNET structure with far vector.

However, for large integrated networks, the relay coordination is formulated as a highly constrained optimization problem and obtaining a global solution becomes a challenging task for metaheuristic techniques. Therefore, this increases the probability of rendering an infeasible solution during the searching process and the model gets stuck in local optima due to the process of updating these infeasible solutions. To overcome this highly constrained protection problem, hybrid optimization techniques have been proposed as discussed in [166]–[168].

The authors in [167], [169] presented an efficient and comprehensive hybrid optimization framework for active distribution networks to solve the relay coordination problem by considering network uncertainties and topological changes.

A work in [169] implemented a hybrid technique based on meta-heuristic and mathematical optimization approach to achieve proper relay coordination settings for MG different operating modes. Moreover, to overcome the protection constraints for high penetrated DGs, the author has proposed a new OCR curve. A robust combinatorial optimization method implemented in [170] to solve the coordination problem using a new characteristic relay. A novel approach based on Rosen Gradient projection Differential evolution (RGP–DE) [171] optimizes the parameters iteratively based on measured voltages available at relay location and currents until the solution is converged. The scheme was tested on different DG sizing and location to verify the efficiency of the proposed technique. However, the scheme has not included relay performance for high impedance faults and inverter-based DGs that may cause sensitivity issues for exiting protection relays majorly. There is still an opportunity left to explore a combination of metaheuristic techniques and mathematical programming to produce an efficient and more accurate protection solution.

c: ARITIFICAL INTELLIGENCE TECHNIQUES

Artificial intelligence (AI) techniques are implemented in the protection system to predict the miscoordination in the relay operating times. This biological-based computer program technique usually imitates the information of the human brain. This technique forecasts the relay parameters using AI techniques to determine the optimal relay settings according to the network operating scenarios. AI techniques cover artificial neural networks (ANN), fuzzy logic (FL) control, and their hybrid approaches (ANN-FL), an adaptive neuro-fuzzy interface system utilized for MG protection [13], [23]. The authors proposed a novel approach based on feed-forward neural networks to identify the fault location and trips the associated zone breakers [172]. However, in this approach, there may be a backup zone failure if a breaker does not open by the tripping signal. Another work-related to feed-forward multi-layer neural network approach for interconnected DNs with DGs to obtain the TMS settings for calculating the relay operating times. Furthermore, A work in [173] proposed an artificial neural network (ANN) technique to mitigate the miscoordination time of relays. The data obtained by ANN output shows the improvement in the operating times and reduces the miscoordination. However, further, improvement is required to overcome the negative values of relay coordination based on fault location. An online adaptive approach was proposed in [174] to alleviate the relay coordination issues with the change in short circuit levels. The approach utilized adaptive fuzzy logic to choose the proper offline settings based on network topology. The results show the effectiveness of implementing AI techniques. However, the relay settings need to be optimized adaptively based on DG capacity and fault types. More applications based on ANN and Fuzzy based methods to mitigate the protection challenges and model the user-defined relay characteristics are discussed in [175]–[178].

In [175] O. Emmanuel *et al.* devised a formation of the inverse-time current characteristics curve for forecasting the real optimal operating time for every protective relay at each line by implementing a GA-ANN hybrid approach. The experimental findings of proposed approaches using the multiobjective function validate the accuracy of the time characteristic curve and able to predict the relay operating time with minimum square error(mse). However, miscoordination elimination among the relay pairs was not improved effectively. Similarly, to overcome the stochastic nature of DGs integrated into the MG, an adaptive protection scheme is suggested by the authors in [176]. A hybrid optimization and fuzzy inference approach are implemented to optimally determining the relay settings (I_{pu}&TSM) as shown in Fig.18.

Moreover, Daryani *et al.* in [178] proposed a flexible approach based on fuzzy logic and Artificial Neural Network (ANN), namely Adaptive Neuro-Fuzzy Interface System (ANFIS). In the proposed system, the ANFIS structure is incorporated into the developed protection relay model to intelligently adapt the protection settings according to the MG topological state. The proposed strategy verifies the relay performance for different fault conditions. Regardless, the proposed protection scheme could malfunction the relay operating times with the change in network configuration and layout.

In the aforesaid solutions, the main hindrance is storing the fault and relay data related to different groups of protection settings in the computer memory. Moreover, an immense quantity of data and network operating states condition to be collected if the network is extended or more DGs are installed. Also, if the prevailing conditions of the MG do not match any of the stored protection settings, then consequently, the interpretation of the proposed structure becomes essential. Therefore, a flexible approach is required to find a solution to the issue related to existing and future operating networks.

This section has discussed the different relaying schemes to provide adequate protection for bidirectional faults in interconnected power networks. The protection device (relay) is carefully chosen for the power equipment, and their settings are optimized based on the system operating conditions. This practice is usually done at the planning stage; moreover, for future planning or any modification in the power network, the DOCR is considered a highly recommended protection relay to mitigate the bidirectional faults and nuisance tripping. Although DOCR is an expensive protection device due to its dual settings property, however, this relay is considered a safe and reliable protection device for meshed and radial DN. Whereas, the power-producing companies need to consider the high capital cost for the protection devices and advanced strategies to obtain the relay settings for all contingency operating states. The incorporation of DOCR with adaptive protection further improves the protection scheme reliability for future smart grids. The deployment of adaptive protection strategies can improve the overall sensitivity of relays. However, the challenges that arise with these adaptive communications assisted OCR in terms of economics and tariff, as discussed in Section 2.3. Therefore, for smart DNs, the new protection strategies must ensure safety and reliability with minimum protection cost. In this regard, the deployment of microprocessor-based digital relays can provide a fast response and inexpensive protection solutions. Whereas the protection settings can be programmed and modified based on the network topology. As discussed in Section 2.6, instead of implementing conventional characteristics, the modified relay characteristics can reduce the fault clearing time. Incorporating UDC with OCR can substantially decrease relay operating time for interconnected MGs under various conditions and operating modes. Keeping the NSC benefits, researchers are still exploring an economic real-time protection scheme for the practical interconnected DNs.

IV. RECOMMENDATIONS

Based on the study conducted and presented in this paper, an intelligent and robust protection scheme is mandatory to mitigate the protection challenges. Therefore, the implementation of UDC can help to optimize the protection settings according to the network behaviour. Considering the possible changes in network configuration following are the recommendations of protection strategies that can be explored for further research:

- One of the economical solutions considering the classical protection approach is optimal network reconfiguration and DG sizing for integrated networks to comply with existing protection settings and coordination constraints during normal and abnormal situations. Further research needs to be explored by considering combined protection strategies to get optimal relay settings and optimal DG benefits integrated into MGs.

