Received: 21 October 2018 | Revised: 1 February 2019 | Accepted: 12 March 2019
DOI: 10.1002/2050-7038.12025

RESEARCH ARTICLE

WILEY

A novel practical method for simultaneous placement of switching and protective devices considering load uncertainty

Amir Reza Yari[1] | Mahmoud Reza Shakarami[1] | Farhad Namdari[1] | Hassan Moradi CheshmehBeigi[2]

[1] Department of Electrical Engineering, Faculty of Engineering, Lorestan University, Khorramabad, Lorestan, Iran
[2] Electrical Engineering Department, Faculty of Engineering, Razi University, Kermanshah, Iran

Correspondence
Mahmoud Reza Shakarami, Department of Electrical Engineering, Faculty of Engineering, Lorestan University, Khorramabad, Lorestan 68151-44316, Iran.
Email: shakarami.mr@lu.ac.ir

Summary
A smart distribution system should be able to restore interrupted customers as quickly as possible after outages. By optimal allocation of switching and protective devices, it is possible to enhance the reliability and increase the restoration capacity of the loads after an outage. In this paper, by taking into account uncertainty in the load data, a novel practical method for the simultaneous planning of optimum location of switching devices including tie-lines and remote-control switches (RCSs), fault indicators, and cut-out fuses is proposed. In this paper, a method for minimization of the costs associated with equipment investment and interruption cost has been proposed. Practical parameters such as geographical position and conditions of the understudy network and feeders, and the configuration and possible constraints of the real network from the experts' viewpoint, have been considered in this study. The actual characteristics of the network are extracted by utilizing the analytical hierarchical process (AHP), the geographic information system (GIS) data, and the event recording software. To optimize the problem, the multi-objective nondominated sorting genetic algorithm II (NSGAII) is employed. The efficacy of the proposed method is proved through simulation of a real medium-voltage (MV) feeder.

KEYWORDS
AHP, multi-objective nondominated sorting genetic algorithm, protective devices, smart distribution network, switch placement

1 | INTRODUCTION

In recent years, because of electric industry restructuring and moving toward privatization, competitive conditions in the electricity market, and the necessity for providing reliable and high-quality energy to the customers, the reliability of distribution systems has gained more attention. The statistics show that approximately 70% of the power system interruptions are due to fault occurrence in distribution networks.[1,2] Power supply availability statistics indicate that the medium-voltage (MV) network has the most significant contribution to the system reliability. Most of the MV equipment faults lead to interruptions in supplying a large number of customers.[3] Consequently, the reliability of electrical distribution networks is one of the critical issues that have attracted the attention of many electricity distribution companies. Under such conditions, one of the serious requirements of the electric power industry is the establishment of an automation system for distribution networks. One of the remarkable advantages of distribution network automation is the limiting of energy not supplied (ENS) in the fault occurrence and the ability to restore the fault-free sections as quickly as possible. By appropriate exploitation of the remote-control switches (RCSs) and protective devices, it is possible to enhance the system reliability in addition to moving toward the establishment of smart grids.

Billinton and Jonnavithula,[4] Levitin et al,[5] Wang and Billinton,[6] and Celli and Pilo[7] are among the initial studies performed on optimal placement of switches and protective devices. Placement of switches by taking into account the investment costs, maintenance costs, and system failure is provided in Billinton and Jonnavithula,[4] and simulated annealing (SA) algorithm has been used to solve the problem. Determination of optimal placement of switches in radial distribution networks is presented in Levitin et al[5] by considering the potential of the alternative power supply sources to adjacent feeders using the genetic algorithm (GA). In Wang and Billinton,[6] the optimal placement of switches is recommended by using a direct search method. The switch placement in radial and ring MV networks is given in Celli and Pilo.[7] Also, in Luth,[8] four rules are suggested to help in locating the protective devices. The related articles in recent years can be categorized into several classes. Some studies separately examine the switch placement problem. In Esteban and Alberto,[9] a method for optimal placement of switches in distribution systems is provided using fuzzy dynamic programming (FDP). In Bernardon et al,[10] an analytical hierarchical method has been suggested to allocate RCSs based on a multi-objective function. The critical points of the electricity distribution network for installing and determining the appropriate and optimal number of remote terminal units (RTUs) based on fuzzy hierarchical method is presented in Razi Kazemi and Dehghanian.[11] Bezerra et al[12] described a multi-objective optimization algorithm for switch placement based on particle swarm optimization (PSO). Modifying the manual switches to RCSs is carried out to maximize the load restoration.[13] Moreover, a graph-based method has been proposed in Mao and Miu[14] for switch placement planning to maintain the electrical supply continuity in fault-isolated areas in the presence of distributed generations (DGs) in a radial distribution system. In Aman et al,[15] a method for simultaneous optimal placement of tie-switches and DGs based on the maximization of system loadability has been presented by discrete artificial bee colony algorithm. Determination of the optimal number and locations of both manual and automatic switches according to the probabilities of all feasible control sequences is given in Shahsavari et al,[16] and an algorithm based on artificial native colony has been used to solve the optimization problem. The second category includes the literature that has separately investigated the protective device placement.[7,17-21] In Celli and Pilo,[7] an innovative method to find the optimal number and place of switches in distribution networks is presented using the Bellman equation optimal control. The feeder-switch relocation for preventing customer interruptions is presented in Teng and Lu[17] to increase reliability and minimization of the costs. A method to determine the type and place of protective devices in a distribution feeder based on the objective of system average interruption frequency index (SAIFI) is presented in Da Silva et al,[18] using the GA. In Pregelj et al,[19] a method to the optimal placement of the recloser and DG allocation to improve the reliability of distribution networks has been proposed. A linear method to find the optimum numbers and locations of fault indicators (FIs) in distribution systems using mixed-integer linear programming is presented in Derakhshandeh and Nikbakht.[21] A number of studies have also addressed placement of switching and protective devices simultaneously.[22-27] Optimization techniques including linear numeric programming[22] and reactive tabu search (RTS) algorithm[23] are suggested to determine the number and location of switches and protective devices considering the outage and maintenance costs, and investments. Simultaneous determination of the optimal number and location of switches and circuit breakers in radial distribution systems has been proposed in Moradi and Fotuhi-Firuzabad.[24] A method for the switch and recloser placement in distribution systems considering uncertainties in loads, failure rates, and repair rates is presented in Alam et al[25] by differential evolution (DE) and mixed-integer nonlinear programming algorithm. In Heydari et al,[27] a method for optimal allocation of automated and manual switches as well as protective devices based on emergency demand response programs (EDRPs) in the presence of load flexibility is presented

In the preceding studies, the minimization of costs associated with the devices and the damages caused by the ENS has been considered as the main objective in the placement problem of switching and protective devices, while the interruption in the network in addition to economic costs can have other dimensions, including social and political considerations for power companies. Nevertheless, electricity distribution companies tend to benefit from the available data such as experiences, characteristics of customers, and some economic and political considerations as a basis to determine the number and place of the mentioned devices. Consequently, implementation of the obtained results from different methods for solving this problem by the managers and operators of electric utilities has encountered serious challenges, and only a part of them have been realized practically. In fact, in most of the distribution networks, the different candidate places for installing switching devices may have different priorities. Topological and structural constraints, the limitations of candidate places, environmental conditions, and geographical situation may have an effect on the priority of a candidate placement. In the previous studies, these priorities have not simultaneously been taken into account in objective functions. Furthermore, in most of the above studies, static loading conditions are taken into account. Yet switching and protective devices are expected to operate during considerable time duration under conditions that the system loading varies from time to time. Hence, uncertainty under system loading conditions should be considered.

