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A Comprehensive review of protection coordination methods in power distribution systems in the presence of DG

Abstract. *This paper presents an overview of solutions proposed in the literature for the overcurrent relay coordination problem in the presence of distributed generators (DGs). Furthermore, several protection issues are identified to study the requirements for protection in the presence of DGs, and possible innovative solutions for resolving the operational conflicts between distribution networks and DGs are also discussed.*

Streszczenie. *W artykule zaprezentowano przegląd metod zabezpieczeń przed przekroczeniem prądów dopuszczalnych w sieci z rozproszonymi generatorami. Szereg rozwiązań przeanalizowano pod kątem możliwych konfliktów między siecią dystrybucyjną i generatorami. (**Przegląd zabezpieczeń prądowych w sieci z generatorami rozproszonymi**)*

Keywords: Protection Coordination Methods, Review, Distribution Networks, Distributed Generation (DG), Protection Issues.
Słowa kluczowe: zabezpieczenia sieci, sieci dystrybucyjne, generator rozproszone.

1. Introduction

Distributed generators (DGs) are a viable alternative for developing countries where the reliability of the grid supply lies below desirable levels. Because utilities are no longer embarking on building large generating plants, distributed generation serves as an alternative for generating energy resources [1]. There are many benefits to be gained from the installation of DGs; however, great penetration of DGs into distribution systems would lead to conflicts with the protection procedures currently in place in the present networks because the present distribution system is designed as a passive and radial network. A typical distribution protection system consists of fuses, relays and reclosers. An inverse overcurrent relay is usually placed at a substation where a feeder originates. Reclosers are usually installed on main feeders with fuses on laterals. The coordination between fuses, reclosers and relays is well established for radial systems; however, when DG units are connected to a distribution network, the system is no longer radial, which causes a loss of coordination among network protection devices [2]. The extent to which a DG affects protection coordination depends on the DG's capacity, type and location [3-5].

Deregulation of the electric power industry, advancements in technology and the desire of customers for cheap and reliable electric power has led to an increased interest in distributed generation. Compared to large generators and power plants, DG units possess smaller generation capacities and lower operational costs in distribution networks. However, the application of DGs with renewable energy resources offers many advantages, such as reduced environmental pollution, high efficiency, distribution loss reduction, improvement of the voltage profile and enhancement of network capacity [6-7]. The high degree of penetration of DGs has a considerable impact on the operation, control, protection and reliability of existing power utility systems [8-11]. An area that is critically affected by DG penetration is protection coordination of utility distribution systems [10]. The introduction of a DG into a distribution system brings about a change in the fault current level of the system and causes many problems in the protection system, such as false tripping of protective devices, protection blinding, an increase and decrease in short-circuit levels, undesirable network islanding and out-of-synchronism reclosers [3, 12-16]. However, when a fault occurs in a distribution network, it is important to quickly locate the fault by identifying either a faulty bus or a faulty line section in the network [17-18]. Depending on the location of the fault with respect to the DG and the existing protection equipment, problems like bi-directionality and changes in the voltage profile can also arise. To ensure selectivity, proper coordination between relays, reclosers, fuses and other protective equipment is necessary. However, this coordination may be severely hampered if a DG is connected to a distribution system [19]. Therefore, many research studies have been carried out to develop possible solutions to overcome the overcurrent relay coordination problem for distribution systems with and without DGs. For distribution networks without DGs, the methods to solve the relay coordination problem are quite established [20-29], but for distribution networks with DGs, the solution to the relay coordination problem is still under development.

This paper presents an overview of research studies related to the development of protection coordination methods in distribution networks with DGs. The operating issues that need to be addressed with regards to distribution protection with DGs are also discussed.

2. Review of Protection Coordination Methods in a Distribution Network with DGs

Due to the introduction of DGs in distribution systems, recent literature has introduced several new approaches to solve the coordination problem. The proposed solutions for the overcurrent relay coordination problem can be divided into two main approaches. The first approach is to obtain a new relay coordination status, and the second one is to limit fault current levels (FCL). These approaches are discussed briefly below.

