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A Review on Protection Schemes and Coordination Techniques in Microgrid System

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Abstract: A protection scheme ensures that short-circuit event is detected and fault is cleared by the protective devices and protective coordination is to ensure that the correct device operates to isolate the faulty parts. Combination of these algorithms affirms the successful operation of protective devices in a distribution system. Significant changes occur in a distribution system when there is a high proliferation of distributed generation in the system. This results in the development of different approaches for tackling the protection issues in a microgrid distribution system. This study presents a review on the available protection schemes and coordination techniques used for addressing the protection issues in a microgrid distribution system. The various protection schemes and coordination techniques applied for microgrid protection are discussed in terms of implementation methods, modes of operation, types of distributed generations, availability of communication links, and lastly their advantages and disadvantages.

Key words: Protection scheme, protection coordination, distribution system, microgrid, distributed generation, relay

INTRODUCTION

Microgrid is a new approach of power generation and delivery system that considers Distributed Generations (DG) and loads as a small controllable subsystem of a distribution system. The subsystem has characteristics such as the ability to operate in parallel or in isolation from the macrogrid, the possibilities to improve service and power quality, reliability and operational optimality (Zamani *et al.*, 2011). It can be operated either in interconnected to or islanded from the main grid depending on factors like planned disconnection, grid outages or economical convenience (Brucoli *et al.*, 2007). Due to the need to capitalize benefits of DG from its high proliferation in distribution systems, the concept has gained interest by many researchers as an alternative and effective solution to the supply and demand related problems. Four classes of microgrid architectures are reported by the Navigant Consulting based on the load sizes of the subsystems. They are single facility microgrid, multiple facility microgrid, feeder microgrid and substation microgrid (Bose *et al.*, 2007). A typical configuration of a microgrid is shown in Fig. 1. It consists of a group of radial feeders, a point of common coupling, critical and non-critical loads and micro-sources (Lasseter, 2007). This subsystem is capable to operate in dual modes, i.e., normal operation in which the microgrid is connected to the main grid and islanded operation in which it is separated from the main grid. During a fault in the main grid, the static switch will ensure fast separation of the microgrid from the main grid to island in less than one cycle (Feero *et al.*, 2002). This action is to ensure that the downstream part from the point of common coupling can operate continuously with the supply from the DG.

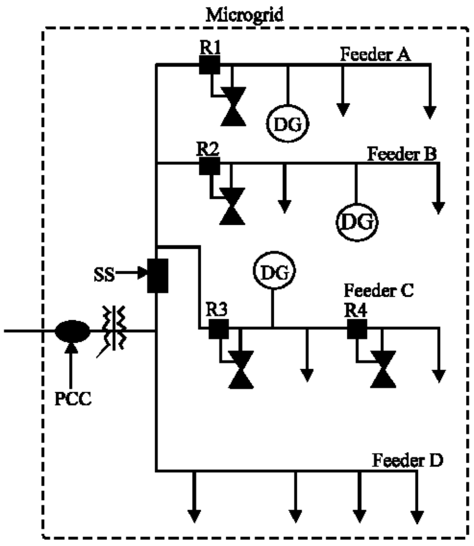

Fig. 1: A basic microgrid architecture (Lasseter, 2007)

