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AC microgrid protection – A review: Current and future prospective

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HIGHLIGHTS

- Advancing the state-of-the-art microgrid protection research.
- A critical review on AC microgrid protection issues.
- A critical review on AC microgrid protection challenges.
- A critical review on AC microgrid protective solutions.
- A critical Discussion on open research issues and recommendation for future scope.

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ABSTRACT

Microgrid is an important component of the evolving smart-grid. It has the ability to increase reliability, decrease costs, and enlarge penetration rates for distribution generation systems. However, the protection coordination may get badly affected due to the bi-directional/variable power flow associated with microgrid system and increasing penetration rates of distributed energy resources. Therefore, a proper protection strategy is highly required to decrease the complexities associated with microgrid system. In this paper, a widespread literature review on the current research and progression in the field of AC-microgrid protection is presented. The prime objective of this survey is to extend the researcher's database comprising relevant reference points which could be highly beneficial to their future research work. This work comprises of the current status, major hitches and existing research efforts focussed in the direction of providing a smooth relaying system under diverse MG operating conditions. Moreover, the work concentrates on analysing the intelligent approaches/devices that help transform the present protection schemes to become smarter.

1. Introduction

The concept of Smart-grid brings about a fresh dimension to the electrical power system. The availability of floods of information along with bi-directional energy flow makes the operation, control, and protection of the present-day power system more challenging. A smart-grid can essentially be viewed as a conglomeration of microgrids and distributed generators impregnated in a conventional grid. Smart-grids have many unique physical characteristics [1,2] such as self-healing, customer approachable, resilient towards physical and cyber-attacks, facilitates optimized asset utilization, environmental friendly, healthy communication channel backup, improved efficacy, dependability and security of power distribution and usage [3,4].

The word "microgrid" has been described in several reports based on diversified viewpoints [5,6]. The Department of Energy (DOE), United States defined the "microgrid" in the following manner [7]:

> "*A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. A remote microgrid is a variation of a microgrid that operates in islanded conditions.*"

Similarly, it was defined by the International Council on Large Electrical Systems (CIGRE) as [8]:

> "*Microgrids are electricity distribution systems containing loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads,) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.*"

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Microgrid is an important component of smart-grid. It is a smaller replica of the larger grid having all the components of the utility grid. While smart grids are large scale happening at the larger utility level, microgrids are smaller scale and can operate independently from the larger utility grid [1]. Microgrids can be treated as means to integrate distributed energy resources (DERs) to the low voltage (LV) networks at the customer's end and in the process; the customer becomes an active participant in the smart grid [9]. Thus, microgrids as a subset of the main grid offer various benefits, for example, better system efficiency, reduced cost, improved power quality and added system reliability [10]. Moreover, the microgrid can be treated as a resilient resource and play an important role in the development of a resilient electric power system (EPS). Therefore, the use of microgrids in EPS can be an advantageous solution for improving the resiliency of transmission and distribution networks. However, notwithstanding its immense advantages and almost indispensable as a technology to meet the growing requirement of non-fossil fuel-based eco-friendly power, it comes with its challenges in terms of implementation, operation, control and more specifically protection of the smart grid [11,12]. The DERs are also termed as micro sources. These micro sources could be sources providing AC or DC power outputs, such as Gas Turbines, Solar Power Plants, Wind Power Generator, Fuel Cell, Small hydroelectric power plant, Diesel generator, Combined Heat, and Power Sources, etc. Electrical Storage System (ESS) is another integral part of a microgrid that helps ensure reliable and stable power supply to the local loads in the concerned microgrid. Battery Packs, Supercapacitors, Flywheels, etc. are few forms of ESS which are generally employed in a microgrid.

A microgrid, which is essentially a power island that exchanges the power with the main grid while operating in grid-connected mode. It meets the power requirements of its local loads and the excess of power produced is exported to the main grid. In the case of a deficit in production, the microgrid imports the required power from the main grid. This need-based exchange of power between the microgrid and the utility not only calls for real-time load management but also makes the power flow within the smart-grid (SG) bidirectional in nature. In this context, it is noteworthy that the traditional power grid is a centralized generation, long-distance meshed transmission lines, and radial distribution network. The SG, on the other hand, is a distributed generation, a network of power islands meeting the local power load, with bidirectional power flow.

The foremost issue arising due to bidirectional power flow is that the existing protection schemes in force for the radial power system appear redundant. The DGs contributing to the fault currents result in unpredictable operating times of the existing protection devices (PDs) leading to loss of protection coordination [13]. Besides microgrids with DGs of different capacities and types will have fault currents of varied levels leading to further degradation of protection coordination. Protection issues such as 'Blinding' and 'Sympathetic Tripping' are the two major events that are expected to take place due to loss of protection coordination.

The topology of a microgrid and for that matter the microgrid embedded smart-grid is a dynamic one [14] for the reasons such as the introduction of new DGs or loads, islanding, fault conditions, scheduled or unscheduled maintenance of system devices, etc. This dynamism of topology of the microgrid, regardless of causes behind it, could impact current direction, its magnitude and subsequent miss-coordination of PDs.

A microgrid can be put to off-grid mode either intentionally as the plan may be or gets cut-off automatically/unintentionally due to fault in the main grid, an event known as islanding. This unintentional islanding also referred to as loss of mains (LOM) [15], may also take place due to malfunctioning of circuit breaker connected to the source. LOM is a situation where the microgrid gets disconnected from the source but it continues to power the loads within its zone causing a possible hazard to the utility workers unaware of the active islanded microgrid. Hence it is required that the DGs within the microgrid must be able to detect the islanding and get disconnected immediately, an action which is known as anti-islanding. The IEEE 1547 standards prescribe that the DGs must stop producing within 2 s of detection of an islanding condition. There are ample numbers of methods of islanding detection for the DG system cited in the literature. However, during microgrid islanding, these methods may result in a 'nuisance trip' causing islanding failure. Hence, the technical challenge lies here with configuring of anti-islanding for DGs within the microgrid along with the microgrid islanding detection. The technical challenge also lays with the need for minimization of transients during islanding and employment of appropriate islanding detection techniques in non-detection zones (NDZ).

It is imperative that in the grid-associated mode of operation, the fault current is of very high value as the fault gets feed by both the utility and the DGs within the microgrid. Whereas the fault current is of very limited value during the islanded mode as sources within the microgrid are low capacity DGs. As such in the case of inverter-based DGs, the fault currents are limited to a maximum of twice the rated current based upon the rating of the devices. This compromises the suitability of traditional overcurrent protection techniques. Thus, here the challenge lies in identifying protection schemes suitable for both the mode of operation of microgrids [16]. Another technical challenge that a microgrid faces resides in the availability of low-cost technologies for its safe and reliable operation, a concern rightly raised by the authors in [17].

In the event of a fault, the DGs in a distributed network (DN) are isolated immediately, as was the prevailing practice for quite a long time. However, with substantially increased DG penetration, the interruption of DGs amounts to a significant reduction of power supply which is unsuitable from the utility and customer viewpoint. In this context, the grid code mandates that the MG operation needs to be continuous even in the course of the fault occurrences. Most of the faults are temporary and of very short duration. Hence, the microgrids are expected to have the fault ride-through capability [18] and low voltage ride through (LVRT) capability [14] in a smart-grid scenario. The issues and challenges with a smart-microgrid can be summarised as follows [16,19]:

i. Unbalanced conditions in-between supply and load demand.
ii. Bi-directional energy flow.
iii. Low inertia leading to critical frequency abnormalities in islanding operation.
iv. Limited short circuit capacity may initiate a noticeable drop in MG fault level [6,20].
v. Scarcity of low-cost protective devices/technologies.

In this work, an attempt has been made to accumulate several articles including both review and full-length research articles highlighting issues related to AC microgrid protection viewpoints. Initially, the paper reviewed several review articles that are directly or indirectly related to the scope of this survey. The details of outcomes from this study are presented comprehensively with a critical analysis. Secondly, a brief discussion is given on the existing microgrid protection issues and their traditional protective solutions. The article also presents a wide survey and review of recent techniques proposed by various researchers to mitigate the effects of DG integration on distribution system protection performance. The implementation challenges of these techniques are discussed and proposals for the future are given. Thirdly, the article highlights the importance of artificial intelligence and computational intelligence on microgrid protection which have gained huge attention over the last few decades. It is already stated that fast islanding detection is one of the most vital areas of the microgrid protection field. Therefore, brief analyses of islanding detection techniques developed recently have been summarized in this article. Finally, the article concludes with some future recommendations for advancing the state-of-the-art MG protection system.

The methodology adopted for the proposed review work on AC microgrid protection is described as follows. The initial step of the work involves the task of collecting existing articles, which directly/indirectly related to the area of microgrid protection. The following websites are considered for the above-mentioned task like IEEE explorer, Science Direct, Wiley, Springer, MDPI, Scopus, and Web of Science. In the next step, the articles related to DC microgrid are excluded from the database with an intention to provide a fair and clean review for only AC microgrid protection. In the subsequent step, the remaining articles have been segregated into two distinct categories like review and research articles. Afterward, in section 2, a comprehensive review of the existing survey articles based on AC microgrid protections are carried out, and the gaps/shortcoming from these reviews are highlighted. In the next section i.e. Section 3, 4 and 5, a detailed analysis of the issues, challenges associated with AC microgrid protections and the available solutions are discussed in a comprehensive manner. In this section, the research articles from our collection databases are used as references with an exclusion criterion (i.e. articles published prior to a decade). In the subsequent section (Section 6), a critical analysis has been carried out along with several miscellaneous protection schemes and future scope. Finally, in section 7 the review work is completed with several concluding remarks.

2. Critical review on existing survey articles

This section provides a brief chronological literature review on survey articles published recently (within a decade) on microgrid protection perspective.

Huayllas et al. in 2010 presented state-of-the-art reviews on MG systems along with the hurdles that are encountered for their incorporation into the main grid. Here, the authors have agreed with the perspective reported in [18], where it was criticized the fact that ‘under present grid protocols, all DG systems must shut down during times of power outages; however, it is in this specific time when these onsite sources could offer their utmost value by delivering power services to locally connected loads’. The review presented by Basak et al. in 2012 [6] emphasizes the solution to two specific protection issues, viz; microgrid behavior during grid side fault and providing sufficient protection coordination when it operates in islanded mode.

The review presented by Bhaskara and Chowdhury in 2012 [20] stresses the need for an appropriate control system designed to ensure the operation of a smart grid under the four different modes as recognized by the IEEE Std. 1547.4-2011, namely: area EPS-connected mode, transition-to-island mode, islanded mode and reconnection mode. Moreover, four different major control architectures have been summarized, such as autonomous control architecture, hierarchical control architecture, agent-based control architecture, and neural network-based energy management systems. The review, however, makes cursory reference to various protection issues including the issues associated with MG service restoration and the available various multi-agent-based load restoration algorithms.

The study presented by Haron et al. in 2012 [21] highlights that a proper microgrid protection scheme has the onus of detecting the short-circuit occurrence and clearing the fault through the PDs, while protection coordination needs to confirm that the appropriate devices are initiated to cut off the faulty sections. The combined implementation of these procedures can ensure the effective operation of PDs in any DN. The review provides a classification of all microgrid protection strategies (MPSs) and the protection coordination methods accessible from the literature until the publication of it. The flow chart related to this study is shown in Fig. 1.

The review reported by Justo et al. in 2013 suggested that the settings of the protective equipment’ need to be updated depending on the mode of operation in view of different levels of fault current during different modes [22]. The microgrid central controller (MGCC) communicates with each connected PDs and the DG unit controllers, to log their ON & OFF status, rated and fault current contribution in order to update the relay setting and detection of fault current direction, which help in fault mitigation. The review identifies two different protection strategies. The first one as a decentralized protection scheme wherein each DG unit to have its own relay, an approach more effective for phase-to-phase faults. However, the approach is restricted to low impedance faults. The second one, which is a voltage based MPS that is centralized in nature. The phase voltages are transformed into d-q-0 axes and compared with reference voltage via MGCC fitted with the central protection unit (CPU). As soon as the change in voltage exceeds its pre-set threshold limit, the PDs are triggered to aptly isolate the faulted section. The schematic sketch of this type of protection arrangement is presented in Fig. 2.

Gupta et al. in 2013 [23] have reviewed the several previously published adaptive protection schemes (APS) and presented the technical challenges associated with them. The survey identifies all the usual concerns of the protection of an MG. It gives specific thrust on the need for a rapid and trustworthy communication system for the implementations of APS. The authors consider this as the foremost challenging issue in the process of designing effective MPS in the SG scenario. The prior knowledge of every state of the grid, the online monitoring and calculation of short circuit fault current level for every small change in grid configuration is needed for the reliable action of any APS. This necessitates the use of high-speed, consistent and robust communication systems with a backup so that the online relay setting can be achieved automatically. As a result, these additional adaptive features can increase the complexity and cost of the protection system. Mirsaeidi et al. in 2014 [24] presented a systematic literature review of the existing MPSs and its implementation challenges. The authors have classified the MPSs into adaptive, distance, differential, voltage, overcurrent and symmetrical current based schemes. Although the authors have presented the concept of each MPSs in a constructive way, a detailed comparative analysis of previously published work related to each MPSs was ignored in this survey. Choudhary et al. in 2014 [25] have presented a literature review on MPSs, where they classified the protection schemes into improved current protection methods and wide area protection (WAP) scheme.

The need for fault ride through keeping in requirement with grid code compliance has been cited as a technical challenge in the literature. The reactive power management during fault occurrences based on modern power electronic converter control can lessen the severity of the fault and helps the EPS to ride through the fault. The survey article presented by Beheshtaein et al. in 2015 provides a brief account of fault ride-through and LVRT capability of EPS in a smart grid scenario in accordance with the grid code requirements [26]. In [9], an extensive literature review on future distribution networks with DG integration has been done. The survey summarizes the adaptive protection schemes under the category of traditional and non-traditional (communication-based) methodologies. The non-traditional methodologies are further categorized into centralized control and distributed control.

Hare et al. in 2016 presented the report on the reviewed fault diagnostic methods in a very unique way [27]. It provides a detailed description of the fault universe (susceptible to all possible fault types) of various components of the microgrid along with their causes and effect. Further, the paper enumerates that all available fault diagnostic methods as depicted in various literature basically fall under two categories, namely, (i) model-based (MB) and (ii) data-driven based (DB). In model-based approaches generally, data from the real system is analyzed and compared with the output of a model of the healthy system to identify the system's health. On the other hand, purely data-driven approaches for fault diagnosis perform analysis of the experimental data measured from the real physical system. Both the fault diagnostic approaches are illustrated in Fig. 3. The paper also provides a classification of all fault diagnostic methods falling under these two categories of approaches. The review was done in [28] also depicts the same.

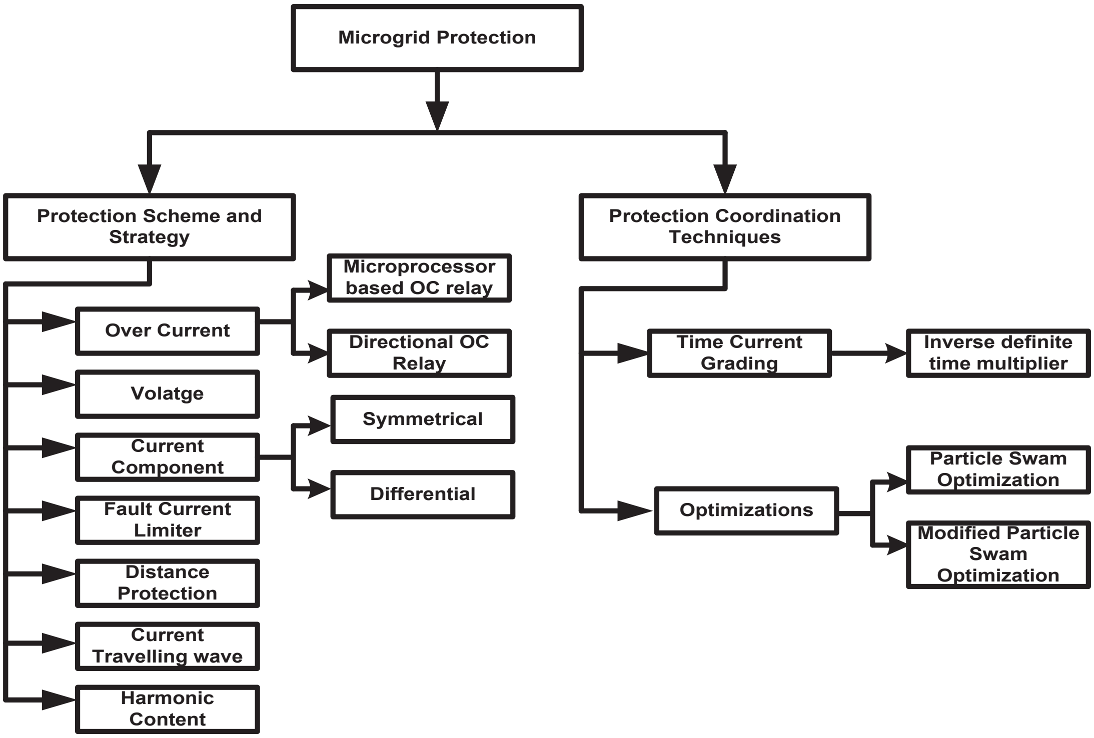

Fig.1. Protection schemes for microgrid operation.

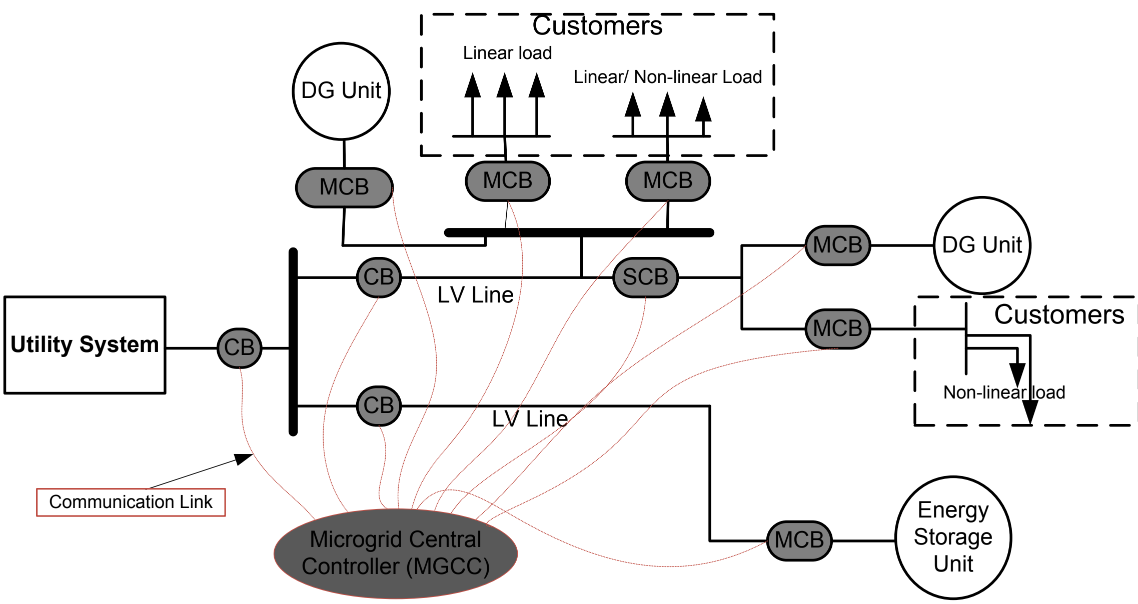

Fig. 2. Centralized protection system in AC microgrid system.

Brearley and Prabu [15] and Mirsaeidi et al. [24] have provided a detailed account of available microgrid protection schemes, and discussed in details about the pros and cons of each scheme. Authors [15] have additionally presented a classification of all such protection schemes as shown in Fig. 4. Researchers [24] at the same time have meticulously listed out the drawbacks of each protection schemes while pointing out the employability of centralized monitor and control through robust, reliable and resilient communication channel for designing an effective microgrid protection scheme. The design of effective adaptive protection, differential protection, voltage based protection, over-current and symmetrical components based protection schemes, etc. invariably rely on communication links.

The review presented in [29] pointed out that based on different grounding configurations, microgrids may be of three types such as ungrounding, uni-grounding, and multi-grounding systems, and accordingly the operating principles of microgrid fault protection systems would differ. The authors view that there have been no references for specific applications of the existing AC microgrid protection systems [29,30] to the aforementioned microgrid topologies and hence provide a detailed review of the existing protection systems applicable to ungrounded low voltage AC microgrids [29]. The review presented in [30] provides a comprehensive literature survey on protection schemes available for uni-grounded AC microgrid systems.

