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Optimal Placement of Protective Relays and Distributed Generation Units in Distribution Networks for Enhancing System Reliability Using the PSO Algorithm

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ABSTRACT

The integration of Distributed Generation (DG) into modern distribution networks introduces several operational challenges, particularly in terms of network protection and reliability. One of the key challenges for distribution network operators is the transition from a traditional radial structure to a more complex meshed configuration due to the presence of DG sources. This structural change alters the short-circuit levels, rendering conventional fixed protection settings ineffective. As a result, the placement and coordination of protective devices such as overcurrent relays, reclosers, and fuses must be carefully reconsidered to ensure effective fault detection and system reliability. This paper proposes an optimization-based algorithm for determining the optimal locations for installing protective devices and DG units within a distribution network. The proposed methodology aims to enhance system reliability by strategically placing protection equipment while considering the impact of DG integration. The objective function in this study is to minimize key reliability indices, such as the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI), while also reducing network losses. The effectiveness of the proposed approach is evaluated using simulation studies conducted on standard test distribution systems. The results demonstrate that the optimized placement of DG and protection devices significantly improves network resilience, enhances fault detection capabilities, and reduces overall power losses. This study provides a comprehensive framework for improving the reliability and efficiency of distribution networks in the presence of DG, contributing to the development of smarter and more adaptive power systems.

1. INTRODUCTION

The primary function of the distribution system is to supply the energy needs of consumers [1-5]. Equipment failures, weather conditions, and the radial structure of the distribution network are some reasons for its low reliability [6]. Utilizing distributed generation sources in the distribution system, besides providing economic

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benefits, increases reliability. These sources are considered connected to the network during peak demand hours and supply the energy needs of a group of consumers in an islanded mode during faults [7].

Protective devices such as fuses, reclosers, and circuit breakers are installed in the distribution network to isolate the faulted section and prevent the spread of failures and increased outages for consumers. In reliability assessment of a distribution system, indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Momentary Average Interruption Frequency Index (MAIFI), and Average Energy Not Supplied (AENS) are commonly used. These indices have been introduced and studied in many related articles [8-9].

It is evident that the reliability of the distribution network is dependent on the configuration and connection of the various devices used within it. Numerous studies have been conducted on the optimal placement of protective and switching devices in the distribution network. For instance, in [10], considering the forced outage and maintenance costs, a model is proposed to find the optimal location for installing switches. Reference [11] optimally places switches by comparing the cost of unsupplied energy and the sectionalizing cost using a genetic algorithm. Other articles have addressed the optimization problem using algorithms such as binary linear programming [12], nonlinear programming [13], and tabu search [14]. Reference [15] offers a multi-objective function for the optimal placement of switching equipment, aiming to minimize the total operating cost and the SAIFI and SAIDI indices. The objective function in [16] includes the installation, maintenance costs, and CENS.

The proposed method in this article is capable of calculating the costs of interrupted loads and restoration energy. In [17], a new formula for the placement of switches and sectionalizers in the distribution system is presented, considering reliability and investment costs, with the solution method based on fuzzy logic. In [18], a novel method for the placement of reclosers and DG units is proposed by combining a genetic algorithm and hierarchical analysis. The objective function in [19] considers increasing reliability, reducing investment costs, and the amount of distributed energy, specifying the type and location of protective switches. Reference [20] proposes the optimal location for installing switches using a fuzzy hierarchical algorithm, with the distribution network of Mashhad city examined in this study.

As briefly reviewed, comprehensive studies on the simultaneous placement of DG sources and primary protective equipment have not been conducted. The aim of this research is to determine the optimal installation locations for DG sources and three primary protective devices in the distribution network, including overcurrent relays, reclosers, and fuses, to minimize system losses and four reliability indices: SAIDI, SAIFI, MAIFI, and AENS. The simulation of this study will be conducted on the 115-bus network of Tabriz. The results indicate the effectiveness of the proposed method in determining the installation locations of the mentioned equipment.

