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A Practical Approach to Planning Reliability-Centered Maintenance in Distribution System Considering Economic Risk Function and Load Uncertainty

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ABSTRACT

Nowadays, power distribution companies are working in a competitive atmosphere. Therefore, a major goal for electricity distribution managers is to provide electrical energy with a high reliability level with considering the economic issues. Reliability-centered maintenance (RCM) is an efficient way of realizing this aim and improving a network's maintenance processes. This approach is an operative step to improve the reliability of critical equipment and overall system performance which may reduce the costs of utilities.

By using RCM, this paper provides a practical model for maintenance scheduling by considering the economic risk function and budget restrictions based on the cost of preventive maintenance (PM) and value of lost load (VOLL). In this method, PM schedules are proposed based on failure causes of different network elements. The studied elements include overhead lines, underground cables, and power switches (circuit breaker (CB), manual and remote control switches (RCSs)). Failure cause and average repair time of each element is determined through data mining in geographical information system (GIS) and ENOX. For more realistic modeling and the consideration of the network loads' uncertainties, the fuzzy triangular method is used. Due to the inconsistency between the goals of the problem, the non-dominated sorting genetic algorithm (NSGA II) is employed. The results show the effectiveness of the proposed method.

Article Info

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I. Introduction

The reliability-centered maintenance (RCM) is a systematic method of deciding about the maintenance performance in which attention is paid to the system's reliability constraint. In this method, while modeling the system, it is important to maintain the function or output of the system instead of maintaining the function of each individual element of the system. The conducted researches for implementing the novel strategy of RCM in nuclear power plants by the electrical energy research institute during the early 1980s can be considered as the first step of applying RCM to the power systems [1]. In Ref. [2], the stages of RCM are investigated together with the tools and techniques required for the improvement of the plan's efficiency with respect to the predicted algorithm. Finally, this plan has been accomplished for a factory as a pilot sample and the plan's profitability has been estimated in terms of short-term and long-term programs. A practical method has been suggested in [3] for RCM budgeting in which desired maintenance and their execution time in distribution feeders are determined aiming to minimize total cost of reliability. An approach has been proposed in [4] to improve the reliability of distribution network feeders which can control and identify the number of switches and their

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locations using a preventive maintenance plan. The design of the priority assessment software has been presented in [5] with respect to the RCM considering the allocated priority to the energy sources and assessing its consequences for the customer. Ref. [6] gives proper and comprehensive approaches for the stable asset management of the wind turbines by implementing a combination of reliability methods and the available information of the service. In ref. [7], a technique for modeling the RCM plans in the system dynamic condition by using the causal loop diagram (CLD) is introduced. Ref. [8] has proposed an approach for the proper decision making in the maintenance activities of the distribution network's feeders considering the weighted cumulative diagnostic importance factor (WCDIF). In [9, 10], based on the opinions of maintenance experts together with the quantitative models, a method has been introduced to implement the RCM in the distribution network with respect to the current status of the equipment and possible maintenances in short-term time. Ref. [11] presents a strategy to determining the maintenance timetable of transmission equipment according to a new risk model and state-based repairs. Ref. [12] introduces a comprehensive model of preventive maintenance planning using the genetic algorithm (GA) in which Markov's model is implemented for modeling the failure rate of the equipment. Ref. [13] uses a combination of failure modes and effects analysis (FMEA) and analytical hierarchical process (AHP) to find the critical equipment ranking with respect to the two criteria of maintenance cost and the number of people in each hour in the production unit. A study has been carried out by [14] to investigate the random planning model for minimizing the lifecycle cost of the distributed generation (DG) considering wind power volatility. Ref. [15] gives an RCM planning for two wind turbines of 600 kW and 2 MW. Ref. [16] presents a method for the reliability and accessibility assessment of an installed gas turbine in a combined cycle power plant. The principle of this technique is based on the reliability concepts such as the development of a fault tree and the application of FMEA to identify the critical equipment. A method for comparing the influence of the different RCM strategies and a system's cost has been suggested by [17]. Ref. [18] presents an RCM process in the distribution network regardless of the effect of other equipment in the operation and reliability of the network for cables. The maintenance challenges of Iran's distribution network have been investigated and analyzed in [19] by providing a questionnaire filled out by the experts of the industry. In Ref. [20], the design and operation of a micro-grid connected to the network to provide the load of a large industrial consumer through risk management has provided. An approach to risk management is proposed for the placement of the distributed generation sources in sub-transmission substations with modeling the economic parameters [21].

In previous studies, the main goal was the PM scheduling of the studied network considering certain failure rate of elements and constant model of loads. In some studies, economic modeling has also been performed for cost-benefit analyses. Further, it is expected that network elements are operated during considerable time duration under conditions that the system loading varies from time to time. Hence, uncertainty under system loading conditions should be considered. On the other hand, in practice, there are some restrictions to improve the reliability of distribution networks in terms of financial budget. Hence, system operators and managers cannot pay more than accessible financial resources for improving reliability.