2.1. Obtaining new relay coordination status

In this approach, researchers try to find new relay coordination methods for distribution networks with DG units using mathematics and computer-based methods.

2.1.1. Adaptive protection scheme for distribution networks with DG

Adaptive protection is a relatively new concept. It is defined as the ability of a protection system to automatically alter its operating parameters in response to changing power system conditions to provide reliable relaying decisions.

A simple example has demonstrated the changes in fault currents passing through protection devices when DGs are connected to the system and suggests that protection coordination must be checked after connecting each DG to the distribution network [30]. However, this approach is applicable only in the presence of low penetration of DGs into a system. In radial distribution systems, the authors of

[31] proved that the protective devices can maintain their coordination based on the available margin in their curves.

A study was performed on the fuse coordination problem, which suggested the disconnection of all DGs when a fault occurs as a solution [32]. The disadvantage of this solution is that it leads to the disconnection of all DGs, even when transient faults occur. The recloser-fuse coordination in the presence of DGs using microprocessor-based reclosers was also addressed. It was suggested that all DGs located downstream to the recloser network must be disconnected first before reclosers takes place to avoid asynchronous connection. This solution is not appropriate if DGs are widely applied in distribution networks [32]. To solve the problem of disconnecting all downstream DGs, an adaptive protection scheme was presented in [2]. It is based on the division of the network into several zones. Zoning was achieved by considering locations, generation capacities of DGs and loads, with one zone for each DG. Starting from the beginning of a feeder, each zone extends to the end of the feeder, as long as the DG within that zone is capable of supplying the peak load of that zone. When the peak load of substations located in the zone exceeds the generation capacity of the zone's DG, the zone border is terminated, and two circuit breakers are installed at the beginning and end of the zone points. When there exists a second DG located within the supply limit of the first zone’s DG and as long as the zone’s average load does not exceed the generation capacity of the first DG while moving towards the end of the feeder, the second DG is regarded as being within the same zone, and the zone border is extended, as long as the zone’s average load does not exceed the sum of the two DGs’ capacities. Zoning from the beginning of a feeder towards its end is considered to allow more loads to be supplied upstream through the network. After network zoning and the determination of zones' boundaries, some switches that are capable of operating quickly and receiving remote signals are placed between each of the two zones of the system, as shown in Figure 1. These switches are also equipped with synchronization-check relays. To implement the protection scheme, a computer-based relay with high processing power and large storage capacity is installed at the sub-transmission substation of the distribution network [2].

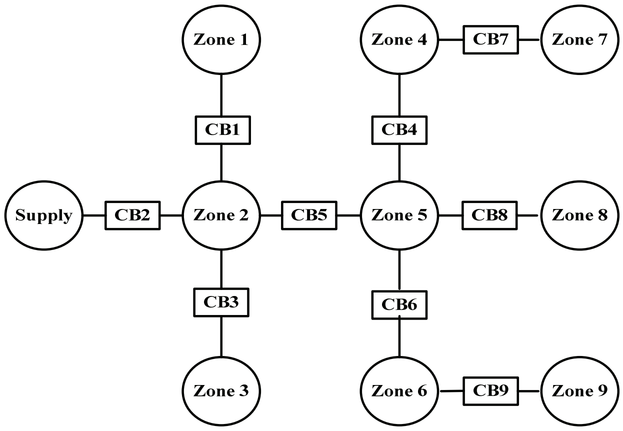

Fig 1: Distribution network divided into several zones

A more recent protection scheme for a distribution network with DGs considers the application of a multi-layer perceptron neural network (MLPNN) [33-34]. However, considering the structure and training algorithm of the MLPNN, the speed of this method is not suitable for fast and accurate protection. Zayandehroodi et al. [35] presented a new protection scheme for a distribution network with DG units using the radial basis function neural network (RBFNN). In the proposed method, the fault type is first determined by normalizing the fault currents of the main source. To determine the fault location, two staged RBFNNs have been developed for various fault types. The first RBFNN is used to determine the fault distance from each power source, and the second RBFNN is used to identify the exact faulty line. For fault isolation, a third-stage RBFNN is also developed to determine the open and closed states of the circuit breakers to isolate the faulty zones. Figure 2 shows an outline of the proposed protection scheme for a distribution network with multiple DG units.

