Exploiting the Power of Genetic Algorithm in Optimization of Distribution Networks

D. Skrlec* S.Krajcar* B.Pribicevic** S.Blagajac**

University of Zagreb
Faculty of Electrical Engineering and Computing
Department of Power Systems
Unska 3, 10000 Zagreb, Croatia
email: caddin@zvne.fer.hr

* IEEE Member, ** IEEE Student Member

ABSTRACT - The paper presents a genetic algorithm approach for optimal primary distribution network planning. Application was developed for optimal structuring of a link configuration of network. The model is based on solving the adapted Multiple Capacited Vehicle Routing Problem by a genetic algorithm. The developed algorithm is described as well as heuristic improvements including the application example with real size distribution network. Some representative results of optimization procedure are presented and discussed in view of optimization parameters, both of genetic algorithm and technical constraints. Network data needed for optimisation procedure are extracted from geographic information system.

I. INTRODUCTION

The objective of the distribution network design process can be divided into three independent parts. These parts are:

- Load forecasting
- Design of secondary system (low voltage distribution network)
- Design of primary system (medium voltage distribution network)

To reduce a problem complexity, each part of the design process is divided into functional subproblems [6,11]. Each of these subproblems can be then much easier to manage. Although nearly independent, some parts of the design process interact, e.g. placement of substation will influence secondary routing which will influence in turn primary routing. The number of possible design solutions that might satisfy a given set of spatial, technical and economical constraints is quite numerous. Multiple, interdependent goals and constraints make conventional procedural optimisation methods inappropriate for distribution network design.

Therefore, the evolution of multi-criteria methods produced heuristic techniques [11] that have a potentiality to find a large set of possibly good solutions, so called "near optimum" or "satisfying" solutions, instead of a single optimum. *Genetic algorithms* (**GA**) [8] share this property by their simulation of natural processes such as: selection, information inheritance, random mutation and population dynamics. It has been proved that genetic algorithms could successfully be applied on a wide range of practical optimization problems. They are particularly powerful in solving combinatorial optimization problems. Genetic algorithm approach is on a real size system. Some results are enclosed in the paper.

II. OPTIMAL STRUCTURING

Due to the load characteristics, requested availability and quality of energy supply, two main configurations of the primary system are used in optimal planning [6,11]. There is a *loop structure* (starting and ending node is the same HV/MV substation and routing nodes are MV/LV substations) and a *link structure* (starting node is one HV/MV substation, routing nodes are MV/LV substations and ending node is another HV/MV substation). In the optimisation process, three different problems are considered:

1. optimisation of the new primary system;
2. reconfiguration of the existing primary system regarding predefined structure, and
3. reinforcement of the existing primary system with defined structure by installing additional capacity in demand nodes or including the new MV/LV substation in the network.

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The optimisation of the link structure is described in the paper. The objectives for primary distribution network planning of a link structure take into consideration minimization of total costs, as well as achieving the acceptable reliability of supply of energy to the customer. Total costs are composed of investment costs (new cables and substations), operational costs (power loss costs, existing cables and substations). Therefore some important technical constraints must be fulfilled:

1. operation of the network under radial configuration with minimal power and energy losses;
2. voltage quality at any node under the normal and emergency operation;
3. in the primary system, regarding the constraint of reliability of energy supply to the customer, each MV/LV substation must have a possibility to be supplied from two sides.

III. OPTIMIZATION PROBLEM

The optimization of the distribution network as a real system has some extensions to the general definition of the *capacited vehicle routing problem* (**CVRP**). The network nodes are substations instead of the customers, each having a different amount of the energy demand. They are connected by underground cables that in network terminology means arcs (or edges). Capacity constraint is represented by the maximum power that can be transferred by the cable of a given size and voltage level. There are some other technically sound constraints such as maximum voltage drop (equivalent to d_{max} in general definition of CVRP), energy and power losses, maximum number of substations per route, minimum cable size, cost of cable per length unit, etc. Existing connections between nodes have different costs from new connections in the network. The costs of each of these constraints are converted into money and the objective is to find a set of routes of minimal total cost. There is also one extension to the problem regarding the constraint that every node (customer) can be visited only once: each node can be expanded into several internal points that allow the algorithm to use the same node several times. It is very important property when GA is used for reconfiguration of the existing network to improve the utilization of the existing cables.

