OPTIMAL LOSS REDUCTION OF DISTRIBUTION NETWORKS USING A REFINED GENETIC ALGORITHM

Vlad TUDOR[1]

Reconfigurarea rețelelor în sistemele de distribuție a energiei este realizată prin modificarea stării dispozitivelor de comutație şi are ca scop reducerea pierderilor de energie sau repartizarea cât mai echilibrată a sarcinii în sistem. O soluție optimă implică menținerea în limite acceptabile a tensiunii în nodurile de rețea, precum şi a valorii curentului care trece prin liniile şi echipamentele electrice, care să asigure necesarul de sarcină al consumatorilor. Complexitatea topologică a rețelelor de distribuție reale implică un număr foarte mare de configurații posibile. Această problemă de optimizare combinatorică poate fi rezolvată eficient utilizând algoritmul genetic rafinat propus în această lucrare. Algoritmul lui Prim este utilizat pentru a asigura radialitatea potențialelor soluții propuse spre evaluare, folosind muchii cu cost aleator.

The network reconfiguration in power distribution systems is realized by changing the status of sectionalizing switches, and is usually done for loss reduction or for load balancing in the system. An optimal loss reduction is obtained to maintain acceptable voltage at customer loads as well as to assure sufficient conductor and substation current capacity to handle load requirements. The topological complexity of real distribution networks implies searching through many possible configurations. This combinatorial optimization problem can be resolved using the efficient refined genetic algorithm proposed in this paper. Prim's algorithm is used with random costs for generating different spanning trees for evaluation.

Keywords: power distribution network, graph theory, loss reduction, optimization, refined genetic algorithm

1. Introduction

Power distribution systems have a complex topology and usually contain a great number of electrical devices, which leads to a wide solution space in the problem of loss reduction using reconfiguration. While the transmission and subtransmission lines are configured in a meshed network, the distribution feeders are configured radially in almost all cases. Network reconfiguration is an important operation problem in on-line configuration management, due to remote control capability to the switches.

[1] Phd student, Faculty of Automatic Control and Computers, University POLITEHNICA of Bucharest, Romania. E-mail: vladhutanu@ls-infomat.ro

The distribution system should be operated at minimum cost, subject to a number of constraints:

- radial configuration;
- all loads are served;
- lines, transformers and other equipment within current capacity limits;
- voltage drop within limits.

A global optimal solution to the problem was proposed by Merlin and Bach [1] using an exhaustive search with branch-and-bound technique. This method works fine if the initial is close to the global optimum. Being a combinatorial method, it's too slow for real distribution systems. Shirmohammadi and Hong [2] tried to overcome some disadvantages of the algorithm, developing a new power flow calculation formula.

Civanlar [3] estimated with an innovative algebraic expression the load loss effected by operating a pair of switches, decreasing the time spent calculating the power flow in the network at each iteration. Moreover, many heuristic methods have been developed using branch exchange technique, including two approximate power flow methods proposed by Baran and Wu [4]. This method is very fast and good for use in real-time operations. Even though it is easily trapped in a local minimum, it can be used to provide a loss reduction after an emergency reconfiguration.

Other methods include neural networks, which were used in several papers and they serve as a state estimator but don't analyze the topologies. Simulated annealing is not a reconfiguration algorithm by itself, but it can be used as a modification to some other basic algorithms.

Many papers proposed genetic algorithms (GA) in order to obtain a fast and efficient solution to this combinatorial optimization problem. The convergence is very fast if the genetic parameters are adapted for the network in case. Therefore, a new type of algorithms were developed, named refined genetic algorithms (RGA), which have the ability to adapt the parameters at each generation, without needing human interaction.

In this paper we propose a refined genetic algorithm which uses Prim's algorithm in order to obtain spanning trees (radial configurations), with random costs for every branch. At every generation, the power flow calculations are made only if the candidate solution is uniqe, i.e. the time spent evaluating the network is notably decreased.

2. Mathematical model

A power distribution network can be modeled topologically as an oriented graph and operationally as an unoriented graph, governed by Kirchhoff's laws.

Let *G(N,M)* be an unoriented graph with n vertices and m edges, where $N = \{n_1, n_2, \ldots, n_n\}$ is a finite non-empty set and M, a finite set of unordered sets $(m_i, m_j),\ i \neq j,\ i, j \in \{1,2,\ldots,m\},\ m_i, m_j \in M$.

