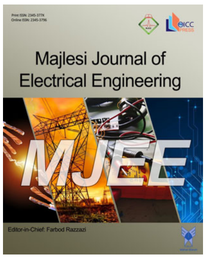

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Original Research

Intelligent Electronic Devices Placement for Reconfiguration of Active Distribution Networks Considering Reliability and Protection

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Abstract:

Utilizing distributed generations (DGs) in distribution networks offers numerous technical and economic benefits. However, DGs can also negatively impact the network by causing protection miscoordination and potential protection scheme failures. Accurate fault location and rapid fault clearance are essential to maintain system stability and ensure continuous load supply. Intelligent Electronic Devices (IEDs) enable fast communication among network components through Generic Object-Oriented Substation Events (GOOSE) messaging. Nevertheless, their deployment is limited due to high investment, installation, and infrastructure costs.

This paper investigates the optimal allocation of IEDs alongside DGs to enhance distribution system reliability and reduce power losses. Network reconfiguration is also incorporated to achieve efficient system operation. Two objective functions—power losses and the Energy Not Supplied (ENS) index—are optimized using the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. Considering ENS in addition to losses allows the operator to achieve higher reliability levels. The Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) method is then employed to select an optimal trade-off solution between the objectives.

The proposed approach is tested on the IEEE 33-bus standard distribution system. Simulation results demonstrate a substantial reduction in power losses and a significant improvement in network reliability through ENS minimization.

Keywords: Allocation; Distributed generation; Intelligent electronic devices; Multi objective particle swarm optimization; Technique for order preference by similarity to the ideal solution; Reconfiguration; Reliability

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1. Introduction

Distributed generations (DGs) are increasingly being integrated into active distribution systems due to their operational and economic advantages. However, integrating DGs into conventional distribution networks may lead to malfunctions in relay operations, resulting in ineffective protection schemes and a decline in system reliability. Distribution companies (DisCos), as owners and operators of distribution networks, aim to enhance reliability by ensuring fast and accurate fault detection and clearance. Intelligent Electronic Devices (IEDs) and Remote-Controlled Switches (RCSs) are modern technologies that support this goal. IEDs can monitor network conditions, issue protection commands, and communicate with other devices via the IEC 61850 communication standard. Specifically, IEC 61850 defines inter-IED communication using Generic Object-Oriented Substation Event (GOOSE) messages [1]. The deployment of RCSs provides significant advantages, including reduced fault detection, isolation, and restoration times. Despite their effectiveness, both IEDs and RCSs impose considerable investment, installation, and infrastructure costs on DisCos. Therefore, developing an efficient strategy for the optimal allocation of a limited number of such devices is of great importance.DG units offer undeniable technical and economic advantages compared to centralized generation systems. Therefore, their optimal sizing and placement play a vital role in power system planning and operation. However, DGs can adversely affect protection coordination due to bidirectional power flows, which is a major concern for distribution network operators. Consequently, many researchers have focused on addressing these issues.This study addresses the same problem by proposing an efficient implementation of IEDs combined with network reconfiguration to improve overall system performance. IEDs, as emerging technologies, are expected to play a key role in future power systems due to their monitoring and communication capabilities. Metaheuristic algorithms such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) have been widely used for DG placement to achieve loss reduction. For example, DG allocation and its effects on power losses and network reconfiguration were studied in [2], though the Energy Not Supplied (ENS) index was not considered. In [3], the impact of DG operation modes on network reconfiguration was analyzed, but reliability assessment was not performed. Several studies have proposed automation and restoration schemes using modern technologies. The network restoration process generally involves three steps: fault location, fault isolation, and power supply restoration [4]. Fault isolation is typically achieved using two types of equipment: circuit breakers (CBs)—which interrupt current flow under load—and sectionalizers (S)-which operate under no-load conditions. Sectionalizers are classified as manual or remote-controlled (RCS), with the latter offering faster operation at higher installation and communication costs. Transitioning from conventional fault location methods to IED-based fault detection has been examined in [**a6**, 5]. IED-based approaches provide faster response times and improved reliability. IEDs have also been widely used for protection purposes. For example, [1] proposed a centralized IED-based protection scheme against single line-to-ground (SLG) faults in ungrounded systems. In [5], integer linear programming was used to determine optimal IED locations by minimizing customer penalty costs. Similarly, [6] optimized IED placement for medium-voltage grids using integer programming and exhaustive scenario analysis. In [4], a novel distribution automation system (DAS) based on sectionalizing switches and interruption cost was developed. IEDs can operate either autonomously or under centralized control. Their communication capability enables fast and accurate fault location and isolation. In this study, IEDs employ GOOSE messaging to exchange fault detection data for accelerated system restoration. In parallel, network reconfiguration has been explored as an effective means of minimizing power losses and improving voltage profiles, typically by altering the switching states in distribution systems. Switch placement methods have been studied extensively. For instance, [7] considered switch failure impacts in reliability assessment, while [8] examined reconfiguration with manual and remote-controlled switches. In [9], a DAS was developed using fault indicators and sectionalizing switches, and [10] investigated the effect of laterals on switch placement, though losses were not calculated.

Protection coordination within reconfiguration frameworks has also been discussed. In [11], a reconfiguration method incorporating DGs and protection devices was presented, though losses and ENS were not evaluated. In [12], reliability indices were applied to a protection and reconfiguration scheme with DGs. Similarly, [13] used IEDs for network reconfiguration, while [14] formulated a mixed-integer linear programming model for the joint selection and coordination of protective devices. Reliability-based reconfiguration methodologies were proposed in [15].