This paper considers load uncertainty and budget restriction of electricity distribution companies and proposes a new model based on economic risk function and reliability indices. The main purpose of the research is to make a balance between maintenance costs and benefits obtained from increased reliability arising from the proposed PM strategies assuming a certain budget. This paper uses the GIS and ENOX data to extract the failure causes of the studied elements including overhead lines, underground cables, and power switches (CB, manual switches, and RCSs). The real failure rate of elements and average repair time of each one are determined through data mining in big data. For each fault occurring in the elements, a separate maintenance schedule is proposed. Additionally, to take account of uncertainty and provide more accurate load model, the fuzzy triangular method is utilized and the effects of uncertainty on the economic risk function and reliability function are evaluated. A non-dominant sorting genetic algorithm (NSGA-II) is used to solve this problem. The application of this algorithm results in a set of solutions (efficient solutions) to the problem instead of one unique optimal solution.

II. The process of RCM

The RCM process and its implementation procedure consisting of initial, basic and final analyses are described here.

The initial design of the RCM process includes four steps. In the first step, the single-line model of the studied grid is prepared. In the second step, the range of studies is identified with respect to the sensitive points. The desired elements are chosen for the RCM analysis in the third step. Finally, the expected performances of the system are determined and estimated in the fourth step.

The basic analysis of the suggested RCM algorithm is performed in eight steps as illustrated by the flowchart in Fig.1.

The final analysis includes reliability analysis after applying each repair, recording, analyzing the spent money in each stage, and finally providing the documents corresponding to the maintenance and data collection.

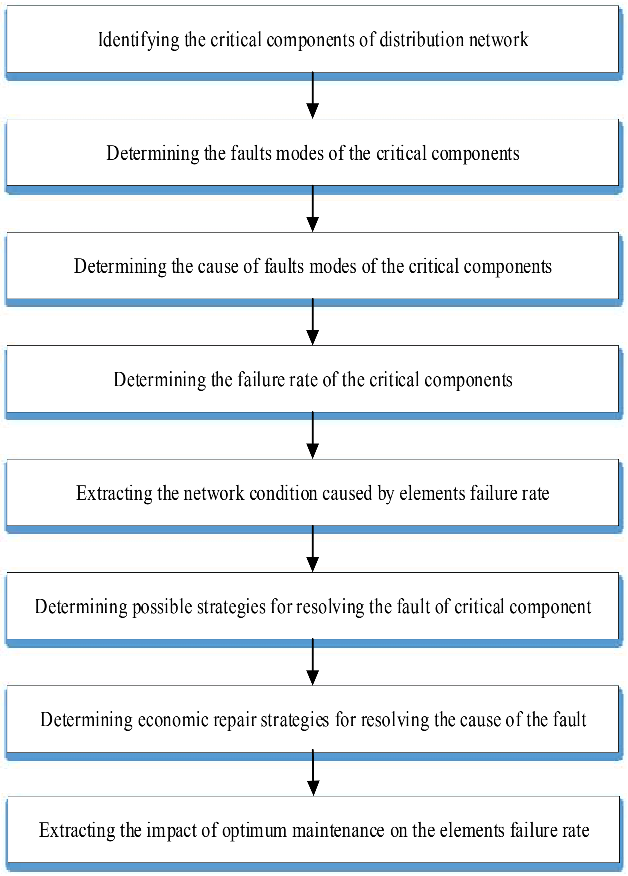

Fig1. The flowchart of the basic analysis of the proposed RCM algorithm.

III. Estimation of the Failure Rate and Equipment's Repair Time in a Sample Network

The first step to evaluate the reliability of the distribution systems is to calculate the failure rate and average repairing time. In an actual electricity distribution network, we are encountered with a high volume of big data, which needs appropriate management and processing to access its valuable information. Processing big data is a series of techniques and methodologies that require a new form of integration to reveal the great values hidden in big, immense, complex and diverse collections of data. With the increasing data growth and the need to exploit these data, the use of big data infrastructure has become especially important.

In this research, using data mining in big data, the number and causes of the equipment failure rate of the system are extracted. The data of GIS and ENOX software in GTEDC are used to obtain this information. Accordingly, failure causes of the overhead lines, underground cables, and power switches, interruption time and energy not supplied (ENS) are calculated according to TABLE I. In addition, TABLE II illustrates the failure rate and average repair time of the network components separately by the cause of failure.