Habib et al. in 2017 presented the outcome of their study related to the implementation challenges accompanied by the classical MPS [31]. One of the major challenges is to provide an adequate MPS for both

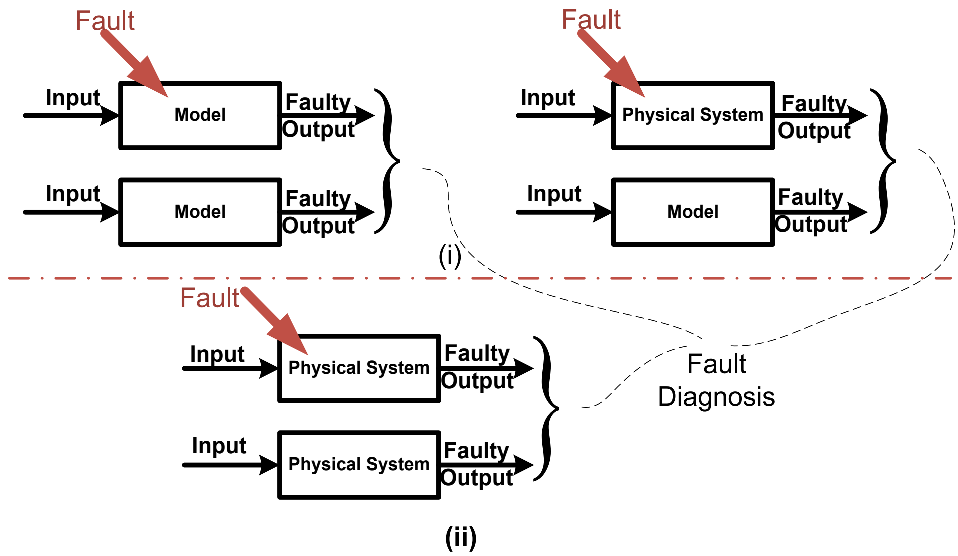

Fig. 3. Fault diagnosis approaches (i) Model Based methods (ii) Data-driven based methods.

grid-associated and grid-disconnected mode of MG operation [31]. One of the major challenges is to provide an adequate MPS for both grid-associated and grid-disconnected mode of MG operation. Moreover, the protection strategy necessitates a fast, dependable ad robust communication system during this mode transition. Additionally, the study reveals that the risk of the communication link and cybersecurity threats remains a challenging task for implementing a reliable adaptive protection scheme. Therefore, a contingency is highly necessary for the event like communication failure, to prevent the maloperation during the grid-connected and islanded mode of operation. In this regard, the authors in [31] proposed an adaptive MPS utilizing the energy storage devices to improve resiliency in contradiction of communication link

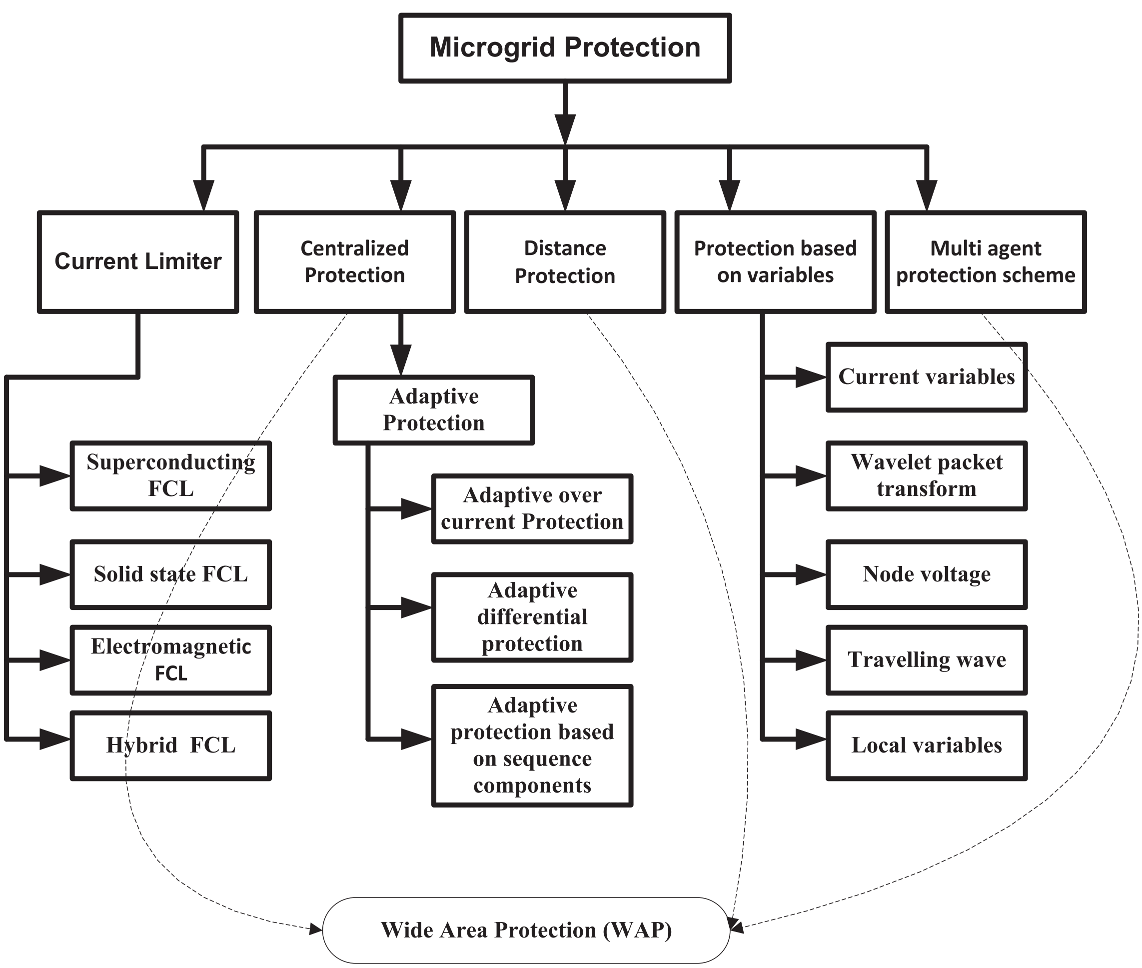

Fig. 4. Classification of microgrid protection schemes.

failure.

Barra et al. in 2020 presented a detailed review of adaptive protection based microgrid protection schemes available in the literature [32]. The main intention of the study was to provide a comprehensive review of adaptive microgrid protection. A bibliometric analysis was also presented in the study on adaptive microgrid protection. Singh and Bansal [33] presented an up-to-date study related to the area of optimization of micro sources based on the economic and reliability constraints. Sarangi et al. [34] and Mirsaeidi et al. [35] have elaborately studied the issues, challenges and protective solutions of hybrid AC/DC microgrid systems. Here, the authors have presented a well-organized survey related to both AC and DC microgrid protection issues and challenges. However, a detailed comparative analysis of previously published work with respect to the output performance, merits and demerits were overlooked in this survey.

Going through the review of all the survey articles published over the last decade it can be inferred that the conventional grid system has gone through a sea change in its topology, from a static one to a dynamic one. The generation of power is distributed with many consumers and end-users chipping in as power producers. The flow of power has become bi-directional. The operation, control, and management of power keeping in view reliability of power supply, stability of the EPS and safety of the PDs, consumer devices and the grid as a whole are becoming increasingly complicated and challenging. In this context power system protection is of utmost importance and the most challenging of all tasks in hand. The traditional protection techniques fall apart and are becoming redundant. The need is of an appropriate self-adaptive protection scheme which changes its settings as the configuration of the grid and the system state keeps on changing. The protection system is expected to detect, locate and mitigate the incipient faults in the system through an extensive communication system that collects data from numerous sensors in the EPS, analyze them in order to detect a possible fault condition, classify the nature of the fault and identify appropriate fault clearance mechanism. All these actions need to be done fast, within the time span less than a standard fault clearance time. Thus, the challenges lie in the processing of such a huge amount of data, a task which is humanly impossible can best be handled by application of Artificially Intelligent (AI) techniques. The review article presented by Miraftabzadeh et al. in 2019 listed out the application of various AI algorithms to short out issues related to various aspects of the present smart microgrid system; however, it does not identify much related to protection [36]. The authors in [37] review the literature on big-data and its usefulness in addressing issues in a SG, again not specific to protection challenges. It can be inferred that there is a very limited literature review on the application of AI in microgrid protection schemes. Thus, in this study, an attempt is made to review each and every smart grid protection issue, available protection techniques and application of AI to make the protection techniques self-adaptive and smarter.

3. Microgrid protection issues and challenges

Before delving into the details of protection solutions, a brief recount of the situations that lead to the potential protection challenges in a microgrid is made here. Fig. 5 depicts a typical connection diagram, where the DGs are directly connected to the main utility grid with CB1 closed. The DGs along with the load is operating in grid-connected mode. When CB1 gets opened, either due to grid fault or deliberate action, the system structure that evolves is called as a microgrid. The operation of DGs in an intentionally islanded mode is referred to as microgrid operation. Fig. 6 depicts an organized presentation of different issues/challenges accompanied by microgrid protection.

A microgrid in grid-connected mode brings in with it many benefits to the condition of the main grid, such as dependable backup during utility outages, enhanced reliability, reduction in voltage sags, energy saving through peak shaving, and dispensing with additional investment for utility expansion in order to meet the future power requirement. However, the microgrid technology comes with its own technical challenges, as discussed in various survey articles which are briefly accounted for in previous sections. The microgrid protection issues as is being discussed in this section can be listed out as follows:

3.1. During grid-connected mode

During the grid-connected mode of microgrid operation, the following are the major challenges in the aspect of microgrid protection.

- Increased fault currents level
- Blinding protection
- Sympathetic tripping
- Reduction in reach of distance relays
- Relay interoperability
- Proper standardizations
- Grid code compliance

The situation which leads to these issues needs deliberation and is provided here. A good protection system should essentially have these features: (i) Selectivity (only the faulty part or the most minimal part of the utility around the fault location should get isolated), (ii) Redundancy (redundant functionalities of relays need to be planned in a way as to act as backup protection), (iii) Grading of relays (to achieve higher redundancy without compromising selectivity), (iv) Security (avoidance of unnecessary disconnection of parts of the EPS due to short-circuit (SC) events or transients which does not qualify as a fault).

Fig. 7 shows a radial distribution feeder. It carries unidirectional current and the protection arrangement is very simple. A circuit breaker or recloser having instantaneous and time over-current protection element has been placed at the beginning of the radial feeder. The lateral feeders are provided with fuses having inverse-time over-current (OC) characteristics. Fig. 8 depicts the conventional time coordination between a CB, a recloser and lateral fuse for the said feeder. The PDs in series are time coordinated in such a way that the device nearest to the fault opens first to isolate the faulty section, allowing upstream PDs to continue to carry the usual load current.

An auto-recloser, in its fastest mode of operation, is ready to act ahead of the fuse, and therefore, doesn't allow a temporary fault to become a permanent one. This type of practice is known as fuse saving [38]. The CB at the head of the feeder provides overall backup protection as its characteristic curve lies above those of all others. Generally, for proper PD (relay) coordination, relay pickup current setting ($I_{pick\text{-}up}$) is fixed at 50% of the minimum line end phase-to-phase (LL) fault current (I_{LL}). Relay current setting of 125–200% of full load current (I_{load}) i.e. $I_{pick\text{-}up}$ greater than 125–200% of I_{load} prevents unnecessary tripping of the feeder under overload condition. An instantaneous element with a setting of 4–6 times the I_{load} or 125% of triple-line fault (I_{LLL}) at the first downstream PD is used to look after the system against severe disturbances [39,40]. However, such time coordination is lost, and system protection is severely affected when either the magnitude or the direction of the fault current through any of these PDs changes, which is the case that happens in the DG-infested DN system as shown in Fig. 8, an example of DG based distribution network [41,42]. Here, a distance relay (R) is installed at the end of bus 1 to protect against fault at sub-transmission line 1 (sub-TL1) and sub-TL2, with an additional back-up relay setting. The load feeder and collector feeders are equipped with encloser that comprises OC-phase and earth fault relays. The impact of DGs to the protection system and the consequences of relay discoordination are discussed one after another in the subsequent section [43].

3.1.1. Fault current level variation

A DG unit, either a synchronous generator or an induction generator or for that matter any other micro sources, when connected to the DN,

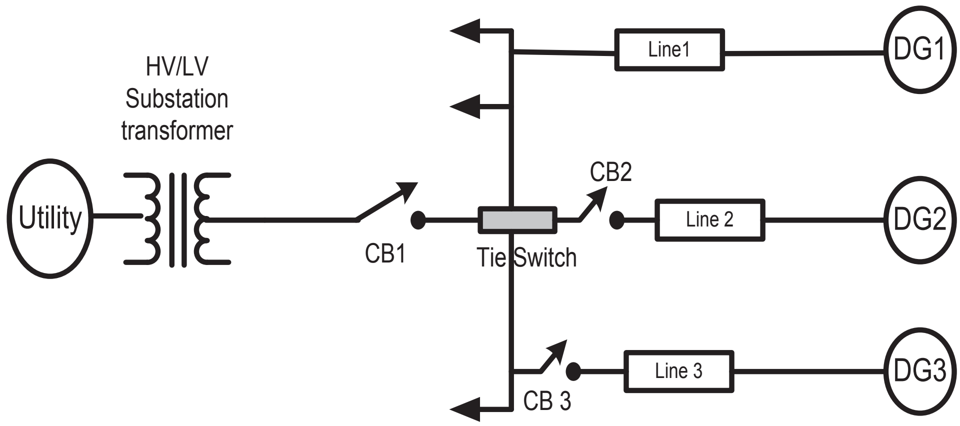

Fig. 5. A typical DG connections to a Distribution Network.

contributes to the fault current level [39]. The level of contribution by these DGs depends on the location, size, nature of interface with the grid, grid impedance, mode of operation (grid-connected/islanding) and network topology (mesh or redial) [44,45]. Let there be a fault detected at bus 9 in the system as in Fig. 8. The bus 9 is at downstream of PCC of DG1. Hence the total fault current at the fault location will be:

$$I_{FT} = I_{FG} + I_{FDG1} + I_{FDG2} \quad (1)$$

where, I_{FT}, I_{FG}, I_{FDG1} and I_{FDG2} are termed as the total fault current, fault current supplied from the utility, fault current supplied from DG1 and fault current supplied from DG2 respectively.

This substantial increase in fault current level will have two major negative impacts on system protection:

(i) It will disturb the fuse-fuse, fuse-recloser and relay-relay coordination [46].

(ii) All DNs are designed based upon a characteristic SC capacity. The PDs employed, are chosen based on this SC capacity. The increased fault current level due to DG contribution far exceeds this SC limit and thus will surpass the thermal and mechanical endurance limit of PDs endangering the network equipment.

3.1.2. Blinding protection

When the location of a DG is between the fault point and the feeding station, the fault current as experienced by upstream PDs may be of the decreased level. For example, if the fault location in the system shown in Fig. 8 is at downstream of PCC of DG1 with the grid, the recloser-2 will only have fault current contributions of utility and DG1 through it, which is less than the total fault current. In such cases, the upstream PDs may not respond in time (i.e. delayed tripping/reduction in the reach of relay/no tripping at all), a situation known as blinding protection [47,48]. Blinding protection generally happens at high impedance points [43,49].

3.1.3. Sympathetic tripping

Assuming a situation, wherein an event of a high resistive triple-line-ground fault at load feeder-2 initiates a high level of fault current contribution from DG1. In such a case, the recloser-3 may get into unnecessary operation. The protection scheme has thus lost its selectivity, unnecessarily isolating a healthy feeder or the connected DG units. This kind of scenario is known as sympathetic tripping.

3.1.4. Reach of distance relay

An impedance relay (also known as distance relay) is set to trigger for faults occurring within a maximum distance (or at a certain time). This value is known as its 'reach'. The distance of the relay location from the fault is calculated based on the fact that impedance is directly proportional to the length. In the event of a fault the measured impedance (Z), which is the ratio of the applied voltage to current at relay location, is less than the set impedance (Z_{set}), i.e. Z less than Z_{set}, the relay gets activated to clear the fault. However, in a DG connected system, the distance relay may not operate in its designated zone. As soon as, a fault occurs downstream of PCC of DG with the utility, the impedance measured by an upstream relay is superficially more than the real fault impedance. Consequently, the relay grading gets affected and they may not operate in their designated zones.

3.1.5. Choosing an appropriate interfacing transformer configuration

The three-phase transformer interconnection configuration and the grounding scheme chosen is very vital for DG connection to utility as it must be compatible with the grid in order to save the system from voltage swell and overvoltages. According to IEEE 1547 standard, the grounding scheme of the DG interconnection should not cause overvoltage that exceeds the rating of the equipment connected to the area EPS and should not dislodge the coordination of ground fault protection of the area EPS.

3.1.6. Reclosing

The job of an auto recloser is to restore the system after a very short interval fault, an act of utmost importance. However, in DG interfaced DNs, two major issues are witnessed in this regard [46,50].

(i) The auto-recloser's attempt may not be successful as a result of fault getting fed by the DGs.
(ii) Prior to reclosing, the utility and the microgrid (which is in islanded mode) make for two asynchronously operating systems, providing active power imbalance and frequency mismatch.

In such circumstances, any attempt to reclose the switch is akin to coupling two asynchronously operating systems. This may cause serious damage to DGs and also may give rise to voltage and current swells in the DN.

As such conventional reclosers are designed to reconnect the circuit only if the utility side is energized and the other side is passive. In the case of MGs, there are active sources on both sides of the recloser. The reclosing scheme needs to be planned by keeping these factors in mind.

3.1.7. Grid code compliance

The "*grid code*" is a technical code for connection and expansion of the National Electricity Transmission System. It defines the parameters that facilitate the integration of additional resources or new networks to the existing grid with an intention to meet the required consumer demand by ensuring safety, security and economic aspect. It is specified by an authority responsible for the system integrity and network operation. However, the timely elaboration in the grid code is highly necessitated concerning the high penetration rate of DERs. The main objective of an adjustment in the current grid code is to enhance the

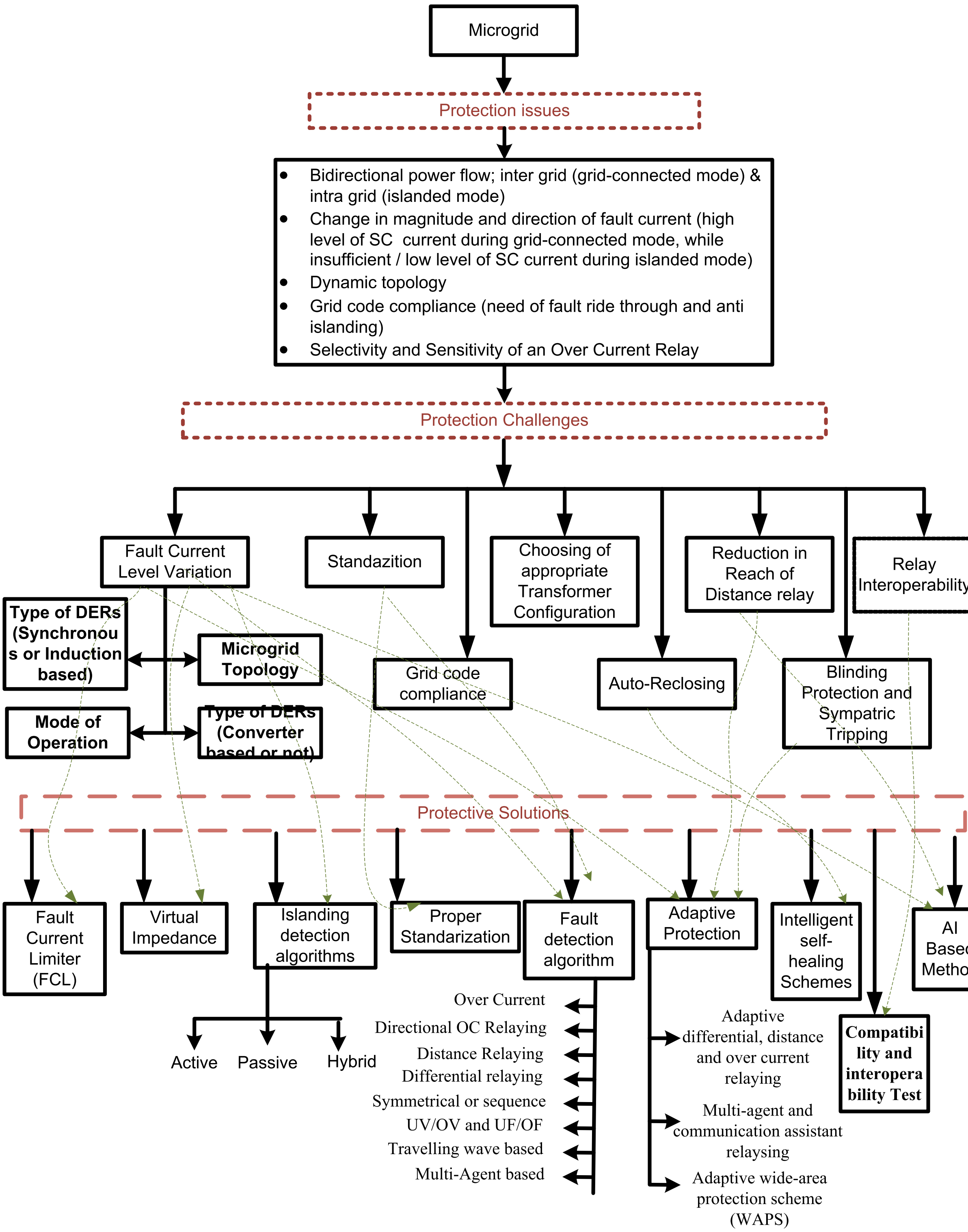

Fig. 6. Microgrid Protection issues, challenges and protective solutions.

stability of the utility grid [51]. The following is the examples related to the requirement towards the elaboration of grid codes: By connecting a wind-based DER to an electric network can increase its LVRT capability, that is, the facility of a generating plant to continue its service to the grid during voltage sags and to actively provide stability to an EPS by injecting reactive power until fault clearance. However, the injection of reactive power during fault occurrence may lead to endangering relays coordination [52]. Furthermore, DERs should satisfy the grid code requirements for protective relay coordination [53].

