International Journal of Research and Technology in Electrical Industry

journal homepage: ijrtei.sbu.ac.ir

Shahid Beheshti University

Reliability Enhancement by Strategic Placement of Remotely-Controlled Automation Devices: A Case Study on Tabriz Distribution Network

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ARTICLEINFO

Article history:
Received 27 November 2021
Received in revised form 08 March 2022
Accepted 19 March 2022

Keywords:
Distribution automation
Modified NSGA-II
Reliability
RCS placement
Distribution system operation

ABSTRACT

Achieving high distribution-reliability levels and concurrently minimizing operating costs are as the main issues in distribution system optimization. Determination of the optimal number and location of remote control switches (RCS) in the distribution system network is an essential issue from the reliability and economic points of view. To address these issues, this paper develops a novel multiobjective model from the distribution system viewpoint, wherein the primary objective, optimal RCS placement is implemented aiming at minimizing the operating costs, while in the second objective, the reliability index improvement is taken into account. So, a novel approach from a robust heuristic algorithm, modified non dominated sorting genetic algorithm (MNSGA-II), is developed and presented to solve this multiobjective mixed-integer non-linear programming problem. Simulation results received by the genetic algorithm have been compared with the other popular optimization algorithms, seperately. Results show that the proposed algorithm provides extensively the best performance, in terms of quality of the answer received and computational efficiency. The feasibility of the proposed algorithm was examined by application to two distribution feeders of the Tabriz city distribution network containing the fourth feeder of the TractorSazai substation.

Nomenclature

F_1	RCS placement cost function
DS_i	Decision variable related to the installation or non-installation of RCS devices at the candidate site
CS	Cost of a RCS
n	Number of candidate locations for RCS installation
DT_j	Decision variable related to the construction or non-construction of maneuver point at the candidate site *j*
CT_j	Cost of the maneuver point construction on the candidate site *j*
m	Number of candidate locations for maneuver point construction
MC	Cost of equipment maintenance and operation
P_W	Economic factor to convert current costs of the study horizon to the current costs
Infr	Annual inflation rate
Intr	Annual interest rate
ny	Study horizon by year
ENS_T	Total energy not supply

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http://dx.doi.org/10.52547/ijrtei.1.1.36

ENS_i	Energy not supply in the distribution post *i*
IC_i	Average cost of blackout in the distribution post *i*
K_i	Demand importance factor of *i*th post
nLP	Number of distribution points on the feeder
$AIC_i(.)$	Blackout cost
P_i	The percentage of each load in distribution post *i*
λ_i	Failure rate in *i*th mode
r_i	Repair rate
P	Average consumption at the load point
η_c	Crossover index
η_m	Mutation index
V_i	Voltage of the *i*th load point
I_i	Current of the *i*th load point
f_{i-1}^{k}	*k*th objective of the (*i-1*)th individual
f_{i+1}^{k}	*k*th objective of the (*i+1*)th individual
r	Iteration number
$x_i^{(1,t+1)}$	Offspring solutions
$x_i^{(2,t+1)}$	
$x_i^{(1,t)}$	Parent solutions
$x_i^{(1,t)}$	
u_i	Random number between 0 and 1
δ_i	Polynomial probability distribution
υ_i	Variance of crowding distance

1. Introduction

The issues and challenges in the distribution network are currently one of the most pressing concerns in the energy area, attracting the attention of all operation professionals. High power losses, voltage drops, and power interruptions are these problems, for which the installation of distribution automation devices is a crucial solution, given the enormous amount of investment and the requirement for optimal operation in this type of network. The network's end-consumers desire to get high-quality power with no disruptions. As a result, the distribution network's functioning is guided by the following two key ideas. 1) Consistency in delivering customer service 2) Keeping a high level of service quality. Due to the expanse of Tabriz city distribution network, the requirement for appropriate installation and placement of distribution network automation equipment is becoming increasingly apparent. The goal of distribution system automation is to reduce the amount of total power loss, energy not supply (ENS), the staff salaries, and the time it needs to discover faults. Aside from the technical benefits, the automation of distribution networks has economic profitability that is dependent on the optimum selection of the function [1], [2].

A reactive tabu search optimization technique is used in [3] to find the best locations for automation devices. The proposed strategy is considered the cost of long-term interruptions, automation equipment's purchase, and maintenance in the objective function. The author in [4] is studied a novel objective containing the cost of long-term interruptions and automation of distribution systems. To solve the suggested mixed-integer non-linear programming problem, the author is proposed a modified particle swarm optimization technique. The heuristic combinatory search technique developed in [5] decomposes the overall automation issue involving numerous types of automation devices into a series of simple sub-problems involving a single type of device. It specifies a set of heuristic criteria for determining the position of single feeding devices. The expense of long-term interruption and the cost of automation equipment is taken into account. In [6], from the metaheuristic algorithms, a genetic algorithm is selected in this paper to solve the optimal sectionalizing switches and reclosers placement problem. The dependability indices are optimized using this method, which takes into consideration the cost of automation equipment.