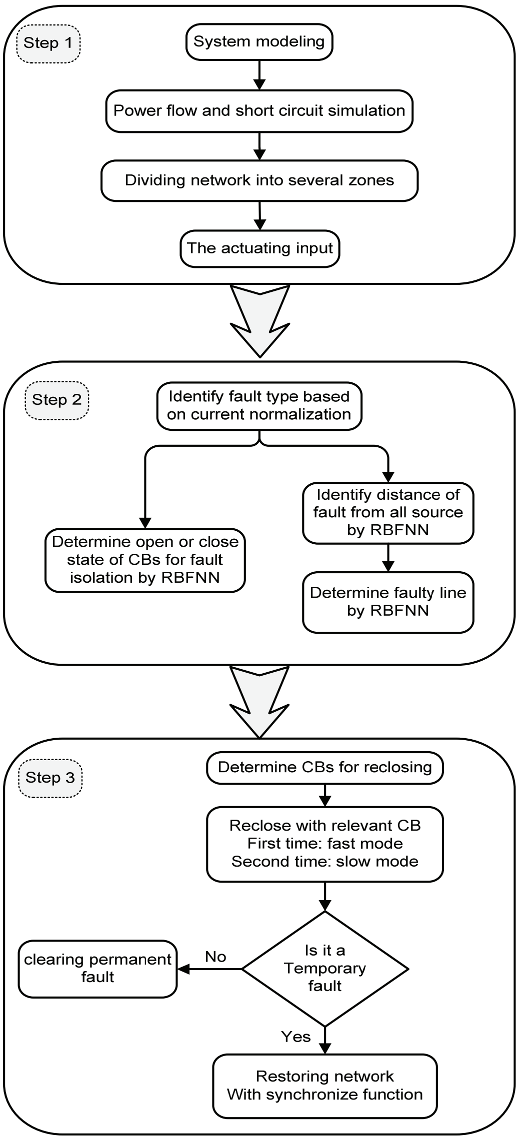

Fig 2: Automated protection scheme with RBFNN [35]

One approach for avoiding major changes in protective devices such that the fuse-based protection is not disturbed by a DG was studied in ref [36]. However, theoretical studies of the impact of a DG on the current sensed by protective devices indicate that DGs may be blind to overcurrent protection [12]. For example, short-circuit current fed by a synchronous generator can decrease the current seen by the feeder relay or fuse, preventing or retarding correct operation. Another adaptive protection scheme for distribution networks with high penetration of DGs based on online diagnosis of occurred faults was introduced [2]. From the fault point of view, every source is presented as a voltage source behind the Thevenin impedance. If a fault point shifts from one bus to the adjoining bus, for a given type of fault, the Thevenin impedance to a given source can increase or decrease. Thus, as shown in Figure 3, if a fault point shifts over a section (i-j) from one bus (i) to another (j), for a given type of fault, the fault current contribution from any given source can either continuously increase (IFmin to IFmax) or continuously decrease (I'Fmin to I'Fmax). Thus, the fault contribution from source "k" for a given type of fault occurring at any point between bus i and bus j will always lie between the contributions from source "k" to the same type of fault on bus i and bus j [2].

