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Improving Reliability by Optimal Allocation of Protection Devices and Distributed Generation Units

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Abstract
In this paper, two protective devices, recloser and cutout fuse, are placed simultaneously. Indeed, main contribution of this research is considering Distribution Generation (DG) placement in this problem. The multi objective function has been formulated based on minimizing power loss and maximizing reliability. Selection of reliability indices has been performed based on a compromise between customer satisfaction and seller. This problem is solved by Particle Swarm Optimization (PSO) algorithm and tested on the part of practical distribution system. The reliability indices are System Average Interruption Duration Index (SAIFI), Cost of Energy Not Supplied (CENS), System Average Interruption Frequency Index (SAIFI) and Momentary Average Interruption Frequency Index (MAIFI). Simulation has been performed in part of practical distribution system by introduced several scenarios and cases.

Keywords: Protection design, Particle swarm optimization algorithm, Reliability improvement, Distribution network.

1. INTRODUCTION

Although there are hundreds of complex elements in power network, outage and distortion may always occur. Breaking of conductors' insulation may results in tremendous losses in equipment and pause power supply. In order to solve such problems, power system equipment should be protected accurately. Protection relays in power networks are designed and applied to protect against tremendous losses and preserve stability of power system. A protective device along with a circuit breaker can improve reliability and security of network with its fast and correct performance [1]. When a fault occurs in feeders of distribution network, power switch of the feeder is first interrupted and distribution substations which are fed by this feeder are blacked out. Thus, it is necessary to identify fault location and isolate damaged part from correct parts of the feeder through disconnecting proper stationers. Then, maximum maneuverability of the system is used to feed the correct part of the feeder; the damaged part and parts of the feeder which cannot be used for maneuver remain blacked out until the problem is resolved. Protection devices of distribution feeder are installed according to instructions of electricity distribution corporate and engineering ideas. In general, protecting a distribution system includes circuit breakers of the substation, line reclosers, stationers and fuses which are along the main feeder and side branches [2]:

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Main purpose of planning and exploiting electrical energy distribution systems is to provide load and energy reliability economically such that it has the required quality. Low cost electrical energy is in conflict with high reliability level, because creating higher levels of reliability requires cost-effective investment and exploitation, which justifies focusing on optimization of costs and reliability.

Considering the above discussion, one of the efficient approaches for improving reliability of distribution networks is to use switching-protection devices in maneuver points of the system effectively, such that not only outage range is shortened, but also restoration time after fault is also reduced. Number and location of these devices affects successful maneuver in distribution networks. Reliability of this part of power network can be improved significantly through proper design of such devices. Optimal placement of switches and protection devices in distribution networks provides the possibility for better performance and improves reliability of the system. Designing such issues is very difficult which is due to different combinational constraints and nonlinear objective functions. Thus, intelligent computer methods like genetic algorithm, PSO, differential evolutionary algorithm are used. Placement of protection devices in strategic points is an important problem in designing distribution network with the purpose of improving reliability indices. In [3], placement of recloser and protection devices is performed for improving reliability using point estimation method (PEM). In optimal placement, minimizing investment costs in different loading conditions, generation penetration level and power factor are considered. Differential Evolutionary (DE) algorithm is used to solve location of recloser and switch. In [4], placement of recloser is performed to maximize reliability. Optimal placement based on cost/profit is performed using Improved Particle Swarm Optimization (IPSO) on a 50-bus network in Qazvin-Iran.

Popuick et.al [5], have employed Nonlinear Integer Programming with binary variables for placement of protection devices in the main feeder and all branches of the air distribution circuit to improve reliability indices and provide the required reliability. Problem is studied considering technical and economic constraints like coordination of protection devices, available equipment, and importance of feeder and topology of the circuit. In [6], recloser switches are introduced. In the proposed objective function for improving reliability indices and increasing profit of system operator, DE optimization algorithm is used.