This paper makes an effort to solve the available shortcomings such as practical and realistic points relating to the placement problem. These include accessibility limitations, the different importance of customers, failure history, and network topology. An efficient and profitable approach is proposed, in this paper, to address the problem, considering the technical and economic requirements and merging the knowledge of distribution systems experts, simultaneously. In this paper, in order to consider the concerns of power utilities, in the first step, the weight of each candidate location is determined according to expert's knowledge (based on the analytical hierarchical process [AHP]) and the use of existing data in recording event software (ENOX), and geographic information system (GIS). Finally, using these results and taking into account the technical and economic considerations, the problem of simultaneous locating of switching and protective equipment is modeled. Additionally, to take account of uncertainty and provide more accurate load model, the fuzzy triangular method is utilized, and the effects of uncertainty on the objective function are evaluated. To solve this problem, the nondominated sorting GA II (NSGAII) has been used. With the use of this algorithm, instead of one unique optimal solution, a set of solutions (efficient solutions) are evaluated. The proposed method has been implemented on a real feeder in Great Tehran Electricity Distribution Company (GTEDC), Tehran, Iran.

2 | LOAD MODELING AND PROBLEM FORMULATION

2.1 | Fuzzy model of load points

Because of the large number of load points in distribution networks, installation of measuring equipment at all points of the load is not economical. Therefore, the load is usually determined by load estimation methods. But these methods are always associated with uncertainty.[28] Probability theory is one of the traditional methods for modeling uncertainty. Despite this, because of the lack of historical information, most of the uncertainties cannot be effectively modeled by this theory. In recent years, fuzzy set theory has been employed in mathematical modeling of uncertainties. The outstanding feature of the fuzzy theory, compared with probabilistic methods, is the facility of calculations, and this feature has helped the practical use of this theory to be attractive. In this study, the uncertainty of the distribution network load is modeled using fuzzy numbers. The consumption power of each load point is described as a triangular fuzzy number, as shown in Figure 1. Each triangular fuzzy number has three parameters (P_L, P_M, and P_R). It shows that the expected amount of load is around P_M. But it will not be less than P_L and greater than P_R.

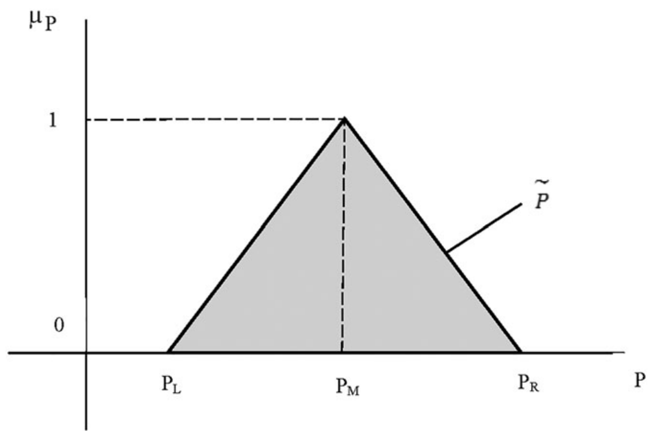

FIGURE 1 Graphical representation of a load as a fuzzy number

Assuming that the estimated power in a load point is equal to P_0 with maximum error e, the fuzzy number parameters corresponding to the load point can be achieved through the following equations.

$$P_{\mathrm{L}} = P_0 \times (1 - e). \tag{1}$$

$$P_{\mathrm{M}} = P_0. \tag{2}$$

$$P_{\mathrm{R}} = P_0 \times (1 + e). \tag{3}$$

Therefore, the triangular membership function of the load amount can be mathematically defined, as follows:

$$\mu_{\mathrm{P}} = \left\{ \begin{array}{ll} 0 & P \leq P_{\mathrm{L}} \ \text{or} \ P \geq P_{\mathrm{R}} \\ \dfrac{P - P_{\mathrm{L}}}{P_{\mathrm{M}} - P_{\mathrm{L}}} & P_{\mathrm{L}} < P < P_{\mathrm{M}} \\ \dfrac{P_{\mathrm{R}} - P}{P_{\mathrm{R}} - P_{\mathrm{M}}} & P_{\mathrm{M}} < P < P_{\mathrm{R}} \end{array} \right\}. \tag{4}$$

According to the high reliability of triangular fuzzy numbers in describing uncertain loads, this method has been utilized in solving most of the problems related to distribution systems.[29-32]

2.2 | Fuzzy power flow in distribution systems

A part of calculations for placement of switching and protective devices is related to network power flow. In distribution networks, it is not feasible to easily use conventional methods of power flow such as the Newton-Raphson because of radial structure and the values of resistance and reactance of lines.[33] As a result, innovative methods are normally used for solving power flow equations. In this paper, a recursive power flow method has been used.[34] Regarding that in this study the load data in consumption points are in the form of triangular fuzzy numbers, the variables during the calculation process are in the form of fuzzy numbers with real or imaginary parameters, and mathematical operators in the form of fuzzy are implemented on them.[35] All fuzzy variables in mathematical equations are specified with a ~ sign.

2.3 | Problem formulation

In this research, the optimal placement problem of switching and protective devices including FI, cut-out fuse, tie-lines, and the RCSs in distribution networks is solved with the objective of minimizing the sum of costs related to the expected ENS (EENS), costs of installation and maintenance, and operation costs of equipment while considering practical parameters of the network. It should be noted that the installation costs are in the form of capital investment, while the cost of EENS (CEENS) and maintenance costs are in the form of current expenses. Therefore, to merge these two costs in the form of a single unique cost function, using engineering economic, parameters of all costs should be transformed into a single form (present value). The objective function of the problem will be as follows:

$$f_{\mathrm{Total}} = \mathrm{Min}\left\{ F_{\mathrm{c}}, \widetilde{F}_{\mathrm{CEENS}} \right\}. \tag{5}$$

The cost function of installation and maintenance of equipment is assumed as Equation (6).

$$F_{\mathrm{c}} = \mathrm{Min}\left\{ IC_{\mathrm{s}} + IC_{\mathrm{cf}} + IC_{\mathrm{fi}} + IC_{\mathrm{tie}} + \left(\sum_{i=1}^{N_{\mathrm{s}}} DS_i + \sum_{i=1}^{N_{\mathrm{tie}}} DT_i \right) \times AC + OC_{\mathrm{eq}} \right\}. \tag{6}$$

$$IC_{\mathrm{s}} = \sum_{i=1}^{N_{\mathrm{s}}} \alpha(i) \cdot C_{\mathrm{s}}. \tag{7}$$

$$IC_{\mathrm{cf}} = \sum_{i=1}^{N_{\mathrm{cf}}} \beta(i) \cdot C_{\mathrm{cf}}. \tag{8}$$

$$IC_{\text{fi}} = \sum_{i=1}^{N_{\text{f}}} \gamma(i) \cdot C_{\text{fi}}. \tag{9}$$

$$IC_{\text{tie}} = \sum_{i=1}^{N_{\text{tie}}} \delta(i) \cdot C_{\text{tie}}(i). \tag{10}$$

$$OC_{\text{eq}} = \sum_{t=1}^{ny} \left(f_{\text{pw}}\right)^{t} \times \{0.05 \times (IC_{\text{s}} + IC_{\text{cf}} + IC_{\text{fi}} + IC_{\text{m}})\}. \tag{11}$$

$$f_{\text{PW}} = \frac{1 + In_{\text{fr}}}{1 + In_{\text{tr}}}. \tag{12}$$

OC_{eq} shows the maintenance and operation cost of equipment, and its value is assumed to be 5% of equipment installation cost. Its current value is calculated based on Equation (11).

The major point in the placement of cut-out fuses is related to the loading current limit of lines that cut-out fuses are placed. Under such conditions, the current of the lines should be less than the rated current of the cut-out fuse. This is considered a constraint as shown in Equation (13).

$$i_{\text{line}} \leq i_{\text{cf}}. \tag{13}$$

According to the system structure, load model, and damages caused by outages for all load models, the annual cost of energy supply for customers in an MV feeder can be obtained through Equation (14). This equation comprises two terms; the first term is related to that part of the EENS, which includes the time interval between the fault occurrence and fault detection. In this duration, the loads are interrupted. The second term of equation is corresponding to that part of the EENS that contains the time duration between the fault occurrence and system repairing.