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Many technical and economical benefits have been reported as a result of microgrid implementation (El-Saadany *et al*., 2007; Colson and Nehrir, 2009; Basu *et al*., 2011; Agrawal and Mittal, 2011). The benefits are: (i) increase in reliability and stability of power supply, (ii) reduction of green-house gases emission as a result from utilization of renewable energy sources, (iii) reduction of line losses and deferral of investment in new construction and upgradation of infrastructures and (iv) provide excess power and assist voltage support to the utility grid during interconnected mode of operation. Nonetheless, a microgrid does not only tender its benefits but also has adverse effects due to the interconnection of DGs. The increasing penetration of DGs in power systems will deeply affect the distribution network topology, amplitude and distribution of short-circuit current in the existing distribution network and consequently affect the operation and control of distribution networks (El-Saadany *et al*., 2007; Wang *et al*., 2008). Several protection issues related to the effects of DG have been addressed in Feero *et al*. (2002), Baghzouz (2005), Driesen *et al*. (2007), Salam *et al*. (2008), Butler-Purry and Funmilayo (2009) and Conti *et al*. (2009). These issues are related to relay selectivity, overcurrent and earth-fault protection, protective disconnection of generators, islanded operation and neutral grounding. Studies related to impacts of DG on the protection of distribution systems have been widely researched to enable its implementation into the distribution grids. It is a fact that addition of DGs to the distribution grid increases the complexity of protecting the distribution system due to the change in magnitude, duration and direction of fault current (Dugan and Rizy, 1984; Hadjsaid *et al*., 1999). The severity of the problem increase significantly when there is increased proliferation of DG into the distribution system. The DG impacts to the distribution protection include loss of protection coordination, unnecessary tripping and reduction of reach (Girgis and Brahma, 2001; Salman and Rida, 2001; Doyle, 2002; Emhemed *et al*., 2007; Colson and Nehrir, 2009). Chilvers *et al*. (2003) proposed the use of microprocessor-based relay with incorporated distance and directional elements but without a communication link to protect the grid with DG from phase and earth fault currents. Vermeyen *et al*. (2004) conducted a detailed simulation study on the effects of the DG to the distribution grid protection for different types of faults and different combination of DG types. Brahma and Girgis (2004) introduced a zonal protection scheme to overcome the effect of high DG penetration into the distribution grid. In this scheme, the grid is divided into zones that have reasonable balance of load and DG, with DG capacity a little higher than the load. Zeng *et al*. (2004) on the other hand proposed a decentralized multi-agent based protection with capability of high impedance fault detection. The method uses digital relay as an agent-based current differential relay which is capable of searching for information from other relay agents, interact with other relay agents and perform tasks of protection with autonomy and cooperation. Multi agent relays cooperate to locate faulty section and shed loads in the isolated DG system.

One of the techniques used to protect the distribution system with DG is known as the adaptive overcurrent protection scheme (Javadian *et al*., 2008). In this scheme, an existing distribution network is divided into two categories of zones, namely, zones without DG and zones with DG. System protection is carried out through a computer-based relay which is installed in sub-transmission substation. The relay determines the system's status after it receives the required network data, and in case of fault occurrence, it diagnoses its type and its location and finally issues a proper command for protection devices to clear the fault and to restore the network. Offline calculation gives the power flow and short-circuit current for all types of faults at all points in the network. Characteristics of minimum melting and total clearance of all fuses in the network are stored in the relay. Zayandehroodi *et al*. (2010) presented an automated protection scheme for distribution networks with high penetration of DGs using Radial Basis Function Neural Network (RBFNN). Here, zoning of the distribution system with dedicated circuit breaker was done and three staged RBFNNs have been developed to detect different types of faults at different fault points. The first RBFNN identifies the distance of fault point from each power source, the second RBFNN determines the faulty lines and the third RBFNN decides which circuit breakers must be triggered to isolate a fault.

Efforts for studying protection scheme for distribution system with microgrid have started since 2002 when a group of researchers from Consortium for Electric Reliability Technology Solutions (CERTS) studied the protection problems that must dealt with to successfully operate a microgrid when the utility is experiencing abnormal conditions. Chen *et al*. (2011) have categorized the microgrid protection schemes according to (i) improved current protection schemes, (ii) protection schemes based on fault current limiter, (iii) wide area protection schemes, (iv) abc-dq transformation protection schemes and (v) THD protection schemes. This paper presents a review of microgrid protection schemes and the coordination techniques that are available in the literature. A critical analysis of the existing schemes and techniques are made in an attempt to suggest a viable protection scheme and coordination technique for a microgrid system.

PROTECTION OF MICROGRID

In designing a protection system of any power system, the protection requirements that must be considered are reliability, speed, selectivity and cost (Gers and Holmes, 2005). The main function of a protection system is to quickly remove from service any component of the system that starts to operate in an abnormal manner. Other functions are to ensure the safety of personnel, to safeguard the entire system, to ensure the continuity of supply, to minimize damage and to reduce resultant repair cost. When a fault occurs, a protection system is required to disrupt as few section of the system as possible. Selective operation of the protective devices will ensure maximum continuity of service with minimum system disconnection.