In [7], Differential Search (DS) algorithm is proposed to solve reliability optimization in the distribution network. Purpose of the problem is to determine optimal number and location of remote control switch (RCS) to maximize reliability of a radial distribution system. In [8], a similar work is conducted which is compared with PSO and proves superiority of DS algorithm. In [9], optimal placement of switches in an IEEE-123 bus network is studied to minimize deterministic cost, remove network imbalance, reduce natural current and power losses using NM algorithm with BF based on multiple-objective fuzzy function. In order to prove superiority of the proposed method, test is performed on a 123-bus network and its results are compared with BF, PSO and genetic algorithms.

Reducing losses, minimizing costs, increasing profitability of the network and improving voltage indices like profile and voltage stability are objective functions which have been widely used in previous studies. Studying different distributed generation resources and their optimal placement is also conducted in [10]. In [11], an intelligent method based on GA is proposed for optimal placement of sectionalizer in a radial intelligent system. In [12], a microprocessor based on control unit which has required compatibility with existing reclosers is proposed. Control unit is able to operate locally or remotely. Required power is so low that lifetime of lithium battery after 10 years is not finished without requiring charging circuit. In [13], effect of high penetration of DG on protection devices is searched and an adaptive protection planning is defined as the solution. Simulation results of executing this scheme on a real distribution feeder are reported.

In coordination of recloser-feeder is studied in [14] using a specific network for protecting the considered fuse. Constraints of recloser equipped with over-current elements compared to fuse storage in the presence of DG are also studied. An adaptive relaying strategy is also proposed to guarantee fuse protection in the new scenario even in worst relaying conditions. Simulation results obtained from adjustment of adaptive variable relay in responding to structural changes of DG in simulation process have been proved. In [15], a step-by-step meta-heuristic algorithm with the purpose of minimizing power loss is proposed. The proposed method is based on Dynamic Switches Set Approach which is updated through structural changes of electrical networks. The proposed algorithm considers demand changes in load curves of the system and determines performance sequence of switches during reconfiguration process to obtain exploitation points. Analytic Hierarchic Process (AHP) is proposed to determine best switching sequence for optimal reconfiguration of distribution network in [16]. Moreover, technical feasibility of feeders with parallel connection during reconfiguration process is analyzed considering transient constraints. This technique assumes that only remotely controlled switches are analyzed. The proposed algorithm in places in monitoring system of the network and provides the possibility for quick response of measurement devices. The proposed method is tested on a real network and the results are discussed.

Jazebi and Vahidi [17] have proposed the best switching sequence with the purpose of improving power quality (reducing harmonic and losses) using DE algorithm. Simulation results in different cases are compared with initial state of the distribution network; then superiority of the proposed method is discussed. In [18], a method based on Bacterial Foraging Optimization for switching sequence is proposed to minimize power losses. A new model is proposed through simplifying the distribution network and reconfiguration problem is formulated as a nonlinear optimization problem. Some modifications are applied to preserve radial structure and reduce search space on characteristics of the distribution network.

By studying objective functions, it can be claimed that none of them are as comprehensive as the objective function proposed in this paper. In the proposed objective function, three reliability parameters along with power loss are included. Selecting parameters of the objective function is performed purposeful to provide customer and seller demands. On the other hand, in studies, only one switching component is placed, while the distribution network has a variety of switches and behavior of switches affects each other. Thus, switches should be places simultaneously. Rest of this paper is organized as follows: section 2 introduces reliability indices in the distribution network. Section 3 presents objective function and the proposed model. Section 4 briefly discusses the optimization algorithm; simulation results and conclusion are given in sections 5 and 6, respectively.

2. INVESTIGATING RELIABILITY INDICES IN DISTRIBUTION NETWORK

In general, common indices of electricity corporate in evaluation of reliability of a distribution system are as follows:

- ***System Average Interruption Frequency Index (SAIFI):*** This index is defined to get information about average number of interruptions of each consumer in a specified region according to Eq. (1).

$$SAIFI = \frac{\sum_{i=1}^{n} U_i}{\sum_{i=1}^{n} N_i} \tag{1}$$

Where, Ni is total number of consumers and Ui is outage duration.