A long-term switch placement problem is presented in [7], considering load forecasting. The problem modeled as mixed-integer linear programming (MILP) formulation to include long-term load forecasting results obtained using the historical load data. A two-stage optimization algorithm is proposed in [8] to find the optimal number and place of automatic switches in the presented distribution network. In the first stage, the greedy optimization algorithm is applied to solve the restoration problem in the presence of contingencies. In the second stage, a cost function containing the ECOST and annual automatic switches cost is modeled and minimized due to the chosen locations of switches. An optimal distributed generation-based sectionalizing switches placement is investigated in [9] for distribution networks. The proposed problem is modeled as a mixed-integer non-linear programming (MINLP) problem and contains the cost of short-term outages and automation equipment. Optimal switch placement in the Ahvaz city distribution network is proposed in [10], in which the genetic algorithm is used to enhance the grid reliability. A model introduces in [11] to find the optimal number and location of automation devices. The presented model takes the benefit of MIP formulation making contributions to solving this extensive problem in an efficient run time and ensures the global optimum solution. The goal of this model is to minimize the total interruption and equipment costs.

Although valuable works have been done in the field of the optimal switch placement, but there are still many problems and deficiencies that need to be addressed properly. Briefly, the shortcomings of previous references are as follows:

a) The determination of the number and location of only one type of switch, mainly sectionalizes, is taken into account.

b) In the previously mentioned studies, switches are normally located in the predetermined positions in the feeders by default.

c) The calculation of operating cost function and the reliability service simultaneously in determining the best network automation solution is not addressed.

To address the shortcomings and drawbacks of previous literature, this paper attempts to provide the following contributions. The objective of this paper is to solve a multiobjective function in order to find compromised solutions both to enhance the reliability by optimal allocation of remote control switches (RCS) and minimize the total operating costs. In most of the prior works, where the optimal placement of switches has been considered, the number of RCS has been taken as fixed. In some literature where the number of RCS has been considered as a variable, multiobjective problem formulation has not been considered. In the present paper, both the number and location of RCS have been considered as variable, and a multiobjective function has been formulated. This paper develops a multiobjective model, wherein the primary objective, optimal RCS is implemented to minimize the total operating costs, while in the second objective, the reliability improvement is taken into account. A novel modified non dominated sorting genetic algorithm (MNSGA-II) is presented in this paper to reach the optimum global solutions. The MNSGA-II achieves solutions to the RCS placement problem instead of a single solution. This makes the proposed solution more adaptable to different utilities' circumstances and eases the decision-making. The outcome of the proposed technique has been compared with well-established optimization techniques like particle swarm optimization (PSO), differential evolution (DE), ant colony optimization (ACO), and so on. The following is a quick summary of the paper's novelties and contribution:

- ❖ Applying a robust optimization algorithm like MNSGA-II to solve the proposed complicated MINLP multiobjective problem.
- ❖ Applying the large-scale and practical distribution test systems like the fourth feeder of the TractorSazi substation post.
- ❖ Developing a mathematical methodology based on MINLP to solve the suggested optimal RCS placement problem for efficient reliability enhancement in distribution grids considering the cost of power losses, construction of maneuvering points, installation of RCSs, and maintenance and operation.

The mathematical formulation of the suggested problem is described in Section 2. The backward-forward sweep-based method is explained in Section 3. Section 4 provides an overview of the MNSGA-II. Section 5 contains the simulation results and discussion. The conclusion is summarized in Section VI.

2. Problem formulation

The suggested method applies a multiobjective mathematical programming paradigm with two competing goals: 1) minimizing the cost of RCS deployment and 2) improving the service reliability (reducing the amount of ENS index). The primary objective is to keep the cost of sectionalizing RCSs as low as possible. To measure service reliability, the energy not supplied index is used.

2.1. First objective: RCS placement cost function

The following costs are involved in RCS placement and their locations design in distribution networks: i) Damages caused by not supplying energy to customers; ii) Costs related to the RCS construction, including price and installation cost; iii) Costs related to the RCS location, including RCS and line price, and iv) Cost of equipment maintenance and operation. In this case, the goal is to minimize the sum of these costs. Of course, it should be noted that some of these costs (items ii and iii) are in the form of initial investment, but items (i and iv) are in the form of current costs, and in combining these two categories into a single cost function, Using the parameters of engineering economics, all costs are converted into a template.

$$\text{Min } F_1 = \left\{ \begin{array}{l} \sum_{\text{i=1}}^{\text{n}} DS_i \times CS + \sum_{\text{j=1}}^{\text{m}} DT_j \times CT_j \\ + \sum_{\text{t=1}}^{\text{ny}} P_W^t \times MC + \sum_{\text{l=1}}^{\text{L}} P_{Loss}^t \times K_{Loss} \end{array} \right\} \tag{1}$$

$$P_W = \frac{1+\text{Infr}}{1+\text{Intr}} \tag{2}$$

2.2. Second objective: Energy not supply function

In this paper, reliability studies based on the analytical method are performed. The analytical method evaluates reliability based on failure mode and effect analysis. At first, the failure modes that affect each load point (distribution posts) are identified. Then, by evaluating their effect, the reliability index (ENS) is calculated in each load point. In this calculation, the impact of RCSs and their locations for fault separation, and the possibility of supplying load points through support communication lines are considered. The amount of ENS related to domestic and industrial consumers plays a crucial role in distribution system automation. Equation (6) shows the consequences of energy not supply function in distribution networks.

