Impact of distributed power generation on protection coordination in distribution network

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ABSTRACT

In the whole world and especially in Morocco, the electric power sector faces significant challenges and the demand for energy is increasing as fossil fuel sources are disappearing. Moreover, the high cost of construction of large production plants and the obligation to reduce greenhouse gas emissions are among the factors pushing the energy sector to integrate distributed generators DGs based on renewable energies into power grids. However, the integration of these generators increased the values of short-circuit currents in the network, which poses a real threat to the existing protection coordination systems in the distribution network. The aim of this article is to bring together in a single platform all available research addressing the issue of protection coordination in the presence of DGs in the distribution network, in order to help researchers identify future scope. This paper presents a review of the impact of distributed generators on the protection coordination of distribution networks. The solutions proposed in the literature, to mitigate the negative impact of DGs, have been investigated in detail, along with the limitations of these proposed techniques.

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1. INTRODUCTION

The predicted depletion of conventional fossil energy sources, deregulation of the electric power sector, technological advancements, and customer demand for reliable electric power have sparked an accumulated interest in decentralized generation based on renewable energies [1], [2]. However, the integration of distributed sources offers many advantages, such as reduced greenhouse gas emissions, higher efficiency, reduced energy transmission costs, improved voltage profile and improved network capacity [3]-[6]. The installation of the generators integrated into the grid also brings new challenges and negative impacts on the protection relays, this is mainly the increase of the short-circuit current, which increases depending on the size and type of distributed generators DGs and their location relative to the fault [7]-[9]. The increase in the short-circuit current can lead to protection coordination problems [10], [11].

When a DG is connected to the distribution system, short circuit levels are altered near the point of connection, which can lead to damage and system failure, resulting in the risk of injury to personnel and interruption of supplies [12]. For the protective equipment in the system, the relay parameters should therefore be changed for the preparation of the protective coordination. If the DG is disconnected, the relay settings should be returned to their previous state. As a result, this may lead to poor coordination of the protection system. The increase of short-circuit levels in the system depends strongly on the type of the DG [13]. For example, the synchronous generator has a much deeper effect on protection coordination than the inverter-based generator. As a result, synchronous distributed generators are considered as the worst case scenario for fault current analysis [14], [15]. The capacity and location of the DGs integrated into the network have a great influence on the protection system. The problem of coordination of protective relays becomes more difficult with the increase in the number and capacity of DGs in the distribution network [16]. Current distribution protection philosophies should be modified especially with the increasing penetration of DGs.

In order to avoid involuntary disconnection of the generators in case of failure in the distribution network, it is essential to set up a fast and reliable protection system.To ensure a reliable operation of the distribution system, as well as to maintain selectivity between protection devices under different types of faults, the coordination of protection devices is necessary [17]. Each protective device is assigned two functions; a primary one to clear faults in a specific zone and a secondary one to clear faults in adjacent or downstream zones, within the limits allowed by that device [18]. When a fault occurs, the area isolated by the protection device must be as small as possible, so that only the device closest to the fault can operate and the fault must be eliminated as quickly as possible [19]. The coordination of relays is considered as an important aspect of the protection system design. The main tasks of coordination are to perform power flow analysis, calculate fault levels, and select appropriate relay settings to meet the basic requirements of protective relays [20]. When two successive relays operate correctly in primary/backup mode, regardless of the system, they are considered to be coordinated. A properly coordinated protection system can quickly isolate faults and maintain the operation of the remaining healthy part of the system [21]. The loss of relay coordination leads to false triggering for some healthy starts [22]. In addition, this can lead to a significant delay in the tripping and isolation of faulty feeders, which results in large excessive fault currents on the power system equipment and reduces their service life [23]. To ensure proper coordination, a minimum coordination time interval (CTI) between the operation of the primary and backup relays needs to be maintained [24].

The development of relay technology is essential to cope with the growing interest in the development of traditional power grids into smart grids, where the increasing penetration of DGs will be an important feature of this smart grid [25]. To overcome the impact of distributed generation, new optimal relay parameters that take into account the presence of DGs need to be determined. Therefore, the problem of coordination of the directional overcurrent relays while considering the integration of DGs has been solved by several methods. Some of these methods are presented in this article.

