# Optimal Network Reconfiguration with Distributed Generation Using NSGA II Algorithm

Jasna Hivziefendić
Faculty of Engineering and Information Technologies
International Burch University
Sarajevo, Bosnia and Herzegovina

Amir Hadžimehmedović
University of Tuzla
Tuzla, Bosnia and Herzegovina

Majda Tešanović
Faculty of Electrical Engineering
University of Tuzla
Tuzla, Bosnia and Herzegovina

***Abstract*—This paper presents a method to solve electrical network reconfiguration problem in the presence of distributed generation (DG) with an objective of minimizing real power loss and energy not supplied function in distribution system. A method based on NSGA II multi-objective algorithm is used to simultaneously minimize two objective functions and to identify the optimal distribution network topology. The constraints of voltage and branch current carrying capacity are included in the evaluation of the objective function. The method has been tested on radial electrical distribution network with 213 nodes, 248 lines and 72 switches. Numerical results are presented to demonstrate the performance and effectiveness of the proposed methodology.**

***Keywords—radial distribution network; distributed generation; genetic algorithms; NSGA II; loss reduction***

## I. INTRODUCTION

Newly formed market conditions articulate the need for adjusted approach in managing distribution network in order to meet not only the requirements imposed by technical conditions of the system but also the requirements imposed by consumers and network regulators. Significant changes in distribution system have been caused by installing distribution generation units which have considerable impact on system voltage profile and power losses, both being important quantities in the process of planning and reconfiguration of electrical network.

DGs are grid-connected or stand-alone electric generation units located within the electric distribution system at or near the end user. The integration of DGs in distribution system would lead to improving the voltage profile, reliability improvement such as service restoration and uninterruptible power supply and increase in energy efficiency. The distribution feeder reconfiguration (DFR) is one of the most significant control schemes in the distribution networks which can be affected by the interconnection of DGs [1].

Generally, the DFR is defined as altering the topological structure of distribution feeders by changing the open/closed status of automatic and tie switches or protective devices located in strategic places in distribution system. By changing the statuses of the sectionalizing and tie switches, the configuration of distribution system is varied, and loads are transferred among the feeders while the radial configuration format of electrical supply is still maintained.

Network reconfiguration is a very effective and efficient way to ensure more even load distribution of network's elements, improve system reliability and voltage profile, and to reduce power losses. All modes are subject to reconfiguration: normal, critical and failure. Provided that all variables are within acceptable limits, network reconfiguration will achieve optimal working conditions in normal mode.

Taking into consideration a large number of switches in distribution network, whose on/off switching affects the network topology, reconfiguration problem can be defined as a complex combinatorial, non-differentiable, and constrained multi-objective optimization problem. Radial network conditions, explicit voltage constraints in all node, line capacities, etc. are viewed as some of the constraints that have to be taken into consideration.

In recent years, different methods and approaches have been used to solve the problem of distribution system reconfiguration with distribution generators installed. The literature related to this problem mainly refers to application of heuristic algorithms and artificial intelligence-based algorithms such as Genetic algorithms, Fuzzy logic, Particle swarm optimization, Tabu search, etc. [2-7]. Most cases address reducing power losses and load balancing, taking into account the effect of generators distributed in the network, while very little attention is paid to system reliability. However, special attention should been paid to the issue of reliability of power supply, in order to increase economic efficiency of distribution companies [14]. Network reconfiguration process can be used as one possibility to improve network reliability indicators. Furthermore, reliability improvement by DGs is possible when intended islanding operation is allowed [8].

In paper [15] NSGA II (Non-Dominated Genetic Algorithm II) is applied to the planning of distribution electrical network problem. This paper is focused on the application of NSGA II on resolving the problem of reconfiguration of distribution network with distributed generation. The effect of distributed generation on voltage in the network, taking into account two objective functions: power losses and reliability function is presented. Depending on characteristics of the power distribution networks (network parameters, characteristics of power lines, failure rates, types of consumers, etc) simultaneous optimization of these functions can be disagreeing, that is the optimum topology for one objective can be very different by the optimum obtained with the other function. Since the proposed method optimizes two objective functions simultaneously, the problem is defined as multi-objective problem taking into account the defined system constraints. The effectiveness of the methodology is demonstrated on real distribution network consisting of 213-buses showing its potential of applicability to the large distribution systems.

