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Distribution Network Reconfiguration in Order to Reduce Losses and Lines Loading Risk, and Improve Voltage Profile and Reliability Using Runner and Root Algorithm

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Abstract—*In this paper, distribution network reconfiguration problem has been modeled and then solved. This problem is related to power system operation studies from the time point of view. Network losses, voltage profile, risk of lines loading, and system reliability are indices that have been considered in operation phase. The network losses has been calculated by power flow tools. Also, uncertainties in demand and topology of radial distribution network have been included in the problem formulation. In present paper, uncertainty in demand has been modeled using fuzzy formulation of the load level and fuzzy power flow by triangular numbers. The proposed framework has been modeled as a multi-objective problem and solved using runner and root algorithm (RRA). Technical limitations beside assumption of radial network considerably reduce the search space of the algorithm. This online problem has to be solved in a short time using intelligent methods like RRA, because mathematical optimization approaches are so time consuming and are not appropriate to solve such online problems. The proposed model has been tested on IEEE 33-bus distribution system. The simulation results show the effectiveness and robustness of the proposed solution method, because it takes a few seconds to solve the problem.*

Index Terms—*Reliability assessment, runner and root algorithm, network reconfiguration, distribution systems, maneuver feeders, automatic switches.*

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I. INTRODUCTION

Power networks consists of three main parts of generation, transmission, and distribution. Distribution system is the last part of power network that provides the connection between loads and the network. Voltage levels of distribution systems are low, so, their power losses are large amount. On the other hand, in distribution networks, maintaining the reliability in a desired level is difficult and its assessment is complicated, because these networks are large-scale and include many devices and equipment. Hence, distribution system operators and engineers should find more optimal methods to reduce the losses and increase the reliability. A way for the distribution losses minimization and reliability improvement is to install the automatic switches and maneuver feeders in these networks. In planning studies, the main goal is to determine optimal number and the best installation place of this equipment (automatic switches and maneuver feeders) economically. In operation studies (present paper), the aim is to find the best way for optimal operation of this equipment in contingency states according to load variations. To do so, all data about network configuration, lines impedance, and consumption of each load bus have to be available, but the information of load level needed to be forecasted. In power systems, load can be modeled in three ways: load with fixed impedance, load with fixed power, or load with fixed current. Thus, for load forecasting, we need to know how much each of above-mentioned amounts (load impedance, load power, or load current) will increase with the time. Usually, the problem of distribution network reconfiguration is solved in order to reach the minimum losses, improve the voltage profile, increase the reliability, and etc. The time of solution for this problem is so important, because it is an online problem and needs to be solved fast. Thus various papers and research proposed different methods to solve this problem.

Ref. [1] presented branch and bound algorithm to minimize the network losses in distribution system reconfiguration. Also, Refs [2]-[7] employed the classic mathematical methods to solve the reconfiguration problem. For the first time, Ref. [8] reduced the distribution losses using genetic algorithm (GA). After publication of [8], also, Ref. [9]-[12] applied the GA to solve the problem. Refs [13] and [14] introduced new genetic algorithm based methods by limiting the search space of genetic operators to decrease the power losses in distribution network reconfiguration. Ref. [15] represented ant colony optimization (ACO) method to solve the reconfiguration problem. Also, Ref. [1] solved a multi-objective reconfiguration problem considering voltage profile and network losses. Later, Ref. [17] modeled the load demand as fuzzy in problem presented by [16].

Also in Iran, much research [18]-[20] has been presented about reconfiguration of distribution systems. Ref. [18] has tried to minimize the losses and maximize the reliability for the reconfiguration problem using different heuristic algorithms. Then, it was compared the solution of each algorithm with another to show which of them is more efficient to solve the problem. Ref. [19] solved the problem in order to only decrease the losses using genetic algorithm. Ref. [20] tried to find the best reconfiguration plan and distributed generation (DG) location using particle swarm optimization (PSO) algorithm. Finally, Ref. [21] solved the distribution reconfiguration problem as a multi-objective optimization problem in order to improve the voltage profile, and decrease the network losses and lines loading.

Thus, in current literature, the problem of [21] is solved by using a new metaheuristic method. Metaheuristic optimization methods were used in [22] for the first time. These methods have been inspired by nature to solve the practical problems. Genetic algorithm [23] is the first metaheuristic method that was applied for solution of the optimization problems. After it, PSO [24], [25], ACO [26], [27], artificial bee colony (ABC) [28], [29], simulated annealing (SA) [30], [31], and other methods presented. Runner and root algorithm (RRA) is the newest metaheurist method that has been used by [32] in 2015.

Heuristic methods are extensively used to solve the reconfiguration problem and determine the maneuver points [33]-[35]. Ref. [33] used the Tabu search algorithm to find optimal arrangement of distribution system in order to minimize the network losses. In addition, Ref. [34] employed the cuckoo search algorithm (CSA) to optimize the distribution losses and voltage profile in reconfiguration problem. Lastly, Ref. [35] applied krill herd algorithm and GA for distribution system reconfiguration in order to improve voltage profile and network losses.