Conventional distribution system is designed to operate radially, where only a single source is present. The current flows in one direction from the higher voltage levels at the substation, through the distribution feeders and laterals at lower voltage levels, to the customers' loads. Based on this characteristic, the system relies on a simple and low-cost protection schemes that consist of fuses, reclosers, circuit breakers and overcurrent relays (Girgis and Brahma, 2001; Gers and Holmes, 2005; Javadian *et al*., 2009). Example of a conventional distribution system with the protective devices installed is shown in Fig. 2. Breakers and reclosers are normally installed at the main feeder to allow clearance of temporary faults before lateral fuses blow. In normal condition, breakers and reclosers are equipped with inverse time overcurrent relays which normally installed at the substation where the feeder originates (Aslinezhad *et al*., 2011). The protective devices are coordinated to operate according to criteria of selectivity based on current or time so as to ensure the device nearest to a fault will operate first. The basic criteria that should be employed when coordinating time or current devices in distribution systems are (Gers and Holmes, 2005):

- The main protection should clear a permanent or temporary fault before the backup protection operates, or continue to operate until the circuit is disconnected. However, if the main protection is a fuse and the back-up protection is a recloser, it is normally acceptable to coordinate the fast operating curve or curves of the recloser to operate first, followed by the fuse, if the fault is not cleared
- Loss of supply caused by permanent faults should be restricted to the smallest part of the system for the shortest time possible

In a traditional distribution system, the protection systems are designed assuming unidirectional power flow and are usually based on overcurrent relays with discriminating capabilities. According to IEEE (2003) for any fault situation, DG sources connected to the system are tripped off. In other words, islanded operation of DG sources is not allowed. When a microgrid is created in a distribution system, the configuration becomes a complex multi-source power system. The protection philosophy of the microgrid is to assure safe and secure operation of the subsystem in both modes operation, i.e., during interconnected mode and islanded mode. However, the two operating modes pose new challenges in protecting the microgrid. Therefore, two sets of protection settings is the most probable solution to the dual modes of operation. During grid-connected operation, the mains supply large fault currents to the fault point. This makes possible the employment of the existing protection devices in the distribution system. Yet, the protection coordination may be compromised or even entirely lost in some cases due to the installation of DGs. On the other hand, such large fault current contribution from the microgrid cannot always be expected, especially when it is dominated by electronically-coupled DGs (Zamani *et al*., 2011). Thus, the use of conventional overcurrent protection in the microgrid is no longer valid due to this low short circuit current contribution from the micro-sources. It is obvious that alternate means of

