Archives of Current Research International

18(2): 1-11, 2019; Article no.ACRI.50763
ISSN: 2454-7077

Review of Microgrids and Associated Protective Systems

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/ACRI/2019/v18i230132
Editor(s):
(1) Dr. Faisal, Lecturer, Institute of Business Studies and Leadership, Abdul Wali Khan University, Mardan, KP, Pakistan.
Reviewers:
(1) Himanshu Dehra, India.
(2) Bankole Adebanji, Ekiti State University, Nigeria.
(3) Rajinder Tiwari, Jammu University, India.
Complete Peer review History: http://www.sdiarticle3.com/review-history/50763

Review Article

Received 02 June 2019
Accepted 10 August 2019
Published 20 August 2019

ABSTRACT

In this century, the human appetite for electrical energy is the highest in history. This high demand for electricity results in increased need for power generation. The current power network is put under pressure to ensure high-quality generation, transmission and distribution of power. The network, in most countries, is aging – requiring higher resources in order to satisfy present-day challenges, in addition to the need to minimize power losses and optimize power production. These challenges have necessitated innovative power production techniques, such as the microgrid. The operation of microgrid comes with emerging challenges. This paper articulates and reviews some of the most noticeable challenges of utility and microgrid operations. The paper also presents some of the recent proposals for microgrid protection, as well as the limitations associated with these proposals.

Keywords: Microgrid; protection; distributed generation; relay.

1. INTRODUCTION AND MOTIVATION

Concerns for primary energy availability and aging infrastructure of current electrical generation, transmission and distribution networks are challenging security, dependability and power supply quality. To improve the power supply, distribution grids are being transformed

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from passive to active networks to facilitate access to distributed generation (DG); enable local energy demand management, interacting with end-users through smart metering systems; and to apply the transmission technologies such as dynamic control techniques to the distribution grid, to guarantee a higher general level of power security, quality and reliability [1].

A microgrid is a power system which comprises of small (micro-), distributed generators, energy storage systems and controllable loads run as a sole controlled and coordinated piece so that it operates in a grid-connected or autonomous (islanded) mode [2]. The primary interest of microgrid is supply of high-quality, unfailing and sustainable power to local consumers. This leads to need for bidirectional power flow. This is contrary to the main purpose of DG which focuses on increasing unidirectional availability of power without focusing on the satisfaction of a local load. Fig. 1 depicts a simplified architecture of a typical microgrid connected to the utility at Point of Common Coupling (PCC).

There are numerous research efforts aimed at full-scale deployment of microgrids. These efforts are largely driven by governments and corporate bodies, resulting in classified research data and findings. This paper presents an up-to-date results of research efforts in microgrid protection systems.

2. CURRENT POWER SYSTEM AND ITS CHALLENGES

In the contemporary power system, bulk energy production starts from centralized large generating systems. The power generated is then transmitted, mostly over long distances, to the distribution network where the energy is consumed. The distribution network is a low-voltage (LV) or medium-voltage (MV) network and radial in nature. Abnormal conditions such as faults could occur at various stages of the system, necessitating incorporation of control and protective devices in the network. The transmission network links the distribution network (consumer end) to the generation (producer end), but introduces power losses which results in economic loss to the utility and poor quality supply to the consumer [3,4,5]. Increasing energy demand and need for sustainable power generation drive growing deployment of renewable energy resources in form of microgrid. This increase in deployment of distributed generation changes the natural topology of the distribution network from radial to mesh or ring [6,7,8,9,10]. Consequently, the LV distribution network can no longer be considered a passive appendage to the transmission network – It becomes an active distribution network; a distributed generation. The impact of DGs on power balance and grid frequency may become obvious in the future [4].