In [16], a GOOSE-based high-speed fault detection and clearance method was developed for three-phase faults. Unlike conventional relays that rely on fixed settings, IEDs enable adaptive protection schemes suitable for dynamic grids with distributed renewable generation and changing topologies [17]. In [18], data clustering was used to limit the number of IED setting groups in adaptive protection, though ENS and loss considerations were omitted. Recent studies [19, 20, 21] have explored reconfiguration with energy storage systems, capacitor banks, and electric vehicles; however, they also lack integrated analysis of DG placement, protection coordination, and ENS evaluation.

The simultaneous allocation of IEDs and DG units, along with network reconfiguration, forms a complex optimization problem with numerous operational constraints. Various technical and economic objectives—such as minimizing losses and improving network reliability—must be addressed. Due to the nonlinear and non-convex nature of this problem, evolutionary optimization algorithms are essential for achieving accurate and globally optimal solutions. Based on the reviewed literature, the following gaps can be identified:

While the effects of DGs, reconfiguration, IEDs, and various protection schemes on ENS have been individually investigated, no study has analyzed all of them simultaneously.

As summarized in Table 1, limited research has examined the specific impact of IED allocation on network ENS.

Therefore, this paper proposes a comprehensive framework that simultaneously considers IED allocation, network reconfiguration, and DG placement using a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. The optimization objectives include minimizing both power losses and Energy Not Supplied (ENS), thereby improving system efficiency and reliability.

Numerous studies have investigated IED allocation, network reconfiguration, and DG placement independently, with objectives such as minimizing power losses and improving reliability indices. However, these aspects have rarely been examined together in a unified

Table 1. Characteristics of different references and comparison with the current study.

Resfs.	Reliability assessment	Losses	Multiobjective	Reconfiguration	DG Protection
[1]	×	√	×	√	×
[2]	√	×	×	×	×
[3]	√	×	×	×	×
[4]	√	×	×	×	×
[5]	×	×	×	×	×
[22]	√	×	×	×	×
[6]	×	√	×	√	√
[7]	×	√	√	√	×
[8]	×	√	√	√	×
[9]	×	√	√	√	×
[10]	×	√	×	√	×
This paper	√	√	√	√	√

optimization framework. The main contributions of this paper can be summarized as follows:

A New Methodology for IED Placement

While previous research has typically focused on one or two of the above aspects separately, the proposed approach simultaneously considers IED allocation, network reconfiguration, and DG placement within a multi-objective Particle Swarm Optimization (MOPSO) framework. The objectives include minimizing power losses and Energy Not Supplied (ENS). To the best of the authors' knowledge, no prior study has integrated all these components concurrently.

Consideration of DG Protection Issues

The reliability of distribution systems with high DG penetration can deteriorate due to inadequate or uncoordinated protection schemes. This paper explicitly addresses this issue by incorporating the protective role of IEDs in systems with DGs. The proposed model ensures coordinated operation and improved fault management in the presence of distributed generation.

Practical Application and Real-World Relevance

By integrating all the above objectives, the proposed methodology provides distribution companies (DisCos) with a practical and efficient strategy for enhancing both operational performance and system reliability. Furthermore, the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) is employed to identify an appropriate trade-off between conflicting objectives, ensuring minimal losses while maintaining acceptable reliability levels. A comprehensive analysis is presented to evaluate the impact of IED locations on fault detection speed and accuracy under different operating scenarios. The effectiveness of the proposed method is validated through multiple simulation cases on the IEEE 33-bus standard test system, demonstrating its capability to improve both reliability and efficiency in active distribution networks. The remainder of this paper is organized as follows:

Section 2 presents the communication-based adaptive protection framework using Intelligent Electronic Devices (IEDs), including both centralized and decentralized protection schemes.

Section 3 provides a comparison between conventional system restoration methods and IED-based restoration, and discusses the challenges associated with Distributed Generation (DG) integration.

Section 4 introduces the problem formulation, detailing the objective functions, constraints, and system parameters. Section 5 describes the optimization procedure, including the implementation of the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. Section 6 presents the simulation results and analysis for various case studies based on the IEEE 33-bus distribution system.

Finally, section 7 concludes the paper by summarizing the key findings and highlighting possible directions for future research

2. Communication-based adaptive protection based on IED

Intelligent Electronic Devices (IEDs) play a vital role in modern distribution networks, particularly in achieving automation and adaptive protection in compliance with the IEC 61850 standard. According to their primary functions, IEDs can be classified into five main categories: protection, control, communication, monitoring, and metering devices. Communication-based adaptive protection systems utilize data exchanged among IEDs to provide fast, reliable, and secure protection coordination. Based on the protection architecture, these systems are generally categorized into centralized and decentralized adaptive protection schemes [23].

2.1 Centralized adaptive protection

In centralized adaptive protection, a central controller collects real-time operational data from IEDs installed across the network. After analyzing system conditions, the controller updates and coordinates protection settings for all IEDs in a unified manner. This configuration requires a high-performance central unit capable of

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storing, processing, and communicating large volumes of data efficiently. The reliability of the overall system depends heavily on this central controller, which must operate with high computational capacity and robust communication infrastructure to prevent single points of failure.