- ***System Average Interruption Duration Index:*** This index commonly indicates interruption duration in minutes which is used to avoid information regarding average interruption time of each consumer:

$$SAIDI = \frac{\sum_{i=1}^{n} N_i U_i}{\sum_{i=1}^{n} N_i} \tag{2}$$

- ***Momentary Average Interruption Frequency Index***: MAIFI is used to measure average number of momentary interruptions of a consumer during one time period. MAIFI is used to study momentary interruptions through calculating total number of system equipment multiplied by number of consumers. In this equation, ID_i is number of operations of interrupted equipment; opening and closure are considered as an event:

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

- ***Average of Energy Not Supplied:*** This index describes not supplied energy for all consumers. This index is a combination of probability of events and their consequences; it provides the possibility to calculate cost of energy not supplied; thus, it is widely used to compare different development and exploitation options:

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

In this equation, $L_{i(a)}$

3. OBJECTIVE FUNCTION AND SYSTEM MODELING

Purpose of placement of system protection devices is to improve reliability indices and reducing system losses. Thus, in the objective function of Eq. (5), all reliability indices in addition to system losses are considered to be normalized. For this purpose, values of parameters of objective function are divided to values before placement and after placement. Using this technique, each parameter is normalized based on a logical and scientific value:

$$OF = \sum_{k=1}^{ny} \left\{ \begin{array}{l} \dfrac{SAIDI_k}{SAIDI_0} + \dfrac{SAIFI_k}{SAIFI_0} + \dfrac{CENS_k}{CENS_0} + \\ \dfrac{MAIFI_k}{MAIFI_0} + \dfrac{Loss_k}{Loss_0} \end{array} \right\} \tag{5}$$

In this equation, indices k and 0 are values before and after placement. In some references, weighting factors are used to solve such problems which are not a logical method for solving these problems, since these factors are initialized by the user; in practice, effect of parameters with lower values in the objective function is reduced. While, in normalization technique, effect of all three parameters on the objective function is the same.

- ***Constraints Governing the Problem***

Constraints governing the problem mainly include exploitation constraints and problems regarding power quality which should be considered.

- ***Power Flow Convergence***

Considering power flow condition is the first constraint which should be met, power flow validity is the first step in optimal placement of capacitor and DG. Eq. (6) and (7) represent power flow relations for active and reactive power.

$$P_{gi} - P_{di} - V_i \sum_{j=1}^{N} V_j Y_{ij} \cos\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{6}$$

$$Q_{gi} - Q_{di} - V_i \sum_{j=1}^{N} V_j Y_{ij} \sin\left(\delta_i - \delta_j - \theta_{ij}\right) = 0 \tag{7}$$

- ***Voltage and Power Range***

After placement, voltage of each bus should be in an acceptable range. Bus voltage which is lower than minimum defined voltage indicates that proper power flow of capacitance banks and DG units has no effect in terms of amplitude and capacity; if the voltage is greater than upper bound voltage, voltage swell is created. Thus considering Eq. (8) which guarantees voltage changes in an acceptable range is one of the objectives of capacitance and DG placement.

$$V_i^{\min} \le V_i \le V_i^{max}, i = 1, \ldots, N \tag{8}$$

$$P_{ij}^{\min} \le P_{ij} \le P_{ij}^{\max} \quad , i = 1, \ldots, N \tag{9}$$

One of the important objectives is to keep system losses under an acceptable value, which is represented by Eq. (9).

- ***Installed capacity***

Maximum installed capacity should be less than or equal to existing reactive load of the network; that is, the installed capacitance should not be so high that network becomes capacitive and show capacitive behavior. This concept is shown in Eq. (10).

$$Q_c^{Total} \le Q_L ,\, Q_c^{Total} = \sum_{i=1}^{N_c} Q_i \qquad (10)$$

In the above relationship

V_i :Voltage bus i

P_{ij} :Active power pass from bus i to j

P_{gi}, Q_{gi}: Active and reactive power generated at the bus i

P_{di}, Q_{di} : Active and reactive loads in the bus i

V_i, δ_i: Size and angle of the bus voltage

θ_{ij}, Y_{ij} : Elements of Admittance Matrix , Angle of Admittance Matrix.

