Microgrid Protection with Penetration of DERs - A Comprehensive Review

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***Abstract*— Distributed Energy Resources (DER) early uses as a backup generation has been progressing toward permanent Distributed Generation (DG), along with the development and enhancement of new technologies over small-scale generation. Over last few years, increasing penetration of renewables in the distribution networks at consumer level raises concerns on protection, control, stability and reliability. Considering the DG integration and wide variations in operating conditions of the microgrid, relays experience protection issues at fault current level violating important tripping decision rules. This study reviews the impact of DG penetration as integration means on traditional overcurrent (OC) protection schemes, being the most common and widely used relaying scheme in radial distribution networks. This paper reviews the most representative methods with respect to various challenges uncovered by exhaustive studies and validations and reported in the literature. Further, potential adaptive and intelligent schemes are also discussed for enhancing the performance over traditional protection schemes in microgrids.**

Keywords—Overcurrent relay, microgrid, adaptive protection, intelligent protection, distributed generation, distributed energy resource, smart grid, Industry 4.0.

I. INTRODUCTION

Distributed Energy Resources (DER) have been commonly utilized to generate power in isolated power grids, or as emergency backup generation. Commonly, they consist of a small size power generator, or a storage unit, to provide support to the traditional power grid. Dispersion of a number of small capacity DER through the entire power grid in distribution networks has led to a new concept of distributed generation (DG). A DG is frequently classified as a variety of DER or small power sources interconnected to the distribution network, delivering power near or at the point of consumption. It can be any kind of power generation and storage unit near the load [1], [2], [3]. An electrical power storage unit is often called a distributed energy storage system (DESS) [4]. A localized autonomous group of DGs is frequently known as a microgrid and can function in grid-connected mode, or independently of the power grid in an event of a main power outage or power islanding, while been capable to operate autonomously of the grid known as standalone or off-grid mode [5], [6].

Generating power near the point of consumption, rather than remotely, greatly reduces the cost, complexity, interdependencies, and inefficiencies related to the power generation at a remote central station and reducing transmission line losses. On the other hand, increasing penetration of DGs at the distribution side of the network has a strong impact on the network reliability, stability, and protection [7], [8]. The main challenges related to microgrid operation include voltage and frequency control along with protection [9]. In a microgrid different energy resources could be utilized and the interfacing scheme in each DG is one of the principal factors having influence on the current protection schemes. A DG based on a coupling rotary machine, such as induction or synchronous generator, has a different response from a DG based on power electronics devices connected with smart inverters [10]. A vast majority of non-traditional sources such as fuel cells and solar PV use a power electronic device known as inverter/converter for integration. Old-fashioned combustion engines coupled with rotating machines are largely synchronous generators, directly connected to the distribution grid [11].

Traditionally, most utilities use radial feeders to deliver power to loads at customer side, where, protection schemes were entirely designed and implemented considering uni-directional power flow. DG integration changes the unidirectional power flow to a bi-directional power flow schemes. As more DG are interconnected to the distribution grid, protection relays will experience important changes in the fault current detection levels, biasing their operation and tripping decisions, where protection schemes are no longer effective. The following protection challenges arise due to DG integration: islanding; short circuit power; auto re-closure; reverse power flow;

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impedance relay's reduced reach; ferro-resonance; voltage profile; grounding; and security, among others [12].

This review presents a literature search about protection solutions for the most critical cases due to the interaction of DGs in a distribution microgrid. The focus of this paper is to bring out the problems that present the challenge for the protection, and propose a general method as a solution for restoring the overcurrent (or other) relay performance when different types of DG and loads are connected. Section II presents the review on protection issues due to DG penetration in microgrid and the impacts on the performance on over-current relays. Section III outlines the prospective protection measures which can enhance the protection performance considering the challenges. Finally, Section IV presents the discussions and generalized conclusions on the possibilities of adaptive and intelligent relaying for enhancing the task in microgrid scenario.