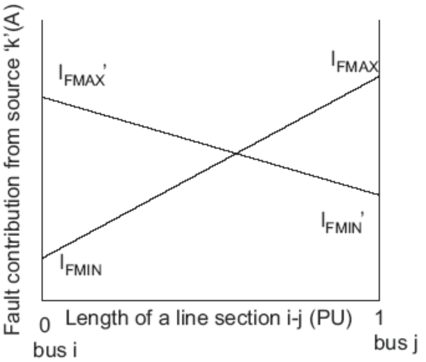

Fig 3 : Nature of fault contribution from a source “k” to a given type of fault on a line section between bus i and bus j [2]

To maximize the generation that can be connected to a distribution network and to avoid unacceptable high fault clearing times, a new protection coordination strategy was proposed [37]. In this scheme, the overcurrent principle and the time-dependent characteristics of current were used. Such a strategy offers the additional advantage of being able to run extensive radial circuits or closed-ring structures, which minimizes the number of customer outages for fault conditions and fault clearing times and consequently fulfills the requirements of a deregulated multi-owner energy market [37]. Furthermore, [38] presents an adaptive overcurrent pickup scheme that updates the OC relay minimum pickup current based on the fault analysis of a system. However, this study focuses only on studying inverter-interfaced DGs. Zamani et al. [39] proposed an algorithm for the coordination of protective devices in typical radial distribution networks with DGs by assuming that a directional relay is employed at the beginning of the feeders that embed the DGs. Figure 4 provides a graphical illustration of the protection coordination algorithm.

2.1.2. Multi-Agent protection scheme for distribution networks with DGs

An agent is a computer system that is capable of performing autonomous actions in this environment to meet its design objectives. Autonomy means that the components in an environment function solely under their own control. Agents operate and exist in some environment, which is typically both computational and physical. The environment provides a computational infrastructure for such interactions to take place. The infrastructure includes communication and interaction protocols [40].

Perera and Rajapakse [41] proposed a multi-agent-based protection scheme for distribution systems with DGs. In the scheme, a power network is divided into several segments. Fault detection and isolation are performed by installing relay agents at the points of interconnection between different network segments, as shown in Figure 5.

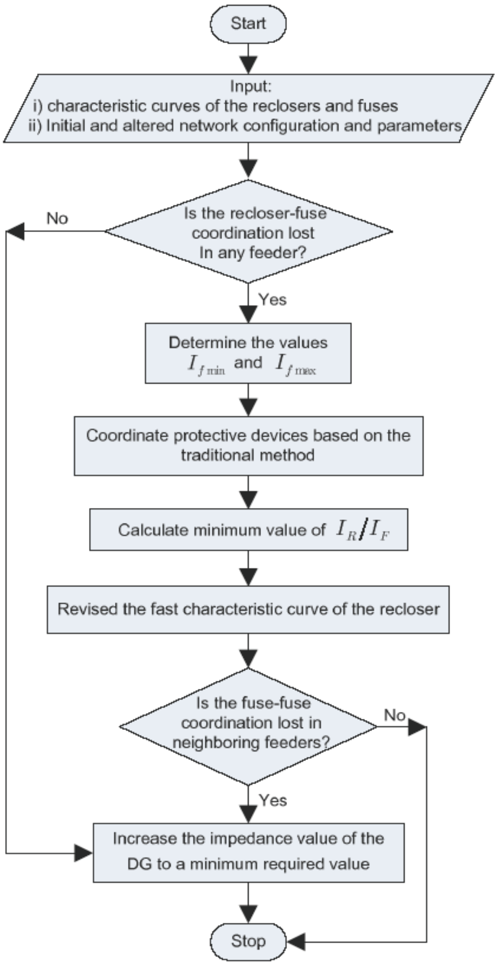

Fig 4: Flowchart of the protection coordination algorithm [39]

The relay agents communicate with the neighboring agents through synchronous communication networks. This scheme uses a wavelet transform technique to identify the direction of fault current with respect to a node in the network. In case of a fault, the assigned relay agents collaboratively determine the faulted zone by acquiring the feedback signals from current transformers CTs situated on the interconnected branches, which measure the currents leaving the node. Wavelet transform coefficients (WTCs) are calculated after measuring the transient currents in these branches. A fault is designated to be internal or external based on the sign of the WTCs of the currents measured at all points. When the sign is the same, then the fault is designated to be internal; otherwise, the fault is deemed external. In cases of external faults, the fault direction can also be determined from the fact that the WTCs of the currents measured on the faulted branch have a sign opposite to that of the currents measured in the other branches.

