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Chapter

Microgrid Protection Systems

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Abstract

Micro grids are miniature version of conventional large power grids functioning either autonomously or with inter connection to the main grid. Primary function of micro grid is to serve power at distribution level. Distributed energy resources (DERs) connected to the micro grid enables reliable and efficient operation of micro grid. Protection of micro grids assumed importance due to increased penetration of distributed energy resources. Most of the distribution systems in earlier days are radial in nature and protection systems are designed for that. These protection systems pose serious challenges when applied to present day distribution systems which are mesh connected and fed by the distributed energy resources. Limitation of the conventional protection scheme demands new insights and methodologies for micro grid protection. Due to intermediate current injection from DERs the conventional coordination of over current (O/C) relays is not possible. Further in meshed systems the fault current flow is bidirectional. Hence the protection of micro grid systems with DERs require different approach to ensure faults are cleared in less time and minimal number of consumers connected to the system are affected. A comprehensive analysis of the suitable techniques applicable for micro grid protection is presented in this chapter.

Keywords: renewable energy sources, distributed energy resources, micro grid, distribution systems, protection, over current relay, distance relay, differential relay

1. Introduction

Protection is a vital aspect of power system which needs lot of attention everywhere. Majority of the existing protection techniques for distribution systems are developed for radial distribution lines. These techniques will not be directly applicable to the micro grids with meshed network in the presence of distributed energy resources (DER). A CIGRE definition of micro grid is given as *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* [1]. A typical CIGRE benchmark LV micro grid is shown in **Figure 1** [2].

The role of DERs in the present and future distribution systems is inevitable. Deployment of distributed generators (DGs) proved to be very effective means of meeting the ever increasing energy needs and concerns for Environment pollution and the depletion of fossil fuels. Employability of proper protection schemes to suit the micro grid environment fed by the renewable energy resources has assumed lot of importance. Protection of micro grids poses several challenges for the utility
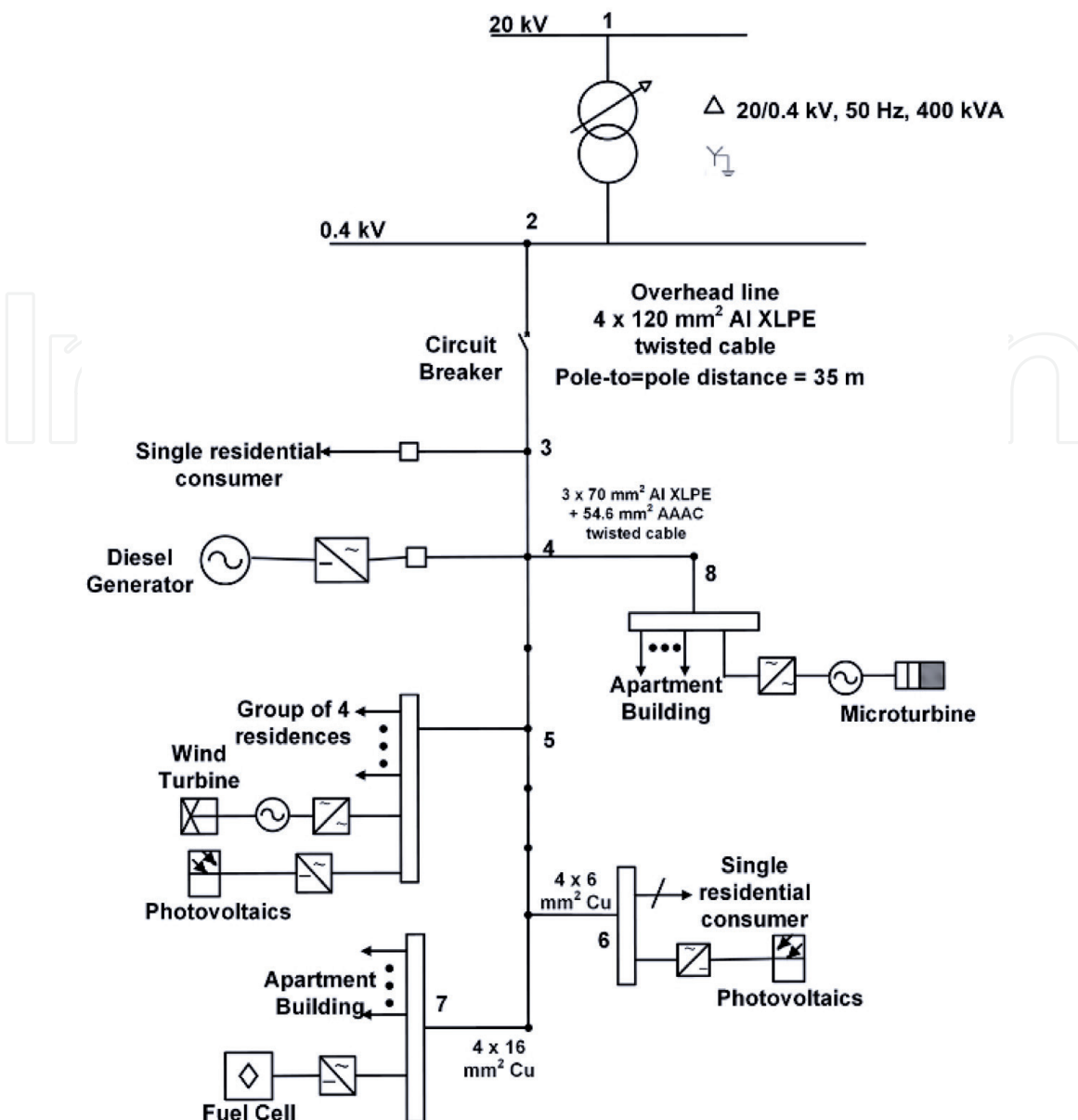
Figure 1.
CIGRE LV benchmark microgrid.

engineers. Protection of micro grids opened the doors for various investigations by the researchers across the globe. Some important aspects related to the protection issues of micro grids are presented in this article.

General protection methods applied to the distribution network are designed for radial systems having unidirectional power flow. With DGs power flow is no longer unidirectional and it causes a serious threat when conventional protection methods are used for the micro grid with DGs. Another concern is that the micro grid is expected to operate safely in grid connected or islanded mode. The intermittent nature of the output power from a DG makes the selection of the operating characteristics of the relays to be complicated. Further, most of the DGs are connected to the grid through converters which have independent control strategies. Limited fault current of the inverter based DGs and maintenance of Fault ride through capability should be given due consideration in protection. Locating the fault and proper isolation of the fault are also important [3, 4].

Time graded and current graded over current protective schemes have been in use for the radial distribution systems. Distance and differential protection schemes are also employed. Voltage based protection and THD (total harmonic distortion) based protection are found to be suitable for protection of micro grids with DGs.