- A multi-objective optimization approach can be employed to solve the relay coordination problem in an extensive DN and reduce the relay operating time by considering the user-defined characteristics. Such an optimization approach can intensify the flexibility of implementing a dual setting relay characteristics curve in comparison to standard relay characteristics to mitigate the high impedance fault scenarios in the presence of inverter-based DGs.
- Development of active management adaptive protection scheme is imperative to update the relay settings via-high and reliable communication links that maintain the selectivity of relays under dynamic load changes, demand response, and change in network topology in the integrated MGs-based DN. However, a secure link and high-performance bandwidth channels are required to exchange secure data among IEDs.
- A real-time fast response protection scheme for the multi-MG systems to detect the formation of islands in case of grid faults and obtain the relay setting to achieve proper coordination for both pre-and post-contingency scenarios.
- A dual voltage-current based user-defined relay characteristic needs to be implemented to avoid misinterpretation of the cold-load pickup with fault current to avoid de-energizing of the un-affected circuit. The scope of utilizing UDC to overcome practical network peculiarities is still an open topic.
- Recent advancements in power electronics instigated to integrate AC and DC microgrids, forming multi-microgrid (MMGs) configuration. Higher power quality, higher reliability, increased energy efficiency, less cost, and reduced carbon emissions are the major advantages of MMGs. Hence, rigorous modifications are required in conventional protection approaches to ensure the system's reliability for MMG configuration.
- In recent years, the area of power system resilience has gained substantial traction. Making the power system resilient entails preparing it for unprecedented high-intensity, low probability events. Fault experienced during these events is far greater than the conventional N-1 & N-2 contingency planning criteria. Therefore, to strengthen the resilience of interconnected MGs during major outages, a study should be conducted to locate the fault and update the associated relays based on fault direction and satisfying the protection constraints.

V. CONCLUSION

This paper has reviewed the protection strategies proposed to mitigate the impact of MGs integration to DNs. The basic features of relays, reviews of established techniques to overcome the protection failure, advantages, and associated shortcomings have been explored. Generally, two strategies can be utilized to overcome the protection failure in the integrated network; either to maintain the existing protection system using grid standards and control techniques or to modify the settings to achieve proper relay coordination. The classical protection approach in the first strategy can be an economical solution for DNOs; however, this may compromise the reliability of the network. Whereas the modified protection approaches could be a costly solution with the connection of advance relaying schemes, but it provides a stable operation to the network.

From the literature review, it can be concluded that the proliferation of various types of DG units in MGs has changed the operational characteristics of the power system. Additionally, the dynamic changes in the active distribution networks, such as network reconfiguration and demand response have introduced coordination issues in the existing protection devices. Therefore, the conventional protection strategies need to be revised to cope with the dynamic changes in the network. Utilizing the features of programmable relays, with the implementation of user-defined relay characteristics, provides better coordination and significantly reduces the total relay operating time for the bi-directional faults in the network. The incorporation of user-defined time-inverse characteristics can provide a robust protection scheme to locate the possible faults and optimize the relay coordination settings according to the network layout.

REFERENCES

[1] 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, doi: 10.1109/MELE.2013.2297031.

[2] A. Pathirana, A. Rajapakse, and N. Perera, "Development of a hybrid protection scheme for active distribution systems using polarities of current transients," *Electr. Power Syst. Res.*, vol. 152, pp. 377–389, Nov. 2017, doi: 10.1016/j.epsr.2017.07.022.

[3] H. F. Habib, A. A. S. Mohamed, M. El Hariri, and O. A. Mohammed, "Utilizing supercapacitors for resiliency enhancements and adaptive microgrid protection against communication failures," *Electr. Power Syst. Res.*, vol. 145, pp. 223–233, Apr. 2017, doi: 10.1016/j.epsr.2016.12.027.

[4] R. Majumder, M. Dewadasa, A. Ghosh, G. Ledwich, and F. Zare, "Control and protection of a microgrid connected to utility through back-to-back converters," *Electr. Power Syst. Res.*, vol. 81, no. 7, pp. 1424–1435, Jul. 2011, doi: 10.1016/j.epsr.2011.02.006.

[5] B. J. Brearley and R. R. Prabu, "A review on issues and approaches for microgrid protection," *Renew. Sustain. Energy Rev.*, vol. 67, pp. 988–997, Jan. 2017, doi: 10.1016/j.rser.2016.09.047.

[6] T. N. Boutsika and S. A. Papathanassiou, "Short-circuit calculations in networks with distributed generation," *Electr. Power Syst. Res.*, vol. 78, no. 7, pp. 1181–1191, Jul. 2008, doi: 10.1016/j.epsr.2007.10.003.

[7] I. Tristiu, C. Bulac, S. Costinas, L. Toma, A. Mandis, and T. Zabava, "A new and efficient algorithm for short-circuit calculation in distribution networks with distributed generation," in *Proc. 9th Int. Symp. Adv. Topics Electr. Eng. (ATEE)*, May 2015, pp. 816–821.

[8] P. T. Manditereza and R. Bansal, "Renewable distributed generation: The hidden challenges—A review from the protection perspective," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1457–1465, May 2016, doi: 10.1016/j.rser.2015.12.276.

[9] M. Norshahrani, H. Mokhlis, A. A. Bakar, J. Jamian, and S. Sukumar, "Progress on protection strategies to mitigate the impact of renewable distributed generation on distribution systems," *Energies*, vol. 10, no. 11, p. 1864, Nov. 2017.

[10] 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, doi: 10.17775/CSEEJPES.2017.00030.

[11] S. Katyara, L. Staszewski, and Z. Leonowicz, "Protection coordination of properly sized and placed distributed generations–methods, applications and future scope," *Energies*, vol. 11, no. 10, p. 2672, 2018.

[12] M. N. Alam, B. Das, and V. Pant, "A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination," *Electr. Power Syst. Res.*, vol. 128, pp. 39–52, Nov. 2015, doi: 10.1016/j.epsr.2015.06.018.

[13] 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, doi: 10.1016/j.rser.2019.109524.

[14] C. A. C. Salazar, A. C. Enríquez, and S. E. Schaeffer, "Directional overcurrent relay coordination considering non-standardized time curves," *Electr. Power Syst. Res.*, vol. 122, pp. 42–49, May 2015, doi: 10.1016/j.epsr.2014.12.018.

[15] H. M. Sharaf, H. H. Zeineldin, D. K. Ibrahim, and E. L. Essam, "A proposed coordination strategy for meshed distribution systems with DG considering user-defined characteristics of directional inverse time overcurrent relays," *Int. J. Electr. Power Energy Syst.*, vol. 65, pp. 49–58, Feb. 2015, doi: 10.1016/j.ijepes.2014.09.028.

[16] H. C. Kılıçkıran, H. Akdemir, İ. Şengör, B. Kekezoğlu, and N. Paterakis, "A non-standard characteristic based protection scheme for distribution networks," *Energies*, vol. 11, no. 5, p. 1241, May 2018. [Online]. Available: https://www.mdpi.com/1996-1073/11/5/1241

[17] H. C. Kılıçkıran, 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, doi: 10.1016/j.epsr.2018.07.008.