$$\text{Min } F_2 = \sum_{i=1}^{nLP} ENS_{\text{T}} = \sum_{i=1}^{nLP} IC_i \times ENS_i \times K_i \tag{3}$$

$$IC_i = \left\{ \begin{array}{l} AIC_i\,(\text{res}).P_i\,(\text{res}) + AIC_i\,(\text{com}).P_i\,(\text{com}) \\ +AIC_i\,(\text{ind}).P_i\,(\text{ind}) + AIC_i\,(\text{agr}).P_i\,(\text{agr}) \\ +AIC_i\,(\text{gen}).P_i\,(\text{gen}) \end{array} \right\} \tag{4}$$

$$\lambda_s = \sum_{\text{i}\in\text{A}} \lambda_i \qquad (\text{f / yr}) \tag{5}$$

$$U_s = \sum_{\text{i}\in\text{A}} \lambda_i r_{\text{i}} \qquad (\text{h / yr}) \tag{6}$$

$$r_s = \frac{U_s}{\lambda_s} \qquad (\text{h / f}) \tag{7}$$

$$ENS = PU_s \qquad (\text{kWh / yr}) \tag{8}$$

The average failure rate and average outage time are given in equations (8) and (9), respectively. Also, the annual average outage time and average ENS are presented as equations (10) and (11), respectively.

3. Backward-Forward sweep based algorithm

The backward sweep and the forward sweep are two phases of this procedure. Backward sweep calculates voltage and current from the farthest bus from the beginning bus, applying KVL and KCL rules. The downstream voltage starts from the beginning bus in the forward sweep. The bus-branch information is used as the algorithm's input data. The active and reactive power flows for sending and receiving buses, impedance, and susceptance of all branches are essential basic information. The significant steps of the suggested algorithm are listed as follows: [12], [13].

1) Assume rated voltages at end nodes only for first iteration and equals the value computed in the forward sweep in the subsequent iteration.
2) Start with the end node and compute the node currently. Apply the KCL to determine the current flowing from node *i*-1 towards node *i*.
3) Compute with this current the voltage at the *i*th node. Continue this step till the junction node is reached. At the junction node, the voltage computed is stored.
4) Start with another end node of the system and compute voltage and current as steps 2 and 3.
5) Compute with the most recent voltage at the junction node.
6) Similarly, compute till the reference node.
7) Compare the calculated magnitude of the rated voltage at the reference node with the specified source voltage.

$$I_i^t = \left(\frac{P_i + jQ_i}{V_i^{t-1}}\right)^* \tag{9}$$

$$I_{i-1,i}^t = I_i^t + \sum_k I_{i,k}^t \qquad k \geq i \tag{10}$$

$$V_i^t = V_{i-1}^{t-1} - \left(R_{i-1,i} + jX_{i-1,i}\right) I_{i-1,i}^t \tag{11}$$

Stop if the voltage difference is less than the specified criteria; otherwise, the forward sweep begins.

Forward Sweep:

1) Start with reference node at rated voltage.
2) Compute the node voltage in forward direction from the reference node to the end nodes.
3) Again start backward sweep with updated bus voltage calculated in forward sweep.

After calculating node voltages and line currents using a standard backward-forward sweep algorithm, the line losses are calculated.

4. Providing an Overview on MNSGA-II

Non-dominated sorting for fitness tasks is utilized by the MNSGA-II [14]. Both polynomial mutation and binary crossover produce different generations, and event choice is later employed to pick out the populace for the subsequent generation. Elitism resolves the trouble of dropping accurate answers for the duration of the optimization cycle because of chance impacts. One manner of coping with this issue is to join the old populace and the generation. The MNSGA-II with dynamic crowding distance (DCD) is utilized to tackle the suggested issue [15].

4.1. Simulated binary crossover (SBC)

In common, SBC places the strain on producing generation close to the parents. This crossover ensures that the volume of the youngsters or generation is equal to the parents' volume, and additionally supports that close to determine people are monotonically much more likely to be selected as youngsters than children remote from the parents with inside the answer space [16]. The process for detecting the generation answers $x_i^{(1,t+1)}$ and $x_i^{(2,t+1)}$ from parent answers $x_i^{(1,t)}$ and $x_i^{(2,t)}$ is presented as follows. u_i is a random number that is define between 0 and 1. Afterward, by using probability distribution function, the β_{qi} is obtained as equation (12):

$$\beta_{qi} = \begin{cases} (2u_i)^{1/\eta_c+1} & ,\text{if } u_i \leq 0.5; \\ \left(\dfrac{1}{2(1-u_i)}\right)^{1/\eta_c+1} & ,\text{ otherwise.} \end{cases} \tag{12}$$

In equation (12), an indicator η_c is a positive number. Since finding β_{qi} , the children's answers are computed as equations (13) and (14):

$$x_i^{(1,t+1)} = 0.5\left[(1+\beta_{qi})x_i^{(1,t)} + (1-\beta_{qi})x_i^{(2,t)}\right] \tag{13}$$

$$x_i^{(1,t+1)} = 0.5\left[(1-\beta_{qi})x_i^{(1,t)} + (1+\beta_{qi})x_i^{(2,t)}\right] \tag{14}$$

The actions developed for the production of children are shortly addressed as below [17]:

Step 1: select a random number $u_i \in [0,1]$

Step 2: compute β_{qi} applying equation (12).

Step 3: a set of mutated parents $x_i^{(1,t)}$ and $x_i^{(2,t)}$ is chosen randomly to generate children's answers $x_i^{(1,t+1)}$ and $x_i^{(2,t+1)}$ by applying equations. (13) and (14).