II. MODELS AND CALCULATION TOOLS

In this section, reconfiguration problem is formulated. To do so, all related models including power flow and reliability criteria calculations, as well as fuzzy numbers have to be described before presentation of objective function and problem constraints. Regarding this fact that mathematical model presented in this paper is nonlinear and discrete, intelligent optimization methods are extensively used by the researchers for problem solution. Therefore, here, RRA method that is one of artificial intelligence algorithms is used to solve proposed multi-objective reconfiguration problem. Consequently, this algorithm needed to be described more in this section.

2.1 Power Flow Calculations

As it is mentioned earlier, forward and backward power flow has been applied in this paper. This method is based on two matrixes that can be driven from network topology. One of them is matrix of branches current versus buses current and another is matrix of buses voltage in terms of branches current. The first matrix is known as "bus injection to branch current (BIBC)" and the second one is called "branch current to bus voltage (BCBV)". In following, first organization method of matrix BIBC and then formation method of matrix BCBV are explained.

1) Matrix of feeders' current to buses injection current (BIBC):

Complex power S_i for bus i can be calculated by (1).

$$S_i = \left(P_i + Q_i\right) \qquad \forall i = 1, 2, ..., n \tag{1}$$

Where, n is number of buses. In this way, currents injected to the buses are computed as follows.

$$I_i^k = \left(\frac{P_i + Q_i}{V_i^k}\right)^* \tag{2}$$

In (2), V_i^k and I_i^k are voltage and current injection of bus i in kth iteration, respectively. Generally, relationship between buses current and lines current can be written as (3).

$$\left[B\right] = \left[BIBC\right]\left[I\right] \tag{3}$$

In above-mentioned relation, [B] is matrix of lines current and [I] is matrix of buses current.

2) Matrix of buses voltage to branches current (BCBV):

Relationship between current of branches and voltage of buses is established by Kirchhoff voltage law (KVL) as equation (4).

$$\begin{aligned} \left[V_j\right] &= \left[V_i\right] - \left[\Delta V\right] \\ \left[\Delta V\right] &= \left[BIBC\right]\left[B\right] \end{aligned} \qquad (4)$$

V_i and V_j indicate voltage of start and end buses of branch *ij*. In this manner, voltage of each bus can be determined by this equation. Equations (1)–(4) describe Kirchhoff current law (KCL) and KVL for a radial distribution system. Therefore, it is necessary that voltages of the buses are available to calculate the power flow through equation (1). However, these voltages are unknown and we need to determine them. Consequently, following iterative process is needed to be employed to calculate the power flows.

Step 1: Assume a predefined amount for voltage of all buses (For example V_i=V_j =1 pu).
Step 2: Calculate current injection to buses using (2).
Step 3: Determine the current of branches (lines) by (3).
Step 4: Calculate voltage of buses via (4).
Step 5: Stop the calculations if new values of voltages are so near to previous values, otherwise go to step 2 and continue the process by new voltages.

2.2 Reliability

A set of reliability indices has to be defined to evaluate the reliability of distribution network in hierarchical level III like other hierarchical levels (generation reliability belongs to hierarchical level I and transmission one is related to hierarchical level II). System average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption frequency index (CAIFI), customer average interruption duration index (CAIDI), and energy not supplied (ENS) are well-known reliability criteria in distribution networks. Among above-mentioned indices, in this paper, ENS criterion is used to assess network reliability, because its efficiency has been evaluated already in calculation of interruption costs by other important literature. Required equations to calculate above-mentioned reliability criteria consist of two stages. In the first stage, nodal indices of each load point are determined as follows:

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \left(\frac{f}{yr}\right) \qquad (5)$$

$$U_s = \sum_{i=1}^{n} \lambda_i r_i \left(\frac{h}{yr}\right) \qquad (6)$$

$$r_s = \frac{U_s}{\lambda_s}\left(\frac{f}{yr}\right) \qquad (7)$$

It should be noted that radial distribution system presented here is modeled as a series system. Therefore failure rate of each load point is equal to sum of failure rates of all equipment located before this point. The second stage is to calculate each reliability criterion. ENS index is computed as (8).

$$ENS = \sum_{j=1}^{n}\sum_{i=1}^{m} \lambda_i r_{ij} P_j \qquad (8)$$

Where, *n* is number of load buses and *m* is number of sections.

2.3 Fuzzy Theory

Fuzzy logic is an efficient method to calculate uncertainties. This conception is based on human knowledge and it does not include any mathematical equations like relations used in probabilistic models. A fuzzy number treat like a probability distribution function without any certain value. It includes a membership function that has uncertain values in a predefined interval. According to Fig. 1, fuzzy numbers used in this paper are considered as a triangular function. This membership function has three characteristics: start, maximum, and end values. Equation (9) describes this function.