[18] A. J. Urdaneta, L. G. Perez, and H. Restrepo, "Optimal coordination of directional overcurrent relays considering dynamic changes in the network topology," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1458–1464, Oct. 1997.

[19] A. J. Urdaneta, L. G. Pérez, J. F. Gómez, B. Feijoo, and M. González, "Presolve analysis and interior point solutions of the linear programming coordination problem of directional overcurrent relays," *Int. J. Electr. Power Energy Syst.*, vol. 23, no. 8, pp. 819–825, Nov. 2001.

[20] M. Singh, B. K. Panigrahi, and A. R. Abhyankar, "Optimal coordination of directional over-current relays using teaching learning-based optimization (TLBO) algorithm," *Int. J. Electr. Power Energy Syst.*, vol. 50, pp. 33–41, Sep. 2013, doi: 10.1016/j.ijepes.2013.02.011.

[21] A. Mahari and H. Seyedi, "An analytic approach for optimal coordination of overcurrent relays," *IET Gener., Transmiss. Distrib.*, vol. 7, no. 7, pp. 674–680, Jul. 2013.

[22] D. S. Alkaran, M. R. Vatani, M. J. Sanjari, G. B. Gharehpetian, and A. H. Yatim, "Overcurrent relays coordination in interconnected networks using accurate analytical method and based on determination of fault critical point," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 870–877, Apr. 2015.

[23] 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, doi: 10.3390/en13092149.

[24] F. Coffele, C. Booth, and A. Dyśko, "An adaptive overcurrent protection scheme for distribution networks," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 561–568, Apr. 2015, doi: 10.1109/TPWRD.2013.2294879.

[25] 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*, early access, Jan. 4, 2021, doi: 10.1109/ACCESS.2020.3048940.

[26] 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, doi: 10.1016/j.epsr.2015.07.006.

[27] W. K. A. Najy, H. H. Zeineldin, and W. L. Woon, "Optimal protection coordination for microgrids with grid-connected and islanded capability," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1668–1677, Apr. 2013, doi: 10.1109/TIE.2012.2192893.

[28] H. Margossian, J. Sachau, and G. Deconinck, "Short circuit calculation in networks with a high share of inverter based distributed generation," in *Proc. IEEE 5th Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG)*, Jun. 2014, pp. 1–5.

[29] 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.

[30] 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, doi: 10.1109/TPWRS.2012.2214489.

[31] V. A. Papaspiliotopoulos, G. N. Korres, V. A. Kleftakis, and N. D. Hatziargyriou, "Hardware-in-the-loop design and optimal setting of adaptive protection schemes for distribution systems with distributed generation," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 393–400, Feb. 2017, doi: 10.1109/TPWRD.2015.2509784.

[32] B. Hussain, S. M. Sharkh, S. Hussain, and M. A. Abusara, "Integration of distributed generation into the grid: Protection challenges and solutions," in *Proc. 10th IET Int. Conf. Develop. Power Syst. Protection (DPSP) Manag. Change*, 2010, pp. 1–5, doi: 10.1049/cp.2010.0347.

[33] N. W. A. Lidula and A. D. Rajapakse, "A pattern recognition approach for detecting power islands using transient signals—Part I: Design and implementation," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 3070–3077, Oct. 2010, doi: 10.1109/TPWRD.2010.2053724.

[34] N. W. A. Lidula and A. D. Rajapakse, "A pattern-recognition approach for detecting power islands using transient signals—Part II: Performance evaluation," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1071–1080, Jul. 2012, doi: 10.1109/TPWRD.2012.2187344.

[35] 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.

[36] I. Xyngi and M. Popov, "An intelligent algorithm for the protection of smart power systems," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1541–1548, Sep. 2013.

[37] *IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems*, Standard 1547-2003, 2003.

[38] A. Notholt, "Germany's new code for generation plants connected to medium-voltage networks and its repercussion on inverter control," in *Proc. Int. Conf. Renew. Energies Power Qual. (ICREPQ)*, 2009, pp. 15–17.

[39] S. Australia, "Grid connection of energy systems via inverters," in *Proc. Grid Protection Requirements*, 2005, p. 7.

[40] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid Converters for Photovoltaic and Wind Power Systems*. Hoboken, NJ, USA: Wiley, 2011.

[41] N. K. Roy and H. R. Pota, "Current status and issues of concern for the integration of distributed generation into electricity networks," *IEEE Syst. J.*, vol. 9, no. 3, pp. 933–944, Sep. 2015.

[42] G. Antonova, M. Nardi, A. Scott, and M. Pesin, "Distributed generation and its impact on power grids and microgrids protection," in *Proc. 65th Annu. Conf. Protective Relay Eng.*, Apr. 2012, pp. 152–161.

[43] R. G. C. Secretariat. (2014). *National Energy Regulator of South Africa*. Accessed: Jan. 26, 2018. [Online]. Available: http://www.nersa.org.za/Admin/Document/Editor/file/Electricity/TechnicalStandards/South%20African%20Grid%20Code%20Requirements%20for%20Renewable%20Power%20Plants%20-%20Version%202%208.pdf

[44] C. Rahmann, H.-J. Haubrich, A. Moser, R. Palma-Behnke, L. Vargas, and M. B. C. Salles, "Justified fault-ride-through requirements for wind turbines in power systems," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1555–1563, Aug. 2011.

[45] H. Yazdanpanahi, Y. W. Li, and W. Xu, "A new control strategy to mitigate the impact of inverter-based DGs on protection system," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1427–1436, Sep. 2012.

[46] M. S. El Moursi, W. Xiao, and J. L. Kirtley, "Fault ride through capability for grid interfacing large scale PV power plants," *IET Gener., Transmiss. Distrib.*, vol. 7, no. 9, pp. 1027–1036, Sep. 2013.

[47] R. K. Varma, S. A. Rahman, V. Atodaria, S. Mohan, and T. Vanderheide, "Technique for fast detection of short circuit current in PV distributed generator," *IEEE Power Energy Technol. Syst. J.*, vol. 3, no. 4, pp. 155–165, Dec. 2016.

[48] B.-I. Crăciun, T. Kerekes, D. Séra, and R. Teodorescu, "Overview of recent grid codes for PV power integration," in *Proc. 13th Int. Conf. Optim. Electr. Electron. Equip. (OPTIM)*, May 2012, pp. 959–965.

[49] T.-N. Preda, K. Uhlen, and D. E. Nordgaård, "An overview of the present grid codes for integration of distributed generation," in *Proc. CIRED Workshop, Integr. Renewables Distrib. Grid*, 2012, pp. 1–4, doi: 10.1049/cp.2012.0716.