Here, weighting factors are used to consider real-time conditions and network constraints, where their values are determined on the basis of the system experts' knowledge using the AHP method (Section 3).

$$\widetilde{F}_{\text{CEENS}} = \sum_{i=1}^{N_{\text{s}}} \lambda_i L_i \left(\sum_{j=1}^{N_{\text{sw}}} P_j T_{\text{sw}}(i) \text{W}_j CE_j + \sum_{j=1}^{N_{\text{rp}}} P_j T_{\text{rp}}(i) W_j CE_j \right). \tag{14}$$

In this equation, CE_j depends on the load model at the consumption points and is obtained from Equation (15).

$$CE_j = \sum_{i \in SP} P_i^j IC_i. \tag{15}$$

3 | DETERMINING THE WEIGHTING FACTOR OF CANDIDATE PLACE USING THE AHP

The designed AHP model is a multi-criteria decision-making method that is extensively employed for complex decision-making processes.[36] The AHP method makes the process of thinking hierarchical and is, therefore, an effective method that can perform weight analysis with a combination of qualitative and quantitative aspects. This method is used by a multi-criteria decision-making network to rank or determine the importance factor of the various options of a complex decision-making process. The AHP is generally composed of four basic steps, as follows:

Step 1:. Setting the hierarchy of decision making, obtaining the main defined criteria, and breaking the problem into a hierarchy of elements.

Step 2:. Paired qualitative comparison of decision-making criteria, the formation of weight tables for defined criteria, identification, and application of all decision makers, experts, and specialists in this work; comparison of elements by experts through chain variables.

Step 3:. Estimating the weight of decision-making criteria, estimating the relative weight of decision-making elements using matrix-based methods, collecting information and judgments of experts, and analyzing the compatibility of the comparisons.

Step 4:. Quantitative comparisons of options and their ranking, utilization of historical and statistical data, and the ranking of options in accordance with the criteria.

3.1 | Steps for the proposed pattern of the AHP

In this section, determining the criteria and weight of candidate locations for placing switches in the distribution network is carried out.

3.1.1 | Criteria determination

In the first step, to assess the objective and determine the essential criteria, and the hierarchical of the problem, based on the knowledge of experts in the GTEDC, some criteria have been determined according to Table 1.

3.1.2 | Hierarchical modeling and weighting

Hierarchical modeling and the relationship between factors, from different levels, for weighting to candidate points are shown in Figure 2.

This figure shows that the objective is to determine the final weight of the candidate place at the highest level, and the criteria are at the middle level, so they will have the same effect on the objective. In the next step, a judgment matrix

TABLE 1 Criteria determination for setting the weights of each candidate place

Criteria	Title
CRI.1	Access restriction
CRI.2	Grid topology and maneuverability
CRI.3	Fault rate in previous
CRI.4	Load capacity
CRI.5	Number of customer
CRI.6	Priority of customers

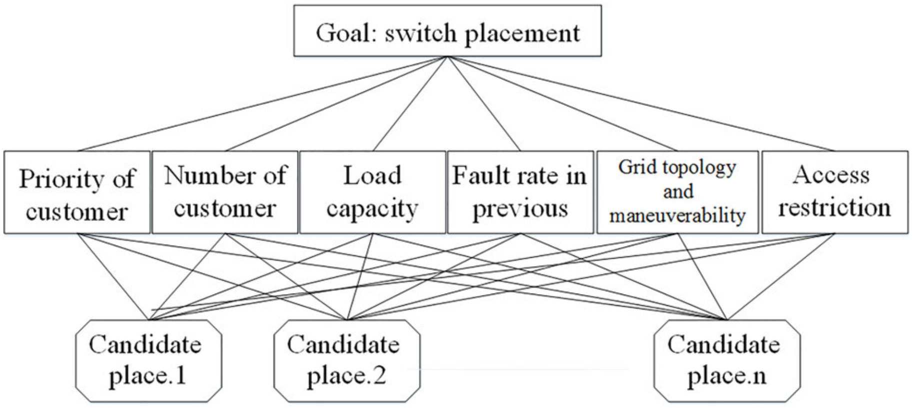

FIGURE 2 The hierarchical structure of the problem for determining the weight of the candidate places

should be formed where the value of the elements in the matrix represents the user's knowledge of the relative importance of each pair of elements. A pairwise comparison is made between the criteria and the elements at a given time. The values of the main criteria are listed in Table 2.

The A_{ij} values in Table 2 are numbers that are determined by the relevant expert, and the final weight of the criteria is shown by A_i. The AHP uses the marking methods 1 to 9 to select these numbers and form the judgment matrix, which contains nine fuzzy linguistic variables. Scales 1 to 9 are given in Table 3.

3.1.3 | Analysis of quantitative and qualitative criteria

To achieve higher precision, the proposed six criteria are divided into quantitative and qualitative categories. The required data and statistical information are extracted from the ENOX and GIS. Examining the number and priority of customer criteria suggests that these two criteria are correlated from the point of view of effectiveness on the considered objective, and it is more appropriate that these two criteria be merged together. The number of customers in each type has a quantitative nature, and their priority has a qualitative characteristic. Therefore, the first step is to compare the quality of various loads according to Table 4.

After the total weight of each load according to this table is determined , the total number of customers to determine the weight of this criterion is considered in accordance with Equation (16).

$$W_{i,1\&2} = R_i r_1 + C_i r_2 + I_i r_3 + S_i r_4. \tag{16}$$

TABLE 2 A pairwise comparison of criteria by each of experts

	CRI.1	CRI.2	:	CRI.6	Final Weight
CRI.1	1	A_{12}		A_{16}	$\boldsymbol{A_1}$
CRI.2	A_{21}	1		A_{26}	$\boldsymbol{A_2}$
:			1		:
CRI.6	A_{61}	A_{62}	:	1	$\boldsymbol{A_6}$

TABLE 3 The analytical hierarchical process scale method for assessment of the judgment matrix

The Relative Importance of the Criteria	1-9 Scale
Equally important	1
Moderately important with one over another	3
Strongly important	5
Very strongly important	7
Extremely important	9
Intermediate values	2, 4, 6, 8

TABLE 4 Pairwise comparison of various loads

Criteria	Residential	Commercial	Industrial	Special	Final Weight
Residential	1	$r_{1,2}$	$r_{1,3}$	$r_{1,4}$	r_1
Commercial	$r_{2,1}$	1	$r_{2,3}$	$r_{2,4}$	r_2
Industrial	$r_{3,1}$	$r_{3,2}$	1	$r_{3,4}$	r_3
Special	$r_{4,1}$	$r_{4,2}$	$r_{4,3}$	1	r_4

Load capacity criterion is assumed as the normalized size of the transformers at each candidate place. The weight of ith candidate place for this criterion ($W_{i,3}$) is obtained from Equation (17).

