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Towards Enhancing Power System Protection in Distribution Systems with Distributed Generation: A Graph Theory-Based Systematic Relay Placement Approach

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ABSTRACT

This manuscript presents an innovative approach to optimize power system protection through strategic relay placement in distribution systems with distributed generation (DG). Traditionally, distribution systems relied on radial configurations, assuming power flow from the grid feeder to downstream networks. However, with the integration of DG technologies, the complexity of relay placement and maintenance increases. The study aims to address protection system issues associated with connecting DGs, such as tripping of production units, blinding of protection, and undesirable islanding. The proposed methodology combines graph theory, energy not supplied (ENS) values, and relay coordination strategies to achieve reliable power system operation. The algorithm is implemented in MATLAB, utilizing data from DigSilent PowerFactory. The key constraints for relay placement, including islanding operation, relay coordination, and load priorities, are considered to minimize the number of power outages and increase overall system reliability. The effectiveness of the algorithm is demonstrated using IEEE 33-bus and 69-bus test systems under different conditions. Results show consistent and reliable relay placement locations, considering DG locations and load priorities. The algorithm's speed, effectiveness, and adaptability to different network topologies make it a promising approach for power system protection planning in distribution systems with distributed generation.

1. Introduction

Traditionally, distribution systems have adhered to radial configurations, wherein a single source exclusively supplies downstream networks. Consequently, protection schemes have been devised under the assumption of unidirectional power flow from the grid feeder to the downstream low-voltage network [1-2]. Effective isolation and restoration mechanisms are pivotal in minimizing

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disruptions to loads during power loss scenarios. However, the integration of distributed generation (DG) within distribution networks adds complexity to this scenario, necessitating meticulous consideration in system design and operation.

DG, characterized as an approach to disseminate energy resources throughout the energy value chain, encompasses both renewable and non-renewable sources, such as wind, solar, small hydro, biomass, geothermal, steam turbines, micro turbines, combustion turbines, and reciprocating engines [3]. It serves as an alternative method to enhance the conventional electric power system, offering advantages including reduced environmental impact, heightened reliability, and increased security [4]. In distribution system planning, DG presents itself as a viable option for new capacity, grid reinforcement, power loss reduction, and enhancement of system integrity, reliability, and efficiency [4-5]. However, its incorporation introduces a plethora of protection system challenges, including tripping of production units, altered fault levels, undesirable islanding, and reclosure complexities [6-7].

Addressing these challenges mandates meticulous placement and coordination of protective relays. Initial investigations underscore the criticality of overcurrent protection, particularly inverse-time overcurrent relays, deemed fundamental in distribution system protection strategies [8-9]. The synchronization between primary and backup relays assumes paramount importance to ensure swift, discerning, and reliable relay operation for fault isolation. Given the bidirectional current flow inherent in DG, judicious selection of relay location and type becomes imperative to effectively detect faults and uphold system reliability. This discourse illuminates the intricate nexus between DG integration, protection system intricacies, and the overarching imperative of ensuring energy security within the global energy landscape [10].

Overcurrent relays, categorized as definite time (DT) and inverse-definite minimum time (IDMT), are vital for enhancing power system protection [11]. DT relays are suitable for short feeders with consistent fault current, providing a fixed delay before tripping. Their operating time and pickup value can be adjusted. Coordination between primary and backup relays is crucial, satisfying the condition. Therefore, both the time and the pickup value can be adjusted. The coordination strategy between the primary and backup relays must satisfy the following condition, as shown in Eq. (1) [12].

$$T_{backup} - T_{primary} \geq CTI \tag{1}$$

where T_{backup} ia operating time of backup relay and $T_{primary}$ is operating time of primary relay

According to ANSI/IEEE Std-242:1986, coordinating DT relays typically requires 0.3 to 0.4 seconds for mechanical relays and 0.1 to 0.2 seconds for microprocessor-based relays. The fault clearing time limit in the system is around 1 second, often reached near the source relay. For IDMT relays, desired fault clearance time near the power source can be achieved, as they show an exact inverse characteristic where operating time varies with current. IDMT relays come in three types: standard inverse, very inverse, and extremely inverse. Optimizing coordination and relay settings as described can significantly enhance power system protection and reliability, especially in distribution systems with distributed generation. Researchers began to be interested in the protection system of the distribution network with DGs, and many methods were proposed in the field of design problems for the protection planning of the power distribution network. According to Javadian *et al.,* [13], the risk analysis in a protection system is done by a computer-based relay that determines the system status after receiving the required network data, and in case of a fault, diagnoses its type and location using some trained multilayer perceptron (MLP) neural networks, and finally issues the proper commands to the protection devices to clear the fault and restore the network. The algorithm did not require many mathematical calculations, but too many cases to be considered for a large network.

