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DISTRIBUTION NETWORK RECONFIGURATION CONSIDERING POWER LOSSES AND OUTAGES COSTS USING GENETIC ALGORITHM

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This paper discusses the problem of finding the optimal network topological configuration by changing the feeder status. The reconfiguration problem is considered as a multiobjective problem aiming to minimize power losses and total interruptions costs subject to the system constraints: the network radiality voltage limits and feeder capability limits. Due to its complexity, the metaheuristic methods can be applied to solve the problem and often the choice is genetic algorithm. NSGA II is used to solve the multiobjective optimization problem in order to get Pareto optimal set with possible solutions. The proposed method has been tested on real 35 kV distribution network. The numerical results are presented to illustrate the feasibility of the proposed genetic algorithm.

K e y w o r d s: radial distribution network, multiobjective optimization, reconfiguration, genetic algorithms, NSGA II

1 INTRODUCTION

Under normal working conditions, electric distribution network must continually supply the consumers connected to the network and must take into account all technical and economic traits imposed by network configuration and topology. Given their direct link to consumers and great investment costs, as well as maintenance costs, electric distribution networks are of great importance for power supply system. Approximately 30–40 % of total costs in power supply system go to distribution networks. Ideally, losses in electric distribution network should be 3–6 %; however, they are higher, and in developed countries they amount to 10 and even up to 20 percent. Moreover, consumers' need for reliable power supply is of paramount importance. It is therefore necessary to adjust the process of managing distribution networks to meet the demands imposed by consumers as well as network controllers. Efficient management of distribution networks makes it possible to reduce costs incurred by losses and to increase power supply reliability without making major investments. Reconfiguring network topology, via opening and closing of switches or protective devices located in distribution network strategic points, is one of the methods to plan and manage distribution networks. Network reconfiguration could ensure uniform load distribution within network's elements. Reconfiguration can be applied in all modes: normal, critical and failure. In normal mode, when all variables are within acceptable limits, network reconfiguration will achieve optimal working conditions. In these situations, objective function usually represents losses in the network. Recently, special attention has been paid to the issue of reliability of power supply, in order to increase economic efficiency of the distribution companies. Therefore, network reconfiguration process can be used as method to improve network reliability indicators [1].

Given the high number of switches in distribution networks, whose on/off state changes network topology, reconfiguration problem can be characterised as a complex combinatorial problem with constraints of various nature. The problem needs to compute the power flow for every topological change resulting due to reconfiguration. Some common constraints are network radiality, voltage limits, feeder thermal limits, power flows *etc.* Furthermore, when discussing reconfiguration, parameters which describe system reliability as well as economic costs associated with distribution lines should be taken into account. In practice, reconfiguring distribution networks turns out to be even harder because distribution networks are composed of hundreds or thousands of loads, hence an exhaustive search approach is not a feasible solution to the problem.

Over the recent years, reconfiguration has been addressed through stochastic, that is, metaheuristic methods, such are the methods based on simulated annealing algorithms [7], fuzzy logics [5], tabu search [12], ant colony [11], and genetic algorithms [1–4].

This paper presents the application of multiobjective genetic algorithm (non-dominated sorting genetic algorithm II -NSGA II) as a method used to solve the network reconfiguration problem, in order to identify Pareto optimal set (optimal feeder topological structure).

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The proposed method simultaneously considers two objective functions, of which one minimizes power losses in the network, and the other minimizes outages costs incurred by supply interruptions for some network consumers. The method has been tested on the example of 35 kV distribution network with 54 nodes.

2 NETWORK RECONFIGURATION PROBLEM

The task of a distribution system is to deliver electric power of certain quality to every consumer. The availability of electric power can be increased by improving the existing structure of distribution network. However, extensive investments can induce additional network operating costs, which result in consumers having to pay increased price for electric power. The losses in the network due to inadequate usage of existing and/or planned capacity of network, additionally burden the system in financial sense. Electric power losses are main indicators which point to business cost-effectiveness and the quality of distribution business. Energy losses in 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 [10]. For this reason, reduction of losses of electric power in distribution network is one of the important goals.