Also let $k\ (k \geq 1)$ special vertices named *substation nodes*.

Every vertex has associated three data (costs):

- $v_i \in V,\ V = \{v_1, v_2, \ldots, v_n\}$ - *customer service voltage* at node *i*;
- $p_i \in P,\ P = \{p_1, p_2, \ldots, p_n\}$ - *customer load's real power* at node *i*;
- $q_i \in Q,\ Q = \{q_1, q_2, \ldots, q_n\}$ - *customer load's reactive power* at node *i*.

Every edge has associated three data (costs):

- $i_i \in I,\ I = \{i_1, i_2, \ldots, i_m\}$ - *complex current* in edge *i*;
- $r_i \in R,\ R = \{r_1, r_2, \ldots, r_m\}$ - *resistance* of edge *i*;
- $x_i \in X,\ X = \{x_1, x_2, \ldots, x_m\}$ - *reactance* of edge *i*.

For generalisation purposes, every edge contains a tie switch which can be opened or closed. Let $C = \{c_1, \ldots, c_m\},\ c_i \in \{0,1\}$ be a set that defines the *current configuration* of the network (1-closed, 0-opened). The process of reconfiguration implies taking the distribution network from one state to another.

The optimization problem can be stated as follows:

$$\text{minimize } f_c = \sum_{i=1}^{m} |i_i|^2 \cdot c_i \cdot r_i \tag{1}$$

subject to the following restrictions

$$V_{\min} \leq v_j \leq V_{\max}, \quad \forall j \in \{1, \ldots, n\} \tag{2}$$

$$|i_i| \leq I_{\max}, \quad \forall i \in \{1, \ldots, m\} \tag{3}$$

where $V_{\min}$ and $V_{\max}$ are the acceptable limits for customer service voltage at node *i* and $I_{\max}$, the maximum current that can flow through edge *j*.

Discussion. If $k = 1$, only one vertice will be a substation node and then the solution will be represented by a minimal spanning tree (radial restriction). If $k > 1$, then the final configuration would be a spanning forest consisting of *k* spanning trees (one for every substation node).

3. The proposed algorithm

The refined genetic algorithm uses Prim's algoritm with random costs for every branch in order to obtain minimal spanning trees (radial configurations) as shown in the flowchart of Fig. 1:

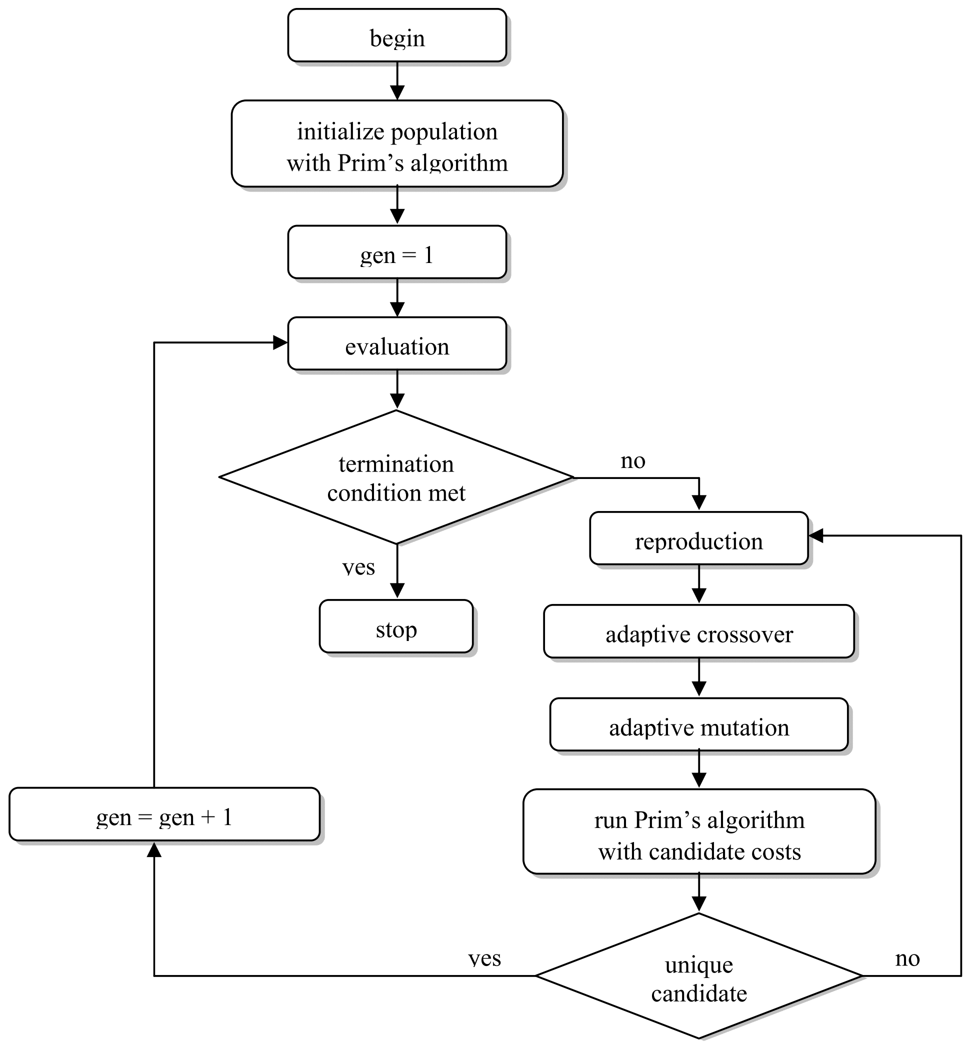

Fig. 1. Algorithm's flowchart

Each generation must ensure that the candidate solution will be unique in the current population. Only a viable configuration would be eligible for evaluation, decreasing the number of power flow calculations.

Chromosome Representation. Similar to the tree configuration in graph theory, each node in distribution networks has only one father node, because of the open loop operation of distribution networks. The connections among load nodes and source nodes in radial distribution networks are represented by tree or forest configurations. Each chromosome will have the form of the incidence matrix with random values for non-zero elements. This leads to a random starting point in running Prim's algorithm.

Initial population. Empirically, I have found that the optimal number of individuals (*nc*) that forms the population is

$$nc = \frac{n}{3}, \tag{4}$$

where n is the number of nodes in the network. So, for each chromosome, the proposed algorithm generates an incidence matrix, with random costs, and then runs Prim's algorithm to create the asociated spanning tree.

Reproduction. At each generation, two individuals are randomly selected for reproduction. If the new chromosome, obtained with crossover and mutation, is not unique in the current population, the process is repreated [5].

Crossover. A new form of operator was developed due to the specific form of the chromosme. Let be $CR \in [1{,}100]$ and $CR\_pos \in [1{,}100]$, two random values at each generation. The new chromosome will be obtained as follows:

- if CR is less than 50, then the first CR_pos lines will be taken from the first chromosome, and the remaining ones, from the second;
- if CR is greated than 50, the first CR_pos lines will be taken from the second chromosome, and the remaining ones, from the first.

This form of crossover ensures that some of the tree structure remains unchanged after this step in the algorithm.

Mutation. It is a very high probability that two different individuals would lead to the same configuration, so mutation is needed to ensure diversity. For each non-zero value in the chromosome structure, a randomly value named $CM \in [1{,}100]$ is generated. If this value is less than 10, the cost (c_{ij}) will be replaced with $\left|100 - c_{ij}\right|$.

Adaptive crossover and mutation. Ass the generations pass and the individuals converge to the global solution, the intervals for the randomly generated variables decrease proportionally with the number of generations left to evaluate.

Evaluation. For each valid configuration, the structure of the network must be tested to see if the imposed restrictions have been violated. A full load flow calculation is made and if the solution is within the limits, it tests if the power loss is less than the most unoptimal solution in the current population. If so, the new candidate solution takes it's place.

Stopping criteria. The number of generations (*gen*) is initially set to three times the number of nodes. Becouse of the condition that every new valid chromosome must be unique, the number of possible configurations could be less than the initial evaluation. In order to stop the process, a new variable have been set for counting the ununique generated solutions. If this number exceeds *gen*, then the program halts.

5. Test cases

Both systems were tested using a Pentium 4 2.4GHz processor and the algorithm was implemented in standard C++ using MinGW Developer Studio.

The first system was proposed by Glamocanin [6] and it is used to verify the algorithm's computer implementation. Table 1 contains the branch impedance and bus load data for the circuit shown in Fig. 2.