[50] E. C. O. Malaysia, Ed., "Guidelines on large scale solar photovoltaic plant for connection to electricity networks," Energy Commission, Putrajaya, Malaysia, Tech. Rep. Gp/St/No.1/2016, Apr. 2016, p. 685.

[51] *Solar Energy Plants Grid Connection Code-In Addition to the Egyptian Transmission Grid Code and the Egyptian Distribution Network*, Egyptian Distribution Network. Egypt ERA Committee. Cairo, Egypt. Accessed: Mar. 2017. [Online]. Available: http://egyptera.org/ar/Download/Code/Egypt_gridcode_for_solar_plant_connectionOnMVandHV.pdf
[52] S. H. A. Aleem, A. Y. Abdelaziz, and A. F. Zobaa, "Egyptian grid code of wind farms and power quality," in *Handbook of Distributed Generation*. Cham, Switzerland: Springer, 2017, pp. 227–245.
[53] H. Jo, S. Joo, and K. Lee, "Optimal placement of superconducting fault current limiters (SFCLs) for protection of an electric power system with distributed generations (DGs)," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, 2013, Art. no. 5600304, doi: 10.1109/TASC.2012.2232958.
[54] S. B. Naderi, M. Negnevitsky, A. Jalilian, and M. T. Hagh, "Fault ride through improvement of fixed speed wind turbine using CR-FCL with its modified control strategy," in *Proc. Australas. Universities Power Eng. Conf. (AUPEC)*, Sep. 2016, pp. 1–6, doi: 10.1109/AUPEC.2016.7749312.
[55] S. B. Naderi, M. Negnevitsky, A. Jalilian, M. T. Hagh, and K. M. Muttaqi, "Low voltage ride-through enhancement of DFIG-based wind turbine using DC link switchable resistive type fault current limiter," *Int. J. Electr. Power Energy Syst.*, vol. 86, pp. 104–119, Mar. 2017, doi: 10.1016/j.ijepes.2016.10.001.
[56] S. Beheshtaein, M. Savaghebi, J. M. Guerrero, R. Cuzner, and J. C. Vasquez, "A secondary-control based fault current limiter for four-wire three phase inverter-interfaced DGs," in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2017, pp. 2363–2368, doi: 10.1109/IECON.2017.8216398.
[57] 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, Apr. 2018, doi: 10.1109/TIA.2017.2776858.
[58] N. Jayawarna, N. Jenkins, M. Barnes, M. Lorentzou, S. Papthanassiou, and N. Hatziagyriou, "Safety analysis of a microgrid," in *Proc. Int. Conf. Future Power Syst.*, 2005, p. 7, doi: 10.1109/FPS.2005.204228.
[59] F. V. Overbeeke, "Fault current source to ensure the fault level in inverter-dominated networks," in *Proc. 20th Int. Conf. Exhib. Electr. Distrib. (CIRED)*, vol. 1, Jun. 2009, pp. 1–4.
[60] R. Akella, H. Tang, and B. M. Mcmillin, "Analysis of information flow security in cyber–physical systems," *Int. J. Crit. Infrastruct. Protection*, vol. 3, nos. 3–4, pp. 157–173, Dec. 2010, doi: 10.1016/j.ijcip.2010.09.001.
[61] O. Badran, S. Mekhilef, H. Mokhlis, and W. Dahalan, "Optimal reconfiguration of distribution system connected with distributed generations: A review of different methodologies," *Renew. Sustain. Energy Rev.*, vol. 73, pp. 854–867, Jun. 2017, doi: 10.1016/j.rser.2017.02.010.
[62] P. Piya, M. Ebrahimi, M. Karimi-Ghartemani, and S. A. Khajehoddin, "Fault ride-through capability of voltage-controlled inverters," *IEEE Trans. Ind. Electron.*, vol. 65, no. 10, pp. 7933–7943, Oct. 2018, doi: 10.1109/TIE.2018.2803765.
[63] F. Gao and M. R. Iravani, "A control strategy for a distributed generation unit in grid-connected and autonomous modes of operation," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 850–859, Apr. 2008, doi: 10.1109/TPWRD.2007.915950.
[64] S. Beheshtaein, R. Cuzner, M. Savaghebi, and J. M. Guerrero, "Review on microgrids protection," *IET Gener., Transmiss. Distrib.*, vol. 13, no. 6, pp. 743–759, Mar. 2019, doi: 10.1049/iet-gtd.2018.5212.
[65] D. H. Popović, J. A. Greatbanks, M. Begović, and A. Pregelj, "Placement of distributed generators and reclosers for distribution network security and reliability," *Int. J. Electr. Power Energy Syst.*, vol. 27, nos. 5–6, pp. 398–408, Jun. 2005.
[66] R. K. Singh and S. K. Goswami, "Optimum allocation of distributed generations based on nodal pricing for profit, loss reduction, and voltage improvement including voltage rise issue," *Int. J. Electr. Power Energy Syst.*, vol. 32, no. 6, pp. 637–644, Jul. 2010.
[67] N. Khalesi, N. Rezaei, and M.-R. Haghifam, "DG allocation with application of dynamic programming for loss reduction and reliability improvement," *Int. J. Electr. Power Energy Syst.*, vol. 33, no. 2, pp. 288–295, Feb. 2011.
[68] T. Saksornchai and B. Eua-Arporn, "Determination of allowable capacity of distributed generation with protection coordination consideration," *Eng. J.*, vol. 13, no. 3, pp. 29–44, Nov. 2009, doi: 10.4186/ej.2009.13.3.29.
[69] Z. Wang, B. Chen, J. Wang, J. Kim, and M. M. Begovic, "Robust optimization based optimal DG placement in microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2173–2182, Sep. 2014.
[70] A. Kumar and V. Verma, "Optimization and implementation of hybrid energy sources in remote and grid active microgrids—A case study for Indian scenario," in *Proc. IEEE 7th Power India Int. Conf. (PIICON)*, Nov. 2016, pp. 1–6.
[71] S. M. Dawoud, L. Xiangning, F. M. F. Flaih, and M. I. Okba, "PSO algorithm for optimal placement of multiple SPV based distributed generators in microgrids," in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Oct. 2016, pp. 125–129.
[72] P. Mahat, Z. Chen, B. Bak-Jensen, and C. L. Bak, "A simple adaptive overcurrent protection of distribution systems with distributed generation," *IEEE Trans. Smart Grid*, vol. 2, no. 3, pp. 428–437, Sep. 2011, doi: 10.1109/TSG.2011.2149550.
[73] *Electrical Relays—Part 3: Single Input Energizing Quantity Measuring Relays With Dependent or Independent Time*, IEC Standard 60255-3, 1989.
[74] S. H. Horowitz and A. G. Phadke, *Power System Relaying*, 4th ed. Hoboken, NJ, USA: Wiley, 2014.
[75] D. Durand and D. Pieniazek, "Overcurrent protection & coordination for industrial applications," in *Proc. Ind. Appl. Soc. Annu. Meeting*, 2010, pp. 1–131.
[76] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi, "MOPSO/FDMT-based Pareto-optimal solution for coordination of overcurrent relays in interconnected networks and multi-DER microgrids," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 12, pp. 2871–2886, 2018. [Online]. Available: https://digital-library.theiet.org/content/journals/10.1049/iet-gtd.2018.0079
[77] M. N. Alam, "Adaptive protection coordination scheme using numerical directional overcurrent relays," *IEEE Trans. Ind. Informat.*, vol. 15, no. 1, pp. 64–73, Jan. 2019, doi: 10.1109/TII.2018.2834474.
[78] S. Chaitusaney and A. Yokoyama, "Prevention of reliability degradation from recloser–fuse miscoordination due to distributed generation," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2545–2554, Oct. 2008, doi: 10.1109/Tpwrd.2007.915899.
[79] A. F. Naiem, Y. Hegazy, A. Y. Abdelaziz, and M. A. Elsharkawy, "A classification technique for recloser-fuse coordination in distribution systems with distributed generation," *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 176–185, Jan. 2012, doi: 10.1109/TPWRD.2011.2170224.
[80] S. S. Gokhale and V. S. Kale, "An application of a tent map initiated chaotic firefly algorithm for optimal overcurrent relay coordination," *Int. J. Electr. Power Energy Syst.*, vol. 78, pp. 336–342, Jun. 2016.
[81] Ł. Huchel and H. H. Zeineldin, "Planning the coordination of directional overcurrent relays for distribution systems considering DG," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1642–1649, May 2016, doi: 10.1109/TSG.2015.2420711.
[82] A. Y. Abdelaziz, H. Talaat, A. Nosseir, and A. A. Hajjar, "An adaptive protection scheme for optimal coordination of overcurrent relays," *Electr. Power Syst. Res.*, vol. 61, no. 1, pp. 1–9, 2002, doi: 10.1016/S0378-7796(01)00176-6.
[83] H. A. Abyaneh, M. Al-Dabbagh, H. K. Karegar, S. H. H. Sadeghi, and R. A. J. Khan, "A new optimal approach for coordination of overcurrent relays in interconnected power systems," *IEEE Trans. Power Del.*, vol. 18, no. 2, pp. 430–435, Apr. 2003, doi: 10.1109/TPWRD.2002.803754.
[84] M. M. Mansour, S. F. Mekhamer, and N. El-Kharbawe, "A modified particle swarm optimizer for the coordination of directional overcurrent relays," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1400–1410, Jul. 2007, doi: 10.1109/TPWRD.2007.899259.
[85] T. Amraee, "Coordination of directional overcurrent relays using seeker algorithm," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1415–1422, Jul. 2012, doi: 10.1109/TPWRD.2012.2190107.
[86] D. Jones and J. J. Kumm, "Future distribution feeder protection using directional overcurrent elements," *IEEE Trans. Ind. Appl.*, vol. 50, no. 2, pp. 1385–1390, Apr. 2014.
[87] H. H. Zeineldin, H. M. Sharaf, D. K. Ibrahim, and E. E.-D. A. El-Zahab, "Optimal protection coordination for meshed distribution systems with DG using dual setting directional over-current relays," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 115–123, Jan. 2015, doi: 10.1109/TSG.2014.2357813.
[88] J. Kennedy, P. Ciufo, and A. Agalgaonkar, "A review of protection systems for distribution networks embedded with renewable generation," *Renew. Sustain. Energy Rev.*, vol. 58, pp. 1308–1317, May 2016.