In addition to the reduction of losses, this paper also deals with the goal to increase reliability in consumers supply. Problems that arise in power supply are mainly caused by faulty network components. Equipment faults can lead to supply interruptions, which causes costs incurred by interruptions. Technical aspect of reliability commonly refers to the calculation of reliability indicators of a part of the system, or the system in general, while economic aspect of reliability refers to damage sustained by deliverer and consumers incurred by power interruptions. Costs incurred by interruptions depend on several factors, for example the type of the consumer, power required at the moment of interruption, and the length of interruption. Given there is no absolutely reliable system, it is in the deliverer's and consumers' best interest to reduce the supply interruptions to the minimum.

Therefore, the aim of network reconfiguration is to reduce power losses and improve the reliability of power supply by changing the status of existing section allying switches and ties. This switching is performed in such way that the radiality of the network is maintained and all the loads are energized. Efficient solution of the problem requires the choice of optimal topology of radial network within the set of possible solutions. The problem of identifying optimal solution simultaneously optimizes two objective functions, taking into account the given constraints.

Depending on characteristics of distribution network (network topology, type of consumer, and statistic parameters of faults) simultaneous optimization of two objective functions can be divergent, that is, the optimum for one objective function can be very different from the optimum for another objective function. The costs of identifying possible network topological solutions are huge, given that the number of possible solutions increases exponentially with the number of switches, thus making the problem rather complex.

3 MATHEMATIC FORMULATION OF THE PROBLEM

The goal of the model proposed to solve reconfiguration is to minimize two objective functions as follows: power losses function (which represents the efficiency indicator of electric power distribution to consumers) and outages costs function incurred due to power supply interruption (as quality indicator of electric power supply). Thermal limits of electric power lines, and limits of other network elements (transformers, protective devices, switches) as well as the voltage and topology limits of the network must be taken into account.

3.1 Power losses function

The losses in distribution system depend on network parameters as well as topology and conditions imposed by network consumers. The losses can be differentiated between active and reactive power losses. Since active power losses directly affect the efficiency of power supply transfer to consumers, this paper only encompasses active losses in calculating network losses (in further text power losses). Other losses terms like those due to insulation of lines and capacitors can be neglected.

Standard program for calculating power flow based on Newton-Raphson method has been provided in order to determine concrete values of losses for the known topology and network parameters.

Mathematically, the total active power losses in distribution network can be calculated by summing up the power loss of each line through the following equation

$$\min f_g = \sum_{i=1}^{n} r_i \frac{P_i^2 + Q_i^2}{V_i^2} \tag{1}$$

where f_g is the function of losses in MW, r_i resistance of the branch i, P_i real power flowing through the branch i, Q_i reactive power flowing through the branch i, V_i voltage at the receiving end of the branch and n is the total number of lines.

3.2 Costs function due to power supply

The second objective function to be considered is the costs function incurred by interruptions in power supply within a system. In distribution networks, these costs are the sum of costs at all load points in the network. The outage cost evaluation is based on the value of energy not supplied and outage cost parameters which, over the recent years, have demonstrated the significant growth tendency. Furthermore, in order to calculate this objective function, it is necessary to consider the following aspects as well: the intensity of the malfunction and the length of interruption in power supply, which is the time necessary to locate the malfunction and the time necessary to repair it. Automatic sectionalizes and switches separate the part of the network where the malfunction occurred, reducing the risk for other consumers in the network. The time needed to repair the malfunction is usually the time needed to isolate the malfunction, to connect the affected consumers to reserve power supply (if possible) and to repair the faults itself.

In order to compute this objective function, we used the power flow calculation to calculate non-distributed energy in consumer nodes without supply, which are 'under' the faults [13].

Statistical parameters for failures occurrence and their length at certain network elements must be available, as well as statistical parameters of failures repairs. Expected annual costs due to power supply interruptions caused by fault, can be mathematically represented as

$$\min f_c = \sum_L \lambda_L \big(k_L + c_L r_L\big) P_L \tag{2}$$

where f_c is the outages costs due to interruptions (E/year), P_L strength (KW), λ_L intensity of failures in the load point L (f/yr), r_L length of failures in load point L (h/f), k_L cost of interrupted power (E/KW), c_L cost of the energy not supplied (E/KWh). Parameters r_L and k_L are different for different kinds of consumers.

Such defined costs function due to the power supply interruption points towards initial costs plus the costs which linearly depend on the length of interruption.

Furthermore, it is necessary to consider an appropriate operation of the system regarding other electrical variables such as currents and voltage levels. These values are considered through defined limits:

$I_i \le I_{\max}$ – Current variable in every element of the network must be within accepted limits,

$V_{\min} \le V_j \le V_{\max}$ – voltage limits. Voltage variable of every node must be within accepted limits.