TABLE I
The results derived from the ENOX software application and GIS experimental data of 2014, 2015 and 2016

Sr. No.	Occurred fault	Average interruption time (min)	Average energy not supplied (MWh)	Average frequency of interruption
1	Fault in indoor MV cable termination	870	10.27	8
2	Fault in outdoor MV cable termination	664	7.8	6
3	MV cable short circuit	2132	24.82	23
4	Collision of external objects	340	3.9	4
5	Collision of birds	38	1.13	1
6	Failure in overhead manual disconnecting switch	174	3.68	2
7	Severe weather conditions	58	0.74	1
8	Fault in CB	1301	1.98	15
9	Fault in RCSs	287	0.47	5
10	Fault in substation	113	0.82	1

TABLE II
Failure rate and average repair time of the network components separately by the cause of failure

Equivalent component	Causes of failure	Failure rate (f/yr.)	Average repair time (min)
Line	MV cable short circuit	0.33	81
	Overhead lines short circuit	2.98	135
	Bird collision	0.051	49
	Severe weather conditions	0.4845	35.505
	Unknown fault	0.8415	45.84
Protective equipment	Fault in cutout fuse	0.1405	113.38
	Fault in CB	0.1385	59.59
	Fault in disconnecting switch	0.0157	61.63
Substation	Fault in transformer	0.002	56.5

In this study, the maintenance of the distribution network element is considered to be in perfect form. Therefore, the condition of every element is assumed to be ''as good as new'' and after PM, the system will have the same failure rate as a new brand one [22].

IV. Fuzzy Model of Load Points

An outstanding feature of the fuzzy theory is the facility of calculations compared to probabilistic methods, and this feature has helped the practical use of this theory to be attractive and extensive. In this study, the uncertainty of the distribution network load is modeled using fuzzy numbers. The consumption power of each of the load points is described as a triangular fuzzy number, as shown in Fig. 2. Each triangular fuzzy number has three parameters (PL, PM, PR), and it shows that the expected amount of load is around PM but it will not be less than PL or greater than P_R.

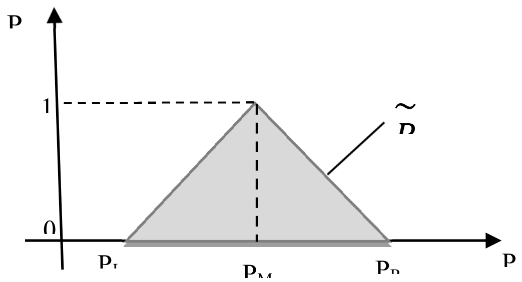

Fig 2. The graphical representation of the load as a fuzzy number

Assuming that the estimated power in a load point is equal to P0 with the maximum error *e*, then the fuzzy number parameters corresponding to the load point can be achieved by the following equations.

$$P_L = P_0 \times (1 - e) \tag{1}$$

$$P_M = P_0 \tag{2}$$

$$P_R = P_0 \times (1 + e) \tag{3}$$

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

$$\mu_P = \begin{cases} 0 & \mathrm{P} \le P_L \ or \ P \ge P_R \\ \dfrac{P - P_L}{P_M - P_L} & P_L < P < P_M \\ \dfrac{P_R - P}{P_R - P_M} & P_M < P < P_R \end{cases} \tag{4}$$

According to the high reliability of the triangular fuzzy numbers in describing uncertain loads, this method has been utilized to solve most problems related to distribution systems [23-26].

V. Problem Formulation

In this paper, RCM scheduling using NSGA-II is investigated to obtain the best possible solution in the presence of load uncertainty. In this case, the proposed algorithm gives a set of efficient solutions instead of one solution which allows the manager to make operational decisions from different aspects. Objective function of the problem includes reliability and cost functions as in Eq. (5).

$$F_T = \min\{\tilde{F}_R, \tilde{S}_{CE}\} \tag{5}$$

where $\tilde{F}_R$ and $\tilde{S}_{CE}$ are the reliability index and the economic risk function, respectively. As would be observed, both parameters of the objective function are given by fuzzy numbers.

A. Calculation of the Reliability Index ($\tilde{F}_R$)

In this paper, three reliability indices of SAIFI, SAIDI, and Expected ENS (EENS) have been implemented to investigate the effectiveness of the RCM planning. For a distribution system, these indices can be estimated in each load point using the annual failure rate (λ_i) and the annual outage duration (Ui) as follows [27].

$$\mathrm{SAIFI} = \frac{\sum_{i=1}^{Nol} N_{Li} \times \lambda_i}{\sum_{i=1}^{Nol} N_{Li}} \tag{6}$$

$$\mathrm{SAIDI} = \frac{\sum_{i=1}^{Nol} N_{Li} \times U_i}{\sum_{i=1}^{Nol} N_{Li}} \tag{7}$$

$$\tilde{E}_{ENS} = \sum_{i=1}^{Nol} U_i \times \tilde{P}l_i \tag{8}$$

in which N_{ol} is the number of load points, N_{Li} defines the number of customers connected to the *i-th* load point, λ_i is the annual failure rate of the i-th load point, Ui is the annual outage duration of the i-th load point, and Pli stands for the load related to *i-th* bus in terms of kW.