2.2 Decentralized adaptive protection

In decentralized adaptive protection, each IED functions autonomously, gathering local system information and adjusting its protection settings independently. Unlike the centralized approach, this configuration minimizes the volume of exchanged messages and reduces dependency on a single controller. However, decentralized systems require IEDs with enhanced processing power, larger memory capacity, and secure, high-speed communication links to ensure proper coordination and consistency of protection settings among neighboring devices.

3. System restoration

System restoration is a crucial process designed to minimize interruption time and reduce outage-related costs for both utilities and consumers following a system fault [24]. The restoration process ensures rapid recovery of service continuity and overall system reliability.

Different approaches to system restoration are discussed in the following subsections.

3.1 System restoration without IED in the traditional method

In conventional distribution networks without IEDs, the fault location and isolation process is typically manual and time-consuming, particularly in long feeder systems. The restoration sequence can be described through the following steps, as illustrated in Fig. 1:

1. The network operates under normal conditions.
2. A fault occurs on Line 2.
3. The relay detects the fault and issues an open command to the circuit breaker.
4. The switches on Line 2 and Line 1 open to isolate the faulted section.
5. The switch on Line 1 is then closed to reroute power.
6. The breaker is closed to attempt system restoration.
7. The breaker opens again and the switch at Bus 2 closes to test fault isolation.
8. The breaker closes once more to restore service.
9. The breaker reopens, indicating that the fault persists and has not yet been cleared.
10. Finally, the switch on Line 2 is closed and the breaker is closed again after fault repair.

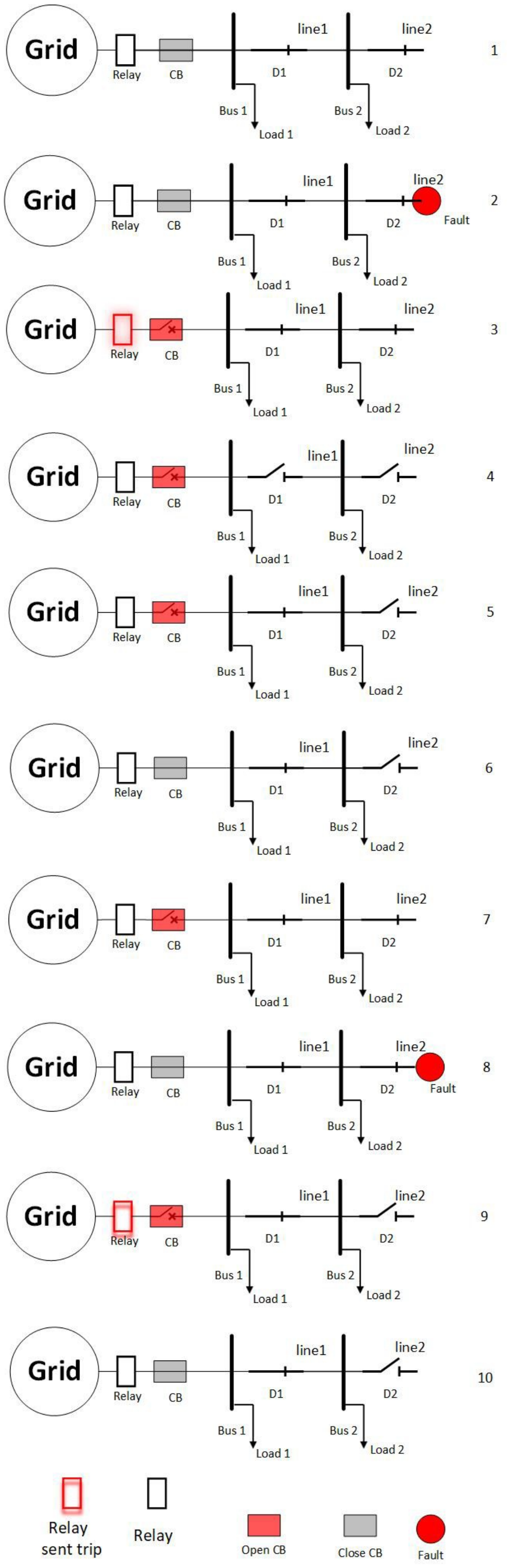

Figure 1. Traditional system restoration.

As a result of this multi-step process, Load 1 is re-energized only after fault clearance, meaning that power restoration is delayed until manual fault isolation and repair are completed. This demonstrates the limitations of traditional restoration methods, where lack of automation leads to longer outage durations and reduced network reliability.

3.2 System restoration with IEDs

System restoration using Intelligent Electronic Devices (IEDs) is significantly faster and more reliable than the traditional manual method. This improvement is primarily due to the high-speed communication and real-time coordination enabled by message exchanges between IEDs via Generic Object-Oriented Substation Events (GOOSE) messaging. The IED-based restoration sequence is illustrated in Fig. 2 and can be described as follows:

1. The IED installed on Line 2 detects an abnormal current indicating a fault condition.
2. The IED on Line 2 immediately transmits a GOOSE message to the corresponding IEDs (IED1 and IED2) located at adjacent network points.
3. Upon receiving the fault signal, the circuit breaker executes an open command to isolate the faulted section.
4. The switch on Line 2 opens, and the breaker recloses, restoring service to the healthy sections of the network.

This process is completed automatically and within milliseconds, resulting in a substantial reduction in fault detection, isolation, and restoration times compared with conventional methods. Consequently, the overall reliability and continuity of power supply are greatly enhanced, minimizing both outage duration and customer interruption cost.