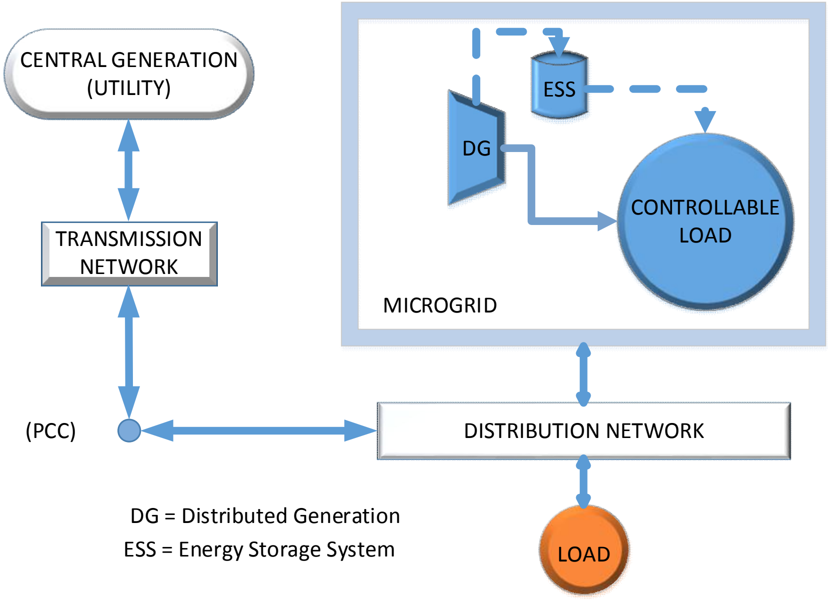


Fig. 1. A simplified utility-microgrid architecture

This topology change, converter-interfacing of microsources based on power electronics (PE) and the imminent bidirectional power flow render the contemporary protective devices such as overcurrent relays (OCRs) inappropriate for optimal system operation, particularly under various control strategies and operating modes [1,3,11].

In general, challenges related to protection can be grouped into two categories:

- Fault detection problems.
- Selectivity problems.

2.1 Blinding of Protection

This is a fault detection problem. Not only does connection of DG change the load flow in the distribution grid but potentially also alters magnitude of fault current whenever the grid is disturbed. Some distribution grid protective systems detect onset of faulty grid situation by discriminating a fault current from the normal load current. Because penetration of DG alters contribution of the grid to the fault current magnitude, the normal operation of existing protective system is potentially disrupted [10,12, 1,13,14,15,16], see Fig. 2.

2.2 Sympathetic Tripping

Sympathetic tripping, also termed false tripping, is a selectivity problem and occurs when a generator installed on a feeder contributes to the fault current in an adjacent feeder connected to the same substation [15,17,18,19], see Fig. 3a.

2.3 Loss of Fuse-recloser Coordination

Protective system for overhead distribution feeders with automatic recloser is an efficient way of protecting against un-sustained disturbances and to minimize the frequency of supply interruptions. Coordination of reclosers and lateral fuses ensures that permanent faults are cleared selectively. Integration of DG to distribution feeders with automatic reclosers causes several protection problems. Detection of

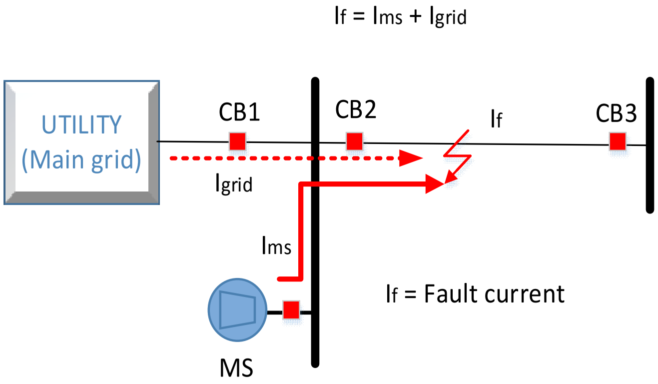
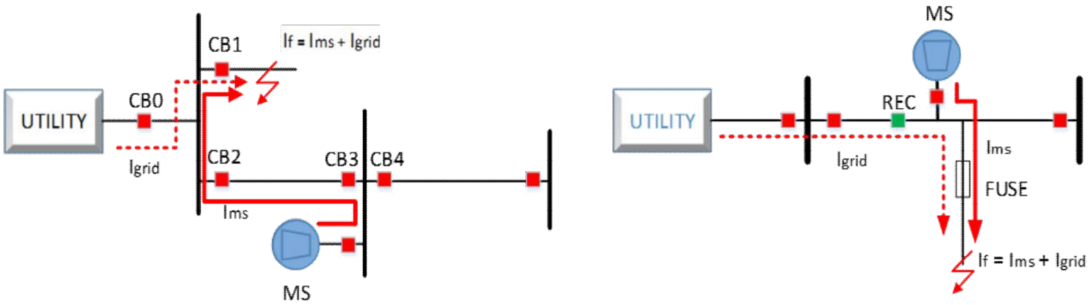