4.2. Polynomial mutation

The possibility of making an answer close to the parents is better than making one remote from it. The form of the probability distribution is immediately managed via an outside parameter and stays constant at some stage in the iterations. Like withinside the SBC operator, the probability distribution also can be a polynomial function, in place of a normal distribution:

$$y_i^{(1,t+1)} = x_i^{(1,t+1)} + (x_i^{(U)} - x_i^{(L)})\delta_i \tag{15}$$

Parameter δ is computed from the polynomial probability distribution

$$P(\delta_i) = 0.5(\eta_m + 1)(1 - |\delta|)^{\eta_m} \tag{16}$$

$$\delta_i = \begin{cases} (2r_i)^{1/\eta_m - 1} - 1 & , \text{ } if \text{ } r_i < 0.5 \\ 1 - \left[2(1-r_i)\right]^{1/\eta_m + 1} & , \text{ } if \text{ } r_i \geq 0.5 \end{cases} \tag{17}$$

For handling the bounded decision variables, the mutation operator is modified for two regions: $[x_i^{(L)}, x_i]$ and $[x_i, x_i^{(U)}]$.

4.3. Dynamic crowding distance (DCD)

In multiobjective evolutionary algorithms, the horizontal diversity of Pareto front is essential. The horizontal diversity is often realized by removing excess individuals in the non-dominated set (NDS) when the number of non-dominated solutions exceeds population size. NSGA-II uses crowding distance (CD) measure as given in Eq. (18) to remove excess individuals. The individuals having lower values of CD are preferred to individuals with higher values of CD in the removal process.

$$CD_i = \frac{1}{r}\sum_{k=1}^{r}\left| f_{i+1}^{k} - f_{i-1}^{k} \right| \tag{18}$$

The main shortcoming of CD is the lack of uniform variety in the occupied non-dominated answers. To overcome this issue, the dynamic crowding distance (DCD) approach is newly proposed in [18]. In this method, one individual with the minimum DCD amount is deleted every time, and DCD is re-computed for the remaining individuals. The individual's DCD are computed as equation (19):

$$DCD_i = \frac{CD}{\log(1/\upsilon_i)} \tag{19}$$

where CDi is computed by equation (18) and V_i is based on equation (20),

$$\upsilon_i = \frac{1}{r}\sum_{k=1}^{r}\left(\left| f_{i+1}^{k} - f_{i-1}^{k} \right| - CD_i \right)^2 \tag{20}$$

v_i is the variation of CDs of individuals which are neighbors of the *i*th individual. V_i can provide data about the different variations of CD in various goals. Assume the population size is N, the non-dominated set at *t*th generation is $Q(t)$, and its size is M. If $M > N$, DCD-based strategy is utilized to delete $M-N$ individuals from the non-dominated set. The following steps can be adopted for the implementation of the MNSGA-II algorithm.

Step 1: Determine the variables for the suggested multi-objective problem.

Step 2: choose the amount of the parameters such as crossover, mutation, and population and generation number.

Step 3: produce the initial population.

Step 4: Assess the objective function for the primary population.

Step 5: Fix the generation number.

Step 6: Perform SBC crossover and polynomial mutation for the set of individuals.

Step 7: Perform non-dominated sorting.

Step 8: Calculate DCD.

Step 9: Perform selection based on tournament selection Thereby a higher fitness is assigned to individuals located on a sparsely populated part of the front.

Step 10: Increment the generation count and repeat the steps from 6 to 9 until the count reaches the maximum number of generations.

To explain the summary of the proposed model and optimization algorithm, a flowchart is desired as figure 1.

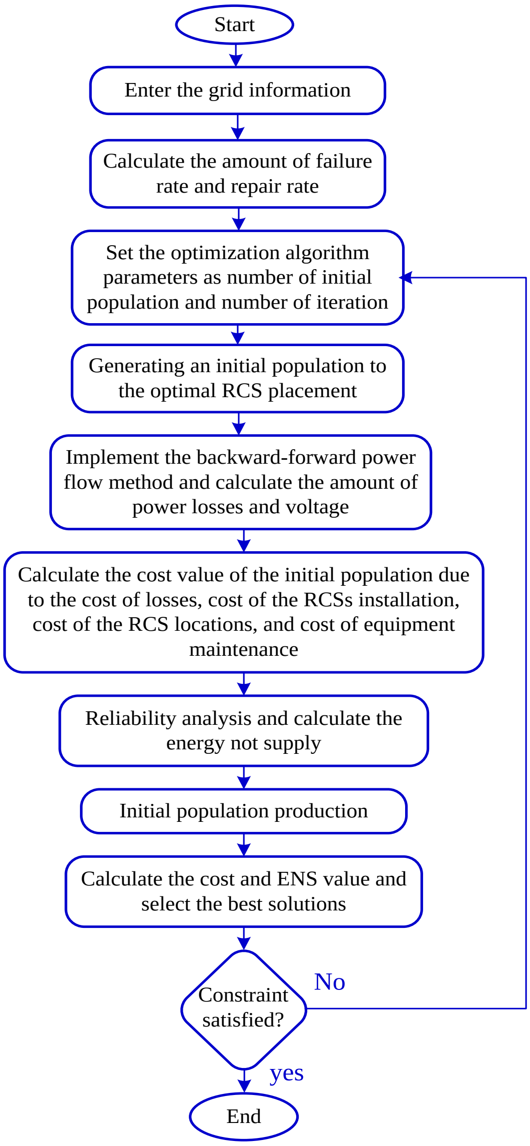
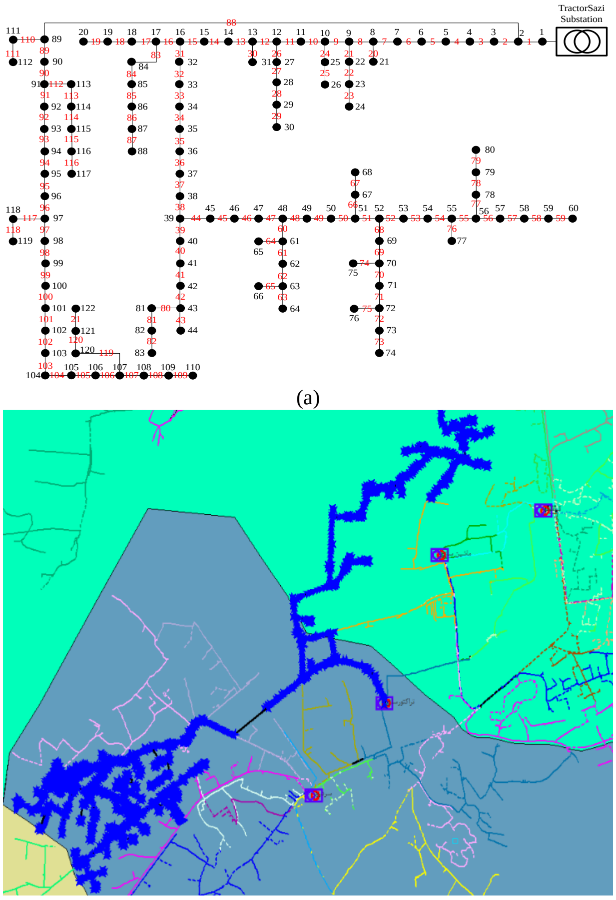