$$W_{i,3} = \frac{s_i}{\sum_{j=1}^{n} s_j}. \tag{17}$$

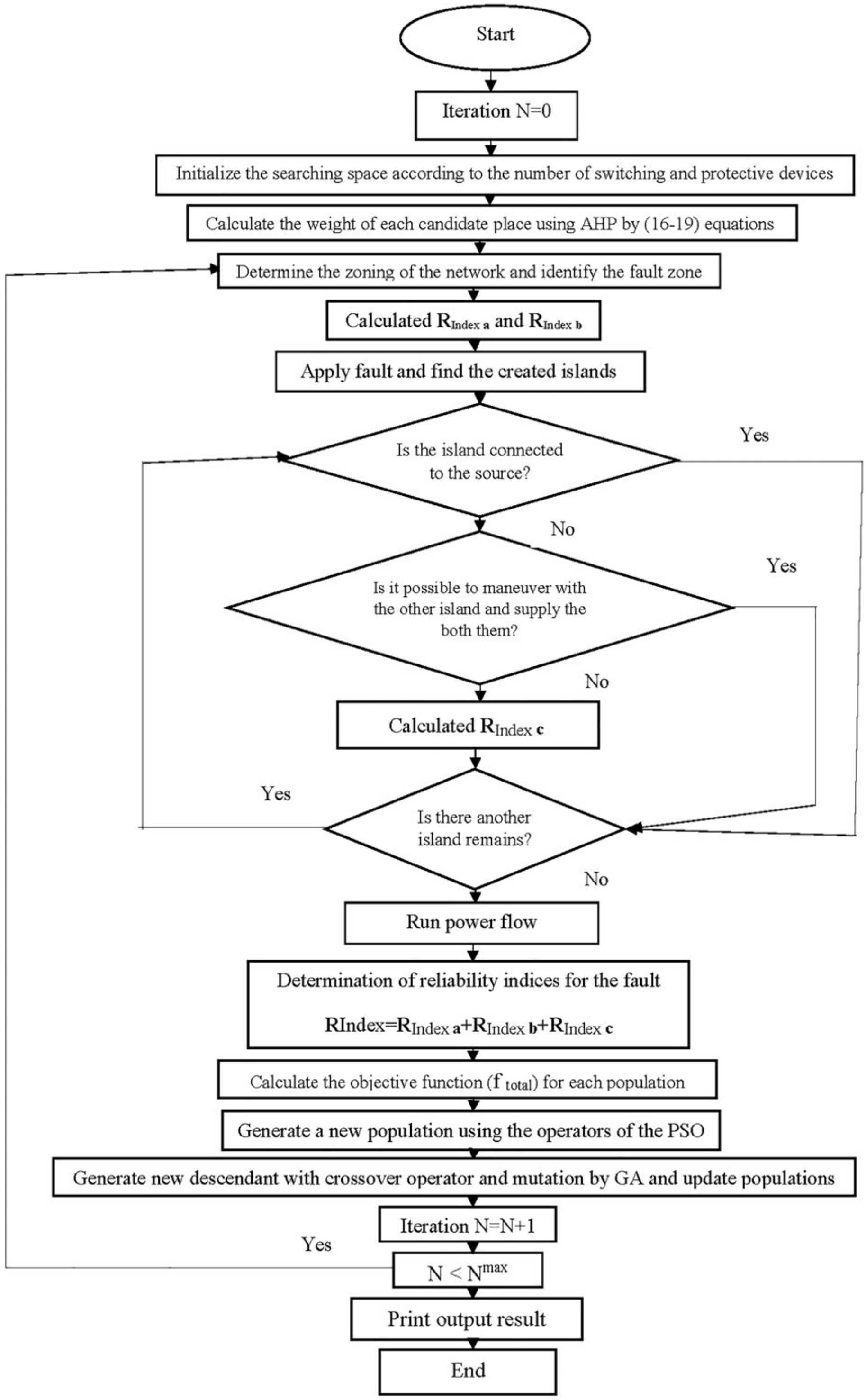

FIGURE 3 Flowchart of the proposed method. AHP, analytical hierarchical process; GA, genetic algorithm; PSO, particle swarm optimization

In the above equation, s_i is the capacity of available transformers at the ith candidate place and n is the number of transformers in the network. Fault rate in previous is taken into account proportional to the number of permanent or transient interruption. The weight of the ith candidate number for this criterion ($W_{i,4}$) is defined according to Equation (18).

$$W_{i,4} = c_1 \times SPFF + c_2 \times STFF. \tag{18}$$

where C_1 and C_2 are the coefficients that show the effects of permanent and transient faults on the network, respectively, and their values are considered as 0.8 and 0.2, respectively. *SPFF* and *STFF* are numbers of permanent and transient faults relevant to each candidate place during the study period. Grid topology and maneuverability criterion is assessed on the basis of the following possible situations of the candidate place:

1. candidate place in the main path of the feeder,
2. candidate place in the branching path,
3. candidate place with the possible maneuvers in the same feeder or having more than one output, and
4. candidate place with the possible maneuvers in adjacent feeders.

The access restriction criterion is evaluated according to three easy, hard, and very hard access modes to the candidate place. For these two criteria, a process similar to that in Table 2 is performed for each candidate place, and the results are extracted. Finally, the final weight of each candidate place will be obtained using Equation (19).

$$W_i = \sum_{i=1}^{n} r_{ij} \times c_j \quad i = 1, 2, \ldots, n. \tag{19}$$

4 | MULTI-OBJECTIVE NONDOMINANT SORTING GENETIC ALGORITHM II

In an optimization problem with multiple criteria, the objectives of the design must be optimized simultaneously. In such cases, the objectives are usually such that no one can improve one of them without further degrading the others.

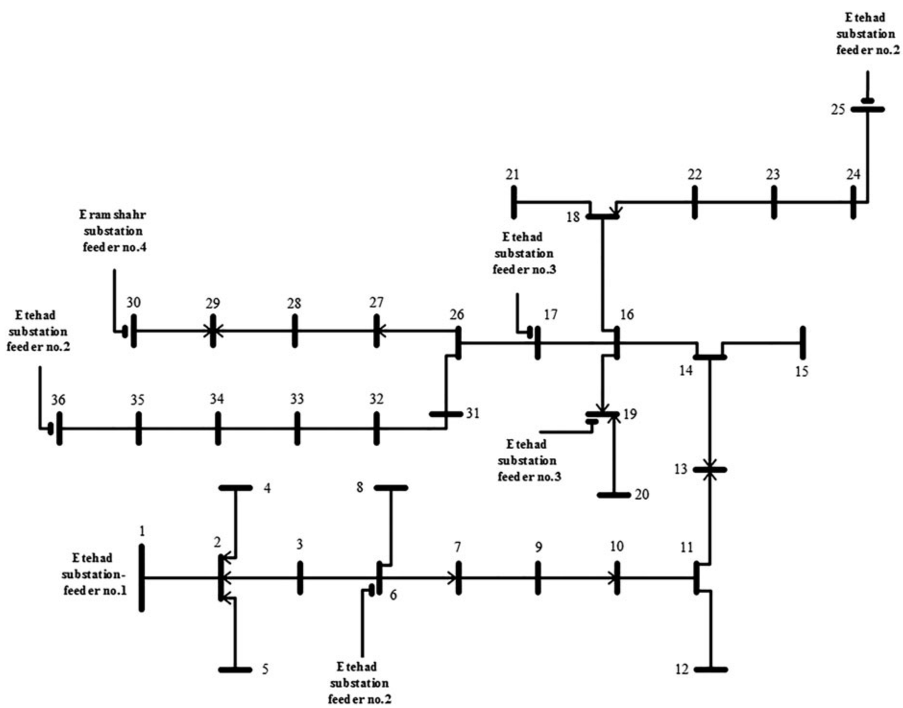

FIGURE 4 The distribution network of feeder 1 of Ettehad sub-transmission substation in the Great Tehran Electricity Distribution Company

Therefore, instead of a single optimal solution, a set of solutions is obtained for the problem. This set is referred to as efficient solutions. Considering the relative importance of the objectives of the optimization problem, the efficient solutions of the problem can have different superiority based on the viewpoints of managers and operators.