For a fault on any designated segment, relay agents determine the direction of the fault current with respect to its location and communicate this information to adjacent relay agents. Based on this information, the relay agents determine the faulted segment to issue correct trip signals to the relevant CBs to isolate the faulted segment. In this algorithm, a relay agent identifies a fault on the busbar at its location as an internal fault. In such a case, the fault is immediately cleared by the relay agent tripping all of the CBs connected to the busbar and communicating its decision to the other relay agents.

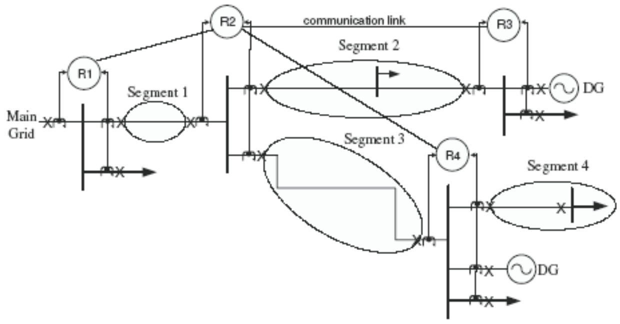

Fig 5: Structure of the multi-agent-based protection scheme [40]

Wan et al. [41] proposed a similar multi-agent protection coordination scheme for a substation with one Java Agent Development (JADE) Agent Container consisting of a substation management agent, a number of relay agents, DG agents and equipment agents, as shown in Figure 6. The coordination strategy is embedded in every relay agent. In the coordination strategy, relay settings and time are not the only parameters that decide the relay coordination. These agents communicate amongst themselves and also with the substation management agent, DG agents and equipment agents to obtain successful coordination. The validity and effectiveness of this scheme have been demonstrated by applying it to an agent-based platform “JADE”. Communication simulation shows that successful information communication between agents can be achieved with this scheme. A major advantage of this scheme is its ability to self-check and self-correct. It can also act rapidly and provide a highly selective fault region backup function when the primary protection fails. Efforts are currently underway to improve the performance of the multi-agent system in coping with protection coordination within a more complex system.

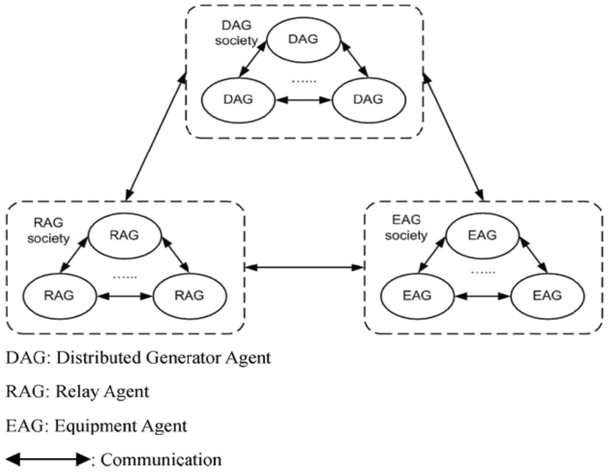

Fig 6 : Multi agent architecture for protection coordination [41]

2.1.3. *Expert system for protection coordination of distribution networks with DGs*

Expert systems are algorithms that function in a manner similar to human experts and can be represented in terms of knowledge, inference ability, and explanation. An expert system provides an explanation of how and why it reaches its decision, which can be used to check the validity of the decision as well as the knowledge and inference procedures associated with it [42]. An expert system has been used for protective relay coordination in a radial distribution network with small power producers [43]. The expert system employs a knowledge base and inference process to improve the coordination settings of protective devices to accommodate the penetration of distributed generators. The expert system feeds input data by means of a graphical user interface and develops coordination settings based on power flow and short-circuit analyses. The proposed structure of the expert system, as shown in Figure 7, has four modules: graphical user interface (GUI), engineering analysis, knowledge base, and inference engine. Initially, the configuration data of the distribution system and DGs are fed into the expert system via the GUI. The engineering analysis module then performs power-flow and short-circuit analyses. The analytical results are kept in the knowledge base module and then passed to the inference engine for the determination of protection coordination settings. Finally, the preliminary settings are displayed via the GUI for approval or revision by the user.