The objective in [26]-[29] is to determine the maximum and minimum capacities of the DGs connected to each node so that miscoordination does not occur. In the presence of distributed generators for a downstream fault, if the current is greater than the current limit, coordination between the relays is not maintained. In order to maintain it, the operating time interval between the relays must be greater than or equal to CTI. Therefore, the maximum capacity that provides the limitation is selected as the maximum capacity of the DG. This solution is applicable for small penetration and is not effective with high penetration of DGs.

In the event of a short circuit in the network, the DGs also inject transient and sub-transient fault currents which contribute to the transient behavior of the network and influence the coordination of the overcurrent OC relays. To restore the coordination of the OC relays, the solution proposed by [30]-[33] is the use of fault current limiter FCL which is one of the effective solutions. FCL is a device that is connected in series with the DG to limit the fault current to an acceptable level during the fault and to obtain very low impedance and pressure drop during normal operation. FCL sizes are determined to restore OC relay coordination without the need to change the relay setting or disconnect the DGs during the fault, but FCLs are not recommended due to their high cost.

Expert systems have been used in [34], to solve various problems related to the power system, including backup protection of the distribution system. The expert system was proposed as a decision tool to examine the impact of the DG connection and to modify the coordination parameter of the protection devices. It has been improved to avoid unnecessary computation time and to be able to adapt to the penetration of the DG in the distribution system, but this method is limited with the change of the network configuration because the processing time calculation will be important.

In [35], [36] the centralized adaptive system is proposed to mitigate the impacts of DGs on directional overcurrent relay DOCR coordination, which consists of a SCADA system that monitors the state of the network and identifies topological and operational changes in the network. The data obtained by the SCADA system were transmitted to a centralized processing server system for analysis and optimization. The main disadvantage of using this adaptive system is the repetition of the process with each change in network conditions.

A multi-agent coordination system is proposed in [37] with further explorations of the use of agent technology applied to the coordination of power system protection. In this system, communication will play an important role in the exchange of information relating to the coordination between relay parameters. Following the analysis of the impact of distributed generation on protection coordination, a new model of protection coordination based on agent technology is proposed to define and coordinate relays online. In this adaptive coordination mode, relays must adapt to new conditions and respond to changing system conditions. The changing system conditions can be operational or topological, such as the connection of a distributed generator (DG). It requires communicable agents such as relays and circuit breakers.

Dual adjustable directional overcurrent relays are offered in [14], [38], to protect DG meshed distribution systems. The settings of the dual setting relays depend on the direction of the fault, the relays are equipped with two pairs of settings, one of them for the primary protection and the other for the backup protection, for both possible directions. To minimize the overall operating time of the relay while satisfying the constraints of the protection coordination scheme, the optimal parameters of the relay, which are the delay time TDS and the pickup current Ip, must be determined. This setting does not have a technical impact on the system, but identifying the entire network is difficult.

This paper presents a state of the art of research related to the development of protection coordination methods and techniques in distribution networks in the presence of DGs. The parts of this paper are organized: The problem statement is described in Section 2. Protection techniques in distribution networks with distributed generation DG are discussed in Section 3. Section 4 presents the limitations of the proposed techniques in the field of protection coordination and the conclusion is presented in Section 5.

2. PROBLEM STATEMENT

The simplest configuration network is presented in Figure 1 in order to explain the coordination of overcurrent relays. The OC relays 1, 2 and 3 are used to protect this network. When a fault is created on line 2-3, relay 2 should first trip as primary protection and relay 1 operates as backup protection. If relay 2 fails to operate, relay 1 will trip after a time delay. The same procedure should be repeated for the coordination between relay 2 and relay 3 when a fault is created on line 3-4.

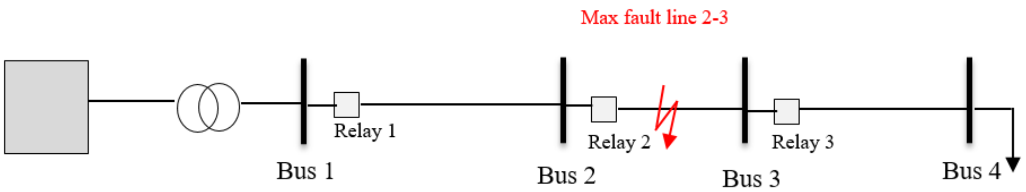

Figure 1. Coordination of overcurrent relays

Distributed generation can bring many economic, technological and environmental benefits, but at the same time bring many challenges [39]. Previous studies have shown that distributed generation poses several problems for the protection of the distribution network, such as false tripping in feeders, nuanced tripping of generation units, blinding protection and fault level modification [40], [41]. The important issue is therefore the coordination of protection devices. Directional overcurrent relays based on a digital microprocessor are currently widely used in distribution systems for safe and effective protection with much more powerful capabilities than conventional electromechanical relays [42]. Relays (DOCRs) are an interesting economic and technical choice for protection. Therefore, it is very important to study the coordination problem when using these protective relays [43].