3.1.8. Standardization

The attention towards the design and placing of several Intelligent Electronic Devices (IEDs) has been increased with an intention to lessening the degree of complexity of the future grid. The IEDs are the devices that are added to an industrial control system to enable advanced power automation. Microprocessor-based voltage regulators, protective relays, CB controllers, etc. with the ability of serial communication with other devices are treated as IEDs. The developing power distribution grid comprises several IEDs in order to handle the

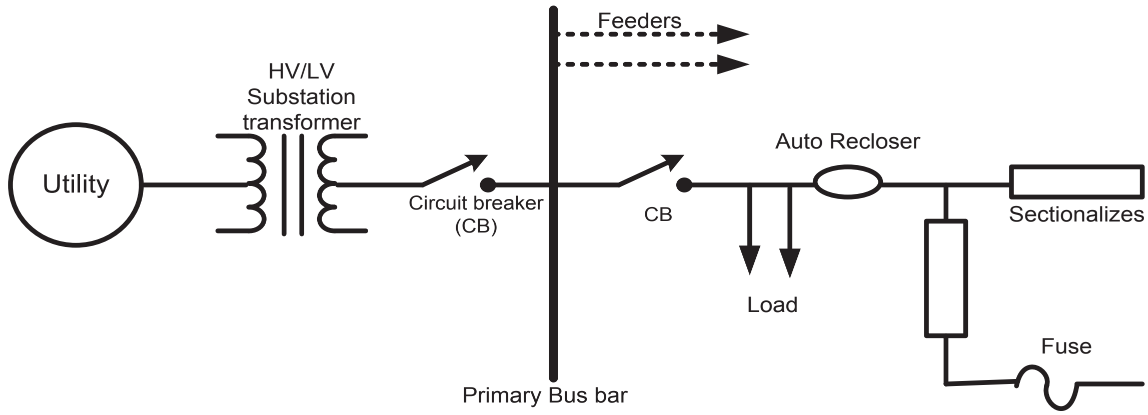

Fig. 7. Typical protection set-up for a simple radial feeder.

complexity of the future power grid. Therefore, a highly immune communication system needs to be developed to cope up with the protection and control challenges, particularly when they are applied to microgrids. Furthermore, this plug-and-play interaction of various components in the grids requires proper standardization regarding implementations.

3.1.9. Relay interoperability

The relay interoperability is one of the major challenges for smart-grid strategies. This issue is also important for digital relays [54]. Compatibility and interoperability are amongst the major driving forces overdue the creation of IEC 61850. These challenges generally address issues such as integration of advanced digital protective devices with classical/conventional systems, coordination of these devices in an effective manner aiming the future developments and limiting the cost to make the system more economical.

3.2. During islanded mode of operation

In contrast to the protection issues associated with a DG connected DN, as briefly discussed above, it would be interesting to observe the challenges involved in microgrid operation i.e. when the microgrid is operating as a stand-alone entity, what is referred as islanded-mode of operation.

"Islanding is a situation wherein a microgrid operates in off-grid i.e. *it operates independently having got dissociated from the main grid. This can happen intentionally in order to meet the peak demand, a very useful aspect of microgrid islanding concept. However, the incidence of intentional islanding is very limited. Islanding often happens unintentionally due to faults in the grid, substation failure, malfunction of equipment, etc."*

Occurrences of this unintentional islanding are very undesirable as they pose a potential threat to the power system. Some of these threat factors as follows:

(i) ominous fluctuation in voltage and frequency in the island that severely affects the connected loads and devices

(ii) Loss of coordination of PDs, leading to the risk of auto-reclosers completing the snapped circuit while the DGs in the islanded microgrid is still active and feeding power to the connected loads. As both the grid and island are out of synchronism with respect to each other, the reconnection at this moment gives rise to huge electro-mechanical forces that can damage the connected DGs. A reason why international standards, such as IEEE 1547 stipulates that the DGs must detect the development of an islanding condition and get disconnected within a time period of 2 s.

(iii) unintentional islanding causes safety hazards to the unaware utility personnel engaged in maintenance or repair works.

(iv) system reliability gets a serious setback due to transient overvoltage during islanding.

The micro sources and energy source devices that essentially form the soul of a microgrid need to be interfaced with the grid and the PCC

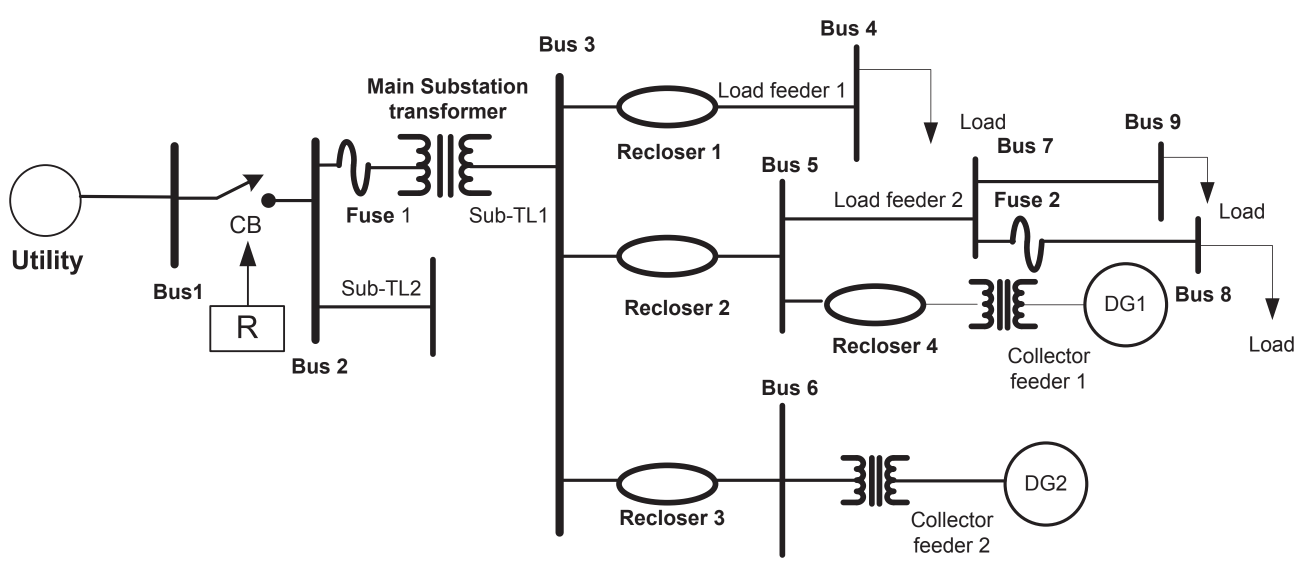

Fig. 8. the conventional time coordination between a CB, a recloser and lateral fuse for the distribution network comprising DGs.

within the microgrid by appropriate PE devices i.e., converters. During islanded mode of operation, the DGs being the only sources of contributors to the fault currents within the ambit of an MG, the fault current level is very low in comparison to the same during the grid-connected mode. The situation is not helped by the fact that these converters have in-built current limitations. Mostly the contribution of converter interfaced DGs to fault current is limited to twice the load current. In such a situation some OC relay may not respond or some may have delayed response to this low level of current. Faults remain undetected leading to high voltage and prolonged presence of these leads to system equipment damage. Besides as the maximum fault current level is limited, the fault level along the feeder will be almost constant. Hence, traditional current-based device discrimination strategies do not work.

The microgrid in islanded mode is a replica of a DN with DGs located at various places with respect to loads. Hence there is variation in magnitude and direction of SC current as well. Fluctuation in generation, continuous change in network topology and aperiodic load variation adds to the woe. All these circumstances are needless to say lead to relay coordination problems.

In short, while issues in grid-connected microgrids are due to high level of variable and bidirectional SC current flow, low level of variable and bidirectional SC current flow accounts for the protection issues in the islanded mode of operation in an MG. Hence the protection strategies adopted for one mode of MG operation will not hold good for the other mode. On this note, it is imperative that the detection of islanding conditions is highly essential thus inviting the need for effective islanding detection methods (IDMs). At the same time, it is also realized that a false alarm by these IDMs to grid faults of not so significant magnitude and/or duration, may lead to unnecessary system disturbance. In short, the microgrids must avoid islanding and should have fault ride-through capability. Hence the IDMs to be employed are required to be highly accurate, reliable, dependable and fast-acting techniques.

4. Microgrid protective solutions

An appropriate protective system is one of the most important elements of microgrid operation with respect to security, reliability and stability viewpoint. However, the traditional/conventional protective systems may be insufficient or incapable to protect the microgrid effectively due to the impact of DGs and their connection topology. Several microgrid protection issues and challenges were already highlighted in section 4. These issues/challenges must be dealt with the state when the utility-grid encounters abnormal conditions. In these abnormal conditions, there are two most specific kinds of problem which required proper attention. One is the characteristic of microgrids during the occurrence of a fault on the grid side and later, offering adequate protection coordination when it operates in islanded mode [55]. The protection coordination should ensure the rapid isolation of faulty feeder as well as islanding the microgrid from one another during the occurrence of a fault. Moreover, intelligent protective relays are demanded to be located cleverly all over the grid as well as the control circuit to trip these relays in time. Consortium for Electric Reliability Technology Solutions (CERTS) recommended essential guidelines and viewpoints on the operation of a microgrid in abnormal conditions owing to the incidence of short circuit fault [56,57].

In section 3, several discussions have been made about the previously published work on microgrid protection schemes. Fig. 1, Fig. 4 and Fig. 5 depict a few structures/classifications of MPS suggested by the authors presented in [6,27], and [15] respectively. In contracts to this, this paper proposed a more simple and unique architecture/flowchart regarding the classification of MPS based on the possible solutions related to the above-mentioned issues and challenges. The proposed architecture of MPS types is detailed in Fig. 6.

4.1. Fault current limiter (FCL)

As stated by the LVRT or UVRT capability, the DERs should remain connected during the fault periods. In this condition, the FCLs are treated as one of the existing solutions to limit the faults [55,56]. The FCLs are the devices that are used for limiting the fault current during the fault in the transmission network without complete disconnections [57,58]. It may be superconducting [59], inductive or solid-state devices [60,61].

4.2. Virtual impedance

Virtual impedance (VI) has been suggested for several reasons, such as improving system stability, improving damping, mitigating the effect of uneven or resistive line impedances, and current limiting [62,63]. In the case of fault occurrences in the microgrid system, VI is one of the corrective measures to limit the fault currents [64,65]. Here, the VI is used to reduce the voltage reference to limit the current [66,67]. Initially, Vilathgamuwa et al. [68] suggested the VI for current limiting. A detailed analysis of virtual impedance including design and implementation viewpoints for converter interfaced DERs system can be accessed from [67].

4.3. Proper standardization

The plug-and-play interaction of various components in the grid requires proper standardization regarding implementation. Table 1 presents several core-standards for the realization of the smart grid suggested by international electrotechnical commission (IEC) [69].

The modelling of the system's elements and information exchange between IEDs has been standardized through the standard IEC 61850. The variants of IEC 61850 standard such as IEC 61850-7-420 and 61850-90-7 were designed later to provide some added features to a primary standard such as power system modelling and communication of distributed energy resources from diverse vendors. Ustun et al. [70] presented the modelling of a MG protection system with logical nodes provided in IEC61850 and IEC61850-7-420 communication standards. The IEC 61499 standard was suggested to simulate the dispersed industrial-process measurement and control systems. The architecture of the IEC 61499 standard is based on function blocks (FBs) summarising functionalities, behaviours, and their signal interconnection. These FBs could combine together to constitute a complex and hierarchical system description. The use of FBs facilitates the implementation of the control system [71]. It is already stated that a proper MPS must be comprised of proper communication links, control system, and intelligent management center. Accordingly, a capable standard essentially covers both communications, modelling and distributed control. The combination of IEC 61850 and IEC 61499 standards could meet the above-mentioned necessities [71,72]. Additionally, IEC 61850 and IEC 61499 can be sourced for the objectives of MG control and monitoring functions. Andrei et al. [73] presented brief descriptions of IEC 61850 and ANSI standards designed for the communication of IEDs in distribution systems.

Table 1
the core standards suggested by IEC.

Standard	Intended for
IEC 61850 IEC 61499	Power utility automation (Both control and monitoring function)
IEC_ 61970/61968	Common Information Model (CIM) for energy and distribution management
IEC TR 62357	service-oriented architecture
IEC 62351	security
IEC 62056	data exchange for meters
IEC 61508	functional safety

4.4. Intelligent self-healing scheme

The smart-grid based power distribution systems have several added features compared to conventional power distribution systems, such as high reliability, self-healing action, self-sufficiency, and interactive characteristics. Self-healing is one of the most important features of smart-grid, which deals with the flexibility and fast recovery of the EPS in response to the faulty conditions [74,75]. 'Self-healing' typically talks about protective actions or to manage faulty events just after their occurrence. Generally, the self-healing action is accomplished in two phases [76]. In the initial stage, detection and localization of fault conditions are carried out followed by an emergency reaction to minimize its effect on the healthy system. In the next phase, several further actions are taken out for improving the system conditions such as system reconfiguration, load shedding or controlling dispatchable generators' output powers [77]. Fuzzy system based [78], multi-agent system (MAS) [79,80], graph theoretic-based and heuristic search [81] are few examples of self-healing approaches available in literature which explain the complexity of restoration in EPS. Conversely, the restoration task is highly challenging in microgrid environment owing to the following issues: bidirectional power flow, mesh configuration topologies, and limited capabilities of DERs [81,82].

4.5. Compatibility and interoperability test

It is already stated that the Compatibility and Interoperability (C&I) are amongst the major driving forces overdue the creation of the IEC 61850 standard. The C&I assignment of all digital and intelligent protective systems necessitates a couple of tests, such as conformance and performance test. The standard IEC 61850-10 provides direction for the conformance test [83]. The conformance test is the initial step to validate the interoperability. The performance test as compared to the conformance test provides more extensive evaluation and is used to define the performance characteristics of the overall system [84]. The literature related to performance testing of the protective system can be explored from the references [85,86]. Moreover, Zhang et al. [54] presented a methodology of the C&I test for the all-digital protective system.

4.6. Microgrid fault detections

In an old-fashioned power distribution system, the protective systems are planned with an assumption of unidirectional energy flow and are typically based on OC relays with discriminating abilities. As stated by IEEE (2003) for any fault condition, DERs associated with the system are tripped off. In other words, islanded conditions of DERs are not acceptable. When the microgrid term is associated with a distribution network, then the network becomes a multi-source power distribution system. The philosophy of the microgrid protection scheme (MPS) must ensure the safe and secure operation of the sub-system in both the mode of the operation, i.e. grid-connected and autonomous mode of operation [87]. Table 2 depicts a summary of different existing MPS in details. To design a MPS that uniformly operates for both grid-connected and islanding modes of operation, the following features must be taken into the account [21,88].

- The MPS should able to act in response to both distribution grid side fault and microgrid fault.
- If the fault occurs within the microgrid, the MPS should be able to isolate the least likely segment of the radial feeder bearing the fault current to throw away the fault.
- The designed MPS must certify an effective operation of consumer's utensils.
- The designed MPS must have high selectivity for isolating the faulty sections. Moreover, the protection system should be able to operate selectively during various faults to disconnect the faulted section. The sensitivity of the relays is essentially adjusted such that the high redundancy can be achieved without disturbing the selectivity of the MPS.
- The protection scheme should have high dependability irrespective of the type of DERs (synchronous/induction based or rotating converter based), the topology of microgrid system (radial/mesh) and type of fault occurrence (low impedance or high impedance fault).
- The designed MPS should ensure a back-up protection which will respond to the failure of primary protection.

4.7. Islanding detection

The unintentional islanding is one of the most important protection issues of microgrid system. Failing to detect this condition i.e. unintentional islanding may cause several hazardous threats to the utility system as briefly described in section 4.2. Therefore, accurate and fast islanding detection plays a vital role/contribution to the grid by facilitating the application of adoptive MPSs and active management.

Usually, the islanding detection methods (IDMs) are categorized into two broad categories such as remote and local, based on the location of measurement of the parametric signals. The local detection methods are further sub-classified as passive, active and hybrid detection methods, based on the underlying principle and microgrid configuration [82]. With the shift in research trends in IDMs and the introduction of fast computational intelligence-based techniques, the classification of IDMs can be further expanded by juxtaposing the classification as in [153] with the third broad category of AI-based IDMs. The working principle of the remote IDMs is based on communication between the utility and distributed energy resources. On the occurrence of islanding, the trip signal is sent to the DGs. Local IDMs rely on recognizing the variations in the observed system parameters like voltage, current, frequency, phase angle, power, and harmonic distortion, etc. on the DG side. The introduction of perturbations into the system parameters and decision to island made based upon the level of impact of these perturbations is the underlying principle of operation of active IDMs. The measurable system parameters at the PCC or target DG terminals, such as voltage, current, frequency, harmonics, etc. are monitored and variations in these above a pre-set threshold value are considered as an islanding condition.

In hybrid IDMs, the passive and active IDMs are used in conjunction exploiting the strength of each other thereby serving more efficiently and effectively in complex systems. Generally, the passive system acts as a primary level while the active system acts as secondary. When the primary fails, the secondary system takes over to detect the islanding condition successfully. The use of signal processing (SP) based time–-frequency techniques to effectively investigate disturbances in power systems drew the attention of researchers and the same has been utilized for feature extraction and analysis of signals for islanding detection. These SP based techniques are mostly used to improve the effectiveness of passive techniques. In SP based islanding detection techniques, the desired features are extracted from the input signal and compared to a threshold value. Selection of appropriate threshold value is quite a tricky task as for a high value of threshold islanding will not get detected, while for a low value of threshold the DGs may get tripped even for minor disturbances. To overcome such an issue, artificial intelligent (AI) based methods like intelligent classifiers are integrated with passive IDM. The detailed analysis of the application of AI in the detection of islanding events is presented in the next section. The effectiveness of these IDMs can be gauged by some vital performance indices as presented in Table 3.

5. Adaptive microgrid protection

The sensitivity and selectivity issues faced by the traditional OC relays during the fault protection in microgrid environment due to different topology and mode of operation, turns the research trends

Table 2
Summary of different existing microgrid fault protection scheme.

