DISTRIBUTION SYSTEM PLANNING USING GENETIC ALGORITHM

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ABSTRACT

Optimal configuration of a distribution system implies topology of the network with adequate conductor cross sections (power line sizes), and active and the reactive powers of source nodes which will simultaneously optimize several objective functions. At the same time all technical constraints must be satisfied like: voltage level limitations, radiality of the network, allowable continuous current limitations, as well as the limitations of the power delivered by the source nodes. The method of multi-objective optimization, as used in this work, is based on a Genetic algorithm and the Pareto principle of optimality. The obtained results verify the applicability of the proposed algorithm for a wide-range of distribution system planning problems.

1. INTRODUCTION

A distribution system (DS) consists of several different elements like: substations, switchyards, overhead lines, and underground cables. The construction, operation and maintenance of DS elements necessitate significant costs. These costs can be reduced by the optimization of DS planning. System optimization implies proper configuration and its timely expansion or reinforcement, based on predictions of future consumption and working conditions in DS.

Working conditions in a DS are continuously change; new consumers and new electric power facilities are connecting every day, the costs of labor and materials are rising, and legal regulations are changing. It is obvious that conditions in the future cannot be accurately predicted, so it is necessary to analyze various possible scenarios by taking into account data uncertainty and random factors. Since the electrical facilities require significant investments and some time to build, any errors when planning lead to wrong decisions which cannot be quickly corrected, and may result in significant financial losses.

The basic problem regarding DS optimization is the optimization of one objective function (mono-objective optimization), which includes the total costs associated with the expansion of DS, knowing what the consumption and working conditions will be in the future and the capacity constraints of power lines and source nodes [1, 2]. However, the future development and current functioning of DS must satisfy a number of different and often conflicting objectives (multi-objective optimization) [3, 4], like: reduction of the investments required for the expansion and/or maintenance in the system, reduction of the technical power losses, enhancement of the DS reliability, etc.

Therefore, the complexity of the DS planning problem is caused primarily by designers' attempts to meet multiple goals, the uncertainty of available data, and the large number of variables.

2. BASIS OF GENETIC ALGORITHMS

Genetic algorithms (GA) [5, 6, 7] belong to the group of evolutionary algorithms and represent the methods of stochastic search for a solution space, based on the principle of natural selection, and the survival of the fittest. The genetic materials of successful individuals are transferred to the next generation and mutually combined, which is called crossover, causing the improvement of required properties. Occasionally, new genetic information is introduced using the method called mutation, in order to prevent the algorithm may get stuck within a local optimum.

The structure of a GA is very simple and has the form:

N = 0; (N – number of generation)

Form the initial population P(0)

{Repeat until the stopping condition is met;

Evaluate individuals of population P(N);

Select individuals for Crossover and mutation from P(N);

Combine selected individuals from P(N);

Mutate selected individuals from P(N);

Form the new population P(N+1);

Increase the number of generations N=N+1;}

These operations result in an improvement of the chromosome characteristics from generation to generation, and in finding the global optimum.

3. THE DEVELOPED GENETIC ALGORITHM

Besides the base power and base voltage, all the data used for the calculation is presented in the forms of matrices in which rows represent system elements, while columns represent the properties of the system element.

These matrices are [8]: node matrix, power-line matrix, matrix of source node sizes, matrix of power-line types (sizes), matrix of required nodes (nodes that have to be in operation), matrix of required power-lines (power-lines that have to be in operation), matrix of existing nodes which represents those nodes that have already been built, and matrix of existing power-lines which represents those power-lines that are already built.

3.1 Coding

Real problem parameters have to be presented in the form of a code which is suitable for the use in GA. The developed genetic algorithm uses a non-binary alphabet rather than a binary because of the simplicity of coding and increased content of the information. Every possible solution of the DS optimization problem is composed of two chromosomes [8, 9].

One chromosome represents a specific topology where each position within the chromosome represents one power line, using different integers for different types of power lines.

The second chromosome was introduced to represent the source nodes and their sizes, which involves the usages of different integers for different sizes of source nodes in each of the possible positions of the chromosome.