Adaptability is the need of any protection method used for micro grid. The continuous change in the network configuration due to the addition of DGs and/or future expansions necessitates that the protection equipment must be adaptable as per the requirement [5]. Communication is another aspect of the protection of the micro grid. IEDs (intelligent electronic devices) are being used for this purpose in the grid. Suitable communication protocols are developed and IEC 61850 is being followed. Protection plays a key role in the development of micro grids due to the increase in the number of DGs, IEDs, storage systems and the requirement of a suitable communication medium [6].

This review article covers the need for changes to be made to the conventional protection systems when applied to micro grids in general and discusses recent advances made in the field of micro grid protection. Brief and critical review of the recent papers published on this subject is included. It is expected that this review article will provide a bird's eye view of the status of protection systems adapted for the micro grids with DERs.

This article comprises of six sections with the introduction as first section. Section 2 discusses conventional distribution system protection along with the deficiencies of the conventional O/C protection systems as applied to typical micro grids. Third section deals with brief description of the renewable energy sources (RES) and the need to replace the conventional generation systems considering environmental considerations. Configuration of micro grids with DERs is explained in Section 4. Problems of interfacing micro grids with conventional grid will be discussed in this section. Section 5 presents critical review of the recent papers dealing with the protection of micro grids. Section 6 concludes the article.

2. Conventional distribution system protection

Any protection system must be simple, fast, reliable and consistent apart from being selective and sensitive to the faults. Any protection system should not operate under normal conditions and must operate under abnormal conditions ensuring security and dependability of the protective system. These are the two important reliability indices which need to be optimized always. The two main classes are the radial distribution system and the meshed system.

For a radial feeder, fault current flows in one direction only as there is a single source of power. Relay setting in this case is relatively easy. This makes designing of strategies for protection become very straightforward for distribution systems typically. Simple devices such as reclosers, fuses and over current relays are used for protection. As a thumb rule fuses are set to operate for permanent fault and reclosers are set for temporary fault clearance. This is done as a part of fuse to recloser coordination with the intention of saving the fuse and also allow for the temporary faults to clear themselves with fast recloser action. Fuse to fuse coordination, relay to relay coordination and relay to fuse coordination are also required to be done. This is to ensure that minimum number of consumers connected to the distribution system are affected. Generally the fuse to fuse coordination is done from characteristic curves or selectivity tables supplied by manufacturer. In relay to relay coordination, time graded/current graded/combination of time and current grading is employed. Definite time, inverse time O/C relays are used. Inverse definite minimum time relays allow the protection engineer for flexible settings of the relay. Discrimination time of 0.5–0.3 s is possible with the fast acting relays and circuit breakers. In relay to fuse coordination, time margin is computed by taking into consideration, the operating time of the upper fuse for proper relay setting. It is essential that for proper coordination, fault current flowing through the protective

devices must be between the set minimum and maximum fault current that is possible and the fault current through all protective devices are almost equal. It is important to note that in case of a radial feeder, ensuring continuity of supply to maximum possible number of consumers after clearance of sustained fault is not possible. Ring main distribution system is an alternative [7].

In ring main system, each load can be supplied power from two different paths. In case of a fault in one feeder, the other feeder continues to supply whole or a percentage of total loads. Directional O/C relays are used along with non-directional O/C relays to minimize the number of consumers affected. Grading of the directional O/C relays starts from the load end to the source in the ascending order of the time, whereas for the non-directional O/C relays time discrimination is from the source side to the load side. In case the ring main is supplied by more than one source, coordination among the relays is not that easy. If two sources are present, the ring is opened at one end usually at one of the sources and the grading is done by presuming the other source as a single source. Employing differential protection for the section between the two sources is another practice. In this case, the rest of the system is treated as being fed from a single source. If more than two sources are present, then the design of protection system becomes more involved [8].

Most of the conventional protective systems are designed for the radial distribution systems where there is only one directional power flow. Design of a proper protection system that can be adapted for radial or ring main system with more than two sources has challenges posed due to bidirectional power flows that are encountered. Dependability of the usage of conventional protection scheme which is suitable only for radial system is very low and is therefore not recommended for the modern meshed distribution systems with DERs. It would be economical if the existing protection system can be modified or upgraded to match the protection needs of the modern system rather than discarding the old systems and going for an altogether new protection system. It is very expensive and is not advisable. Ways and means of using the existing protection system without losing the important aspects of protection is highly desirable [9]. Lot of research is focused in this direction to find out effective utilization of the existing infrastructural facilities of the convention distribution protection systems.

3. Need of renewable energy sources (RES)

In order to meet the increased demand and to reduce the transmission/distribution losses, generation at the load points is being done using the RES. There is a pressing need to redesign the conventional protection systems incorporating the RES. Another point worth mentioning is that the conventional protection systems are designed for radial systems expecting large values of fault currents. With the introduction of the RES, there are two possible modes of operation namely grid connected mode and islanded mode. In case of grid connected operation, there is a possibility of large magnitude fault currents but may not be always true in islanded operation and it poses serious concerns related to protection. Inclusion of a DER will causes bidirectional power flows in the distribution system. It reduces the possible upper and lower limits of fault current along with reduction in the fault current through protective devices posing serious threat to the conventional protection coordination [10].

DERs and their associated control, communication and protection devices have become an integral part of modern distribution systems. In any distribution system, if the penetration of these DERs is more in any area then that geographical area is being referred as a micro grid. Micro grid is a part of the main distribution grid and it operates independently to some extent. Major element of a micro grid is a

DER. DER can be a PV cell, fuel cell, wind turbine, diesel generator, energy storage system mainly based on Battery, etc. There are many advantages of DERs like reduction of transmission and distribution losses, eco-friendly power generation reducing the carbon emission, possible reduction in congestion in the networks, enhance the energy efficiency by proper utilization of the solar and wind energy.

Major differences between a conventional distribution system and micro grid can be categorized into three parts namely interfacing of the inverter fed DGs, grid connected and islanded operation and bi directional power flows. A micro grid is expected to operate successfully and independently even when there is a disturbance in the main grid. The main challenges posed in the protection of micro grids when compared to conventional system are listed below.

1. Sensitivity and selectivity of the protective relays gets affected due to the local generation by the DG. Settings should be done in such a way that protection is ensured even in islanded mode of operation.

2. Due to the presence of DGs interfaced to the grid through inverters, fault current seen by the relays is reduced during islanded operation. It affects the protective action by the relays in terms of, either delay in the protective action or non-detection of the fault.

3. DGs will also affect the maximum and minimum fault currents through a feeder and it results in serious coordination problems between recloser, fuse and O/C relays.

4. Undesired tripping of the non-directional O/C relay in a healthy feeder when the DG feeds a fault outside the healthy feeder. It happens because the DG tries to feed the fault through the healthy feeder.