These indices are considered a weighted objective function and their total weight is considered through determining the coefficient of each index as in Eq. (9). In this equation, the values of W_1, W_2 and W_3 are considered to be 0.33, 0.33 and 0.34, which shows that their significance is assumed to be close to each other. As can be seen, due to load uncertainty, EENS is considered a fuzzy number.

$$\tilde{F}_R = W_1 \times \frac{SAIFI_b - SAIFI}{SAIFI_b} + W_2 \times \frac{SAIDI_b - SAIDI}{SAIDI_b} + W_3 \times \frac{\tilde{E}_{ENSb} - \tilde{E}_{ENS}}{\tilde{E}_{ENSb}} \quad (9$$

During different stages of the reliability calculations, these computations are performed for different elements of the system.

B. Estimation of the Economic Risk Function

In most real distribution networks (including Iran), there are restrictions upon improving reliability from the financial viewpoint. Therefore, the managers of the system are unable to spend more than the available financial sources on improving reliability; in other words, the PM budget is constant. Considering this fact, the PM should be so planned that this restriction is not exceeded. If the cost of PM exceeds the allocated budget, it will pose an economic risk to electricity distribution companies. Hence, the economic risk of increasing the maintenance cost that threatens the distribution company can be defined as the following inequality degree:

$$\tilde{C}_E \leq \tilde{C}_{E0} \tag{10}$$

$$\tilde{C}_E = \sum_{i=1}^{N_{el}} C_{mat\,i} + C_{LS\,i} + C_{lab\,i} + \sum_{i=1}^{N_{el}} \tilde{A}_{IC}.\tilde{E}_{ENS_i} + \sum_{i=1}^{N_{el}} \alpha.\tilde{E}_{ENS_i} \tag{11}$$

$$\tilde{C}_{E0} = C_{COM} + \sum_{i=1}^{N_{el}} \tilde{A}_{IC}.\tilde{E}_{ENS0_i} + \sum_{i=1}^{N_{el}} \alpha.\tilde{E}_{ENS0_i} \tag{12}$$

where

$C_{mat\,i}$ is the cost of consumables for PM,

$C_{LS\,i}$ is the cost of equipment depreciation,

$C_{lab\,i}$ is the cost of manpower for PM,

$\tilde{E}_{ENS_i}$ is the fuzzy number of the EENS after PM,

α is the penalty factor of the customer's dissatisfaction by interruptions considering its level of importance,

$\tilde{A}_{IC}$ is the coefficient of each outage with respect to its level of importance,

N_{el} is the number of elements involved in the PM,

C_{COM} is the cost restriction specified by the distribution company for the PM, and

$\tilde{E}_{ENS0_i}$ is the fuzzy amount of the EENS before PM.

Due to the load uncertainty, the cost functions of $\tilde{C}_E$ and $\tilde{C}_{E0}$ are modeled as a fuzzy number. In Eq. (10), the costs of PM, EENS, and customer's dissatisfaction in the modes of with and without budget restriction have been compared. Given the graphical representation of $\tilde{C}_E$ and $\tilde{C}_{E0}$ shown in Fig. 3, the degree of feasibility (10) can be defined as below:

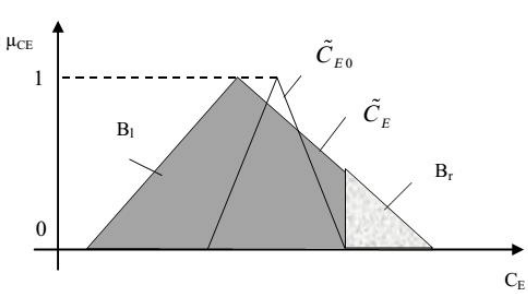

Fig 3. The graphical representation of $\tilde{C}_E$ and $\tilde{C}_{E0}$

$$S_{C_E} = \frac{B_r}{B_r + B_l} * 100 \quad [\%] \tag{13}$$

Therefore, the economic risk function will be as follows [28].

$$Min \quad F_E = S_{CE} \tag{14}$$

It can be inferred from the concept of this objective function that assuming budget restriction upon PM, it is not possible to implement all PM plans. Hence, the implementation of the activities of RCM-based prioritized PM will reduce the economic risk to electrical companies. In Fig. 3, the space occupied by *Br* represents the level of economic risk emanating from budget restriction.

VI. Objective Non- Dominant Sorting Genetic Algorithm (NSGAII)

In an optimization problem with multiple criteria, the objectives of the design must be optimized simultaneously. In these cases, the objectives are usually in a way that they may not be improved with the degradation of others. Hence, instead of a single optimal solution, a set of solutions – called efficient solution – is obtained for the problem. With respect to the relative importance of the design objectives, the efficient solutions of a problem can have different priorities from the designer's viewpoint. Since Genetic Algorithm (GA) seeks an answer space from different points and in a parallel manner, it can be appropriately used to find a subset of efficient solutions. The NSGAII is a version of GA designed for solving the multi-criteria optimization problems [29].