The positions of the chromosomes marked with zeros means that the corresponding power lines or source nodes are not in operation.

3.2 Generation of a Initial Population

The generation of those chromosomes that constitute the initial population is done randomly, checking-in every moment on the radiality of the obtained solutions topology. If a chromosome represents non-radial topology it can easily be discarded and a new chromosome generated. This method is suitable for smaller networks (up to fifty nodes), while for larger networks the method causes a long search for those chromosomes which represent radial topology, due to the large number of possible combinations.

Another way of generating the initial population of chromosomes is to force the radiality of topology. Radiality forcing implies a process of modifying the initial chromosome, which represents non-radial topology in order to obtain a chromosome that represents radial topology. This process is done in several stages.

The first thing to do is to determine the existence of consumer nodes that are not connected with the rest of the network (isolated nodes). Isolated nodes are those nodes that have no corresponding power-line (nodes that are not connected with any other node). If the isolated node exists, it has to be connected with one of the possible neighboring nodes, based on a matrix of power lines. Node that connects to the isolated node is selected randomly.

After the isolated nodes are detected and connected, it is necessary to synchronize chromosome that represent source nodes and the corresponding chromosome that represent power-lines. Since the chromosomes are generated randomly, it is possible to appear the source node that is not connected with the rest of the system. Gene of such source nodes should be set to zero, if it is not a source node that must be in operation. If it is a source node that has to be in operation, this pair of chromosomes is rejected.

Another possibility is that the gene of the source node is set to zero, which means that the source node is not in operation, while in the chromosome of power-lines exist the corresponding power-line that connects the source node with the rest of the system. In this case, the respective source node should be randomly assigned a value other than zero. If it is required that the respective source node is not in operation, based on a matrix of required source nodes, then this pair of chromosomes is rejected.

After synchronization of chromosomes that represent source nodes and power-lines, it is necessary to check the radiality of obtained network. To have a network of radial character, the total number of power-lines, which are in operation, must be equal to the difference of the total number of nodes and the number of source nodes that are in operation. If the number of power-lines does not fit, the required number of lines has to be added or subtracted. Selection of power-lines that will be revoked or added is done randomly.

Removing the power-line loops is the last step of radiality forcing. It is necessary to detect loops, and execute their "breaking", which means that one randomly chosen power-line of the loop is abolished, and one randomly chosen power-line of the system added. The process of removing the loops usually has to be executed multiple times, until a radial network is obtained. Since the adding and subtracting of power-lines is done randomly, the previous stages must be repeated to identify and eliminate isolated consumer nodes, synchronize chromosomes of source nodes and power-lines and check the radiality of the network.

In addition to the above steps, it is necessary to set the size of the existing source nodes and power-lines. Affiliation of each source node and power-line, selected to be in operation, to the matrices of existing source nodes and existing power-lines, respectively, is tested. If the observed source node or power-line belongs to the matrix of existing source nodes or matrix of existing power-lines, then its size sets to the size determined in those matrices, respectively.

This method of generating chromosomes significantly reduces the time required to generate the initial population [8, 10].

The power-flow calculation can be done once the radial topology is obtained. Power-flow calculation provides the voltage of each network node, the current through each power-line, and the active and reactive powers of each source node.

Each obtained solution must satisfy all the technical constraints. The observed pair of chromosomes can become rejected as a possible solution if the power-flow calculation does not meet the technical constraints. Rejection of the solutions has to be made if at least one node exceeds the voltage limits, at least one source node exceeds the active or reactive power capacities, or at least one power-line exceeds the limit of allowable continuous current.

3.3 Fitness Function

The fitness function of the obtained solutions is calculated using the values for the objective functions. The first objective function, used in this work, is the calculation of losses in the DS power lines, which is based on the results of the power flow calculation. The second objective function is the calculation of the maintenance or construction costs of the power-lines and source nodes, which is calculated on the basis of the obtained topology.

Since there are two objective functions, instead of searching for a single optimal solution it is necessary to search for a set of non-dominant solutions (set of Pareto optimal solutions) [4]. Moving from one non-dominant solution to another and by improving at least one objective function, it is inevitable that one or more of the other objective functions will deteriorate.