5. An auto recloser clears a temporary fault by fast opening and reclosing of the circuit. If a synchronous DG is present in the micro grid, during this auto recloser action, it might experience a slight shift in synchronism. In that case, recloser will be connecting two systems which are not synchronous causing a serious threat to the entire system. Also the DG will be trying to maintain the system voltage and in turn the arc at the fault location. It might make the temporary fault to appear as a permanent fault.

4. Micro grid and DER integration

Integration of DER is an important aspect of micro grid operation. There are different control strategies applied in micro grid operation. Basically these can be classified as overall network control and DER control. Supervisory control of the network is done in centralized and decentralized mode using distribution management systems (DMS). DER control is normally chosen depending on the circumstances considering the network operation scenarios and the interaction with other DERs. In grid connected mode real and reactive power control is adopted where as in islanded mode frequency and voltage control is used [11].

In a micro grid, apart from DER, there are many other types of equipment such as data interfaces, monitoring devices, communication protocols, protective devices etc. Communication is another important element of modern distribution systems. Effective communication protocols have been established and standardized for use in substations. IEC 61850 is a global standard communication protocol which plays

a significant role in all aspects of distribution system viz. control, metering and protection. If the state of the micro grid is subjected to frequent changes due to intermittent nature of DGs and changes in load profile, operation strategies of different equipment need to be adjusted accordingly. Thus the system integration efficiency depends on the equipment integration. Further, the conversion of the operating mode of the micro grid from grid connected mode to islanded mode or vice versa also demands the adjustments in operation strategies of different equipment. IEC 61850 provides a flexible architecture, service and service essential for interoperability and upgrading required for various needs of modern distribution systems.

IEDs (intelligent electronic devices) are required as the devices are expected to be intelligent enough for data acquisition, transmission to control centres as well as decision making whenever necessary. These devices are being used extensively and are having the latest technology for sensing. It allows for two way communication and greater awareness on the situation in the power distribution system. These devices can be controlled remotely thus allowing efficient operation during disturbances. Another feature of the IEDs is that they can communicate with other devices present in the system allowing effective fault identification and restoration. With the application of FPGA technology, IEDs are becoming more effective [12].

As the micro grid is interconnected to the main grid, it is essential that the protective system must ensure the safety for faults in micro grid as well as for the faults in main grid. In case of a fault in main grid, micro grid should be isolated such that the consumers supplied by micro grid are not affected. If the fault is in the micro grid itself, then smallest possible percentage of consumers must be disconnected. Under these two circumstances, many challenges are there in the protective system design [13]. Some points to be considered while designing the protective system are (i) intermittent nature of the power generation by DGs due to changes in solar power, wind power, etc., (ii) variations in the load (iii) number of DGs, (iv) type of DGs such as inverter fed DG or synchronous DG, etc., and (v) topology of the network. In the grid connected mode, islanding may result accidentally or incidentally due to faults/human error/intentional opening for servicing/faulty operation of protective devices/natural disasters/and equipment failure. IEDs are employed for control and protection in modern distribution systems. Active management of the network and adaptive protection is possible through IEDs [14]. Inverter based DERs are expected not to get disconnected following a fault or contingency immediately. They should possess the ability to remain connected to the Grid for some time. It is called Fault ride through (FRT) capability. It is necessary to have sufficient fault current for the relays to sense the fault and to maintain the voltage during any contingency. Unlike a synchronously connected DER, inverter based DERs do not possess the FRT capability inherently [3]. FRT requirements in micro grids can be easily accomplished with IEDs by employing suitable controllers for inverters. To change over the protection strategies when the micro grid isolates from the main grid either intentionally or otherwise there is a need to detect quickly such isolation and secure the micro grid. The detection techniques adapted for sensing isolation and taking appropriate action for the controls and protection are outlined in the next section.

5. Islanding detection and recommended practices for micro grid protection

An efficient protection scheme must ensure proper protection to the micro grid in its both modes of operation, i.e., grid connected mode and islanded mode. It also should ensure proper functionality during the transition from one mode to another depending on the requirement. The topological network changes due to the transition

from one mode to other demands for the changes in the settings of the protective relays. Before proceeding further, one must understand the nature of the fault currents during grid connected mode and islanded mode. There are several factors that need to be taken into consideration such as the size of the DERs, type of DER, no. of DERs, how they are integrated to the main grid and the islanding detection methodologies. Many functional differences in the operation of a synchronous DER and inverter based DER calls for alternative protection strategies for them. Initially the effect of micro grid operation on the fault currents is discussed in this section. Later, general categories of O/C protection, distance protection, differential protection along with voltage based methods applied to suit the requirements of micro grid in grid connected and islanded mode are discussed. Adaptive protection is the main ingredient of micro grid protection.

5.1 Effect of micro grid integration with main grid

Micro grid is integrated with the main grid with an interfacing switch. As per the IEEE standard 1547-2003, a DG should be immediately get disconnected for any type of fault occurrence in the grid [15]. If a fault occurs anywhere in the main grid or micro grid, the static switch connecting the two gets opened and thus the micro grid goes into the islanded mode of operation. Along with opening the static switch, location of the fault also should be detected simultaneously. If incase, the faults happens to be within the micro grid, a suitable protective system should be brought into operation immediately. It should be done online, i.e., detection of the fault location and the initiation of protective action within the micro grid [16]. For faults in the main grid the static switch opens and islands the micro grid so that the DGs do not contribute to the fault current. Then the control system for islanded operation comes into play. For faults in the micro grid the static switch opens to remove the fault current contribution from main grid and the protection system of the micro grid comes into play and clears the fault. Therefore, one should recognize the importance of islanding detection preceding the protective action. In time and accurate detection of islanding is essential for fulfilling adequate protection requirements in micro grid operation.

Few points worth mentioning are as follows:

1. In inverter based DER, fault current gets affected by the limitation of 2 pu rated current of the interfacing inverter [17].

2. If the DER is connected to a single phase load, it might result in considerable unbalance between the phases in a three phase system.

3. Intermittent nature of the power output of a DER throws serious challenges in assessing the possible fault currents and relay settings.

4. Short circuit level of the main grid is considerably increased when micro grid is connected if the size of the DER is large enough.

5. Impact of appreciable amount of load being met by voltage sourced converters makes the fault currents to be significantly different.

5.2 Over current protection

Over current protection that has been in use for conventional distribution system protection requires some modifications to be made so that it can be used for the protection of mesh connected micro grid with DERs.

In order to understand the proper functioning of the overcurrent protection, let us consider a simple structure of a micro grid shown in **Figure 1**. In general this can be divided into four zones namely MV feeder and busbar protection zone (Z1), transformer protection zone (Z2), LV feeder protection zone (Z3) and micro grid protection zone (Z4) as shown in **Figure 2**.