II. PROTECTION ISSUES DUE TO DG PENETRATION IN MICROGRID

High penetration of DGs have been raising new issues in the operation of distribution grids. The principal impact of the rapidly growing DG penetration is on the protection. For operation in radial configuration, traditional protection schemes could be compromised under normal operation. Present protection systems are a conglomerate of fuses utilized for protection of lateral feeders and reclosers backing up fuse operation on the main feeder, and circuit breakers at the different terminals which are protected by relays [12]. The protection issues that were relevant to transmission are now also becoming pertinent to distribution. Thus, new operation technologies, for managing and protecting the microgrid are necessary [13]. After an investigation of the likely issues, the following protection concerns are presented considering DG integration in the microgrid. Reference [14] provides parameters of the testbed for generating results of the following issues. The results in following Tables having I_R, I_Y, and I_B denote the three phases of the fault currents measured at relay R_1 in each of the sub sections.

A. *Short circuit capacity*

The fault current level varies when microgrid changes its operating mode between grid-connected and islanded modes. During the islanded mode of operation, the short circuit capacity of the network is lower compared to that of the grid-connected mode where only utility supply is connected [14].

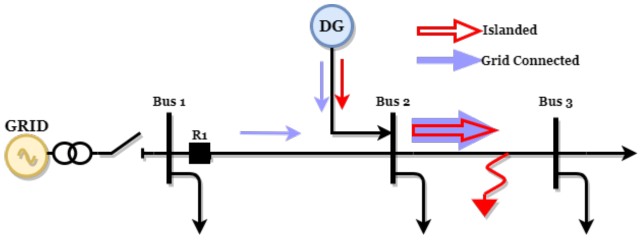

Fig. 1. Short circuit capacity in different modes.

TABLE I. VARIATION IN SHORT CIRCUIT LEVEL

Phasor Current magnitude Sensed by Relay R_1 (in pu)	Grid-Connected mode	Islanded mode
I_R	8.7	4.6
I_Y	1.0	1.0
I_B	1.0	1.0

Thus, the threshold setting of the relay for grid connected mode may not operate in islanded mode during a fault in the microgrid. As shown in Fig. 1, fault current contribution during islanded mode is because of the DG only whereas it is contributed by both DG and utility grid in case of grid-connected mode. Table I shows variation in fault currents in both modes for a single line to ground (SLG) fault in the middle of the line connecting Bus 2 and 3 as shown in Fig. 1.

B. *Bidirectional power flow*

One of the major challenges in the protection of microgrid arises due to bidirectional flow of power. The microgrid is an active network and hence, close to each load, there may exist DGs, which could contribute to feeding power to the load leading to possibly bidirectional flow of power during normal operation. The existing protective schemes are, for the most part, designed for the unidirectional flow of power and may not be able to protect the system under these circumstances [15]. Fig. 2 illustrates the bidirectional flow of power in microgrid scenario. Without the DG, the power flows from grid to the load radially. However, when the DG is integrated, the relay R_1 placed at Bus 1 senses lower current compared to the earlier case (without DG integration), which signifies bidirectional power flow. Table II depicts the variation in phase currents with and without DG at relay R_1 for the SLG fault as shown in the Fig. 2.

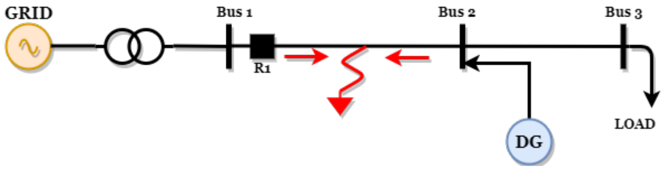

Fig. 2. Bidirectional Power Flow.