In a related study, Haddadnia et al. (2014) proposed a method for fault detection in induction motor ball bearings using pattern recognition techniques. They utilized artificial neural networks to classify faults based on time and frequency domain characteristics of vibration signals. This approach demonstrated high accuracy in detecting faults without the need for complex calculations [21].

2. FORMULATION OF THE PROBLEM

The primary goal of placing protective devices and distributed generation (DG) units is to improve reliability indices and reduce system losses. To this end, reliability indices that assess power quality and system performance are used. The smaller these indices, the higher the system reliability. The most important reliability indices in the distribution system are as follows:

1. System Average Interruption Duration Index (SAIDI): This index represents the total duration of interruptions for customers divided by the total number of customers and is defined by equation (1):

$$SAIDI = \frac{\sum_{j=1}^{n_j} \sum_{k=1}^{n_k} \lambda_j r_j P_k}{\sum_{l=1}^{n_l} P_l} \tag{1}$$

where:

- λ_j is the average failure rate of incident j,
- r_j is the average outage duration of incident j,
- P_k is the number of customers connected to the network,
- nj is the number of incidents leading to outages,
- nk is the number of islanded loads due to incident j.

2. System Average Interruption Frequency Index (SAIFI): This index indicates the average frequency of power interruptions in the system and is calculated using equation (2):

$$SAIFI = \frac{\sum_{i=1}^{n}\sum_{s=1}^{m}\lambda_{is}N_i}{\sum_{i=1}^{n}N_i} \tag{2}$$

Where λ_{is} is the failure rate of load center i due to section s and Ni is the total number of customers at load center i.

3. Momentary Average Interruption Frequency Index (MAIFI): This parameter measures the average number of momentary interruptions experienced by consumers within a specified time period and is calculated using equation (3):

$$MAIFI = \frac{\sum_{i=1}^{n}\gamma_i N_i}{\sum_{i=1}^{n}N_i} \tag{3}$$

where $\gamma_i$is the momentary failure rate of section i, Ni is the total number of customers at load center i.

4. Average Energy Not Supplied (AENS): This index measures the average total unsupplied energy to customers. Equation (4) is used to calculate this parameter:

$$AENS = \frac{\sum_{i=1}^{n}L_{a(i)}U_i}{\sum_{i=1}^{n}N_i} \tag{4}$$

Where La is the average load connected at location i ,Ui is the annual outage duration,

Ni is the total number of customers at load center i.

5. System Loss Index (PLoss): This index represents the losses in the distribution lines in kilowatt-hours. The equation used to obtain system losses is given by (5):

$$P_{Loss} = 0.33\ LF + 0.67\ LF^2 \tag{5}$$

where LF is obtained by dividing the average load by the maximum load [22].

To minimize the combined effect of these indices, a multi-objective function is used. This objective function includes the per-unit values of the four reliability indices and the system loss index, formulated as equation (6):

$$MOF = W_{SAIDI}\frac{SAIDI_k}{SAIDI_0} + W_{SAIFI}\frac{SAIFI_k}{SAIFI_0} + W_{MAIFI}\frac{MAIFI_k}{MAIFI_0} + W_{AENS}\frac{AENS_k}{AENS_0} + W_{P_{Loss}}\frac{P_{Loss\,k}}{P_{Loss\,0}} \tag{6}$$

In this equation, indices k and 0 refer to the values before and after placement, respectively. The weight coefficient Wi assigned to index i is chosen based on the importance and impact of that index on the objective function, ensuring:

$$\sum_{i=1}^{5} W_i = 1 \qquad W_i \epsilon [0 \;\; 1]$$

Table 1 shows the weight values assigned to each index in this paper.