As being reviewed by several authors [14-15], one of the most powerful swarm-intelligence based ideas called particle swarm optimization (PSO) was presented, which works with a population of individuals in parallel to optimize the optimal location as well as the direction of relays in a distribution system with DGs. This strategy can handle cases in large networks but does not have a general convergence theory applicable to practical multidimensional problems. Apart from that, genetic algorithms have been used in many complex applications due to their excellent merits such as parallel computing, random search, and adaptive optimization [16-17]. The strategy can be applied in most cases related to protection systems, but it is time consuming, and optimization cannot be performed if the population size is big.

The graph theory method has been used by Mathews *et al.*, [18] to determine the type of protection that should be placed on each line in a meshed transmission network. The proposed algorithm utilizes a minimal number of directional devices and places instantaneous reclosers in locations that cause the system to temporarily become radial when a fault occurs. Directional and nondirectional overcurrent (OC) relays are placed in locations that allow for standard radial coordination techniques to be utilized while the reclosers are open to clear any sustained faults. Graph theory is a concept of linked nodes that can figure a wide range of processes taking place on graphs or networks. It takes concern about how the network can be encoded and its properties measured. Radial distribution network is the type of power distribution where the power is delivered from the main branch to sub-branches then it split out from the sub-branches again [19]. Hence, the busbar and lines are described as nodes, trees, and branches as the path of different radial network topologies can vary like the branches of tree. The main reason of applying graph theory algorithm in the radial distribution network is to refine the locations for placing relay to find the best candidate locations [20]. The possible locations are predetermined by checking continuously the short circuit levels and length of lines throughout the execution of the algorithm. Figure 1 illustrates the graph theory in this study. The first step is to select the node corresponding to the source number, i. The tree is then determined from the node, n, before it reaches the end, j. If n is less than zero, the operation will go to 1 as in Figure 2.