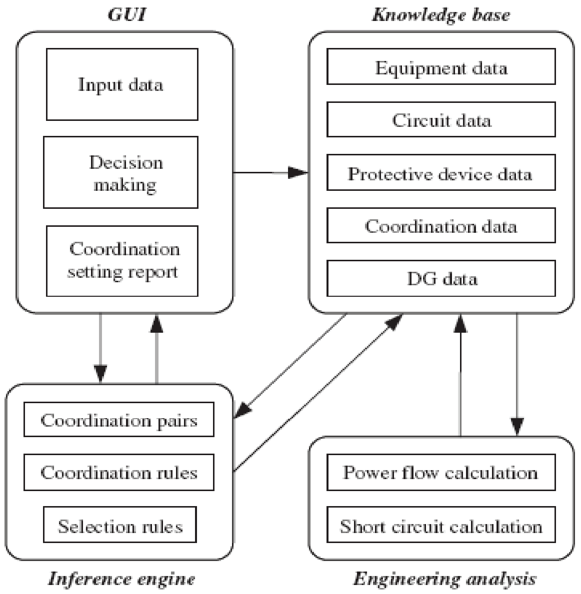

Fig 7 : Proposed structure of an expert system for protection coordination [43]

2.2. *Limiting fault current levels*

Network splitting, sequential network tripping schemes, current-limiting reactors and fault current limiters (FCLs) can be used to limit fault current values. Fault current limiters are low-impedance devices that produce no action during normal operation. However, during a fault, an FCL takes fast action by inserting high impedance in series with the distribution system (DS) to limit the fault current value to a preset limit [44]. An FCL was applied at the beginning of a radial distribution feeder equipped with a DG in [45], as shown in Figure 8. In this configuration, the proposed approach restores the original relay setting by locally installing the FCL to DGs in series to limit their fault currents. Thus, by suppressing the DG impact during fault, the distribution system can be pushed toward its original state as if no DG existed. Based on the aforementioned suppression, the existing relay settings can be used without disconnecting the DGs.

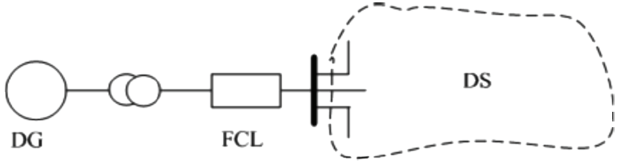

Fig 8: FCL–DG system interconnection [45]

El-khattam and Sidhu [46] proposed two approaches based on an existing protection system’s capability for regaining the directional overcurrent relay coordination status in a distribution system equipped with multiple DGs and without disconnecting the DGs during faults. For an existing adaptive protection system, the first approach is able to obtain the optimal number of relays and their locations and settings. Moreover, it considers the adaptive available relay setting groups (ARSG) under all ON-State DG combinations as well as the no-DG case. However, this approach may not be applicable when the number of DGs increases. In the second approach, for an existing non-adaptive protection system, an FCL is introduced to locally limit the current drawn by a DG during fault and obtain a new relay coordination status without altering the original relay setting. The feasible minimum FCL impedance value for all of the ON-State DG combinations is then obtained. However, as individual DG capacity increases, the value of the FCL impedance and its cost increases, and this may become economically unfeasible.