Based on the location of fault with respect to DER, they can be classified into external (in Z1 and Z2) and internal faults (in Z3 and Z4). If the CB1 is open the micro grid is in islanded mode and if it is closed it is in grid connected mode [18].

5.2.1 Fault outside micro grid

If the fault is in zone Z1 or Z2 then main grid protection system will clear the fault. As per the requirements of IEEE Standard 1547-2003, the micro grid has to be islanded by opening the CB1. If there are inverter based DERs in the micro grid, then the fault current will be limited by them. If conventional over current relays
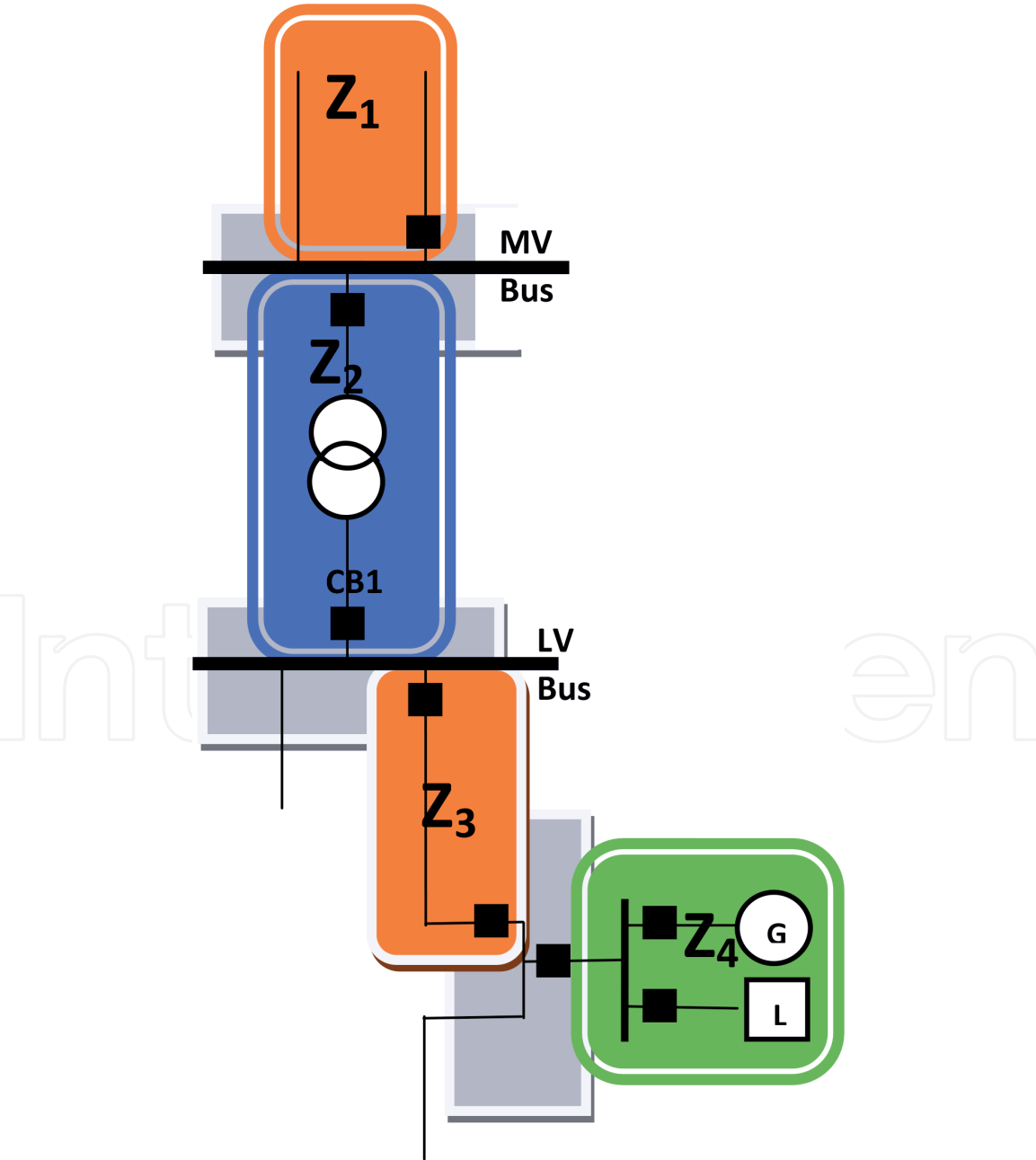
Figure 2.
Typical micro grid showing the zones.

are used for tripping CB1, then the fault current will not be sufficient to trip the breaker. By employing a directional over current relay at LV bus, protection can be ensured. Alternatively changes in frequency or voltage can also be taken as useful indicators for detection of Islanding to initiate the desired protective action. The current setting of this relay should be the cumulative weighted sum of fault current contribution by all the DERs present in the micro grid governed by (Eq. (1)). The weighting factor varies from 1.1 (for inverter based DG) to 5 (for synchronous DG) depending on the number and type of DERs.

$$I_{kmin} = \sum_{1}^{n} k_{DER} * I_{rDER} \qquad (1)$$

Here the I_{kmin} is the required adaptive relay current setting, k_{DER} and I_{rDER} are the weighting factor and rated current of the DER [19]. Based on the permissible voltage sag considerations, if sensitive loads are present in micro grid, CB1 should be opened in 70 ms [20].

5.2.2 Fault inside the micro grid

If the fault occurs on the LV feeder or the consumer end, i.e., Z3 or Z4 then the protective system should isolate the faulty section ensuring that minimum number of consumers get affected.

Here again the two cases of grid connected and islanded modes of operation must be considered. Also the presence of inverter based DERs and synchronous based DERs should be given due consideration. Following are the key points to be considered.

- If there is a fault in Z3 or Z4 in grid connected mode, main grid will supply sufficient fault current and faulty section will be isolated.

- If a large synchronous DER is present, then the fault current seen by the relay will be smaller than the fault current without DER causing protection blinding in case of a fault in Z3. It may also lead to delay in tripping the breaker if inverse definite minimum time (IDMT) over current relays are employed for protection. It is due to the fact that the IDMT relay characteristic has inverse characteristic for low magnitude portion of the fault current against the definite time characteristic for higher fault currents.

- A low power diesel generator has low inertia. If there is a delay in the tripping, it might lead to unwanted tripping of the synchronous DER if the power rating is low. To avoid this, a proper adaptive coordination among the relays is essential.

- In islanded mode, if there is fault on Z3 and if there are inverter based DGs, they will limit the fault current as described in the case of faults outside the micro grid earlier.