[89] I. Chilvers, N. Jenkins, and P. Crossley, "Distance relaying of 11 kV circuits to increase the installed capacity of distributed generation," *IEE Proc. Gener., Transmiss. Distrib.*, vol. 152, no. 1, pp. 40–46, Jan. 2005, doi: 10.1049/ip-gtd:20041205.
[90] S. Voima and K. Kauhaniemi, "Using distance protection in smart grid environment," in *Proc. IEEE PES Innov. Smart Grid Technol., Eur.*, 2014, pp. 1–6.
[91] P. Kundur, N. J. Balu, and M. G. Lauby, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994.
[92] M. Dewadasa, A. Ghosh, and G. Ledwich, "An inverse time admittance relay for fault detection in distribution networks containing DGs," in *Proc. IEEE Region Conf. (TENCON)*, Jan. 2009, pp. 1–6.
[93] S. Mirsaeidi, D. M. Said, M. W. Mustafa, M. H. Habibuddin, and K. Ghaffari, "An analytical literature review of the available techniques for the protection of micro-grids," *Int. J. Electr. Power Energy Syst.*, vol. 58, pp. 300–306, Jun. 2014.
[94] M. Dewadasa, A. Ghosh, and G. Ledwich, "Fold back current control and admittance protection scheme for a distribution network containing distributed generators," *IET Gener., Transmiss. Distrib.*, vol. 4, no. 8, pp. 952–962, 2010, doi: 10.1049/iet-gtd.2009.0614.
[95] N. A. Mohamed and M. M. A Salama, "A review on the proposed solutions to microgrid protection problems," in *Proc. IEEE Can. Conf. Electr. Comput. Eng. (CCECE)*, May 2016, pp. 1–5.
[96] Z. Y. Xu, Z. Q. Du, L. Ran, Y. K. Wu, Q. X. Yang, and J. L. He, "A current differential relay for a 1000-kV UHV transmission line," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1392–1399, Jul. 2007.
[97] H. Nikkhajoei and R. H. Lasseter, "Microgrid fault protection based on symmetrical and differential current components," *Power Syst. Eng. Res. Center*, vol. 1, pp. 71–74, 2006.
[98] J. G. Rao and A. K. Pradhan, "Differential power-based symmetrical fault detection during power swing," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1557–1564, Jul. 2012.
[99] T. Selim 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.
[100] I. Almutairy, "A review of coordination strategies and techniques for overcoming challenges to microgrid protection," in *Proc. Saudi Arabia Smart Grid (SASG)*, Dec. 2016, pp. 1–4.
[101] 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.
[102] M. R. Miveh, M. Gandomkar, S. Mirsaeidi, and H. Nasiban, "Micro-grid protection by designing a communication-assisted digital relay," *Amer. J. Sci. Res*, vol. 51, pp. 62–68, Feb. 2012.
[103] K. O. Oureilidis and C. S. Demoulias, "A fault clearing method in converter-dominated microgrids with conventional protection means," *IEEE Trans. Power Electron.*, vol. 31, no. 6, pp. 4628–4640, Jun. 2016.
[104] Z.-H. Zhang, B.-Y. Xu, P. Crossley, and L. Li, "Positive-sequence-fault-component-based blocking pilot protection for closed-loop distribution network with underground cable," *Int. J. Electr. Power Energy Syst.*, vol. 94, pp. 57–66, Jan. 2018.
[105] S. M. Brahma and A. A. Girgis, "Development of adaptive protection scheme for distribution systems with high penetration of distributed generation," *IEEE Trans. Power Del.*, vol. 19, no. 1, pp. 56–63, Jan. 2004.
[106] R. J. Best, D. J. Morrow, and P. A. Crossley, "Communication assisted protection selectivity for reconfigurable and islanded power networks," in *Proc. 44th Int. Universities Power Eng. Conf. (UPEC)*, 2009, pp. 1–5.
[107] 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.
[108] M. Y. Shih, A. Conde, Z. Leonowicz, and L. Martirano, "An adaptive overcurrent coordination scheme to improve relay sensitivity and overcome drawbacks due to distributed generation in smart grids," *IEEE Trans. Ind. Appl.*, vol. 53, no. 6, pp. 5217–5228, Dec. 2017, doi: 10.1109/TIA.2017.2717880.
[109] T. S. Ustun, "Interoperability and interchangeability for microgrid protection systems using IEC 61850 standard," in *Proc. IEEE Int. Conf. Power Energy (PECon)*, Nov. 2016, pp. 7–12.
[110] X. Wang and X. Li, "Fault recovery of micro-grid based on network reconfiguration," in *Proc. Asia–Pacific Power Energy Eng. Conf.*, Mar. 2012, pp. 1–4.
[111] B. P. Bhattarai, B. Bak-Jensen, S. Chaudhary, and J. R. Pillai, "An adaptive overcurrent protection in smart distribution grid," in *Proc. IEEE Eindhoven PowerTech*, Jun. 2015, pp. 1–6.
[112] T. Gangwar and S. Sarangi, "Adaptive relay setting for distribution system during reconfiguration," in *Proc. 14th IEEE India Council Int. Conf. (INDICON)*, Dec. 2017, pp. 1–6.
[113] T. Senarathna and K. U. Hemapala, "Review of adaptive protection methods for microgrids," *AIMS Energy*, vol. 7, no. 5, p. 557, 2019.
[114] H. Al-Nasseri, M. A. Redfern, and R. O'Gorman, "Protecting micro-grid systems containing solid-state converter generation," in *Proc. Int. Conf. Future Power Syst.*, 2005, p. 5, doi: 10.1109/FPS.2005.204294.
[115] H. Al-Nasseri, M. A. Redfern, and F. Li, "A voltage based protection for micro-grids containing power electronic converters," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2006, p. 7, doi: 10.1109/PES.2006.1709423.
[116] 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.
[117] X.-P. Wang, Y. Li, and Y.-Y. Yu, "Research on the relay protection system for a small laboratory-scale microgrid system," in *Proc. 6th IEEE Conf. Ind. Electron. Appl.*, Jun. 2011, pp. 2712–2716.
[118] P. T. Manditereza and R. C. Bansal, "Multi-agent based distributed voltage control algorithm for smart grid applications," *Electr. Power Compon. Syst.*, vol. 44, no. 20, pp. 2352–2363, Dec. 2016.
[119] P. T. Manditereza and R. C. Bansal, "Fault detection and location algorithm for DG-integrated distribution systems," *J. Eng.*, vol. 2018, no. 15, pp. 1286–1290, Oct. 2018.
[120] P. T. Manditereza and R. C. Bansal, "Protection of microgrids using voltage-based power differential and sensitivity analysis," *Int. J. Electr. Power Energy Syst.*, vol. 118, Jun. 2020, Art. no. 105756.
[121] S. R. Ola, A. Saraswat, S. K. Goyal, V. Sharma, B. Khan, O. P. Mahela, H. H. Alhelou, and P. Siano, "Alienation coefficient and wigner distribution function based protection scheme for hybrid power system network with renewable energy penetration," *Energies*, vol. 13, no. 5, p. 1120, Mar. 2020. [Online]. Available: https://www.mdpi.com/1996-1073/13/5/1120
[122] Y. Fang, K. Jia, Z. Yang, Y. Li, and T. Bi, "Impact of inverter-interfaced renewable energy generators on distance protection and an improved scheme," *IEEE Trans. Ind. Electron.*, vol. 66, no. 9, pp. 7078–7088, Sep. 2019, doi: 10.1109/TIE.2018.2873521.
[123] F. Harrou, B. Taghezouit, and Y. Sun, "Robust and flexible strategy for fault detection in grid-connected photovoltaic systems," *Energy Convers. Manage.*, vol. 180, pp. 1153–1166, Jan. 2019, doi: 10.1016/j.enconman.2018.11.022.
[124] D. S. Kumar, D. Srinivasan, and T. Reindl, "A fast and scalable protection scheme for distribution networks with distributed generation," *IEEE Trans. Power Del.*, vol. 31, no. 1, pp. 67–75, Feb. 2016, doi: 10.1109/TPWRD.2015.2464107.
[125] C. Pavlatos and V. Vita, "Linguistic representation of power system signals," in *Electricity Distribution*. Berlin, Germany: Springer, 2016, pp. 285–295.
[126] T. Suman, O. P. Mahela, and S. R. Ola, "Detection of transmission line faults in the presence of solar PV generation using discrete wavelet," in *Proc. IEEE 7th Power India Int. Conf. (PIICON)*, Nov. 2016, pp. 1–6, doi: 10.1109/POWERI.2016.8077203.
[127] P. K. Ray, A. Mohanty, B. K. Panigrahi, and P. K. Rout, "Modified wavelet transform based fault analysis in a solar photovoltaic system," *Optik*, vol. 168, pp. 754–763, Sep. 2018, doi: 10.1016/j.ijleo.2018.03.131.
[128] S. R. Ola, A. Saraswat, S. K. Goyal, S. K. Jhajharia, B. Khan, O. P. Mahela, H. H. Alhelou, and P. Siano, "A protection scheme for a power system with solar energy penetration," *Appl. Sci.*, vol. 10, no. 4, p. 1516, Feb. 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/4/1516
[129] P. Khandare, S. Deokar, and A. Dixit, "Relay coordination and optimization techniques using DWT-differentiation algorithms for fault detection in microgrid," *AIMS Energy*, vol. 8, no. 4, pp. 563–579, 2020.
[130] M. Abdel-Salam, R. Kamel, K. Sayed, and M. Khalaf, "Design and implementation of a multifunction DSP-based-numerical relay," *Electr. Power Syst. Res.*, vol. 143, pp. 32–43, Feb. 2017.
[131] T. Keil and J. Jager, "Advanced coordination method for overcurrent protection relays using nonstandard tripping characteristics," *IEEE Trans. Power Del.*, vol. 23, no. 1, pp. 52–57, Jan. 2008, doi: 10.1109/TPWRD.2007.905337.
[132] M. Ojaghi and R. Ghahremani, "Piece–wise linear characteristic for coordinating numerical overcurrent relays," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 145–151, Feb. 2017, doi: 10.1109/TPWRD.2016.2578324.