In an IED-based radial distribution network operating under the IEC 61850 standard, customers can be classified into three categories when a fault occurs [5]:

Upstream Customers:

These customers are located between the main grid and the faulted section. Their power supply remains uninterrupted, as they are electrically isolated from the faulted zone.

Faulty Customers:

These customers are situated within the faulted zone. Their service is interrupted immediately upon fault detection and remains unavailable until fault clearance and restoration are completed.

Downstream Customers:

These customers are located beyond the faulted section. Their power supply is temporarily interrupted but can be restored automatically once network reconfiguration is completed through IED coordination.

The key distinction between IED-based and traditional restoration methods lies in the service restoration speed for downstream customers. In IED-based systems, the use of GOOSE-enabled communication allows for rapid fault detection, isolation, and automatic switching operations, leading to much faster service restoration compared with conventional manual procedures.

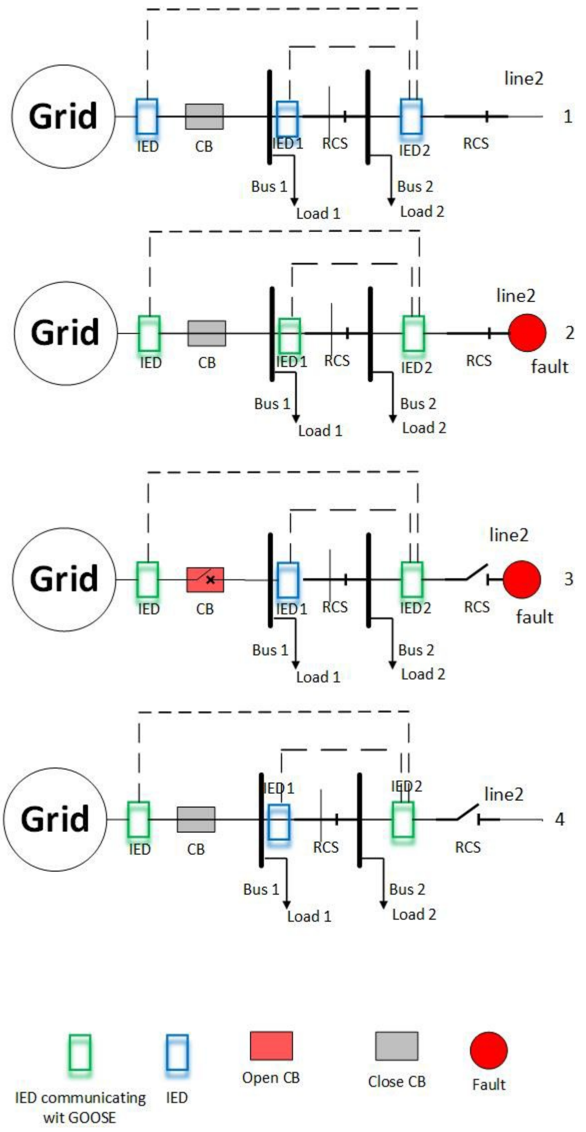

Figure 2. Automated system restoration with IED.

3.3 System restoration considering DG integration

Integrating Distributed Generators (DGs) into active distribution networks introduces several operational and protection challenges. These issues arise primarily due to the bidirectional power flow, variable fault current levels, and dynamic network topology. To ensure secure, reliable, and safe DG integration, Intelligent Electronic Devices (IEDs) are increasingly employed in modern protection and control schemes, as reported in several studies. Some of the major challenges associated with DG integration, along with the corresponding solutions or mitigation strategies using IED-based systems, are summarized in Table 2.

Ommunication between Intelligent Electronic Devices (IEDs) can effectively address several problems associated with Distributed Generation (DG) integration. In this study, it is assumed that each bus with a connected DG is equipped with an IED. Through coordinated communication, IEDs can exchange protection signals to ensure selective fault isolation and minimize unnecessary outages. For example, during a fault on line 2, IED3

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Table 2. DG integration problems in the active distribution network.

	Effect	Problem	Reference
1	Bidirectional current flow	Protection system miscoordination.	[11]
2	Sympathetic tripping	An unwanted outage of the healthy feeder.	[12]
3	Islanding	Networks are energized from DG independently.	[13]
4	Blinding of protection	Reduce the sensitivity of the protection system.	[14]
5	Change in fault level	Excessive fault currents may destroy circuit breakers.	[11]

can transmit a blocking command to IED2 and IED1, thereby preventing unwanted disconnection of buses 3 and 1. This coordinated response enhances system reliability and reduces downtime. The proposed IED-based DG protection scheme is illustrated in Fig. 3.

4. Problem formulation

The proposed method for the allocation of IEDs besides DGs placement and network reconfiguration can be formulated as an optimization problem as follows:

4.1 Objective function

The objective function includes the following components.