Fig. 1. The flowchart of the proposed method.

5. Simulation results and discussion

5.1. Case study

The suggested algorithm is used in a more complicated and effective system to investigate the model's applicability in actual conditions. The 4th feeder of TractorSazi substation from Tabriz city distribution network is shown in Fig. 2. It consists of 122 load points and there are 121 possible RCS locations in this system. The total load demand of this practical test system is 6.183 MW and 3.1 MVAR, respectively. The system is operated with the nominal bus voltage of 20 kV and 100 MVA base. The line and trans capacity data are given in Table IV. Also, the total length of the ground and overhead lines is 3.23 and 19.70 km, respectively. Moreover the consumption load data are presented in Fig. 3.



(a)

(b)

Fig. 2. 4th feeder of TractorSazi substation

There are some assumptions and modifications are applied to the fourth feeder of TractorSazi substation post.

1) The failure rate of all RCSs is assumed to be zero.

2) The proposed system is supplied only from the TractorSazi substation post.

3) The proposed feeder consists of both overhead and underground types.

4) From the viewpoint of providing the minimum level of protection in distribution systems, it is assumed that the main breaker feeder is installed before using the optimization method to optimally locate the RCSs.

5) Optimization algorithm is constrained to the limitation of (21) and (22)

$$V_i^{min} < V_i < V_i^{max} \tag{21}$$

$$I_i^{min} < I_i < I_i^{max} \tag{22}$$

The voltage limit V^{min} and V^{max} are assumed between 0.95 and 1.05 pu, respectively [19].

6) In this paper, the cost of each RCSs is supposed to be $ 4,700. The annual maintenance cost is 2% of the annual investment cost [20].

7) Average durations and number are presented in Table I [21].

Table I. Medium duration and number of proposed feeder

Failure	Average time (m)	Number
Unfavourable weather conditions	14	5
Bird encounter	45	12
Transient	5	6
Connecting in the cable of medium voltage	5	1
Replacement of defective bushings	72	1
Failure in cut-outs	55	5
Dealing with annoying trees	32	1
Problems in transformers	106	1
Problems in the insulator (plate, needle)	90	3
Failure in internal Pothead of Medium voltage	30	1
The network conductors collide with each other or with the body	41	2
Failure in Breakers	198	2
Unknown failure	20	12

8) The optimal RCS placement problem has been modeled and solved from the distribution system commission viewpoint.

9) The configuration of the proposed distribution network is assumed as a radial network, which is operating radially and not a closed-loop grid. So that, the RCSs are placed in such a way that the network does not lose its radial structure. Also, the protection relays are designed for the radial distribution network. If the RCSs places in such a way that the distribution network operates as a closed loop grid, the forecasted protection relays are acted and the feeder will be interrupted.

10) Since the proposed network type is considered as a distribution network, the R/X ratio is high and it can not use Newton-Raphson and Gauss-Seidel power flow methods. Therefore, in this paper, the sweet backward-forward power flow method is used.

11) The proposed model is a non-convex model and for this reason a meta-heuristic algorithm is used to solve this problem.

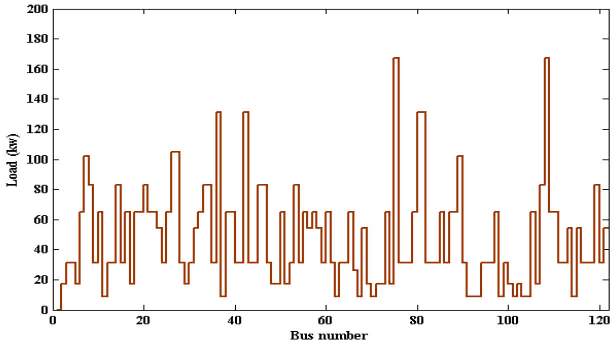


Fig. 3. Load curve of the suggested network

This article summarizes the steps, data collection, and implementation of simulation as follows:

Step 1: Obtaining the static data of the fourth feeder of TractorSazi substation from GIS containing the structure, load points, load data, and transformer types.