TABLE II. VARIATION IN CURRENT DUE TO BIDIRECTIONAL FLOW

Phasor Current magnitude Seen by relay R_1 (in pu)	Without DG	With DG
I_R	4.56	3.4
I_Y	1.0	0.55
I_B	1.0	0.55

C. *Unnecessary tripping/Sympathetic tripping*

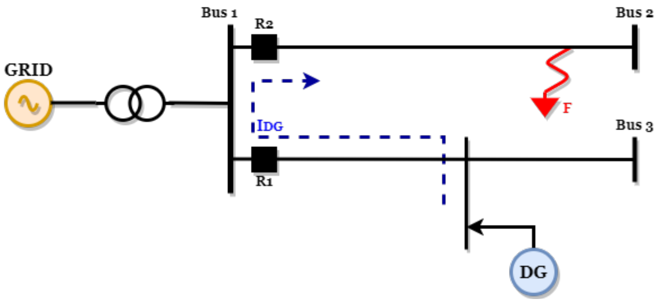

Fig.3. Unnecessary tripping.

When the fault is initiated in a feeder which is close to another feeder where DG is connected, the DG possibly may start contributing to the fault through its own feeder. Under this condition, the relay placed at one end of the healthy feeder which is non-directional type may incorrectly detect the fault

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and may trip the feeder which is unacceptable [15]. The example of unnecessary tripping is shown in Fig. 3, where the fault in the upper feeder causes the relay R_1 in the healthy lower feeder to operate incorrectly. Table III shows the SLG fault current sensed by relay R_1 without and with the integration of DG.

TABLE III. SYMPATHETIC TRIPPING

Phasor Current magnitude Sensed by Relay R_1(in pu)	**Without DG**	**With DG**
I_R	0	8.87
I_Y	0	0
I_B	0	0

D. *Blinding of protection system*

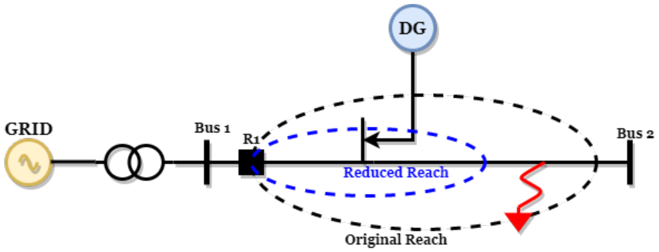


Fig. 4. Blinding due to DG integration.

When a DG is integrated somewhere between the feeding substation and fault location as indicated in Fig. 4, it contributes to the SLG fault current. Due to DG's contribution to the fault, the relay R_1 placed at the feeding substation measures the lower amount of current compared to when there is no DG, as depicted in Table IV. This may result in delayed operation of the relay or relay may not operate. Hence, the introduction of DG in the grid may disturb the operation of the relay, and may even stop the relay from operating properly, which is termed as blinding of protection system [16].

TABLE IV. BLINDING OF RELAYS

Phasor Current magnitude Seen by Relay R_1 (in pu)	**Without DG**	**With DG**
I_R	4.78	3.4
I_Y	1.0	0.55
I_B	1.0	0.55

E. *Unintentional islanding*

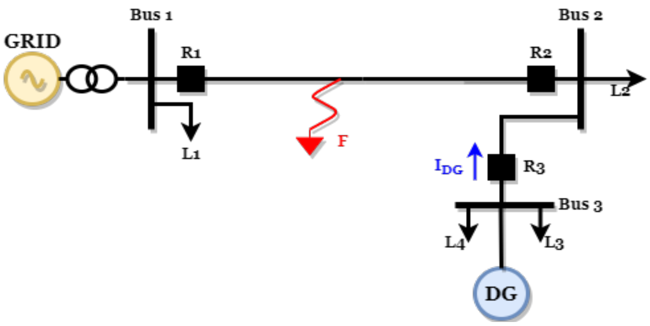
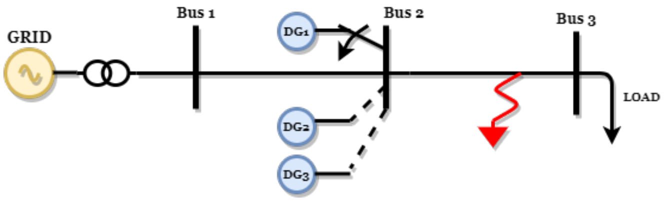


Fig. 5. Unintentional Islanding.