2.1. Objective function

The relay settings are generally calculated by formulating an optimization model in which the main objective is to minimize the duration T calculated by (1) while respecting the constraints of selectivity, sensitivity, reliability and characteristic curves of the relays [26], [44].

$$Minimise\ T = \sum_{i=1}^{N}\sum_{j=1}^{M}\left(t_{ij}{}^{p} + t_{ij}{}^{b}\right) \quad (1)$$

Where N and M represent the total number of relays and the total number of fault locations studied respectively. $t_{ij}{}^{p}$ is the operating time of the primary relay and $t_{ij}{}^{b}$ is the operating time of the backup relay.

2.2. Coordination criteria

The coordination time interval CTI is the difference between the operating time of the backup protection relay and the primary protection relay, usually specified between 0.2 and 0.5 s [45], [46]. The CTI depends on certain factors such as the operating time of the circuit breaker, the delay and the response time of the measuring element. A coordination time interval should be imposed between a primary and backup coordination pair to maintain selectivity and coordination [47]. The protection coordination constraint can be expressed in (2),

$$t_b - t_p \geq CTI \qquad (2)$$

where t_b is the operating time of the backup relay and t_p is the operating time of the primary relay, when a fault occurs in the fault zone [48].

Some constraints must be taken into account, such as the selectivity constraint used to maintain selectivity between primary and backup protection, the sensitivity constraint used to ensure that the fault is within the protection range by correctly setting the relay parameters, and the reliability constraint used to ensure that when a fault occurs within the protection range of a relay, the relay must operate within the operating time limits [49].

2.3. Relay characteristics

The operating time t of a directional overcurrent relay is an inverse function of the short-circuit current [50]. The equation that models the operation of the numerical inverse time overcurrent relay is defined by two parameters, i.e ; the delay time TDS or the delay factor TMS, the value of TMS usually varies between 0.1 to 1.1 s [51] and the pickup current I_p, which is the minimum current value above which the relay will start to operate [52]. This function has two constants, A represents the constant for the relay characteristics and B represents the inverse time type, which are defined as 0.14 and 0.02 respectively [53], [54]. The general operating characteristics of the relays corresponding to the IEC standard are given in (3).

$$t = TDS \frac{A}{\left(\frac{If}{Ip}\right)^{B} - 1} \qquad (3)$$

I_f represents the short-circuit current of the relay and I_p the pickup current of the relay. Figure 2 summarizes the mathematical optimization model related to coordination protection.

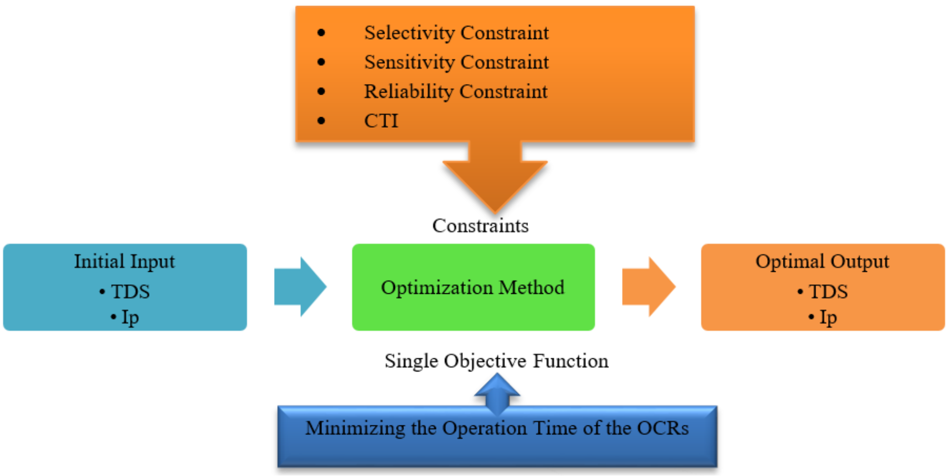

Figure 2. Mathematical optimization model related to the protection of coordination