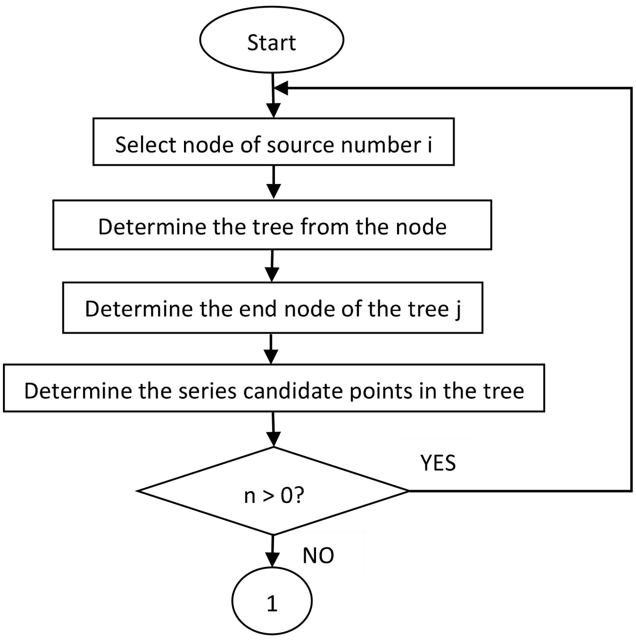

Fig. 1. Preliminary relay location identification based

on graph theory algorithm

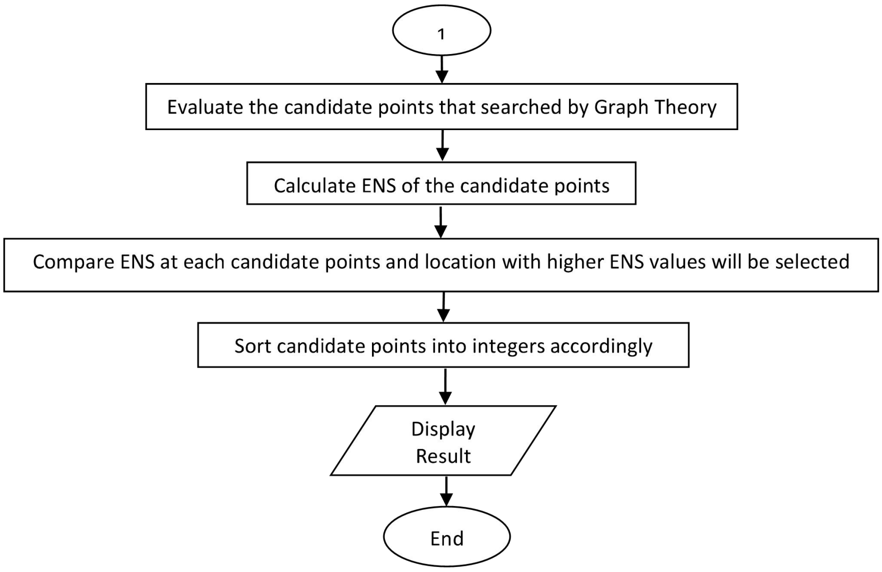

Fig. 2. Refining relay location based on ENS algorithm

From the reviews, this research found that it fills an important research gap in power system protection by focusing on relay placement strategies in distribution systems with distributed generation. While existing literature has explored various aspects of relay placement, there is a lack of comprehensive methodologies that integrate graph theory technique and ENS aspect, which is essential for reliable power system operation. To address this gap, this study proposes an innovative approach that integrates relay placement, graph theory method, and ENS values. The main objective is to optimize the protection of the power system through strategic relay placement considering factors such as islanding operation, relay coordination, and load priorities. By using graph theory techniques, the goal is to develop a systematic and efficient relay placement strategy that minimizes the number of power outages and increases the reliability of the overall system. The significance of this research lies in its potential to contribute to the development of robust and effective power grid protection systems in distribution systems with distributed generation.

2. Methodology

In this paper, the proposed algorithm is implemented by utilizing MATLAB and loading the data needed from DigSilent PowerFactory into MATLAB.

2.1 Constraints of Relay Placement

2.1.1 Islanding operation

There are several reasons for the need for intentional islanding in distribution systems, but the most common case is preventive disconnection from the grid due to a foreseeable event, such as an overload resulting in a fault current. The purpose of this intentional islanding is to prevent the entire grid from failing when potential outages or quality problems occur in the main grid. However, one of technical issues to be solved in an islanded zone of distribution network is the distributed generation and load balancing. The fluctuations in both quantities depend on customer needs and capacity of generation [1]. The constraint is formulated based on Eq. (2) for each islanded zone such that the number of loads in each zone is less or equal to the capacity of DG in each zone.

$$\sum_{i=1}^{n} P_L \leq P_G \quad (2)$$

where n is number of loads in each zone, P_L is loads in each zone and P_G is capacity of DG in each zone.

2.1.2 Relay coordination

IDMT relays have an inverse characteristic where the operating time varies with current, but they are not suitable when the fault current varies widely, or the impedance is high. Instead, DT relays are used to coordinate multiple relays in these situations, with a CTI of 0.3 seconds. The maximum number of feeder sections protected by a DT overcurrent relay can be calculated using Eq. (3), assuming the maximum fault clearing time (FCT_{max}) is 1 second.

$$n = \frac{FCT_{max}}{CTI} = \frac{1}{0.3} \approx 3 \quad (3)$$

With three maximum feeder sections protected by a DT overcurrent relay, a 33 radial bus system requires about 11 relays, while 69 radial bus system requires at least 23 relays.

2.1.3 Load priorities

During critical loads in a distribution network, relays should be placed accordingly at the load sides. The more load with high priority in the substation, the more important this substation is. When relays are installed in these locations, the critical loads shall be supplied during an outage occurs because the relays will trigger the circuit breaker to trip with a minimum relay operating time.

2.2 Objective Function

In this paper, minimizing energy not supplied/energy not served (ENS) is the objective function. The ENS is defined as in Eq. (4):

$$ENS = \sum_{j=1}^{N_C} \sum_{k=1}^{NIL} L_{kj} \times r_j \times \lambda_i \quad (4)$$

where *NIL* is number of isolated load points due to contingency j, N_c is number of contingencies, L_{kj} is curtailed load at load point due to contingency j, r_j is average outage time due to contingency j andλ_j is average failure rate of contingency j.

Load curtailment is explained in a way that to balance electricity supply and demand by controlling consumption patterns. When a fault occurs, the generators may not have enough supply for every load hence the loads are being curtailed at certain level to balance the loads. The operations at the loads will return to normal after the fault is cleared. The average outage time/repair duration and failure rate are defined equally for all the contingencies on every line. In this paper, the corresponding outage time is assumed to be 10 hours and the failure rate is one for each kilometer per year.