- In islanded mode, if there is a fault in Z4, it can be isolated by proper relay setting based on the possible fault current supplied by the inverter based DERs without any selectivity problem

In a nutshell, the major challenge in over current protection is the potential difference in the fault currents due to the presence of DERs in grid connected and islanded mode. This calls for adaptive schemes which demand expensive and

complex communication infrastructure. The decision of disconnecting/keep it connected/shut down the micro grid depends on several factors such as reliability, cost and the number of customers that get affected. [18] Lot of research is focused on the application of the adaptive over current protection which demands effective communication infrastructure and the IEDs.

5.3 Distance protection

Based on the challenges of relay settings and coordination of the over current relays due the large difference in the fault currents in grid connected and islanded mode, research has been diverted towards the application of distance protection to micro grid in which the tripping decision is based on the impedance seen by the relay and not on the current magnitude [21, 22]. The DER output may result in under reach and power drawn by the loads may cause over reach of the distance relays. By employing more number of distance relays, these issues can be addressed. The impedance seen by the distance relay gets affected by the fault current limiting nature of the inverter based DERs. In case of induction motor generator based DGs employing SCIM (squirrel cage induction motor), when the machine starts absorbing reactive power, the line current leads the voltage. It poses the over reach problem to the connected distance relay which measures it. In case of a DFIM (doubly fed induction motor) based DG, the power factor of the DG unit is controlled by the control system of DFIM during fault conditions. If an unbalanced fault occurs and the fault currents are not large, then the control system can easily maintain the power factor of DFIM. It may lead to protection problems similar to that encountered in case of an inverter based DG [3]. This hinders the application of distance relays for protection of micro grid.

5.4 Differential protection

Difference between the measurements made at different points located in a micro grid (preferably at the two ends of a feeder section) is considered as an actuating quantity for this type of protection. Employing symmetrical components (zero sequence) a differential protection applying the directional features of the difference current can be used in three different ways as shown below [23].

In the first method (shown in **Figure 3**), in order to protect the micro grid and main grid a master micro grid control center (MGCC) is used. Using MGCC it is possible to integrate all protective schemes. Based on the information received from monitoring relays it is expected to protect the main grid and micro grid. However, this method is found to be costly and unreliable to protect either micro grid or main grid alone due to the complex communication infrastructure and the associated data analysis to be carried out.

Second method (shown in **Figure 4**) logic employed only local controllers. Every relay communicates with its neighboring relay directly and monitors the current direction. In this there is no master control center. Whenever a reversal of current is sensed, the faulted section is isolated.

Third method (refer to **Figure 5**) is an improvised version of second method. Each feeder has two monitoring relays. In this method, magnitude of the fault current also is considered in addition to direction unlike the previous two methods. With this the problem of low magnitude fault currents can be handled successfully.
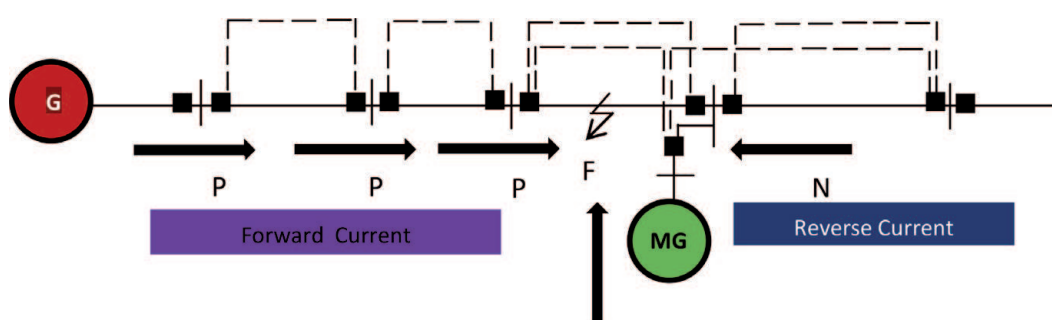
Out of the three methods, second method is more cost effective. In the first method there would be a time delay as the data analysis has to be completed before the protective action is initiated and hence it cannot serve the purpose of primary
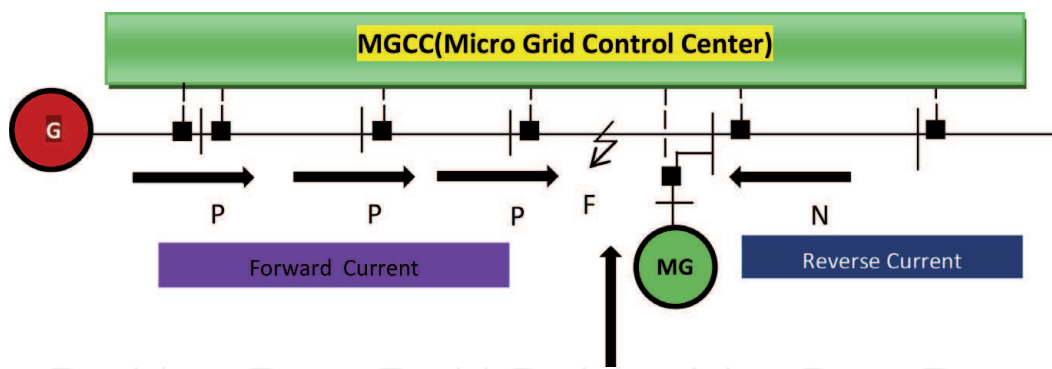
Figure 3.
Method 1 with microgrid control center.
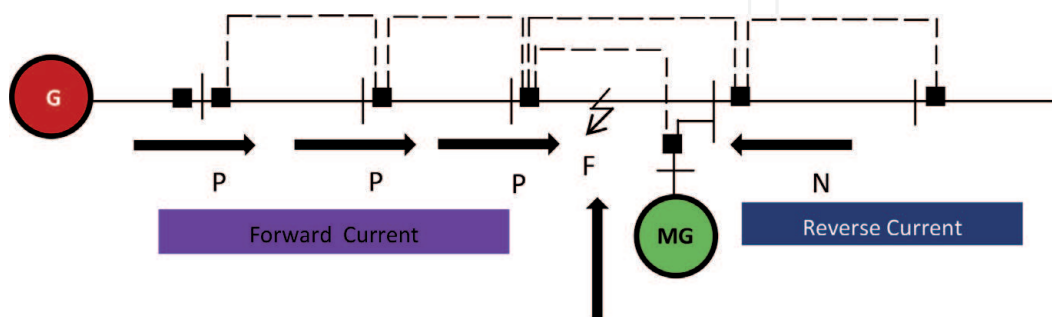
Figure 4.
Method 2 with local controllers.

Figure 5.
Method-3 improvized version with local controllers.

protection. In the third method, there is an addition of one more directional monitoring unit in each feeder making it expensive. In all these three methods the fault detection and clearance are reliable and only the faulted section is isolated causing minimum number of consumers to be affected. These schemes do not require any change in the configuration or in the relay settings for both modes of operation of the micro grid and are independent of the type and number of DERs connected to the micro grid [24].