4.1.1 ENS index

Reliability assessment [15] for a general feeder at section s1 of a sample network:

$$\lambda_{s1} = \sum_{i=1}^{m} \lambda_i \tag{1}$$

$$U_{s1} = \sum_{i=1}^{m} \lambda_i \times r_i \tag{2}$$

$$r_{s1} = \frac{U_{s1}}{\lambda_{s1}} \tag{3}$$

where i is the line index, m is the number of lines at section s1. λ_{s1} is the failure rate of section s1. U_{s1} is the unavailability of section s1 and r_{s1} is restoration time of section s1. Energy not supplied (ENS) is one of the reliability indices and can be calculated from equation (5) [16]. In equation (4) U_{ei} is unavalilablaity. r_{ei} is restoration time and λ_{ei} is failure rate of element i. In equation (5) U_{ei} is unavalilablaity and P_i is average power at load point i and n_l is number of loads. Assumptions about the restoration time of IEDs and relays are mentioned in section 6.1

$$U_{ei} = \lambda_{ei} r_{ei} \tag{4}$$

$$\text{ENS} = \sum_{i=1}^{n_l} P_i \times U_{ei} \quad \text{(kwh/year)} \tag{5}$$

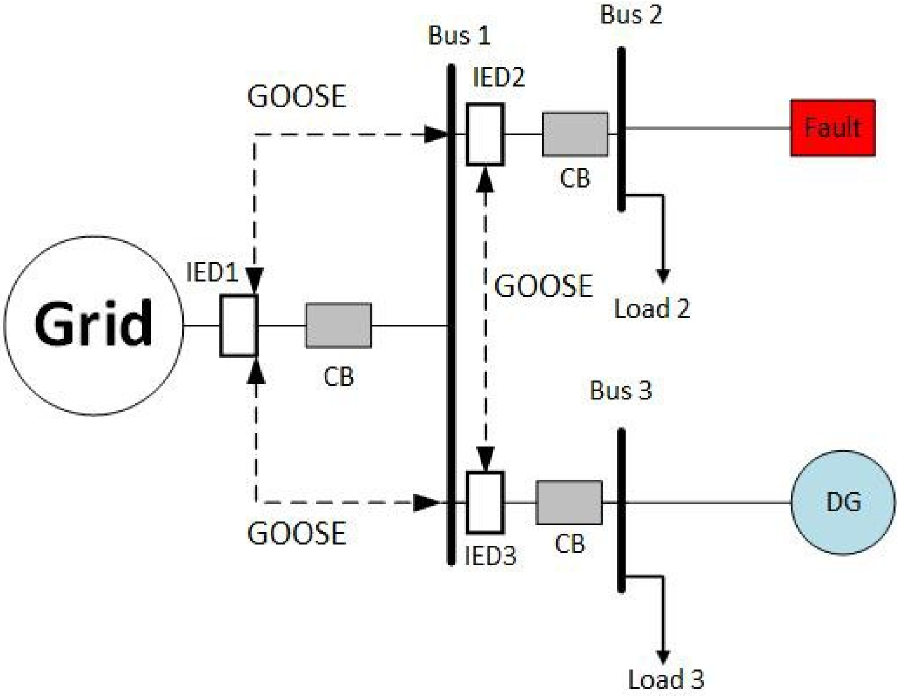

Figure 3. DG protection scheme with IED.

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4.1.2 Losses

Total network losses are equal to the sum of losses of all network lines [17]. It can be calculated according to equations (6) and (7).

$$I_l = \left| \frac{V_i - V_j}{R_k + jX_k} \right| \tag{6}$$

$$P_{\text{loss}} = \sum_{l=1}^{N_b} R_l I_l^2 \tag{7}$$

In equation (6), I_l is the line l current magnitude, V_i voltage of bus i and V_j is voltage of bus j. Line l is between bus i ana j. R_k and X_k are resistance and reactance of line l respectively. In equation (7), l is the line index. R_l and X_l are the resistance and reactance of the l^{th} line, respectively. I_l is the line l current magnitude, N_b is the number of grid branches and P_{loss} is total network losses.

4.1.3 Reconfiguration

There are two types of switches in active distribution networks (ADNs): sectionalized switches which are normally closed and tie switches which are normally opened. A new configuration for ADN is achieved by changing the status of the existent switches [18]. The important issues due to DN reconfiguration are the management of opening or closing switches as follows [19]:

1. There must be no closed loop in the network,
2. Each load in the network must be connected to a single substation and all loads to be powered,

4.1.4 Objective function

The final objective function is according to equation (8). Where SW_{state} is switches/tie lines state, DG_{loc} is location of DGs and IED_{loc} is location of IEDs.

$$\text{minimize } \text{F}(\text{SW}_{\text{state}}, \text{DG}_{\text{loc}}, \text{IED}_{\text{loc}}) = (\text{ENS} + P_{\text{loss}}) \tag{8}$$

4.2 Control variables

The control variables include switches/tie lines state, DG units' location, and their size besides IEDs location.

4.3 Constraints

Equality and inequality constraints are shown in equations (9) to (11). Constraint (9) keeps the voltage magnitude between its lower and upper bands.

$$V_i^{\min} \leq V_i \leq V_i^{\max} \tag{9}$$

where V_i is the voltage magnitude of the i^{th} node. $V_i^{\min}$ and $V_i^{\max}$ are constraint (11) prevents the feeder current from overloading.

$$|I_l| \leq I_l^{\max} \tag{10}$$

where, $I_l^{\max}$ is maximum current according to the thermal limits of lines.