Qc^{Total}: Total reactive power Connected by Capacitive Bank for Radial Distribution Network.

Q_L^{Total}: Reactive loads in Radial Distribution Network

4. PSO ALGORITHM

Main idea of PSO algorithm is based on a population which is called swarm. Swarm includes people where each member is called a particle. Each particle in the swarm represents a potential solution of the problem. Each particle moves with a random velocity through a D-dimensional search space.

P is the average load connected at loading place.

Basic concept of PSO is shown in Fig. 1. Each particle updates its speed, position and flight experience. If each particle, which is called particle i, is located at (xik) in two-dimensional search space randomly, the particle flies with a random speed (vik) through search space of the problem. Remained particle is the best position and it is stored as (pbestik). Then, each particle shares its information with the neighboring particle. In other words, each particle compares its best position with best position of other particles. Finally, each particle stores its position in the whole swarm as gbestk [20].

The problem encoding in the MATLAB application is follows.

Step 1, Introduction of information:

In the first step, information required for executing the program should be presented. In general, 3 classes of information are required. Information of equipment including number of reclosers, number of cut out fuses, number of secondary relays and number of DGs. Network information including reactance and resistance of line, tap changer coefficient, number of nodes, Active power of buses, reactive power of buses and line length. Algorithm information are including maximum iteration, number of iterations, number of particles, mutation rate and selection measure

Step 2, Creating Section Matrices:

Section matrix is a matrix which has two columns where the first column includes number of sections and number of second column is the number of last section which the protection system protects from section of the first column to that section. In this step, fault detection duration is also considered.

Step 3, Creating Random Matrix:

In this step, a random matrix of initial population size and number of generation parameters is created to execute PSO algorithm.

Step 4, Creating Network Information Matrix:

A matrix with power, line length, number of consumers and fault detection time of protection regions are completed to be used for optimization.

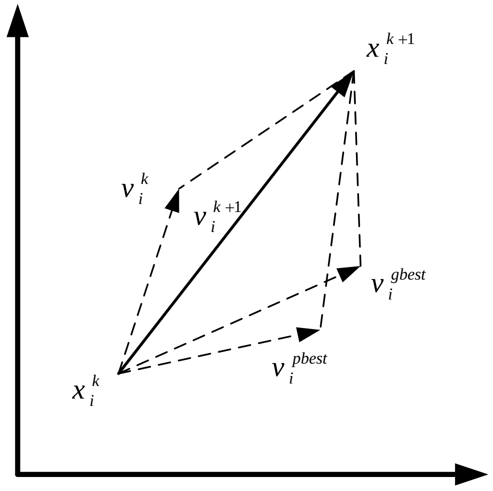

Fig. 1. Basic concept of PSO algorithm.

Step 5, Creating Maintenance Matrix for Protection regions:

For this purpose, maintenance matrix for protection regions and it can be converted into column or row from like other matrices (in terms of dimension).

Step 6, Executing PSO Algorithm:

Operators of PSO algorithm are applied to existing generations so that solutions become better. To this end, three operators of selection, crossover and mutation are executed in this step [20].

Step 7, Investigating Devices

In this step, a matrix is created to detect side feeders and detect side supply points; devices are selected considering available information.

Step 8, Investigate values of reliability parameters.

Step 9, Investigate vectors for maintenance, transient and permanent states.

Step 10, Calculating final protection power in maintenance.

Step 11, Classifying costs and its parameters

Step 12, Investigating if number of iteration is met and return to step 4 if the condition is not met.

Step 13, Extracting optimal outputs

5. SIMULATION RESULTS

Simulation is performed on 115-bus network of Tabriz. Fig. 3 shows single-line diagram of this network [21]. Since performing this study requires type of consumer and consumption loads, standard networks cannot be used in practice. Thus, there is no way other than implementing the program on a real network.