GA is one of the powerful evolutionary optimization methods that have been used in many single-objective optimization problems. The GA method is capable of solving linear or nonlinear continuous or discrete problems, or even a combination of them.[37] Since this algorithm searches for space from a few points in parallel, it can be suitably used

TABLE 5 Line data of the studied feeder

Line Number	From Bus	To Bus	Line Length, m	Resistance, Ω	Reactance, Ω	Line Type
1	1	2	350	0.1400	0.0700	Underground
2	2	3	300	0.1200	0.0600	Overhead
3	2	4	80	0.0320	0.0160	Overhead
4	2	5	10	0.0040	0.0020	Overhead
5	3	6	110	0.0440	0.0220	Overhead
6	6	7	180	0.0720	0.0360	Underground
7	6	8	20	0.0080	0.0040	Overhead
8	7	9	220	0.0880	0.0440	Underground
9	9	10	197	0.0788	0.0394	Underground
10	10	11	170	0.0680	0.0340	Overhead
11	11	12	110	0.0440	0.0220	Overhead
12	11	13	65	0.0260	0.0130	Overhead
13	13	14	100	0.0400	0.0200	Overhead
14	14	15	60	0.0240	0.0120	Overhead
15	14	16	50	0.0200	0.0100	Overhead
16	16	17	160	0.0640	0.0320	Overhead
17	16	18	70	0.0280	0.0140	Overhead
18	16	19	230	0.0920	0.0460	Overhead
19	19	20	450	0.0120	0.0060	Overhead
20	18	21	56	0.0224	0.0112	Overhead
21	18	22	235	0.0940	0.0470	Underground
22	22	23	30	0.0120	0.0060	Underground
23	23	24	90	0.0360	0.0180	Underground
24	24	25	110	0.0440	0.0220	Underground
25	17	26	50	0.0200	0.0100	Overhead
26	26	27	200	0.0800	0.0400	Overhead
27	27	28	80	0.0320	0.0160	Underground
28	28	29	350	0.1400	0.0700	Underground
29	29	30	295	0.1180	0.0590	Underground
30	26	31	389	0.1556	0.0778	Underground
31	31	32	135	0.0540	0.0270	Underground
32	32	33	90	0.0360	0.0180	Underground
33	33	34	110	0.0440	0.0220	Underground
34	34	35	100	0.0400	0.0200	Underground
35	35	36	520	0.2080	0.1040	Underground

to find a subset of efficient solutions. The NSGAII is a modified version of a GA designed to solve multiple optimization problems.[38] The flowchart of problem setup and solution algorithm for the proposed method is shown in Figure 3.

5 | NUMERICAL RESULTS AND DISCUSSION

Calculation of reliability indices has been performed using failure mode and effects analysis (FMEA).

TABLE 6 Load points data of the studied feeder and their fuzzy values

Load Point	Load Type	Used Load, kW		
		The Least Possible Value	Value with the Highest Probability	The Highest Possible Value
2	Industrial	441	617.4	787.5
3	—	0	0	0
4	Industrial	140	196	250
5	Industrial	70	98	125
6	—	0	0	0
7	Residential	560	784	1000
8	Commercial	140	196	250
9	Residential	441	617.4	787.5
10	Residential	441	617.4	787.5
11	—	0	0	0
12	Residential	280	392	500
13	Residential	560	784	1000
14	—	0	0	0
15	Residential	350	490	625
16	—	0	0	0
17	Residential	280	392	500
18	—	0	0	0
19	Commercial	224	313.6	400
20	Residential	350	490	625
21	Industrial	220.5	308.7	393.75
22	Industrial	700	980	1250
23	Industrial	220.5	308.7	393.75
24	Industrial	441	617.4	787.5
25	Residential	350	490	625
26	—	0	0	0
27	Residential	560	784	1000
28	Residential	441	617.4	787.5
29	Residential	350	490	625
30	Industrial	560	784	1000
31	Industrial	560	784	1000
32	Industrial	875	1225	1562.5
33	Industrial	560	784	1000
34	Industrial	350	490	625
35	Industrial	441	617.4	787.5

5.1 | A case study on a real feeder

In this section, the presented method has been implemented on the 20-kV feeder number 1 of Ettehad sub-transmission substation in the GTEDC. As shown in the single-line diagram of Figure 4, this feeder consists of 36 buses and 70 candidate places for installing switches and FIs. The specifications of the conductors of the lines and sections of this network are listed in Table 5. Table 6 also shows network load information as triangular fuzzy numbers. In order to make the studies more precise, the failure rates of the lines have been extracted on the basis of the information in the GIS and the ENOX at both underground and overhead levels. Accordingly, the overhead and underground failure rates are considered as 2.56 and 0.69 per kilometer (f/y), respectively. In this study, the performance of the distribution network equipment is considered to be in the useful life period. Therefore, the failure rates are assumed to be constant.[39] Because of the operation limitations of the MV feeders, their maximum permitted loading capacity is assumed to be 7 MW. Therefore, the tie-lines and their loading capacity, on the basis of the reserve capacity of adjacent feeders, are presented in Table 7. The value of lost load (VOLL) for residential, commercial, and industrial customers is provided on the basis of Bae et al.[40] The economic data are presented in Table 8.

To implement the proposed method, the following five scenarios are studied:

Scenario 1:. In this case, the system is in the base mode and different parts of the objective function are calculated without adding any other equipment. Under such conditions, the overall cost related to the ENS is due to the outage and system faults.

Scenario 2:. In this scenario, it is assumed that the FI and cut-out fuse can be installed in the system, and the optimization problem is solved and compared with the results of Scenario 1.

Scenario 3:. In this mode, it is possible to manually install switch and tie-lines in the system. Also, the optimization problem is solved and compared with the results of previous scenarios.

Scenario 4:. In this case, the system is studied with the possibility of simultaneous installation of the FI, the cut-out fuse, switch, and tie-lines in a manual manner. Then, after solving the optimization problem, the results are compared with those of the previous scenarios.

TABLE 7 Data of the tie-lines of the studied feeder

Candidate Place	Bus Number	Capacity, kW
1	6	3500
2	17	3000
3	19	3000
4	25	3500
5	30	4000
6	36	3500

TABLE 8 The required economic information for the studied network

Parameter	Amount
Cost of switch installation, $	2143
Cost of automated switch installation, $	5476
Cost of fault indicator installation, $	1430
Cost of cut-out fuse installation, $	230
T_{sw}, manual, h	1
T_{sw}, automatic, h	0.1
Repair time, h	5
Planning time, y	15
Annual inflation rate	0.16
Annual interest rate	0.20

Scenario 5:. In this case, the system is investigated with the possibility of simultaneous installation of the FI, the cut-out fuse, RCSs, and constructing tie-lines with automation and remote-control capability. After the optimization problem is solved, the obtained results are compared with those of the previous scenarios.

5.2 | Result analysis of real feeder

The FMEA analytical method is used to calculate reliability indices. Simulations have been implemented on a 2.270-GHz Core i5 computer with 2 GB of RAM by MATLAB. By performing multiple experiments, the parameters of the algorithm in this numerical study are set, as follows.

- Number of population = 100
- Number of generation = 50
- The probability of crossover operator = 0.9
- The probability of mutation operator = 0.125

The final weight of the criteria for determining the weight of the tie-lines for installing equipment is obtained by experts and based on the AHP, which are given in Table 9.

The results of implementing the proposed method on the studied network are listed in Figure 5 and Table 10 in accordance with the five proposed scenarios. As expected, the highest amount of the EENS is in the first scenario. In

TABLE 9 The final weight of the proposed criteria in the studied feeder by using the analytical hierarchical process

Criteria	Priority of Costumers	Number of Costumers	Load Capacity	Grid Topology and Maneuverability	Access Restriction	Fault Rates in Previous
Final weight	1.6248	1.4306	1.0800	1.7627	1.6904	1.6790
Normalized final weight	0.1753	0.1544	0.1165	0.1902	0.1824	0.1812