Also, there are some constraints on control variables. Constraint (12) limits the DG's output power to its maximum capacity. Where $P_{\text{DG},i}^{\max}$ is maximum power of i^{th} DG.

$$P_{\text{DG},i} \leq P_{\text{DG},i}^{\max} \tag{11}$$

5. MOPSO

Coello Coello and Salazar Lechuga developed this method [20] in 2002 Generally, the steps of MOPSO are described as follows:

1- Generate a random initialize population and velocity for each individual in the population,

2- Separate non-dominated contents of the population and store them in the repository,

3- Generate a hypercube of the search space explored so far,

4- Select a leader from the repository and move the particle position using this leader and each particle's best individual experience,

5- Update the position and velocity of the population,

6- Adding the current non-dominated population to the repository and update the contents of it,

7- Determine the non-dominated repository contents,

8- Omit repository contents if all population repositories are more than its nominal capacity,

9- Check the satisfied finishing condition of the algorithm; if not, continue Mentioned steps from step 4.

5.1 Topsis

In multi-objective optimization, a set of Pareto-optimal solutions is typically generated, representing the trade-offs between conflicting objectives. However, it is often desirable to rank these solutions and identify a smaller subset of the most suitable options using a Multiple Attribute Decision-Making (MADM) framework. MADM is a systematic process for selecting the best alternative from a set of feasible options based on multiple criteria. In this study, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is employed to evaluate and rank the Pareto-optimal solutions, facilitating the selection of a compromise solution that balances competing objectives such as loss minimization and reliability improvement.

6. Simulation

The IEEE 33-bus radial distribution system, illustrated in Fig. 4, is employed as the case study. The system comprises 33 buses, 32 branches, and 5 normally open tie-lines, along with 6 circuit breakers and 32 sectionalizing switches [25]. The total system load is 3.72 MW, with a nominal voltage of 12.66 kV and a nominal power

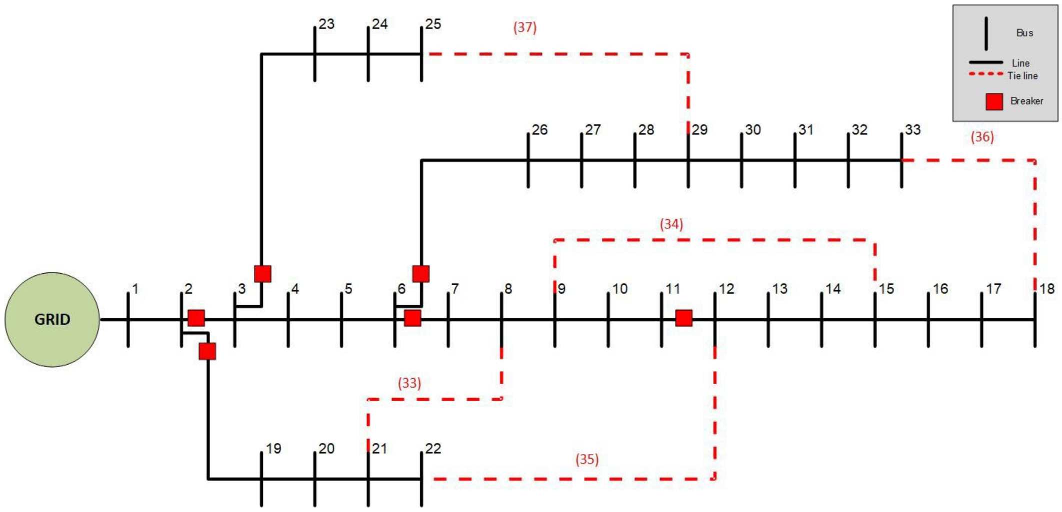

Figure 4. The IEEE standard 33 bus test system in the base condition.

of 10 MW. Under base conditions, the system experiences power losses of 202.67 kW, a minimum voltage of 0.913 p.u., and an Energy Not Supplied (ENS) index of 15,108 kWh/year. The overall methodology proposed in this study is summarized in the flowchart shown in Fig. 5, illustrating the integration of DG allocation, IED placement, network reconfiguration, and multi-objective optimization using MOPSO with TOPSIS for solution ranking.

6.1 Assumption

The failure rate of the line is considered 0.1 to 0.4 faults per year according to line impedances [21]. Other components of the system are assumed to be ideal. Also, the failure rate of IEDs is assumed to be zero because they are electronic devices without mechanical parts.

The number of IEDs is assumed to be 10.

The maximum capacity of DG units is considered to be 550 kW.

The maximum permissible current of feeders is selected according to (equation (10)).

V_i^{min} and V_i^{max} are equal to 0.95 and 1.05, respectively.

I_l^{max} is considered to be 215 ampers.

Fault detection and isolation with IEDs is 50% faster than relays because of their GOOSE massage connections. Also, the assumptions for the MOPSO algorithm are as follows:

The population size is considered to be 50.

The number of iterations is set to 500 iterations.

The learning coefficients are assumed to C1 = 2 and C2= 2

Also, the weight factor for updating the velocity of the particle is assumed W = 1.

6.2 Scenarios

To show the efficiency of the proposed method, three scenarios are considered in this study. In the first scenario, the base case is evaluated. The effect of DGs is evaluated in the second scenario. The protection scheme of this scenario is provided by conventional methods. Finally, in the third scenario, the optimal locations of IEDs are found besides the DG allocation problem. In all scenarios, the reconfiguration is conducted to have a flexible operating of the distribution system.