It should be mentioned that in these studies, based on scenarios and various states, main focus is on investigating three parameters of reliability. Mainly, profit of seller and customer are totally different. Distribution corporate as the seller tends to sell as much electricity as possible, even if it results in outage and reduces customer satisfaction. In fact, distribution corporate prioritizes increasing its agreements and not customer satisfaction. Thus, reducing CESN is important for the distribution corporate and improving SAIDI and SAIFI is not much important. on the contrary is customer for which it is not important that distribution corporate as the interface between customer and main electricity resource sells how much electricity; quality is important for the customer. Electricity seller wants to receive electricity with minimum interruption (SAIFI) and shortest interruption time (SAIDI) and reducing average energy not supplied is not important. Therefore, considering the confliction between profit of the seller and consumer and different definition of seller and consumer, reliability improvement in each scenario is discussed based on number of placed equipment and comparison of reliability parameters.

For the above network, 4 scenarios based on number of placed equipment are proposed

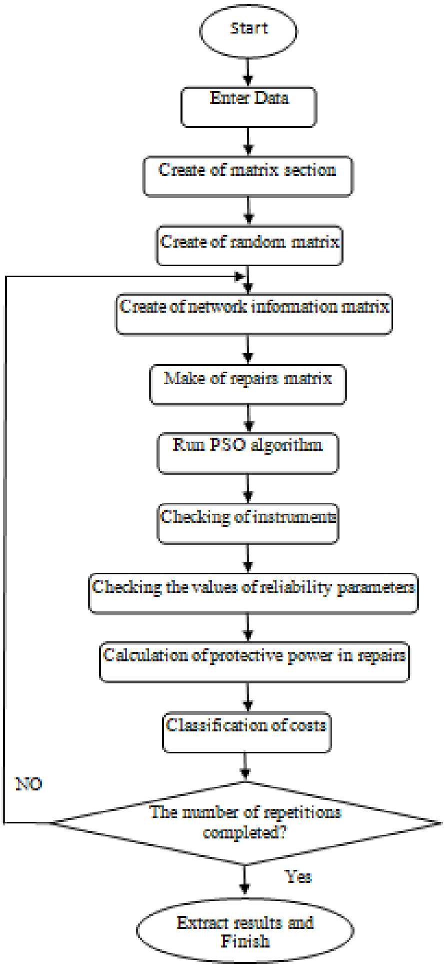

Fig. 2. Flowchart of executing the program.

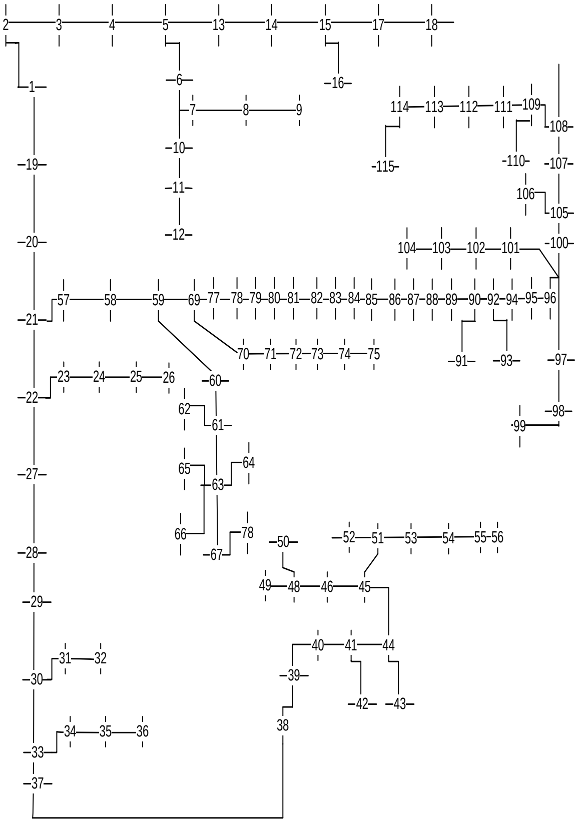

Fig. 3. Single Linear 115-Bus Diagram of Tabriz.