Protection Scheme	Applications	Benefits	Drawbacks	Influenced by microgrid topology	Cost	Ref
Over Current	• Line protection (both T&D) • Generator protection	Simple and economical	• Needs supplementary study to differentiate short-circuit fault from other transient conditions. • Ineffective for islanding mode of operation.	Yes	Reasonable	[89–107]
Directional OC Relaying	• Line protection (both T&D lines) • Generator protection	The decent aspirant for the interconnecteddistribution system	• It has additional complex coordination process • Needs supplementary study to differentiate short-circuit fault from other transient conditions.	No	Expensive than OC relaying	[108–114]
Distance Relaying	• Line protection (both T&D) • Generator protection • Busbar protection	It is not influenced by source impedance variations	• High impedance fault (HIF), power swing, bidirectional power flow, and highly resistive fault can weaken the performance of the protection systems	Yes	Expensive thanOC relaying	[115–120]
Differential relaying	• Line protection (both T&D) • Generator protection • Busbar protection • Transformer protection	pretty simple, quickness, high sensitivity, inherent selectivity, immune to power swings andexternal fault and suitability for HIF detections	• error in current measurement and communication delay affect the performance • Not always effective especially when unbalanced microgrid and load are connected to the network which causes the zero and negative sequence current.	No	Very Expensive	[121–124]
Symmetrical or sequence components based	• Line protection (both T&D) • Generator protection • Transformer protection	The intended schemes have the ability to renovate their pickup setting in pursuit of any structural variation in microgrid, thus shielding microgrids against subsequent fault.	• The requirement of massive communication system, if it fails some point, jeopardizing the whole MPS, • inability to offer protection for mesh topology MGs.	Yes	Expensive	[125–131]
Voltage and frequency based (UV/OV and UF/OF)	• Islanding detection • Load shedding • satisfying LVRT requirements	The islanding detection method (IDM) usingUF/OF and UV/OV are less costly. It has no impact on power quality.	• IDM using UF/OF and UV/OV have large NDZ. • Proper thresholding is required.	No	Reasonable	[132–138]
Travelling wave based	• Transmission line protection. • Distribution line protection	It is highly suitable to detect and locate fault in the microgrid system.It shows an ultrafast response in fault detection and applicable microgrid zone protection.	• It requires high sampling rates to attain better resolution. • The method necessitates a low-bandwidth communication channel to attain high-speed operation and adequate discrimination levels in looped networks.	Yes	Reasonable	[139–141]
Multi-Agent System (MAS) based	• Transmission line protection. • Distribution line protection	MAS based technology can be applied to incorporate legacy data assessment tools with the intention of advanced diagnosis of power systems having several data sources.	• As several platforms of MAS do exist, the sensible selection is necessary to confirm durability, compatibility, and robustness for online implementation. • Owing to the peer-to-peer nature of agent systems, security can be the main concern. • Mobility, Security, Data Standards and Intelligent agent design are few concerns yet to be solved completely.	Yes	Expensive	[142–152]

Table 3
Comparison of IDMs based on different performance indices.

Features	Remote	Local			SP Based	AI-based
		Active	Passive	Hybrid		
Operational principle	Communication between utility and DERs	Inject disturbance to the inverter	Monitor the change in bus parameter	Both active and passive operated simultaneously	Monitor the variation of parameters w.r.t. time and frequency	Feature extraction with training and testing
Impact on Power Quality	X	High	X	Very little	X	X
Non Detection Zone	X	Trivial	Huge	minor	X	X
Operating time	Very less	Greater than passive IDMs	Slightly lesser than active IDMs	Greater than active IDMs	Very less	Less
Impact on the distribution system	X	Direct impact	X	Fewer compared to active IDMs	X	X
Multiple DG operation	Feasible	Not Feasible	Feasible	Feasible	Feasible	Feasible
Cost of implementation	X	Fewer	Fewer	Insignificant	Fewer	Fewer
Effect of enhanced inverter-based DG integration	X	√	X	√	X	X

towards the development of adaptive MPS [154]. The adaptive protection scheme (APS) is defined as an online protection scheme that has the ability to modify the response of the relay according to the microgrid topology and mode of operation. This requires the assistance of a dependable communication and high-speed data acquisition system amongst the DERs, the protecting appliances and loads, etc. [155]. The data processing unit computes the new-fangled value of the settings and sends a control signal instantly to adjust the relay settings of APS. The APS can be categorized into an adaptive overcurrent scheme, adaptive differential scheme, and adaptive symmetrical components scheme. A summary of the implementation strategies, challenges and implementation issues of several existing APS are discussed in Table 4.

5.1. Wide area protection based adaptive MPS

Currently, the research on WAPS has gained huge attention owing to the rapid development of smart grid communication infrastructure by which a wide-area and wide-range of information exchange can be easily achieved. Several works have presented the concept of WAP schemes applied to the transmission and distribution network [168–173]. These works have discussed wide-area differential protection, wide-area longitudinal protection, and wide-area sequence components protection. However, the work on the application of WAP concept to build an adaptive MPS still remains in the early phase. In this regards, the following are the few works that show the concept of WAP in microgrid environment.

Researchers [174,175] presented the concept of WAPS for the distribution network integrated with DERs. This WAPS principle is based on an adaptive fault searching region lock matrix algorithm which is used to identify the fault location and subsequently mitigate the fault through appropriate control actions in a distribution network. The WAP scheme is generally implemented in two stages. Firstly, the IEDs located at different points of the network determine the fault search direction by comparing the magnitude of branch current, which narrows down the search space to two/three-branch buses. Secondly, the phasor relationship between the current positive sequence component and load current at both ends of the feeder is used to locate the faulted section of the feeder by the help of the adaptive fault searching region lock matrix algorithm. Since the algorithm considers the short circuit current direction, it is therefore, capable of locating a single fault in a single-sourced distribution network as well as multiple fault sections in a multi-sourced distribution network. Wide area direction protection, differential current protection, and distance protection are realized based on the above principle. Gopalan et al. [176] discussed a wide-area differential protection scheme to determine the faulted section in a microgrid, to be used as primary protection. In case of failure of this primary protection, backup protection equipped with current sensors and Global Positioning System (GPS) coordinates is used to locate and isolate the fault.

Zhang et al. [177] presented a WAPS for active distribution networks (ADNs) with DERs. In this approach, a wide-area measuring module was used to collect the faulty phase information from different IEDs, and localization of fault was accomplished by the phase comparisons of distribution lines. The wide area measuring module is operated for time-synchronous measurement and effective communication, which improves the speed and reliability of data transmission, offering strong technological support to efficient phase comparison approaches. On the other hand, establishing a wide-area communication system is comparatively costly. Moreover, the scheme doesn't support backup protection and the inability to detect the faults that occurred in individual feeder branches, are treated as disadvantages of this approach. Intending to improve the scheme suggested by Zhang et al. [177], the same group of researchers have suggested a novel concept of integrated WAPS using the fault component principle [178]. In this concept, the ADN is split into a number of integrated protection units (IPUs). Afterward, the faulty feeder and faulty line are localized by assessing the phase difference of the positive sequence current fault components between the main feeder and slave feeders. The main advantage of the approach is that, albeit communication failure or data loss in the integrated WAP system, the protection scheme can effectively isolate the fault through proper coordination and cooperation between the upstream and downstream IPUs.

5.2. AI-based adaptive MPS

AI refers to a broad spectrum of algorithms that have the ability to learn and reason like humans. The authors in the review [179] opine that AI can smarten the grid in many ways, such as in load forecasting, scheduling, system monitoring, controlling, etc. It is well-known that self-healing is a hallmark characteristic of a smart grid, for which smart diagnosis is very essential [180]. Optimal relay co-ordination can also be achieved through the application of AI. The article [181] provides a review of all research articles on the application of AI in obtaining optimal relay coordination, however in a traditional grid system.

Intelligent fault detection, classification, and location are highly necessary for smart-MG for its effective control and operation. The integration of inverter-based DERs in MGs makes customary fault recognition systems unsuitable owing to their dependency on significant fault current levels. Several techniques were presented to resolve these issues and have been an emerging topic for research over the last decade. With the hypotheses related to smart-MG appealing maturing alarm amongst electric utility industry (EUI) scientists, the significance of developing a smart fault monitoring and identification scheme capable of recognizing and locating different sorts of faulty events can't be

Table 4
Summary of several APS implemented for microgrid protection.

Adaptive Protection Schemes (APS) as proposed in various literature	Implementation strategy	Technical challenges associated with the particular APS / Drawbacks / Additional Remarks
Updating the relay settings in synch with MG configuration [155]	Using digital relay with the help of efficient communication infrastructure. It can incorporate the additional feature in the form of a directional interlock for better performance in terms of fault detection and selective detachment of power electronics interfaced based MGs.	● All electromechanical and solid-state relays or fuses stand redundant. All of them need to be replaced with directional digital OC relays featured with the capability of resetting their relay tripping characteristics. ● Requires a fast, efficient and effective communication system ● The cost-benefit analysis needs to be made properly before real-time implementation.
An algorithm for auto-instantaneous OC protection[156]	Real-time calculation of system impedance using voltage and fault current. The relay operating characteristics gets updated based on the updated grid and microgrid impedances.	● The method stands valid within 2 cycles of occurrence a fault event. ● Suitability of the method is limited to PE interfaced microgrids only.
Recloser-fuse coordination minimization (by user defined characteristic based reclosers)[157].	These adaptive and multifunctional reclosers provide the user a range of operating curves to be chosen as per the need.	● System complexity gets enhanced due to the availability of option to the users to select and develop operating curves of their choice. ● As a single PD is provided with multi-functionality, the method is prone to common-mode failures.
A system parameter independent APS(to solve relay coordination issues in a highly impregnated DG system) [158]	● The scheme is based on communication between a centralized computer system (CPU) and the PDs. Grid data, accumulated by DAS, are processed by the CPU and appropriate action signals sent to the PDs need to be activated. ● The Thevenin's equivalent circuit representation for each source in the network is used for fault detection. The change in Thevenin's impedance of a source on the event of a fault serves as the vital data for detection of a fault, its type, location and the CBs needed to be activated for necessary fault clearance.	● Possibility of false detection in case of resistive faults as the proposed method makes short circuit analysis assuming zero fault resistance.
Voltage based fault detection in tandem with an APS [159]	The PDs change their time–current characteristics in the events of short-circuits and overloads by measuring the difference in voltage drops during the said two events.	● The current limitation of PE devices and system earthing are the factors which pose a challenge in defining the ratings of the PDs.
An Adaptive OC Protection System [160]	It is a combined approach of real-time traditional protection systems and offline adaptive protection system. The first one makes real-time data monitoring and executes necessary protection action. While the later relies on prediction data calculated offline using a decentralized energy management system (DEMS) for ensuring system protection. The DEMS predicts the PDs new settings every time the grid configuration undergoes a change.	● Fuses stand redundant. Need to be replaced with multifunctional relays with directional sensitivity. ● Requires high speed, long-distance communication infrastructure. ● Implementation of DEMS itself is very challenging. ● Investment vs. profit analysis.
Zero sequence component of current (ZSCC) based APS, suitable for both grid-connected and off-grid mode [161]	The scheme works on three aspects of a microgrid, namely, Detection of Mode of Operation, Detection of Fault during different modes and Protection Coordination. The major advantage of the scheme lies in non-dependency on a communication system.	● Setting up a correct threshold for the ZSCC based relay. ● Possibilities of reduced operational speed due to non-dependency on communication network. ● Validation of the scheme through practical implementation is not cited by the paper.
An offline relay tripping characteristic fixing approach (for OC relays for both off-grid and islanded mode of operation) [162]	The relay setting automatically gets shifted from one group to another group of setting as suitable for different mode of operation. The approach helps to detect faults with much smaller level of short circuit current.	● The islanding condition of a microgrid needs to be identified in the fastest possible time. The problem is that there are very limited numbers of fast islanding detection methods. ● Requires fast communication between the digital relays and CBs in order to update the PD settings appropriately.
OC and Overload (OL) Protection of Directly Voltage-Controlled DERs (VC-DER) based MG [90]	Provides two additional features to voltage control scheme of VC-DERs based MG such as OC and overload protection. The OC system senses the fault, confines the output current magnitude of the DG unit, and reestablishes the MG to its normal operating conditions. The OL protection system confines the output power of the VC-DER unit.	● The scheme is designed for only islanded microgrid.
Fault Current Coefficient and Time Delay Task for MPS with CPU[89]	The scheme is executed by the assessment of two novel parameters such as fault current coefficient (i.e. fault current delivered by any DER to any point inside the system) and modification of relay hierarchy for careful operation of relays. The self-programmed assignment of these parameters aids the idea of self-acting MPS.	● A proper pre-assessment is necessary considering of all possible configurations of a MG relating to different locations and types of faults,

(*continued on next page*)

Table 4 (*continued*)

Adaptive Protection Schemes (APS) as proposed in various literature	Implementation strategy	Technical challenges associated with the particular APS / Drawbacks / Additional Remarks
Differential strategy for medium-voltage microgrid (MV-MG) [121]	This differential MPS uses traditional OC relay and communication channels which are able to protect MV-MG considering both converter and synchronous based DERs.	● Although the fiscal concern is respected in this system, it is incompetent to offer protection in the course of unbalanced load.
Communication-assisted digital relays [122]	A three levels of MPS based on differential strategy using digital relays and phasor-measurement units (PMUs) accompanied by communication links. The scheme is also useful against HIF.	● However, the proposed technique is costlier due to the involvements of PMUs.
Microgrids using differential relays [123]	This is a differential current based method useful to protect transmission line, distribution lines and busbars. The OC,OV/UV and synchronism check relays are located in this system.	● Even though the stated approach can offer a robust protection for both the mode of microgrid operation, it may mal-operate with response to the unbalanced loads and switching transients.
APS based on symmetrical and differential current components [125]	It uses the zero and negative sequence current component for the detection and isolation of single-line to ground and double-line faults in islanded MG.	● The scheme requires advanced communication channels during its operation and exclusion of HIFs during performance evaluation are some disadvantages of the scheme.
Microprocessor-based relay (MBR) for low-voltage microgrids [126]	This MBR based MPS is designed to protect LV-MG against both LIF and HIFs using zero and negative sequence current components. It doesn't require any communication links, which is a major advantage.	● The stated approach is not able to provide protection in mesh topology MG system.
Positive-sequence component based APS [127]	The scheme is based on MBRs, PMUs and digital communication system. It is useful for the protection of each topology of microgrid architectures (radial and mesh). The intended scheme has the ability to renovate their pickup setting in pursuit of any structural variation in microgrid, thus shielding microgrids against subsequent fault.	● It may be less economical, as the costs of PMUs are too high.
An APS using digital relays and reclosers [163]	The relay at the sub-station point locates all the DGs by running an algorithm fed by measured current values at all PD locations. Depending on elative current magnitudes, recloser fast curves are reset for sustained PD coordination.	● The method is not useful for high level of DG penetration. ● Economic viability of the method is strongly negative.
Prims-Aided Dijkstra algorithm for APS [164] andGraph theory and optimization algorithm for APS [165]	The stated Prim-aided Dijkstra algorithm performed constantly in the CPC is accountable for recognizing the present topology of the microgrid and assists in detecting the quickest path from the faulted point to the adjacent operating source. The function of the CPC is to monitor the MG continuously, detect faulty section, and identify the faulty branch.	● The suggested adaptive relay coordination system is capable to detect the fault within 1sec. ● Although the stated scheme was effective for a 7-bus microgrid system, the performance of the scheme needs to be validated for a bigger system with multi-DG environments.
Quadrature and zero sequence current components based APS [166]	Considering the importance of grid-connected mode without DGs, a new APS is proposed based on quadrature and zero sequence components of fault current. The scheme is able to detect the topology of DERs, fault location and nature of faults by analysing the X/R ratio of DGs along above-mentioned sequence current components.	● The test system considering for the experiment was a single-DG based system. ● Stability analysis needed to be revalidated through further study of current coefficient.
An APS for Small ScaleMGs based on Fault current level[167]	Here, an APS has been suggested by installing communication and CPU of MG. The DG impact factor (K) is used to estimate the instantaneous fault current contribution of each DERs before the fault occurrences. The proposed MPS is capable of handling the dynamic behaviour of MGs and involuntarily modifies its settings with the intention of novel uses.	● One of the most critical scenarios, i.e. the communication malfunction wasn't conferred in this article. As the author assumed that there is only one MG connected to the utility-grid, the effect of other MGs on considered MG need to be discussed further.
Application of μ-PMUs for adaptive coordination of OC relays (OCRs) in MG [105]	Mis-coordination problem of OCRs arises as a result of varying fault currents and uncertainties of network topology. This article suggested an approach for online detection of these uncertainties. To detect uncertainties in transmission side, μPMUs are mounted in-between transmission network and PCC; thus, the topology changes such as line outage can be noticed by monitoring of Thevenin impedance estimated by the installed μPMU. Uncertainties detection in a MG can be carried out by the signals which are sent by μPMUs and installed throughout the MG.	● The outcomes from the study reveals that it is able to detect the uncertainties for reconfiguration of main and back-up relay and to adapt the relays settings. However, the high cost of PMUs makes the system costlier.

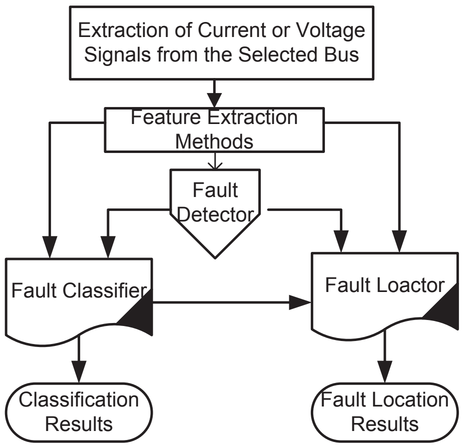

Fig. 9. Typical flowchart of fault detection, classification and location [184].

overstated. A basic framework for fault detection, classification and location is shown in Fig. 9. Several fault detection and classification approaches based on intelligent classifiers were reported in recent years [27,182,183].

There have been very limited research articles paying particular attention to the area of AI implementation in protection aspects of a microgrid embedded smart grid system. The AI methods generally used in MPS are decision tree (DT), artificial neural network (ANN), probabilistic neural network (PNN), adaptive neuro-fuzzy inference system (ANFIS), random forest (RF), support vector machine (SVM), artificial immune system (AIS), extreme learning machine (ELM), fuzzy logic, etc. References [183] to [199], which are finger countable in numbers, throw light on a few aspects of only microgrid fault protection issues. Table 5 provides a brief summary of these articles.

To overcome the issue of proper thresholding in passive islanding detection, the AI-based methods like intelligent classifiers are integrated with passive IDM as shown in Fig. 10. Table 6 provides a brief summary of existing IDMs based on intelligent classifier.

The above-mentioned analysis and interpretation from Tables 5 and 6 infer that intelligent MPS is necessary for the smart operation of an MG. Intelligent protection can be imparted by the application of advanced communication links and artificial intelligence-based methods. From these tables, it can be analyzed that ANN, SVM, DT are most popularly used classifiers albeit varying degrees of performance at the varied level of system complexities considered for studies. The table 5 is quite indicative of the fact that even though the recent research trend is veering into the application of AI in power system and smart grid, there have been very few research articles paying particular attention to the area of AI implementation in protection aspects of a microgrid embedded smart grid system. However, the applications of AI to solve the other MG protection issue (i.e. unintentional islanding detection) have been widely studied in the last decades. Therefore, table 6 concentrates on the presentation of a few examples of this application which are more recently published.

5.3. On-line relay coordination algorithm for APS

An APS for the transmission or distribution system should be self-capable of adapting and implementing the required relay settings for the stable operation of EPS [53]. Directional-OC (D-OC) relays based protection is a common and economical choice for the interconnected sub-transmission and distribution systems. It is used to measure the fault current level in each phase and generate a trip command considering a particular operating time delay (OTD) [217]. This OTD generally depends on relay-pickup and time setting parameters. In an EPS, a successful operation of DOCRs is possible if the primary and backup relays are arranged and coordinated properly [217]. The mathematical optimization approaches have been successfully implemented in the EPS without DERs to achieve the relay coordination and minimise the relay operating time [111]. Few such examples of optimization approaches are like: Linear programming (simplex and generalised reduced gradient methods) [218], a simplex two-phase method [92], dual simplex [219], binary programming [220] and quadratically constrained quadratic programming [221]. Similarly, a few researches cited the application of these techniques in DERs based EPS [111,222]. Two such approaches (adaptive or non-adaptive) towards the solution of D-OC relay coordination problem associated with DG integrated interconnected EPS were suggested by El-Khattam et al. [111]. The adaptive type approach relies on the selection of optimum number of relays, their locations and adaptive relay setting. The other one, i.e. non-adaptive approach implemented a training method to attain optimum relay coordination status deprived of the variation of original relay setting. Here, a two-phase LP optimization model was used using GAMS software. A new D-OC relay protection coordination approach was suggested utilizing the concept of dual setting [222]. Therefore, each D-OC relay has been associated with two pairs of settings for the two possible directions; two TDSs, and two pick-up current settings.