Fig. 2. Blinding effect of MS on CB1



a

b

Fig. 3. Typical challenges associated with use of OCRs in distributed generation (a) Sympathetic tripping, (b) Loss of fuse-recloser coordination

fault current by the recloser is affected by contribution of current from the generator, leading to fault detection problem. The coordination between reclosers or fuse and recloser can be lost which directly causes selectivity problem [20,21,22,23], see Fig. 3b. This is a selectivity problem.

Other problems related to use of overcurrent relays (OCRs) in microgrid include:

- Islanding and Non-synchronized Reclosing.
- Disabling of automatic reclosing.

3. MICROGRIDS AND FUTURE POWER SYSTEMS

The ever-increasing human appetite for electric power, changes in regulatory and operational climates of contemporary electric utilities, and the evolution of small generating units – including photovoltaic, microturbines, fuel cells, and internal combustion engines have opened new opportunities for electricity users to generate power at their premises. This makes distributed generation (small power generators usually located at sites where the energy they generate is consumed) a promising option to meet growing customer needs for economic and reliable electric power. This could make a consumer to become a net producer of electricity. Organizing these distributed energy resources (generators, energy storage and controllable loads) into a microgrid has the potential to meet environmental, regulatory, customer and utility needs. Some of the features of microgrid that make it promising as a solution to the challenges of meeting the foreseeable future energy demand include:

- High reliability – providing quality power to consumers.
- Potential for "plug-and-play" – addition of energy resources to the microgrid is flexible.
- Capacity for seamless islanding – this helps ensure supply continuity in the event of fault on the utility [24].

A microgrid is a "building block of smart grids" [25]. A microgrid could be ac, dc or hybrid. It is essentially a conversion of the passive distribution network to an active network. An active distribution network facilitates distributed decision-making and control, and the power flows are bidirectional in the network, in contrast to contemporary power system where power flow is unidirectional. It eases the integration of DG, renewable energy resource (RES), demand side integration (DSI) and energy storage technologies. It also enables use of intelligent electronic devices (IED) and controllers, which conform to common client-server protocol-based communication services based on uniform standards. The main functionality of a microgrid is to efficiently link power generation with consumer demands, allowing both to decide how best to operate in real-time [2-4].

It is a group of interconnected DGs, loads and energy storage units that co-operate in a manner that they are collectively treated by the grid as a single controllable load or generator. It is usually connected to the grid at the PCC, see Fig. 1. DGs are connected to the distribution networks, mainly at MV and LV levels. DGs include microsources (microgenerators) such as microturbines, fuel-cells and photovoltaic (PV) arrays together with storage devices, such as flywheels, energy capacitors, batteries and controllable loads e.g. electric vehicles [4].