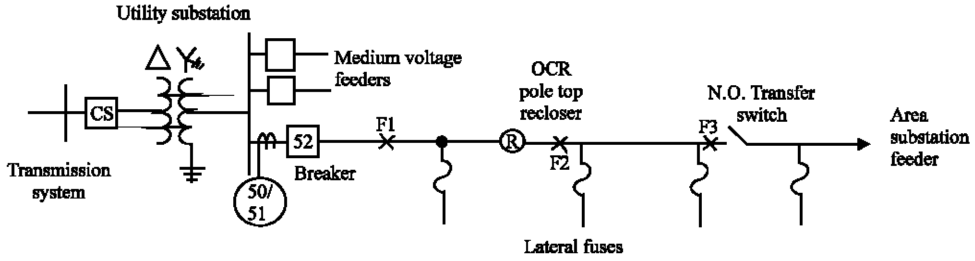

Fig. 2: Typical distribution system with protection devices

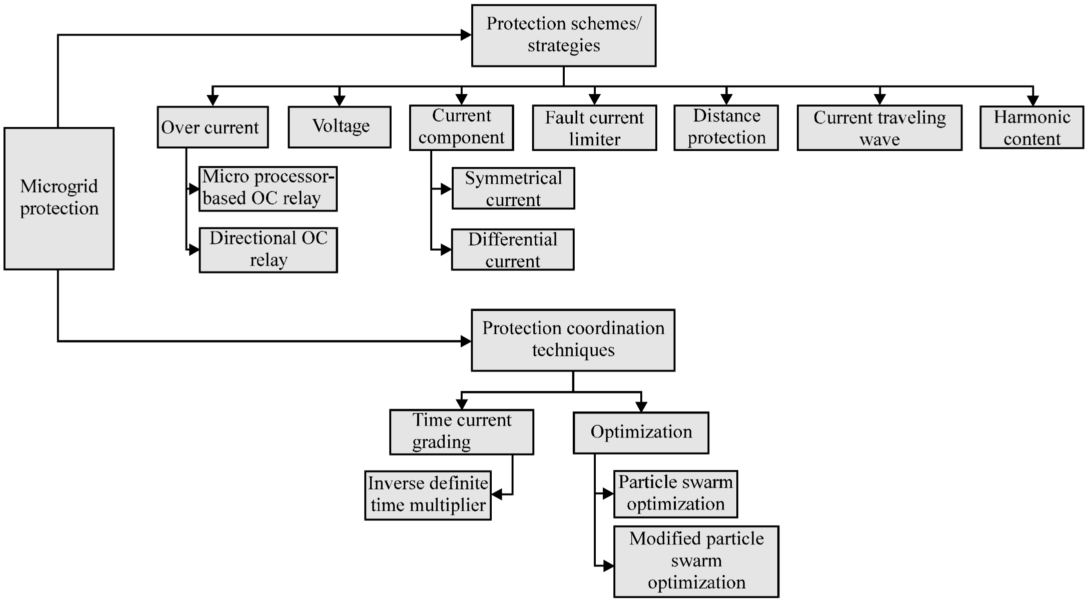

Fig. 3: Different types of protection schemes for microgrid operation

detecting an event within an isolated microgrid must be studied and new protection schemes have to be devised.

In order to design a microgrid protection system that suits both grid-connected and islanded modes of operation, the following features must be considered (Jenkins *et al*., 2005):

- The system must be able to respond both to distribution system and microgrid faults
- For a fault on the main grid, isolate the microgrid as quickly as possible
- For a fault within the microgrid, isolate the smallest possible section of the radial feeder carrying the fault to get rid of the fault
- The protection scheme must ensure an effective operation of customers' protection

Microgrid protection schemes: The protection of a microgrid must respond to both main network and microgrid faults. If a fault occurs on the main grid, the desired response is to isolate the microgrid from the main network as rapidly as necessary to protect the microgrid loads. This caused islanding of the microgrid operation. If a fault occurs within the microgrid, the protection system is required to isolate the smallest possible faulted section of the microgrid to eliminate the fault. Various possible microgrid protection schemes and coordination techniques that are available from the literature are summarized as shown in Fig 3. The protection schemes can be divided into overcurrent-based, voltage-based, current component-based, harmonic content-based, fault current limiter-based and current traveling wave-based. As for protection coordination techniques, time-current grading and optimization algorithms are used to ensure selectivity of the protective devices. The functionality and reliability of different types of protection schemes have been studied to fulfill different mode of operations, different types of DGs that exist in a microgrid, different issues that it has to tackle like bi-directionality of power flow and location of DG placement.

Overcurrent scheme: Jenkins *et al.* (2005) simulated a simple microgrid system containing 200 kW flywheel storage system, a number of micro sources and a group of residential consumers, in order to investigate possible protection schemes for a microgrid. Two scenarios are studied, i.e., when microgrid is connected to the main network and when the microgrid is islanded from the main network. For a fault on the main distribution network, overcurrent relay protection and balanced earth fault protection were installed at the grid side of the circuits between the main distribution network and the microgrid, with the capability of inter-tripping the microgrid. Investigation was also made to the test system for different location of faults. For fault on the microgrid, overcurrent relay protection and Residual Current Device (RCD) are used to protect the feeder from the fault. During the fault, the flywheel supplies a high fault current (e.g., 3 p.u based on its rating or above) if the microgrid is operated in islanded mode. After the fault, the protection disconnects the faulty feeder from the microgrid and has the capability of inter-tripping all the micro sources on the feeder at the same time. For a fault at the residential consumer, a Short Circuit Protective Device (SCPD) like Miniature Circuit Breaker (MCB) or fuses and a RCD can be installed at the grid side of the residential consumer. The SCPD is used to protect the residential consumer against the phase to phase and phase-to-neutral faults while the RCD is used for phase-to-ground or earth fault. However, the use of conventional overcurrent protection scheme gives rise to problems such as less sensitivity, refusing to operate and mal-operation (Chen *et al.*, 2011).