Fig. 1 presents three possible solutions for a certain multi-objective optimization problem, in which it is necessary to obtain the minimum value of the objective functions f_1 and f_2. According to the criterion of Pareto optimality, solutions S_1 and S_3 are the better solutions for the given problem and these two solutions represent a set of solutions obtained by this criterion. The curve shown in the Fig. 1 represents the limit of possible optimal solutions and it is called Pareto front.

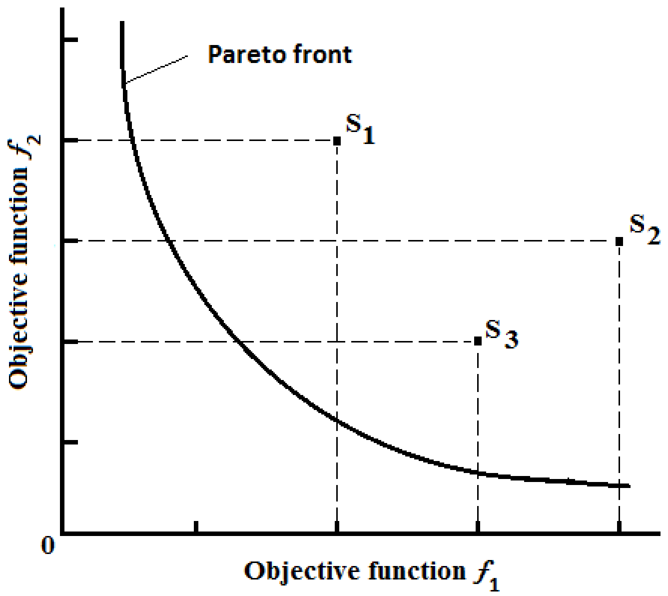

Fig.1. Presentation for three solutions of multi-objective optimization problem

There are a number of ways of choosing the best solution from a set of non-dominant solutions. In this work it is assumed that the best solution, apropos the solution with the best value of fitness function, is a solution that is the closest to the origin [8]. In doing so, the abscissa presents one objective function, and the ordinate presents the other objective function.

3.4 Probability of Selection

Using the values for fitness function, each pair of chromosomes enters a process of selection in which the individuals are selected for crossover and mutation.

When calculating the probability of selection, it is necessary to avoid the better solutions obtaining too high probability values compared to the other solutions. Too much difference in the probability values may cause premature convergence of the algorithm. This situation arises when some of the best solutions have too high probability values and their impact on the production of new solutions becomes too strong, while other solutions do not have the ability to pass on their genes to the next generation and are rapidly disappearing. There is a risk that very similar solutions that are difficult to improve appear in just a few generations. When the probability values are very similar, the process of natural selection would not be effective because all the solutions contribute to the creation of the next generation. In order to avoid this situation, probability values have to be standardized in such a way that there is a difference between them, but not too big.

The probability value of one individual is usually determined based on the relationship between its fitness function and the fitness functions of other individuals, which can be done in several ways. The function that provides a linear distribution of probability values and uses the ordinal number of solutions in a string of solutions sorted by the value of fitness function, will be presented in this work [8]. When the ordinal number of each solution has been determined, the following variables (Total, Probability) can be defined as:

Total = sum of the ordinal number differences between the worst solution and each other solution, and

Probability = (ordinal number of the worst solution – ordinal number of the observed solution) / Total.

This method provides a linear distribution of the probability values.

3.5 Operators of Crossover and Mutation

The crossover operator application should result in a certain number of feasible solutions, which are determined by the default crossover rate. The application of this operator is done by selecting two chromosomes with probabilities that depend on the values of their fitness functions. In this work, those chromosomes that represent DS power-lines cross at one point and those that represent source nodes are assigned directly to the new chromosomes obtained by a crossover [8, 9].