Due to sudden load change and severe fault conditions, the protection scheme may shut down the DG and disconnect it from the grid, as shown in Fig. 5. This situation is known as unintended islanding [15]. It compromises the reliability of the system because any kind of temporary fault may lead to the service disturbance to the end users. As illustrated in Fig. 5, the supply to the load L_2 is interrupted after the fault occurrence and the DG disconnection, which normally is fed by the DG without fault scenario. This problem arises due to unintended islanding of DG from the utility.

F. *Integration of different types of DGs*

The short circuit level of the corresponding network buses may increase due to the integration of DGs to the microgrid. The amount of increment depends on the location, size, and type of the interconnecting DG. Penetration of different types of DGs such as synchronous, induction and the inverter-interfaced DGs (IIDGs) poses several protection challenges. The magnitude of fault current significantly varies with the types of DG technologies. The amount of current contribution made by synchronous and induction machine-based DGs is much higher than the IIDGs during a fault. Synchronous based DGs and IIDGs can contribute up to 8-10 times and 1.5 to 2 times of the rated current respectively. Induction based DGs may contribute 7-8 times that of the rated conditions [17]. Thus, there may be significant variations in fault level depending upon the types of DG integration.



DG1: Synchronous Based, DG2: Inverter Based, DG3: Induction Based

Fig. 6. Integrating various types of DGs.

TABLE V. VARIATION OF FAULT CURRENT WITH TYPES OF DGS [17]

Type of DGs	**Contribution to Fault Current**
Inverter-based	1–2 times the inverter rated current
Synchronous-based	8-10 times the generator rated current
Induction-based	7-8 times the generator rated current

Among all types, IIDGs pose serious concerns as the current is restricted to 1.5 to 2 times of the rated condition, and the relay may fail to operate with the set threshold. Further, the voltage and current controllers are responsible for such behavior of these DGs. In case of the current-controlled scheme, the output current is regulated, unaffected by the type of fault (as opposed to the voltage-controlled scheme). On the other hand, during the fault, the voltage-based controller regulates the terminal voltage within the acceptable range [18]. Fig. 6 shows the possibilities of type of DG integration and Table V depicts the fault current contribution during the fault situation considering types of DG units.

G. *Relay miscoordination*

The integration of the DG also affects the relay-relay, fuse-fuse and reclosure-fuse coordination. Existing traditional coordination strategies are effective for a certain range of current values and cannot ensure the coordination if the current falls beyond certain range. In case of microgrids with DG, the fault current varies to a larger extent, which may seriously compromise the coordination between the protective devices.

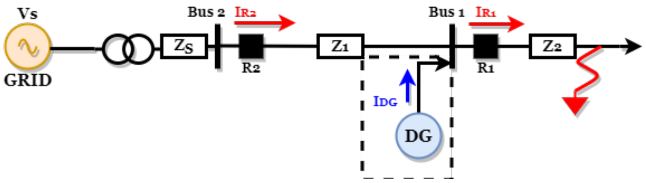


Fig. 7. Coordination failure of relays [19].

As shown in Fig. 7, the fault current without DG interconnection seen by the relay R1 and R2 are [19],

$$I_{R1} = I_{R2} = \frac{V_S}{Z_S+Z_1+Z_2} \quad (1)$$

Where, V_s is the equivalent internal voltage of grid. Z_S, Z_1 and Z_2 are the source impedance and line impedances respectively. With the DG integration, the fault currents sensed by the relays are changed as follows:

$$I_{R1} = \frac{V_S}{Z_S+Z_1+Z_2} + I_{DG}\frac{Z_S+Z_1}{Z_S+Z_1+Z_2} \quad (2)$$

$$I_{R2} = \frac{V_S}{Z_S+Z_1+Z_2} - I_{DG}\frac{Z_S+R_F}{Z_S+Z_1+Z_2} \quad (3)$$

It is seen from (2) and (3) that, after with integration of DG, the fault current sensed by relay R1 increases and that of relay R2 decreases. So, the operating points on the time-current characteristics curves of the relays will be affected due to addition of DG which may lead to miscoordination of relays.