Fig. 1: Triangular fuzzy number

$$\mu_A(x)=\begin{cases} 0 & for\ x \prec a_1 \\ \dfrac{x-a_1}{a_2-a_1} & for\ a_1 \le x \le a_2 \\ \dfrac{a_3-x}{a_3-a_2} & for\ a_2 \le x \le a_3 \\ 0 & for\ x \succ a_1 \end{cases} \qquad (9)$$

In following, four main algebraic operations on fuzzy numbers with triangular membership function are explained, because they are used in power flow calculations.
Assume two fuzzy numbers with triangular membership function are available as follows:
A= (*a₁*, *a₂*, *a₃*) and *B*= (*b₁*, *b₂*, *b₃*)
In this case, four main algebraic operations are defined as (10) to (13).

$$\tilde{A}+\tilde{B}=\left(a_1+b_1, a_2+b_2, a_3+b_3\right) \qquad (10)$$

$$\tilde{A}-\tilde{B}=\left(a_1-b_3, a_2-b_2, a_3-b_1\right) \qquad (11)$$

$$\tilde{A}*\tilde{B}=\begin{pmatrix} \min\left(a_1b_1, a_1b_3, a_3b_1, a_3b_3\right), a_2b_2, \\ \max\left(a_1b_1, a_1b_3, a_3b_1, a_3b_3\right) \end{pmatrix} \qquad (12)$$

$$\tilde{A}/\tilde{B}=\begin{pmatrix} \min\left(\frac{a_1}{b_1}, \frac{a_1}{b_3}, \frac{a_3}{b_1}, \frac{a_3}{b_3}\right), \frac{a_2}{b_2}, \\ \max\left(\frac{a_1}{b_1}, \frac{a_1}{b_3}, \frac{a_3}{b_1}, \frac{a_3}{b_3}\right) \end{pmatrix} \qquad (13)$$

In order to calculate forward and backward power flow below steps have to be considered.
Step 1: Assume predefined values for voltage of all buses as triangular fuzzy numbers (Eq. (14)).

$$V=\left(1,1,1\right) \qquad (14)$$

Step 2: Calculate current injected to the buses using equations (2) and (9).
Step 3: Determine current of branches by equations (3) and (8).
Step 4: Compute voltage of buses through equations (4) and (7).
Step 5: Stop the algorithm if new voltages are near to previous predefined voltages. Otherwise, go to step 2 and continue calculations with new values of voltages.

III. OBJECTIVE FUNCTION OF THE PROBLEM

As it is mentioned earlier, the objective of this paper is to minimize the risk of losses, voltage and lines loading. Also, objective function includes the forth component of reliability, i.e. ENS criterion. Generally, first three components are called "technical risk" and the fourth one is known as "reliability". To calculate the technical risk, each component has to be computed separately and then maximum value of them is put in the objective function. In this way, total risk is minimized by obtaining the lowest amount for maximum risk. Accordingly, the objective function is defined as follows.

$$OF=Min\left[RISK\right] \qquad (15)$$

$$RISK=Max\left(Risk_{voltage}, Risk_{current}, Risk_{loss}\right) \qquad (16)$$

$$Risk_{voltage}=Max\left(Risk_{voltage}(i)\right) \qquad (17)$$

$$Risk_{current}=Max\left(Risk_{current}(i)\right) \qquad (18)$$

The risks in above-mentioned equations are equal to area located in out of permissible limits divided by whole area of fuzzy triangles for losses, current, and voltage (see Figs 2 and 3 for more details about risks).

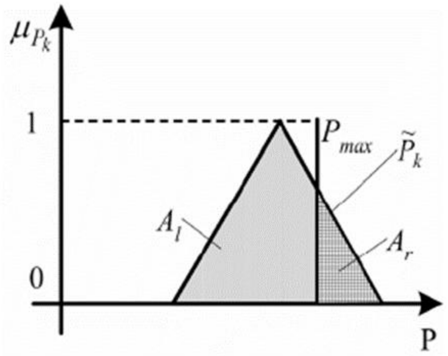

Fig. 2: Calculation method of losses and current risks

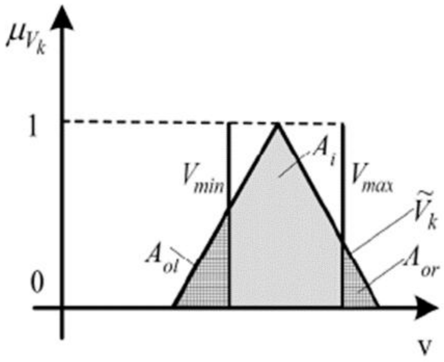

Fig. 3: Calculation method of voltage risk

Technical constraints are not considered in the problem, because they have been included in the objective function already. Only restriction of the problem that remains is being radial of distribution network. This limitation can be recognized by two simple calculations from network situation.

1) Number of existing lines in the network has to be one number less than number of nodes.

2) Determinant of reduced branch-node incidence matrix has to be calculated after first step (after evaluating number of existing lines) to prevent the bus isolation. Reduced branch-node incidence matrix is the branch-node incidence matrix without row related to substation bus (root node in the network graph). The network will be radial if the value of this determinant is 1 and it will include isolated bus if the value of the determinant is 0.