4. CHALLENGES OF MICROGRID OPERATION

One of the main challenges faced in microgrid operation is related to large difference between the fault current level in the grid-connected mode and the islanded mode [26], caused by the fact that the short circuit levels of converter-interfaced microsources are typically controlled to not be more than 2-3 times their rated capacities by their controllers [27]. Also, in a microgrid the control strategy such as P or Q control determines the values of critical network variables such as magnitudes and angles of current and voltage. When the microgrid is in grid-connected mode, the grid dictates the control; when it is in autonomous mode of operation, operating conditions and operational codes dictate its control. For the same fault condition, the fault current or other parameters could differ under different control strategies. Some of the challenges limiting full-scale deployment of microgrids include:

1. Design of protection systems – due to:
    - Bidirectional power flow.
    - Network topology change - meshed network.
    - Converter interfacing – PE interfaced microsources include controllers which

limit current magnitudes, even during system stress.

2. Voltage and frequency control strategies – power electronics (PE).
3. Reliable islanded mode of operation – small rotating inertia in PE interfaced microsources (MSs). This results in low transient stability when the system is disturbed. This further causes inability to meet Low-Voltage Ride-Through (LVRT) and related grid codes.
4. Seamless change from islanded to grid-connected mode and vice versa – disconnection and reconnection incite fluctuation in voltage as well as oscillation in frequency.
5. Seamless integration – this is related to plug-and-play and peer-to-peer features.
6. Inadequate certainty in dispatch and reserves – this is related to natural intermittency of primary energy resource and relatively high cost of large storage systems [2,28].

5. MICROGRID PROTECTION SYSTEMS IN LITERATURE

Fig. 4 presents a graphical view of the basic quantities associated with different protective systems for microgrids.

5.1 Overcurrent Protection Schemes

Proposals for microgrid current magnitude protection evolved from the popular utility-scale overcurrent protection. This is done by either modifying the magnitude of current or by adding measurement of other quantities in order to solve the problem of blinding of overcurrent. For example, in 2006, Nikkhajoei and Lasseter [29, 30] proposed use of sequence quantities (negative- and zero-sequence) to distinguish between line-to-line and line-to-ground faults. In 2008, Best et al. [31] proposed a 3-stage scheme for overcurrent protection. In this technique, stage 1 detects the fault event using local measurements; stage 2 activates inter-breaker communication; and stage 3 adjusts relay settings through a supervisory controller. In 2012, Zamani et al. [32] developed an overcurrent protection using relays with microprocessor for low-voltage microgrids protection against faults in both islanded and grid-connected modes of operation. Operation of the proposed system is based on definite-time grading of relays in the microgrid and requires communication links. The major drawbacks of these proposals which are based on overcurrent protection include blinding and vulnerability to communication failures. This makes them less reliable and capital intensive.

5.2 Protection Schemes Based on Voltage Measurement

These schemes essentially utilize measurement of voltage in protecting the microgrid from faults. In 2006, Al-Nasseri et al. [33] reported a scheme that monitors and transforms output voltages of microsources to direct current quantities based on the *d-q* reference frame so that the scheme could be used to protect the microgrid against both in-zone and out-of-zone faults. In 2009, another protection scheme based on voltage measurement was reported by Loix et al. [34]. The scheme utilizes the effect of fault types on Park's components of measured voltage. It could be used to protect the microgrid from three phase, two phase and one phase-to-earth faults. Its basic operation does not require communication links, but it requires communication links for optimal operation. The most prominent feature of this scheme in comparison with the one proposed by Al-Nasseri et al. [33] is that it is versatile – that is, it could be used to protect all configurations of microgrids.

5.3 Current Differential Protection Schemes

Current differential scheme is a type of protection for elements such as transformers, buses, generators, lines and feeders. It generally uses differential relay which works on the basis of Kirchhoff's current law. The law states that the algebraic sum of currents entering and exiting a node equals zero [35]. This scheme operates when the differential between these currents exceeds a pre-set value. One strength of this scheme is that it is not sensitive to bidirectional power flows and attenuation in magnitudes of fault current which typically occurs in islanded microgrids. In 2006, Nikkhajoei and Lasseter [30] reported a procedure for microgrid protection using combination of differential protection and symmetrical components measurements. The proposal utilizes zero-sequence and negative-sequence currents of the microgrid to detect Single Line-to-Ground (SLG) and Line-to-Line (LL) faults, respectively. Zeineldin et al. [36] reported a work on the future of microgrids in 2016 and expressed concern on two major challenges; protection and control of voltage/frequency. Consequently, they proposed a scheme which employs differential relays at both ends of each line.