As there are no zero sequence currents in case of a phase to phase fault, negative sequence components of currents are used for fault detection [25]. Using the positive sequence components also considering both amplitude and phase angle the differential protection system is discussed in [26]. However, if there is unbalance and negative and zero sequence currents flow is due to unbalance in the micro grid rather than a fault, these methods need to be examined more carefully. Challenges in this type of protection may be summarized as high cost, communication infrastructure, need for synchronized measurements, effect of unbalanced loads etc.

5.5 Voltage based methodologies

Extensive research has been carried out on these methods initially at University of Bath [27]. In this method voltage is considered for the detection of fault and subsequently for isolation. There are two methods. One is transformation method and the other is harmonic method.

5.5.1 Transformation method

In this method, the output voltage of DER is transformed in two steps. (i) transform voltages from abc to dq frame using Eqs. (2) and (3).

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & 1/2 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2}$$

(ii) From dq transform to dc values

$$\begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} \cos \omega t & -\sin \omega t \\ \sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \tag{3}$$

Any fault condition will get reflected as a change in d-q values.

$$V_{DIST} = V_{qref} - V \tag{4}$$

By comparing with the reference value, it can be easily inferred which type of fault and it can be isolated [27]. Application of transformations is an involved process and becomes complex in certain faults detection. Even a small difference in the voltage drop in case of a short line, shows a considerable effect on protection. Network topology also plays a major role in the application of this method when large numbers of DERs are present.

5.5.2 Harmonic method

In this method, when a fault occurs the total harmonic distortion (THD) of the terminal voltage increases. By comparing the THD of the terminal voltage of the converter with a predefined reference value, the type of fault can be identified. In this method discrete Fourier transforms are employed to convert the phase voltages Va, Vb, Vc into frequency domain. By using proper communication channel between the relays, fault area can be located and isolated [28]. This is used as backup protection. A correct setting for the reference value of THD is often challenging.

5.6 Adaptive protection

In this type of protection, the protection strategy must be modified in line with the existing operating conditions in the micro grid. It is to be done online. To accomplish this, numerical directional O/C relays are a good choice. Existing conventional fuses, electro mechanical and static relays settings and characteristics cannot be changed online. It necessitates that the existing protection equipment be upgraded to meet the requirement. Complying to IEC 61850 and installation of IEDs (Intelligent Electronic Devices) at appropriate places can make the relays to be adaptive with the ability to adjust their settings and characteristics accordingly on receiving the signals

online or following a time sequence. Thorough study of all possible topological configurations is to be carried out offline prior to the operation. It also necessitates conducting power flow studies and carrying out short circuit analysis for each configuration that might occur. For adjusting the settings and characteristics, fast and effective communication infrastructure should be in place [29].

5.7 Methods of improving protection

Considerable changes in fault current magnitudes during the grid connected and islanded modes of operation calls for alternative measures to be taken to improve the protection. If it is possible to modify the fault current magnitude whenever there is a change of operating mode of the micro grid, the existing protective systems can be used with some changes without the need of replacing them. If the fault current can be modified suitably by deploying some additional components, it would be very useful. These may be used either to increase or decrease the fault current suitably to have correct protective action along with the coordination among different protective equipment used. Response of a synchronous DER is different from an inverter fed DER during fault conditions. In case of an inverter fed DER, fault current need to be increased and in case of synchronous DG it should be reduced. Usage of fault current limiters (FCL), employing an interfacing unit at the point of micro grid interconnection with main grid to avoid the fault feeding from main grid are some of the available options. These options demand huge investment and maintenance. They depend on the proper functioning of islanding detection methods employed. Fault current limiting poses challenges if the size and penetration level of the DERs is high.

5.8 Protocols and standards

Some of the relevant standards related to micro grid operation are listed here for reference. IEEE Standard 1547 series covers Standard for Interconnecting Distributed Resources with Electric Power Systems. Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems are given by IEEE Std 1547.1, Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems is presented in IEEE Std 1547.3. Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems is IEEE Std 1547.4 and recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary Network are presented in IEEE Std 1547.6 [30]. There are reports prepared by CIGRE Working group also for reference. WG C6.22: Micro grid Evolution Roadmap contains the definitions and nomenclature of micro grid, WG C6.24 explains Capacity of Distribution Feeders for Hosting DER Connection and Integration of DER [31].

5.9 Recommendations

Of all the protection methods discussed above, differential current relaying is the most suited protection system for micro grid. This will enable fault location and also clearing in minimal time. Either one can have pilot lines for connecting the relays differentially (normally the feeder length in Distribution systems is not high so the cost of pilot lines also will be low) or one can locate RTUs at the two ends of each feeder and they will communicate the current magnitude, phase and direction to a central station where the fault location and tripping decisions are taken. The current measured at each end of the feeder is applied to Directional Over current

relay with fixed operating time to provide backup protection. This system will not require any changes either in configuration or settings for faults in the micro grid or in the main grid. Also this is not affected by the number and location of DERs and whether the micro grid is connected or isolated from the main grid.

5.10 Detection of islanding

It plays a major role in proper functioning of protective system. If differential relaying is adapted there is no necessity to detect islanding. However for the Control of micro grid operation and to maintain the power quality the control system for each DER has to be changed since the reference signal for frequency and voltage which is taken from the grid will not be available when the micro grid is isolated. There are different methods available in the literature for islanding detection such as rate of change of frequency, voltage, power factor, THD. Also the use of FFT or Wavelet transform of the terminal voltage will give out different spectrum when isolation takes place. Artificial intelligence techniques also have been employed for detection of islanding. Some new hybrid techniques employing these techniques can be found in Refs. [32–35].

Year	Title	Ref No.	Methodology	Type of faults discussed	Micro grid features	Remarks
2004	Brahma SM, Girgis AA. Development of adaptive protection scheme for distribution systems with high penetration of distributed generation. IEEE Transactions on Power Delivery. 2004;**19**(1):56-63	[36]	Here protection scheme is developed for micro grids with Synchronous DERs operating in grid connected mode addressing the fuse to fuse, fuse to recloser co-ordination issues that arises due to large number of DERs. The relaying strategy is adaptable in view of temporary faults and permanent faults and extension of the scheme to additional feeders.	Balanced and unbalanced faults	(i) Grid connected mode (ii) Radial system (iii) Synchronous based DER	(i) Applicable only in grid connected mode (ii) Protection in the islanded mode of operation is not included (iii) Works well when large number of DERs are connected in the micro grid. If the number DERs is less, it poses challenges.
2005	Wan H, Li KK, Wong KP. A multi-agent approach to protection relay coordination with distributed generators in industrial power distribution system. In: Fortieth IAS Annual Meeting. Conference Record of the 2005 Industry Applications Conference, 2005. Vol. 2. IEEE; 2005. pp. 830-836	[37]	Protective relay coordination using a multi agent communication approach is presented. It is capable of providing back up protection in case of primary protection failure in grid connected mode is developed. Make use of the Java agent Development Framework (JADE) platform for simulation of communication.	Fault type is not specified	(i) Grid connected mode (ii) Radial system (iii) Both synchronous based and inverter based DERs	(i) Applicable only in grid connected mode (ii) Relay coordination is dependent on communication (iii) Capable of providing backup protection