IV. PROPOSED ALGORITHM

In this study, RRA was proposed to solve the problem [32]. This method is based on runner and roots of plants that are growing and developing underground in order to reach water resources and mineral materials. As it is shown in Fig. 4, root of a plant consists of two parts. Thicker part is known as runner and thinner one plays role of the root in solution algorithm. Fig. 4 illustrates solution process of RRA for N=3. In this figure, directions with different colors indicate algorithm iterations. Also, points of x_1 (0), x_2 (0), and x_3 (0) are initial random vectors (mother plants). As it is seen, two directions have been connected to each point. Direction that is near to the point is determined by root index and that is located farer from the point is specified by runner index. This fact demonstrates that each mother plant is searching the optimal solution using runner in the air and root in underground.

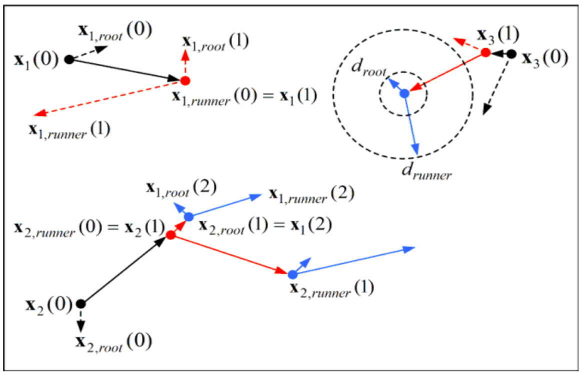

Fig. 4: Graphics display of RAA process

Parameters d_{runner}, d_{root}, N_{pop}, $stall\_max$, tol, and a are mutation rate in runner stage, mutation rate in root stage, number of initial population, maximum number of local iterations, minimum expected progress rate of objective function in order to continue global search, and selection operator in roulette wheel, respectively. Minimum and maximum values of parameters (x_u and x_l) are determined by (19) and (20), and initial population with N_{pop} is generated as (21). Also, counters are initialized using (22).

$$x_l = [1,1,1,1,1] \qquad (19)$$

$$x_u = \begin{bmatrix} N_{line} + N_{tie}, N_{line} + N_{tie}, N_{line} + N_{tie}, N_{line} + N_{tie}, \\ N_{line} + N_{tie} \end{bmatrix} \qquad (20)$$

$$x^k_{mother}(1) = x_1 + rand \times (x_u - x_l) \qquad k = 1, \dots, N_{pop} \qquad (21)$$

$$stall_{count} \to 0 \qquad i \to 1 \qquad (22)$$

In equation (20), N_{line} and N_{tie} are number of normal lines and maneuver feeders of under study test system, respectively. It should be noted that values of algorithm parameters for reconfiguration problem are initialized according to Table 1. Fig. 5 illustrates flowchart of proposed algorithm.

TABLE 1

INITIAL VALUES OF ALGORITHM PARAMETERS

d_{runner}	d_{root}	N_{pop}	$Stall\_max$	tol	a
$x_l - x_u$	$0.01 \times (x_l - x_u)$	50	500	2% to 5%	0.01

V. CASE STUDY

The proposed model was applied to IEEE 33-bus distribution test system (Fig. 6) in order to investigate the effectiveness of proposed idea. Simulation is carried out step by step regarding the stages of proposed algorithm, and then the results will be analyzed. This network includes one main feeder (sub-transmission substation) and 33 buses (distribution substations). It contains 5 open lines (open normal switch) and 32 closed lines (closed normal switch). The network will be radial before reconfiguration if feeders 33 to 37 are disconnected. It is assumed that there is a switch between each two buses. In simple words, all lines of the network can be opened or closed.