[133] O. A. Soria, A. C. Enríquez, and L. A. T. Guajardo, "Overcurrent relay with unconventional curves and its application in industrial power systems," *Electr. Power Syst. Res.*, vol. 110, pp. 113–121, May 2014.
[134] N. El-Naily, S. M. Saad, T. Hussein, and F. A. Mohamed, "A novel constraint and non-standard characteristics for optimal over-current relays coordination to enhance microgrid protection scheme," *IET Gener., Transmiss. Distrib.*, vol. 13, no. 6, pp. 780–793, Mar. 2019, doi: 10.1049/iet-gtd.2018.5021.
[135] S. M. Saad, N. El-Naily, and F. A. Mohamed, "A new constraint considering maximum PSM of industrial over-current relays to enhance the performance of the optimization techniques for microgrid protection schemes," *Sustain. Cities Soc.*, vol. 44, pp. 445–457, Jan. 2019, doi: 10.1016/j.scs.2018.09.030.
[136] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, "Optimal coordination of directional overcurrent relays using a new time–current–voltage characteristic," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 537–544, Apr. 2015, doi: 10.1109/TPWRD.2014.2341666.
[137] K. A. Saleh, M. S. El Moursi, and H. H. Zeineldin, "A new protection scheme considering fault ride through requirements for transmission level interconnected wind parks," *IEEE Trans. Ind. Informat.*, vol. 11, no. 6, pp. 1324–1333, Dec. 2015, doi: 10.1109/TII.2015.2479583.
[138] S. Jamali and H. Borhani-Bahabadi, "Non-communication protection method for meshed and radial distribution networks with synchronous-based DG," *Int. J. Electr. Power Energy Syst.*, vol. 93, pp. 468–478, Dec. 2017, doi: 10.1016/j.ijepes.2017.06.019.
[139] S. Jamali and H. Borhani-Bahabadi, "Self-adaptive relaying scheme of reclosers for fuse saving in distribution networks with DG," *Int. J. Power Energy Res.*, vol. 1, no. 1, Apr. 2017.
[140] S. Jamali and H. Borhani-Bahabadi, "Recloser time–current–voltage characteristic for fuse saving in distribution networks with DG," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 1, pp. 272–279, Jan. 2017, doi: 10.1049/iet-gtd.2016.0979.
[141] H. A. Abdel-Ghany, A. M. Azmy, N. I. Elkalashy, and E. M. Rashad, "Optimizing DG penetration in distribution networks concerning protection schemes and technical impact," *Electr. Power Syst. Res.*, vol. 128, pp. 113–122, Nov. 2015.
[142] W. Huang, T. Nengling, X. Zheng, C. Fan, X. Yang, and B. J. Kirby, "An impedance protection scheme for feeders of active distribution networks," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1591–1602, Aug. 2014.
[143] A. Yazdaninejadi, S. Golshannavaz, D. Nazarpour, S. Teimourzadeh, and F. Aminifar, "Dual-setting directional overcurrent relays for protecting automated distribution networks," *IEEE Trans. Ind. Informat.*, vol. 15, no. 2, pp. 730–740, Feb. 2019, doi: 10.1109/TII.2018.2821175.
[144] Y. Damchi, J. Sadeh, and H. R. Mashhadi, "Optimal coordination of distance and overcurrent relays considering a non-standard tripping characteristic for distance relays," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 6, pp. 1448–1457, Apr. 2016, doi: 10.1049/iet-gtd.2015.1087.
[145] M. Singh, V. Telukunta, and S. G. Srivani, "Enhanced real time coordination of distance and user defined over current relays," *Int. J. Electr. Power Energy Syst.*, vol. 98, pp. 430–441, Jun. 2018, doi: 10.1016/j.ijepes.2017.12.018.
[146] A. Yazdaninejadi, V. Talavat, and S. Golshannavaz, "A dynamic objective function for communication-based relaying: Increasing the controllability of relays settings considering N-1 contingencies," *Int. J. Electr. Power Energy Syst.*, vol. 116, Mar. 2020, Art. no. 105555, doi: 10.1016/j.ijepes.2019.105555.
[147] M. N. Alam, "Overcurrent protection of AC microgrids using mixed characteristic curves of relays," *Comput. Electr. Eng.*, vol. 74, pp. 74–88, Mar. 2019, doi: 10.1016/j.compeleceng.2019.01.003.
[148] A. Yazdaninejadi, M. S. Naderi, G. B. Gharehpetian, and V. Talavat, "Protection coordination of directional overcurrent relays: New time current characteristic and objective function," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 1, pp. 190–199, Jan. 2018, doi: 10.1049/iet-gtd.2017.0574.
[149] E. Sorrentino, "Nontraditional relay curves for the coordination of the ground overcurrent function with downstream fuses," *IEEE Trans. Power Del.*, vol. 29, no. 3, pp. 1284–1291, Jun. 2014, doi: 10.1109/TPWRD.2013.2288134.
[150] A. Yazdaninejadi and S. Golshannavaz, "Robust protection for active distribution networks with islanding capability: An innovative and simple cost-effective logic for increasing fault currents virtually," *Int. J. Electr. Power Energy Syst.*, vol. 118, Jun. 2020, Art. no. 105773, doi: 10.1016/j.ijepes.2019.105773.