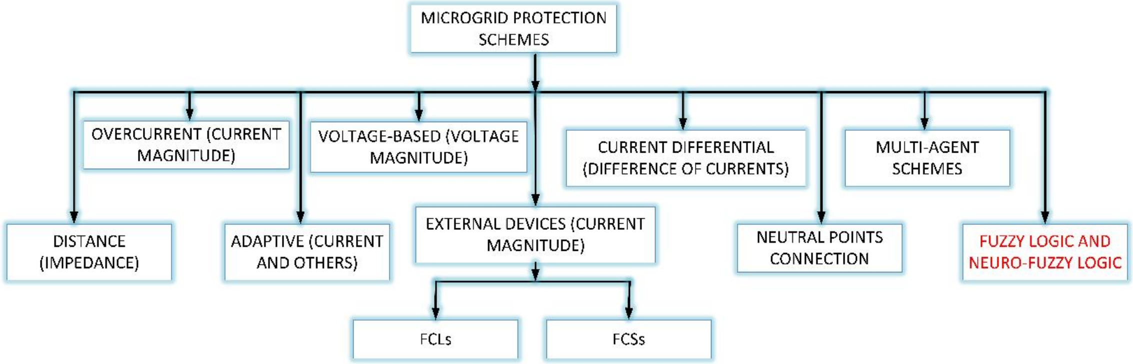


Fig. 4. Block diagram showing the current state of microgrid protection schemes in literature

These relays, designed to operate in 50ms, could protect the microgrid in both grid-connected and islanded operation modes. In 2010, Sortomme et al. [37] reported a protection scheme using synchronized phasor measurements and microprocessor relays for recognition of all kinds of faults, including High Impedance Faults (HIFs). They demonstrated that it provides robust protection when the relays are installed at the end of each microgrid line. In 2010, Parsai et al. [38] reported a scheme called Power Line Carrier (PLC). The scheme uses communication link to provide multiple levels of protection for meshed micrograms. In 2011, a differential scheme was reported by Dewadasa et al. [39]. This scheme considers all the protection challenges such as bidirectional power flow as well as attenuation of fault current level in islanded microgrids. The system displays capability to protect the microgrid in both modes of operation. One of the major contributions of this scheme is its potential to satisfactorily protect feeders and microsources in a microgrid.

5.4 Distance (Impedance) Protection Schemes

The principle of operation of a distance relay (sometimes called impedance relay) differs from other forms of protection because its response is not directly determined by current or voltage magnitude but determined by the ratio of voltage-to-current or vice versa. Impedance relays are double actuating types, since one coil is energized by voltage while the other is energized by current. A positive or pick-up torque is produced by the current element while the negative or reset torque is produced by the voltage element. The relay operates only when the V/I (impedance) ratio or I/V (admittance) ratio falls below or above a preset value (or set value). In 2008, Celli et al. [40] reported a distance relay scheme in order to detect grounded faults in distribution systems which have high penetration of distributed generation. This proposal uses wavelet coefficients of the transient fault current at critical points of the network. The proposed scheme operates without communication link or synchronized measures. However, if communication is used to enhance communication among the relays, the scheme provides robust protection for the distribution network against ungrounded faults.

5.5 Adaptive Protection Schemes

Adaptive protection could alleviate the challenge of protecting a microgrid in both modes of operation. In this scheme of protection, automatic change of relay settings is triggered whenever the microgrid changes from one mode to the other and vice versa. Typically, it modifies the favored protective response to change as conditions of the system change in a manner which is sufficiently timely through externally generated control stimulus or signals.