H. Auto reclosing failure

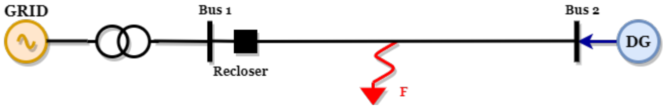


Fig. 8. Auto recloser failure.

TABLE VI. RECLOSER FAILURE [20]

Time (in Sec.)	**Breaker Status**	
	Normal Operation	**Abnormal Operation**
After 10	Open	Open
After 10.3	Open	Close
After 10.5	Close	Open

The function of the auto recloser as shown in Fig. 8 is to close the circuit breaker after a momentary interruption. Since the breakers open many times during small and large interruptions, which are not faults, a recloser improves the service continuity by automatically restoring the power in such cases. However, this fault clearing method may fail in presence of DG in the system. If the protection system of DG does not trigger during the operating time of recloser, the temporary fault will not be cleared and will become more permanent. Hence, the presence of DG may also affect the performance of the auto reclosing mechanism [20]. In [20], a fault of duration 0.5 sec. is introduced in the system at 10 sec. In abnormal condition the breaker tries to reclose at 10.3 sec and fails since the fault is still not cleared.

III. PROSPECTIVE PROTECTION MEASURES FOR MICROGRID

DG integration in microgrids has brought about different challenges, as seen in Section II. Such problems have close relation with the fault current levels affecting proper fault identification by traditional relays at distribution level [21], [22]. Frequent restructuring of the network topology with DG at load proximity, and various operation modes of microgrids, such as grid-connected and islanded mode of operation, decrease the range of relay-based protection and compromise the reliability, while at the same time pose complexity for the new protection schemes [23]. An enhancement of the present protection schemes is needed, where they can easily adjust to the changing structure and operating conditions of the distribution system. The present summary focuses on some of the prospective protection solutions for AC microgrid to cope with the challenges seen in Section II.

A. Adaptive protection schemes

Adaptive protection scheme is a method which updates the relay setting corresponding to the change in power system conditions. There are some techniques for applying adaptive protection in a microgrid. The classic approach is to have two different set points for each relay, the first one for islanded mode, and the second one for grid-connected mode. So, the microgrid can be protected under both circumstances by shifting the relay curve characteristics, based on the change of new fault current levels considered at the design and implementation state [24]. As seen in Section II, the foremost problem of relay detection techniques at distribution level arises with high amounts of DG penetration at the user side, affecting the most widely utilized relay in the distribution level, which is the OC relay. An additional degree of concern is the lack of knowledge about when a new DG is energized without prior notice (studies are normally only required for larger capacity DG additions). Henceforth, another application for adaptivity can target the enhancement of traditional OC relay operation. Generally, this method does not require to have prior knowledge of the new microgrid state to perform fault detection. It basically adapts the previous state to a newer state, while changing relay trip settings in near-real time considering DG penetration and different types of fault exposure [25]. There are some modernization upgrades over traditional OC protection, such as microprocessor-based relays, addition of extra communication networks and software programs allowing appropriate monitoring and control [26], the later upgrades tend to require a replacement of the traditional relay or the addition of new equipment, thus increasing its cost. Furthermore, angle-based adaptive relaying schemes are also gaining momentum which provides reliable protection measure considering wide variations in operating conditions of the microgrid [27].