Step 2: Obtaining peak load information from the Tazarv software.

Step 3: Collect data related to medium voltage outages from the dispatching control center and events record software.

Step 4: Transfer network structure and data from GIS to MATLAB environment.

Step 5: Calculates the current flow of lines and voltage drop to implement the backward-forward power flow method.

Step 6: Find the best optimum global solutions using MNSGA-II.

Step 7: Print the results of minimum ENS and operating costs.

5.2. Simulation and numerical results

The results related to the first objective function are given in Table III. Because the suggested test system is a practical and large-scale system, it is obvious that the optimal positions for placing the RCSs are the critical points and main feeders. The outcomes achieved by using the suggested method show that the optimal positions for placing the RCSs are the critical points and main feeders containing the 3, 39, 44, and 88, proving the excellent performance of the MNSGA-II for this practical network. Figure 4 shows the ENS of the each section. The ENS of each section is calculated by using the objective function (6) and the MNSGA-II is used to minimizing the total amount of ENS in order to enhance the reliability service goals in the proposed distribution test system.

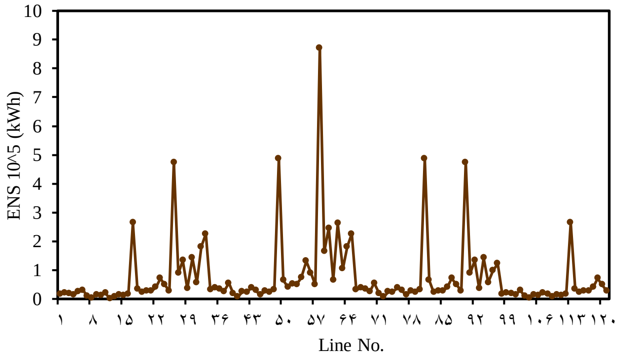


Fig. 4. Energy not supply

Figure 5 shows the voltage profile after and before applying the proposed method. As can be seen from this figure, after using proposed model the voltage magnitude of each node is significantly smooth in compare to the initial case. Figure 6 depicts the active power losses of the. It is clear that, employing the proposed multi-objective approach can be remarkably reduce the amount of power losses related to each line. Finally, these results deducted that optimal placement of remotely controlled automation devices have good impact on the system technical specification like voltage profile and total active power losses.

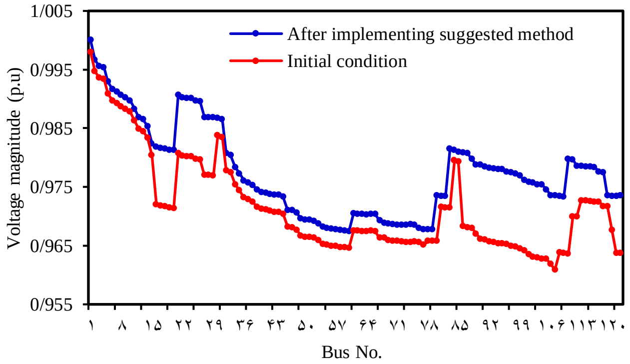


Fig. 5. Voltage profile after and before implementation of proposed model.

Table II shows the comparison of the real and optimal placement of RCSs in the proposed distribution system. This table declares that using a good performance with high convergence rate meta-heuristic algorithm like MNSGA-II has remarkably impact on the obtained results.

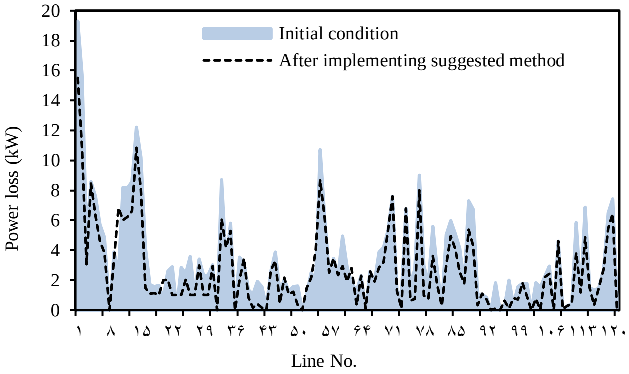


Fig. 6. Active power losses of the network.

So that, the minimum cost of switching equipment in optimal placement condition is reduced near to %79 of it's real and experimental placement condition. Also, the number of RCSs are decrease from 5 to 4 RCSs, which the proposed algorithm find the critical points of system according to the first objective function to locating these RCSs. Finally, the total ENS of the all section is reduced near to %23, which prove using MNSGA-II algorithm improve the reliability service of the distribution system. Table III presents the best results for the optimal switch placement obtained applying various methods. The best results related to optimal placement of automation devices with various methods are presented in Table III, and compared with each other by considering different elements. Regarding to this table, it is obvious that the proposed method had has more impact on the operating cost reduction and reliability service (energy not supply) improvement compared to other conventional methods.

Figure 7 displays the optimal Pareto curve obtained from MNSGA-II. All dominated members are eliminated, and non dominated members remain. The optimal solution is the blue square around it. This point is the best and optimum global solution, which is the minimum amount of operating cost and average ENS of all sections have been achieved.