The problem formulation is discussed in detail in section II. The network reconfiguration algorithm using a multi-objective NSGA II is described in section III. The simulation results in terms of power loss and energy not supplied are discussed in Section IV and finally the last section presents the conclusion of the study.

## II. Problem Formulation

The objective of the proposed solution model for reconfiguration of distribution network problem is to minimize two functions as follows: power losses function and reliability function presented by Energy not supplied index (ENS). The optimal results of the defined functions do not lead to the same optimal network topology what creates trade-off between reliability and power losses function.

Electrical power losses are one of the most important factors which point to business cost-effectiveness and quality of distribution. Energy losses in electrical distribution network in the amount of 1% cause the increase in company's business costs of up to 2% to supply energy to cover the losses [9]. Therefore, the reduction of power losses is one of the most important issues in distribution system operation.

In addition to the power losses function, reliability function is also defined in the paper, with the objective to increase reliability in consumers supply by minimizing expected energy not supplied due to power interruptions. The essential attributes of interruptions in the power supply of the customers are the frequency and duration. While duration is predominantly influenced by the distribution system structure (radial, meshed, weak meshed) and the existing automations, the frequency is mainly influenced by the adopted operational configuration; it can be minimized by the suitable choice of the effective configuration [7]. Since there is no 100% reliable system, it is in the best interest of both suppliers and consumers to minimize power supply interruptions. This function will be presented through Energy not Supplied function (ENS).

These two objectives can be met by identifying optimal network topology. Efficient solution of the described problem requires the choice of optimal topology of radial network within the set of possible solutions.

### A. MathematicalFormulation of Problem

The purpose of distribution network reconfiguration is to find optimal radial operating structure that minimizes two functions: the system power losses and ENS function within the operating constraints. Accorindg to the literature [2], [14] thus the problem can be formulated as follows:

$$\min P_{loss} = \sum_{i=1}^{n} (I_i + D_i I_{DI})^2 R_i \tag{1}$$

where $D_i = 1$ if line $i \in \alpha$ , otherwise is equal to 0.

$$\min f_{ens} = \sum_{i=1}^{N_V} P_i \lambda_i r_i \tag{2}$$

where $P_{loss}$ is total real power losses function, $f_{ens}$ is the ENS function, $I_i$ current in the branch $i$; $R_i$ resistance in the branch $i$; α is set of branches connected to the distribution generators node $m$, $P_i$ real power flow through branch $i$; $\lambda_i$ failure rate of branch $i$ (number of failure per year and per kilometer of branch $i$); $r_i$ failure duration of branch $i$; $N_v$ number of branches. The DG produces active current $I_{DI}$, and for a radial network it changes only the active component of current of branch set α.

Subject to the system constraints:

- $I_i \le I_{\max_i}$ - the current in each branch cannot exceed the branch capacity,
- $V_{\min} \le V_j \le V_{\max}$ - voltage constraint.

The voltage in each load buses in the system has to be within the defined limits. The minimum voltage is 0.95 and maximum voltage is 1.05 (±5%).

- $P_S + \sum_{i=1}^{n} P_{g,i} = \sum_{i=1}^{n} P_i + P_{loss}$ - power balance constraint
- $\sum i = n-1$ - topological constraint.

Electrical distribution systems are operated in radial configuration.

Generator operation constraints:

DG units are only allowed to operate within the acceptable limit where $P_i^{\min}$ and $P_i^{\max}$ are the lower and upper bound of DG output and $P_i^{\min} \le P_g \le P_i^{\max}$ .

The search space for this problem is the set of all possible network configurations.

In order to check the defined constraints, voltage magnitude and angle at each bus in the system have to be known at any time. When the voltage magnitude at any bus in the system is not within the defined limits, network configuration cannot be considered as a possible solution.

Since this information is included in the state variable $x$, it can be presented as follows:

$$x = [q_2, q_3, \ldots, q_n, |V_2|, |V_3|, \ldots, |V_n|]^T \tag{3}$$

and state space as is $IR^{6(n-1)}$, where

$|V_i| = \left[|V_i^a|, |V_i^b|, |V_i^c|\right]^T$ and $\theta_i = \left[\theta_i^a, \theta_i^b, \theta_i^c\right]^T$ are

voltage magnitude and angels respectively for load buses $i$, and the bus 1 is substation.

For three-phase distribution network with n buses, bus 1 presents substation and buses 2, 3, ...n, are load buses. Equation (3) can be solved by power flow calculation solving the system of (6n-6) non-linear algebraic equations.