IV. SHORT REVIEW OF GENETIC ALGORITHMS

In nature, individuals in a population compete with each other for resources to survive and reproduce. Only those individuals which are most successful in the life battle have a chance to produce large and qualitative number of offsprings. GA simulate the process of natural evolution. They work with a population of individuals, each representing a possible solution to a given problem. Each individual is assigned a fitness score according to how good a solution to the problem it represents. The highly fit individuals are given opportunities to reproduce, by cross-breeding with other individuals in the population. This produces new individuals as offspring, which share some features taken from each parent. The power of GAs comes from the fact that the technique is robust, and can deal successfully with a wide range of problem areas. GAs are not guaranteed to find the global optimum solution to a problem, but they are generally good at finding "acceptably good" solutions to problems "acceptably fast".

The operators commonly used are selection, recombination and mutation. The selection ensures that better solutions get higher probability of being selected in the next generation. The recombination and mutation provide means of creating new individuals through exchanging the genetic material between the members of the current generation and by randomly introduced changes in a single individual.

V. THE APPLIED GENETIC ALGORITHM

The optimization of the link structure of a distribution network is based on solving the *multi-depot CVRP* (**MCVRP**). The MCVRP is a generalization of the CVRP in which the vehicles are initially located at a given set of depots. Same as in the CVRP, the customers and the depots are represented as a set of nodes on an undirected graph. We denote by $\mathbf{N}_c$ and $\mathbf{N}_d$ the set of customers and the set of depots, respectively. There are two variants of the problem, and the optimization of the distribution network falls into the second variant in which it is required that the vehicle depart from one depot and return to some other depot (this is called the non-fixed destination MCVRP).

Optimization procedure consists of three phases. In the first phase the supply areas are determined for each supply node in the network by the Ford & Fulkerson transportation problem.
In the second phase, on each supply area consisting of a single supply node and a number of nodes is applied GA.
The lowest level that is used in the recombination process is the connection (arc or edge) between two nodes in the network. The genetic algorithm uses "one-at-a-time" recombination [2], where the newly created offspring replaces the lowest ranking individual in the population (if the offspring is better than currently the worst one) rather than a parent. Parent selection mechanism uses the rank of the individual in the population rather than fitness proportionate reproduction.
To reduce searching space of possible solution and to make a faster convergence, some heuristics are involved in the genetic algorithm [3,5]. For each node a set of the

closest neighboring nodes is determined as well as for the supply node. Forming of the initial population starts by the randomly selected node from the aforementioned set of the supply node. The next node in the route is chosen from the previous node set of the closest nodes and the same procedure continues with this and any following route. The forming of the single route continues until a constraint on the maximum capacity or any other important constraint is violated. In the case of previous node set being empty, i.e. all nodes in the set have already been used, a random node out of the remaining ones must be chosen.

The evaluation of some less important technical constraints is involved through penalty functions. Once the entire population is created and each member evaluated, a simple ranking is applied. A member of the population represents the set of routes for one solution. The member that represents the best solution becomes the first, and the worst solution comes to the last position. 32-bit random generator [2] is used in the selection process of the members from the population. After the selection process, recombination is performed over the selected members [1]. Regardless of some experiences found in references stating that mutation mechanism is not a necessary part of the genetic algorithm in the case of CVRP, we have built in the procedure that could be qualified as mutation. After every m generation local improvement operator called *"3-opt operator"* introduced by *Lin & Kernighan* [9] is applied on a randomly selected member in the population. m is the standard input optimization parameter.