B. Intelligent protection schemes

Computational Intelligence (CI) based methods are systems addressing complex problems where traditional schemes are no longer feasible and effective [28]. In this context, the concept of smart grid plays a big role [29]. Intelligent protection schemes are further enhancement of traditional relays techniques for fault detection, classification and location determination. They exploit the CI based techniques for binary, or multi-class classification along with estimation capability for identifying fault conditions in microgrids. Once the grid monitoring process is active, the CI based algorithm is used to build decision making in a microgrid environment being part of smart grid [1]. Applications of Wide Area Measurements (WAMs) in microgrids are gaining momentum due to operational [30] and monitoring requirements [31], [32]. As PMUs are measurement devices with reporting rate of 60 samples per frame (or more), while operating at 60 Hz, thus faster data processing is possible when assisted with communication systems. This creates the centralized platform for microgrid protection, and generates large data sets for different applications [33]. Data-mining becomes the building block for development of the intelligent relay performing the relaying task accurately and reliably.

Among the identified decision-making CI methods are Data mining (DM), Machine Learning (ML), and Nature-Inspired Algorithms (NIA). These techniques are used to derive new schemes and algorithms for enhancing protection systems. There are three main areas where an intelligent protection scheme can be appropriate: real-time topology identification, computation of protection set points, and rule-based (RB) application. Artificial neural network (ANN) and DM approaches can significantly increase the efficiency of these methods, and reduce the computational complexity when used for network topology identification. Big Data (BD) as a combination of data mining and data analytics also has implementation potential. Massive BD aggregated produces extensive records that could be utilized for decision-making algorithms in an intelligent setting [34, 27, 30]. The vast amounts of BD in storage provide the foundation for applying intelligence-based methods for microgrid protections. The following case studies present some of the most interesting and state of the art methods demonstrating the creation of intelligent protection algorithms. Decision tree (DT) based microgrid protection schemes were proposed in [35], [36] for identifying faults and its classification. In the second method, a simple Binary DT is used to identify the system and an Artificial NN (ANN) model for relay functionality. An ML based protection system [37], obtains microgrid uncertain elements with Pearson correlation and adaptivity by RB. Further ANN based fault identification and a Support Vector Machine (SVM) based fault locations provides promising performance. NIAs can re-calculate relay settings relatively easy and faster [38].

A further application of CI in microgrid protection, where a high level of automation and digitalization exist; Industry 4.0 plays part with improvement and adaptation of new technology, enhanced communication, and cloud-based computing. With reference to the 4th industrial revolution, were all components for the increasing energy necessities for efficient, dependable, and smart are applied, while establishing a definite meaning for Smart Grid (SG). Enabling a total new adaptive defense scheme restoring, balancing and ensuring supply with high reliability [39], [40].

IV. DISCUSSION AND CONCLUSION

The objective of protection in a power system is to quickly recognize and isolate the faulted sections of the system without much disturbing the rest of the system. It is crucial for preventing blackouts and isolating disturbance propagation across the power grid. Distribution grid becomes heavily interconnected with proliferation of DGs creating independent microgrids, traditional relays with static settings are becoming less effective. Adaptive protection schemes mentioned in this paper show promise for implementation in detection and isolation of the faults, leading to safe and secure microgrid operation. Due to frequent changes in the microgrid, relays with fixed parameters could misoperate under certain circumstances; under heavy distribution load, or under significant DG penetration, islanded and grid connected modes of operation, radial or mesh topology, etc.

This review delivers a summary of applications from the perspective of misoperation of relays under various microgrid operational scenarios. Solutions are proposed for enhancing protection operation with adaptivity. Those solutions may prove to be feasible alternatives for protecting an evolving microgrid with high DER and DESS penetration. The conclusions are summarized as follows.

- Adaptive and intelligent relays are thus introduced to provide an enhanced protection measure over traditional protection techniques.
- New protection schemes can be either decentralized or centralized (in which case WAMS provides assistance via communication links for enhancing reliability).
- The application of various CI based data-mining models for building protection schemes is growingly popular. The implementation of effective protection schemes may be hampered by their complexity.
- DM, ML and NIA based approaches may prove as effective substitutes for traditional relaying algorithms, being capable of controlling circuit breakers for fault clearance in real time.
- Industry 4.0 also plays a big role for a high reliable cloud-based operation, control and protection systems.

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