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Optimal placement of switching and protection devices in radial distribution networks to enhance system reliability using the AHP-PSO method

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Abstract: This paper presents a new method to determine the optimal number and locations of autorecloser and sectionalizer switches (AR/S) in distribution networks. The costs of AR/S investment, switch maintenance, and undistributed energy as well as reliability coefficients are considered in the objective function. Reliability parameters such as SAIFI, SADI, MAIFI, and ENS are evaluated in the case study system. As a new method, the weights of the reliability parameters are obtained by decision-makers using the analytical hierarchy process (AHP). The optimal size, type, and location of automatic switches are determined by minimizing the objective function using the particle swarm optimization (PSO) algorithm. The effectiveness of the proposed method is tested by implementing it on two feeders of Isfahan's electric distribution network. The results indicate the efficiency and applicability of the proposed method.

Key words: AHP analysis, reliability parameters, objective function, PSO algorithm, autorecloser and sectionalizer switches, optimal placement

1. Introduction

The supply of stable and continuous energy for electrical customers has a vital role in our lives. Past experiences show that a high percentage of network interruptions are related to power distribution networks. Since most of the faults that occur are transient, using automatic switching devices in appropriate points of the network can substantially reduce customer outages [1]. If automatic switches are used at optimal points of the system, undistributed energy (ENS) will be effectively reduced. When a fault occurs in a section of the system, the autorecloser disconnects the faulty section from the system. After a few moments, the autorecloser reconnects this section to the system. If the fault has not been resolved, the recloser operates for the second time and the sectionalizer isolates the faulty section. There are various methods for determining the optimal points of automatic switches in distribution networks. A genetic algorithm (GA) based on cost/worth analysis was used for switch placement in distribution networks in [2]. The GA and PSO algorithms were used to determine the optimal locations of automatic switching devices with minimum cost and maximum reliability in [3,4]. A computer program was presented to reduce service blackouts using switching devices by using cost/worth analysis in [5]. A scheme based on cost minimization was applied to obtain the locations of switching devices in electrical distribution networks by using a GA in [6]. Reliability indices for customer services were studied using automatic control switches in a case study network [7]. Remote-controlled sectionalizers were placed in radial distribution systems to minimize the cost function in the mixed-integer linear programming method in

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[8]. The weights of the reliability indices obtained by the AHP algorithm were used to determine the optimal location of switches in distribution networks in [9,10]. The GA and graph theory were used to specify the location of switching devices in radial distribution systems [11]. The PSO algorithm based on cost/worth analysis was applied for switch placement. The locations and numbers of faults that occurred were considered in order to specify autorecloser switches in a test system in [12]. The reliability parameters were improved by relocating the switches based on minimization of customer outage costs in [13]. A GA approach was used to obtain optimal points of switching and protective equipment on a power distribution system in [14]. By use of sectionalizers in optimal points of the networks, SAIDI was reduced, while using autoreclosers as protection equipment can significantly decrease SAIFI and MAIFI. The weights of the reliability parameters (SAIFI, SAIDI, and MAIFI) are obtained by decision-makers using the AHP algorithm as a new approach presented in this paper. A reliability factor is defined based on the weight of the reliability parameters, and the cost function is formulated by using investment cost, maintenance cost, and undistributed energy cost. A PSO algorithm using cost/reliability analysis is applied to determine the types, sizes, and locations of autoreclosers and sectionalizers in radial distribution networks [15,16]. A computer program is presented to implement the proposed method in two sample feeders of Isfahan's electric distribution network.

2. Problem statement

In this paper, the optimal locations of AR/S switches are determined as shown in the proposed flowchart in Figure 1. The network information including source, line and load data, reliability parameter data, and the decision-maker's opinion are entered into the computer program as system data. The weights of the reliability parameters are obtained by decision-makers using the AHP algorithm. This program can calculate the load flow of the system using the forward/backward method. The system data and the results of load flow analysis are utilized to obtain the cost function and reliability factors. To minimize the objective function using the PSO algorithm, the optimal points of autorecloser and sectionalizer switches are determined. The locations of AR/S devices are indicated in their geographic position on the network.

2.1. Load flow

A radial distribution system can be simulated with a source and n-sections as shown in Figure 2. The forward-backward method is used to calculate the electrical parameters [17]. In this method, the voltage magnitude of each bus is set to 1.0 per unit. The reactive and active power of the sections and the bus voltages can be obtained through the backward sweep shown in Eqs. (1) and (2).

$$P_{j-1} = P_j + r_j \frac{P_j^2 + Q_j^2}{V_j^2} + P_{Lj}\,, \quad Q_{j-1} = Q_j + x_j \frac{P_j^2 + Q_j^2}{V_j^2} + Q_{Lj} \tag{1}$$

$$V_{j-1}^2 = V_j^2 + 2(r_j P_j + x_j Q_j) + (r_j^2 + x_j^2)\frac{P_j^2 + Q_j^2}{V_j^2} \tag{2}$$

In the forward sweep, the power losses and new voltages are calculated as in Eqs. (3) and (4). This procedure will be continued until convergence is achieved. The results of load flow analysis are applied to obtain the reliability parameters [18].

$$V_{j+1}^2 = V_j^2 - 2(r_j P_j + x_j Q_j) + (r_j^2 + x_j^2)\frac{P_j^2 + Q_j^2}{V_j^2} \tag{3}$$

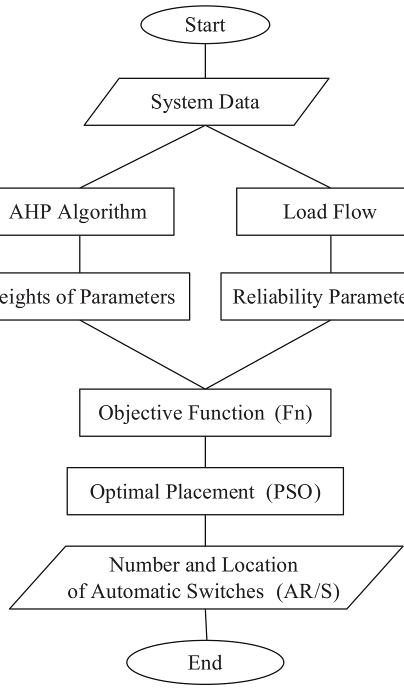

Figure 1. Flowchart of the AR/S optimal placement.