$\sum i = n-1$ – network radiality where each node has to be supplied from a single feeder, where I_i is the current of power line i in A; $V_{\min\max}$ accepted limits of voltage in nodes in kV; $I_{\max_i}$ maximum accepted currents of power line i in A and n is the number of nodes in the network.

Since the problem of reconfiguration of distribution network involves two objectives with given constraints, it is difficult to determine global optimal solution; instead, there is a set of solutions from Pareto-front within the accepted search area. In order to address these optimization problems, multiobjective genetic algorithms are used, among which are NSGA II, which give wider Pareto front when compared with classic methods. 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.

4 METHOD TO SOLVE MULTIOBJECTIVE NETWORK RECONFIGURATION PROBLEM

The development of heuristic algorithms and advances in computer performances contributed towards solving the problem of multiobjective optimization. While solving multiobjective 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 [14]. Evolution algorithms, among which are genetic algorithms, have provided very good results in reconfiguration of distribution networks [1–4].

Genetic algorithm is a stochastic algorithm involving search methods and using the principles and mechanisms of natural evolution and genetics. Unlike traditional search methods, GA starts with a set of solutions — starting population. Every individual in population is a possible solution to the problem and is represented through a chromosome. The basics of genetic algorithms are provided in the Literature [9].

One of the main advantages of genetic algorithm over conventional methods is the fact that GA can find global optimum regardless of the characteristics of target functions (non-convexity, existence of many local optimums, non-differentiability ...). In other words, GA application can resolve complex problems with discrete objective functions and can search the solutions area in different directions, which reduces the possibility to end in local optimums, regardless of the shape of objective function (continual or discrete), limits and search area of possible solutions.

4.1 NSGA-II algorithm

NSGA II is a genetic algorithm developed by Deb in 2003. The main advantage of NSGA II algorithm over conventional genetic algorithms is that it can preserve population diversity, which enables uniform distribution of solutions within Pareto front. The problem of preserving diversity with NSGA II algorithm was addressed by applying 'crowding distance approach' which also solves the convergence problem. Provided there are l solutions in certain non-dominated front, it is necessary to calculate crowding distance *Ldistance* for every solution, Fig. 1.

Sorting possible solutions with NSGA II algorithm is done through 'the fast non-dominated sort strategy' with the aim to define dominant solutions and classifications in Pareto front. The main NSGA II procedure is as follows: initial, randomly selected population $P0$ of value N is sorted per non-domination. The first generation of $Q0$ is created using normal binary tournament, recombination and mutation. The procedure then changes. Elitism is introduced to compare flowing population with the previously defined non-dominated solution. After first generation the procedure is as follows: union $Rt = Pt \cup Qt$ of the value $2N$ is created and sorted on the basis of non-domination. The best non-dominated front is transformed into new child population until N members are reached. If randomly defined front is larger than there is space in the population, those members with higher *Ldistance* are selected. To select solutions for new $Qt + 1$ population, one must use binary tournament selection based on non-domination and crowding distance, followed by a simple crossover and mutation [8].

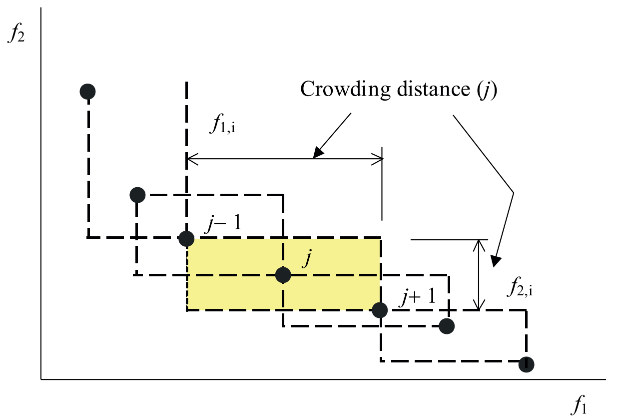

Fig. 1. Crowding distance approach

4.2 Proposed methodology

Application of multiobjective genetic algorithms NSGA II generates potential solutions to network reconfiguration, using binary overview in which every byte of chromosome defines the status of the network switch (open/closed). Every byte can have the value of zero or one to identify the status of the switch – open or closed.