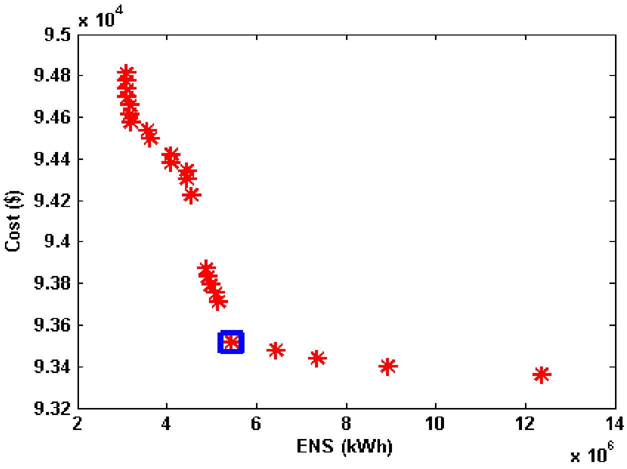


Fig. 7. Pareto curve of the proposed algorithm

This paper introduces a model for the optimal placement of the active distribution network. This model has been solved by the MNSGA-II algorithm to reach the optimum global solutions. Fig. 8 shows the convergence characteristic of the

RCS cost function. Due to Fig. 8, the first objective function (optimal placement of RCS) has been run in 100 iterations, and the amount of the objective function at every iteration has been depicted. The best optimum solution is obtained at iteration 46. Moreover, in this figure, the GA efficiency in comparison with other popular meta heuristic algorithms like PSO, GWO, DE, ABS, and ACO has been shown. It is clear the convergence rate and speed of the proposed algorithm are higher than other optimization algorithms. Fig. 9 shows the convergence curve of the second objective function (ENS function). Due to Fig. 9, the second objective function has been run in 100 iterations, and best optimum solution is obtained at iteration 49.

Table II. Comparison of the real and optimal placement of RCSs in the proposed distribution network

Item	Real and experimental placement condition (current condition)	Optimal placement condition using MNSGA-II
Minimum cost of switching equipment	116896.1938 ($/yr)	93516.9551 ($/yr)
Number of RCSs	5	4
RCS placement	S9, S22, S50, S88, S97	S3, S39, S44, S88
Total ENS	7055804.3384 (kWh)	5454100.5079 (kWh)

Table III. Best results for the optimal switch placement obtained applying various methods

Ref.	Proposed method	Test case	Type of automation device	Optimal device No.	ENS reduction (%)	Total cost ($)
[22]	Mixed integer linear programming	38 bus DN	Sectionalizing switch, fault passage indicator and Recloser	23	---	% 19.8
[23]	Fuzzy multiobjective model	23 bus DN	Sectionalizing switch	12	% 18.57	% 7.2
[24]	Multiobjective optimization based	IEEE 123 bus DN	Manual switch	28	% 4.91	---
[25]	Multiobjective optimization based	118 bus DN	Remote control switch	16	% 8.08	% 16.93
[7]	Mixed integer linear programming	38 bus DN	Remote control switch	30	---	% 8.50
[8]	Two-level optimization	1069 bus DN	Upgraded automatic switch	5	% 13.86	% 16.08
This paper	**Suggested method**	**122 bus DN**	**Remote control switch**	**4**	**% 22.70**	**% 21**

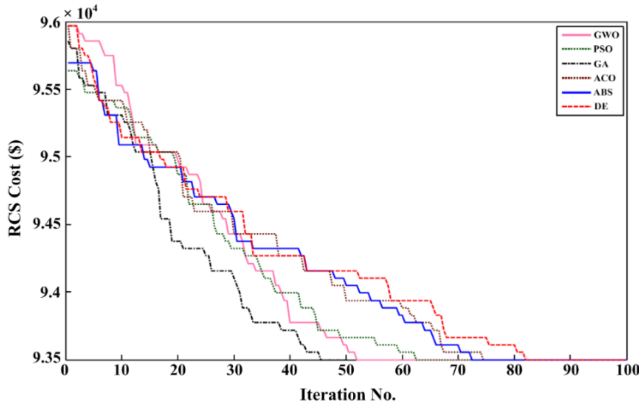


Fig. 8. Convergence curves of first objective function minimization.

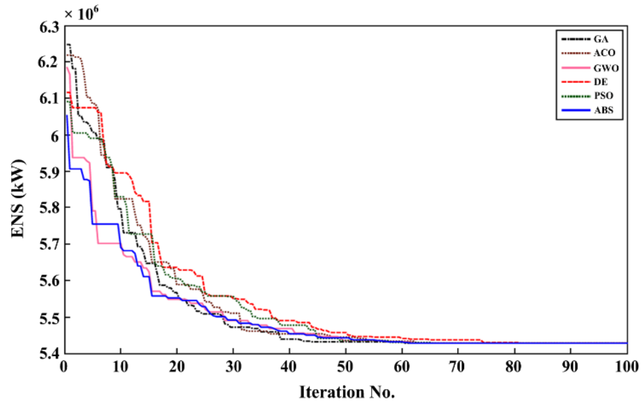


Fig. 9. Convergence curves of second objective function minimization.