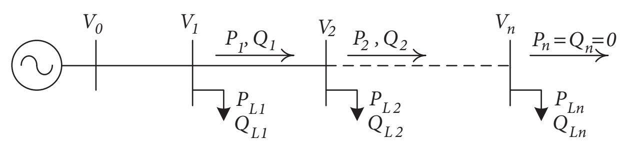

Figure 2. Single-line diagram of radial distribution system.

$$P_{Loss} = \sum\nolimits_{j=1}^{n-1} r_j \left(\frac{P_j^2 + Q_j^2}{V_j^2} \right) \tag{4}$$

2.2. Load center

The load center is one of the major points in power distribution networks and all loads can be considered to be located at that point. Experience shows that the optimal points for placement of transformers, capacitors, regulators, and reclosers are obtained to be near the load center. The load center point is calculated from Eq. (5) as follows:

$$X_{lc} = \sum\nolimits_{i=1}^{n} P_i \frac{X_i}{\sum P_i} \ , \ \ Y_{lc} = \sum\nolimits_{i=1}^{n} P_i \frac{Y_i}{\sum P_i} \tag{5}$$

Here, n is the number of loads, Pi is the active power at bus i in KW, Xi and Yi are the geographic coordinates of the load related to bus i, and Xlc and Ylc are the geographical coordinates of the load center.

2.3. Objective function

Switching and protective devices such as reclosers and sectionalizers are used in power distribution networks to reduce system interruptions during the occurrence of a fault [19]. Using this equipment imposes some costs, as shown in Eq. (6).

$$TC_n = (IC_n + MC_n - PER_n) \tag{6}$$

Here, TCn is the total cost for n years, INVCn is the price of buying automatic switches, MAINTCn is the maintenance cost, and PERn is the profit of reducing ENS for n years.

2.3.1. Investment cost

Investment cost includes the cost of purchasing the equipment and installation costs as formulated in Eq. (7).

$$ICn = (C_{R\_INV} \cdot N_R + C_{S\_INV} \cdot N_S)(1 + IntR)^n \tag{7}$$

Here, n is the study period in years, INVC is investment cost, C_{R_INV} is price of a recloser, NR is the number of reclosers, C_{S_INV} is price of a sectionalizer, NS is the number of sectionalizers, and IntR is annual interest rate.

2.3.2. Maintenance cost

Maintenance cost defines operation and service costs of AR/S switches as calculated in Eq. (8).

$$MCn = \sum\nolimits_{i=0}^{n} (C_{RM} N_R + C_{SM} N_S)(1 + InfR)^i \tag{8}$$

Here, n is the study period in years, MAINTC is the maintenance cost, CRM is the maintenance cost of reclosers, NR is the number of reclosers, CSM is maintenance cost of sectionalizers, NS is the number of sectionalizers, and InfR is the annual inflation rate.

2.3.3. The profit of undistributed energy reduction

When a permanent fault occurs, a specific amount of energy (known as ENS) is not delivered to the electrical customers. This energy is expressed by Eq. (9).

$$EC_n = \sum\nolimits_{i=1}^{m} C_i \cdot L_i \cdot U_i \tag{9}$$

Here, n is the study period in years, ENSC is the energy not supplied for m loads, Ci is the interruption cost in \$/KWH, Li is the average energy in KW, and Ui is the interruption time in h/year. If AR/S switches are used in power distribution networks, undistributed energy is decreased significantly. The profit gained by reduction in ENS is obtained as shown in Eq. (10).

$$\begin{cases} PERn = \sum_{i=1}^{n} K(EC_w - EC_S).k^i \\ K = (1 + grf).(1 + IntR) \end{cases} \tag{10}$$

Here, n is the study period in years, PERn is the profit of ENS reduction, ENSCw is the cost of ENS without any switches, ENSCS is the cost of ENS with automatic switches, grf is the annual load growth factor, intR is the annual interest rate , and K is the coefficient of the equation.

2.3.4. Reliability indices

In this paper, reliability parameters are described as SAIFI, SAIDI, and MAIFI. The system average interruption frequency index is called SAIFI and the per-unit value of SAIFI is defined as formulated in Eq. (11).

$$SAIFI = \sum\nolimits_{i=1}^{m} \frac{\lambda_i \cdot N_i}{NT}, \quad SAIFI(p.u) = \frac{SAIFI_s}{SAIFIw} \tag{11}$$

Here, m is the number of load buses, i is the failure rate in the ith branch (f/year), Ni is the number of customers connected to load bus i, NT is the total number of loads, SAIFIW is SAIFI without any switches, and SAIFIS is SAIFI with automatic switches installed. The system average interruption duration index is called SAIDI and the per-unit value of SAIDI is defined as formulated in Eq. (12).

$$SAIDI = \sum_{i=1}^{m} \frac{U_i \cdot N_i}{NT}, \quad SAIDI(p.u) = \frac{SAIDI_s}{SAIDIw} \tag{12}$$

Here, Ui is the average restoration time in the ith branch (h/year), SAIDIW is SAIDI without any switches, and SAIDIS is SAIDI with automatic switches installed. MAIFI is defined as momentary average interruption frequency index and the per-unit value of the MAIFI index is formulated in Eq. (13).

$$MAIFI = \sum_{i=1}^{m} \frac{\gamma_i \cdot N_i}{NT}, \quad MAIFI(p.u) = \frac{MAIFI_s}{MAIFI_w} \tag{13}$$

Here, i is the average rate of momentary interruptions at load point i (m.f/year), MAIFIW is MAIFI without any switches, and MAIFIS is MAIFI with automatic switches installed.

The weights of the reliability parameters are obtained by decision-makers consisting of operators, engineers, and managers using the AHP method. These weights are defined as SAIFIw, SAIDIw, and MAIFIw, to be discussed in Section 4.1.2. To obtain the optimal location and number of AR/S switches, it is necessary to optimize the cost function (TCn) and reliability factors (RFa or RFw).