Another approach for restoring the original relay coordination in distribution systems with DGs is by implementing a thyristor-controlled series capacitor (TCSC) as an FCL. When the TCSC operates in the fault-current-limiting mode, it limits the contribution of the DG in the fault current in the event of a disturbance anywhere in the distribution system [47]. The basic structure of a TCSC is shown in Figure 9. It mainly consists of four parts: a series-compensating capacitor C, bypass inductor L, bi-directional thyristor SCR and zinc oxide voltage-limiter MOV. The degree of a TCSC's basic compensation is controlled by the capacity or size of the capacitor C. The main function of the bypass inductor L is to reduce the short-circuit current and the energy absorbed by the MOV. The capacitor Xc and inductor XL are selected with respect to the minimum capacitive and inductive reactance requirement of the distribution system. Two impedance behavior regions for a TCSC can be identified: inductive and capacitive. When the firing angle reaches the resonance angle, the impedance of a TCSC can be infinitely large, and this region should be avoided. Therefore, implementing TCSCs provides an economical opportunity to limit the buses' short-circuit currents without the need to upgrade the buses' equipment. During the normal operation of distribution systems, a TCSC operates as a voltage regulator, thereby allowing more DG power to the grid without violating the voltage limits [47].

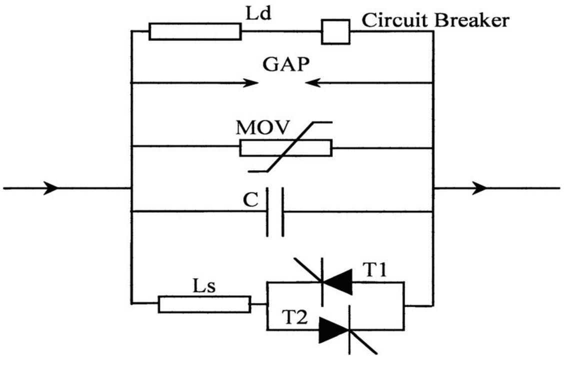

Fig 9: Configuration of TCSC [47]

3. Protection Issues in the presence of DGs

Conflicts between DG and protection schemes are typically due to unforeseen increases in short-circuit currents, lack of coordination in the protection system, ineffectiveness of line reclosing after a fault, undesired islanding and untimely tripping of generator interface protection. Conflicts between DG and protection schemes have been discussed in the literature, but effective and practical methods to solve protection malfunction due to the presence of DGs must be further investigated. Some practical cases related to these issues in a typical distribution network will be discussed in the following sections.

3.1. Increase in short-circuit currents

The fault contribution from a single small DG unit is not large, but the aggregated contributions from many small DG units, or a few large units, can significantly increase the short-circuit levels and cause fuse-relay or fuse-fuse miscoordination, which could affect the reliability and safety of distribution systems [6]. The incorporation of DGs may result in the mal-operation of existing distribution networks by providing the flow of fault currents, which are not expected when protection systems are originally designed. Generally, an increase in fault current largely depends on a number of factors, such as capacity, penetration, technology, interface and the connection point of a DG, in addition to other parameters such as system voltage prior to the fault [48].

3.2. Reverse Power Flow

Radial distribution networks are usually designed for unidirectional power flow, forming the in-feed downstream to the loads. This assumption is reflected in standard protection schemes with directional overcurrent relays. With a DG in the distribution feeder, the power flow situation may change. If the local production exceeds the local consumption, the power flow will change direction. Reverse power flow is problematic if it is not considered in the protection system design [49].

3.3. Overcurrent Protection

Overcurrent protection schemes for radial distribution systems are designed based on the available short-circuit ratios, maximum load currents, system voltage and insulation levels. The addition of generation on the feeder results in altered current flows in various parts of the feeder for faults at different points on the feeder. The primary concerns for DG interconnection are typically sympathetic tripping issues, failure of fuse-saving schemes, and the reduction of station breaker reach, potentially resulting in undetected faults. These issues are briefly addressed separately in the next section.

3.3.1. Sympathetic tripping

Sympathetic tripping is a concern due to the connection of DGs, which alters the flow of fault currents. This tripping occurs when a protective device operates unnecessarily for faults in other protection zones. Such tripping could be caused by the additional fault currents contributed by the DGs that were are included in the original feeder protection design calculations for typical radial distribution systems [50].