3. PROTECTION TECHNIQUE IN DISTRIBUTION NETWORKS WITH DG

As discussed in the previous sections, the integration of DGs in distribution systems influences the coordination of overcurrent OC relays. Conventional protection coordination (CPC) is therefore not suitable for distribution systems in the presence of distributed generators. This section discusses various techniques to solve protection coordination problems, as shown in Figure 3.

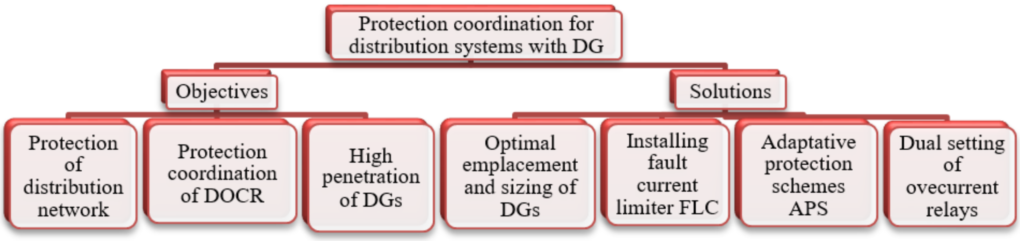

Figure 3. Protection coordination schemes for distrubtion systems with DGs

3.1. Limiting DGs capacity

The protection coordination index PCI is proposed in [26] to maximize the DG penetration with respect to the value of CTI. The PCI is defined as the ratio of the rate of change of P and the rate of change of CTI as shown in (4).

$$PCI = -\frac{\Delta P}{\Delta CTI} \tag{4}$$

This method is proposed to deal with the impact of synchronous generators on directional overcurrent relays in the distribution network. To calculate the PCI, the problem is formulated as a two-phase nonlinear optimization problem NLP, the first phase consists in determining the optimal settings of the relays which are the delay time TDS and the pickup current I_p. These parameters present the inputs of the second phase; the main objective of this phase is the determination of the maximum values of the DGs penetrated in each bus while respecting the constraints of the protection coordination. Results show that DG penetration levels are higher with less impact on protection coordination when PCI is higher at some locations. In [27], [28] the proposed approach is solved using the Particle Swarm Optimization algorithm PSO, due to its faster convergence speed, to determine the maximum penetration of inverter-based and synchronous-based DG taking into account the coordination of the protection of the directional overcurrent relays DOCRs.

Redesigning, reconfiguring or replacing the original protection system of a distribution system introduces technical and financial difficulties. If not handled properly, this problem can be a major obstacle. An optimal DG placement and sizing method is proposed in [29] to maximize the penetration level of the DG while considering the relay protection, and without changing the original relay protection system. This problem is solved using the genetic algorithm GA in order to facilitate the integration of more DGs.

3.2. Installing fault current limiter (FCL)

A hybrid genetic algorithm and linear programming method GA-LP with installing fault current limiter FCL is applied in [30] to coordinate the protection devices in the presence of synchronous machine-based distributed generations SMDGs. The proposed method is formulated as a multi-objective optimization to determinate the optimal coordination of different protective devices, and the optimal FCL sizing. FCL sizes are determined based on two objectives; limitation of the fault current to guarantee the safety of network equipment and limitation of reverse fault currents of DG. In [31], the proposed approach is based on the genetic algorithm GA to achieve the optimal setting of relays in transient behaviour of FCL and DG. To obtain the coordination of overcurrent relays OCR, the dynamic models of FCL and DG are used in this research. The FCL placement and sizing problem in [32] is solved using muti-objective particle swarm optimization algorithm PSO to solve the problem of OCR coordination in the presence of DGs. This algorithm is studied when the network includes directional and non-directional OCR, which are optimally set to isolate faults in a coordinated manner with minimal impact on the electrical system. The main objective in [33] is to find the reduced impedance values of FCL when re-adjusting the setting of only one adaptive relay and all other relays are kept at their original settings. The proposed schemes used the linear programing method to ensure good performance of coordination protection with minimum cost.