Improved overcurrent with directional element: The deficiency of the traditional overcurrent to protect the microgrid due to bi-directional flow of current has led to the use of directional element in the overcurrent devices. Hadzi-Kostova and Styczynski (2006) and Oudalov and Fidigatti (2009) suggest the use of directional overcurrent relay with communication for microgrid protection. The relays are capable of detecting and isolating the faults external and internal to the microgrid. However, this type of protection scheme requires a relatively high investment cost in comparison to the conventional protection system using fuses. Chunguang *et al.* (2009) proposed the use of directional comparison and current comparison pilot protection based on two terminals information to distinguish internal faults from external faults without coordination with other protection devices. A master-slave concept of the protection devices has been used to protect the microgrid where through communication the fault direction and its position could be identified. Zamani *et al.* (2011) presented a new scheme for protecting low voltage grid-connected and islanded microgrid using programmable microprocessor-based relays with directional elements. This scheme does not rely on communication link and fairly independent of fault current magnitudes and mode of operation. The improved overcurrent with directional element protection scheme still has some limitations and can only suit the requirements to some extent due to the continuously addition of DGs and uncertainty of connecting and disconnecting of DGs from the main grid, the distribution network topology and protection setting values that change frequently (Chen *et al.*, 2011).

Voltage-based scheme: The protection scheme based on DG output voltage measurement was used to detect and clear faults (Al-Nasseri *et al.*, 2006; Redfern and Al-Nasseri, 2008). The output voltages were monitored and transformed into dc quantities using the d-q reference frame. Any disturbance at the DG output due to a fault on the network will be reflected as disturbances in the d-q values. Zones of protection and use of communication link between relays to aid the protection scheme in discriminating between in-zone and out of zone faults are also considered. Verification via simulation has been done for different fault locations and different types of faults. However, the proposed scheme is devised for islanded operation only without considering the grid-connected mode of operation and high impedance fault.

The use of voltage based protection scheme for islanded microgrid dominated by inverter-based DGs was presented (Hou and Hu, 2009). In this scheme, a new fault judgement method based on detecting the positive sequence component of the fundamental voltage was used to judge the fault location and fault types in a microgrid. The waveforms of the 3-phase voltages and the voltage magnitudes under symmetrical and unsymmetrical fault conditions were transformed into the d-q reference frame and compared with the amplitude of the fundamental positive sequence voltages in the d-q coordinate system.

Symmetrical and differential current component scheme: Nikkhajoei and Lasseter (2006) proposed a method for protection of microgrid based on symmetrical and differential current components against SLG and LL faults. In this method, a microgrid is divided into several protection zones with relays. The differential current components are used to detect fault that occurs in the up-stream zone of protection and the symmetrical current components (zero-and negative-sequence current components) are used to detect SLG fault in down-stream zone of protection and LL faults in all zones of protection. Simulations were done at different location of faults for inverter-based DG microgrid and the results showed that the scheme is capable of protecting the microgrid in islanded mode of operation.

Zeineldin *et al.* (2006a) applied a differential current protection scheme for inverter-based DG in grid-connected and islanded microgrid. Current sensors at both ends of a line will determine whether a relay should send a tripping signal to the breakers or not. The scheme has been tested for faults inside the microgrid. Conti *et al.* (2009) also applied the differential protection scheme for a test microgrid consisting of synchronous-based and inverter-based DGs. Various solutions using zero-sequence directional current for differential protection was presented.

Sortomme *et al.* (2010) presented a protection scheme using differential protection and communication-assisted digital relays. The synchronized phasor measurements and microprocessor based relays were used to detect all types of fault conditions including high impedance faults. Here, the primary protection for each feeder relies on instantaneous differential protection. If absolute values of two samples are found to be above the trip threshold, a tripping signal is sent to the switching device.

Overcurrent protection based on fault current limiter: Connection of DGs to a distribution network increases the fault current closer to the rating of the protection devices and disturbs overcurrent protection coordination (Kumara *et al*., 2006; El-Khattam and Sidhu, 2008; Ustun *et al*., 2011). The existing protective devices can be replaced with higher rating devices but this choice is costly. One way to overcome overrating of protective devices is to limit the fault current to an acceptable level. The fault current limiter device is connected in series with power lines to limit the fault current contribution from the DGs while contributing a small impedance and power loss under normal operations.