The operator of mutation introduces the stochastic characteristic into the GA to avoid premature convergence of the algorithm. If the number of mutated positions within the chromosome that represents power-lines is not big enough, then any changes in the genetic information of the chromosomes do not have a significant influence on a solution. In this situation it is not possible to avoid convergence towards less satisfactory solutions. This difficulty is absent in chromosomes that represent source nodes because they are usually shorter. Hence, it is necessary to mutate at least 10% of the chromosomes that represent power-lines, versus 1% of the chromosomes that represent source nodes.

3.6 Treatment of New Chromosomes

During the process of crossover and mutation, some solutions are replaced by new solutions. However, the total number of individuals within a population has to be constant throughout the generations.

New solutions, obtained by crossover and mutation, have to be evaluated in order to be compared with other solutions, which mean that their fitness functions have to be calculated.

In order to avoid the possibility of losing solutions with the highest values of fitness function, a certain number of the better solutions are transferred to the next generation without modification. The best solutions are those solutions with the highest fitness functions from the set of all the solutions. The set of all the solutions consists of the set of solutions from the existing population and the set of new solutions obtained by crossover and mutation. This technique of protecting of the best solutions is called ‘elitism’ [6].

The remaining number of solutions that are needed to compose the population is selected from the remaining solutions on the basis of the fitness function value, in the same way the chromosomes are selected for crossover or mutation.

4. APPLICATION OF THE DEVELOPED GENETIC ALGORITHM

The test system shown in Fig. 3 was used to present one of the possible applications regarding the developed algorithm. It consisted of 2 source nodes, 21 consumer nodes, and 25 power-lines, and represents part of a real DS.

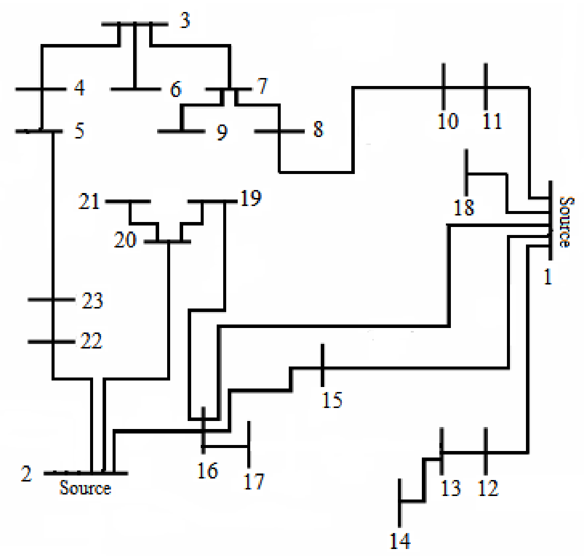

Fig.3. Schematics of the test system

The case when expanding an existing system with a new consumer node, using the developed genetic algorithm, can be observed. This is the most common problem of DS planning. The existing system in this case is actually the test system with radial topology of operative power-lines. Non-operative power lines are used as reserves. This topology of the system is in use most of the time and will be called normal switching condition.

The properties of the existing system (types of conductors, consumer loads, etc.) were known together with the location of the new consumer node, the load of the new node, and the possible power-line routes with which the new node can be connected to the existing system.

The existing system is shown in Fig. 4 and represented the test system with marked new system elements, elements during the operation, and elements that could be but were not operative.

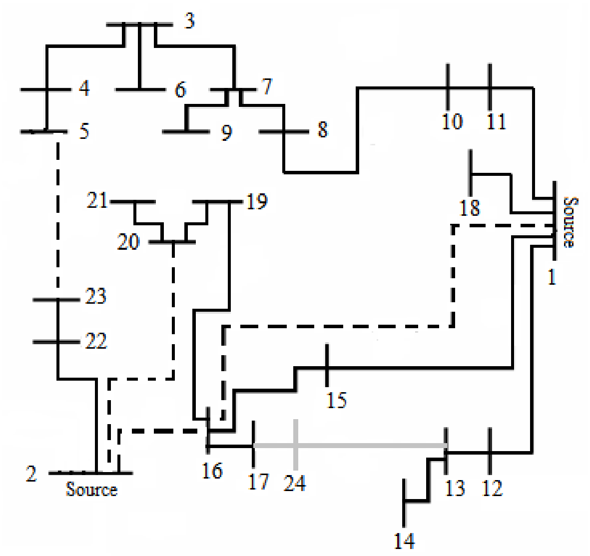

Fig.4. Schematics of an existing system

The solid lines show those power-lines that belong to the normal switching condition of the existing network. The dashed lines show those power-lines that do not belong to the normal switching condition, while solid gray lines show new consumer node and power-lines with which it is possible to connect the new consumer node to the existing system. The connection of the new node (node number 24) can be done from the existing nodes 13 and 17.