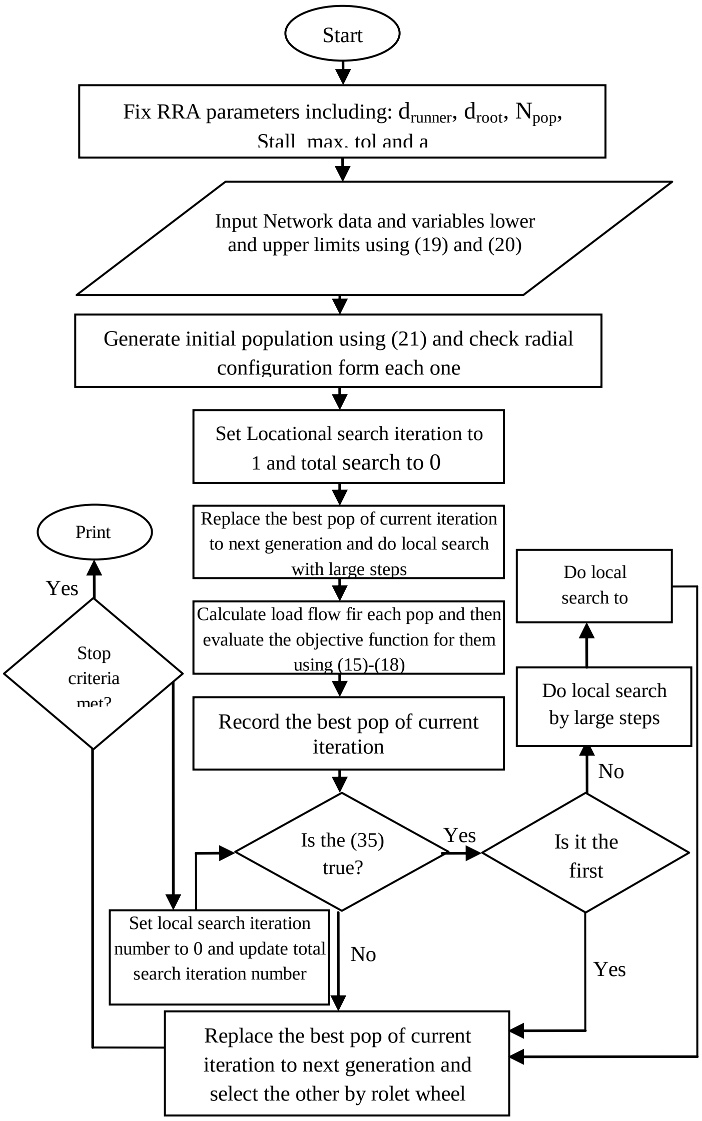

Fig. 5: Flowchart of proposed algorithm

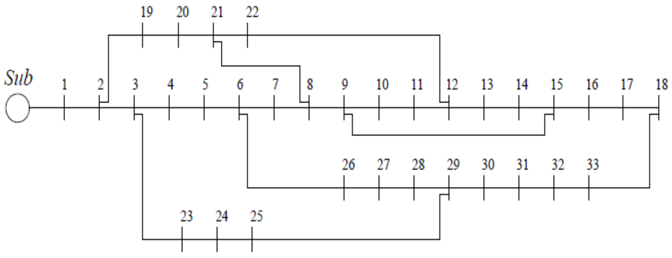

Fig. 6: IEEE 33-bus test system

The generation uncertainty of renewable energy resources has been included in the reconfiguration problem by considering variance of 20% in daily power generations of wind units on buses 6, 7, 23, 24, 29, 30, and 31. Also, the demand uncertainty is formulated by taking into account variance of 15% in daily consumption of all load buses. Other data of the test system are available in [34]. It should be mentioned that, in normal operation (Fig. 6), each line number is one digit less than its end bus number.

In this network, the rated voltage is 12.66 kV, and total active and reactive powers are 3715 kW and 2300 kVAr, respectively. In present work, daily load curve has been considered as coefficients of basic consumption in each hour. Table 2 shows these factors.

TABLE 2
HOURLY LOAD FACTORS

Load Factor	Hour	Load Factor	Hour	Load Factor	Hour
0.1	1	0.63	9	0.57	17
0.12	2	0.65	10	0.65	18
0.13	3	0.7	11	0.85	19
0.14	4	0.75	12	1	20
0.15	5	0.8	13	0.95	21
0.25	6	0.6	14	0.9	22
0.4	7	0.53	15	0.49	23
0.6	8	0.45	16	0.2	24

In order to provide better realization about reconfiguration, first, power flow of the network under normal operation has been calculated. In this situation, power losses is 86.34 kW and value of ENS index is 540 kWh. Voltage profile has been shown in Fig. 7 with minimum voltage amount of 93.22%.

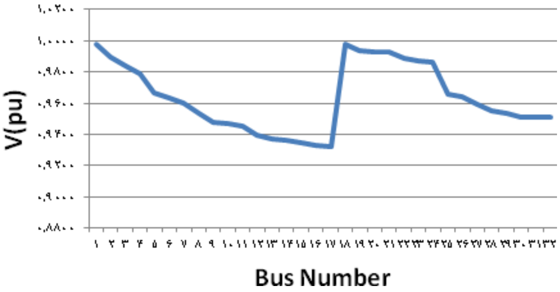

Fig. 7: Voltage profile for basic load before reconfiguration

Table 3 represents the technical risk and other components of the risk after modeling the load and generation uncertainties by fuzzy theory in normal state (operation). Also, fuzzy power losses has been calculated according to Table 4.

TABLE 3
TECHNICAL RISK IN NORMAL STATE (BEFORE RECONFIGURATION)

Maximum technical risk	Maximum voltage risk	Maximum current risk	Losses risk	ENS
100%	100%	81.73%	60.26%	540.4 kWh

TABLE 4
FUZZY LOSSES IN NORMAL STATE

End point of membership function	Maximum value of membership function	Start point of membership function
153440 MW	86380 MW	42155 MW

Proposed model has been studied in three cases. In case 1, the goal was optimization of technical risk and number of switching. In case 2, objective function includes only the reliability and switching. In case 3, technical risk, reliability and number of switching have been considered in the objective function. It should be mentioned that cases 1 and 2 were studied for basic load.

5.1 Case 1

Pareto points were given in Table 5 and shown in Fig. 8.