[151] A. Kalam, K. R. Niazi, A. Soni, S. A. Siddiqui, and A. Mundra, *Intelligent Computing Techniques for Smart Energy Systems: Proceedings of ICTSES 2018*. Cham, Switzerland: Springer, 2019.
[152] A. Swarnkar and A. Swarnkar, "Artificial intelligence based optimization techniques: A review," in *Intelligent Computing Techniques for Smart Energy Systems*. Singapore: Springer, pp. 95–103.
[153] P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Optimum coordination of overcurrent relay timing using simplex method," *Electr. Power Compon. Syst.*, vol. 38, no. 10, pp. 1175–1193, Jul. 2010, doi: 10.1080/15325001003652900.
[154] M. Singh, B. K. Panigrahi, and A. R. Abhyankar, "Optimal overcurrent relay coordination in distribution system," in *Proc. Int. Conf. Energy, Autom. Signal*, Dec. 2011, pp. 1–6.
[155] A. S. Noghabi, H. R. Mashhadi, and J. Sadeh, "Optimal coordination of directional overcurrent relays considering different network topologies using interval linear programming," *IEEE Trans. Power Del.*, vol. 25, no. 3, pp. 1348–1354, Jul. 2010.
[156] M. Singh, "Protection coordination in distribution systems with and without distributed energy resources- a review," *Protection Control Modern Power Syst.*, vol. 2, no. 1, p. 27, Dec. 2017, doi: 10.1186/s41601-017-0061-1.
[157] 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, doi: 10.1109/TPWRD.2005.861325.
[158] J. Ehrenberger and J. Švec, "Protection settings optimization in distributed generation system," in *Proc. IEEE Int. Energy Conf. (ENERGYCON)*, Apr. 2016, pp. 1–6, doi: 10.1109/ENERGYCON.2016.7514109.
[159] H. R. E. H. Bouchekara, M. Zellagui, and M. A. Abido, "Optimal coordination of directional overcurrent relays using a modified electromagnetic field optimization algorithm," *Appl. Soft Comput.*, vol. 54, pp. 267–283, May 2017.
[160] M. N. Alam, B. Das, and V. Pant, "An interior point method based protection coordination scheme for directional overcurrent relays in meshed networks," *Int. J. Electr. Power Energy Syst.*, vol. 81, pp. 153–164, Oct. 2016, doi: 10.1016/j.ijepes.2016.02.012.
[161] V. Chakor and V. Aranke, "A review on impact of distributed generation on directional overcurrent relay coordination," *IOSR J. Electr. Electron. Eng.*, pp. 44–49, 2017.
[162] H. H. Zeineldin, E. F. El-Saadany, and M. M. A. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," *Electr. Power Syst. Res.*, vol. 76, no. 11, pp. 988–995, Jul. 2006.
[163] A. I. Atteya, A. M. El Zonkoly, and H. A. Ashour, "Adaptive protection scheme for optimally coordinated relay setting using modified PSO algorithm," *J. Power Technol.*, vol. 97, no. 5, pp. 463–469, 2017.
[164] A. Y. Hatata and A. Lafi, "Ant lion optimizer for optimal coordination of DOC relays in distribution systems containing DGs," *IEEE Access*, vol. 6, pp. 72241–72252, 2018.
[165] R. Thangaraj, M. Pant, and K. Deep, "Optimal coordination of overcurrent relays using modified differential evolution algorithms," *Eng. Appl. Artif. Intell.*, vol. 23, no. 5, pp. 820–829, Aug. 2010.
[166] F. A. Albasri, A. R. Alroomi, and J. H. Talaq, "Optimal coordination of directional overcurrent relays using biogeography-based optimization algorithms," *IEEE Trans. Power Del.*, vol. 30, no. 4, pp. 1810–1820, Aug. 2015, doi: 10.1109/TPWRD.2015.2406114.
[167] K. A. Saleh, H. H. Zeineldin, and E. F. El-Saadany, "Optimal protection coordination for microgrids considering N–1 contingency," *IEEE Trans. Ind. Informat.*, vol. 13, no. 5, pp. 2270–2278, Oct. 2017, doi: 10.1109/TII.2017.2682101.
[168] V. N. Rajput and K. S. Pandya, "A hybrid improved harmony search algorithm-nonlinear programming approach for optimal coordination of directional overcurrent relays including characteristic selection," *Int. J. Power Energy Convers.*, vol. 9, no. 3, pp. 228–253, 2018, doi: 10.1504/IJPEC.2018.092688.
[169] M. Shabani and A. Karimi, "A robust approach for coordination of directional overcurrent relays in active radial and meshed distribution networks considering uncertainties," *Int. Trans. Electr. Energy Syst.*, vol. 28, no. 5, p. e2532, May 2018, doi: 10.1002/etep.2532.
[170] A. Darabi, M. Bagheri, and G. B. Gharehpetian, "Highly sensitive microgrid protection using overcurrent relays with a novel relay characteristic," *IET Renew. Power Gener.*, vol. 14, no. 7, pp. 1201–1209, May 2020, doi: 10.1049/iet-rpg.2019.0793.
[171] A. Darabi, M. Bagheri, and G. B. Gharehpetian, "Highly accurate directional overcurrent coordination via combination of Rosen's gradient projection–complex method with GA-PSO algorithm," *IEEE Syst. J.*, vol. 14, no. 1, pp. 1171–1182, Mar. 2020, doi: 10.1109/JSYST.2019.2904383.