2.3 Energy Not Supply (Ens) Values

The candidate locations of relay placement can be further filtered from the refined results of graph theory to the final optimal locations based on the ENS values as shown in Figure 2. The locations with high ENS values have high possibility to be chosen [18]. There are two types of overcurrent relay applied which are directional and non-directional. For these cases, “0”, “1” and “2” are the integers used to determine the existence and type of relays in each candidate location. “0” means candidate location is not suitable for placement of relay due to no critical load or unnecessary, “1” and “2” are meant for non-directional and directional OC relay respectively. This means the algorithm shall be able to acknowledge the presence of DG and critical loads. Therefore, each candidate location can pick integer values of “0”, “1” or “2”. But first of all, these particles are filtered by graph theory output to satisfy the coordination constraint.

3. Results

This study only considers IEEE 33-bus and 69-bus radial test network to demonstrate and verify how the algorithm works on relay placement systematically. In both networks, the DG was considered to be located at different locations and load priorities are set as well. The results showed that the locations of relay placement will be affected by the location of DG and load priorities.

3.1 IEEE 33-Bus Test System Network

One of the test systems used to demonstrate and verify the algorithm is shown in Figure 3. Considering load priorities and location of DG, four conditions have been carried out in order to demonstrate the different series of definite time overcurrent relay placement as shown in Table 1.

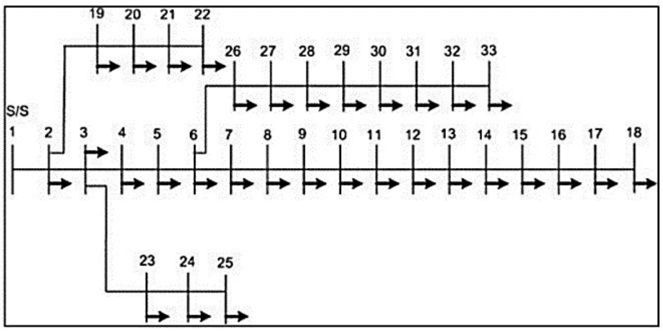

Fig. 3. 33-bus test system

Table 1
Four conditions considered in 33-bus test system

Condition	Load priorities	Location of DG
A	All equal	Busbar 6, 12
B	All equal	Busbar 12 only
C	15, 19, 20	Busbar 6, 12
D	8, 18	Busbar 6 only

The line number on which relays were installed was summarized and tabulated in Table 2. The line number where DOCR was installed, and load priorities were highlighted respectively in each series relay.

Based on Figure 4, it shows that the optimal location for DOCR when DG was placed at busbar 6 was at upstream of Line 3 while for DG at busbar 12, the optimal location of DOCR was at upstream of Line 5.

Table 2
Series of relay under different conditions

	Condition			
	A	B	C	D
Line number on which relays are installed	2	2	2	2
	3	3	3	3
	5	10	5	5
	10	11	10	8
	11	18	11	10
	18	19	15	18
	19	21	18	19
	21	22	19	22
	22	23	20	23
	23	24	22	24
	24	25	23	25
	25	28	24	28
	28		25	
			28	

Directional over current relay
Load priorities

When DG was installed at busbar 6, the optimal location of DOCR was supposed to be at Line 5 but since Line 3 has the lowest ENS, hence Line 3 was chosen instead of Line 5. The same situation happened to DG at busbar 12. When the fault current occurs at the upstream of that point, the relay will isolate the entire downstream of the network and form an islanded zone with the supply from DG. DOCR should be installed at the optimal location such that the ENS value is the lowest. Hence, the ENS values should be recalculated at the lines nearby the place where DG is being installed before making decision to place the DOCR. This is the strategy to make sure the DOCR is placed systematically to fulfill the islanding operation constraint.