To calculate the second objective function, ENS index due to interruption in supply, it is necessary to consider two elements: failure rate and the length of interruption in power supply for each load point. The latter is consisted of two components: time necessary to locate failure and the time necessary to repair it. Automatic sectionalizers and switches separate the part of the network where the failure occurred, reducing the risk for other consumers in the network. The time needed to repair the failure is usually the time needed to isolate the failure, to connect the affected consumers to reserve power supply (if possible) and to repair the fault itself [10]. In order to calculate this function, load flow studies should be performed to calculate not-distributed energy in all consumer nodes without supply, which are located "under" the fault in the network.

## III. Optimization Method for Multi-Objective Reconfiguration Network

The development of heuristic algorithms and computer performances have contributed towards solving the problem of multi-objective optimization. While solving multi-objective optimization problems, it is necessary to pay attention to convergence to optimal set of solutions (Pareto set) and maintain diversity of solutions within the set of current solutions [11]. Suggested methodology for solving the defined multi-objective optimization problem is based on multi-objective Non-Dominated Sorting Genetic Algorithm II. (NSGA II).

Genetic algorithms use population of solutions in every optimization path within optimization process. The objective is to come as close as possible to the true Pareto-front and simultaneously gain as many solutions as possible. This ensures that the decision-maker will have a wider choice of quality solutions with a better overview of all possible optimal topologies of a distribution network [11].

### *A. NSGA II Algorithm*

Multi-objective evolutionary algorithms are suitable for multi-objective optimization due to their ability to handle complex problems, involving features such as discontinuities, multimodality, disjoint feasible spaces and noise functions evaluation [12]. NSGA II is a multi-objective genetic algorithm developed by Deb, 2003 [13]. Basic advantage of NSGA II over other multi-objective genetic algorithms is reflected in possibilities for diversity preservation of population, which further enables uniform distribution of solutions within Pareto front. The crowding distance approach is introduced into NSGA II as the fitness measure to make comparison of solutions in the same Front. This approach estimates the density of solutions surrounding a particular solution by calculating the average distance of two points on either side of the observed solution for all objective functions defined for particular problem. The fast non-dominated sort strategy is used to evaluate solution dominance and classify the solution into Pareto fronts that corresponds to the cluster with the same solution dominance. Furthermore, NSGA II uses elite strategy that significantly helps in speeding up the performance of the genetic algorithm [13].

### *B. Proposed Methodology*

Algorithm starts with randomly selected radial functional solution that is typical for electrical distribution network, as a basis for a first generation of trade-offs in the part of a genetic algorithm code. By applying NSGA II algorithm new potential solutions of the network are generated. The binary alphabet has been used to implement the optimization model, in which every bite of chromosome represents the status of switches (open/closed). Every bite can have value of 0 or 1, which identifies the status of every electric line, 0-open, 1-closed. In the reconfiguration network problems, only a certain number of lines have a changeable bit in chromosome, and therefore only those lines are subject to genetic operators, crossover and mutation, while other lines have a fixed value in chromosome (always have the value of 1 in operation).

If newly created solutions meet topological constraints (radial conditions), evaluation of the objective functions is carried out, i.e. power flow and calculation of objective functions are performed. Power flow calculation is done in MATLAB. For that purpose, a part of the code for power flow calculation based on Newton-Raphson method is modified for the need of objective functions evaluation, transfer of variables, storage of diverging solutions and visualization. Based on the power flow results, convergence of specific network configuration is verified, as well as other constraints which refer to the capacities of lines, power stations and distributed generations. Solutions which do not satisfy defined constraints are eliminated or penalized, depending on convergence of power flow calculation. For other solutions, which meet defined limits, evaluation of objective function is done.

The procedure is repeated until stopping criteria are met. The criteria for stopping calculation can be based on a maximum number of generations, minimum of evaluated solutions, time limits to simulation, average change in solution distribution, etc.

Suggested model uses the concept of Pareto domination in the evaluation of the objective functions. Input data to describe multi-objective optimization problem are system parameters and constraints, lines, the loads, reliability parameters, failure rates, and the repair times.

MATLAB functions for genetic algorithms which are used for calculation are modified for specific discrete function for calculating power flow, power losses and testing system's constraints for network solutions.

CPU time spent for calculating and identifying the set of possible solutions depends on the time necessary for the objective functions evaluation, time for verification of defined constraints by power flow calculation and active losses. To speed up the calculation, parallel processing of genetic algorithm, in the part of evaluation of the objective function and constraints, is done.