For example, chromosome [1 0 1 1 0 1 1 0 1 1] illustrates the status of 10 switches in the network, where switches 2, 5, and 8 are opened (their value equals zero) and others are closed (value equals one).

Every individual, or his chromosome, represents possible topological solution for distribution network. The proposed model uses the concept of Pareto domination in evaluating target function. Pareto front is a set of solutions for the state of network topology and is defined through chromosomes. The solutions which do not satisfy network radiality criterion are rejected during calculation.

Input data for the described multiobjective optimization problem are system parameters and limits (characteristic data for power lines, buses, loads, and generators), initial topological network solution, intensity of power line failures, statistic annual data on the length of failures and outages cost parameters. Algorithm begins with selected radial initial solution of the state of the switch in the network, for which it is necessary to calculate power flows and objective functions, as basis for the first generation of solutions in the part of a genetic algorithm code. The code with applied genetic algorithm generates new states of switches for which new power flow and objective functions are calculated, as a way to verify the given limits. Solutions which do not satisfy limits are eliminated or penalized depending on convergence of power flow calculations. 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.*

Processor's time required for calculation, that is, identifying the set of optimal solutions, depends on time for evaluation of objective function, time for verification of given limits through power flow calculation and active losses. Due to nature of isolated calculation of the single individual, as well as independent calculation of given topology it is possible to speed up calculations using parallel processing. Parallelization requires a definition of master node (gathering individual results and distributing new generation variables for the calculations) and slave nodes (calculation and result reporting). In this architecture modern multicore processors can be utilized at full power, or a calculative job can be implemented in distributed manner at computing cluster. Computing cluster can speed up independent calculations within application of the executable code and is used for large scale cumulative analysis in systems consisting of higher number of network components. It is necessary to implement such speed optimizations for analysis of large distribution networks with large number of nodes.

Matlab built in functions for genetic algorithm application were utilized during calculation and were parameterized with specific discrete objective functions which are used to calculate power flow, power losses, and to evaluate system's constraints of the potential topological solutions.

Data referring to statistics on annual malfunctions of power lines, their length and outage cost parameters were used in the calculation as known values. The result of application of NSGA II is a Pareto front of optimal solutions which are possible optimal topological solutions for the network.

5 RESULTS AND DISCUSSION

In order to illustrate the efficiency of proposed methodology for finding optimal configuration of distribution network, a simulation was performed on a test system of 35 kV of a distribution network with 54 nodes, 64 power lines and 26 switches (Fig. 2).

All simulations were performed on Dual 3.00 GHz Xeon E5450 CPU architecture with 32 GB RAM memory which enabled parallel calculation on 8 available processor cores.

The values of interruption costs for different groups of customers used in calculations are taken from [6]. The minimum and maximum voltages are set at 0.95 and 1.05 pu, respectively. The study period is taken on a year basis.