TABLE 5
PARETO FRONT POINTS IN CASE 1 (OBJECTIVE FUNCTION INCLUDES TECHNICAL RISK AND SWITCHING)

Pareto points number	Open switches number	Value of objective function for technical risk	Value of objective function for ENS	Value of objective function for number of switching
1	6, 13, 15, 21, 27	0.6	449.6	6
2	6, 14, 21, 26, 34	0.5244	551.9	7
3	7, 11, 14, 17, 27	0.7224	541.9	4
4	12, 19, 28, 35, 36	0.2223	424.7	8
5	5, 12, 21, 28, 31	0.2133	504.1	4
6	6, 10, 13, 16, 27	0.8385	551.8	2

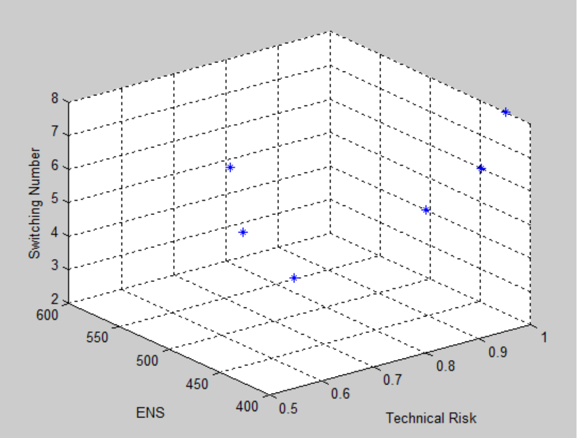

Fig. 8: Tridimensional display of Pareto points for case 1

Pareto point 2 is selected as the final solution using minmax method, but its reliability is less than normal state.

5.2 Case 2

In this case, Pareto points are listed in Table 6.

TABLE 6
PARETO FRONT POINTS IN CASE 2 (OBJECTIVE FUNCTION INCLUDES RELIABILITY AND SWITCHING)

Pareto points number	Open switches number	Value of objective function for technical risk	Value of objective function for ENS	Value of objective function for number of switching
1	12, 19, 28, 35, 36	0.8558	367.26	4
2	8, 10, 14, 20, 27	1	274.62	6
3	4, 10, 17, 21, 27	0.9011	267.9	8

Fig. 9 shows these points in a 3-dimension space.

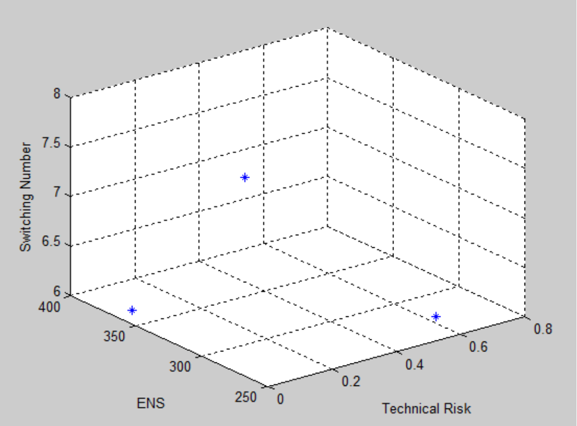

Fig. 9: Display of Pareto points in 3-dimension space in case 2

In this case, Pareto point 2 was selected by minmax method as final solution, but its technical risk is not good.

5.3 Case 3

Following results are obtained after running the proposed algorithm for network reconfiguration. The algorithm has been converged to the optimal solution after 3681.77 seconds. Tables 7 to 9 describe Pareto points for hour 1 (minimum load), hour 8 (average load), and hour 20 (peak load).

TABLE 7
PARETO FRONTS POINTS AFTER MULTI-OBJECTIVE OPTIMIZATION FOR HOUR1

Pareto points number	Open switches number	Value of objective function for technical risk	Value of objective function for ENS	Value of objective function for number of switching
1	8, 14, 15, 27, 33	0	44.41	8
2	4, 9, 28, 34, 36	0	44.51	6

TABLE 8
PARETO FRONTS POINTS AFTER MULTI-OBJECTIVE OPTIMIZATION FOR HOUR8

Pareto points number	Open switches number	Value of objective function for technical risk	Value of objective function for ENS	Value of objective function for number of switching
1	10, 13, 17, 22, 33	0.0558	367.26	6
2	3, 10, 12, 15, 27	0.6267	274.62	6
3	8, 10, 16, 28, 33	0.0011	267.9	8

TABLE 9

PARETO FRONT POINTS AFTER MULTI-OBJECTIVE OPTIMIZATION FOR HOUR 20

Pareto points number	Open switches number	Value of objective function for technical risk	Value of objective function for ENS	Value of objective function for number of switching
1	7, 13, 26, 32, 35	1	449.6	6
2	10, 12, 26, 33, 36	0.5244	451.9	8
3	10, 13, 16, 33, 36	0.7224	541.9	4
4	7, 9, 14, 25, 32	1	424.7	8
5	9, 13, 15, 25, 33	1	504.1	4
6	11, 13, 15, 24, 33	0.8385	551.8	2

The best solutions for 24 hours have been listed in Table 10.