In the NSGAII, the population members are ranked based on the non-domination concept. The non-dominated members in the existing population compose the first level. Then, these members are temporarily discarded from the population and the new non-dominated members, which form the second level, are identified from the remaining members. This process will be continued until all the levels are identified and each member of the population is allocated to one of these levels. The general steps of the NSGAII for solving optimization problems in a distribution system are given as below

1- Initial population
2- Cross over
3- Mutation
4- Objective functions assessment
5- Population ranking
6- Density assessment in which the members placed in a non-domination level are ranked based on the density and according to the following index.

$$cd\left(X_i\right)=\prod_{j=1}^{k} cd\left(X_i\right) \quad (15)$$

$$cd_j(X_i)=\left|\frac{f_i(X_{i+1})-f_i(X_{i-1})}{f_j^{\max}-f_j^{\min}}\right|, \qquad i\in S^r \quad (16)$$

The value of $cd_j\ (X_i)$ shows the distance between the *i-th* member and the nearest members in level S^r with respect to the *j-th* objective function. The subtraction of $f_j^{\min}$ and $f_j^{\max}$ in the denominator of Eq. (16) indicates the variation range of the objective function *fj*.

7- Selection is performed on the basis of the rank and the amount of population density.

8- Stopping and printing the system outputs

Having obtained the set of efficient solutions by NSGAII, the designer must choose the final response from this set according to the specialized prioritizations and the satisfaction rate from the objective functions. In this research, the max-min method is proposed to achieve the best answer for the problem. The flowchart of this algorithm is shown in Fig. 4.

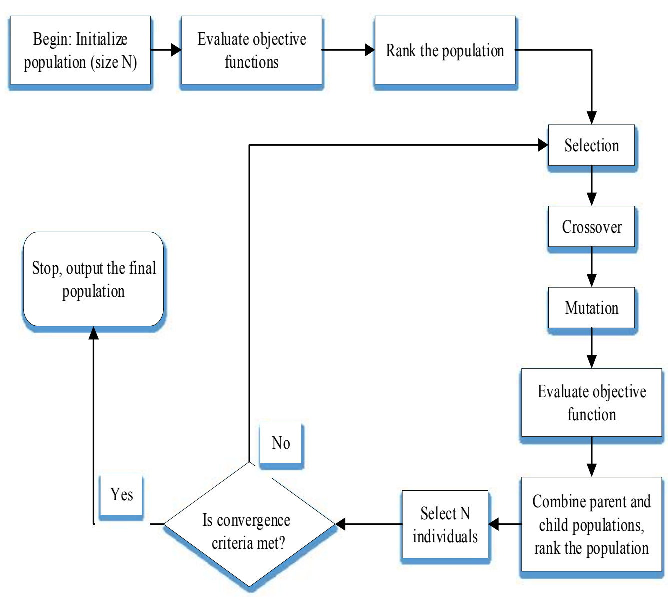

Fig 4. The flow-chart of the NSGAII

VII. CASE STUDIES AND NUMERICAL RESULTS

To carry out the numerical studies, a 33-bus standard network, as well as a medium voltage (MV) feeder from the GTEDC distribution network, has been used as a real network in Iran.

A. Case Study on Real Feeder:

To verify the capability of the proposed method, the problem is implemented on a real 22-bus from feeder 4 of ESHRAGH sub-transmission substation in the GTEDC as shown in Fig. 5. The line data and load point data as triangular fuzzy numbers of the studied feeder are listed in TABLE I and TABLE II in the Appendix section. Four maneuver points are considered for the system with specific capacities whose information is listed in TABLE III. The studied feeder consists of 22 buses, 4 manual switches, and 1 RCS, respectively. In this network, three load types, i.e. residential, commercial and industrial, are available, each of them having different interruption cost.

In this paper, the PM is conducted on the elements of the overhead lines and underground cables, CB, manual switches, and RCSs of the distribution system to increase the network reliability and decrease the interruption. In these conditions, the budget considered for the PM of this feeder is USD 8000. The value of lost load (VOLL) for residential, commercial, and industrial customers is provided based on the reference [30].

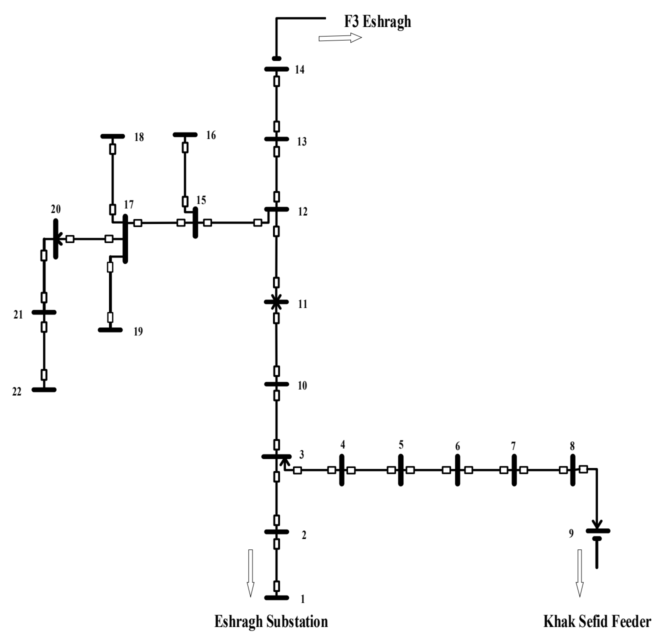

Fig 5. The single-line diagram of a real feeder 4 of ESHRAGH sub-transmission substation in the GTEDC

TABLE III
Maneuver points data

Maneuver points	Bus number	Capacity (kW)
1	9	3700
2	14	4500
3	18	4000
4	22	4200

In this study, two scenarios have been studied as described below:

Scenario 1: In this case, the system is in the base mode and different parts of the objective function are calculated without PM planning.