The optimal solution provides the best routes and types of power lines which need to be built as well as the sizes of the source nodes, while satisfying all of the technical constraints. One of the optimization solutions is presented in Fig. 5.

This solution is the closest to the origin (explained in 3.3.) and it shows the obtained radial network with the determined types for each power-line, and the sizes of each source node. Actually, most of the power-lines were already built from known sizes, except for those power lines that connect the new node to the existing system.

This is not the only solution from the optimization. Since the optimization problem is multi-objective, there are several other solutions that satisfy the optimization objectives. Each of these solutions can be chosen for realization. Which one would be actually realized would be a question for decision makers, and it would depend on a variety of economical and/or technical factors.

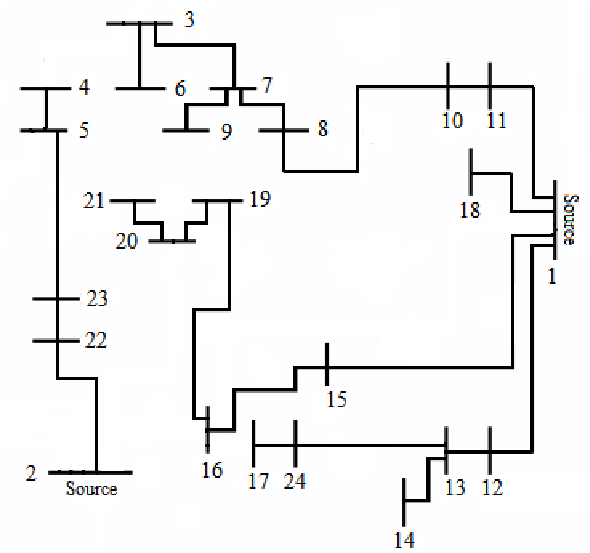

Fig.5. One of the optimal configurations of the expanded system

5. CONCLUSION

The application scope for the developed GA regarding DS optimization includes a wide range of possible scenarios for the construction and expansion of the system. It is possible to determine the configuration of a completely new DS which needs to be constructed with appropriate types of power-lines and strengths of the source nodes. Besides, it is possible to perform expansion optimization of the existing already built DS. Expansion of DS can be optimized in the case of increased consumption, apropos the increased number of consumer nodes, as well as in the case of increasing the number of source nodes. Source nodes can be substations or power plants of any type, with the known data of maximum and minimum active and reactive power that source nodes can provide.

The developed GA can be applied using more than one objective function. These functions can be the function of losses within the power-lines, the function of maintenance costs of the power-lines and the source nodes that are in operation, a function of system reliability, a function of environmental protection, etc.

When applying the developed algorithm to the test and the real DS, certain deficiencies were noted like the long time of execution in the case of large DS – the DS with few hundred nodes. Furthermore, there are occasional inconsistencies in the sizing of the power-lines, which is caused by an inability of GA to determine the absolutely optimal solution.

One of the advantages of the proposed algorithm is its universality in terms of the power system which needs to be optimized. It is very easy to extend or adapt the developed algorithm for the optimization of transmission or industrial systems.

One of the possibilities for the proposed algorithm's further development is the addition of another chromosome to the optimization solution, which would represent the locations and sizes of capacitor batteries. In this way, one solution for optimization would be composed of three chromosomes of which one chromosome would represent the source nodes, than other would represent the power-lines, and the third would represent the capacitor batteries. With solutions defined in this way, it would be possible to expand the scope of application regarding the developed GA.

6. REFERENCES

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