TABLE 10
THE BEST SOLUTIONS FOR MULTI-OBJECTIVE OPTIMIZATION DURING 24 HOURS

Hour	Open switch number				
1	8	14	33	15	27
2	14	27	6	15	8
3	12	17	27	6	21
4	15	10	27	34	6
5	6	21	12	27	17
6	10	6	27	12	17
7	21	27	4	17	10
8	27	3	12	10	15
9	21	13	27	15	6
10	26	14	21	6	34
11	7	17	11	14	27
12	28	12	19	36	35
13	28	5	12	31	21
14	8	18	12	35	28
15	17	7	10	28	8
16	6	28	10	14	17
17	10	14	4	20	15
18	33	13	15	21	37
19	13	24	33	7	15
20	24	13	16	33	10
21	25	33	13	10	16
22	16	13	33	7	24
23	20	16	24	33	13
24	13	16	6	27	10

Table 11 explains the values of objective function for solutions presented in Table 10.

TABLE 11
THE VALUES OF OBJECTIVE FUNCTION FOR SOLUTIONS OF TABLE 10

Hour	Technical risk	ENS	Number of switching
1	0	44.410	8
2	0	52.332	2
3	0	56.576	6
4	0	60.382	6
5	0	65.280	6
6	0	105.425	2

7	0	181.160	4
8	0.6267	274.620	6
9	0.0772	280.980	6
10	0.2272	300.820	6
11	0.0860	294.140	8
12	0.0597	364.350	10
13	1	366.400	6
14	0.5684	335.220	6
15	0	231.769	6
16	0	189.225	4
17	0.9877	340.917	6
18	0.0241	347.360	8
19	0.4161	478.975	4
20	0.7224	541.900	4
21	0.9521	459.515	2
22	0.4722	502.830	4
23	0	286.846	2
24	0	84.580	6

Finally, Table 12 represents different components of technical risk for hours 1, 8, and 20.

TABLE 12
COMPONENTS OF TECHNICAL RISK FOR THE BEST SOLUTIONS OF HOURS 1, 8, AND 20 IN MULTI-OBJECTIVE OPTIMIZATION CASE

Hour	Voltage risk (%)	Current risk (%)	Losses risk (%)
1	0	0	0
8	0	17.21	62.67
20	38.09	37.23	72.24

From above-mentioned tables, it is clear that losses risks in hours 8 and 20 cause high technical risks.

5.4 Results Validation

In this section, simulation results of the paper is compared with results of Ref. [34] to investigate efficiency of the proposed algorithm for problem solution and verify the simulation results. Regarding the fact that this literature has studied the problem with and without presents of distributed generations (DGs), if desired reference has been considered the DG in its problem formulation, the results of this paper considering DGs will be compared to its results.

Ref. [34] has solved the problem of this paper using CSA regardless of DG and uncertainties for basic load. Also, objective function for losses and voltage are formulated in a different way. Therefore, the presented model was revised according to these changes and the problem was solved ignoring the DGs and uncertainties again to provide a correct comparison. Accordingly, objective functions of losses and voltage risks are modeled using (23) and (24) [34].

$$RV = \max_i \left(\frac{V_1 - V_i}{V_1} \right) \qquad (23)$$

$$Rloss = \frac{loss}{loss\_base} \qquad (24)$$

It should be noted that calculation of voltage and losses risks using above-mentioned equations is counted a serious problem for this reference, because after reconfiguration if minimum voltage level is 60% and the power losses is 100 kW (for example), risk of voltage component will be less than risk of the losses. However, this amount for the voltage is not acceptable, while value of network losses is so desirable. Due to equation (23), value of voltage risk for voltages more than 95% (acceptable voltage amounts) will be 0 and it changes between 0 and 100% for voltages less than 95% and more than 90%. In other words, voltage risk will be more than 100% for lower voltages than 90% if it is calculated by (23). This value of risk is not acceptable. Also, in this reference, the losses calculated for basic load is 203.679 kW. The reason for deference between this amount and losses value of present work is a little deference between rated voltages. Rated voltage for present study has been adopted from Ref. [26] that is considered to be 12380 V, while this amount for Ref. [34] is 12660 V. If the rated voltages for both studies are the same, the simulation results for losses and voltage profile will be similar. To do so, the problem is solved for basic load and rated voltage 12660 V that the amount of 202.7 kW for network losses was obtained. Also, voltage profile is shown in Fig. 10 before reconfiguration.

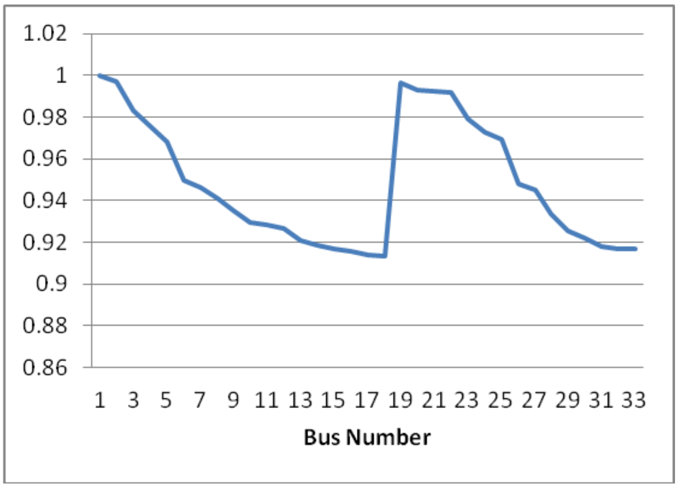

Fig. 10: Voltage profile for 33-bus network before reconfiguration

In this case, optimal arrangement, value of each component, and technical risk amount are given in Table 13. Moreover, voltage profile after network reconfiguration is shown in Fig. 11.