2.3.5. Objective function

As defined in Eq. (6), the total cost consists of investment cost, maintenance cost, and the profit of ENS reduction. The average of the reliability parameters (RFa) and the reliability factor based on weights of indices (RFw) can be formulated using Eq. (14). The objective function (Fn) is defined as the minimum value of total cost and weight-reliability factor as formulated in Eq. (15).

$$\begin{aligned} &RFa = (SAIFIp.u + SAIDIp.u + MAIFIp.u)/3 \\ &RFw = SAIFI_w .SAIFI + SAIDI_w . SAIDI + MAIFI_w .MAIFI \end{aligned} \tag{14}$$

$$F_n = min(\mathrm{TC}, RFw) \tag{15}$$

3. Heuristic model

3.1. Determining the weights of the reliability parameters using the AHP algorithm

In this paper, the weights of the reliability parameters are obtained using the AHP algorithm in Figure 3. The proposed algorithm is defined as three models with three levels. The first level is referred to as the target function to determine the weight of the reliability parameters. The second level shows decision-makers, including the operators, engineers, and managers. The third level is the weight of the reliability parameters including SAIFIw, SAIDIw, and MAIFIw, to be determined by decision-makers [20]. In Section 4, the weights of the reliability factors are determined for two feeders that are studied here.

3.2. Optimal placement of AR/S in the PSO algorithm

The PSO algorithm is a technique utilized to evaluate the search space of a given problem for determination of the variables required to maximize a particular objective [21]. In this algorithm, each particle consists of two

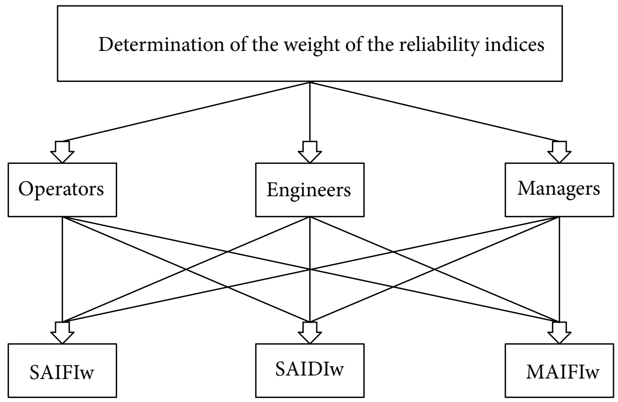

Figure 3. Determination of the weights of reliability indices in the AHP algorithm.

parameters: position parameter xik (consisting of candidate solution and its fitness) and velocity parameter vik, where k is the number of repetitions for the ith particle. The PSO algorithm maintains the best fitness value obtained among all particles, called the global best fitness (gbest), and the candidate solution that obtains this fitness is called the best global position (pbest).

This scheme consists of three steps:

1) Particle fitness determination,

2) Updating the position and global best fitnesses,

3) Updating particle position and velocity.

This process is repeated to obtain the optimal condition. The swarm updates its velocity and position variables through Eqs. (16) and (17).

$$v(t+1) = v(\mathrm{t}) + c_1 r_{1,t}\left[p_{best} - x(t)\right] + c_2 r_{2,t}\left[g_{best} - x(t)\right] \tag{16}$$

$$x(t+1) = x(\mathrm{t}) + v(t+1) \tag{17}$$

Here, t is the iteration number, v(t) is particle velocity, x(t) is particle position, pbest is the best particle solution, gbest is the global best solution at iteration number, r1,t and r2,t are random numbers (0<r1,t<1, 0<r2,t<1), and c1 and c2 are effective factors in the algorithm's convergence rate (and usually c1=c2=2). Two conditions are considered for automatic switches in this paper (0: no switch installation and 1: switch installation).

There are three states in each location defined as:

a) Autorecloser switches.

b) Sectionalizer switches.

c) None of the automated switches.

To determine the optimal location and size of AR/S devices, the Fn costs (PSI values) are obtained for each section as shown in Figure 4. In this case, each section is a candidate for autorecloser or sectionalizer placement. Thus, it is disconnected to calculate the ENS, SAFI, SAIDI, and MAIFI values in states a, b, and c. In state a, the use of autoreclosers can significantly reduce SAIFI and MAIFI. The SAIDI index can improve in state b), when the sectionalizers are applied in this method. To calculate the PSI value in each state, the optimal size and locations of AR/S switches are obtained by cost/worth analysis in this algorithm [22].

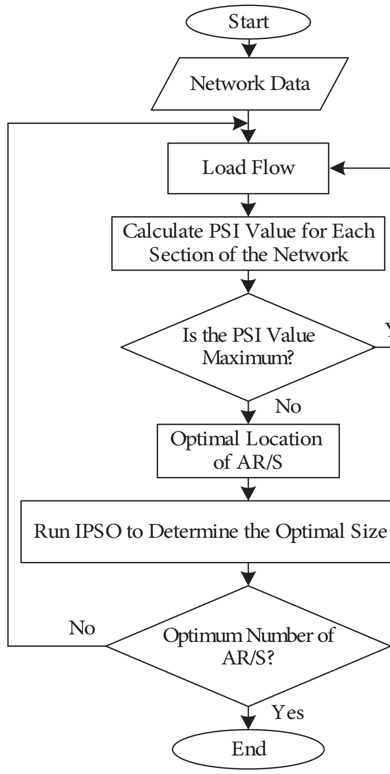

Figure 4. AR/S placement using the PSO algorithm.

4. Simulation results

The proposed method is simulated by a program supported with Visual Basic 6 and Access database. This program has the following features:

- Drawing the system in the geographical scheme.
- Tracing the sections and nodes.
- Calculation of load flow.
- Determination of weights of reliability parameters.
- Automatic switch placement using the PSO algorithm.
- Indicating the results in the geographic state of the system.

Two test feeders of Isfahan's electrical distribution network are studied in the present work.