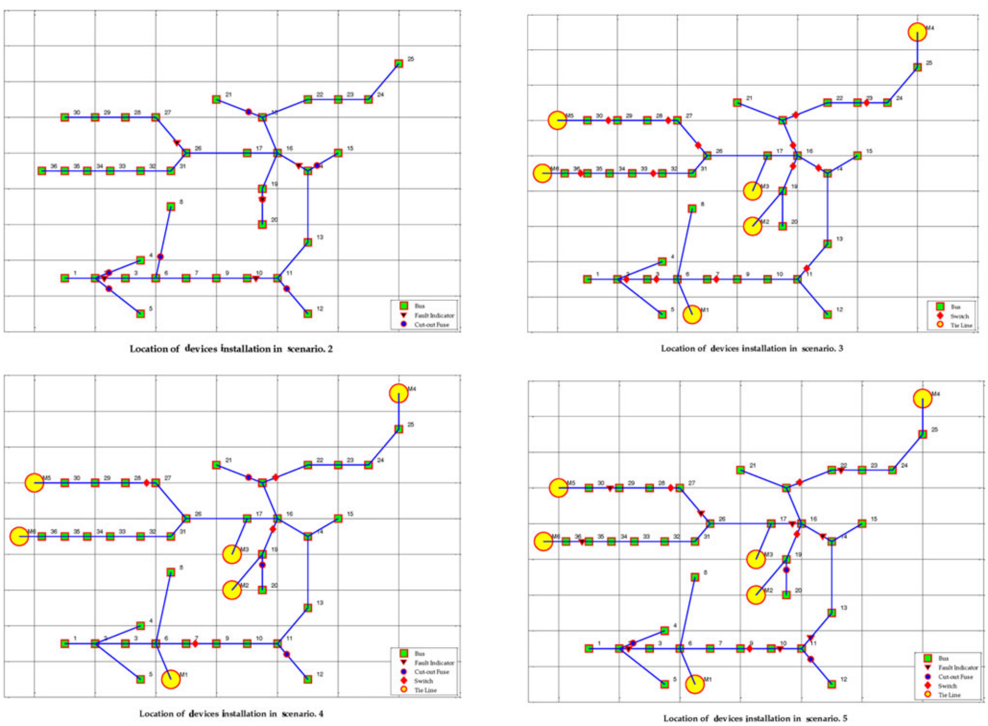

FIGURE 5 Location of the device installation

TABLE 10 Simulation results of the proposed method on a real feeder according to the considered scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Number of fault indicator	—	5	—	5	5
Number of cut-out fuse	—	7	—	3	10
Number of switches	—	—	4	4	2
Number of tie-lines	—	—	6	6	6
Cost of devices installation, $	—	12220	18 245	22 984	66 650
Cost of devices maintenance and operation, $	—	611	968	2083	5049
DE fuzzy value of EENS, kWh	919 372.6	395 218.9	285 314	149 134	132 649
DE fuzzy value of CEENS, $	1 244 071	468 816	342 569	235 703	120 813.9
SAIFI	0.2267	0.2136	0.1963	0.1457	0.1156
SAIDI	2.1659	1.5185	1.3917	1.2060	1.007

Abbreviations: CEENS, cost of expected energy not supplied; DE, differential evolution; EENS, expected energy not supplied; SAIDI, system average interruption duration index; SAIFI, system average interruption frequency index.

spite of no allocation of costs for the installation of protective and switching devices in this case, the objective function has the highest (the worst) possible value.

The use of the FI reduces the time for determining of the fault location. Also, it accelerates the faulty zone isolation and recovery of the system. On the other hand, the cut-out fuse also prevents outage of the whole network by restricting the fault to a single zone. The results of using these two devices in the second scenario, compared with the first scenario,

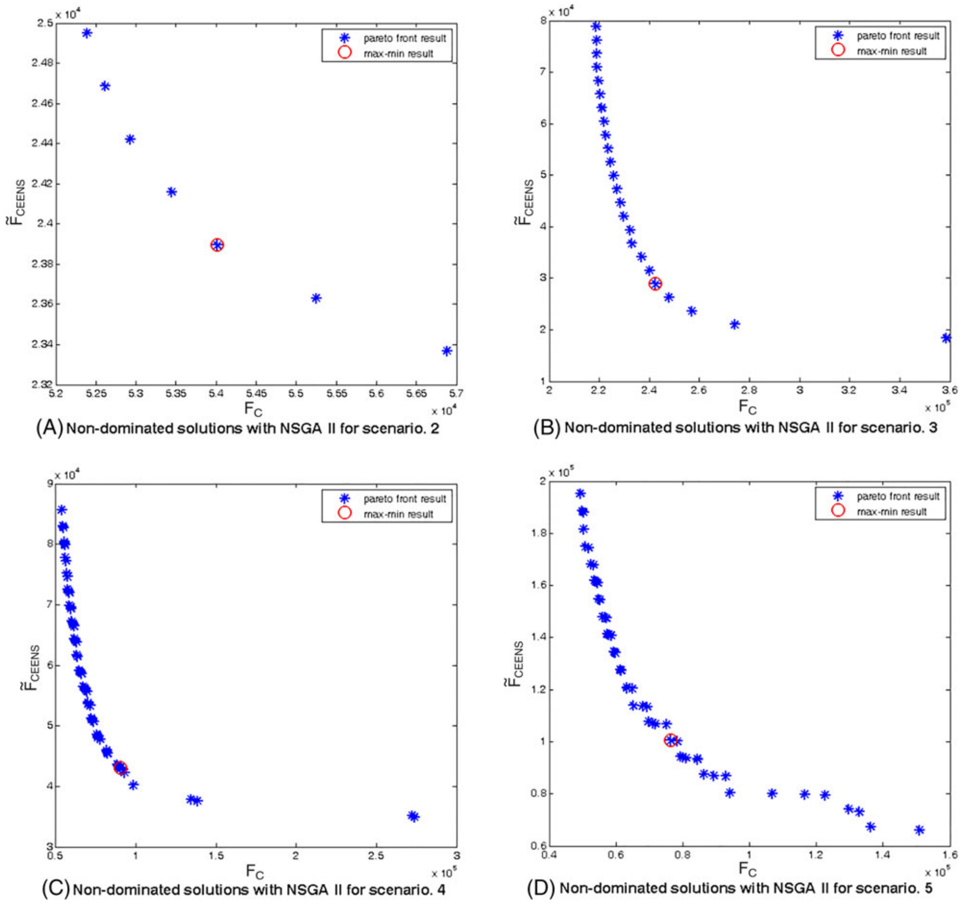

FIGURE 6 Nondominated solutions with NSGAII for various scenarios. NSGAII, nondominated sorting genetic algo1rithm

show that by installing five FIs and seven cut-out fuses, the EENS and the CEENS have dropped by 57% and 62%, respectively.

In the third scenario, the purpose of using switches and tie-lines is to increase the possibility of maneuvering the network in case of fault occurrence and accelerating load restoration. The results of the implementation of this scenario, compared with the first scenario, indicate that by installing four manual switches and six tie-lines, the EENS has reduced more than 68%. In this case, despite the cost of equipment, the total cost of the system has also reduced than in compared the previous one. In this case, in spite of the increase in installation and maintenance costs of the equipment, the amount of the EENS and the CEENS has decreased by about 28% and 27%, respectively, in comparison with that in the second scenario.

Solving the optimization problem in the fourth scenario, compared with the previous scenarios, shows that by installing four manual switches, six tie-lines, and five FIs and the three cut-out fuses, the EENS, the SAIFI, and the system average interruption duration index (SAIDI) have the lowest (the best) value. In this case, the CEENS has decreased 48% and 31% with respect to scenarios 2 and 3, respectively.

The application of the proposed method in the fifth scenario, in comparison with previous scenarios, clearly proves that despite the allocation of the highest cost of equipment, the highest improvement in the reliability indexes has been realized in this case. A remarkable point in the results is that the proposed location for the switching devices has the highest weight gain from the AHP method.

The space of the resultant efficient answers is exhibited in Figure 6. From the obtained efficient answers, one answer is chosen as the result, which can be calculated using the max-min operator.

TABLE 11 Result of comparison between the fifth scenario of the proposed method and the test case A-3-3 of Falaghi et al[41] on the modified distribution feeder connected to bus 4 of the Roy Billinton Test System

	Proposed Sections for Switch Installation	Proposed Sections for Fault Indicator Installation	Proposed Sections for Cut-out Fuse Installation	The EENS, kWh
Result of Falaghi et al[41]	42u, 44d, 45u, 49d, 50u, 60u	—	—	42 509
Result of the proposed approach	39d, 50u, 53u, 59u	41u, 57u, 63u	38u, 44u, 56u, 60u	36 487

Note. Every section has two candidate locations for device installation: u (source side of the section) and d (load side of the section).