TABLE 13
COMPARISON OF SOLUTION METHODS

Method	Optimal arrangement	Voltage risk (%)	Losses risk (%)	Technical risk (%)	Minimum voltage (p.u.)
Present paper	1, 8, 31, 34, 37	5.92	73.6	79.52	94.08
Ref. [34]	7, 9, 14, 32, 37	5.76	68.18	73.94	94.23

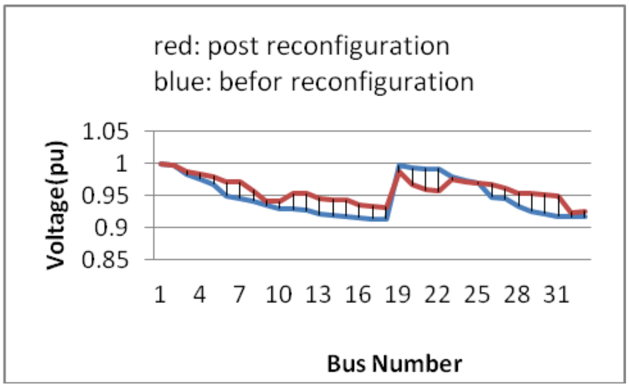

Fig. 11: Voltage profile for of 33-bus network after reconfiguration

In this evaluation, net power losses is calculated to be 149.78. For more precise assessment, optimal arrangement proposed by Ref. [34] in Table 13 was included in power flow equations of this paper, but different results yield. Whereas, initial results of present study and Ref. [34] (the results before reconfiguration) were nearly the same (the initial losses of the reference and this research were 203.679 and 202.7, respectively. Also, minimum voltage under normal operation for correspond reference and the paper were 0.9108 and 0.913, respectively). Nevertheless, minimum voltage and power losses of optimal arrangement proposed in this paper are 93.28% and 141.66 kW. Thus, losses risk is 69.55% and voltage risk is 6.72% with objective function value of 76.27 if assumptions and equations presented in Ref. [34] are considered. Although, these results are more optimal and better in comparison with present research, risk of voltages for voltages less than 0.95 per unit is higher than this paper.

It should be considered that only solution algorithms of both papers were compared till now. However, amount of network losses, minimum voltage, and specially solution time are more important. The solution time has not been presented in related tables of Ref. [34], because it took a short time (almost 17 seconds) for the algorithm to find the optimal solution. In order to compare efficiency of objective functions used in the paper and those of Ref. [34], all proposed models in this paper were applied to this reference and results are provided in Table 14.

TABLE 14
COMPARISON OF PROPOSED MODELS

Method	Optimal arrangement	Voltage risk (%)	Losses risk (%)	Technical risk (%)	Minimum voltage (p.u.)	Losses (kW)
Present paper	7, 8, 31, 34, 37	28.4	0	28.4	93.65	140.88
Ref. [34]	7, 9, 14, 32, 37	34	0	34	93.28	141.66

Process of convergence for the proposed algorithm is depicted in Fig. 12.

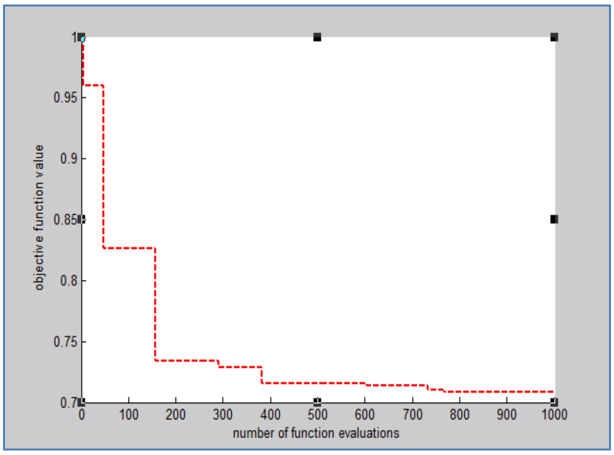

Fig. 12: Convergence process of proposed algorithm with objective functions of [34]

VI. CONCLUSION

In this paper, numerical study on a distribution test system is carried out to consider front of Pareto points, optimal solutions, and values of different objective functions and their effects on problem solutions. Three cases were considered for this study. In case 1, the aim was optimization of technical risk, but it was not appropriate to study energy not supplied because of high ENS. In case 2, energy not supplied was minimized in objective function, but it caused the unacceptable risks, because of blackout and stability problems. Finally, in case 3, a multi-objective optimization was presented by considering both objective functions of technical risk and ENS besides minimizing the number of switching.

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