4.1. Simulation of Isfahan's 32-bus electric system

In this part, a radial 20-kV feeder of Isfahan's electric distribution network with 32 buses (feeder F1) connected to the 20/0.4-kV transformers is simulated using the section by section method.

4.1.1. Calculation of load flow and reliability parameters

It is essential to collect the existing data of the feeder under study (F1) for calculating the electrical and reliability parameters. These data include section number (Sec), section nodes (Nod I, NodJ), line impedance (Rl, Xl) in Ω/KM, section length (L) in km, load active power (PL) in kW, load reactive power (QL) in kVAR, failure rate (λ) in f/year, mean restoration time (U) in h/year, average rate of momentary interruptions γ in m.f/year, load number connected to the 20/0.4-kV transformer (N), and geographical location of load (X,Y). In this feeder, the load factor is considered to be 0.5 and the accuracy class of the calculation is assumed to be 0.001. For calculation of short-circuit currents, the earth resistance is assumed to be 5 ohm, the three-phase short-circuit capacity (SCC) is considered to be 350 MVA, and the base capacity (Sb) is set to be 100 MVA. The system data and load flow results of feeder F1 are shown in Table 1. As seen, the results of load flow analysis include node voltage (V) in kV, load active power (PL) in kW, load reactive power (QL) in kVAR, section losses (PK) in kW, line current (I) in A, three-phase short-circuit current (Isc) in KA, and earth fault current (Ief). The cost of undistributed energy (ENSCn) is calculated using the results of load flow analysis in Eq. (9). The short-circuit current can be used to coordinate the protection relays of the 63/20-kV substation with the autoreclosers and fuses located in the feeder being studied [23]. The reliability parameters (SAIFI, SAIDI, and MAIFI) are calculated with the section by section method using Eqs. (11), (12), and (13) and collected data of feeder F1 (N_i, U_i, λ_i, and γ_i). The value of U_i, λ_i, and γ_i is estimated by past statistical information of the feeder studied and the obtained results of the similar feeders.

Table 1. The input data and load flow results of feeder F1.

Sect	NodI	NodJ	V	PL	QL	PK	I	Isc	Ief	N	??	U	γ
1	1	2	20	100	100	26	170	10.4	1.9	30	0.2	2	3
2	2	3	20	160	160	25.4	168	7	1.6	52	0.2	2	3
3	3	4	19.9	0	0	24.5	165	5.4	1.5	0	0.1	1	2
4	4	5	19.9	250	250	24.7	164	4.4	1.4	84	0.25	2	3
5	5	6	19.8	250	250	23.3	160	3.7	1.3	91	.025	2	3
6	6	7	19.8	315	300	21.8	155	3.2	1.2	75	0.3	2	3
7	7	8	19.8	0	0	20.1	149	3	1.1	0	0	1	2
8	8	10	19.8	160	150	0.1	3	2.5	1	40	0.2	2.5	4
9	8	10	19.8	400	400	19.2	146	2.2	1	83	0.3	2.5	4
10	10	11	19.8	0	0	17.2	138	2.2	1	0	0.1	1	2
11	11	12	19.8	100	100	0.05	7	2	0.9	32	0.2	2.5	4
12	12	13	19.8	250	250	0.02	5	1.9	0.9	78	0.25	2.5	4
13	11	14	19.8	1000	1000	15.5	131	1.7	0.8	215	0.2	3	4

4.1.2. Determining the weights of the reliability parameters

The weights of the reliability parameters are very important and the optimal location of AR/S switches can be affected by their variations. The weights of these parameters including SAIFIw, SAIDIw, and MAIFIw are obtained by decision-makers using the AHP algorithm. In Table 2, the rating scales for comparing two objects are defined in four states consisting of: 1- equally preferred, 2-: moderately preferred, 3- strongly preferred, and 4- extremely preferred. The worth of each parameter is assumed to be 1 to itself, while its worth to other parameters can be considered 1, 2, 3, or 4. These comparisons and valuations will be decided by the experts of the electric companies. In Isfahan's electric distribution company, the points of decision-makers (operators, engineers, and managers) are collected according to the above criteria and the value of each parameter is shown in Table 2. For example, the worth of SAIFI is 4 to MAIFI in operators' opinion, while this worth is 1/2 and 2 in engineers' and managers' opinions, respectively. By specifying the share of each parameter, the average weights of the reliability parameters are calculated as shown in Table 3. The mean values of the parameters computed in Table 3 are shown in Table 4. In this table, the weight of SAIFIw is more important than those of others in the operator's opinion, while SAIDIw and MAIFIw are important weights for engineers, and SAIFIw and SAIDIw are the main indices from the viewpoint of managers. In the second layer of the AHP model, the worth of each decision-maker is obtained based on their organizational responsibilities and obtained surveys. The average of their normalized weights is calculated and shown in Table 5. By multiplying the mean column of Table 5 by the corresponding column of Table 4, the final weights of the indices are obtained as shown in Table 6. According to this table, SAIDIw has a higher weight than the other parameters.

Table 2. Indices' weights based on decision-makers' opinions.

Operators	SAIFIw	SAIDIw	MAIFIw
SAIFIw	1	2	4
SAIDIw	0.5	1	0.5
MAIFIw	0.25	2	1
SUM	1.75	5	5.5

Table 3. Average weights of reliability indices.

Operators	SAIFIw	SAIDIw	MAIFIw	Mean
SAIFIw	0.57	0.4	0.73	0.57
SAIDIw	0.28	0.2	0.09	0.19
MAIFIw	0.14	0.4	0.18	0.24

Table 4. Average weights in decision-makers' opinions.

Target	SAIFIw	SAIDIw	MAIFIw
operators	0.57	0.19	0.24
Engineers	0.16	0.52	0.32
Managers	0.30	0.53	0.17

Table 5.

Target	SAIFIw	SAIDIw	MAIFIw
operators	0.57	0.19	0.24
Engineers	0.16	0.52	0.32
Managers	0.30	0.53	0.17

4.1.3. Optimal placement of AR/S switches in the PSO algorithm

Using system data and load flow results, the per-unit values of SAIDI, SAIFI, and MAIFI are calculated for all sections of the feeder under study. In this case, the objective function is obtained by using the total cost and

Table 6. Final weights of reliability parameters.