Harmonic content based scheme: Another method for protecting microgrid has been presented by Al-Nasseri and Redfern (2008) based on harmonic content of inverter output voltage. When the type of DG embedded in the distribution system is of inverter-based type, the fault current contribution from the DG during islanded operation is limited to about twice the inverter's rated output. The inverter-based DG is a good source of harmonics that are injected into the network during a fault. Using the harmonic content based protection scheme, the protection relay continuously monitors the Total Harmonic Distortion (THD) of the inverter terminal voltage and shut down the inverter if the THD exceeds a threshold value during a fault.

Distance protection scheme: Distance protection scheme is another solution for converter-controlled microgrid as investigated by Dewadasa *et al*. (2008). Distance relays having Mho characteristic with two zones of protection were used in the study. Zone settings were chosen such that Zone-1 covers 80% of the protected line and Zone-2 covers the whole protected line, plus 50% of the adjacent line. In this method, the fault currents in the faulted phases were limited by reducing the converter output voltage. Next, by analyzing fault characteristics, the sequence currents and voltages at the relay locations are calculated. Simulations were done for grid-connected and islanded modes of operation for different types of faults at different locations with changes in fault resistance and load conditions. However, the effectiveness of this scheme is still not proven.

Uthitsunthorn and Kulworawanichpong (2010) suggested the use of distance relaying for multisource systems so as to reduce complication in impedance-based setting of distance relays. Three zones of protection have been considered to protect the lines. A comparison was made between the use of distance protection scheme and directional overcurrent protection scheme.

Adaptive scheme: Brahma and Girgis (2004) introduces a Global Positioning System (GPS) based adaptive protection scheme for a distribution network with high penetration of DG. The distribution network was divided into a number of zones by the circuit breakers according to a reasonable balance of the DG and local loads. The main relay at the substation has the capability of storing and analyzing large amounts of data and communicating with the zone breakers and the DG. The measurements of the GPS based adaptive protection were the synchronized current vectors of all three phases from every DG and the main source and the current directions of the zone breakers. The synchronized vectors were obtained using a global positioning system based phase measurement unit. In normal operating conditions, the sum of all these current phasors would be equal to the total load in the network. In case of fault condition, the sum will be significantly larger than the total load.

Oudalov and Fidigatti (2009) presented a novel adaptive protection scheme using digital relaying and advanced communication technique which is based on a centralized architecture where protection settings are updated periodically by the microgrid central controller with regards to the microgrid operating states. The scheme was realized using numerical directional relay with directional interlock capability to selectively protect the microgrid.

Han *et al*. (2010) presented an adaptive fault current protection algorithm for inverter interfaced DG based microgrid. By calculating the system impedance, the method adaptively changes the setting value of the protection to adapt to the grid-connected or islanded modes of operation. As the operating modes of a microgrid affect the fault component, a comparison is made between the system impedance and the microgrid side impedance such that current instantaneous protection can automatically adjust the settings.

In a more recent study, Voima *et al*. (2011) presented a novel adaptive protection scheme based on telecommunication using Intelligent Electronics Device (IED). The method depends on information available through measurement of current flow direction and voltage from multiple measurement locations. Implementation of this method was done in two phases involving detection of fault condition based on undervoltage and detection of faulted zone based on current flow information from the IEDs.

Current traveling waves: Shi *et al.* (2010) introduced the current traveling waves protection based on local information without using communication to determine an event caused by fault of switching operation. The scheme uses busbar voltages to determine whether a fault occurs and current traveling waves to identify the faulted feeder. When a fault occurs in one feeder, the power frequency voltages in the busbar connected to the faulted feeder will change according to the fault types. Current traveling waves are measured by current transformers in lines and wavelet multi-resolution analysis is used to decompose the traveling wave signals. The initial traveling waves are compared with each other in terms of magnitude and polarity to determine the faulted feeder. The protection is independent of microgrid operation modes and immune to power flow, fault current, unbalanced load and plug-and-play generators.

PROTECTION COORDINATION TECHNIQUES IN MICROGRID

Protective device coordination or selectivity is the process of applying and setting the protective relays that overreach other relays such that they operate as fast as possible within their primary zone but have delayed operation in their backup zone (IEEE, 2001; Blackburn and Domin, 2006). The goal is to ensure maximum service continuity with minimum system disruption. Historically, protective device coordination was done on translucent log-log paper but modern methods normally include detailed computer based analysis and reporting. A properly coordinated protection maximizes power system selectivity by isolating faults to the nearest protective device, as well as avoiding nuisance operations that are due to transformer inrush or motor starting operations. System protection is said to be selective if only the protection device closest to the fault is triggered to remove or isolate a fault. If this takes too long, the protection at a higher level takes over. This rule of thumb allows disconnection of those components that are faulty.