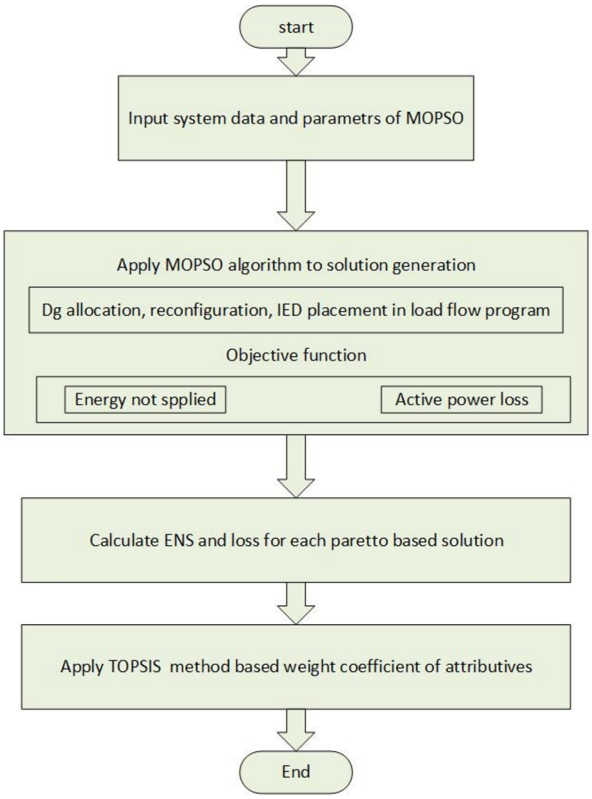

Figure 5. The flowchart of the proposed method.

6.2.1 Scenario 1: Conventional protection scheme

In this scheme, the network reconfiguration and DG allocation are conducted while the network is protected by conventional breakers and sectionalizers located at pre-defined places. Table 2 shows the switches and

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Table 3. Optimal solution in Scenario 1.

	Scenario 1	Base case
Open switches/tie lines	7, 8, 32/ 34, 37	33, 34, 35, 36, 37
DGs places/sizes (kW)	14/700, 24/1200, 30/1200	none
Losses (kW)	59.45	202.67
ENS (MWh/year)	5.6	15.1

tie-lines state, DG unit sizes, and places. Also, the value of the objectives is presented in Table 3.

According to Table 2, switches between nodes 7 and 8 (7), nodes 8 and 9 (8), and nodes 32 and 33 (32) are changed from closed to open and tie lines 34 and 37 remain open, in this scenario. Also, the DG units are placed on nodes 14, 24, and 30 with sizes of 700, 1200, and 1200, respectively. With this solution, losses were reduced from 202 kW at the base case to 59 kW, approximately. The minimum voltage is improved from 0.93 at the base case to 0.98. Also, the ENS index decreased from 10750 kWh/year at the base case to 4648 kWh/year.

6.2.2 Scenario 2: Proposed protection scheme

In this scenario, the effect of the proposed protection method is focused. For this purpose, the network reconfiguration and DG allocation are re-optimized besides the IEDs location. Table 4 shows the switches and tie-lines state, DG unit sizes and places, and IED locations. To better visualize the solution, the optimal locations of DG units and IEDs in the reconfigured network are shown in Fig. 6. As shown in the figure, six breakers four RCS, and ten IEDs are used. The number of breakers is the same as the base case just they are equipped with IED and their places are changed.

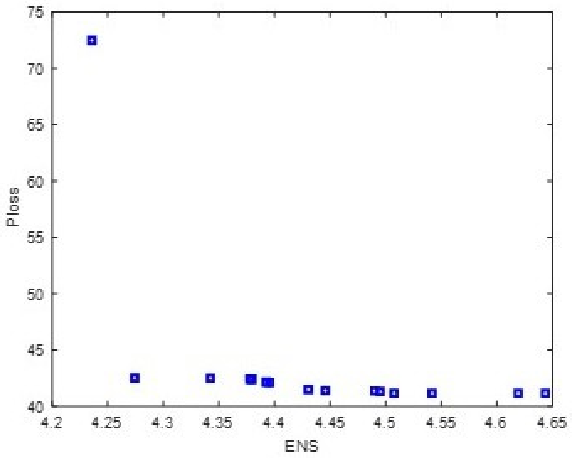

Figure 6. MOPSO solutions.

6.2.2.1 MOPSO solutions

Objective function minimization in scenario 2 for the IEEE 33 node network using MOPSO algorithm and its solutions is shown in Fig. 6 and Table 5.

Table 4. MOPSO results.

Solution	ENS (MWh/year)	Loss (kW)
1	4.49	41.30
2	4.43	41.49
3	4.34	42.49
4	4.45	41.40
5	4.51	41.17
6	4.49	41.36
7	4.54	41.17
8	4.62	41.17
9	4.64	41.17
10	4.39	42.12
11	4.38	42.38
12	4.40	42.09
13	4.24	72.48
14	4.38	42.41
15	4.27	42.50

6.2.2.2 TOPSIS outputs

Pareto optimal solutions ranked for the IEEE 33 node network using TOPSIS based on various weights coefficients are shown in Table 5. As observed, the IEDs are strategically allocated near the DG units.

A comparison between the results in Table 3 and Table 6 indicates that installing IEDs at optimal locations not only reduces the ENS value but also decreases power losses. However, in the second scenario, the minimum voltage does not improve significantly compared to the first scenario; nevertheless, it remains within the allowable limits defined in equation (9).