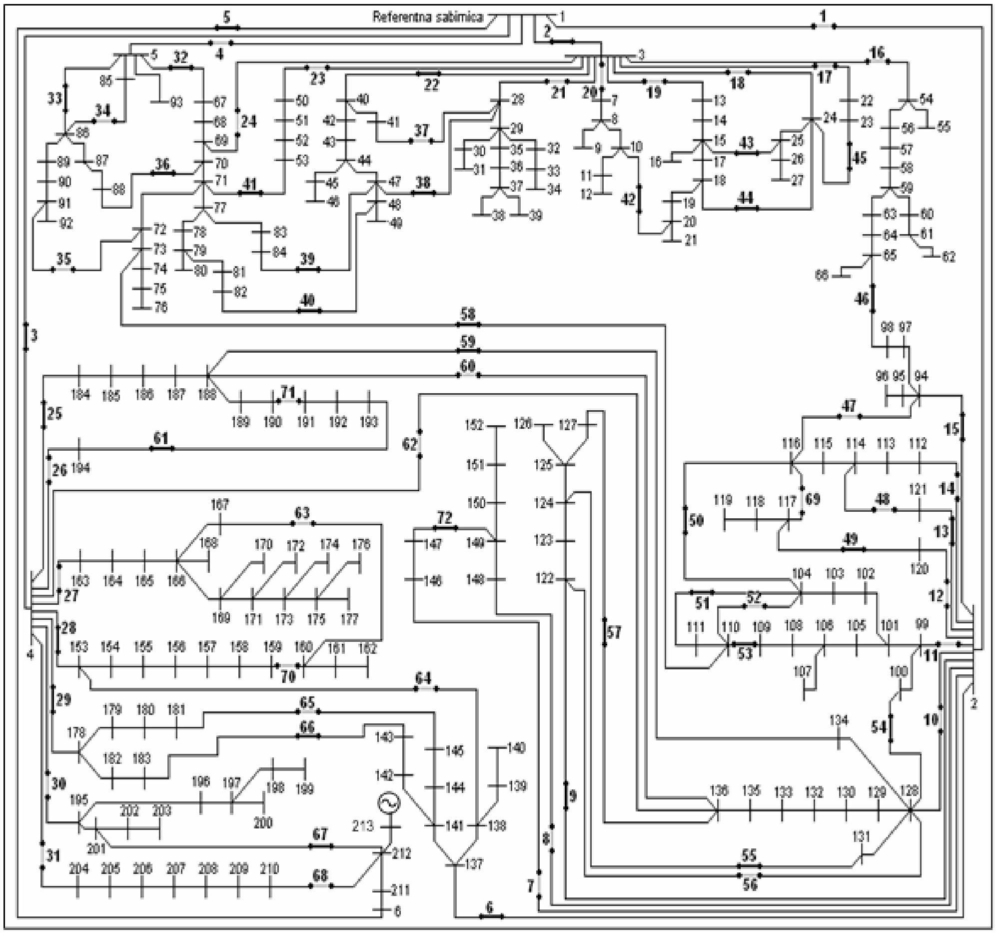


Fig. 1. Part of a distribution network with distributed generation

Taking into consideration that evaluation of one individual (solution) is completely independent of some other individual, independent of some other individual, evaluation of the entire population is distributed to 8 available processors, which significantly speeds up the calculation process.

The results of the described algorithm is a Pareto front of possible optimal topological solutions for the electrical distribution network

## IV. Case Study and Numerical Results

The test system for the case study is 10 KV radial distribution network with distributed generation (Fig. 1.) with 213 buses, 248 lines and 72 switches. Distributed generation is connected to the node 213 and generates the active power of 5 MW. It is assumed that DG does not generate reactive power to the network.

All simulations are done on Intel Xeon E5-2699V3 with 32 GB RAM, that enables parallel data processing on 18 processor units. In initial network topology, presented in Fig. 1., switches 2–3, 5–6, 9, 13, 15, 22, 25, 28–29, 32–33, 36, 38–46, 49–51, 53–55, 57–59, 61, 66–67 and 72 are closed, while 1, 4, 7-8, 10–12, 14, 16–21, 23–24, 26–27, 30–31, 34–35, 37, 47–48, 52, 56, 60, 62–65 i 68–71 switches are open. For initial solutions, total power losses are 51.630 KW and ENS due to interruption in supply is 24.1387 KWh.