6. Conclusion

This paper presents a new multiobjective model that includes two compromising goals: the cost of minimizing RCS placement and improving reliable service. The results showed that system reliability and total operating costs were significantly improved and reduced by optimizing RCS placement. The proposed approach is applied to a real distribution network, and the effectiveness of the MNSGA-II-based method for solving this MINLP problem is demonstrated through the obtained results. This work minimizes the RCS equipment cost to %79 of its real and experimental condition. Moreover, the amount of energy not supplied from reliability indices reduced to % 77.3 of its initial condition. Also, some system technical features such as voltage profile and total active power loss have been improved. Based on results, the following issues are achieved.

i. Optimal placement of RCS could minimize the operation costs of system and improve the reliability service.
ii. Multiobjective modelling was proposed to solve two compromising objectives simultaneously.
iii. Technical characteristics of the system such as voltage profile and power losses are improved.

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8. Appendix

Table IV. The bus and line data of the proposed distribution network

Bus No.	Transformer capacity	Bus No.	Transformer capacity	Line No.	Impedance (Z)		Line No.	Impedance (Z)	
					Resistance (R)	Reactance (X)		Resistance (R)	Reactance (X)
1	200	62	25	1	0.0303	0.0999	62	0.04	0.1356
2	50	63	100	2	0.0129	0.0424	63	0.038	0.127
3	100	64	200	3	0.00176	0.00798	64	0.0601	0.189
4	100	65	200	4	0.0241	0.108	65	0.0191	0.0625
5	50	66	75	5	0.0119	0.054	66	0.0715	0.323
6	200	67	25	6	0.00459	0.0208	67	0.0715	0.323
7	315	68	160	7	0.00244	0.0305	68	0.0684	0.186
8	250	69	50	8	0	0.0267	69	0.0179	0.0505
9	100	70	25	9	0.00258	0.0322	70	0.0267	0.0752
10	200	71	50	10	0.0209	0.0688	71	0.0486	0.137
11	25	72	50	11	0.0203	0.0682	72	0.0203	0.0588
12	100	73	200	12	0.00595	0.0196	73	0.0405	0.1635
13	100	74	50	13	0.0187	0.0616	74	0.0263	0.122
14	250	75	100	14	0.0484	0.16	75	0.073	0.289
15	100	76	100	15	0.00862	0.034	76	0.0869	0.291
16	200	77	100	16	0.02225	0.0731	77	0.0169	0.0707
17	50	78	100	17	0.0215	0.0707	78	0.00275	0.00955
18	200	79	200	18	0.0744	0.2444	79	0.00488	0.0151
19	200	80	400	19	0.0595	0.195	80	0.0343	0.0966
20	250	81	400	20	0.0212	0.0834	81	0.0474	0.134
21	200	82	100	21	0.0132	0.0437	82	0.0343	0.0966
22	200	83	100	22	0.0454	0.1801	83	0.0255	0.0719
23	160	84	100	23	0.0123	0.0505	84	0.0503	0.2293
24	100	85	200	24	0.01119	0.0493	85	0.0825	0.251
25	200	86	100	25	0.0252	0.117	86	0.0803	0.239
26	315	87	200	26	0.012	0.0394	87	0.04739	0.2158
27	315	88	200	27	0.0183	0.0849	88	0.0317	0.145
28	100	89	315	28	0.0209	0.097	89	0.0328	0.15
29	50	90	100	29	0.0342	0.159	90	0.00264	0.0135
30	100	91	25	30	0.0135	0.0492	91	0.0123	0.0561
31	160	92	10	31	0.0156	0.08	92	0.00824	0.0376
32	200	93	25	32	0	0.0382	93	0	0.0386
33	250	94	100	33	0.0318	0.163	94	0.00172	0.02
34	250	95	100	34	0.01913	0.0855	95	0	0.0268
35	100	96	100	35	0.0237	0.0943	96	0.00901	0.0986
36	400	97	160	36	0	0.0388	97	0.00269	0.0302
37	25	98	25	37	0.00431	0.0504	98	0.018	0.0919
38	160	99	100	38	0.00799	0.086	99	0.018	0.0919
39	200	100	50	39	0.0474	0.1563	100	0.0482	0.218
40	100	101	25	40	0.0108	0.0331	101	0.0258	0.117
41	100	102	50	41	0.0317	0.1153	102	0	0.037
42	400	103	25	42	0.0298	0.0985	103	0.0224	0.1015
43	100	104	25	43	0.0229	0.0755	104	0.00138	0.016
44	100	105	200	44	0.038	0.1244	105	0.0844	0.2778
45	250	106	50	45	0.0752	0.247	106	0.0985	0.324
46	250	107	250	46	0.00224	0.0102	107	0	0.037
47	100	108	500	47	0.011	0.0497	108	0.03	0.127
48	50	109	200	48	0.0415	0.142	109	0.00221	0.4115
49	50	110	200	49	0.00871	0.0268	110	0.00882	0.0355
50	200	111	100	50	0.00256	0.0094	111	0.0488	0.196
51	50	112	100	51	0	0.0375	112	0.0446	0.18
52	100	113	160	52	0.0321	0.106	113	0.00866	0.0454
53	250	114	25	53	0.0593	0.168	114	0.0401	0.1323
54	100	115	160	54	0.00464	0.054	115	0.0428	0.141
55	200	116	100	55	0.0184	0.0605	116	0.0405	0.122
56	160	117	100	56	0.0145	0.0487	117	0.0123	0.0406
57	200	118	100	57	0.0555	0.183	118	0.0444	0.148
58	160	119	250	58	0.041	0.135	119	0.0309	0.101
59	100	120	100	59	0.0608	0.2454	120	0.0601	0.1999
60	200	121	160	60	0.0413	0.1681	121	0.00376	0.0124
61	100	122	160	61	0.0224	0.0901			