In 2006, Tumilty et al. [41] proposed an adaptive scheme of protection which does not require communication assistance. The proposal employed a voltage-based fault detection method in discerning the typical voltage drop occasioned by over-load and short circuit events. In 2009, Oudalov and Fidigatti [42] proposed a novel adaptive microgrid scheme employing digital relay and advanced communication link. The proposal is based on a centralized topology which determines the state (grid-connected or islanded) of the microgrid and consequently adapts protective settings accordingly. In 2011, Dang et al. [43] employed Energy Storage (ES) and isolation transformers to sense the mode of microgrid. Thereafter, identification of the fault is implemented through comparison of zero-sequence current and a preset value. In 2012, Khederzadeh [44] proposed an adaptive scheme in which digital relay is efficiently used for protection of microgrids. In this scheme, relay settings are adapted depending on status of the microgrid, i.e., utility grid-connected or islanded operation.

5.6 Protection Schemes Driven by External Devices

As stated in 4, the fundamental challenge facing microgrid protection is related to the wide difference between fault current levels in the grid-connected and islanded modes [26]. Consequently, it becomes necessary to realize adequate protection scheme which has the capability to operate satisfactorily in both grid-connected and islanded modes. Some methods in literature have proposed modification of short-circuit level whenever the microgrid operation changes mode. These systems can be classified into two groups:

5.6.1 Fault current limiters (FCLs)

FCLs are used to attenuate net contribution of all MSs. FCL technique is capable of effectively changing the short circuit current level to surpass the design limit of various system elements. In 2011, Ustun et al. [45] proposed design of a microgrid protective scheme based on current limiters. The scheme is communication-assisted and monitors the microgrid to update fault current settings of relays according to system variations. The proposed system dynamically responds to changes in the system including connection and disconnection of MSs. In 2012, Ghanbari and Farjah [46] proposed a novel FCL scheme using resonant type solid-state fault current limiter (SSFCL) which exhibits very low impedance through a series resonant circuit under normal condition. Under fault condition, the fault current limiter offers a very high impedance through a parallel resonant circuit. In 2013, Ghanbari and Farjah [47] proposed a unidirectional fault current limiter (UFCL). The proposed UFCL is installed between the upstream and downstream network, such that it only limits the current contribution of the downstream network during a fault in the upstream. Inversely, during a fault in downstream, the UFCL is inactive and allows a full contribution of the upstream network. It was shown that by this strategy, the proposed UFCL can preserve the coordination protection of the upstream over-current relays.

5.6.2 Fault current sources (FCSs)

As stated in 4, the typical short-circuit current level in a microgrid is restricted to about 2-3 times of the rated current because of controls in PE-interfaced MSs. Fault current sources such as energy storage devices (flywheels or batteries) can be employed to deliver supplementary short-circuit level to the network [26]. In 2013, Oudalov et al. [1] reported a FCS for protection of microgrid. In this scheme and whenever operating conditions are normal, the FCS power circuit is inactive. Whenever fault occurs, the network voltage typically drops, activating the FCS. The FCS tries to restore the nominal network voltage through injection of fault current into the network. Usually, the fault current injected is sufficiently high to activate OC relay trip logic which energizes a circuit breaker.

5.7 Protection Based on Multi-agent Schemes

In 2016, Hussain et al. [48] proposed an N-version programming-based protective scheme for microgrids using multi-agent method. Developed in MATLAB Simulink, the scheme has three protection versions namely, Clarke's transformation-based current protection, positive-sequence phase differential-based protection and conventional over-current-based protection. The software in this proposal determines the decision about the type of fault and which of the three protection versions to deploy via a decision tree process. The process depends on a truth table and a K-map for decision making. This proposal applies to both balanced and unbalanced faults in both grid-connected and islanded modes. However, it suffers from dependence on inter-agent link which makes the system susceptible to communication failure and capital intensive. Also, the cost of implementing the system is further exacerbated since it requires three different hardware for detection and clearance of fault. Generally, the system uses two non-over-current schemes in addition to the over-current protection used in conventional schemes, this results in heavy hardware redundancy and increased failure points.