Abbreviation: EENS, expected energy not supplied.

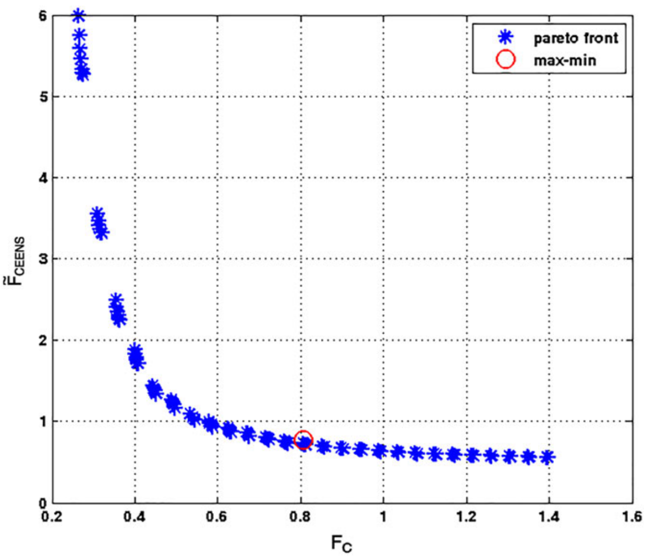

FIGURE 7 Nondominated solution with nondominated sorting genetic algorithm for the modified distribution feeder connected to bus 4 of the Roy Billinton Test System

5.3 | Comparison proposed method with benchmark result

In spite of the different switching and protective equipment as well as the objective function in this paper compared with other articles, in order to verify its authenticity, the presented approach has been compared with the results of Falaghi et al.[41] In this reference, a rural distribution network connected to bus 4 of the Roy Billinton Test System (RBTS) has been modified to conduct the case studies. The possibility of weighting the candidate locations for the installation of equipment by the AHP does not exist for all points in the RBTS. Therefore, in the objective function, the weight of all the candidate locations is considered to be equal. The results of the implementation of scenario 5 of the proposed method and the test case A-3-3 of Falaghi et al[41] are presented in Table 11. In the A-3-3 test case, the installation of sectionalizing switches in presence of a DG with 4-MVA capacity has been studied.

The results show that with the installation of four switches, four FIs, and three cut-out fuses, the amount of the EENS has decreased by 14% in comparison with the result of taste case A-3-3 in Falaghi et al.[41] The space of the resultant efficient answers is exhibited in Figure 7.

6 | CONCLUSIONS

Optimal location of switching and protective devices, considering the economic constraints, plays a crucial role in the reliability of distribution networks. The abundance of candidate places for the installation of these devices and, on the other hand, the need to pay attention to the geographical location of feeders, the possible constraints of the real network, and the unique features of each of the MV feeders are the main concerns of distribution managers and utilities in the optimal location problem.

In this research, an innovative and applied method for simultaneous installation of switching and protection equipment using the AHP and NSGAII optimization algorithm has been presented. The ranking of candidate locations for equipment installation according to the criteria set by the distribution experts is included as an effective factor in the objective function. Over a period of time, the system loading condition is likely to vary. Therefore, a triangular fuzzy model has been used to account for load uncertainty. The obtained results show that applying the weight coefficient obtained from the AHP method in the objective function has an important effect on the proposed locations for installing the equipment. It seems that the expectations of network experts have been realized in the context of the practical conditions of the network. In the proposed method, the placement of the FI, the cut-out fuse, the manual switches, and the RCSs are implemented in five different scenarios on an MV feeder of the GTEDC. The obtained results indicate that the simultaneous allocation of the RCSs and protective devices can lead to achieve the highest improvement in system reliability indexes (EENS, SAIFI, and SAIDI) than does installing the switching and protective devices separately.

LIST OF SYMBOLS AND ABBREVIATIONS

c_1	The effect of permanent faults on the network
c_2	The effect of transient faults on the network
C_{cf}	The installation cost of a cut-out fuse
CE_{j}	The load model at the consumption points
C_{fi}	The installation cost of a fault indicator
C_{i}	The number of commercial loads
c_j	The weight of jth criterion
C_{s}	The installation cost of a switch
$C_{\mathrm{tie}}(i)$	The installation cost of a tie-line in the ith candidate place
DS_i	Decision-making variables of installation or noninstallation of automation equipment in ith switch
DT_i	Decision-making variables of installation or noninstallation of automation equipment in ith tie-line
e	Maximum error of the estimated power in a load point
F_{C}	Cost functions of equipment
$\widetilde{F}_{\mathrm{CEENS}}$	The fuzzy amount of cost function of Expected END
f_{pw}	Function for transforming the related costs to the present value
f_{total}	The objective function

IC_{cf}	Cost of installing cut-out fuses
i_{cf}	The rated current of the cut-out fuse
IC_{fi}	Cost of installing fault indicator
$\boldsymbol{IC_i}$	The cost of not-supplying each energy unit related to load i
IC_{s}	Cost of installing switches
IC_{tie}	Costs of installing, tie-lines
I_{i}	The number of industrial loads
i_{line}	The line current
In_{fr}	Annual inflation rate
In_{tr}	Annual interest rate
L_i	The length of the ith branch (km)
n	The number of transformers in the network
N_{rp}	The number of loads that is still interrupted after switching operations
N_{s}	The number of feeder branches
N_{sw}	The number of interrupted loads during fault occurrence
OC_{eq}	The maintenance and operation cost of equipment
OC_{s}	Cost of maintenance and operation of equipment
P_0	The estimated power in a load point
$\boldsymbol{P_i^j}$	The load percentage not supplying each energy unit related to load i in the consumption node j
P_{L}	The least possible value of load
P_{M}	Expected amount of load with the highest probability
P_{R}	The highest possible value of load
r_i	The geometric average value of the ith row of Table 4
R_i	The number of residential loads
r_{ij}	The relative weight of the ith candidate place corresponding to the jth criterion
$R_{\mathrm{Index\ a}}$	EENS index for the total interrupted loads after the fault occurrence in the network
$R_{\mathrm{Index\ b}}$	EENS index for the loads in the faulted zone
$R_{\mathrm{Index\ c}}$	EENS index for the loads that remain interrupted even after the switching
s_i	The capacity of available transformers at the ith candidate place
S_i	The number of special loads (hospital, political and military centers, etc)
SP	Set of all load tariffs (residential, commercial, industrial, etc)
$T_{\mathrm{rp}}(i)$	The repair time of the line
$T_{\mathrm{sw}}(i)$	The fault detection and switching time duration of the line
$W_{i,j}$	The weight of ith candidate place for jth criterion
W_j	The weighting factor associated with the priority of each candidate place
$\alpha(i)$	The presence or absence of a switch in the ith candidate place
$\beta(i)$	The presence or absence of cut-out fuse in the ith candidate place
$\gamma(i)$	The presence or absence of fault indicator in the ith candidate place
$\delta(i)$	The presence or absence of tie-line in the ith candidate place
λ_i	The annual rate of fault occurrence in the ith branch of the feeder

ORCID

Amir Reza Yari https://orcid.org/0000-0001-8104-4707
Mahmoud Reza Shakarami https://orcid.org/0000-0002-7206-8341
Hassan Moradi CheshmehBeigi https://orcid.org/0000-0002-4802-6117

REFERENCES

1. Billinton R, Allan RN. *Reliability Evaluation of Power Systems*. 2nd ed. New York: Plenum Press; 1996.
2. Vanoirsove P M, Provoost F.. Fault localization in an MV distribution network. in CIRED, 17 International Conference on Electricity Distribution, Barcelona, 12-15 May 2003.