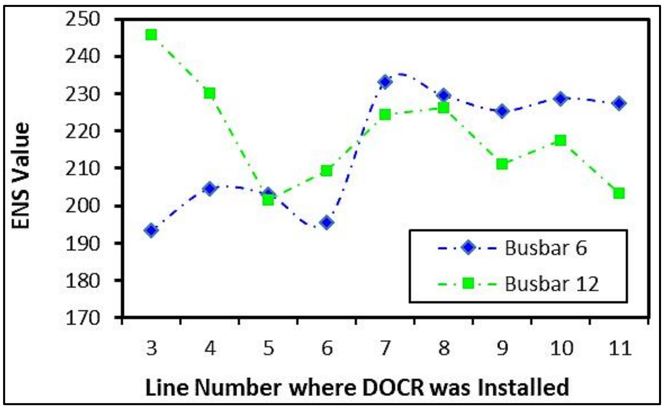

Fig. 4. ENS values versus line number when DGs were installed at busbar 6 and 12

3.2 IEEE 69-Bus Test System Network

The 69-bus system is shown in Figure 5. Like the 33-bus test system network, four different conditions are tested for the 69-bus test system network as shown on Table 3. The line number on which relays were installed were summarized and tabulated in Table 4. The line number where DOCR was installed, and load priorities were highlighted respectively in each series relay.

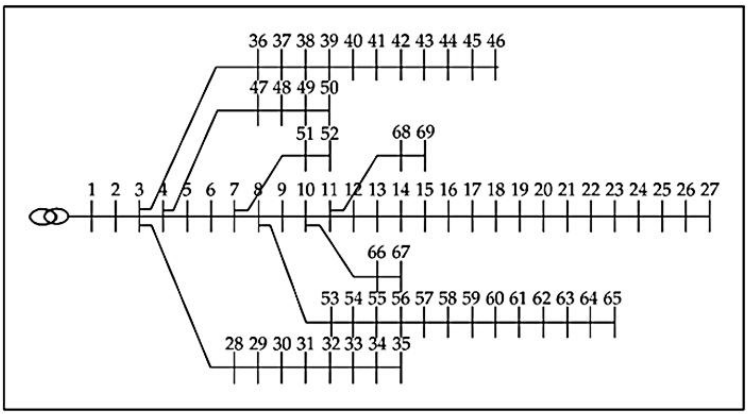

Fig. 5. 69-bus test system

Table 3
Conditions set in 69-bus test system

Condition	Load Priorities	Location of DG
A	All equal	Busbar 10
B	All equal	Busbar 59
C	17, 22, 62	Busbar 10
D	18, 28	Busbar 59

Table 4
Series of relay under different conditions

	Condition			
	A	B	C	D
Line number on which relays are installed	3	3	3	3
	4	4	4	4
	7	7	7	7
	8	8	8	8
	9	10	9	9
	10	27	10	10
	27	28	17	18
	28	29	22	27
	29	30	27	28
	30	35	28	29
	35	36	29	30
	36	37	30	35
	37	38	35	36
	38	39	36	37
	39	40	37	38
	40	41	38	39
	41	46	39	40
	46	47	40	46
	47	50	46	47
	50	51	47	50
	51	52	50	51
	52	54	51	52
	54	58	52	54

58	65	54	65
65		58	
		62	
		65	

Directional overcurrent relay
Load priorities

The values of ENS changed with the different locations of DG and load priorities. When there are critical loads, the locations of relay shall be allocated near to the upstream and downstream of the feeder so that the customers at that load point will experience the minimum outage. For the location of DG, the directional relay shall be placed upstream of the DG feeder so that when the fault current occurs the network can perform islanding operation.

However, when there are critical loads in the network, normally the relay will put those load points as the priority although the ENS values might be slightly higher than other series relay. ENS values have high dependency on the curtailed load at the load point. Some load points have high load power, and this will increase ENS.

Note that despite there are many conditions being carried out, there are many similarities in the line numbers to install relay in these different conditions because these are the line numbers which have high value of ENS. The results showed the consistency and reliability of this algorithm through the different conditions. Hence, the repeated line numbers were the critical locations that were necessary to place relay to minimize the ENS values and reduce the number of customers being affected during fault current.

Based on Figure 6 and 7, it shows that the optimal location for DOCR when DG was placed at busbar 10 was at upstream of Line 9 while for DG at busbar 59, the optimal location of DOCR was at upstream of Line 58. However, for the case in which DG was installed at busbar 59, due to the ENS value at Line 5 being close to Line 58, two DOCR can be placed for better protection strategy.