Table 1

Branch impedance and bus load data for test case 1

Bus		Impedance [Ω]		Load at To Bus [kVA]	
From	To	R	X	P	Q
1	2	0.7820	0.2120	600.0	400.0
1	3	0.7820	0.2120	500.0	300.0
1	4	1.5640	0.4240	100.0	90.0
2	5	0.7820	0.2120	600.0	400.0
2	6	1.1730	0.3180	1300.0	1100.0
3	7	1.3685	0.3710	1300.0	1000.0
4	8	1.1730	0.3180	100.0	90.0
3	9	0.7820	0.2120	800.0	600.0
2	10	1.1730	0.3180	300.0	100.0
3	5	1.1730	0.3180		
6	9	0.7820	0.2120		
8	9	1.1730	0.3180		
4	10	1.1730	0.3180		

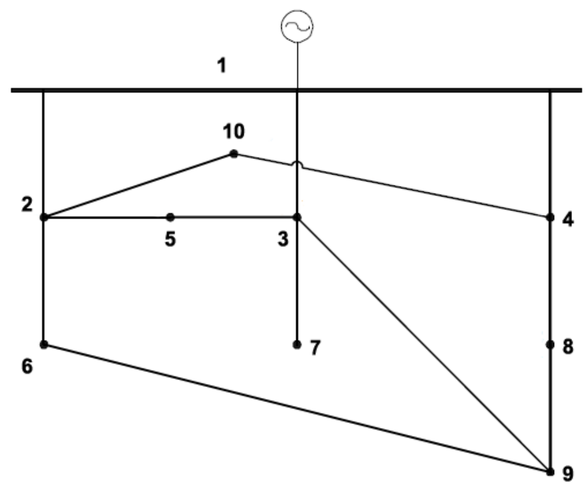

Fig. 2. First test case's circuit

Each line segment is assigned a conductor with a rating of 194A. The nominal substation voltage is 10kV line-to-line and the distribution transformer ratio is 48.11:1 in each line segment. The voltage drop constraint is 5%, corresponding to a customer service voltage of 114V.

The global optimum (247.436kW – active loss) was obtained after 3 generations in 2ms. The tie switches left open after configuration are: 2-10, 3-5, 6-9 and 8-9.

The second system was proposed by Baran and Wu [7] and is more severe than the first, because of the low voltage conditions, the large reactive load at bus 30, and the number of tie switches within a single feeder. Table 2 contains the branch impedance and bus load data for the circuit.

The substation voltage is 12.66kV line-to-line, which requires a transformer ratio of 60.91:1 in each segment.

The large reactive load at bus 30 can make a traditional algorithm to find a sub-optimal solution. The real and reactive loads at bus 30 must be served together. Considering only the real power, the losses increase by a disproportionate amount due to the current drawn by the reactive load.

The global optimum (127.847kW – active loss) was obtained after 34 generations in 171ms (see Fig. 3).

Table 2

Branch impedance and bus load data for test case 2

Bus		Impedance [Ω]		Load at To Bus [kVA]	
From	To	R	X	P	Q
1	2	0.0922	0.0470	100.0	60.0
2	3	0.4930	0.2511	90.0	40.0
3	4	0.3660	0.1864	120.0	80.0
4	5	0.3811	0.1941	60.0	30.0
5	6	0.8190	0.7070	60.0	20.0
6	7	0.1872	0.6188	200.0	100.0
7	8	0.7114	0.2351	200.0	100.0
8	9	1.0300	0.7400	60.0	20.0
9	10	1.0440	0.7400	60.0	20.0
10	11	0.1966	0.0650	45.0	30.0
11	12	0.3744	0.1238	60.0	35.0
12	13	1.4680	1.1550	60.0	35.0
13	14	0.5416	0.7129	120.0	80.0
14	15	0.5910	0.5260	60.0	10.0
15	16	0.7463	0.5450	60.0	20.0
16	17	1.2890	1.7210	60.0	20.0
17	18	0.7320	0.5740	90.0	40.0
2	19	0.1640	0.1565	90.0	40.0
19	20	1.5042	1.3554	90.0	40.0
20	21	0.4095	0.4784	90.0	40.0
21	22	0.7089	0.9373	90.0	40.0
3	23	0.4512	0.3083	90.0	50.0
23	24	0.8980	0.7091	420.0	200.0
24	25	0.8960	0.7011	420.0	200.0
6	26	0.2030	0.1034	60.0	25.0
26	27	0.2842	0.1447	60.0	25.0
27	28	1.0590	0.9337	60.0	20.0
28	29	0.8042	0.7006	120.0	70.0
29	30	0.5075	0.2585	200.0	600.0
30	31	0.9744	0.9630	150.0	70.0
31	32	0.3105	0.3619	210.0	100.0
32	33	0.3410	0.5302	60.0	40.0
8	21	2.0000	2.0000		
9	15	2.0000	2.0000		
12	22	2.0000	2.0000		
18	33	0.5000	0.5000		
25	29	0.5000	0.5000		