Year	Title	Ref No.	Methodology	Type of faults discussed	Micro grid features	Remarks
2006	Al-Nasseri H, Redfern MA, Li F. A voltage based protection for micro-grids containing power electronic converters. In: IEEE Power Engineering Society General Meeting; 2006. p. 7	[27]	Here DER output voltage transformation from abc to dq frame is performed and then the deviations of these values from reference values are computed. Based on the difference the protective action is initiated. A communication link is provided between relays. (Voltage based protection schemes)	Balanced and unbalanced faults	(i) Islanded mode (ii) Radial system (iii) Inverter based DER (iv) Constant MVA load (v) Overhead line with voltage level 11 kV/0.48 kV	(i) Protection against high impedance faults is not considered (ii) Effect of single pole tripping is not explained (iii) Relay functioning depends on the communication link between the relays
2006	Perera N, Rajapakse AD, Agent-based protection scheme for distribution net-works with distributed generators. In: IEEE Power Engineering Society General Meeting; 2006. p. 6	[38]	Network is divided into several segments. Relay agents communicate through an asynchronous communication link. Time domain simulation is done using wavelets for fault location. Central data processing is not required as the decisions are done in a distributed manner.	Phase to ground and phase to phase to ground fault high impedance fault	(i) Both grid-connected and islanded mode (ii) D-DGs (iii) Constant MVA Load (iv) OHL radial 24.9 kV	(i) Requires only current measurements and these measurements need not be time synchronized (ii) Demands high speed communication for proper determination of fault section (iii) Poses challenges to avoid relay functioning during switching transients
2007	Nikkhajoei H, Lasseter RH. Microgrid protection. In: IEEE Power Engineering Society General Meeting; 2007. pp. 1-6	[17]	A static switch is placed at the point of common coupling. Entire system is divided into different zones. Makes use of symmetrical components and system residual current is used for protective action.	Phase to ground and phase to phase faults	(i) Islanded mode (ii) Radial system (iii) Inverter based DER (iv) kW load (v) 0.48 kV distribution voltage	(i) Protection against high impedance faults is not considered (ii) Effect of single pole tripping is not explained (iii) Three phase faults are not discussed
2008	Al-Nasseri H, Redfern MA. Harmonics content based protection scheme for micro-grids dominated by solid state converters. In: 12th International Middle-East Power System Conference, 2008 (MEPCON 2008); 2008. pp. 50-56	[28]	Protection System is based on the measurement of amount of harmonic content present during the fault condition. For each type of fault a threshold value of THD is evaluated and set as a reference. Based on the measured value of harmonic content, required protective action will be initiated. (Voltage based protection schemes)	Balanced and unbalanced faults	(i) Islanded mode (ii) Radial system (iii) Inverter based DER (iv) Constant MVA load (v) Overhead line with voltage level 11 kV/0.48 kV	(i) It is required to assess the reference THD values for different fault scenarios which would be challenging (ii) If any DER supplies a harmonic free voltage or with lesser harmonic content, protection system may fail. (iii) Variable fault impedances, large dynamic load switching poses sensitivity issues demand for proper settings of threshold limits of THD

Year	Title	Ref No.	Methodology	Type of faults discussed	Micro grid features	Remarks
2009	Dewadasa M, Ghosh A, Ledwich G. An inverse time admittance relay for fault detection in distribution networks containing DGs. In: 2009 IEEE Region 10 Conference (TENCON 2009); 2009. pp. 1-6	[39]	These relays have the ability to operate for faults in both forward direction and reverse direction. Its operation is based on the measured admittance and has an inverse time characteristic. The protection system can operate for low fault currents also and thus provide protection under islanded mode also. It is possible to supply the load in islanded mode also. Network is divided into different zones .	Balanced and unbalanced faults	(i) Both grid-connected and islanded mode (ii) Inverter based-DGs (iii) Constant MVA (iv) OHL radial and closed loop (v) 11 kV	(i) fundamental frequency component extraction may lead to measurement errors due to harmonics and dc offset (ii) Takes more time of operation for high impedance faults (iii) Does not use any communication link
2010	Sortomme E, Venkata M, Mitra J. Microgrid protection using communication-assisted digital relays. In: IEEE PES General Meeting; Providence, RI; 2010. p. 1	[40]	In this method, digital relays are employed along with communication network. An additional line is added in the system to simulate the loop structure in this paper. A new modeling for high impedance fault simulation is presented.	Balanced and unbalanced faults	(i) Grid connected and islanded mode (ii) Both inverter and synchronous based DGs (iii) Radial and loop structure (iv) 18 bus system with multiple DGs included (v) Unbalanced load is also included	(i) Highly expensive and time synchronization is not considered (ii) Imbalance created between generation and demand due to line removal in the radial mode makes the protection challenging and calls for effective communication infrastructure and sensors. (iii) In case of communication failure, protection against high impedance faults is at stake
2010	Shi S, Jiang B, Dong X, Bo Z. Protection of microgrid. In: 10th IET International Conference on Developments in Power System Protection (DPSP 2010); Managing the Change; 2010. pp. 1-4	[41]	This protection scheme is based on current travelling waves. Here detection of the faults is done using busbar voltages and location of the fault is found out employing current travelling waves. No communication link is used. Based on the information available locally, protective relay works.		Both grid-connected and islanded mode - - 10/0.4 kV distribution voltage	(i) Method is independent of unbalance between the load and generation, level of fault current or power flow (ii) Simulation results are not presented