3. Brown RE. *Electric Power Distribution Reliability*. New York, Basel: Marcel Dekker Inc; 2002.
4. Billinton R, Jonnavithula S. Optimal switching device placement in radial distribution systems. *IEEE Trans Power Delivery*. 1996;11(3):1646-1651.
5. Levitin G, Mazal-Tov S, Elmakis D. Genetic algorithm for optimal sectionalizing in radial distribution systems with alternative supply. *Electr Pow Syst Res*. 1995;35(3):149-155.
6. Wang P, Billinton R. Demand-side optimal selection of switching devices in radial distribution system planning. *IEE Proc, Gener Transm Distrib*. 1998;145(4):409-414.
7. Celli G, Pilo F. Optimal sectionalizing switches allocation in distribution networks. *IEEE Trans Power Delivery*. 1999;14(3):1167-1172.
8. Luth J. Four rules to help locate protective devices. *Electr World*. 1991;1(1):36-37.
9. Esteban A, Alberto A. Optimal selection and allocation of sectionalizers in distribution systems using fuzzy dynamic programming. *Energy Power Eng*. 2010;02(04):283-290.
10. Bernardon DP, Sperandio M, Garcia VJ, Canha LN, Abaide AR, Daza EFB. AHP decision-making algorithm to allocate remotely controlled switches in distribution networks. *IEEE Trans Power Delivery*. 2011;26(3):1884-1892.
11. Razi Kazemi AA, Dehghanian P. A practical approach on optimal RTU placement in power distribution systems incorporating fuzzy sets theory. *Int J Electr Power Energy Syst*. 2012;37(1):31-42.
12. Bezerra JR, Barroso GC, Leão RPS, Sampaio RF. Multiobjective optimization algorithm for switch placement in radial power distribution networks. *IEEE Trans Power Delivery*. 2015;30(2):545-552.
13. Xu Y, Liu C-C, Schneider KP, Ton DT. Placement of remote-controlled switches to enhance distribution system restoration capability. *IEEE Trans Power Syst*. 2016;31(2):1139-1150.
14. Mao Y, Miu KN. Switch placement to improve system reliability for radial distribution systems with distributed generation. *IEEE Trans Power Syst*. 2003;18(4):1346-1352.
15. Aman MM, Jasmon GB, Mokhlis H, Abu Bakar AH. Optimum tie switches allocation and DG placement based on maximization of system loadability using discrete artificial bee colony algorithm. *IET Gener Transm Distrib*. 2016;10(10):2277-2284.
16. Shahsavari A, Fereidunian A, Mazhari SM. A joint automatic and manual switch placement within distribution systems considering operational probabilities of control sequences. *Int Trans Electr Energy Syst*. 2015;25(11):2745-2768.
17. Teng JH, Lu CN. Feeder-switch relocation for customer interruption cost minimization. *IEEE Trans Power Delivery*. 2002;17(1):254-259.
18. Da Silva LGW, Pereira RAF, Mantovani JRS. Allocation of protective devices in distribution circuits using nonlinear programming models and genetic algorithms. *Electr Pow Syst Res*. 2004;69(1):77-84.
19. Pregelj A, Begovic M, Rohatgi A. Recloser allocation for improved reliability of DG-enhanced distribution networks. *IEEE Trans Power Syst*. 2006;21(3):1442-1449.
20. Prommee W, Ongsakul W. Multi-objective optimal placement of protective devices on microgrid using improved binary multi-objective PSO. *Int Trans Electr Energy Syst*. 2014;25(11):2621-2638.
21. Derakhshandeh SY, Nikbakht M. A new mixed-integer linear formulation for optimal placement of fault indicators in distribution systems. *Int Trans Electr Energy Syst*. 2018;28(12):e2631.
22. Sohn JM, Nam SR, Park JK. Value-based radial distribution system reliability optimization. *IEEE Trans Power Delivery*. 2006;21(2):941-947.
23. Da Silva LGW, Pereira RAF, Abbad JR, Mantovani JRS. Optimised placement of control and protective devices in electric distribution systems through reactive tabu search algorithm. *Electr Pow Syst Res*. 2008;78(3):372-381.
24. Moradi A, Fotuhi-Firuzabad M. Optimal switch placement in distribution systems using trinary particle swarm optimization algorithm. *IEEE Trans Power Delivery*. 2008;23(1):271-279.
25. Alam A, Pant V, Das B. Switch and recloser placement in distribution system considering uncertainties in loads, failure rates and repair rates. *Electr Pow Syst Res*. 2016;140:619-630.
26. Alam A, Alam MN, Pant V, Das B. Placement of protective devices in distribution system considering uncertainties in loads, temporary and permanent failure rates and repair rates. *Int Trans Electr Energy Syst*. 2017;12(7):1474-1485.
27. Heydari S, Mohammadi-Hosseininejad SM, Mirsaeedi H, Fereidunian A, Lesani H. Simultaneous placement of control and protective devices in the presence of emergency demand response programs in smart grid. *Int Trans Electr Energy Syst*. 2018;28(5):e2537.
28. Das D. A noniterative load flow algorithm for radial distribution networks using fuzzy set approach and interval arithmetic. *Electric Power Compon Syst*. 2005;33(1):59-72.
29. Popovic DS, Popovic ZN. A risk management procedure for supply restoration in distribution networks. *IEEE Trans Power Syst*. 2004;19(1):221-228.
30. Ramirez-Rosado IJ, Dominguez-Navarro JA. Possibilistic model based on fuzzy sets for the multiobjective optimal planning of electric power distribution networks. *IEEE Trans Power Syst*. 2004;19(4):1801-1810.
31. Ramirez-Rosado IJ, Dominguez-Navarro JA. Distribution planning of electrical energy using fuzzy models. *Int J Power Energ Syst*. 1996;16(2):49-55.

32. Nazarko J, Zalewski W. The fuzzy regression approach to peak load estimation in power distribution systems. *IEEE Trans Power Syst*. 1999;14(3):809-814.
33. Shirmohammadi D, Hong HW, Semlyen A, Luo GX. A compensation-based power flow method for weakly meshed distribution and transmission networks. *IEEE Trans Power Syst*. 1988;3(2):753-762.
34. Shakarami MR, Beiranvand H, Beiranvand A, Sharifipour E. A recursive power flow method for radial distribution networks: analysis, solvability and convergence. *Int J Electr Power Energy Syst*. 2017;86:71-80.
35. Kauhaniemi K. Fuzzy models and techniques for the calculation of radial distribution networks. in IEEE/NTUA Athens Power Tech Conf 1993;1:423-428.
36. Saaty TL. *The Analytic Hierarchy Process*. New York: McGraw-Hill; 1980.
37. Goldberg DE. *Genetic Algorithms in Search, Optimization, and Machine Learning*. Reading, MA: Addison-Wesley; 1989.
38. Deb K, Agrawal S, Pratap A. A Fast Elitist Non-dominated Sorting Genetic Algorithm for Multi-objective Optimization: NSGAII, Indian Inst. Technol, Kanpur, India, Tech 2000;1917:849-858.
39. Bazovsky I. *Reliability Theory and Practice*. Mineola, New York: Courier Corporation; 2004.
40. Bae IS, Kim JO, Kim JC, Singh C. Optimal operating strategy for distributed generation considering hourly reliability worth. *IEEE Trans Power Syst*. 2004;19(1):287-292.
41. Falaghi H, Haghifam MR, Singh C. Ant colony optimization-based method for placement of sectionalizing switches in distribution networks using a fuzzy multiobjective approach. *IEEE Trans on Power Delivery*. 2009;24(1):268-276.

How to cite this article: Yari AR, Shakarami MR, Namdari F, Moradi CheshmehBeigi H. A novel practical method for simultaneous placement of switching and protective devices considering load uncertainty. *Int Trans Electr Energ Syst*. 2019;e12025. https://doi.org/10.1002/2050-7038.12025