As a result of the second phase, we get for each supply area the optimal radial structure of the network. This radial structure is used as input data into the third phase.

The third phase consists in connecting the radial paths of all supply areas into a complete link structure. The procedure is very similar to the previous one. Neighboring radials from different supply nodes are determined in order to form the initial population. The selection process and convergence criteria are the same as previous, only the recombination process has a task to find "correct" pairs of radials from different supply nodes.

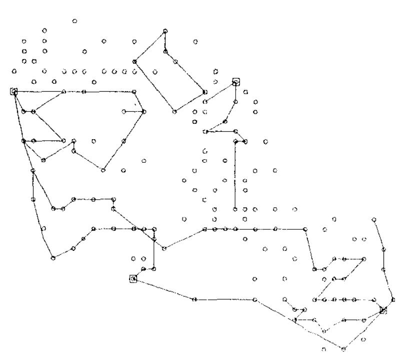

Figure 1. Initial state of a distribution network

The genetic algorithm was applied to the part of real primary distribution network shown in Figure 1. The algorithm was tested on several real size networks. It is possible to order results and comparisons from the authors, by request.

Distribution network is first optimized as a completely new, neglecting existing cables ("Arabian desert" approach). Figure 2 represents the solution of the new network.

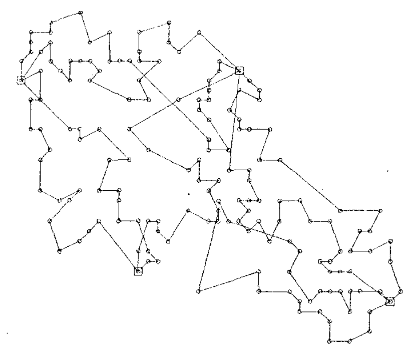

Figure 2. Solution of the new distribution network ("Arabian desert" approach)

Second optimization differed in taking existing cables into account. On Figure 3. one solution of optimized network with existing cables and routes is presented.

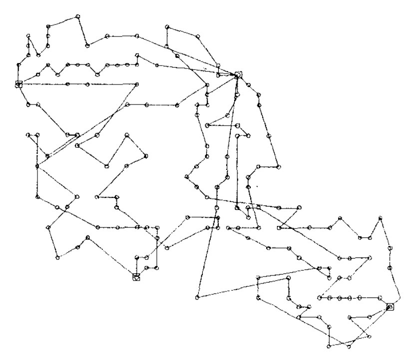

Figure 3. Solution for reconfiguration of existing network

Data used in optimization of test example is partially listed in Table I.

Time window	5 years
Discount rate	10 %
Nominal voltage	20 kV
Voltage tresholds	5%; 8%
Average load	90 %
No. of HV/MV substations	4
Total no. of MV/LV substations	170
No. of new MV/LV substations	69
Age of cable	< 25 years
No. of existing cables	96
Feeder cost (monetary unit/m)	400/m

Table 1.

In Table 2. cost comparison of two solutions is presented.

Type of network	otal cost (with/without Lin&Kern. improvement) [DEM]
"Arabian desert"	2,372.974 / 2,780.744
Existing network	1,891.795 / 2.184.802

VI. CONCLUSION

The research results reported in this paper demonstrate that the usage of genetic algorithms to optimization problem of linked primary distribution network with more than two HV/MV substations is feasible. GA allows the representation of non-linearities which are hard to include in pure mathematical programming methods.

The goal of our research is to integrate this application based on genetic algorithm in geographic information system [12] and build the user-friendly and precise system that will take the advantages of both GA and GIS (high precision of existing and possible feeder routes, fast algorithm). In searching for further improvements of genetic algorithm the work on parallel genetic algorithms and on possibilities of integrating genetic algorithm and a *simulated annealing*-like mutation operator continues. From our point of view GA approach is an adequate direction in the distribution network optimization.

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