3.3.2. Fuse-Saving Disruption

Many distribution companies employ fuse-saving schemes for their line reclosers that are installed at urban/rural boundaries. Fuse-saving is the practice of coordinating the feeder breaker or recloser to operate quickly relative to the lateral fuses. It can be accomplished by setting the first one or two recloser operations on "fast" curves, followed by two or three "delayed" operations. The fast operations are designed to beat the fuse melting time so that temporary faults caused by lightning, conductor slaps, or tree branches can be cleared without blowing a fuse. The presence of DGs downstream from the fuse will obviously contribute to fault current during breaker or recloser operation; hence, fuse-saving may not be possible [51].

3.3.3. Reduction of station breaker reach

Another potential overcurrent protection disruption is the de-sensitization of the feeder overcurrent protection, also referred to as the reduction of reach of feeder protective devices. “Reach” refers to the distance downstream of the protective device at which the device can detect a fault. Without a DG, only the utility source feeds a fault, and the currents flowing into the fault in a radial circuit are easily calculated. Utility protection engineers typically coordinate protective devices by setting the pickup current such that the device will operate for the selected smallest minimum fault current expected, which correlates to the highest impedance fault to be detected. The sensitivity of the feeder protection is reduced by inclusion of a DG between the protective device and the fault, because the DG unit will hold up the voltage profile across the up-line portion of the feeder. The presence of DG reduces the current seen by the protective device and reduces its sensitivity to the fault such that the fault must be closer to the protective device to be detectable. Another way of visualizing this situation is to picture the fault farther away as a result of the DG [51].

3.4. Temporary faults

In radial systems, fault-clearing requires the opening of only one device because there is only one source contributing to the fault current. In contrast, meshed transmission systems require breakers at both ends of a faulted line to open. Obviously, when a DG is present, there are multiple power sources and opening only the utility breaker does not guarantee that the fault will clear quickly. Therefore, a DG is required to disconnect from the system when a fault is suspected and before the fast reclosing time has elapsed so that the system reverts to a true radial system, and the normal fault clearing process may proceed. In actuality, there is the possibility that a DG will disconnect either too quickly or too slowly, producing a detrimental impact on the distribution system., which creates numerous potential operating conflicts with respect to overcurrent protection and voltage restrictions. In this view, distributed generation seems to be rather incompatible, especially with fast reclosing during temporary faults. This procedure may not allow the DG units to have enough time to be disconnected from the network. In this case, DG units may sustain the voltage and fault arc, preventing successful reclosing in case of temporary faults.

From the above consideration, it seems that the reliability of a power delivery system may be worsened due to the presence of a DG, unless anti-islanding methods and protection schemes are revised to ensure timely DG disconnection. However, changes in the present procedures will also be required to locate and isolate a fault, to determine whether it is sustained or not and, finally, to restore power to customers [52].

3.5. Undesired islanding and untimely tripping for faults on different feeders

For islanding, distribution operators require DG units to be equipped with additional protective devices called generator interface protection, which is often referred to as anti-islanding protection using voltage relays, frequency relays and maximum zero-sequence voltage relays. This protection is required to disconnect the generator from the network when a feeder is tripped under abnormal system conditions. Anti-islanding protection prevents network portions from working under an islanded mode with the DGs, as in general, islanding is not allowed by standards in the majority of developed countries because it would cause safety and reliability problems. If islanding takes place, each generator is usually allowed to supply the preferential loads of a privately owned plant after disconnection from the network.

4. Conclusion

Grid-connected DGs have experienced rapid growth in the recent past and are expected to see exponential expansion in the future. In this paper, the existing technologies involved in development of the DG have been reviewed. Furthermore, the various methods for solving the overcurrent relay coordination problems in the presence of DG have been discussed. Several protection issues have been identified for situations in which DGs are connected in a distribution system. The protection requirements in the presence of DGs and some possible innovative solutions for resolving the operation conflicts between distribution network and DGs have also been addressed.

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