On the account of high penetration of DERs in the EPS, the coordination becomes more complicated and therefore, the current research trend has been shifted towards the development of more reliable coordination strategies based on advanced optimization algorithm (AOA). Some popular optimization techniques used for this purpose are as follows: Ant colony optimization (ACO) [93], Cuckoo Optimization Algorithm (COA) [223], Particle Swam Optimization (PSO) [224], Genetic Algorithm (GA) [225], Teaching Learning Based Optimization (TLBO), etc. [226]. The optimum coordination problem of D-OC relays based on the AOA comprises of minimizing an objective function bound by limits on problem variables (for example, overall relay operating time) and specific coordination parameters. In this regard, the APS should ensure the data updation corresponding to the state-of-the-art parameter variations of the EPS, and subsequently execute the load-flow and fault analysis to acquire input data utilized by the AOA [93]. In [93], authors have studied the ACO and GA for D-OC relays coordination inside APS in the DG based EPS. Dehghanpour et al. [223] introduced COA with its integration of Linear programming (LP) in order to optimize coordination protection of D-OC relays in MG environment and calculate the optimal value of FCL at PCC. The optimal settings of D-OC relays are determined for both islanded and grid-connected mode of operations. A hybrid PSO-LP algorithm was presented by Papaspiliotopoulos et al. [224] for the optimal D-OC relay coordination problem in DGs integrated electrical distribution system. The studied approach was used to determine the pick-up current setting and time-dial setting (TDS) of each D-OC relay and optimize the overall relay's operating time bound by specific constraints. Authors in [225] have studied a MPS that depends on optimally sizing FCL and optimally setting D-OC relays. The optimal settings of D-OC relays and size of FCL were determined for both islanded and grid-connected mode of operations. This approach was formulated as a constrained NLP problem and was solved using GA. A similar approach was proposed by Ray [226] using TLBO. OCRs are commonly used in MGs and it is essential to improve the TMS of relays, which consecutively reduces the tripping time of the relay. Avachat et al. [227] presented a Dual Simplex and Revised Simplex optimization techniques for optimization of the TMS value of OCR and thus to attain rapid fault clearance. The mis-coordination issues due to dynamic characteristics of fault current that arise in conventional OCRs based protective systems as a result of high penetration of DERs into the distribution system is a key factor of system reliability degradation. Implementation of directional-FCL (DFCL) is one of the effective solutions to this issue, but the setting of DFCL is still remaining a challenging task. In this regard, Arzinfar et al. [228] proposed a novel strategy for the setting of DFCL parameters to increase the OCRs coordination. El-Naily et al. [229] proposed a

Table 5
Summary of AI based microgrid protection scheme.

MPS	ANN	SVM	DT	KNN	RF	NB	ELM	DL	Other	Complexity	Remark
Data-Mining Model-Based Intelligent DifferentialMPS [185]		√	√							1,4,6,9,10	Provide performance accuracy of 99% with a relaying speed of not more than 1.5 cycles.
A Combined WT and Data-Mining Based Intelligent MPS [186]			√		√					1,3,7,9,10	Response time is within 2 cycles. Both the classifiers RF and DT shows approximately equal accuracy, but being a black-box solution, the RF faces execution problems.
Detection of micro-grid faults based on Hilbert transform and ML techniques [187]		√				√	√			1,3,5,6,8,10	Response time is within 2 cycles. ELM based approach outperforms to another classifier regardless of the type of DERs, the topology of MG and type of fault considered.
Adaptive Overcurrent Protection for Microgrids in Extensive Distribution Systems [188]	√									2,4,7,9	Advancement and deployment of the advanced communication and measurement system in MG, MPS can adjust the relay settings intelligently.
Smart MPS Based on S-transform and Data-Mining [189]			√							1,3,7, 9,10	Classification with accuracy above 99% with relaying speed below 1.5 cycles.
A Fuzzy Rule Based MPS [91]									√ Fuzzy DT	1,3,6,9,10	The relaying speed of suggested MPS is about 2.25 cycles. Proposed MPS shows better performance compared to existing current differential and overcurrent relays for fault detection in a mesh topology.
Data-Mining based Complete Primary and Backup MPS [121]			√							1,3,5,6,9,10	Provide performance accuracy of 99% with a relaying speed of not more than 1.5 cycles.
Adaptive protection combined with ML [190]	√	√								1,4,6, 9,10	This approach has been proved to be effective by modifying the settings properly and intelligently for different operating situations such as varying topology and operating state
A MPS Based on Feature Cosine and Differential Scheme [192]									√ Threshold	1,4,6,9,10	The scheme is useful for locating the faulty section effectively by calculating differential direction from the phase voltage and current. This approach has been proved to be effective regardless the different grounding resistances and faulty types.
Fuzzy Decision and graph algorithm based MPS [191]									√ Fuzzy DT	1,4,7,9,10	The result states that the suggested MPS may be suitably employed to any dimension of microgrid.
Microgrids Fault Detection Scheme based on WT and Deep Neural Networks [193]								√		1,3, 6,9,10	The results prove that the suggested MPS can able to classify and locate the fault more accurately compared to other available approaches. Furthermore, it has been validated under the influence of noisy environments.
MPS Based on Combined ANFIS and Hilbert Space-Based Power Setting [194]									√ ANFIS	1,3, 6,9,10	This technique provides a quite worthy estimation of reliable, precise, and fast determination for each fault type. Additionally, the scheme is computationally efficient and provides good stability during the fault occurrence.
Bagged DT (BDT), Fast Fourier and Wavelet Transforms Based protection scheme Using Windowed [195]			√							1,4,7,9,10	The architecture of the BDTs and their relevant inputs were selected separately for the different zone protections. The use of BDTs confirmed to be an intelligible decision as significant improvements in fault recognition accuracy was attained. It was also proved to be robust against noisy data.
Mathematical morphology and ELM techniques based MPS [196]		√				√	√			1,3,5,6,8,10	The relaying speed of suggested MPS is about 2 cycles for primary and backup protection. Proposed MPS shows better performance compared to existing current differential and overcurrent relays for fault detection in a mesh topology.
An interval type-2 fuzzy logic MPS [197]									√ type-2 fuzzy	1,4,5,6,9,10	Here, an interval type-2 fuzzy logic system (IT2FLS) based scheme was proposed to detect, classify and locate the fault in microgrid. It can provide backup relaying in response to the failure of primary protection. It does not require any training stage compared to DT, ANN, SVM and ANFIS. Therefore, it has less computational burden.
SVM based MPS [198]		√								1,2,7,9	Although the approach proves its effectiveness in both modes of MG operation, the detection accuracy in mesh topology network and noisy environment needs to be further explored.
Modular ANN (MANN) based MPS [199]	√								MANN	1,3,5,6,8,10	The experimental outcome reveals that the stated approach can provide the complete protection of MG within 1 cycle.

Complexity of Test Environment: If the approach considered
both grid-connected and islanding mode: 1
either grid-connected or islanding mode: 2
both Synchronous and Inverter based DERs mode: 3
either Synchronous or Inverter based DERs mode: 4
back-up protection : 5
both radial and Mesh based system: 6
either radial and Mesh based system: 7
both LIF and HIF based Fault condition: 8
either LIF or HIF based Fault condition: 9
test system is a standard test system: 10

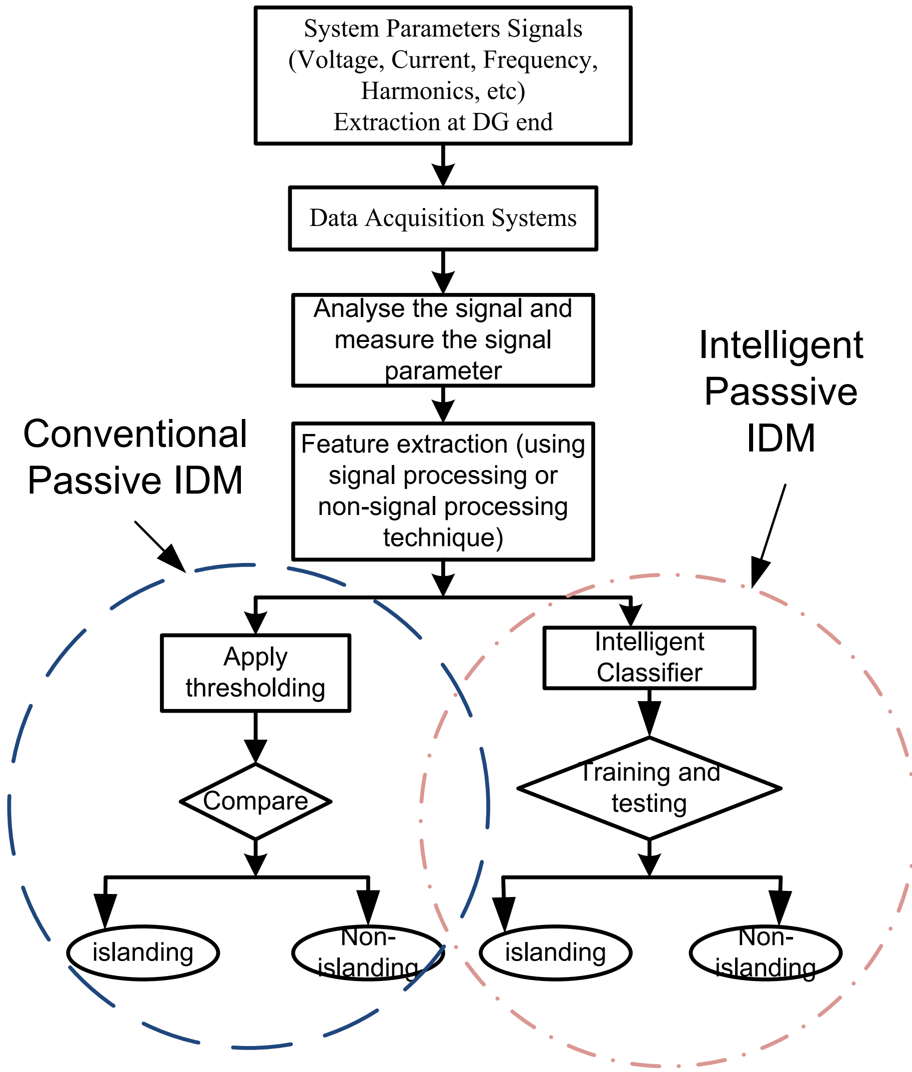

Fig. 10. Typical flowchart of IDMs.

modifying OC relays coordination strategy based on a different objective functions for both phase and earth OC relays. The scheme does not require any communication links for its operation. The proposed strategy was helpful to improve the reliability of the MPS and decrease the tripping time resulting from the coordination time needed for backup OC relays on previous substations.

6. Critical analysis and discussion

This paper presented a detailed analysis regarding the issues, challenges and protective solutions to AC microgrid protection. The conventional MPS designed for passive radial distribution networks may not work satisfactorily for the increasingly complex active distribution system, i.e. microgrid system. Different network topology, diverse operating principle based DERs, energy storage, and controllable loads make the microgrid system based distribution network more complex in nature. Therefore, the protective solution to this type of system needs to be updated by considering some novel design philosophies of protective devices, digital relays, PMU, smart sensors, and intelligent reclosers. Concerning the further protection necessities demanded by the emerging microgrid based distribution network, this article reviewed several existing relaying algorithms based on the technical challenges available in the literature followed by several suggestions recommended on the R &D point of view. Form this survey, it is seen that nowadays, more emphasis has been given to the design of adaptive protection schemes as it provides a promising paradigm to microgrid protection. Each MG has different priorities and complexities, which adds to difficulties in the design of unique protective and coordination schemes. Therefore, the protection engineer must utilize a complete checklist of issues/challenges to consider during the design phase of the protection strategy. Therefore, additional effort is still required in terms of overwhelming the boundaries of planned MPS for all circumstances and developments. Moreover, considerable research is still required particularly for the islanded MGs.

6.1. Resilience-oriented protection strategies to improve the microgrid network resiliency

Stable and reliable power supplies are some of the features most expected from an EPS. However, natural calamities, either foreseen or unforeseen in nature, leaves behind major destruction in the power system infrastructure. Continuity of supply is disrupted for a period varying a short to prolonged period and sometimes complete blackout. Power being the lifeline to most critical installations such as the supply of water, operation of healthcare units, etc., it is imperative that the power system should be incorporated with adequate features to get back to operation in the shortest possible time. At least, it should be in a position to supply installations engaged in post-calamity recovery activities and hospitals with the shortest interruption or no interruption at all, before the main grid gets back to life. In short, what is expected of

Table 6
A sampled analyses of literatures available on various intelligent islanding condition detection techniques (IDTs).

IDTs	FETs	ANN	SVM	DT	KNN	RF	NB	ELM	DL	PNN	RPNN	Other	Complexity of test environment	Remark
ML classifier boosted with a modified performance optimizer for Islanding Detection [200]	SLT									X	X	X	3, 5, 6	● RPNN backed by MDE (optimizer) & SLT (feature extraction) outperforms other combinations of techniques RPNN + DWT, PNN + SLT, and PNN + DWT in terms of both classification accuracy and detection time. ● Performance optimization by proposed MDE is much more effective in comparison to GA, PSO and DE(classical).
IDT for a low-voltage PV Generator network [201]	WPT											X(BT)	3,5,7	● Performance accuracy not quantified. Effectiveness of the proposed method under noisy condition not explored ● The method does not generate any negative impact on PQ of the system and has a reduced run on time of 5 ms with zero NDZ.
IDT based on DL [202]	MRSSE								X				3,5,6	● For the first time, a deep-learning-based method is proposed for binary-classification of islanding and disturbance conditions in a microgrid with high penetration of distributed energy. ● MRSSE method outperforms the wavelet energy co-efficient method. Besides, it is insensitive to noise ● Massive sample number required for better classification accuracy
Optimal selection of parameters for SFS method for detection of islanding condition [203]	None											X (AIS)	3,5,6	● AIS used as an optimizer of input parameters for SFS technique, where the NDZ depends upon the appropriate parameter setting.
Intelligent islanding detection using SFS method [204]	None			X									3,5,7	● Two-layer detection method comprising of DT based passive and SFS based active IDT. Active IDT acts when the passive method fails.
Intelligent islanding detection during low power imbalance [205]	None		X										3,5,6	● DR (Detection Rate) and FA (false Alarm) has been taken as the performance indicators of the classifier. ● The result indicates a 100% DR with 0% FA rate. The authors at the same time indicate that in theory this is not possible. The reason being the empirical results are obtained from a finite data sample and it is possible that the ROC (receiver Operating Characteristic) will jump from 0% to 100% DR without any change in FA rate. To obtain a smoother ROC curve, a significant number of events are needed. ● However, the results still indicate a very high DR at a very low FA rate.
ML based IDT [206]	None	X	X									X (ANFIS)	3,5,7	● The performance of MLP and RBF (two different types of ANN structures) are compared and MLP is shown to be having better performance. MLP model of ANN is shown to be the better performer in terms of classification accuracy over SVM and ANFIS. ● NDZ is significantly reduced but not to absolute zero. ● Future study possibilities based on the selection of other system parameters at the DG terminals in order to bring NDZ to zero. ● Effectiveness of the proposed method under noisy condition not explored
Intelligent IDTs based on Hilbert-Huang Transformation.[207]	EMD + HHT	X	X					X				X	1,5,6	● A comparison amongst various ML tools based on HHT is done. The proposed WBELM is shown to have the best performance in terms of run on time and classification accuracy in both ideal and noisy conditions. ● The method is simple, effective and easy to implement with less computational overhead.
Intelligent IDTs based on WPT [208]	WPT	X	X	X				X					2,5,6	● The overall classification accuracy of WPT based ELM classifier far outperforms the other three classifiers based on WPT feature extraction method.
Intelligent IDTs based on WPT [209]	FDST	X	X					X					2,5,6	

(*continued on next page*)

Table 6 (*continued*)

IDTs	FETs	ANN	SVM	DT	KNN	RF	NB	ELM	DL	PNN	RPNN	Other	Complexity of test environment	Remark
														● The ELM (as a classifier) with FDST (as a feature extraction tool) is shown to be better performing with respect to ELM based on either WT or ST. ● The FDST + ELM classifier is faster and more accurate in comparison to FDST + SVM and FDST + ANN.
Intelligent IDTs based on Phase Space Technique [210]	PS / WT									X		X (RBFNN)	3,5,7	● Two different SP tools (PS & WT) are used separately in conjunction with each of the classifiers PNN & RBFN. PNN + SP proven to be more effective than the other three combinations both in terms of classification accuracy and detection time.
Intelligent IDTs based on SVM classifier with different SP tools for feature extraction [211]	WT/ST/HST/ TTT/MM		X										2,5,6	● WT as an SP tool is very sensitive to noisy conditions and along with SVM classifier completely fails to detect islanding under any noisy condition. ● Degradation in detection performance with an increase in noise level is observed in SVM, ST combination. ● Asserts that TTT and MM (being time-time transforms) show better accuracy than the time–frequency multi-resolution analyses in the form of ST and HST.
Combined passive and active method of intelligent IDT [212]	None											X (BT)	3,5,7	● The islanding detection method is a combination of active as well as passive islanding detection techniques. ● The threshold filter design is being achieved by BT, to avoid false detection. The accuracy of BTC in this perspective is not explicit.
Pattern recognition based IDTs [213]	None	X	X	X		X	X						2,5,7	● RF is shown to outperform all classifiers taken under study in terms of detection time and classification accuracy. ● NB as a classifier is seen to have much lesser accuracy compared to RF, DT, SVM and NN ● ANN is shown to have better classification accuracy and almost as robust and reliable as RF besides being much better compared to NB and DT. ● Effectiveness of the proposed method under noisy condition not explored
IDT using Naive Bayesian classifier [214]	None						X						3,5,7	● Simple NB classifier is seen outperforming the more complex SVM in every aspect. ● Effectiveness of the proposed method under noisy condition not explored.
IDT based on DWT-ANN [215]	DWT	X											3,5,7	● Reasonably good classification accuracy. ● Effectiveness of the proposed method under noisy condition not explored
IDTs based on various classifiers [216]	None		X	X						X			2,5,6	● Amongst the three the best classification accuracy was achieved from DT. ● Training the generator-specific classifiers separately gives better accuracies than a common classifier. ● The accuracy needs improvement over the presented level for the proposed method to be of practical use.

Complexity of the test environment: If the approach considered
all three of the Synchronous, Induction and Inverter based DERs mode: 1
any two of the three DERS; Synchronous, Induction and Inverter based DERs mode: 2
any one of the three DERS at a time; Synchronous, Induction and Inverter based DERs mode: 3
both Radial and Mesh based system: 4
either of the two: Radial or Mesh based system: 5
noisy condition: 6
non-noisy (ideal) condition: 7

the power system is high resiliency. Inherently most power systems are designed to have a certain degree of resilience to system faults caused by internal or external interferences. However, resiliency as an issue has gained the attention of researchers and designers only after there has been an unprecedented increase in the frequency of otherwise rarely happening calamities with the potential of catastrophic devastation, termed as “low probability high impact (LPHI)” events. The cyber-physical component of a power system, which makes for the backbone of the system, also comes under the devastating effects of LPHI events besides vulnerability to man-made cyber-attacks. In this context, cyber-physical resilience is of paramount importance as the critical functionalities of the EPS must remain operational during and after the LPHI events [230].

At this stage, it is important to note the subtlety in the difference between “reliability' and ”resiliency“ of an EPS. The present EPS assures the reliability of supply during normal and foreseeable abnormal conditions and low impact damaging eventualities. Contrary to this, the continuity of supply during LPHI events remains a challenging issue. So, we can say, the existing EPSSs are reliable but not resilient. The resiliency of an EPS is defined as its ability to return to the equilibrium (stable operation point) after a major disruption event [231]. 'Robustness', 'resourcefulness', 'rapid recovery', and 'adaptability' are the four features considered as the attributes of resilience by the National Infrastructure Advisory Council (NIAC), USA [232]. What these attributes refer to is indicated in Fig. 11. Rapid recovery and adaptability to an unprecedented disruption, makes microgrid the most suitable solution to enhance the resiliency of an EPS remarkably. Presence of renewable energy sources, ability to feed critical loads during system contingencies through the islanded mode of operation, operational flexibility and self-healing capabilities are the features that qualify microgrids as the most suitable and effective resilient resources for service restoration in the event of LPHI events.

Many strategies are employed to use the microgrids for fast system recovery as a part of post-rehabilitation measures in the event of disruptions during LPHI disasters. One such strategy is to isolate the outage area from the main grid and divide it into multiple self-supported microgrids. Another strategy is to couple a microgrid to other microgrids in order to support the critical loads of the one having insufficient supply [230,233]. The microgrids in such cases serve as a local resource or as a community resource, either way enhancing the resiliency of the EPS [234]. Microgrids can also be used as a black-start resource to start the main generators [235]. Additionally, conversion of existing EPS into tie connected microgrids [236], the formation of dynamic microgrids [237], or formation of networked microgrids [238] are the strategies that can be employed to increase the system resiliency.

Another premise that is gaining ground amongst the researchers is that a resilient microgrid in an EPS will inevitably contribute to an increase in the overall resilience of the EPS. Hence, the development of new strategies for the microgrid to enhance its own resiliency in the event of major outages is another research area, in its nascent stage. In this context, proactive scheduling [239], outage management [240] and advanced operation strategies [240,241] are some of the options discussed in various literature [242,243]. The authors in [244] share the similar perception and opined that a microgrid to serve as an excellent resilient resource needs to be resilient itself to physical and cyber threats. The study proposes a methodology for designing resilient microgrids based on appropriate microgrid features selection through careful evaluation of the factors, such as, threats, vulnerabilities and consequences as viewed by the designers and site owners. It has been ascertained in this study that protection is integral to stable, reliable and robust operation of a microgrid. An appropriately designed microgrid protection scheme can further augment the resiliency of an EPS to major outages. In this context, improving the protection strategies of microgrids in order to increase the resilience of the network or design of resilient-oriented protection strategies is a new area of research. There are very few literatures that could be identified addressing this particular aspect of microgrid protection leaving future scope for research. Authors in [245] list out the issues related to microgrid protection schemes and microgrid islanding that are needed to be addressed to make a network more resilient. In [246], a microgrid protection scheme is proposed in order to discriminate between inverter faults in a PV system and the distribution line faults. In a sense, the method enhances the microgrid resiliency to faults but the protection scheme's contributions in strengthening the system resiliency towards LPHI events are not quantified.