For the above network, 4 scenarios based on number of placed equipment are proposed. In each scenario, a number of cases are presented. Each case has 4 numbers which represent number of reclosers, secondary relays, cut out fuse and DG. These scenarios are as follows:

- Scenario 1: placing less than 5 equipments
- Scenario 2: placing 5 equipments
- Scenario 3: placing 6 equipments
- Scenario 4: placing more than 6 equipments

Scenario 1, placing less than 5 equipments:

In the first scenario, less than 5 equipments (1, 2, 3 and 4) are placed. Results of placing 1, 2, 3 and 4 equipment can be seen in Table 1.

Considering values of Table 1, as expected, 1011 has the best solution which is obvious considering number of placed units. It should be noted that 1111 state has almost reached 1011. Worst possible solution is given by 0100. Table 2 shows location of placed equipment in the first scenario.

Table 1*: Allocation results in scenario 1.*

State	CENS	MAIFI	SAIFI	SAIDI	Losses (kw)	Objective Function
0001	512805	17.00	76.00	99.38	190.81	1.3197
0010	303585	12.56	56.17	54.79	336.88	1.4840
0011	272633	12.56	56.17	56.17	213.74	1.1055
0100	345352	13.77	61.56	66.30	336.88	1.5495
0101	351077	14.99	67.01	79.05	190.78	1.1692
0110	282274	12.22	54.65	52.66	336.88	1.4641
0111	243068	12.22	54.65	52.66	219.99	1.1006
1000	328985	13.28	59.39	61.05	336.88	1.5220
1001	289012	13.70	61.26	65.39	190.78	1.0890
1010	211959	9.61	42.99	36.31	336.88	1.3495
1011	207527	10.94	48.95	45.61	190.78	0.9595
1100	205411	11.61	51.93	42.75	336.88	1.3985
1101	211306	12.83	57.38	51.81	190.78	1.0102
1110	235360	10.74	48.04	44.71	336.88	1.3991
1111	183802	10.18	45.53	37.30	207.62	0.9669

Table 2*: Location of placed equipment in the first scenario.*

State	Cut Out Fuse	Secondary Relays	Recloser	Number of bus DG (kw-kvar)
0001	-	-	-	(0.6-1)114
0010	69	-	-	-
0011	69	-	-	(0.5-0.75)114
0100	-	88	-	-
0101	-	105	-	(0.6-1)114
0110	69	105	-	-
0111	69	105	-	(0.5-0.95)86
1000	-	-	78	-
1001	-	-	86	(0.6-1)114
1010	69	-	2	-
1011	4	-	86	(0.6-1)114
1100	-	88	22	-
1101	-	105	22	(0.6-1)114
1110	4	105	86	-
1111	69	93	38	(0.45-0.95)100

Considering results of Table 2, buses 86, 105, 69 and 114 are the most possible locations for installing recloser, secondary relay, cut out fuse and DG.

Scenario 2, placing 5 equipments:

In this scenario, total number of placed equipment is 5. Optimal values of reliability, power loss and objective function of 5 components are shown in Table 3.

Considering results of Table 3, states 1112 and 1121 give the best and worst solutions. Significant reduction of MAIFI in 1211 is considerable. However, except in 1121 state, in other states, no power is injected to the network but power loss varies negligibly. Optimal location of protection devices, location and optimal capacity of DG resources in the second scenario can be seen in Table 4.

Scenario 3: placing 6 equipments:

In the third scenario, total number of 6 equipments is placed in Tabriz network. Results of scenario 3 are shown in Table 5.

Considering what is offered in Table 5, it can be said that 1122 state is the worst possible state and the only state in which objective function has exceeded 1. 2211 state is also the best possible solution. This state generates the best possible solutions for SAIFI, MAIFI and power losses. Table 6 represents location of placed equipment based on concept of the third scenario.

Considering results of Table 6, it can be said the most probable location for installing recloser, secondary relay, cut out fuse and DG is in buses 19, 88, 105 and 97.

Scenario 4: placing more than 6 equipments:

Last scenario is placing more than 6 equipments. Optimal values of reliability, power loss and objective function parameters for this case are shown in Table 7.

Considering Table 7, it can be said that the best solution is obtained in 2212 state, while worst solution is obtained in 2222 state.