5.8 Protection Based on Neutral Points Connection

In 2016, Kamel, Alsaffar and Habib [49] reported a protection scheme for islanded microgrids. The proposed scheme increases magnitude of the fault current when in islanded mode of operation so that it becomes sufficiently large for detection and clearance using current magnitude devices. Operation of the system is achieved through connection of the neutral terminals of all microgrid loads to the neutral line of the microgrid's earth. This provides a path of least resistance and increases magnitude of the current whenever it is faulted. On one hand, the system is simple, cost-effective and reliable. It also fulfills the peer-to-peer requirement of microgrid. On the other hand, it fails the plug-and-play requirement of microgrid. It also applies to only islanded microgrids. If the microgrid is grid-enabled, the scheme is not only inadequate but also inappropriate. This is for the reason that under utility short circuit, the scheme has potential to be counter-productive and harmful to other equipment as well as personnel due to large magnitude of utility short circuit MVA.

5.9 Protection Based on Fuzzy Logic and Neuro-Fuzzy Logic

In 2018, Maruf [50] proposed a multi-variable relay based on combination of fuzzy rules. The proposed relay consists of two distinct sub-relays: feeder sub-relay and micro-source sub-relay. The feeder sub-relay measures four parameters (active power, reactive power, voltage and current) of the feeder while the micro-source sub-relay measures similar parameters of the micro-source. Online as well as offline response test of the proposed relay indicates that it generates logic 1 during short circuits and logic 0 during normal operating conditions in both grid-connected and islanded modes of operation of the microgrid. The proposed relay also provides equivalent response under both voltage and reactive power control strategies. This is consistent with response of a reliable protective relay as reported in related literature. The proposed relay also supports plug-and-play and peer-to-peer requirements of microgrids. Similar to digital relays reported in literature, the proposed relay departs from conventional relays wherein protection is based on threshold of short circuit current. In the proposed relay, protection is based on nominal parameters of micro-sources and feeders.

Table 1. Merits and demerits of proposals for micro-grid protection in literature

Basic measurement in proposal	Merits	Demerits
Current magnitude	Effective for both short-circuit and high impedance faults	Blinding of OCRs
Voltage magnitude	Blinding of OCRs/Effective for in-zone and out-of-zone faults	Susceptible to communication failures
Current differential	Very effective for micro-grids protection of various faults	Very expensive and vulnerable to communication failures
Distance (Impedance)	Operation may not require communication links	Intermediate in-feed of microsources has impact on the measurement of the fault impedance
Essentially current, but other quantities could be employed	Adapts to changes in network configuration	Vulnerable to communication failures and adaptation may not be instantaneous
Current - Use of external devices	Effective for both grid-connected and islanded operating modes	Expensive and potentially counter-productive
Multi-agent approach	Applicable to both balanced and unbalanced faults in both modes of operation.	Over-redundancy of hardware and increased failure points.
Neutral points connection	Simple, cost-effective and reliable. It also satisfies the peer-to-peer requirement of micro-grid	It fails the plug-and-play requirement of microgrid. Its applicability is also limited to micro-grids in islanded mode of operation
Fuzzy Logic	Applicable to both balanced and unbalanced faults in both modes of operation	Rules have to be formulated to meet requirements of each microgrid, resulting in programming of hardware for specific microgrid

6. MERITS AND DEMERITS OF PROTECTION SYSTEMS IN LITERATURE

Table 1 shows the strength and weaknesses associated with the proposals for microgrid protection in literature.

7. CONCLUSION

This paper articulates the challenges of utility power system and the drivers for innovative power system, such as the microgrid. It has also thoroughly discussed the obvious operational challenges of the microgrid, particularly with respect to protection. A summary of the various categories of proposals for the protection of microgrids in literature as well as the deficiencies of each category of proposal has also been presented in this work. The aim of this study, which was to conduct an overview on microgrids and associated protective systems, has been achieved.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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Peer-review history:
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