Scenario 2: In this scenario, it has been attempted to improve the system reliability using the PM of the different elements and with the minimum cost. In this regard, the PM is performed for overhead lines and underground cables, CB, manual switches, and RCSs.

The PM schedule and its practical activities are identified based on failure causes, experience of experts, ENOX data, and GIS. TABLE IV presents PM plans for overhead lines and underground cables, CB, manual switches, and RCSs. As can be seen, with regard to different failure modes of the overhead lines, four PM plans are considered for it. One type of maintenance plan for other elements under study is considered. Due to the inconsistency between the problem objectives (the reliability index and economic risk), the NSGA II is used to solve it.

TABLE IV

Activities related to the PM caused by different fault modes

Row	Title	The PM activities
1	Overhead lines PM Plan 1	1- Inspecting overhead lines 2- Modifying/correcting overhead line connections 3- Modifying jumpers 4- Adjusting overhead line sag 5- Maintaining/replacing faulty disconnectors 6- Partially discharging by an ultrasonic device 7- Thermally imaging overhead lines equipment 8- Trees trimming 9- Restoring crooked pole 10- Adjusting insulator rod and replacing insulator 11- Installing overhead spacer 12- Modifying faulty or torn wire 13- Cross arm modification/maintenance 14- Changing or installing line covers 15- Fixing loose connections 16- Regulating cutout or arrester 17- Installing or changing earth wire
2	Overhead lines PM plan 2	1- Inspecting overhead lines 2- Trees trimming 3- Installing overhead spacer 4- Removing objects from overhead lines 5- Washing insulators and installing birds guard
3	Overhead lines PM plan 3	1- De-icing overhead lines 2- Trees trimming 3- Removing objects from overhead lines 4- Fixing loose connections
4	Overhead lines PM plan 4	1- Inspecting overhead lines 2- Adjusting overhead lines sag 3- Modifying jumpers 4- Trees trimming 5- Removing objects from overhead lines 6- Installing birds guard 7- Installing overhead spacer
5	CB PM plan	1- Inspecting equipment 2- Minor repair of CB 3- Major repair of CB
6	Underground cables PM plan	1- Inspecting underground cables 2- Maintaining outdoor oil-filled cable terminations and resolving oil leakage if needed 3- Maintaining indoor oil-filled cable terminations and resolving oil leakage if needed 4- Replacing outdoor underground cables terminations 5- Replacing indoor underground cables terminations 6- Fixing loose connections 7- Changing or installing line covers
7	Manual switches PM plan	1- Inspecting equipment 2- Minor repair of switches 3- Major repair of switches
8	RCSs PM plan	1- Inspecting equipment 2- Service and testing of communications modems and media 3- Service and testing of communications equipment power supply and RTU 4- Minor repair of switches 5- Major repair of switches

B. Analysis of the Results of the Real Feeder

The failure mode and effects analysis (FMEA) has been used to estimate the reliability indices.

Simulations have been implemented by MATLAB on a 2.270 GHz Core i5 computer with 2 GB of RAM. By performing multiple experiments, the parameters of the algorithm in this numerical study are set as follows.

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

The space of the resultant efficient solutions is exhibited in Fig. 6 and TABLE V. From the obtained efficient solutions, one answer is chosen as the result which is calculated using the max-min operator.

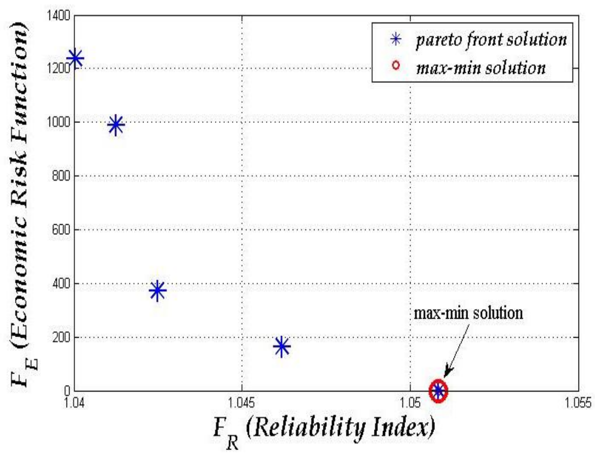

Fig. 6. The non-dominated solutions with NSGA II

TABLE V
The results of the NSGA II and the values of the objective functions for each answer

Efficient solution number	The reliability objective function ($\tilde{F}_R$)	The economic risk (B_r)
1	1.040038	1237.22
2	1.041245	989.22
3	1.050850	0
4	1.044946	2399.75
5	1.046191	3826.65

As would be observed in Table 5, the third response is selected as the basic max-min solution. In this case, the economic risk is about zero. However, the reliability index of this condition is higher than that of the other solutions. On the other hand, according to the first solution, the amount of the economic risk is 1237.22 when the reliability index meets its minimum amount, which is the worst case among the efficient solutions considering the economic justification.