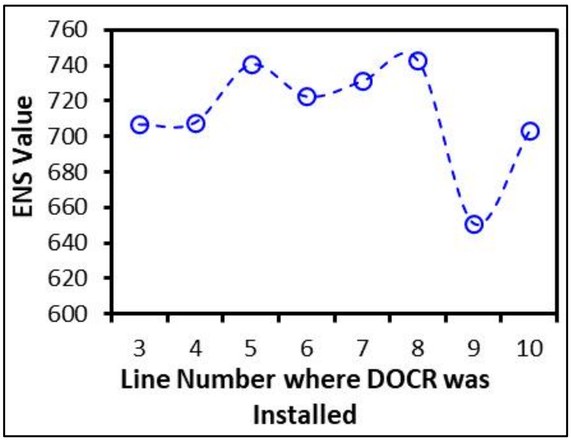

Fig. 6. ENS values versus line number when DG was installed at bus 10

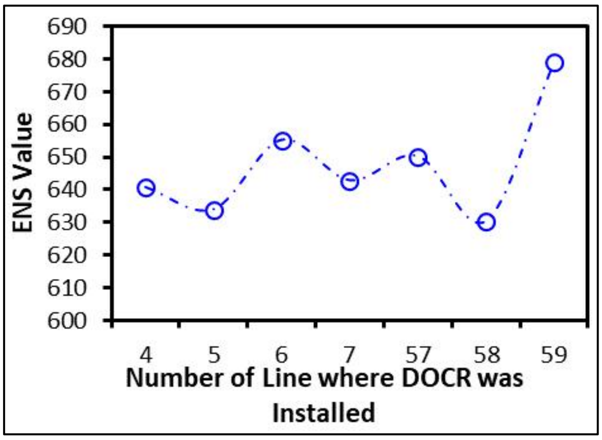

Fig. 7. ENS values versus line number when DG was installed at bus 59

In terms of reliability and effectiveness, the algorithm has been applied in two different network topologies which are IEEE 33-bus and 69-bus test networks. The proposed algorithm is fast, reliable, and effective to be applied in different radial network topologies. The findings show consistent output although the results might not be the most optimized condition compared to the other optimization methods proposed by other researchers in distribution system protection planning. The proposed algorithm's effectiveness in determining specific relay placement locations is demonstrated through its application to the IEEE 33-bus and 69-bus test systems under various conditions. The specific locations of relay placements are justified based on two main factors:

energy not supplied (ENS) values and load priorities. ENS values represent the amount of energy not served to customers during a fault condition. Lower ENS values indicate better performance and more reliable power supply to consumers. The algorithm calculates ENS values at different locations in the distribution network and identifies the locations with the lowest ENS values as the optimal placement points for protective relays. In the presence of critical loads in the distribution network, the algorithm prioritizes placing relays near these load points. Critical loads are those that require uninterrupted power supply and must be protected during fault events. By placing relays strategically at these load points, the algorithm ensures minimal outage times and prioritizes reliable power supply to critical consumers.

Combining ENS values and load priorities, the algorithm selects specific locations for relay placement that offer the best compromise between minimizing ENS values and protecting critical loads. Additionally, the algorithm considers the location of distributed generation (DG) sources to ensure effective islanding operation when faults occur. For example, in the IEEE 33-bus test system with DG installed at busbar 6, the algorithm identified Line 3 as the optimal location for directional overcurrent relay (DOCR) placement. This decision was based on the ENS values at different line locations, and despite Line 5 having slightly lower ENS, the critical load priority at Line 3 justified its selection.

Similarly, in the IEEE 69-bus test system with DG installed at busbar 10, the algorithm determined Line 9 as the optimal location for DOCR placement. The ENS values and the load priorities at different line locations supported this decision, ensuring minimal outage times for critical loads. In some cases, when DG was installed at busbar 59 in the IEEE 69-bus test system, the ENS values at Line 58 and Line 5 were close. Therefore, the algorithm allowed the placement of two DOCRs at these locations to improve protection strategy and enhance system reliability. The results consistently demonstrated that the proposed algorithm provides reliable and effective relay placement locations, considering both network specific ENS values and load priorities. This approach contributes to minimizing power outages, optimizing system reliability, and enhancing the protection of distribution systems with distributed generation.

4. Conclusions

This paper presents an algorithm for systematic placement of relays in distribution networks considering distributed generations. The algorithm could be used to determine the types of overcurrent relays and the placement of series relays under different conditions in the distribution network with distributed generation. The general concept of this algorithm was to use knowledge based on graph theory to determine the type and structure of a radial network, and then determine the relay locations based on the coordination constraints to achieve the objective function of the project, which is ENS. The results showed that the location of DG and load priorities can affect ENS and further influence the relay placement locations. The results were conducted with different network topologies to evaluate the reliability and effectiveness as well as the consistency of the results of the proposed algorithm.

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