Target	SAIFIw	SAIDIw	MAIFIw
Weight	0.31	0.47	0.22

reliability factor as shown in Eq. (15). The optimal number and locations of AR/S switches are determined by the PSO algorithm. In this method, RFa, RFw, and TC values are calculated for each section. In feeder F1, the growth factor and the annual inflation rate are considered to be 8% and 5%, respectively. The life period of AR/S devices is assumed to be 20 years, the cost of energy interruption is set to be 1 $/KWH, the prices of an autorecloser and an autosectionalizer are considered to respectively be 3000$and 1000$, and the maintenance cost is assumed to be 35 $/year. If we run the PSO algorithm for this system, different scenarios are obtained as shown in Table 7. In scenario 1 without any switches, reliability factors RFa and RFw are calculated to be 1.0 and the cost function TC is obtained to be 17,622$. Although at least TC values are related to scenarios 3, 4, 5, 7, 8, and 9, scenario 10 with three reclosers and five sectionalizers (3R+5S) in sections 1, 11, 14, 15, 25, 26, 27, and 32 is preferred as the best option since the TC value of this scenario is less than the TC value of scenario 1. Moreover, the average reliability factor of this scenario is less than that of other scenarios. In this case, the optimal locations of AR/S switches are determined in four points at nodes 1, 11, 15, and 27 as shown in Figure 5. This figure shows that the selected points are located near the load center. The results show that the other scenarios with more locations are not economical in this system. If the weights of the reliability parameters are obtained by decision-makers as shown in Table 6, the RFw of each option is computed as shown in Table 7. In scenarios 1 through 10, the values of RFa and RFw are obtained to be close together. In scenario 11 with various values of reliability indices, RFw is obtained to be less than RFa (0.67). In scenario 12 with more number of sectionalizers and the least SAIDI, RFw is computed to be the minimum value (0.62). In this option, two reclosers and seven sectionalizers (2R+7S) are selected at optimal locations of the feeder studied, where two autoreclosers are located in sections 1 and 14, and seven sectionalizers are installed in sections 11, 15, 20, 23, 25, 27, and 32 as shown in Figure 6. The results show that significant changes of the indices weights can move the AR/S locations to other points.

4.2. Simulation of Isfahan's 52-bus electric system

Isfahan's 52-bus electric system is selected as the other radial medium voltage feeder of Isfahan's distribution network (feeder F2). The basic data that consist of load factor, accuracy class, earth resistance, Sb, and SCC in this feeder are considered to be the same as that of feeder F1. The weights of reliability parameters are obtained as shown in Table 8. In this table, the value of SAIFIw is greater than other parameters. To run the program for this system, the TC values of the candidate points are calculated for different scenarios. If the average reliability factor is considered in this system, the best option is obtained in scenario 9 with the least values of RFa and TC related to the other scenarios. In this case, two autoreclosers are selected in sections 18 and 34 and six sectionalizers are determined in sections 19, 27, 31, 35, 39, and 41 as shown in Figure 7. In this figure, nodes 19, 27, and 35 are only located near the load center. If the weight-reliability factors (RFw) are obtained as shown in Table 9, the best option is selected in scenario 8 with the least value of RFw and a TC value less than the value related to the first scenario. In this case, three reclosers are located in sections 1, 18, and 34 and five sectionalizers are installed in sections 6, 19, 26, 35, and 39 as shown in Figure 8. In

Table 7. The result of AR/S placement in feeder F1.

Scenario	Section	Device	SAIFI	SAIDI	MAIFI	RFa	RFw	TC
1	-	None	1	1	1	1	1	17622
2	4,5	R+S	0.8	0.75	0.9	0.82	0.80	11982
3	8,9	R+S	0.75	0.71	0.86	0.77	0.76	11503
4	1,14,15,25	2R+2S	0.71	0.69	0.88	0.76	0.74	10266
5	15,16	R+S	0.81	076	0.86	0.81	0.80	11703
6	1,19,20,23	2R+2S	0.74	0.68	0.85	0.76	0.74	15301
7	1,26,27,32	2R+2S	0.69	0.67	0.83	0.73	0.71	11670
8	27,28	R+S	0.85	0.79	0.92	0.85	0.84	11601
9	32,33	R+S	0.79	0.74	0.89	0.81	0.79	11546
10	1,11,14,15,25,26,27,32	3R+5S	069	0.64	0.71	0.68	0.67	15836
11	8,9,14,15,25,26,27,32	3R+5S	065	0.59	0.86	0.70	0.67	19439
12	1,11,14,15,20,23,25,27,32	2R+7S	0.75	0.41	0.89	0.68	0.62	15985