Year	Title	Ref No.	Methodology	Type of faults discussed	Micro grid features	Remarks
2011	Voima S, Kauhaniemi K, Laaksonen H. Novel protection approach for MV microgrid. In: CIRED 21st International Conference on Electricity Distribution; 6–9 June, 2011; Frankfurt; 2011. Paper No. 0430	[42]	This is an adaptive protection scheme which uses tele-communication infrastructure. Network is divided into four different zones. IEDs used have directional over current protection function along with current and voltage measurements. To achieve proper selectivity, interlocking signal is sent along with the direction of fault. Applicability of distance relay also is presented.	Specific type of fault details are not mentioned	(i) Islanded mode (ii) Radial system (iii) Inverter based DER (iv) Constant MVA load (v) Over head line with voltage level 20 kV	(i) High dependency on the communication infrastructure (ii) With reliable communication links it can be made adaptable to different modes of operation (iii) Details of simulation of different fault scenarios is missing
2012	Samantaray SR, Joos G, Kamwa I. Differential energy based microgrid protection against fault conditions. In: IEEE PES Innovative Smart Grid Technologies (ISGT); 2012. pp. 1-7	[43]	In this method, differential energy applying time frequency transform is used to initiate the protective action. On either end of the feeder, amount of spectral energy is found out. High impedance faults are also considered.	Balanced and unbalanced faults	(i) Both grid-connected and islanded mode (ii) Both inverter and grid connected mode (iii) Constant MVA (iv) OHL radial and closed loop 25 kV distribution voltage	(i) Differential energy is used to recognize the fault patters (ii) Makes use of both time and frequency data where as in other schemes only one data is used. (iii) Setting the threshold limit for the differential energy plays crucial role
2013	Ustun TS, Ozansoy C, Ustun A. Fault current coefficient and time delay assignment for microgrid protection system with central protection unit. IEEE Transactions on Power Systems. 2013;**28**:598-606	[44]	In this method communication based coordination has been presented. Amount of fault current contribution by any DG is represented as a coefficient. Selectivity of the relays is controlled by automatic adjustment of the current setting.	Balanced faults	(i) Grid connected and islanded mode (ii) Inverter based and synchronous based DGs (iii) Radial system	(i) Requires human input however it can be minimized if the structure of the network is obtained by running an automated algorithm (ii) Delay in the communication depends on the type of protocol used (iii) faults within the micro grid only are considered
2014	Kar S, Samantaray SR. Time-frequency transform-based differential scheme for microgrid protection. IET Generation, Transmission & Distribution. 2014;**8**:310-320	[45]	The protection scheme identifies the fault current patterns based on the S transforms. Differential energy is computed considering both ends of the feeder and it is used for protective action.	Balanced and unbalanced faults	(i) Both grid-connected and islanded mode (ii) Inverter based and synchronous DGs (iii) Constant MVA load (iv) OHL radial and closed loop 25 kV	(i) Results are compared with the current differential technique for all fault scenarios (ii) Differential energy is less sensitive to time synchronization errors compared to current difference

Year	Title	Ref No.	Methodology	Type of faults discussed	Micro grid features	Remarks
2015	Kanakasabapathy P, Mohan M. Digital protection scheme for microgrids using wavelet transform. In: 2015 IEEE International Conference on Electron Devices and Solid-State Circuits (EDSSC). IEEE; 2015. pp. 664-667	[46]	Using wavelet transforms a microprocessor based protection scheme is developed for grid connected mode of the micro grid with fault detection and classification. Cumulative sum of the high frequency details of power signal is computed and is compared against a threshold value to send the trip signal using the digital relay.	Balanced and unbalanced faults	(i) Grid connected and disconnected mode (ii) Radial system (iii) Both Synchronous based and inverter based DERs	(i) Fault location depends on the power signal high frequency details (Phfd) (ii) Threshold value of Phfd depends on sampling frequency of the analog signal and the type of wavelet chosen
2016	Gururani A, Mohanty SR, Mohanta JC. Microgrid protection using Hilbert–Huang transform based-differential scheme. IET Generation, Transmission & Distribution. 2016;**10**(15):3707-3716	[47]	Hilbert-Huang transform (HHT) has been employed to determine the differential energy in this method. To discriminate faults in islanded mode and in case of high impedance fault an appropriate setting for the differential energy is used as threshold value.	Balanced and unbalanced faults	(i) Both grid connected and islanded modes (ii) Radial system (iii) Inverter based DERs	(i) Setting of proper threshold value is important to discriminate different fault conditions (ii) When noise is included in the signals protection becomes challenging
2017	Hooshyar A, Iravani R. Microgrid protection. Proceedings of the IEEE. 2017;**105**(7):1332-1353	[3]	A comprehensive review of the micro grid protection techniques has been presented along with several case studies using different relays in different modes of operation employing synchronous based and inverter based DGs. The fault ride through capability also is discussed. DC microgrid protection is also discussed briefly.	Balanced and unbalanced faults	(i) Both grid connected and islanded modes (ii) Radial system and mesh system, voltage 12.47 kV (iii) Inverter based and synchronous based DERs	(i) DG ride through capabilities in islanded mode for different fault scenarios is presented. (ii) Effect of ECDG units on directional over current relays and distance relays is shown to be more than in case of differential relays. (iii) Frequency of fault current is shown to be dependent on the slip of induction machine. (iv) In case of DFIG based microgrid, response of the relay is shown to be dependent on the type of control strategy employed

Year	Title	Ref No.	Methodology	Type of faults discussed	Micro grid features	Remarks
2018	Aghdam TS, Karegar HK, Zeineldin HH. Variable tripping time differential protection for microgrids considering DG stability. IEEE Transactions on Smart Grid	[48]	This method discusses the stability aspect also along with fault clearance. A multi agent approach along with the zoning principle is employed. For coordination and backup purposes each agent has three layers namely primary, backup and bus protection. The critical clearing time (CCT) curves of the DGs employed are analysed to establish the mechanism for checking the constraints on the CCT are developed.	Balanced fault	(i) Both grid connected and islanded mode (ii) Modified CIGRE benchmark micro grid test system (iii) Synchronous DG (iv) 20 kV.	(i) Micro grid has only synchronous DGs (ii) Specific type of fault is not mentioned (iii) Fuse tripping slower for the same fault current as the nominal current of the fuse increase. (iv) Settings of several differential layers depend on the fuse size for coordination.

Table 1.
Summary of research on protection of micro grids.

Table 1 gives a consolidated picture of ongoing efforts for protection of Micro Grids.

6. Conclusions

A comprehensive review of various protection methods as applicable to micro grid protection is presented. DERs are becoming an integral part of distribution systems but the adequate changes necessary in the protection system has not yet picked up the pace. Lot of research is going on in this area to use the existing protective infrastructure justifiably without compromising on the safety aspect. It is apparent that well-built communication infrastructure is essential for meeting the requirement of micro grid protection. It is due to the fact that there are inevitable topological changes in the network due to the transition of micro grid operating mode from grid connected to islanded and vice versa. Also, the intermittent nature of the DER output and the fault limiting features of inverter fed DGs present several technical challenges to the micro grid protection engineers. Making the protective system to be adaptive is the need of the hour. But it involves lot of infrastructure development and is costly. Many methods based on directional O/C relays, distance relays and voltage based protection schemes have been proposed for effective implementation. However, effective utilization of the existing protective systems with minimal changes in the infrastructure appears to be possible with differential protection scheme. With the advancements in communication technology, micro grid protection can be made adaptive in a cost effective manner.

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