Figure 7 illustrates the network reconfiguration scenario incorporating Distributed Generation (DG) units and Intelligent Electronic Devices (IEDs). In the first scenario, due to the limitations of the conventional protection scheme, DG units could not be placed in their optimal locations. Moreover, network reconfiguration was restricted, as certain changes could have adversely affected the ENS index. In contrast, the proposed protection scheme provides greater flexibility for network reconfiguration and allows more candidate locations for DG unit installation. Additionally, switches and tie-lines can be operated with increased flexibility without undesirably impacting the ENS index.

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Table 5. TOPSIS results.

weights $w_{\mathrm{ENS}} = 0.5$ $w_{\mathrm{Loss}} = 0.5$		$w_{\mathrm{ENS}} = 0.8$ $w_{\mathrm{Loss}} = 0.2$		$w_{\mathrm{ENS}} = 0.2$ $w_{\mathrm{Loss}} = 0.8$	
Rank	Solution	Rank	Solution	Rank	Solution
1	15	1	15	1	5
2	3	2	3	2	1
3	14	3	14	3	4
4	11	4	11	4	7
5	10	5	10	5	6
6	12	6	12	6	2
7	2	7	2	7	8
8	4	8	4	8	9
9	6	9	6	9	12
10	1	10	1	10	10
11	5	11	5	11	11
12	7	12	7	12	14
13	8	13	13	13	3
14	9	14	8	14	15
15	13	15	9	15	13

Table 6. Optimal solution in Scenario 2.

Open switches/tie lines	7, 8, 13, 17, 25
DGs places/sizes (kW)	15/550, 18/550, 10/550
IEDs locations	31, 36, 10, 11, 14, 21, 19, 1, 37, 15
Losses (kW)	41.16
ENS (MWh/year)	4.64

To further demonstrate the efficiency of the proposed technique, a comparison with other optimization methods is presented in Table 7. In this table, HAS refers to the Harmony Search Algorithm, FA denotes the Firefly Algorithm, and EP represents the Evolutionary Programming algorithm..

7. Conclusion

his study investigates the optimal placement of IEDs alongside Distributed Generations (DGs) in distribution networks to enhance system reliability, reduce power losses, and improve overall operational efficiency. In addition, network reconfiguration is incorporated in conjunction with the allocation of DGs and IEDs. To demonstrate the benefits of optimal IED installation, two scenarios were analyzed: Scenario 1: Optimal DG

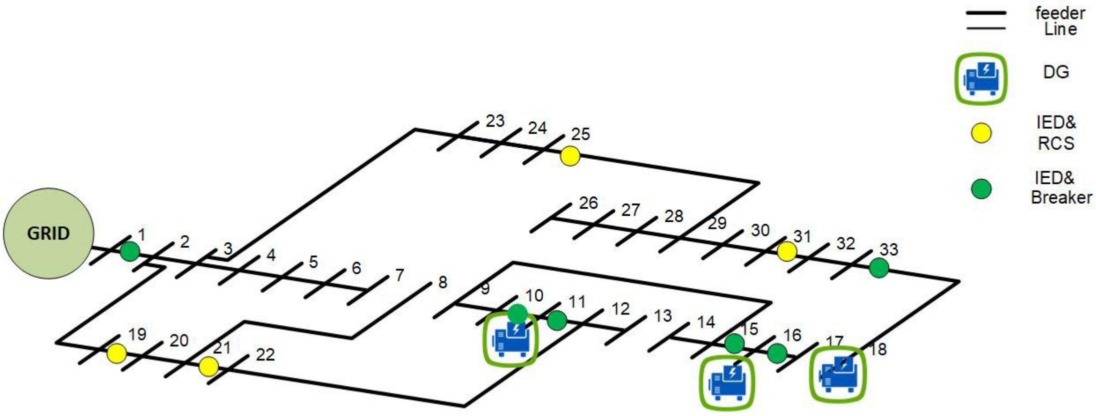

Figure 7. Reconfiguration with DG and IED.

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Table 7. Efficiency of the proposed method compared to different methods.

Technique	Open switches	Power loss (kW)	Loss reduction (%)	Min voltage (p.u.)	ENS	DG number
FA [6]	7,10, 13,28,32	72.36	64.30	0.97	Not calculated	3
EP [6]	7,10, 27,32,34	73.34	63.84	0.97	Not calculated	3
EP [9]	7, 8, 9, 28, 32	63.51	63.51	0.97	Not calculated	3
HSA [24]	7, 14,9, 32, 37	97.13	52	0.94	Not calculated	3
HSA [24]	7, 10, 14, 28, 32	73.05	63.95	0.97	Not calculated	3
Proposed method	7, 8, 13, 17, 25	41.16	79	0.97	4.64	3

placement and network reconfiguration were performed using a conventional protection scheme. Scenario 2: Optimal DG placement and network reconfiguration were conducted in combination with strategically placed IEDs. The IEEE 33-bus test system was used to evaluate and compare the performance of both scenarios. The results indicate that installing IEDs at the proposed locations, instead of relying solely on conventional protection devices, led to a 70% reduction in Energy Not Supplied (ENS) and a 79% reduction in power losses compared with Scenario 1. These findings demonstrate that IED deployment enhances the flexibility and effectiveness of DG allocation and network reconfiguration, contributing to a reliable, intelligent, and economically efficient active distribution network. Furthermore, from the ENS perspective, the study suggests that IEDs should be placed near DG units to provide optimal protection against network faults.

Authors contributions
All authors contributed equally to the conception, design, execution, and writing of this work. All authors read and approved the final manuscript.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests
The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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