Ample literature is available enumerating the developments in the field of the resiliency of power systems and the role of microgrids as a resilient resource, even though there are large numbers of issues yet to be addressed. The study here only gives a cursory assessment in order to give a peek into this aspect of power system protection as the primary focus of this study has been limited to microgrid protection. However, it can be stressed that there is a dearth of literature on the aspect of resilient-oriented microgrid protection schemes, leaving wide scope for a further probe by researchers.

6.2. Impacts of flexible AC transmission (FACT) devices on microgrid protection

The ever surging power demand is spurring the rapid expansion of the power systems. However, in the process, it invites complexities due to interconnected network and associated issues of system instability, difficulty in control of power flow and compromises the reliability of power supply, etc. The issues are more accentuated when the EPS is more unbecoming of a traditional system, rather a smart one impregnated with distributed generators and resources. One of the ways out of this situation is to ensure the optimum flow of power through the existing power system, thereby limiting the need for capacity expansion. Incidentally, Flexible AC Transmission Systems (FACTS) is an enabling technology in this respect. Enhancement of power transfer capacity, bettering the control on power flow over the assigned route of the transmission line, and ensuring optimal secured loading of the transmission lines are the prime objective of FACTS devices [247].

There are abundant of literature on the applications of FACTS devices in improving the MG performance through power quality improvement, reduced feeder losses, and bus voltage stabilization [248]. However, as much as FACTS as technology become imperative in the smart grid scenario, the presence of FACTS devices in an MG itself raises the concerns on the effectiveness of certain MG protection schemes. For example, the distance protection scheme, one of the widely used protection schemes for transmission lines could be adversely affected due to the presence of static synchronous compensators (STATCOMS) in the given transmission line. Subverting the adversities associated with FACTS technology, while banking upon its immense virtues in the improvement of power quality of an EPS, is a daunting task and comprises an interesting research area yet to be fully explored.

A few proposed MG fault detection and protection performance improving schemes in the presence of certain FACTS devices at different test conditions are cited here in this section. Thyristor controlled series capacitors (TCSC) is one of the most effective FACTS devices which provides series compensation. But, the TCSC control mechanism brings about many changes in the system parameters such as change in load currents and line impedances, causing concern about maloperation of traditional protection relays. Besides TCSC dynamics cause overreaching and loss of security, adding to the aforementioned problem. The authors in [249] have proposed a new approach to have enhanced fault detection and location based on traveling waves and fast discrete S-transform (FDST) for TCSC compensated lines connected to wind farms. Authors in [250] emphasize the need for a relaying strategy for transmission lines including a unified power flow controller (UPFC) and wind farms. UPFC suitably assists in the compensation of wind farm connected transmission systems. However, UPFC in a transmission line

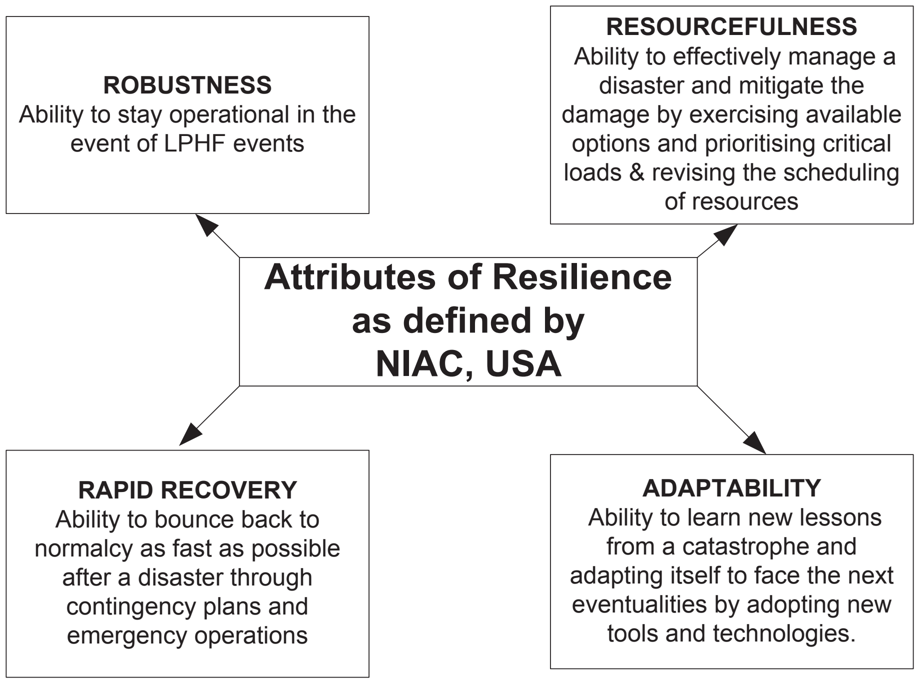

Fig. 11. Attributes of resilience of a microgrid.

presents a different impendence calculation inside from the one while outside of it. This can lead to maloperation of protective relays. The paper presents a highly reliable decision tree-based intelligent differential relaying scheme for a wind farm connected transmission system with UPFC compensator. Similarly, authors in [251] have proposed a potentially better protection scheme based on adaptive distance relay setting for parallel transmission lines connected to wind farms and including a UPFC.

6.3. Miscellaneous microgrid protection scheme

Ghadiri and Mazlumi [252] proposed a Self-Organizing Map (SOM) clustering algorithm for digital OC relays provided with a number of settings. The stated APS focuses on solving the miscoordination amongst primary and back-up relays. The scheme is helpful to improve the coordination between OC relays and operating time of relays. Strezoski et al. [253] proposed an APS for microgrid system comprising inverter and induction based DERs. The posed APS satisfy the fault ride-through requirements for reactive current injection. As per the DER's disconnection times, extremely accurate time-intervals are fabricated, wherein the fault currents through the relays may significantly vary, in advance to the operation of the relays. According to these time-intervals and the corresponding fault current values, the relay operation times are iteratively calculated with a high accuracy, which subsequently confirms highly accurate coordination of protective appliances. Sharma and Panigrahi [254] proposed a phase-OC relay which was helpful in mitigating sympathetic tripping in-ring distribution network. The unnecessary relay operation in the distribution network was limited by dumping some additional features on the traditional OC relay coordination problem using the Shannon–Wiener DE algorithm. In this work, the author tested each and every kind of fault except single-line to ground fault.

Manditereza and Bansal [255] proposed an innovative voltage-based relaying protection scheme. The relaying algorithm does its protection work by active power differential and sensitivity calculations through voltage measurements in a stated protection zone. The relaying algorithm was modelled in Dig silent Power Factory software and mounted at the nodes of an MG test system. The performance of the relaying scheme was examined under diverse faulty environments. Esfahan and Mohammed [256] proposed an intelligent-MPS to deal with extreme fault currents in the distribution system and the un-necessary installation of FCLs. This MPS utilizes communication capabilities defined in IEC 61850 to design smart cascading switching actions to isolate the faulty feeder from the healthy parts. Actually, it was defined as a supervisory MPS along with the conventional distance protection, which was the key protection of high voltage transmission systems. The suggested MPS will trigger if the fault current exceeds the braking capability of CBs; otherwise, the conventional distance protection will operate fault clearance. Jarrahi et al. [257] suggested a new fault detection and classification algorithm for MG using the current-only signal. As stated by the proposed approach, the Teager–Kaiser energy operator based index for squared three-phase current signal shows a change in the studied MG during the fault occurrence. Furthermore, a simple rule-based method was recommended for fault classification that classifies the fault type within half-cycle after change detection. The method was found to be very firm, simple, and cost-effective.

6.4. Open research issues and further discussion

In this section, several innovative thoughts or research ideas are stated for the future research and development of advanced microgrid protection scheme.

- Design of more robust MPSs needs to be done which are less sensitive to types of loads, inverter-based DERs (IDERs), and MG network topologies. These schemes may include traveling wave concept, PMU based approach, pilot-protection, and should be adaptive in nature. Moreover, it is also required to design APS for MG stability when power swing and out-of-step protection function may no longer be applicable with IDERs.
- Designing an appropriate fault location technique is often a challenging task in the evolving MGs. Therefore, more research in the direction of developing new MG fault location techniques is needed in the near future.
- There is hardly any article addressing the implementation of AI in specific areas of smart grid protection such as loss of protection coordination, fuse saving, blinding protection, sympathetic tripping,

device discrimination etc. during on-grid and off-grid mode of operation of a microgrid. The research addressing these specific areas of AI application in smart grid protection is apparently minimal and leaves a wide scope for further attention by researchers.

- Deep Learning (DL) is one of the new evolving AI techniques which has several advantages as compared to conventional ML techniques. However, very few researches have been reported in last couple of years focussed on DL applications in MG protection. Therefore, the application of DL in MG protection is still a future scope.
- During the implementation of smart adaptive MPSs, the risk of communication link failures and cyber-attacks are few major challenges for the protection engineers. The cyber-attacks in MG communication networks create disturbances in the authenticity of data exchanged during the transfer of messages between different IEDs, severely compromising the performance of MG protection [258]. Therefore, this is a high time to consider these challenges as future scope and work for the betterment of MPS.
- The transition of old-fashioned power-grid into smart-microgrid (SMG) can additionally be enabled by the application of the internet of thing (IoT). Both the IoT-based SMG and smart-grid have several different security issues and challenges owing to the involvement of intelligent technologies in the old-fashioned power-grid. The security issues that a smart or intelligent grid must deal with are as follows: Eavesdropping, Data tampering, Authorization and control access, Spoofing, Malicious code and Cyber-attacks. These issues get automatically accrued to a IoT based smart grid apart from the usual challenges of implementing IoT itself. These security issues and challenges may hold up the growth and incorporation of IoT-based power facilities [259]. Controlling and protecting the MGs via IoT thus still remains an unsolved research domain.
- Further research on advanced sensing and measuring devices and equipment needs to be done. This may include high-frequency sensing, dynamic and low-cost sensors for varying MG fault currents, relays having improved directional elements and non-electrical sensors. Moreover, the design of advanced current interrupting equipment such as solid-state CBs and improved MCCBs are also highly essential for smart MG protection.
- Several research works are available enumerating the developments in the field of the resiliency of EPSs and the role of MGs as a resilient resource, even though there are large numbers of issues yet to be addressed. High penetration of non-conventional energy sources (NCES) may cause unintentional islanding that may lead to the loss of robustness and ingenuity, and therefore, decrease in EPS resilience. Thus, such particular MPS should be developed which are applicable to EPS with large penetration of NCES and proficient in dealing with LPHI events.
- Wide area situation awareness (WASA) comprises of a collection of several advanced tools/technologies to boost EPS monitoring infrastructure and presents a dynamic view of the grid functionalities for the grid-operators [260]. The foremost objectives of the WASA are to supervise the EPS modules and to identify, prevent, and handle the problem before its occurrences. The WASA scheme collects a large stream of information from outsized topographical areas to build an automatic monitoring infrastructure (AMI) for the power grid [261]. As a result, the wide-area managements, wide-area communications system, and wide-area protection system (WAPS) can be achieved through the application of WASA infrastructure. In this regard, some recent works in this domain, especially microgrid are still in their early phases.
- Design of new MG protection standards which can spot the gaps in-between real-time power projects and its current solutions, and guide the future research development.

7. Conclusion

This paper has presented a detailed analysis regarding the issues, challenges and protective solutions to AC microgrid protection. The development of microgrid architecture for the solution to the greenhouse effect and global warming is still emergent and encouraging research field. The control and protection of microgrid are more challenging as compared to conventional distribution networks due to the bi-directional power flow and varying topology characteristics. This work comprises the current status, major hitches and existing research efforts focussed in the direction of providing a smooth relaying system under diverse microgrid operating conditions. Initially, the paper reviewed several survey articles that are directly or indirectly related to the scope of this work. The detail outcomes from this study are presented comprehensively with a critical analysis. Secondly, a brief discussion is given on the existing microgrid protection issues and their traditional protective solution. Thirdly, the article highlights the importance of artificial intelligence and computational intelligence on microgrid protection which has gained huge attention in the last decades. The article also presents a wide survey and review of recent techniques proposed by various researchers to mitigate the effects of DG integration on distribution system protection performance. In addition, we have presented several key challenges that are directed towards several open research scope. We hope that this survey will be helpful for the readers/researchers to gain an absolute picture and deep vision into this area.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Yoldaş Y, Önen A, Muyeen SM, Vasilakos AV, Alan İ. Enhancing smart grid with microgrids: Challenges and opportunities. Renew Sustain Energy Rev 2017;72:205–14.
[2] Bansal R. Power system protection in smart grid environment. CRC Press; 2019.
[3] Feng W, Jin M, Liu X, Bao Y, Marnay C, Yao C, et al. A review of microgrid development in the United States – A decade of progress on policies, demonstrations, controls, and software tools. Appl Energy 2018;2018(228):1656–68.
[4] Ustun TS, Ozansoy C, Zayegh A. Recent developments in microgrids and example cases around the world—A review. Renew Sustain Energy Rev 2011;15(8):4030–41.
[5] Jiayi H, Chuanwen J, Rong X. A review on distributed energy resources and microgrid. Renew Sustain Energy Rev 2008;12(9):2472–83.
[6] Basak P, Chowdhury S, nee Dey SH, Chowdhury SP. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renewable and Sustainable Energy Reviews, 2012; 16(8):5545–5556.
[7] Pesin Michael. U.S. Department of Energy Electricity Grid Research and Development, presentation at the American Council of Engineering Companies, Environment and Energy Committee Winter Meeting. 9 February; 2017.
[8] CIGRÉ, Working group C6.22. Microgrids 1: Engineering. Economics, & Experience, In CIGRE session Technical Brochure; 2015.
[9] Harmouch, F.Z., Krami, N., Benhaddou, D., Hmina, N., Zayer, E. and Margoum, E. H., Survey of multiagents systems application in Microgrids. In IEEE International Conference on Electrical and Information Technologies (ICEIT), 2016; p. 270-275.
[10] Adefarati T, Bansal RC. Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources. Appl Energy 2019;236:1089–114.
[11] Adefarati T, Bansal RC. Integration of renewable distributed generators into the distribution system: a review. IET Renew Power Gener 2016;10(7):873–84.
[12] Manditereza PT, Bansal RC. Review of technical issues influencing the decoupling of DG converter design from the distribution system protection strategy. IET Renew Power Gener 2018;12(10):1091–100.
[13] Manditereza PT, Bansal R. Renewable distributed generation: The hidden challenges – A review from the protection perspective. Renew Sustain Energy Rev 2016;58:1457–65.
[14] Beheshtaein, S., Savaghebi, M., Vasquez, J.C. and Guerrero, J.M., Protection of AC and DC microgrids: challenges, solutions and future trends. In IECON 41st Annual Conference of the IEEE Industrial Electronics Society ,2015; p. 005253-005260.
[15] Brearley BJ, Prabu RR. A review on issues and approaches for microgrid protection. Renew Sustain Energy Rev 2017;67:988–97.
[16] Kang X, Nuworklo CE, Tekpeti BS, Kheshti M. Protection of micro-grid systems: a comprehensive survey. The J Eng 2017;13:1515–8.
[17] Huayllas TDC, Ramos DS, Vasquez-Arnez RL, Microgrid systems: Current status