NSGA II parameters

In the consideration of optimal parameters 60 simulations were run with different values. Only the best performing parameters are presented in this paper and they are: initial population size is 150, crossover probability pc is 0.8, maximum number of generation is 200 and Pareto fraction is 0.45. Tournament selection is used, as well as two-point crossover. The stopping criterion of the algorithm is an imposed maximum number of generations or limit of the average change in distribution of solutions within the Pareto set (less than 10). Certain number of simulations is done by using adaptive mutation which search the larger solution space in the smaller number of generation (in this case the number of generation was 114), but evaluation time is longer. After the multiple independent runs of algorithm, it was concluded that the best results are achieved with fixed mutation probability of 0.01.

Furthermore, it was observed that fitness values significantly improve in early generations, when the solutions are farther from optimal values. The best fitness values slowly improve in later generations, whose population is closer to the optimal solutions. Number of generations for achieved solutions was in the range from 110-140 generations, for all tests with fixed crossover and mutation factor.

### A. *Result Analysis*

Application of the described methodology to identify optimal network configuration based on NSGA II algorithm resulted in a set of possible solutions, out of which 9 Pareto optimal solutions are presented in Fig. 2. Pareto set of optimal solutions is achieved for 138 generations, while total number of achieved possible solutions is 49.

Total algorithm execution time on 18 processor units was 15 minutes and 36 seconds.

Table 1. shows values of objective functions for solutions from Pareto optimal set, as well as the on/off change of switches.

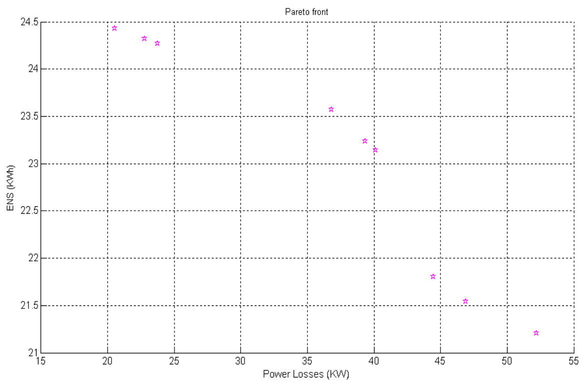


Fig. 2. Pareto optimal solutions for network reconfiguration with distributed generation

TABLE I. VALUES OF OBJECTIVE FUNCTION FOR PARETO OPTIMAL SOLUTIONS FROM FIG. 2

| No. | Switch on | Switch off | Losses KW | IS Wh |
|---|---|---|---|---|
| 1. | 62 | 3 | 20.6344 | 24.4875 |
| 2. | 7 | 72 | 23.7643 | 24.2683 |
| 3. | 63 | 6 | 25.8799 | 24.2139 |
| 4. | 68 | 67 | 37.1474 | 23.5844 |
| 5. | 60 | 59 | 38.7454 | 23.2314 |
| 6. | 31 | 5 | 40.1339 | 23.1442 |
| 7. | 62 | 5 | 44.4429 | 21.8045 |
| 8. | 71 | 61 | 46.8351 | 21.6585 |
| 9. | 63 | 8 | 52.2096 | 21.2066 |

Considering the results shown in Table 1, the best solution for losses function is solution 1. However, this is the worst solution for ENS function. It is evident that changes in the value for ENS function are smaller than for losses function. Therefore, based on practical network topology implementation, functional and economical benefit the best compromise solution can be solution 3, given the evident small changes in ENS function between solutions 3, 4 and 5, while the difference in losses function is somewhat bigger. Solution 3 has power losses of 25.8799 KW, while ENS is 24.2139 KWh.

The achieved near-optimal solutions show traits of each solution from the Pareto front (the fact that not a single individual solution from Pareto front can be improved for one function without affecting the other in the opposite manner). This trait does not apply for all permissible searched solutions. The character of the achieved searched and near-optimal solutions depends on all set values, where different intensities and length of fault on lines are of special importance.

If intensity and fault length at all lines are equal, the variability of solution would be considerably lower, with a unique optimum for both functions. It is obvious that many searched solutions can be simultaneously improved from the aspect of both functions which are optimized; subsequently, the considered objectives are not necessarily in conflict with each other. This does not provide values which are approximately optimal for either of the objective functions.

Objective function assessing reliability, interruptions in supply, is incidental. Therefore, when descending sort order strategy is applied, the probability for local minimum is higher for reliability criterion that for power losses function.