Table 1. Weight values assigned to the objective function indices

Index	W_{SAIDI}	W_{SAIFI}	W_{MAIFI}	W_{AENS}	$W_{P_{Loss}}$
Value	0.3	0.2	0.1	0.2	0.2

3. PSO ALGORITHM

The PSO algorithm is recognized as a stochastic search method for function optimization. The main idea of this algorithm is based on a population called a swarm. Members of the swarm are called particles. Each particle in the swarm represents a potential solution to the problem and moves through the D-dimensional search space with a random velocity. This particle updates its velocity and position based on its own best position and the best position found by other particles. Each particle ultimately stores its best position within the entire swarm as the best overall position. The PSO algorithm execution can be summarized in the following steps:

1. Random Initialization of Particles in the D-dimensional Search Space:

To initialize a particle between two bounds, equation (7) is used:

$$Rand(0,1) \times (b_u - b_i) + b_i \tag{7}$$

where $Rand(0,1)$generates a random number between zero and one, $b_u$is the upper bound, and $b_i$is the lower bound. The population size does not change during the optimization process.

2. Evaluation of Fitness for the Entire Swarm:

After creating the population, the fitness value for each particle is calculated. Each particle has a fitness value called the best pbest, and after computing the fitness, the algorithm compares it with the global best gbest and updates if necessary.

3. Updating the Global Best Position:

The swarm optimizer tracks the overall optimal value. This value is the best fitness obtained from all current values and is denoted as gbest.

4. Updating the Velocity and Position Vectors of Each Particle:

Each particle updates its velocity and position according to equations (8) and (9):

$$v_{id}^{k+1} = wv_{id}^{k} + c_1 r_1 \left(pbest_i^k - x_{id}^k\right) - c_2 r_2 \left(gbest_i^k - x_{id}^k\right) \tag{8}$$

$$X_{id}^{k+1} = X_{id}^{k} + v_{id}^{k+1} \tag{9}$$

Where w is the inertia weight, c1 and c2 are acceleration constants, r1 and r2 are random numbers in the range [0, 1], $v_{id}^{k+1}$is the velocity of the particle in step k+1, $X_{id}^{k+1}$is the position of the particle in step k+1.

5. Repeating Steps 2 to 4 Until the Stopping Criterion is Met:

The algorithm continues until a specified stopping condition is reached, which can be a set number of iterations, maximum iterations after the last gbest update, reaching a predefined fitness value, etc. [23].

4. PROBLEM SOLVING USING THE PSO ALGORITHM

To determine the optimal installation locations for equipment, necessary data for program execution must be provided in the first step. This data includes information about the equipment (number of reclosers, fuses, overcurrent relays, and DG), network information (line specifications and active/reactive power of buses), and algorithm information (number of iterations, population size, mutation rate, etc.). In the next step, a matrix is formed with the values of customer load, fault occurrence time, and fault diagnosis time of protective zones, followed by executing the PSO algorithm. After executing the algorithm, system reliability parameters are reviewed, and vectors for transient and permanent repair and diagnosis states are formed. In the next step, the final power and costs are calculated, and the stopping criterion is checked, repeating the process if necessary.

5. SIMULATION RESULTS

To evaluate the proposed method for the optimal placement of protective devices and distributed generation, the 115-bus Tabriz network was selected. Multiple scenarios can be considered based on the number of devices placed, with two comprehensive examples included here:

- Scenario 1: Placement of Five or Fewer Devices
- Scenario 2: Placement of Six or More Devices

For each scenario, multiple cases are considered. Each case is characterized by four numbers, which represent the number of reclosers, overcurrent relays, fuses, and DGs (Distributed Generators), respectively.

5.1. Placement of Five or Fewer Devices

In the first scenario, the number of placed devices is five or fewer. The results from the placement of one, two, three, four, and five devices are presented in Table 2.