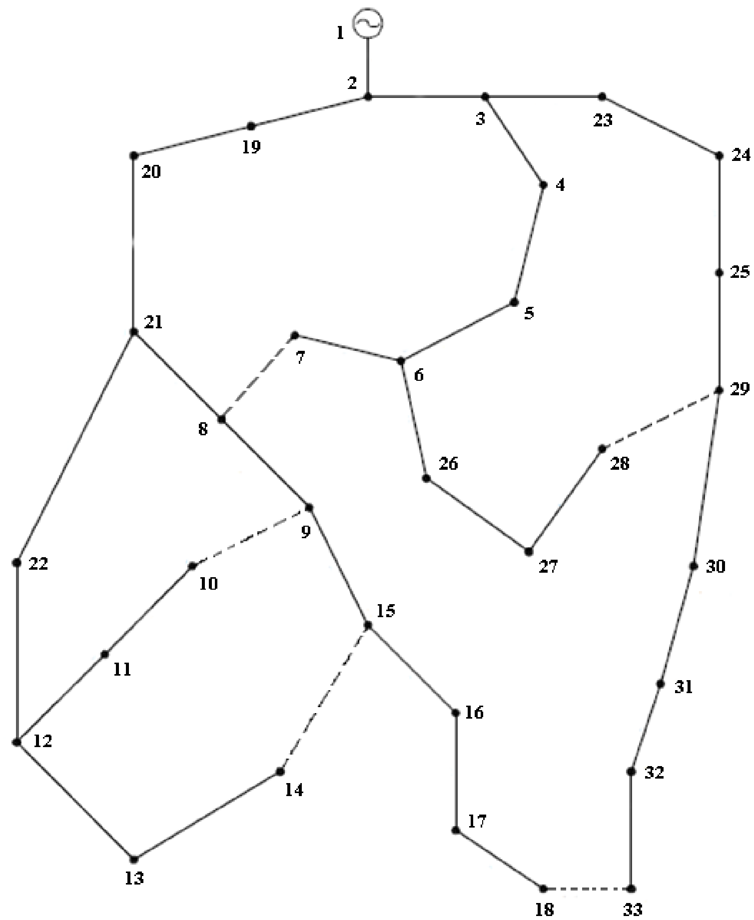

Fig. 3. Second test case circuit – final configuration

The global optimal configuration has lower system losses, but still does not meet the normal operating voltage criteria of at least 114V (see Table 3). This can be done using voltage regulators and, in practice, some shunt capacitor banks installed. The algorithm was using an emergency limit of 112.5V in order to obtain viable solutions in rapid time for evaluation.

Table 3

Node-voltage profile for optimal configuration

1	2	3	4	5	6	7	8	9	10	11
120.0	119.7	118.5	118.3	118.1	117.8	117.7	115.7	115.3	115.7	115.7
12	13	14	15	16	17	18	19	20	21	22
115.8	115.5	115.4	114.6	114.4	114.1	113.9	119.4	117.5	117.0	116.6
23	24	25	26	27	28	29	30	31	32	33
117.7	116.0	114.7	117.7	117.7	117.6	114.1	113.7	113.3	113.3	113.9

The final population contains a set of sub-optimal solutions which can be used if the global optimal configuration cannot be utilized:

Table 4

Final set of configurations in losses [kW]

1	2	3	4	5	6	7	8	9	10
130.5	127.8	128.5	130.1	131.5	130.7	131.6	130.8	129.8	130.4

Using this technique leads to a list of optimal configurations, becouse all the individuals that form the final generation are close to the global optimal.

7. Conclusions

In this paper a fast and reliable refined genetic algorithm has been proposed by the author for configurating a power distribution network. For reconfiguration, it can be very easily adapted by putting the initial configuration in one of the individuals that forms the initial population of chromosomes.

For future work, the algorithm could be adapted for multiple substations and tested with more complex topologies, using multiprocessor machines.

R E F E R E N C E S

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