3.3. Utilizing adaptive protection

The expert system was proposed in [34] to solve the problem of protection coordination with the integration of DGs into the distribution grid. The proposed expert system structure consists of four modules: graphical user interface GUI, engineering analysis, knowledge base and inference engine. The expert system feeds the input data using a graphical user interface and develops coordination parameters based on power flow and short circuit analyzes. The knowledge base module includes data on equipment, circuits, protective devices, coordination and DGs. The structure of inference engine for the protection coordination contains the coordination pair generator, the coordination rule processor and the selection rule processor. The coordination pair generator is processed to construct a coordination pair to be used in the coordination rule processor. From the load current and short circuit data in the knowledge base, the coordination rule processor can generate a list of satisfactory coordination settings of protection devices and can store it in the knowledge base to be used in the processor selection rule. The role of the selection rule processor is to select the best coordination setting for the protective device. This technique is helpful for utility enegineers to survey the impact of the DG connection and to modiy the coordination setting of protection relays.

In [35], [36] the centralized adaptive system is proposed to mitigate the impacts of DGs on DOCR coordination. This adaptative protection scheme APS requires a central host with a powerful computer to send and receive data from the protection relays before and after adding DGs. The APS consists of a SCADA system that monitors the state of the network and identifies topological and operational changes in the network. The data obtained by the SCADA system were transmitted to a centralized processing server system for analysis and optimization. The coordination problem is solved using differential evolution algorithm (DE). A single cycle is performed and each time a new operating condition changes, the cycle is executed again. The server performs an analysis of load flow, failures, contingencies and sensitivity based on network status data, then recalculates the pickup current and optimizes directional overcurrent relay coordination so that DOCRs are best suited to the current network operation.

A multi-agent architecture is proposed in [37] for power system protection coordination, which includes relay agents, DG agents and equipment agents. The agents can communicate with each other not only within the same agent company, but also within different agent companies in order to achieve successful coordination. In a multi-agent system, each agent must not only be able to perform the tasks that occur locally, but must also interact effectively with other agents. In order to facilitate the exchange of information for communication between the relay agents themselves and to ensure that this information is correctly exchanged between the different agents, a communication simulation of peer-to-peer relay coordination has been developed.

3.4. Dual setting protection schemes

A new protection coordination scheme is proposed in [14], [38] based on double parameter DOCRs. When the fault current flows in the forward direction, the relay will operate as primary protection and when the fault current flows in the reverse direction, the relay will operate as backup protection. Figure 4 (a) presents an example of meshed system with the conventional DOCR. The settings of the dual setting relays depend on the direction of the fault, the relays are equipped with two pairs of settings, one for the primary protection and the other for the backup protection, for both possible directions as shown in Figure 4 (b).

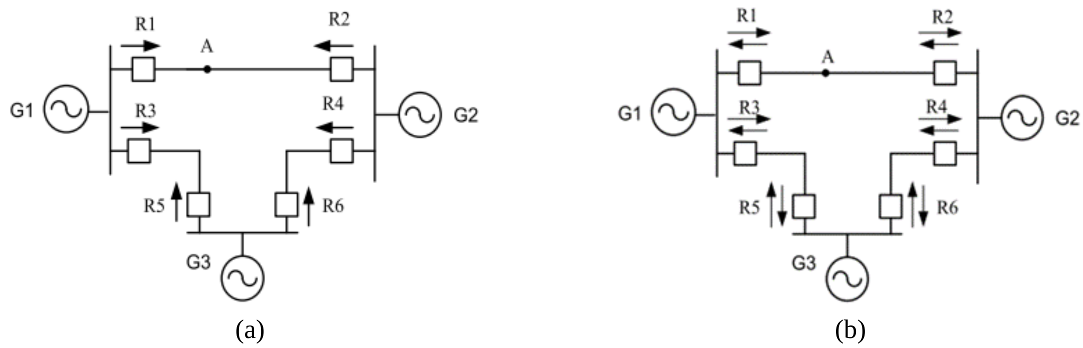

Figure 4. (a) Conventional directional overcurrent relays and (b) Protection with dual setting of DOCRs [13]

4. SYNTHESIS OF PROTECTION TECHNIQUE IN DISTRIBUTION NETWORKS WITH DG

In this section, a synthesis of protection techniques used to solve the coordination protection in distribution networks with integration of DGs is presented. The most common objective in these methods is to respect the constraints of the protection coordination with large penetration of DGs. Although these proposed protection techniques can mitigate the negative impacts of distributed generation integration on the performance of protective relays, but these techniques also suffer from several limitations in the field of protection coordination. Table 1 presents the summary grouping together all discussed coordination techniques. It can be used as a guide for choosing the most feasible and effective technique for modeling similar problems and for solving the problem by reviewing a large number of studies that have been validated using these methods. It can also open up additional and original research opportunities.