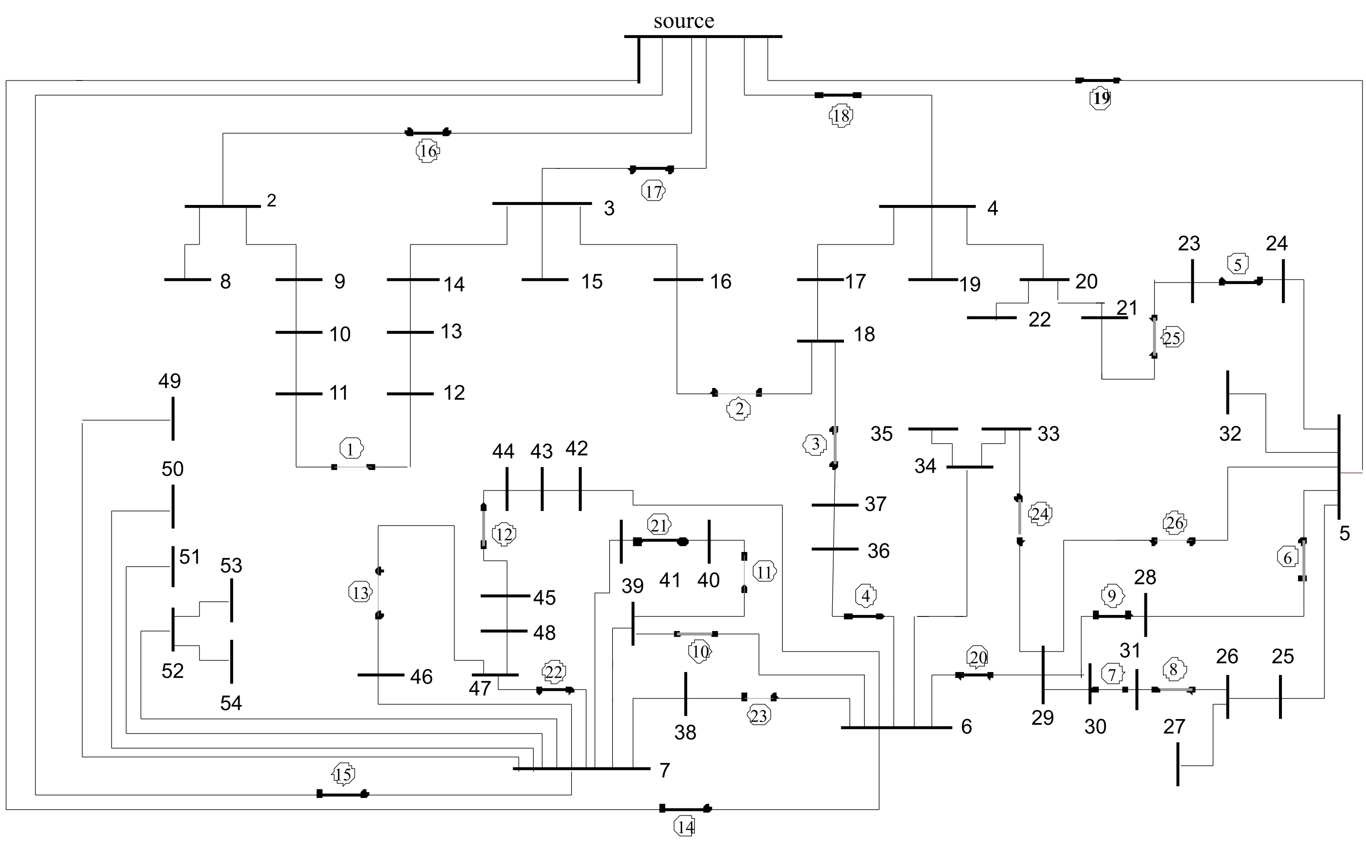

Fig. 2. 35 kV distribution network subject to the described methodology

Table 1. Parameters for the NSGA II

Population size	180
Max. Number of generation	200
Crossover probability	0.85
Mutation probability	0.01
Preto fraction	0.35
TolFun	10^{-2}

Table 2. Numerical results for Pareto optimal solutions

Solutions	Branches off	Power Losses (MW)	Outages costs (103Euro)
	Initial configuration	1.4673	141.62
1	1–3, 6,8,10,12,13,21, 23–26	1.0487	141.30
2	1, 2, 3, 6, 7, 10–13, 23–26	1.0979	141.07
3	1, 2, 4, 6, 8, 10–13, 23–26	1.2805	140.60
4	1, 2, 3, 8, 10–13, 19, 23–26	1.3950	140.12
5	1, 2, 3, 6, 8, 10, 11, 13, 22–26	1.6737	139.05
6	1, 2, 3, 8, 10–13, 20, 23–26	4.7635	129.30
7	1, 2 , 3, 6, 8, 10–14, 23–25	4.8925	128.20

The parameters used for NSGA II algorithm are shown in Table 1.

Tournament selection was used as well as two-pints crossover, and limits to the maximum number of generations or limit of the average change in distribution of solutions within Pareto set was used as a stopping criterion.

In the initial network configuration shown in Fig. 2, switches 1, 2, 3, 6, 8, 10–13 and 23–26 are off, and switches 4, 5, 7, 9 and 14–22 are on. This topological solution has power loss of 1.4673 MW, and the function of costs due to power interrup2ion is 1.4162×10^5 Euros.

Application of genetic algorithm NSGA II on the system presented in Fig. 2 has resulted in a total 56 solutions, 7 of which are Pareto optimal. The values of power losses and outages costs for certain optimal solutions, that is Pareto front, are provided in Table II. Figure 3 shows acceptable solutions provided by algorithm — Pareto front, as well as other possible solutions which are not on Pareto front. This plot (Fig. 3), in the objective function space, shows the trade off between two objective functions. Although the maximum number of generations was set to 200, all runs were interrupted under the convergence threshold.