and challenges. In IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T&D-LA), 2010. p. 7-12.
[18] Asmus P, The Microgrid Revolution, [online] [accessed date 20-04-2020]. Available: http://www.peterasmus.com/journal/2009/11/6/the-microgrid-revolution.html.
[19] Memon A A, Kauhaniemi K. A critical review of AC Microgrid protection issues and available solutions. Electr Power Syst Res 2015;129:23–31 In this issue.
[20] Bhaskara SN, Chowdhury BH, Microgrids—A review of modeling, control, protection, simulation and future potential. IEEE Power and Energy Society General Meeting, 2012. p. 1–7.
[21] Haron AR, Mohamed A, Shareef H. A review on protection schemes and coordination techniques in microgrid system. J Appl Sci 2012;12(2):101–12.
[22] Justo JJ, Mwasilu F, Lee J, Jung JW. AC-microgrids versus DC-microgrids with distributed energy resources: A review. Renew Sustain Energy Rev 2013;2013(24):387–405.
[23] Gupta P, Bhatia RS, Jain DK. Adaptive protection schemes for the microgrid in a smart grid scenario: technical challenges. IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia) 2013:1–5.
[24] Mirsaeidi S, Said DM, Mustafa MW, Habibuddin MH, Ghaffari K. An analytical literature review of the available techniques for the protection of micro-grids. Int J Electr Power Energy Syst 2014;58:300–6.
[25] Choudhary NK, Mohanty SR, Singh RK. A review on microgrid protection. IEEE Int Electr Eng Congress (iEECON) 2014;:1–4.
[26] Beheshtaein S, Savaghebi M, Vasquez JC, Guerrero JM, November. Protection of AC and DC microgrids: challenges, solutions and future trends. 41st Annual Conference of the IEEE Industrial Electronics Society, 2015. p. 005253-60.
[27] Hare J, Shi X, Gupta S, Bazzi A. Fault diagnostics in smart micro-grids: a survey. Renew Sustain Energy Rev 2016;60:1114–24.
[28] Bansal Y, Sodhi R. Microgrid fault detection methods: reviews, issues and future trends. IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia) 2018:401–6.
[29] Bui DM, Chen SL. Fault protection solutions appropriately proposed for ungrounded low-voltage AC microgrids: Review and proposals. Renew Sustain Energy Rev 2017;75:1156–74.
[30] Bui DM, Chen SL, Lien KY, Chang YR, Lee YD, Jiang JL. Investigation on transient behaviours of a uni-grounded low-voltage AC microgrid and evaluation on its available fault protection methods: review and proposals. Renew Sustain Energy Rev 2017;75:1417–52.
[31] Habib HF, Lashway CR, Mohammed OA. A review of communication failure impacts on adaptive microgrid protection schemes and the use of energy storage as a contingency. IEEE Trans Ind Appl 2017;54(2):1194–207.
[32] Barra PHA, Coury DV, Fernandes RAS. A survey on adaptive protection of microgrids and distribution systems with distributed generators. Renew Sustain Energy Rev 2020;118:109524.
[33] Singh R, Bansal RC. Review of HRESs based on storage options, system architecture and optimisation criteria and methodologies. IET Renew Power Gener 2018;12(7):747–60.
[34] Sarangi S, Sahu BK, Rout PK. Distributed generation hybrid AC/DC microgrid protection: A critical review on issues, strategies, and future directions. Int J Energy Res 2020;44(5):3347–64.
[35] Mirsaeidi S, Dong X, Said DM. Towards hybrid AC/DC microgrids: critical analysis and classification of protection strategies. Renew Sustain Energy Rev 2018;90:97–103.
[36] Miraftabzadeh SM, Foiadelli F, Longo M, Pasetti M. A survey of machine learning applications for power system analytics. IEEE International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) 2019:1–5.
[37] Tu C, He X, Shuai Z, Jiang F. Big data issues in smart grid – A review. Renew Sustain Energy Rev 2017;79:1099–107.
[38] Hussain B, Sharkh SM, Hussain S, Abusara MA. An adaptive relaying scheme for fuse saving in distribution networks with distributed generation. IEEE Trans Power Delivery 2013;28(2):669–77.
[39] Lakervi, Erkki, Edward J. Holmes. Electricity distribution network design. No. 21. IET, 1995.
[40] Gers JM, Holmes EJ. Protection of electricity distribution networks. (Vol. 2004;47):IET.
[41] Anderson PM, 1998. Power System Protection. Wiley, 1998.
[42] Blackburn JL, Domin TJ. Protective relaying: principles and applications. CRC Press; 2014.
[43] Hussain B. Protection of distribution networks with distributed generation *(Doctoral dissertation.* University of Southampton); 2011.
[44] Kauhaniemi K, Kumpulainen L. Impact of distributed generation on the protection of distribution networks. Eighth IEE International Conference on Developments in Power System Protection 2004;1:315–8.
[45] Maki K, Repo S, Jarventausta P. Effect of wind power based distributed generation on protection of distribution network. Eighth IEE International Conference on Developments in Power System Protection 2014;1:327–30.
[46] Barker PP, De Mello RW, Determining the impact of distributed generation on power systems. I. Radial distribution systems. Power Engineering Society Summer Meeting (Cat. No. 00CH37134), 2000; 3: 1645-1656.
[47] Dugan RC, Mcdermott TE. Distributed generation. IEEE Ind Appl Mag 2002;8(2):19–25.
[48] Bansal R. Handbook of distributed generation. Springer International Publishing; 2017.
[49] Switzerland Valsan SP, Swarup KS. Wavelet transform based digital protection for transmission lines. International Journal of Electrical Power Energy System 2009;31(7–8):379–88.
[50] Working group D3, “Impact of distributed resources on distribution relay protection,” Line protection subcommittee of the Power System Relay Committee of the IEEE Power Engineering Society, Aug. 2004.
[51] Tsili M, Papathanassiou S. A review of grid code technical requirements for wind farms. IET Renew Power Gener 2009;3(3):308–32.
[52] Yazdanpanahi H, Li YW, Xu W. A new control strategy to mitigate the impact of inverter-based DGs on protection system. IEEE Trans Smart Grid 2012;3(3):1427–36.
[53] Laaksonen HJ. Protection principles for future microgrids. IEEE Trans Power Electron 2010;25(12):2910–8.
[54] Zhang P, Portillo L, Kezunovic M. Compatibility and interoperability evaluation for all-digital protection system through automatic application test. IEEE Power Engineering Society General Meeting 2006:7-pp.
[55] Babu PS, Kumar SJ, Chaitanya PRK. Digital relay based adaptive protection for distributed systems with distributed generation. Int J Energy Sci 2011;1(2):72–7.
[56] Ma J, Mi C, Wang T, Wu J, Wang Z. An adaptive protection scheme for distributed systems with distributed generation. IEEE Power and Energy Society General Meeting 2011:1–6.
[57] Linden J, Nikulshin Y, Friedman A, Yeshurun Y, Wolfus S. Phase-coupling effects in three-phase inductive fault-current limiter based on permanent magnets. IEEE Trans Magn 2020;56(2):1–7.
[58] Farzinfar M, Jazaeri M. A novel methodology in optimal setting of directional fault current limiter and protection of the MG. Int J Electr Power Energy Syst 2020;116:105564.
[59] Firouzi M. Low-Voltage Ride-Through (LVRT) Capability Enhancement of DFIG-Based Wind Farm by Using Bridge-Type Superconducting Fault Current Limiter (BTSFCL). J Power Technol 2020;99(4):245–53.
[60] Manigilla PKR, Sharma NK, Samantaray SR. Application of superconducting fault current limiter to cloud the presence of distributed generation. IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC) 2017:1–6.
[61] Shukla V, Mohapatra A, Singh SN. On adaptive fault current limiter in distribution systems with distributed generations. IEEE region 10 symposium (TENSYMP) 2017:1–5.
[62] Paquette AD, Divan DM. Virtual impedance current limiting for inverters in microgrids with synchronous generators. IEEE Trans Ind Appl 2014;51(2):1630–8.
[63] Plet CA, Green TC, A method of voltage limiting and distortion avoidance for islanded inverter-fed networks under fault. In IEEEProceedings of the 14th European Conference on Power Electronics and Applications 2011. p. 1-8.
[64] Salha F, Colas F, Guillaud X. October. Virtual resistance principle for the overcurrent protection of PWM voltage source inverter. IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010. p. 1–6.
[65] Rowe CN, Summers TJ, Betz RE, Moore TG, Townsend CD, September. Implementing the virtual output impedance concept in a three phase system utilising cascaded PI controllers in the dq rotating reference frame for microgrid inverter control. 15th IEEE European Conference on Power Electronics and Applications (EPE), 2013. p. 1–10.
[66] Lu X, Wang J, Guerrero JM, Zhao D. Virtual-impedance-based fault current limiters for inverter dominated AC microgrids. IEEE Trans Smart Grid 2016;9(3):1599–612.
[67] He J, Li YW. Analysis, design, and implementation of virtual impedance for power electronics interfaced distributed generation. IEEE Trans Ind Appl 2011;47(6):2525–38.
[68] Vilathgamuwa DM, Loh PC, Li Y. Protection of microgrids during utility voltage sags. IEEE Trans Ind Electron 2006;53(5):1427–36.
[69] SMB Smart Grid Strategic Group (SG3). IEC Smart Grid Standardization Roadmap. International Electrotechnical Commission (IEC), Geneva, Switzerland, Tech. Rep. Ed. 1.0, 2010.
[70] Ustun TS, Ozansoy C, Zayegh A. Modeling of a centralized microgrid protection system and distributed energy resources according to IEC 61850-7-420. IEEE Trans Power Syst 2012;27(3):1560–7.
[71] Higgins N, Vyatkin V, Nair NKC, Schwarz K. Distributed power system automation with IEC 61850, IEC 61499, and intelligent control. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews) 2010;41(1):81–92.
[72] Andren F, Bründlinger R, Strasser T. IEC 61850/61499 control of distributed energy resources: concept, guidelines, and implementation. IEEE Trans Energy Convers 2014;29(4):1008–17.
[73] Andrei H, Gaiceanu M, Stanculescu M, Marinescu I, Andrei PC. Microgrid Protection. In Microgrid Architectures: Control and Protection Methods Springer, Cham; 2020. p. 605–30.
[74] Ghosn SB, Ranganathan P, Salem S, Tang J, Loegering D, Nygard KE. Agent-oriented designs for a self-healing smart grid. First IEEE International Conference on Smart Grid Communications 2010:461–6.
[75] Zangeneh A, Moradzadeh M, Self-healing: Definition, Requirements, Challenges and Methods. In Microgrid Architectures, Control and Protection Methods, Springer, Cham. 2020. p. 509-525.
[76] Colson CM, Nehrir MH, Gunderson RW. Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing. 4th IEEE International Symposium on Resilient Control Systems 2011;p.:83–8.
[77] Arefifar SA, Mohamed YARI, El-Fouly TH. Comprehensive operational planning framework for self-healing control actions in smart distribution grids. IEEE Trans Power Syst 2013;28(4):4192–200.
[78] Lim SI, Lee SJ, Choi MS, Lim DJ, Ha BN. Service restoration methodology for

multiple fault case in distribution systems. IEEE Trans Power Syst 2006;21(4):1638–44.
[79] Solanki JM, Khushalani S, Schulz NN. A multi-agent solution to distribution systems restoration. IEEE Trans Power Syst 2007;22(3):1026–34.
[80] Gupta R, Jha DK, Yadav VK, Kumar S, A multi-agent based self-healing smart grid. In IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2013. p. 1-5.
[81] Morelato AL, Monticelli A. Heuristic search approach to distribution system restoration. IEEE Power Eng Rev 1989;9(10):65–6.
[82] Pham TTH, Bésanger Y, Hadjsaid N. New challenges in power system restoration with large scale of dispersed generation insertion. IEEE Trans Power Syst 2009;24(1):398–406.
[83] Communication networks and systems in substation-Part 10: Conformance testing, IEC Std. 61 850. https://webstore.iec.ch/publication/6008 [Accessed date 20-05-2020].
[84] Kezunovic M, Popovic T. Assessing application features of protective relays and systems through automated testing using fault transients. IEEE/PES Transmission and Distribution Conference and Exhibition 2002;3:1742–7.
[85] Kezunovic, Mladen, and Bogdan Kasztenny. Design optimization and performance evaluation of the relaying algorithms, relays and protective systems using advanced testing tools. In: Proceedings of the 21st IEEE International Conference on Power Industry Computer Applications. Connecting Utilities. PICA 99. To the Millennium and Beyond (Cat. No. 99CH36351),1999; p. 309-314.
[86] Kezunovic M, Popovic T, Sevcik, D, DoCarmo H, Transient testing of protection relays: Results, methodology and tools. In International Conference on Power Systems Transients (IPST) 2003.
[87] Mishra M, Rout PK. A comprehensive micro-grid fault protection scheme based on S-transform and machine learning techniques. Int J Adv Mechatr Syst 2017;7(5):274–89.
[88] Jenkins N, Wu X, Jayawarna N, Zhang Y, Lopes JP, Moreira C, Madureira A, da Silva JP. Protection guidelines for a microgrid. Final Draft as part of deliverable of WP E on Microgrids EU-project; 2005.
[89] Ustun TS, Ozansoy C, Ustun A. Fault current coefficient and time delay assignment for microgrid protection system with central protection unit. IEEE Trans Power Syst 2012;28(2):598–606.
[90] Etemadi AH, Iravani R. Overcurrent and overload protection of directly voltage-controlled distributed resources in a microgrid. IEEE Trans Ind Electron 2012;60(12):5629–38.
[91] Laaksonen H, Ishchenko D, Oudalov A. Adaptive protection and microgrid control design for Hailuoto Island. IEEE Trans Smart Grid 2014;5(3):1486–93.
[92] Chattopadhyay B, Sachdev MS, Sidhu TS. An on-line relay coordination algorithm for adaptive protection using linear programming technique. IEEE Trans Power Delivery 1996;11(1):165–73.
[93] Shih MY, Salazar CAC, Enríquez AC. Adaptive directional overcurrent relay coordination using ant colony optimisation. IET Gener Transm Distrib 2015;9(14):2040–9.
[94] Singh M, Vishnuvardhan T, Srivani SG. Adaptive protection coordination scheme for power networks under penetration of distributed energy resources. IET Gener Transm Distrib 2016;10(15):3919–29.
[95] Kano I, Takahashi Y. Effect of electric field generated by micro sized electrode on pool boiling. IEEE Trans Ind Appl 2013;49(6):2382–7.
[96] El Naily N, Saad SM, Wafi J, Elhaffar A. Husseinzadch N, Adaptive overcurrent protection to mitigate high penetration of distributed generation in weak distribution systems. 9th IEEE-GCC conference and exhibition (GCCCE), 2017. p. 1-9.
[97] Momesso AE, Bernardes WMS, Asada EN. Fuzzy adaptive setting for time-current-voltage based overcurrent relays in distribution systems. Int J Electr Power Energy Syst 2019;108:135–44.
[98] Ojaghi M, Mohammadi V. Use of clustering to reduce the number of different setting groups for adaptive coordination of overcurrent relays. IEEE Trans Power Delivery 2017;33(3):1204–12.
[99] Liu C, Chen Z, Liu Z. A communication-less overcurrent protection for distribution system with distributed generation integrated. IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG) 2012:140–7.
[100] Coffele F, Booth C, Dyśko A. An adaptive overcurrent protection scheme for distribution networks. IEEE Trans Power Delivery 2014;30(2):561–8.
[101] Piesciorovsky EC, Schulz NN. Comparison of Programmable Logic and Setting Group Methods for adaptive overcurrent protection in microgrids. Electr Power Syst Res 2017;151:273–82.
[102] Ferreira RR, Grilo AP, Teixeira JC, Santos RC. Method for adaptive overcurrent protection of distribution systems with Distributed synchronous Generators. In2015 IEEE Power & Energy Society General Meeting 2015 Jul 26; p. 1-5.
[103] Ferreira RR, Colorado PJ, Grilo AP, Teixeira JC, Santos RC. Method for identification of grid operating conditions for adaptive overcurrent protection during intentional islanding operation. Int J Electr Power Energy Syst 2019;105:632–41.
[104] Baran M, El-Markabi I. Adaptive over current protection for distribution feeders with distributed generators. IEEE PES Power Systems Conference and Exposition 2004:715–9.
[105] Zanjani MGM, Mazlumi K, Kamwa I. Application of μPMUs for adaptive protection of overcurrent relays in microgrids. IET Gener Transm Distrib 2018;12(18):4061–8.
[106] Alam MN. Overcurrent protection of AC microgrids using mixed characteristic curves of relays. Comput Electr Eng 2019;74:74–88.
[107] Slabbert MJ, van Zyl SJ, Naidoo R, Bansal RC. Evaluating phase over-current protection philosophies for medium-voltage feeders applying let-through energy and voltage dip minimization. Electr Power Compon Syst 2016;44(2):206–18.
[108] Nale R, Chandrakar R, Verma H, Biswal M. A directional relaying scheme for microgrid protection. Intel Comput Tech Smart Energy Syst 2020:331–40.
[109] Ocampa-Wilches JA, Ustariz-Farfan AJ, Cano-Plata EA. Modeling of a communications-based directional overcurrent protection scheme for microgrids. IEEE ANDESCON 2018:1–6.
[110] El-Khattam W, Sidhu TS. Restoration of directional overcurrent relay coordination in distributed generation systems utilizing fault current limiter. IEEE Trans Power Delivery 2008;23(2):576–85.
[111] El-Khattam W, Sidhu TS. Resolving the impact of distributed renewable generation on directional overcurrent relay coordination: a case study. IET Renew Power Gener 2009;3(4):415–25.
[112] Khederzadeh M, Application of tcsc to restore directional overcurrent relay coordination in systems with distributed generation. In 20th International Conference and Exhibition on Electricity Distribution (CIRED), 2009; 41(4).
[113] Huchel Ł, Zeineldin HH. Planning the coordination of directional overcurrent relays for distribution systems considering DG. IEEE Trans Smart Grid 2015;7(3):1642–9.
[114] Dewadasa M, Majumder R, Ghosh A, Ledwich G. Control and protection of a microgrid with converter interfaced micro sources. IEEE Int Conf Power Syst 2009:1–6.
[115] Tsimtsios AM, Korres GN, Nikolaidis VC. A pilot-based distance protection scheme for meshed distribution systems with distributed generation. Int J Electr Power Energy Syst 2019;105:454–69.
[116] Chilvers IM, Jenkins N, Crossley PA. The use of 11 kV distance protection to increase generation connected to the distribution network. Eighth IEE International Conference on Developments in Power System Protection 2004;2:551–4.
[117] Uthitsunthorn D, Kulworawanichpong T. Distance protection of a renewable energy plant in electric power distribution systems. IEEE International Conference on Power System Technology 2010:1–6.
[118] Ma J, Li J, Wang Z. An adaptive distance protection scheme for distribution system with distributed generation. 5th IEEE International Conference on Critical Infrastructure (CRIS), 2010; p. 1–4.
[119] Lin H, Liu C, Guerrero JM, Vásquez JC. Distance protection for microgrids in distribution system. *41st.* Annual Conference of the IEEE Industrial Electronics Society 2015:000731–6.
[120] Chaitanya BK, Yadav A, Pazoki M. An improved differential protection scheme for micro-grid using time-frequency transform. Int J Electr Power Energy Syst 2019;111:132–43.
[121] Conti S, Raffa L, Vagliasindi U. Innovative solutions for protection schemes in autonomous MV micro-grids. International Conference on Clean Electrical Power 2009:647–54.
[122] Sortomme E, Venkata SS, Mitra J. Microgrid protection using communication-assisted digital relays. IEEE Trans Power Delivery 2009;25(4):2789–96.
[123] Dewadasa M, Ghosh A, Ledwich G. Protection of microgrids using differential relays. IEEE 21st Australasian Universities Power Engineering Conference (AUPEC) 2011.
[124] Aghdam TS, Karegar HK, Zeineldin HH. Variable tripping time differential protection for microgrids considering DG stability. IEEE Trans Smart Grid 2018;10(3):2407–15.
[125] Nikkhajoei H, Lasseter RH. Microgrid fault protection based on symmetrical and differential current components. Power System Engineering Research Center 2006:71–4.
[126] Zamani MA, Sidhu TS, Yazdani A. A protection strategy and microprocessor-based relay for low-voltage microgrids. IEEE Trans Power Delivery 2011;26(3):1873–83.
[127] Mirsaeidi S, Said DM, Mustafa MW, Habibuddin MH. A protection strategy for micro-grids based on positive-sequence component. IET Renew Power Gener 2015;9(6):600–9.
[128] Muda H, Jena P. Sequence currents based adaptive protection approach for DNs with distributed energy resources. IET Gener Transm Distrib 2017;11(1):154–65.
[129] Muda H, Jena P. Superimposed adaptive sequence current based microgrid protection: a new technique. IEEE Trans Power Delivery 2016;32(2):757–67.
[130] Guo C, Liu Y, Zhao C, Wei X, Xu W. Power component fault detection method and improved current order limiter control for commutation failure mitigation in HVDC. IEEE Transactions on Power Delivery 2015;30(3):1585–1593.
[131] Casagrande E, Woon WL, Zeineldin HH, Svetinovic D. A differential sequence component protection scheme for microgrids with inverter-based distributed generators. IEEE Trans Smart Grid 2013;5(1):29–37.
[132] Al-Nasseri H, Redfern MA, Li F. A voltage based protection for micro-grids containing power electronic converters. IEEE Power Eng Soc General Meeting 2006:1–7.
[133] Ma J, Ma W, Wang X, Wang Z. A new adaptive voltage protection scheme for distribution network with distributed generations. Can J Electr Comput Eng 2013;36(4):142–51.
[134] Al-Nasseri H, Redfern MA. Harmonics content based protection scheme for micro-grids dominated by solid state converters. IEEE 12th International Middle-East Power System Conference 2008:50–6.
[135] Redfern MA, AL-Nasseri H. Protection of micro-grids dominated by distributed generation using solid state converters. In: IET 9th International Conference on Developments in Power System Protection (DPSP) 2008;pp. 670–674.
[136] Hou C, Hu X. A study of voltage detection based fault judgement method in micro-grid with inverter interfaced power source. In: the International Conference on Electrical Engineering, 2009; p. 1–5.
[137] Tephiruk N, Hongesombut K, Urathamakul Y, Poonvasin S, Tangsatit S. Modeling