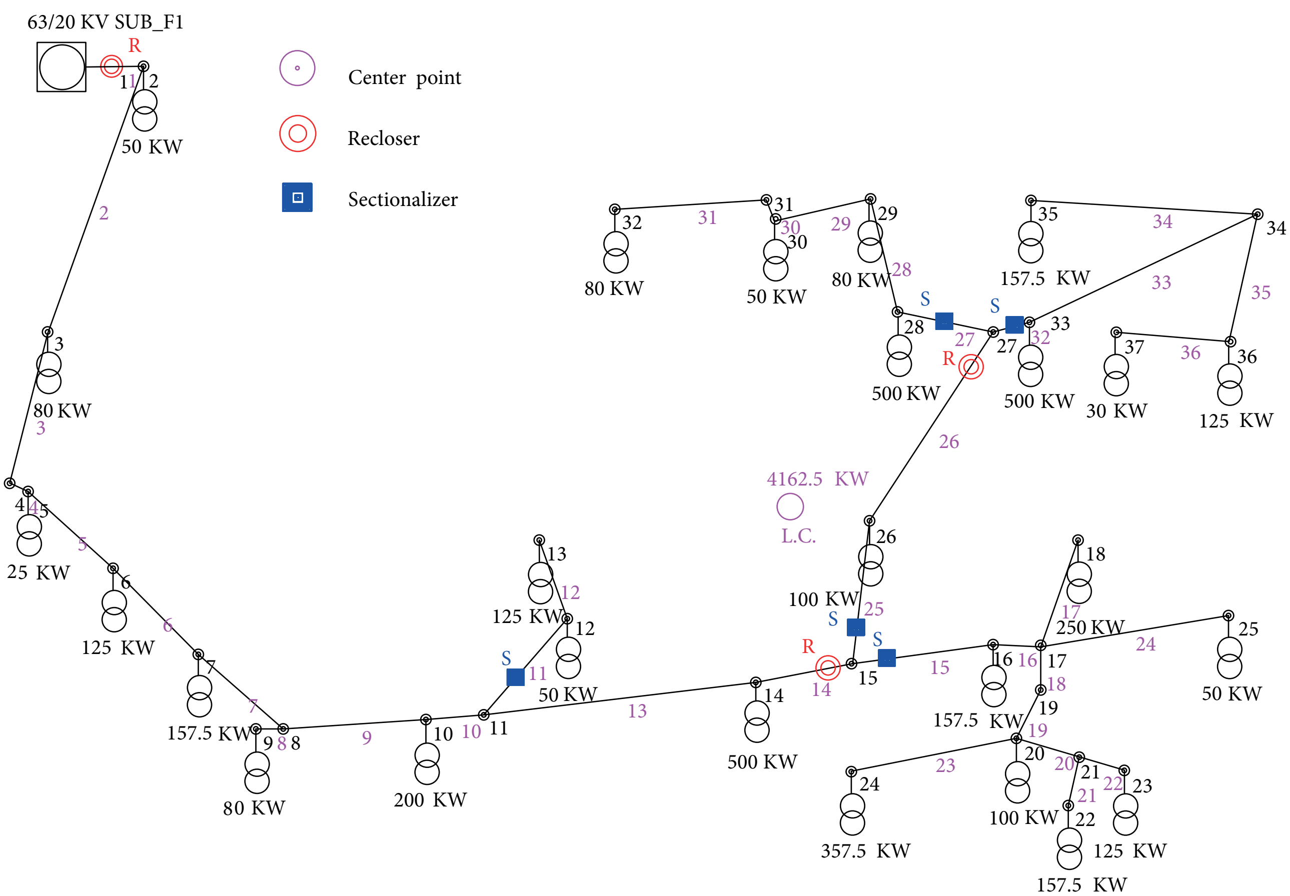

Figure 5. Optimal locations of AR/S in feeder F1 with RFa.

this case, an autorecloser is added in section 1 to reduce SAIFI to the lowest value (0.42), and the numbers and locations of some sectionalizers have been changed. In scenario 10, reliability factors RFa and RFw have

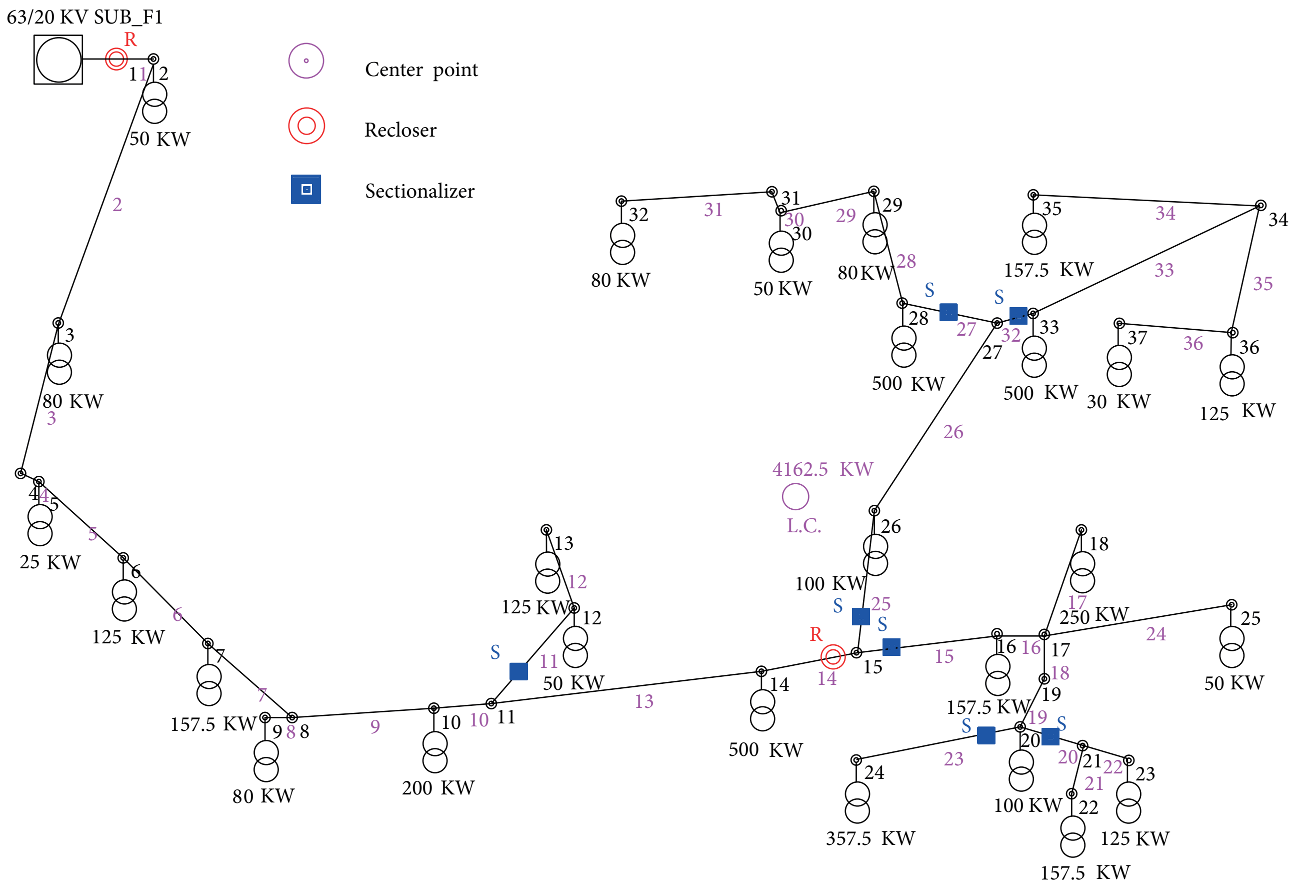

Figure 6. Optimal locations of AR/S in Feeder F1 with RFw.

the lowest values, but the TC value of this scenario is greater than the TC value of the first scenario and this option is not selected. The obtained results show that the weights of the indices can reduce the RFw related to the RFa, as a result of which the selected option may change. After placement of AR/S switches in a radial power distribution network, it is essential to coordinate the autoreclosers with the protective relays located in the high voltage substation. The optimal type, size, and location of protection and switching equipment can significantly improve system reliability.