Among the obtained solutions, optimal solution from the aspect of power loss is the solution in which total losses are $P_g = 1.0487 \times 10^5$ Euros. However, this solution provides poorer conditions for network reliability. From the aspect of reliability indicators, that is costs due to power interruptions, the best solution is provided by CENS $= 1.2820$ MWh/year; however, in this case the

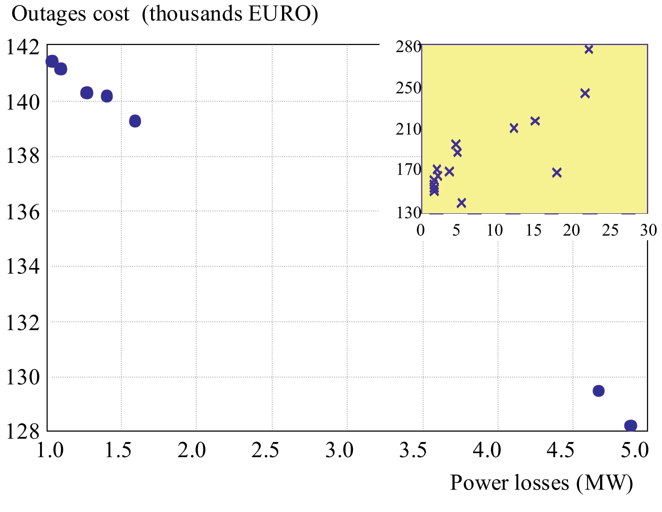

Fig. 3. Pareto optimal solutions

power losses are the largest (even larger than the values from the initial state). The first solution from Table 1 provides better solutions than the initial solution from the aspect of both objective functions.

For solution I, reduction of losses compared to initial arbitrary solution is 28.50 %, and the reduction of costs due to power supply interruption is 0.22 %. In case when both objectives are equally important, none of these solutions would be sufficient from the aspect of both objective functions.

However, the decision on selection of network working configuration among the possible solution is made by a dispatcher of distribution network, depending on needs and demands of decision-maker, as well as depending on other circumstances and criteria not modelled by the algorithm.

If decision-maker is unsatisfied with the obtained results he can start algorithms again to get other solutions that can be compared with the previous.

Based on obtained results, we can conclude that the total customer interruptions costs as well as power losses can be reduced by network reconfiguration.

Moreover, obtained optimal results manifest a known trait of Pareto solutions; that is, the fact that no individual solutions from Pareto front can be improved for one function without affecting the other in opposite way. This trait is not applicable to all searched acceptable solutions shown in Fig. 3. The character of obtained searched and optimal solutions depends on all set values, with special emphasis on different intensity and length of failures of certain power lines. Otherwise, in the case of equal intensity and length of failures of all power lines, the variability of solutions would be significantly smaller, with a unique optimum from the aspect of 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. All described facts are presented for other real and test systems in [2].

Computer time requirements are significantly reduced when using the parallel processing. CPU time is reduced for 66 %, from 45 to 15 minutes. This reduction in CPU time is of special importance when it comes to bigger systems, where the search space of possible solutions is much bigger.

Although the proposed methodology does not guarantee identification of all solutions belonging to Pareto front, its application in addressing the problems of network reconfiguration provides useful results, as can be seen in the demonstration.

6 CONCLUSION

In current analyses of distribution systems, multiobjective optimization provides an additional evaluation in managing and identifying optimal solutions. This paper demonstrates the application of multiobjective genetic algorithm NSGA II when addressing the problem of reconfiguration of distribution network with the aim to identify optimal topological solution, taking into account existing limitations. Multiobjective problem is formulated with intention to reduce total losses in the network and improve system reliability through minimization of total costs incurred due to power supply interruptions.

The results obtained show it is possible to find optimal state of the switches for which the observed network has smaller total losses and smaller total customer interruption costs.

The application of this algorithm also makes it possible to evaluate behaviour of the network and required objective functions should new switches be installed in the network, since application of the algorithm can identify branches that could provide better values for defined objective functions, if new switches are installed.

Manifold improvement of performances in analyses of objective functions, by parallelization, enable modelling of large systems or application of genetic algorithm for dispatcher's quick decisions after disturbances occurred.

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