of rate of change of under frequency relay for microgrid protection. Int Electr Eng Congress (iEECON) 2017:1–4.
[138] Ranjbar S, Farsa AR, Jamali S. Voltage-based protection of microgrids using decision tree algorithms. Int Trans Electri Energy Syst 2020;30(4):e12274.
[139] Aftab MA, Hussain SS, Ali I, Ustun TS. Dynamic protection of power systems with high penetration of renewables: a review of the traveling wave based fault location techniques. Int J Electr Power Energy Syst 2020;114:105410.
[140] Shi S, Jiang B, Dong X, Bo Z. Protection of microgrid. In: Proceeding of the managing the change 10th IET International Conference on Developments in Power System Protection, March 29-April 1, Manchester, UK, 2010; p.1–4.
[141] Li X, Dyśko A, Burt GM. Traveling wave-based protection scheme for inverter-dominated microgrid using mathematical morphology. IEEE Trans Smart Grid 2014;5(5):2211–8.
[142] Davydova N, Hug G. Travelling wave protection with disturbance classification for distribution grids with distributed generation. J Eng 2018;2018(15):830–5.
[143] George SP, Ashok S. Multiagent based adaptive relaying for distribution network with distributed generation. IEEE International Conference on Energy, Power and Environment: Towards Sustainable Growth (ICEPE) 2015:1–6.
[144] Faria IM, Furlan RH, Martins PET, Menezes TS, Oleskovicz M, Coury DV. The proposition of a multiagent system for adaptive protection of a distribution system. IEEE Simposio Brasileiro de Sistemas Eletricos (SBSE) 2018:1–6.
[145] Daryani MJ, Karkevandi AE. Decentralized cooperative protection strategy for smart distribution grid using multi-agent system. IEEE 6th International Istanbul Smart Grids and Cities Congress and Fair (ICSG) 2018:134–8.
[146] Zheng Y, Song Y, Hill DJ, Zhang Y. Multiagent system based microgrid energy management via asynchronous consensus ADMM. IEEE Trans Energy Convers 2018;33(2):886–8.
[147] Liu W, Gu W, Sheng W, Meng X, Wu Z, Chen W. Decentralized multi-agent system-based cooperative frequency control for autonomous microgrids with communication constraints. IEEE Trans Sustain Energy 2014;5(2):446–56.
[148] Alwala S, Feliachi A, Choudhry MA. Multi agent system based fault location and isolation in a smart microgrid system. IEEE PES Innovative Smart Grid Technologies (ISGT) 2012:1–4.
[149] Karavas CS, Kyriakarakos G, Arvanitis KG, Papadakis G. A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids. Energy Convers Manage 2015;103:166–79.
[150] Hussain A, Aslam M, Arif SM. N-version programming-based protection scheme for microgrids: a multi-agent system based approach. Sustain Energy Grids Networks 2016;6:35–45.
[151] Habib HF, Mohammed O. Decentralized multi-agent system for protection and the power restoration process in microgrids. Ninth Annual IEEE Green Technologies Conference (GreenTech) 2017:358–64.
[152] Rahman MS, Orchi TF, Saha S, Haque ME. Multi-agent approach for overcurrent protection coordination in low voltage microgrids. IEEE Power & Energy Society General Meeting (PESGM) 2019:1–5.
[153] Mishra M, Chandak S, Rout PK. Taxonomy of islanding detection techniques for distributed generation in microgrid. Renewable Energy Focus 2019;31:9–30.
[154] Kai-Hui Z, Ming-Chao X. Impacts of microgrid on protection of distribution networks and protection strategy of microgrid. IEEE International Conference on Advanced Power System Automation and Protection 2011;1:356–9.
[155] Oudalov A, Fidigatti A. Adaptive network protection in microgrids. Int J Distribut Energy Resour 2009;5(3):201–26.
[156] Han Y, Hu X, Zang D. Study of adaptive fault current algorithm for microgrid dominated by inverter based distributed generators. IEEE International Symposium on Power Electronics for Distributed Generation Systems 2010:852–4.
[157] Brahma SM, Girgis AA. Microprocessor-based reclosing to coordinate fuse and recloser in a system with high penetration of distributed generation. In: IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 02CH37309), 2002; 1: 453-458.
[158] Brahma SM, Girgis AA. Development of adaptive protection scheme for distribution systems with high penetration of distributed generation. IEEE Trans Power Delivery 2004;19(1):56–63.
[159] Tumilty R, Brucoli M, Burt GM, Green T, Approaches to network protection for inverter dominated electrical distribution systems. In: 3rd IET International Conference on Power Electronics, Machines and Drives 2006; p. 622-626.
[160] Schaefer N, Degner T, Shustov A, Keil T, Jaeger J. Adaptive protection system for distribution networks with distributed energy resources. In: 10th IET International Conference on Developments in Power System Protection (DPSP). Managing the Change; 2010. p. 1–5.
[161] Dang K, He X, Bi D, Feng C. An adaptive protection method for the inverter dominated microgrid. IEEE International Conference on Electrical Machines and Systems 2011:1–5.
[162] Khederzadeh M. Adaptive setting of protective relays in microgrids in grid-connected and autonomous operation. In: 11th IET International Conference on Developments in Power Systems Protection (DPSP), 2012; p. 1–4.
[163] Shah PH, Bhalja BR. New adaptive digital relaying scheme to tackle recloser - fuse miscoordination during distributed generation interconnections. IET Gener Transmiss Distribut 2014;8:682–8.
[164] Swathika OG, Hemamalini S. Prims-aided Dijkstra algorithm for adaptive protection in microgrids. IEEE J Emerg Select Top Power Electron 2016;4(4):1279–86.
[165] Swathika OG, Hemamalini S. Graph theory and optimization algorithms aided adaptive protection in reconfigurable microgrid. J Electr Eng Technol 2020;15(1):421–31.
[166] Singh M, Basak P. Adaptive protection methodology in microgrid for fault location and nature detection using q0 components of fault current. IET Gener Transm Distrib 2018;13(6):760–9.
[167] Peiris WLT, Eranga WH, Hemapala KTMU, Prasad WD. An adaptive protection scheme for small scale microgrids based on fault current level. IEEE 2nd International Conference on Electrical Engineering (EECon), 2018; p. 64–70.
[168] Sharafi A, Sanaye-Pasand M, Aminifar F. Transmission system wide-area back-up protection using current phasor measurements. Int J Electr Power Energy Syst 2017;92:93–103.
[169] Elghazaly H, Emam A, Saber A. A backup wide-area protection technique for power transmission network. IEEJ Trans Electr Electron Eng 2017;12(5):702–9.
[170] Mallikarjuna B, Varma PV, Samir SD, Reddy MJB, Mohanta DK. An adaptive supervised wide-area backup protection scheme for transmission lines protection. Protect Control Modern Power Syst 2017;2(1):22.
[171] Eissa MM, Masoud ME, Elanwar MMM. A novel back up wide area protection technique for power transmission grids using phasor measurement unit. IEEE Trans Power Delivery 2009;25(1):270–8.
[172] Miao S, Liu P, Lin X. An adaptive operating characteristic to improve the operation stability of percentage differential protection. IEEE Trans Power Delivery 2010;25(3):1410–7.
[173] Sheng S, Li KK, Chan WL, Zeng X, Shi D, Duan X. Adaptive agent-based wide-area current differential protection system. IEEE Trans Ind Appl 2010;46(5):2111–7.
[174] Lin X, Lu Y, Wang L. New current protection scheme considering distributed generation impact. Automat Electric Power Syste 2008;32(20):50–6.
[175] Lin X, Lu Y, Wang L. New fault region location scheme in distribution system with DGs. Trans China Electrotech Soc 2008;11:023.
[176] Gopalan SA, Sreeram V, Lu HH. A review of coordination strategies and protection schemes for microgrids. Renew Sustain Energy Rev 2014;32:222–8.
[177] Zhang F, Mu L. Wide-area protection scheme for active distribution networks based on phase comparison. In: the 5th IEEE International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT) 2015; p. 927-932.
[178] Zhang F, Mu L, Guo W. An integrated wide-area protection scheme for active distribution networks based on fault components principle. IEEE Trans Smart Grid 2017;10(1):392–402.
[179] Harley RG, Liang J. Computational intelligence in smart grids. IEEE Symposium Series on Computational Intelligence (SSCI) 2011;1:1–8.
[180] Gao X, Ai X. The application of self-healing technology in smart grid. IEEE Asia-Pacific Power and Energy Engineering Conference 2011:1–4.
[181] Hussain MH, Musirin I, Rahim SRA, Abidin AF. Computational intelligence based technique in optimal overcurrent relay coordination: a review. The International Journal of Engineering and Science (IJES) 2013;2(1):01–9.
[182] Bansal RC. Overview and literature survey of artificial neural networks applications to power systems (1992-2004). Journal of Institution of Engineers (India)–Electrical Engineering, 2006; 86(1): 282–296.
[183] Beheshtaein S, Cuzner R, Savaghebi M, Guerrero JM. Review on microgrids protection. IET Gener Transm Distrib 2019;13(6):743–59.
[184] Chen K, Huang C, He J. Fault detection, classification and location for transmission lines and distribution systems: a review on the methods. High Voltage 2016;1(1):25–33.
[185] Kar S, Samantaray SR, Zadeh MD. Data-mining model based intelligent differential microgrid protection scheme. IEEE Syst J 2015;11(2):1161–9.
[186] Mishra DP, Samantaray SR, Joos G. A combined wavelet and data-mining based intelligent protection scheme for microgrid. IEEE Trans Smart Grid 2015;7(5):2295–304.
[187] Mishra M, Rout PK. Detection and classification of micro-grid faults based on HHT and machine learning techniques. IET Gener Transm Distrib 2017;12(2):388–97.
[188] Lin H, Guerrero JM, Jia C, Tan ZH, Vasquez JC, Liu C. Adaptive overcurrent protection for microgrids in extensive distribution systems. IEEE 42nd Annual Conference of the IEEE Industrial Electronics Society 2016:4042–7.
[189] Kar S, Samantaray SR. Combined S-transform and data-mining based intelligent micro-grid protection scheme. IEEE Students Conference on Engineering and Systems 2014:1–5.
[190] Lin H, Sun K, Tan ZH, Liu C, Guerrero JM, Vasquez JC. Adaptive protection combined with machine learning for microgrids. IET Gener Transm Distrib 2019;13(6):770–9.
[191] Swathika OG, Angalaeswari S, Krishnan VA, Jamuna K, Daya JF. Fuzzy decision and graph algorithms aided adaptive protection of microgrid. Energy Procedia 2017;117:1078–84.
[192] Lei L, Wang C, Zhao J, Wang X. A protection method based on feature cosine and differential scheme for microgrid. Math Prob Eng 2019:7248072https://doi.org/10.1155/2019/7248072. In press.
[193] James JQ, Hou Y, Lam AY, Li VO. Intelligent fault detection scheme for microgrids with wavelet-based deep neural networks. IEEE Trans Smart Grid 2017;10(2):1694–703.
[194] Abdulwahid A, Wang S. A novel approach for microgrid protection based upon combined ANFIS and Hilbert space-based power setting. Energies 2016;9(12):1042.
[195] Netsanet S, Zhang J, Zheng D. Bagged decision trees based scheme of microgrid protection using windowed fast fourier and wavelet transforms. Electronics 2018;7(5):61.
[196] Mishra M, Panigrahi RR, Rout PK. A combined mathematical morphology and extreme learning machine techniques based approach to micro-grid protection.

Ain Shams Eng J 2019;10(2):307–18.
[197] Bukhari SBA, Haider R, Zaman MSU, Oh YS, Cho GJ, Kim CH. An interval type-2 fuzzy logic based strategy for microgrid protection. Int J Electr Power Energy Syst 2018;98:209–18.
[198] Manohar M, Koley E, SVM based protection scheme for microgrid. International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT), 2017; p. 429–432.
[199] Chaitanya BK, Yadav A, Pazoki M. Wide area monitoring and protection of microgrid with DGs using modular artificial neural networks. Neural Computer & Application 2020;2020(32):2125–39. https://doi.org/10.1007/s00521-018-3750-4.
[200] Ahmadipour M, Hizam H, Othman ML, Radzi MA. Islanding detection method using ridge let probabilistic neural network in distributed generation. Neurocomputing 2019;329:188–209.
[201] Gupta N, Garg R. Algorithm for islanding detection in photovoltaic generator network connected to low-voltage grid. IET Gener Transm Distrib 2018;12(10):2280–7.
[202] Kong X, Xu X, Yan Z, Chen S, Yang H, Han D. Deep learning hybrid method for islanding detection in distributed generation. Appl Energy 2018;210:776–85.
[203] Hatata AY, Abd-Raboh EH, Sedhom BE. Proposed Sandia frequency shift for anti-islanding detection method based on artificial immune system. Alexandria Eng J 2018;57(1):235–45.
[204] Azim R, Li F, Xue Y, Starke M, Wang H. An islanding detection methodology combining decision trees and Sandia frequency shift for inverter-based distributed generations. IET Gener Transm Distrib 2017;11(16):4104–13.
[205] Alam MR, Muttaqi KM, Bouzerdoum A. Evaluating the effectiveness of a machine learning approach based on response time and reliability for islanding detection of distributed generation. IET Renew Power Gener 2017;11(11):1392–400.
[206] Hashemi F, Mohammadi M, Kargarian A. Islanding detection method for microgrid based on extracted features from differential transient rate of change of frequency. IET Gener Transm Distrib 2017;11(4):891–904.
[207] Mishra M, Sahani M, Rout PK. An islanding detection algorithm for distributed generation based on Hilbert-Huang transform and extreme learning machine. Sustain Energy Grids Networks 2017;9:13–26.
[208] Mishra M, Sahani M, Rout PK. An islanding detection method based on wavelet packet transform and extreme learning machine. Int J Renew Energy Res (IJRER) 2016;6(3):856–65.
[209] Mishra M, Rout PK. Time-frequency analysis based approach to islanding detection in micro-grid system. Int Rev Electr Eng 2016;11(1):116–29.
[210] Khamis A, Shareef H, Mohamed A, Bizkevelci E. Islanding detection in a distributed generation integrated power system using phase space technique and probabilistic neural network. Neurocomputing 2015;148:587–99.
[211] Raza S, Mokhlis H, Arof H, Laghari JA, Wang L. Application of signal processing techniques for islanding detection of distributed generation in distribution network: a review. Energy Convers Manage 2015;96:613–24.
[212] Dhar S, Dash PK. Performance analysis of a new fast negative sequence power injection oriented islanding detection technique for photovoltaic based voltage source converter based micro grid operation. IET Gener Transm Distrib 2015;9(15):2079–90.
[213] Faqhruldin ON, El-Saadany EF, Zeineldin HH. A universal islanding detection technique for distributed generation using pattern recognition. IEEE Trans Smart Grid 2014;5(4):1985–92.
[214] Faqhruldin ON, El-Saadany EF, Zeineldin HH. Naive Bayesian islanding detection technique for distributed generation in modern distribution system. IEEE Electrical Power and Energy Conference 2012:69–74.
[215] ElNozahy MS, El-Saadany EF, Salama MM. A robust wavelet-ANN based technique for islanding detection. IEEE Power and Energy Society General Meeting 2011:1–8.
[216] Lidula NWA, Perera N, Rajapakse AD. Investigation of a fast islanding detection methodology using transient signals. IEEE Power & Energy Society General Meeting 2009:1–6.
[217] Mohammadzadeh N, Chabanloo RM, Maleki MG. Optimal coordination of directional overcurrent relays considering two-level fault current due to the operation of remote side relay. Electr Power Syst Res 2019;175:105921.
[218] Urdaneta AJ, Restrepo H, Marquez S, Sanchez J. Coordination of directional overcurrent relay timing using linear programming. IEEE Trans Power Delivery 1996;11(1):122–9.
[219] Abyaneh HA, Al-Dabbagh M, Karegar HK, Sadeghi SHH, Khan RJ. A new optimal approach for coordination of overcurrent relays in interconnected power systems. IEEE Trans Power Delivery 2003;18(2):430–5.
[220] Corrêa R, Cardoso Jr G, de Araújo OC, Mariotto L. Online coordination of directional overcurrent relays using binary integer programming. Electr Power Syst Res 2015;127:118–25.
[221] Papaspiliotopoulos VA, Korres GN, Maratos NG. A novel quadratically constrained quadratic programming method for optimal coordination of directional overcurrent relays. IEEE Trans Power Delivery 2015;32(1):3–10.
[222] Zeineldin HH, Sharaf HM, Ibrahim DK, El-Zahab EEDA. Optimal protection coordination for meshed distribution systems with DG using dual setting directional over-current relays. IEEE Trans Smart Grid 2014;6(1):115–23.
[223] Dehghanpour E, Karegar HK, Kheirollahi R, Soleymani T. Optimal coordination of directional overcurrent relays in microgrids by using cuckoo-linear optimization algorithm and fault current limiter. IEEE Trans Smart Grid 2016;9(2):1365–75.
[224] Papaspiliotopoulos VA, Kurashvili TA, Korres GN. Optimal coordination of directional overcurrent relays in distribution systems with distributed generation based on a hybrid PSO-LP algorithm. Athens, Greece: Proc. IET Conf. MedPower; Nov. 2014. p. 2–5.
[225] Najy WK, Zeineldin HH, Woon WL. Optimal protection coordination for microgrids with grid-connected and islanded capability. IEEE Trans Ind Electron 2012;60(4):1668–77.
[226] Ray P. Intelligent relay coordination method for microgrid. In: Microgrid: Operation, Control, Monitoring and Protection, 2020; pp. 239-261.
[227] Avachat T, Tibrewala S, Barve R, Swathika OG. Overcurrent relay coordination in a grid-connected microgrid system. Journal of Telecommunication, Electronic and Computer Engineering (JTEC) 2018;10(1–9):1–5.
[228] Arzinfar M, Jazaeri M. A novel methodology in optimal setting of directional fault current limiter and protection of the MG. Int J Electr Power Energy Syst 2020;116:105564.
[229] El-Naily N, Saad SM, Mohamed FA. Novel approach for optimum coordination of overcurrent relays to enhance microgrid earth fault protection scheme. Sustain Cities Soc 2020;54:102006.
[230] Arghandeh R, Von Meier A, Mehrmanesh L, Mili L. On the definition of cyber-physical resilience in power systems. Renew Sustain Energy Rev 2016;58:1060–9.
[231] Hussain A, Bui VH, Kim HM. Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience. Appl Energy 2019;240:56–72.
[232] Bajwa AA, Mokhlis H, Mekhilef S, Mubin M. Enhancing power system resilience leveraging microgrids: A review. J Renew Sustain Energy 2019;11(3):035503.
[233] Pashajavid E, Shahnia F, Ghosh A. Development of a self-healing strategy to enhance the overloading resilience of islanded microgrids. IEEE Trans Smart Grid 2015;8(2):868–80.
[234] Mahzarnia M, Moghaddam MP, Baboli PT, Siano P. A review of the measures to enhance power systems resilience. IEEE Syst J 2020. https://doi.org/10.1109/JSYST.2020.2965993.
[235] Strbac G, Hatziargyriou N, Lopes JP, Moreira C, Dimeas A, Papadaskalopoulos D. Microgrids: enhancing the resilience of the European megagrid. IEEE Power Energ Mag 2015;13(3):35–43.
[236] Yuan C. Resilient distribution systems with community microgrids (Doctoral dissertation, The Ohio State University); 2016.
[237] Chen C, Wang J, Qiu F, Zhao D. Resilient distribution system by microgrids formation after natural disasters. IEEE Trans Smart Grid 2015;7(2):958–66.
[238] Li Z, Shahidehpour M, Aminifar F, Alabdulwahab A, Al-Turki Y. Networked microgrids for enhancing the power system resilience. Proc IEEE 2017;105(7):1289–310.
[239] Wang C, Hou Y, Qiu F, Lei S, Liu K. Resilience enhancement with sequentially proactive operation strategies. IEEE Trans Power Syst 2016;32(4):2847–57.
[240] Balasubramaniam K, Saraf P, Hadidi R, Makram EB. Energy management system for enhanced resiliency of microgrids during islanded operation. Electr Power Syst Res 2016;137:133–41.
[241] Hussain A, Bui VH, Kim HM. Fuzzy logic-based operation of battery energy storage systems (BESSs) for enhancing the resiliency of hybrid microgrids. Energies 2017;10(3):271.
[242] Chen J, Zhu Q. A game-theoretic framework for resilient and distributed generation control of renewable energies in microgrids. IEEE Trans Smart Grid 2016;8(1):285–95.
[243] Dehghanpour K, Colson C, Nehrir H. A survey on smart agent-based microgrids for resilient/self-healing grids. Energies 2017;10(5):620.
[244] Mishra S, Anderson K, Miller B, Boyer K, Warren A. Microgrid resilience: A holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies. Appl Energy 2020;264:114726.
[245] Arghandeh R, Brown M, Del Rosso A, Ghatikar G, Stewart E, Vojdani A, von Meier A. The local team: Leveraging distributed resources to improve resilience. IEEE Power and Energy Magazine 12(5); 2014:76-83.
[246] Manohar M, Koley E, Ghosh S. Enhancing resilience of PV-fed microgrid by improved relaying and differentiating between inverter faults and distribution line faults. Int J Electr Power Energy Syst 2019;108:271–9.
[247] Albatsh FM, Mekhilef S, Ahmad S, Mokhlis H, Hassan MA. Enhancing power transfer capability through flexible AC transmission system devices: a review. Frontiers of Information Technology & Electronic Engineering, 2015; 16(8), 658-678.
[248] Abdelsalam AA, Gabbar HA, Sharaf AM. Performance enhancement of hybrid AC/DC microgrid based D-FACTS. Int J Electr Power Energy Syst 2014;2014(63):382–93.
[249] Sahoo B, Samantaray SR. An enhanced fault detection and location estimation method for TCSC compensated line connecting wind farm. Int J Electr Power Energy Syst 2018;96:432–41.
[250] Jena MK, Samantaray SR. Data-mining-based intelligent differential relaying for transmission lines including UPFC and wind farms. IEEE Transactions on Neural Networks and Learning Systems, 2016;27(1),8-17.
[251] Dubey R, Samantaray SR, Panigrahi BK, Venkoparao GV. Adaptive distance relay for parallel transmission network connecting wind farms and UPFC. Int J Electr Power Energy Syst 2015;2015(65):113–23.
[252] Ghadiri SME, Mazlumi K. Adaptive protection scheme for microgrids based on SOM clustering technique. Appl Soft Comput 2020;88:106062.
[253] Strezoski L, Stefani I, Bekut D. Novel method for adaptive relay protection in distribution systems with electronically-coupled DERs. Int J Electr Power Energy Syst 2020;116:105551.
[254] Sharma A, Panigrahi BK. Interphase Fault Relaying Scheme to Mitigate Sympathetic Tripping in Meshed Distribution System. IEEE Trans Ind Appl 2018;55(1):850–7.

[255] Manditereza PT, Bansal RC. Protection of microgrids using voltage-based power differential and sensitivity analysis. Int J Electr Power Energy Syst 2020;118:105756.
[256] Esfahani MM, Mohammed O. An intelligent protection scheme to deal with extreme fault currents in smart power systems. Int J Electr Power Energy Syst 2020;115:105434.
[257] Jarrahi MA, Samet H, Ghanbari T. Novel change detection and fault classification scheme for AC microgrids. IEEE Syst J 2020. https://doi.org/10.1109/JSYST.2020.2966686.
[258] Habib HF, Lashway CR, Mohammed OA. On the adaptive protection of microgrids: a review on how to mitigate cyber-attacks and communication failures. IEEE Industry Applications Society Annual Meeting 2017:1–8.
[259] Birleanu FG, Bizon N, Control and protection of the smart microgrids using internet of things: technologies, architecture and applications. In Microgrid Architectures, Control and Protection Methods, 2020; p. 749-770.
[260] Ghorbanian M, Dolatabadi SH, Masjedi M, Siano P. Communication in smart grids: A comprehensive review on the existing and future communication and information infrastructures. IEEE Syst J 2019;13(4):4001–14.
[261] Yan Y, Qian Y, Sharif H, Tipper D. A survey on smart grid communication infrastructures: Motivations, requirements and challenges. IEEE Commun Surv Tutorials 2012;15(1):5–20.