For a distribution system without DG, power flows in one direction during normal operation as well as when a fault occurs. This allows for the use of a selective system by applying time grading to overcurrent relays. When DG is installed, this system becomes inadequate. A possible scenario is disconnection of a healthy feeder by its own protective relay because DG contributes to short-circuit current flowing through a fault in a neighboring feeder. On the other hand, if a fault occurs on the connection between the supplying grid and a local network, disconnection of feeders or generators should take place. In an islanded microgrid, the voltage drop caused by a fault is almost the same across the entire network, due to limited geographical span. Therefore, it is almost impossible to coordinate protective devices based on voltage profile (Zamani *et al.*, 2011).

Coordination using time-current discrimination: Nikkhajoei and Lasseter (2006) presented time delay discrimination for coordinating all relays in a microgrid. Here, the SLG faults and LL faults are detected based on symmetrical and differential current components. A threshold value is selected for all relays to detect downstream SLG fault based on a zero-sequence current component and another threshold value is set for relays to detect upstream SLG faults based on differential current component. For detecting a LL fault, another threshold value is selected based on negative-sequence current component..

To ensure coordination of protective devices during islanded mode of operation, Zamani *et al.* (2011) proposed the use of microprocessor-based overcurrent relay with directional element, in conjunction with fault detection module. The relays are discriminated based on the definite-time scheme, starting at the load side of secondary main and ending at the microgrid interface point. This will cause a longer fault clearance time at the generation side of the grading path but will not damage the microgrid equipment. The upper limits for the definite time delays at the generation side are determined based on constraints such as the sensitivity of the critical loads to voltage disturbances, the duration over which electronically-coupled DGs can contribute to the fault current and the stability of the rotating-machine based DGs.

Coordination using particle swarm optimization algorithm: Zeineldin *et al.* (2006b) presented a protection coordination algorithm using directional overcurrent relays for protecting microgrid consisting of synchronous-based DGs. The relay coordination problem was formulated as a Mixed Integer Nonlinear Programming (MINLP) problem and was solved using the Particle Swarm Optimization (PSO) technique, which was one of the heuristic techniques capable of solving constrained optimization problems. The main advantage of MINLP formulation is that it takes into account the discrete pickup current (I_p) thus providing better results than linear programming formulation. However, the complexity of the problem increases as the number of available discrete current settings, I_P increase for each relay. For this reason heuristic techniques such as PSO and genetic algorithm became the best solution to solve such complex problems. The scheme also used central protection unit via communication link to change the settings of the relays based on the system configuration.

Coordination using modified particle swarm optimization algorithm: Qu *et al*. (2010) presented the Modified Particle Swarm Optimization (MPSO) technique derived from Zeineldin *et al*. (2006a) to coordinate the directional relays in a microgrid. The relay coordination problem was solved by improving the initialization and weight of PSO algorithm and choosing suitable pickup current. The optimal settings of the relays were determined using the PSO algorithm. The improvement over the initial PSO algorithm is in the phase initialization part and phase up dating part of the PSO algorithm. In the initialization phase, the space for feasible solutions is defined as $x_{max} = (x_{max}-x_{min})$ x rand + $x_{max})$, $v_{max} = (v_{max}-v_{min})$ x rand + v_{min},whereas in the update phase, all particle positions in the D-dimensional space are not moved simultaneously but only one in each dimensional space at a time. The particles's position in the PSO algorithm is updated based on feasibility, fitness value and acceptance ratio. The study showed that the PSO algorithm is capable of obtaining a close to optimal solution.

CRITICAL ANALYSIS AND SUGGESTION

As mentioned in Gers and Holmes (2005), the attributes of protection scheme are reliability, selectivity, speed, cost and yet simple. However, it is impossible to have all the attributes in a single protection scheme due to many contributing factors like topology change, bi-directionality and relays characteristic. Thus, each protection scheme is designed uniquely for a specific test system and DG technology. Table 1 shows the comparison of the available protection schemes based on their application in a distribution system with microgrid.