Table 8. Computed weights of reliability parameters.

Target	SAIFIw	SAIDIw	MAIFIw
Weight	0.55	0.24	0.21

4.3. The accuracy of the proposed method

In most of the present articles, the objective function is defined as the minimum cost function and reliability indices. In this paper, the objective function is formulated as the minimum cost considering the least weight-reliability factor. If the weights of the reliability indices are considered as a new method, TC and RFw will be minimized to obtain the best option. Using the AHP model, the sum of weights of the indices is obtained to

Table 9. The result of AR/S placement in feeder F2.

Scenario	Section	Device	SAIFI	SAIDI	MAIFI	RFa	RFw	TC
1	-	None	1	1	1	1	1	15491
2	1,6,18,19,26	2R+2S	0.68	0.71	0.76	0.72	0.71	6905
3	1,6,34,35,39	2R+2S	0.73	0.77	0.79	0.76	0.75	9988
4	1,6,26,27,31	2R+2S	0.69	0.73	0.74	0.72	0.71	11936
5	5,6,8	R+2S	0.91	0.94	0.96	0.91	0.92	5149
6	26,27,32,34, 35,39	2R+4S	0.65	0.66	0.78	0.69	0.68	11936
7	5,6,8,26,27 , 31	2R+4S	0.68	0.76	0.88	0.77	0.74	13085
8	1,6,18,19,26,34,35,39	3R+5S	0.42	0.58	0.73	0.55	0.45	14187
9	18,19,27,31 ,34,35,39,46	2R+6S	0.61	0.51	0.62	0.57	0.52	13256
10	1,6,18,19,27,31,34,35,39,46	3R+7S	0.38	0.48	0.61	0.51	0.42	16256

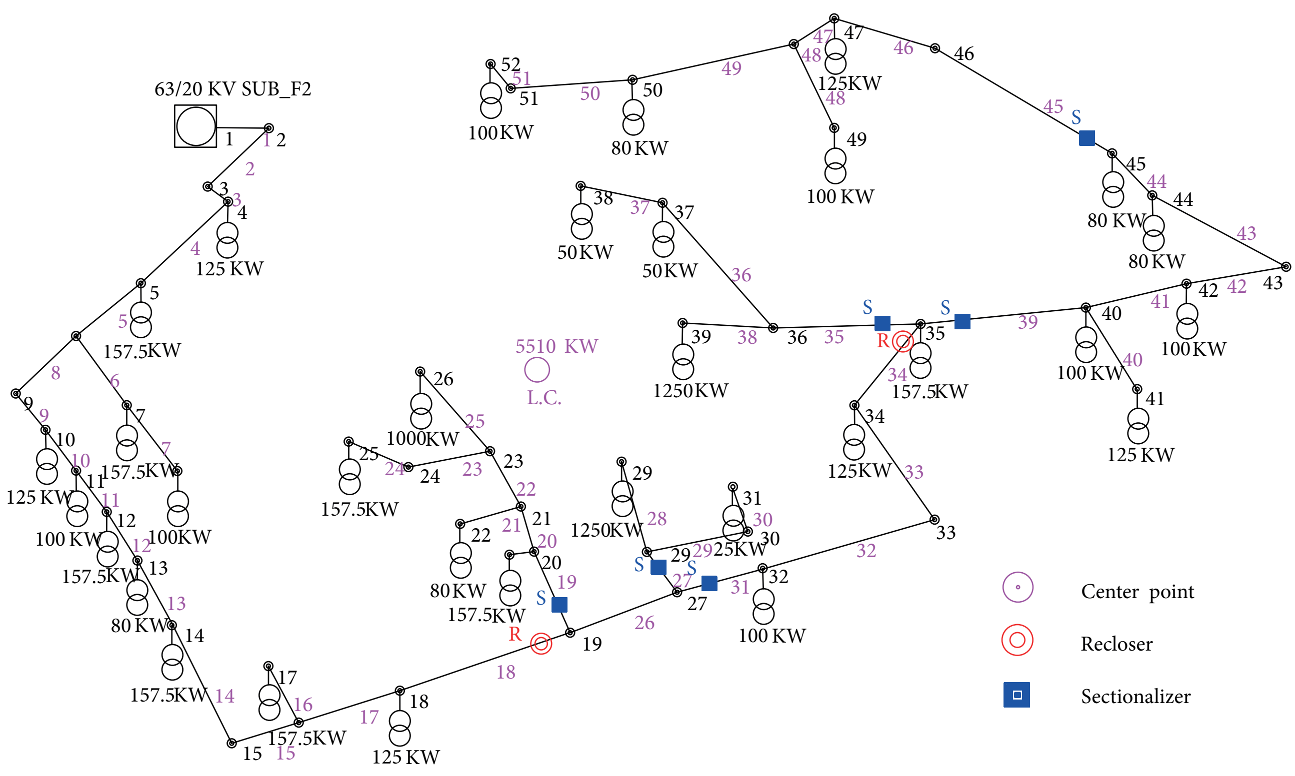

Figure 7. Optimal locations of AR/S in feeder F2 with RFa.

be equal to 1.0 in each state and RFw is found to be close to the RFa. The optimal type, size, and location of AR/S switches may be changed based on the computed weights. After running the presented program for various states of the power distribution feeders, correct and acceptable results are obtained.