The proposed PM plan for the overhead lines based on the efficient answer of No. 3 is presented in TABLE VI. The proposed PM plans for underground cables and power switches are listed in TABLE VII.

TABLE VI
The proposed PM plans for the overhead lines

Number of PM plan	Proposed overhead lines for PM implementation
PM plan 1	2, 5, 6, 8, 9, 14, 16
PM plan 2	3, 12, 15, 17, 18
PM plan 3	7, 21
PM plan 4	4, 10, 19

TABLE VII
The proposed PM plans for the underground cables and power switches

Elements	Number	Result of proposed method
Underground cables PM plan	1	-
	13	-
	20	Ok
CB PM plan	1	-
Manual switches PM plan	1	-
	2	-
	3	-
	4	-
RCS PM plan	1	Ok

As shown in Table 6, PM plan 1 is proposed for seven overhead lines. This plan is intended to prevent short circuit of the network due to defects in the overhead lines equipment. Plan 2, which is anticipated to avoid the failure caused by the collision of birds with the network, is proposed on five overhead lines. Plan 3 has been proposed to reduce the effects of severe weather conditions on the network for two overhead lines. In accordance with plan 4, which is proposed for the three overhead lines, the frequency of failures due to unknown faults on the network is reduced. Also, the results of Table VII show that in underground cables, only PM is proposed for Section 20, and in other sections, PM is not required. Based on the results obtained from the implementation of the proposed method, only PM for RCSs is proposed and PM is not required for the manual switches.

The results of different system parameters of the cost and network reliability by the first and second scenario are given in TABLE VIII.

TABLE VIII
The results of different parameters of the real feeder for the first and second scenarios

Row	Item	Results in first scenario	Results in second scenario
1	Fuzzy value of EENS (kWh)	(L:2067.64, m: 2035.89, R:1978.6)	(L:856.4, m:1175.64, R:1579.6)
2	DE fuzzy value of EENS (kWh)	2568.7344	1037.184
3	SAIDI index	0.9366	0.4438
4	SAIFI index	2.487	0.9723
5	The cost of PM ($)	-	24427.02

CONTINUED TABLE VIII

6	The value of reliability objective function (F_R)	-	1.05085
7	The value of economic risk (Br)	-	0

The results show that after solving the optimization problem, the values of SAIFI and SAIDI have been reduced by 60% and 49% respectively. EENS has also dropped by more than 59%. It is worth noting that this improvement in network reliability with an economic risk is zero. In other words, without additional costs and with a constant budget for PM, reliability has been improved.

If the reliability indices without considering the costs of PM is to be desired (risk-neutral), the first solution is selected as the basic max-min solution in which the risk level is the highest. In this case, the value of reliability objective function and the economic risk are 1.040038 and 1237.22, respectively. The cost of PM and reliability indices in risk-neutral (first solution) and risk-averse (third solution) case are presented in TABLE IX.

TABLE IX
The cost of PM and reliability indices in risk-neutral and risk-averse case of the real studied feeder

Row	Item	Result of the risk-averse	Result of the risk-neutral
1	Fuzzy value of EENS (kWh)	(L:856.4, m:1175.64, R:1579.6)	(L:823.14, m:1098.41, R:1508.54)
2	DE fuzzy value of EENS (kWh)	1196.82	1132.125
3	SAIDI index	0.02219	0.02117
4	SAIFI index	0.16205	0.15024
5	The cost of PM ($)	24427.02	25587.02
6	The value of reliability objective function (FR)	1.05085	1.040038
7	The value of economic risk (Br)	0	1237.22

The results show that in the risk-neutral case, the amounts of EENS, SAIDI, and SAIFI indices have been improved versus the risk-averse case. But, the cost of PM and the value of the economic risk in risk-neutral case have increased vis-à-vis the risk-averse case.

C. Case Study of Standard Network

In this step, a 33-bus standard network [31] is studied using the parameters presented in this study whose results are given in TABLES X - XII.