As shown in the table, the scheme for protecting a microgrid differs from each other depending on the type of relay used, microgrid operating mode, type of DG connected in the microgrid, and availability of communication link. For a certain microgrid configuration, the selection of protection scheme also depends on the availability of high fault current and cost (Jenkins *et al*., 2005). It is obvious that a single protection scheme cannot fully protect a distribution system with microgrid. Therefore, a new protection scheme is required for a distribution system connected to a microgrid. The use of communication for microgrid protection is useful to ensure fast and reliable operation of protective devices but adverse effect due to breakdown of communication is intolerable.

As for protection coordination, the grading of the relays is either based on time or current discrimination. By maintaining a specific coordination time interval between relays, the selectivity can be assured. The optimum relay settings can be obtained through optimization techniques like PSO. As the system configurations and operating conditions often change, a review of the existing settings should be done when the available short-circuit current to a plant changes or when significant changes in plant loading occur.

Table 1: Comparison of protection schemes in a distribution system with microgrid

Protection Strategy	Type of relay used	Mode of operation	Types of DG	Availability of communication link	Merits	Demerits
Overcurrent (Jenkins *et al*., 2005)	Overcurrent relay	Grid-connected	Rotating-based and inverter-based	No	Do not require change of existing protection relay, more economical	Ineffective for Islanded mode of operation
Symmetrical and differential current components (Nikkhajoei and Lasseter, 2007)	Overcurrent relay	Islanded	Inverter-based	No	Combination of symmetrical and differential current allow full protection from LL and SLG faults	Does not allow single phase tripping and do not consider three-phase faults
Differential current components (Sortomme *et al*., 2010)	Digital relay	Grid-connected and islanded	Rotating-based and inverter-based	Yes	- Have the capability to detect high impedance fault	Costly implemention and assume technical features that are absent in the state-of-the-art equipment
Differential current (Conti *et al*., 2009)	Overcurrent relay	Grid-connected and islanded	Rotating-based and inverter-based	Yes	- Make use of traditional protection device Implementation cost reduced	Not always effective, especially when imbalanced microgrid and loads are connected to the network that will cause the zero and negative sequence current

Table 1: Continued

Protection Strategy	Type of relay used	Mode of operation	Types of DG	Availability of communication link	Merits	Demerits
Voltage (Al-Nasseri *et al.*, 2006)	-	Islanded	Inverter-based	Yes	- Generator has separate protection	Applied only for islanded operation. Does not consider single-phase tripping and high impedance faults.
Harmonic content Al-Nasseri and Redfern (2008)	-	Islanded	Inverter-based	Yes	-	- Might fail to trip in cases where several dynamic loads have been installed in the network
Current traveling waves (Shi *et al.*, 2010)	-	Grid-connected	-	No	Independent from high fault current, power flow direction, unbalanced load and plug-and-play generator	No simulation work has been conducted
Distance Dewadasa *et al.* (2008)	Distance relay	Grid-connected and islanded	Inverter-based	No	Zone of protection depends on the impedance of the protected lines	Relay downstream to a fault operates unnecessarily for the ground faults when a star connected load is connected downstream to the fault
Adaptive (Oudalov and Fidigatti, 2009)	Numerical directional overcurrent cost	Grid-connected relayand islanded	Rotating-based and inverter-based	Yes	Fast tripping action via communication Relay tripping decision is made locally	High implementation cost
Adaptive Voima *et al.* (2011)	Directional overcurrent relay	Islanded	Inverter-based	Yes	Ensure fast protection in all operating states	Applicable for isilanded mode of operation only

CONCLUSION

This paper has presented an introspective review of the protection schemes and coordination techniques that have been developed or presented in the literatures. All the presented protection schemes and coordination techniques have their own merits and demerits that draw interest to their application in the microgrid operation. A good protection should be capable of fulfilling the requirements of reliability, selectivity, speed and cost. For accurate selection of a protection scheme, a thorough study has to be done on the network characteristic and suitability of the scheme to be adopted based on the network itself. For microgrid protection, it is always better to use a scheme that utilizes communication links as it will ensure fast operation of the protective devices. As for existing distribution system connected to a microgrid, maximizing the existing infrastructure without much investment will be the most economical decision although not always the most desirable.

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