[172] N. Rezaei and M.-R. Haghifam, "Protection scheme for a distribution system with distributed generation using neural networks," *Int. J. Electr. Power Energy Syst.*, vol. 30, no. 4, pp. 235–241, May 2008, doi: 10.1016/j.ijepes.2007.07.006.

[173] S. Karupiah, M. Hussain, I. Musirin, and S. Rahim, "Prediction of overcurrent relay miscoordination time using urtificial neural network," *Indonesian J. Electr. Eng. Comput. Sci.*, vol. 14, no. 1, pp. 319–326, 2019.

[174] N. El Naily, S. M. Saad, T. Hussein, and F. A. Mohamed, "Minimizing the impact of distributed generation of a weak distribution network with an artificial intelligence technique," *Appl. Sol. Energy*, vol. 53, no. 2, pp. 109–122, Apr. 2017, doi: 10.3103/S0003701X17020128.

[175] O. Emmanuel, M. L. Othman, H. Hizam, N. Rezaei, and M. M. Othman, "Time-current characteristic curve prediction for directional overcurrent relays in interconnected network using artificial neural network," *ARPN J. Eng. Appl. Sci*, vol. 10, no. 1, pp. 10679–10685, 2015.

[176] D. S. Kumar and D. Srinivasan, "A numerical protection strategy for medium-voltage distribution systems," in *Proc. IEEE Innov. Smart Grid Technol. Asia (ISGT Asia)*, May 2018, pp. 1056–1061, doi: 10.1109/ISGT-Asia.2018.8467835.

[177] D. O. Anggriawan, E. Prasetyono, F. Fahrisi, A. Budikarso, A. Tjahjono, and H. R. P. Rogonondo, "Digital overcurrent relay implementation with non-standard inverse curve modelling using adaptive neuro fuzzy inference system," in *Proc. Int. Conf. Artif. Intell. Inf. Technol. (ICAIIT)*, Mar. 2019, pp. 327–330, doi: 10.1109/ICAIIT.2019.8834549.

[178] M. J. Daryani, A. E. Karkevandi, and O. Usta, "A hybrid approach for microgrid protection system based on neural network and fuzzy logic," in *Proc. IEEE PES Innov. Smart Grid Technol. Eur. (ISGT-Europe)*, Sep./Oct. 2019, pp. 1–5, doi: 10.1109/ISGTEurope.2019.8905476.

[179] H. Sadeghi, "A novel method for adaptive distance protection of transmission line connected to wind farms," *Int. J. Electr. Power Energy Syst.*, vol. 43, no. 1, pp. 1376–1382, Dec. 2012.

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

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