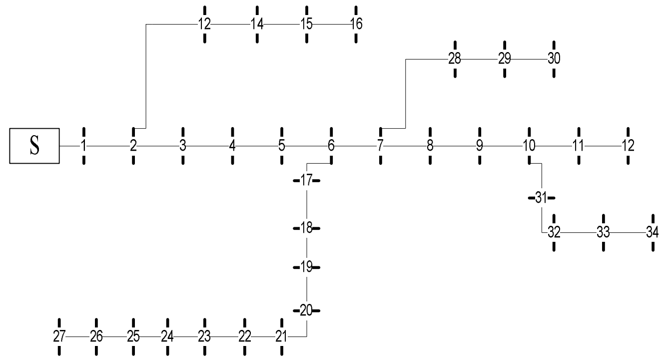

Fig. 7. Single-line diagram of a 33-bus Standard network

TABLE X
The proposed PM plan for the overhead lines

Number of PM plan	Proposed overhead lines for PM implementation
PM plan 1	2, 3, 4, 12, 13, 17, 18, 20, 30, 32, 33
PM plan 2	8, 9, 11, 21, 31
PM plan 3	5, 7, 10, 14, 23, 24, 27
PM plan 4	1, 6, 15, 25, 26, 28

TABLE XI
The proposed PM for the underground cables and manual switches

Elements	Number	Result of proposed method
CB PM plan	1	Ok
Manual switches PM plan	1	-
	2	Ok
	3	-
	4	-

TABLE XII
The results of different parameters of the standard network for the first and second scenarios

Row	Item	Results in first scenario	Results in second scenario
1	Fuzzy value of EENS (kWh)	(L:45007.07, m: 45131.9, R: 45225.53)	(L: 33041.13, m: 33057.03, R:33068.95)
2	DE fuzzy value of EENS (kWh)	45124.10	33056.03
3	SAIDI index	0.161365	0.08219
4	SAIFI index	1.30833	0. 69061
5	Cost of PM ($)	-	40531.18
6	The value of reliability objective function (F_R)	-	1.02578
7	The value of economic risk (Br)	-	0

As can be seen, PM has prominent effects on a system's reliability indexes and the EENS has been considerably improved.

VIII. Conclusions

The main impetus of the present paper is to improve the network's reliability and reduce the interruption of the distribution network by considering the restrictions on PM budget.

To this aim, RCM is implemented to identify the critical elements of the system and the PM strategies. For a more accurate modeling of a system, the system's loads and their corresponding costs are modeled in terms of fuzzy numbers. The economic risk function has been used to assure the balance between the cost of PM and the restriction of PM budget. In this paper, RCM is done on overhead lines, underground cables, CB, manual switches, and RCSs. Based on the various causes of failure in overhead lines, four PM plans are considered. For other elements, one PM plan is included. In order to simultaneously improve the reliability indices of the system with economic restrictions, a multi-objective model based on NSGA II has been used. The proposed technique has been successfully applied to a 33-bus standard network and an MV feeder of the GTEDC. The results of applying the proposed method show that the reliability indexes (EENS, SAIFI, and SAIDI) have been significantly improved with considering budget restrictions and without imposing additional costs.

Appendix

TABLE I
Line data of the studied feeder

Line number	From bus	To bus	Line length (m)	Resistance (ohm)	Reactance (ohm)	Line type
1	1	2	500	0.1935	0.069	Underground
2	2	3	520	0.20124	0.07176	Overhead
3	3	4	25	0.009675	0.00345	Overhead
4	4	5	350	0.13545	0.0483	Overhead
5	5	6	272	0.105264	0.037536	Overhead
6	6	7	80	0.03096	0.01104	Overhead
7	7	8	265	0.102555	0.03657	Overhead
8	8	9	251	0.097137	0.034638	Overhead
9	3	10	132	0.051084	0.018216	Overhead
10	10	11	310	0.11997	0.04278	Overhead
11	11	12	142	0.054954	0.019596	Overhead
12	12	13	152	0.058824	0.020976	Overhead
13	13	14	205	0.079335	0.02829	Underground
14	14	15	350	0.13545	0.0483	Overhead
15	15	16	350	0.13545	0.0483	Overhead
16	16	17	150	0.05805	0.0207	Overhead
17	17	18	165	0.063855	0.02277	Overhead
18	18	19	261	0.101007	0.036018	Overhead
19	19	20	274	0.106038	0.037812	Overhead
20	20	21	325	0.125775	0.04485	Underground
21	21	22	310	0.11997	0.04278	Overhead

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

Load points	Number of customers	Load type	Load		
			The least possible value	The value with the highest probability	The highest possible value
2	5	Residential	78	120	150
3	0	-	0	0	0
4	28	Residential	214.5	330	412.5
5	30	Residential	266.5	410	512.5
6	14	Residential	79.95	123	153.75
7	12	Commercial	195	300	375
8	5	Residential	78	120	150

Continued TABLE II					
9	2	Residential	92.3	142	177.5
10	3	Residential	57.85	89	111.25
11	5	Residential	71.5	110	137.5
12	-	-	0	0	0
13	12	commercial	117	180	225
14	3	Industrial	149.5	230	287.5
15	-	-	0	0	0
16	23	Residential	201.5	310	387.5
17	3	Residential	16.25	25	31.25
18	8	Industrial	316.55	487	608.75
19	10	Residential	84.5	130	162.5
20	7	Industrial	57.85	89	111.25
21	14	Industrial	123.5	190	237.5
22	33	Commercial	247	380	475

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