Table 1. Summary of DG protection coordination techniques

Ref	Technique	Main feature	Benefits	Drawbacks
[26]	Protection Coordination Index PCI	Determining the values of DGs penetrated into each bus while respecting the constraints of protection coordination	Measure for utility operators to determine the optimal location for DG allocation with minimal impact on the protection coordination	Not suitable for large DG penetration
[27], [28]	Particle swarm optimization algorithm PSO	Determining optimal location and size of distributed generation	Good planning tool for the utility operator to optimally allocate DGs of different types in distribution systems to achieve better penetration level	Applicable for a low penetration level
[29]	Genetic algorithm GA	Finding the optimal locations and sizes of the DG without changing the original relay protection system	Facilitate the integration of more DGs	In order to increase profits and avoid excessive CO2 emissions generated by conventional power plants, decentralized generation based on renewable energy should be fully exploited but this technique is temporary
[30]	Hybrid genetic algorithm GA and linear programing LP method GA-LP/Fault current limiter FCL	Modifying the TMS and Ip of the protection devices in order to overcome conventional problems of installing SMDGs/restoring the coordination of the protection system with high penetration of SMDGs	Feasible and effective solutions for optimal coordination restoration, while minimizing FCL size	High cost which is undesirable for both utilities and DG owners.
[31]	Genetic algorithm GA/ dynamic models of DG and FCL	Determining the accurate setting of relays in transient behaviours of FCL and DG	Feasible and effective solutions for optimal setting of relays in transient conditions	Expensive
[32]	Multi-objective particle swarm optimization PSO	Determining the optimal placement and sizing of FCL to maintain the DOCR-coordinated operation without the need to reset OCRs regardless of DG status	The Model considers the FCLs sizes (cost) and the OCRs coordination as two conflicting objectives to be optimized	Expensive
[33]	Linear programing method LP/ FCL	Finding the reduced impedance values of FCL to achieve relay coordination	Reducing the FCL value (decreasing its cost)	
[34]	Expert system	Monitor the state of the DGs and study the effect of their integration and propose relay parameters for protection coordination	Helpful for utility enegineers to survey the impact of DG connection and to modiy the coordination setting of protection relays	Identifying any potential network topologies is difficult. With the change of network configuration, the processing time is important
[35], [36]	Adaptive protection scheme APS using differential evolution algorithm DE	Optimization of the relay setting according to the network conditions, using a SCADA server	Fulfillment of selectivity requirements, overall sensitivity improvement and automatic online coordination. Robust for future operational and topological system changes	For each change in network conditions, the process is repeated
[37]	Multi-agent systems MAS	Online coordination of relays	Online calculation of new settings, ensuring superior performance and accurate coordination	Requires communicable agents such as relays and circuit breakers.
[14], [38]	Non-linear programming problem NLP/ dual setting DOCR	Achieving reduced relay operating times regardless of DG size and location	Faster fault isolation, thus increasing DG's chances of overcoming fault events	Difficulty in identifying the entire network

5. CONCLUSION

The penetration of DGs into distribution networks creates new protection problems, namely the coordination of protection relays. Their impact on network protection depends mainly on their type, size and location. Fault current flows become bidirectional on most feeders with large-scale penetration of distributed generators into the distribution system and the existing protection schemes in this system are unidirectional so they cannot clear the fault for these fault conditions. In order to maintain protection coordination in distribution networks in the presence of DGs, there are several methods proposed in the literature that solve this problem by updating the parameters of the protection relays and locating the impact of distributed generation whenever necessary. This review article summarizes some of these methods and their optimization algorithm in the field of overcurrent directional relay coordination. Visible gaps in research and the possible future scope of research in protection coordination were also presented in this article.

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