Optimal minimization of losses will be achieved when the voltage in lines is closer to the maximum allowed value $U_{max}$. Since calculations were done with assumed constant load values (values of peak loads), maintaining voltage at lines as closer as possible to $U_{max}$ ensures considerably less values for losses in the network. If voltage limitation is $U_{max}$ = 1.20, losses values for solution 3 would be 11.256 KW.

Power losses for line 211-212 for initial solution are 0.73 KW, and for the identified optimal solution it is 0.49 KW (solution 3). Values for losses at the same line without distributed generation connected is 0.58 KW with the same switch state.

Since distributed generation is of small capacity in relation to the strength of distributive network into which it is connected, there is a reduction in the losses in the line onto which it is connected.

*Impact on voltage*

On Fig. 3. is shown voltage profile of bus system for solution 3 from Table 1. It is clear that the voltage is within the allowed limits. On Fig. 4. is shown the change in voltage in network nodes when distributed generation is not connected into the network (voltage shown in blue) and when the distributed generation is connected (voltage shown in red). The shapes of voltage profiles are almost the same in both cases, except for minor changes in the voltage strength at end lines, which is a consequence of connected distributed generation. Lines with distributive generation connected have an increase in voltage from 0.9723 p.u. to 0.9813 p.u. after installing the distributed generation into the network.

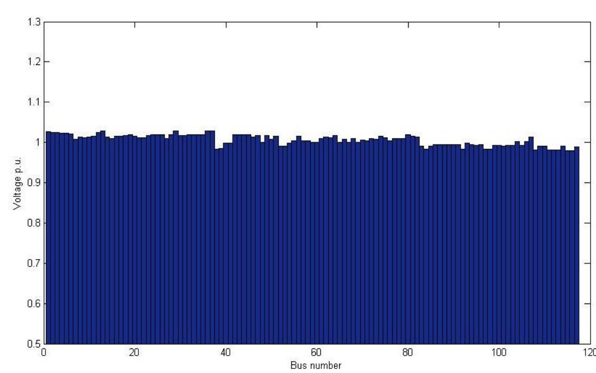


Fig. 3. Voltage profile for solution 3

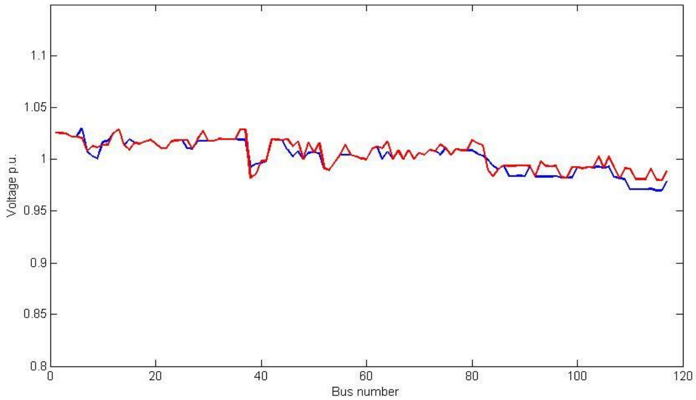


Fig. 4. Voltage profile with distributed generation connected and disconnected

## V. CONCLUSION

Reconfiguration represents one of the most important measures which can improve performance in the operation of a distribution system. The paper shows application of multi-objective genetic algorithm NSGA II on resolving the problem of reconfiguration of distributive network with distributed generation, in order to identify optimal topological solution taking into account the set limitations. Algorithm is tested on a part of a network with 213 nodes, 248 lines and 72 switches. Multi-objective problem is formulated in order to decrease overall network losses and improve system reliability through minimizing ENS. The achieved results show the efficiency of the proposed methodology. Identification of near-optimal network configuration is presented. It is evident in decreasing overall network losses and ENS index compared to network initial state. The paper also shows the effect of distributed generation on voltage profile in distributive network. The results show that network reconfiguration in the presence of DG improve the voltage profile in the network.

It is obvious that application of the proposed methodology enables a more complex approach to improving the operational conditions in distributive networks, compared to traditional methods. The methodology proposed is also a useful tool for quick identification of optimal network configuration in case of faults, and it can also be beneficial for planning and upgrading existing network.

So, both the NSGA II efficiency in finding solutions and the increased efficiency of the the distribution network after using NSGA II are presented in the paper.

The achieved results for both objective functions can be represented in financial terms as well, and these are economic indicators to improve efficiency in managing a distributive network.

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