Table 3*: Allocation results in scenario 2.*

State	CENS	MAIFI	SAIFI	SAIDI	Losses (kw)	Objective Function
1112	198517	12.79	57.18	59.15	190.81	1.3197
1121	192646	10.38	46.40	42.13	336.88	1.4840
1211	103723	7.88	35.23	24.38	213.74	1.1055
2111	159078	10.38	46.41	35.37	336.88	1.5495

Table 4*: Location of placed equipment in the second scenario.*

State	Cut Out Fuse	Secondary Relays	Recloser	Number of bus DG (kw-kvar)
1112	10	105	86	(0.6-0.95)114 , (0.6-1)105
1121	18 , 23	88	2	(0.4-0.95)114
1211	4	70 , 88	22	(0.4-0.9)114
2111	10	26	22 , 78	(0.5-0.9)114

Table 5*: Allocation results in scenario 3.*

State	CENS	MAIFI	SAIFI	SAIDI	Losses (kw)	Objective Function
1122	246233	12.22	54.64	52.23	192.23	1.0186
1212	135080	9.16	40.96	33.38	186.83	0.8569
1221	155156	10.29	46.02	41.77	204.40	0.9572
2112	100059	12.03	53.80	39.50	169.33	0.8576
2121	162482	11.89	53.16	39.94	208.63	0.9988
2211	108494	9.74	43.54	38.50	212.17	0.9210

Table 6*: Location of placed equipment in the third scenario.*

State	Cut Out Fuse	Secondary Relays	Recloser	Number of bus DG (kw-kvar)
1122	23 , 4	22	19	(0.4-0.45)100 , (0.6-0.45)105
1212	69	105 , 88	2	(0.45-0.4)97 , (0.25-0.85)44
1221	23 , 4	105 , 88	86	(0.5-0.95)44
2112	69	93	19 , 78	(0.25-0.7)97 , (0.1-0.9)114
2121	26 , 23	70	19 , 88	(0.55-0.85)100
2211	10	88 , 70	19 , 22	(0.45-0.85)97

Table 7*: Allocation results in scenario 4.*

State	CENS	MAIFI	SAIFI	SAIDI	Losses (kw)	Objective Function
1222	144485	9.33	41.71	34.27	195.30	0.8911
2122	108544	8.99	40.20	33.10	170.23	0.7927
2212	791458	8.45	37.81	26.64	141.94	0.6721
2221	109990	6.53	29.21	20.08	253.56	0.9658
2222	114278	7.50	33.55	24.28	277.13	1.0650

Table 8*: Location of placed equipment in the forth scenario.*

State	Cut Out Fuse	Secondary Relays	Recloser	Number of bus DG (kw-kvar)
1222	69 , 4	93 , 88	2	(0.35-0.8)53 , (0.55-1)114
2122	23 , 4	70	86 , 78	(0.25-1)97 , (0.25-0.4)114
2212	10	105 , 88	22 , 2	(0.6-0.95)97 , (0.05-0.85)114
2221	42 , 23	70 , 26	78 , 2	(0.1-0.7)100
2222	10 , 4	70 , 26	86 , 38	(0.55-0.595)55 , (0.3-0.8)44

In other words, although it was expected that increasing number of units improves the solution, it has been degraded; which is due to saturation of the network. In other words, number of placed equipment is more than required. Thus, placement procedure is stopped. Optimal location of protection equipment, optimal location and capacity of DG units of the fourth scenario can be seen in Table 8.

Considering Table 8, it can be said that buses 2, 70, 4 and 114 are the best locations for installing recloser, relay, fuse and DG.

6. CONCLUSION

In this paper, placement of protection devices along with DG in distribution network with the purpose of improving reliability is proposed. For this purpose, 4 reliability parameters are considered in formulation of the problem which include: Cost of energy not supplied (CENS), system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI) and momentary average interruption frequency index (MAIFI). Parameters are selected based on improvement of reliability from seller and customer points of view and improving reliability of transient and permanent faults. Simulation is performed on 114-bus network of Tabriz considering 4 scenarios. Simulation results show that considering the objective function, it can be claimed that optimal placement of protection devices with the purpose of improving reliability of distribution networks is of great importance.

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