Table 2. Results of Equipment Placement Based on Scenario 1

Index Status	AENS	SAIDI	SAIFI	MAIFI	PLoss	MOF
0001	512805691	99.38	76.00	17.00	190.81	1.3197
0010	303585557	54.79	56.17	12.56	336.88	1.4840
0100	345352097	66.30	61.56	13.77	336.88	1.5495
1000	328988549	61.05	59.39	13.28	336.88	1.5220
0011	272633424	56.17	56.16	12.56	213.74	1.1055
0101	351077066	79.05	67.01	14.99	190.78	1.1692
1001	289012544	65.39	61.26	13.70	190.78	1.0890
0110	282274742	52.66	54.65	12.22	336.88	1.4641
1010	211959828	36.31	42.99	9.61	336.88	1.3495
1100	205411281	42.75	51.93	11.61	336.88	1.3985
0111	243068707	52.66	54.65	12.22	219.99	1.1006
1101	211306969	51.81	57.38	12.83	190.78	1.0102
1011	207527027	45.61	48.95	10.94	190.78	0.9795
1110	235360315	44.71	48.04	10.74	336.88	1.3991
1111	183802612	37.30	45.53	10.18	207.62	0.9669
1112	198517194	59.15	57.18	12.79	114.25	0.7929
1121	192646314	42.13	46.40	10.38	206.23	0.9808
1211	103723208	24.38	35.23	7.88	209.48	0.8671
2111	159078530	35.37	46.41	10.38	202.91	0.9419

Based on the results in this table, the worst possible outcome corresponds to the 0100 configuration, while the best result is achieved with the 1112 configuration. The optimal placement of protective devices and distributed generation, along with the optimal capacity of distributed generation in the 1112 configuration, is shown in Table 3.

Table 3. Location and Capacity of Placed Equipment in Scenario 1

Equipment / Status	Recloser	Overcurrent Relay	Fuse	Distributed Generation (Active-Reactive)
1112	86	105	10	105 (0.6-1.0)

5.2. Placement of Six or More Devices

In the second scenario, six or more devices are placed. The optimal values of reliability parameters, losses, and the objective function are listed in Table 4.

Table 4. Results of Equipment Placement Based on Scenario 2

Index / Status	AENS	SAIDI	SAIFI	MAIFI	PLoss	MOF
1122	246233830	52.23	54.64	12.22	192.23	1.0186
1212	135080588	33.38	40.96	9.16	186.83	0.9569
1221	155156024	41.77	46.02	10.29	204.40	0.9572
2112	100059986	39.50	53.80	12.03	169.33	0.9576
2121	162482324	39.94	53.16	11.89	208.63	0.9988
2211	108494824	28.50	43.54	9.74	212.17	0.9210
1222	144485251	34.27	41.71	9.33	195.30	0.8911
2122	108544285	33.10	40.20	8.99	170.23	0.7927
2212	79145842	26.64	37.81	8.45	141.94	0.6721
2221	109990980	20.08	29.21	6.53	253.56	0.9658
2222	114278874	24.28	33.55	7.50	277.13	1.0650

Examining the results in Table 4, the best response is achieved with the 2212 configuration, while the worst response is observed with the 2222 configuration. This indicates that although increasing the number of units was expected to improve the network response, the network response deteriorated due to saturation. In other words, the number of placed devices exceeded the needs of the load and the network. Therefore, the placement process is halted. The optimal locations for installing protective devices and distributed generation, as well as the optimal capacity of distributed generation corresponding to the 2212 configuration, are presented in Table 5.

Table 5. Location and Capacity of Placed Equipment in Scenario 2

Equipment / Status	Recloser	Overcurrent Relay	Fuse	Distributed Generation (Active-Reactive)
2212	22, 2	88, 105	10	114 (0.05-0.85)

6. CONCLUSION

In this paper, an algorithm was presented to determine the optimal placement of protective devices and distributed generation using the PSO algorithm. The objective function in this study aimed to minimize four reliability indices: System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Momentary Average Interruption Frequency Index (MAIFI), Average Energy Not Supplied (AENS), and network losses. The proposed algorithm was tested on the 115-bus distribution network of Tabriz. In two scenarios, the optimal locations for installing protective devices and distributed generation, as well as the capacity of distributed generation, were determined. The results of this study indicate that for the network under discussion, installing 2 reclosers, 2 overcurrent relays, 1 fuse, and 2 distributed generation sources leads to the best objective function response.

Transparency Statement

The data supporting this study are available upon reasonable request to the corresponding author, subject to ethical and confidentiality considerations.

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Declaration of Interest

The authors declare that they have no competing interests.

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