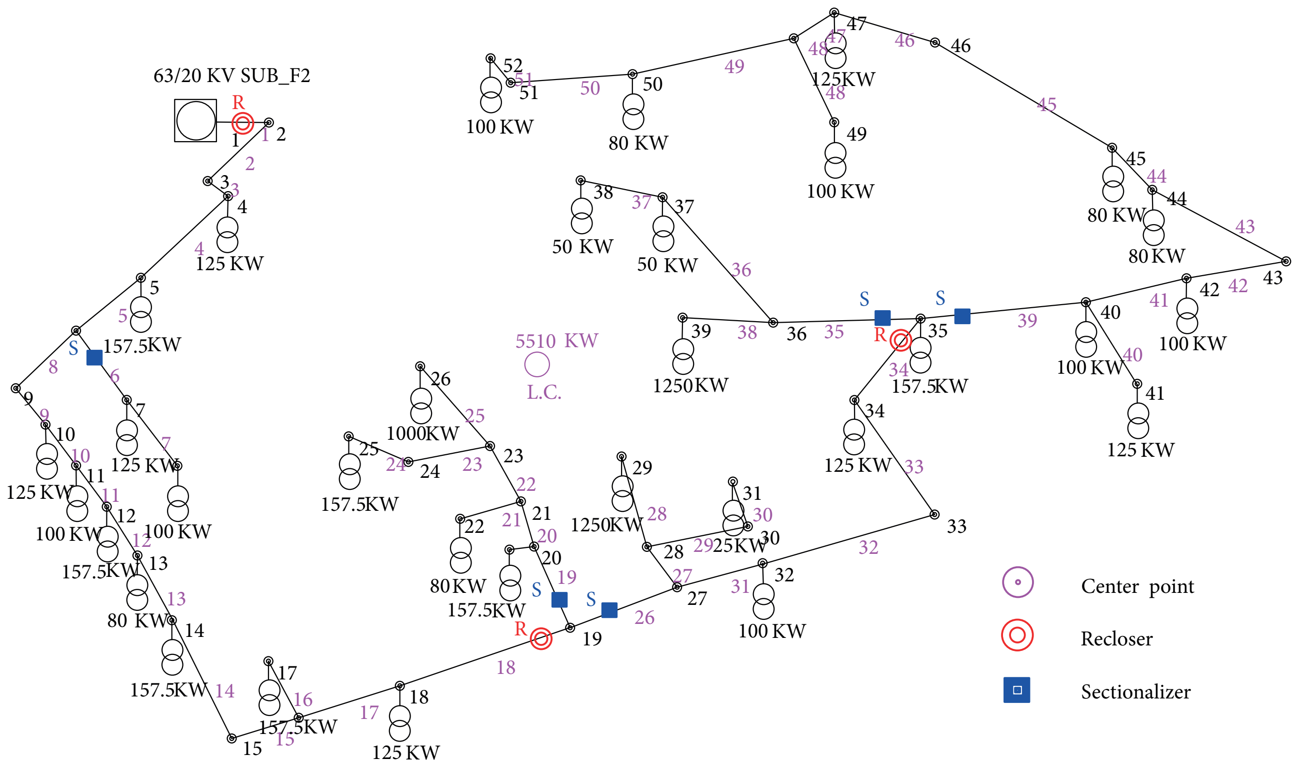

Figure 8. Optimal locations of AR/S in feeder F2 with RFw.

5. Conclusion

A new model to determine the location and number of AR/S switches including reclosers and sectionalizers in power distribution networks is presented in this paper. The AHP algorithm is used to obtain the weights of reliability parameters by decision-makers. The objective function is derived considering the cost of undistributed energy, investment cost, maintenance cost, and weight-reliability factor. The optimal size and location of automatic switches are determined using the PSO algorithm based on worth/cost analysis. A computer program is presented to implement the proposed method in two 20-kV feeders of Isfahan's electric distribution network. The importance of the protective and switching devices' placement has been shown in reducing the energy not supplied and enhancing system reliability by means of the results in this case study. As a new method in this paper compared with similar literature studies, the viewpoint of decision-makers based on the suggested weights of the reliability indices is considered in AR/S placement. Using the suggested scheme in real and large networks with distributed generations will show the greater effectiveness of the proposed method.

6. Nomenclature

Indices and sets

i,m	Index and set of the system buses
j,k	Index and set of the system sections
i,j	Index and set of the section nodes
Vj	Voltage of load j
rj/xj	Line resistance/Line reactance in section j
Pj/Qj	Active power/Reactive power of section j

PLj/QLj	Active power/Reactive power of load j
SAIFIw,i	Weight and index of SAIFI
SAIDIw,i	Weight and index of SAIDI
MAIFIw,i	Weight and index of MAIFI
Nj/NT	Number of load in bus j/Total number of load
Ci/Li	Interruption cost/Average energy
Parameters and constants	
Sect/Nod	Section of system/Node of section
L	Section length
Pk	Power losses
V	Node voltage
I	Section current
SAIFI	System average interruption frequency index
SAIDI	System average interruption duration index
MAIFI	Momentary average interruption freq. index
CR_INV/NR	Cost of recloser/Number of recloser
CS_INV/NS	Cost of sectionalizer/Number of sectionalizer
CRM/CSM	Maintenance cost of recloser/sectionalizer
ENS	Energy not supplied
AR/S	Autorecloser switch/Sectionalizer switch
AHP	Analytical hierarchy process
PSO	Particle swarm optimization
grf	Annual load growth factor
GA	Genetic algorithm
Isc/Ief	Short circuit current/Earth fault current
U	Average interruption time
γ	Momentary interruption
λ	Failure rate
$X,\ Y$	Load location
XL, YL	Load center location
Functions and variables	
INVC	Investment cost
MAINTC	Maintenance cost
ENSC	ENS cost
PER/K	Profit of ENS reduction/Equation factor
TC /Fn	Total cost/Objective function
RFa	Reliability factor based on indices average

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