SERVICE RESTORATION IN DISTRIBUTION SYSTEMS USING AN EVOLUTIONARY ALGORITHM

Buğra AKDUMAN
Siemens A.Ş. – Turkey
bugra.akduman@siemens.com

Belgin TÜRKAY
Istanbul Technical University – Turkey
turkayb@itu.edu.tr

ABSTRACT

This study proposes an efficient and computationally feasible solution approach based on evolutionary algorithms, to the distribution system restoration problem. When a fault occurs in a distribution system, the faulted area should be isolated from the system and as much load as possible has to be restored to this area. This is done by transferring de-energized loads from out-of-service areas through the distribution system without violating or disturbing the existing operation constraints. The solution of this problem, which can be defined as obtaining an optimum system configuration providing minimization of de-energized areas on the system after a fault occurred, is known as service restoration in distribution networks. This is achieved by finding an optimal operation configuration via changing the status of sectionalizing switches, taking into account the objectives and the constraints of the system. This makes the distribution system restoration problem a complex combinatorial optimization problem with multiple constraints. Therefore, to solve this problem and obtain feasible solutions of good quality, with an acceptable amount of computational effort, an evolutionary algorithm approach is proposed. The proposed evolutionary algorithm is applied to a radially configured distribution system model and analysis results are presented.

INTRODUCTION

In modern age, the demand for energy has gone up day by day. Because of this, the state of de-energization has begun not to be tolerated. Furthermore, the enlargement of electric power networks and optimum operation strategy planning are essential for supplying energy consumption which has increased owing to development of technology and industry without any interruption. The main problem is to be formed de-energized areas, because short circuit, frequency and voltage changes, overloading etc. may cause outages in the system. Besides, the outage can be seen on areas which have not any fault. At this condition, minimum impact to customers is aimed. When a fault occurs in a distribution system, the faulted area should be isolated from the system and as much load as possible has to be restored to this area. This is done by transferring de-energized loads from out of service areas to these areas through the distribution system without violating or disturbing the existing operation constraints. The solution of this problem, which can be defined as obtaining an optimum system configuration providing minimization of de-energized areas on the system after a fault occurred, is known as service restoration in distribution networks. The main concern of this problem is to minimize the impact of an outage on the system. This is achieved by finding an optimal operational configuration via changing the status of sectionalizing switches, taking into account the objectives and constraints of the system.

Since this problem can be formulated as a mathematical model, some solution techniques were applied to obtain exact solutions [1]-[8]. For this, various approaches have been used such as heuristic [3] and knowledge-based [4], [5], programming strategies were previously applied and recent years, soft computing [6] and mathematical programming [5] have begun to use so often.

Restoration problem solution has more objectives and constraints, so this makes this problem a complex combinatorial optimization problem with multiple constraints. Therefore, to solve this problem and obtain feasible solution with an acceptable amount of computational effort, an evolutionary algorithm [3], [7] is proposed.

The early studies on distribution system restoration were firstly mentioned by Baran M.E. [8]. His project intended optimum network planning and load balance of the system by minimizing system losses. In a study done by Ucak C. et. al., new solution algorithm was developed. His purpose was to energize the de-energized loads taking into account dynamic conditions of the system. After them, Grainger J. J. and Civanlar S. [2] made a model that has sourced to other people. This model has two objectives and lots of constraints. They used mathematical programming. In addition, they gave detailed information about how to apply this problem to what kind of systems. Recently, Liu C. C., Vittel V., and Tomsovic K. in PSERC [8] have made an project in 2009. In this study, they investigated generator starts effects on restoration and restoration of transmission distribution and power systems. They applied more than three example systems to obtain optimum solutions in different restoration strategies mentioned above.

RESTORATION STRATEGY

The restoration problem is a multi objective constraint optimization problem which is applied to radial distribution systems by changing switching conditions like open or close according to operational conditions [11]. The applied system is designed as mesh system but operated as radial. In addition, if all the switches of the system are closed, the formation will be mesh. Thus, in order to obstruct this mesh structure, one or more switches must be opened according to system topology [2]. These switches are called sectionalizing switch. Distribution systems have some characteristics;

- They have a complex structure and switching diversity,

- They have lots of different electrical elements and this makes them non linear.
- They have lots of electrical data such as transformer, line and motor data.

Because of these properties, restoration problem is a complex combinatorial optimization problem and it requires mare detailed information. They cause too spend time to obtain feasible solutions. The main aim of restoration is; when a fault occur in the system, the faulted area should be isolated from the system and as much load as possible has to be restored to this area. The other aims are;

- To minimize the switching number during restoration,
- To minimize the system losses,
- To retain the radial structure of the distribution system after restoration,
- To maintain busbar voltage levels approximately ±5% of previous voltages,
- To protect lines from overloading.

In restoration strategy, important loads can be classified and multiplied a constant that is between 0 and 1. It is determined according to their importance. If the system is unable to restore for entire loads, the low priority loads can be combined. This makes faster solution arrival.

The restoration problem can be applied only radial distributed networks. If it is used for mesh or other complex systems, the solutions should be local optimum, but in radial systems, we can reach global solutions, which are desired.

EVOLUTIONARY ALGORITHM

Evolutionary algorithm is kind of algorithm which based on a principle that is "best is live". It is a search and optimization solution algorithm based on Darwin's evolution theory. It is generally used for solving complex and combinatorial optimization problems to find a best solution. The best individual of the population is selected and others are eliminated [12]. Evolutionary algorithm starts in a gene pool that is called population. This population is created randomly. Population consists of strings called chromosomes. Chromosomes are formed by genes. Genes are coded in binary representation and consist of combination of ones and zeros. First of all, the fitness function values are evaluated for each individual. On fitness assignment, each individual in the pool takes a probability constant depending on own objective value. Evolutionary algorithm usually consists of three main operators; selection, crossover and mutation. Individuals, which are available for own desired fitness, are selected via selection operators. In this study, tournament selection is decided to use because it is the most adequate selection type for restoration problems and binary optimization solutions. After selection, crossover is applied to parents. Crossover is a recombination operator which combines parts of two parent chromosomes to produce new individuals that contain some parts of genetic characteristics of both parents. The crossover probability constant is specified between 0 and 1. This should be a larger value. Generally, this parameter takes 0.8. Single point crossover is applied to this study. Last operator is mutation. In this part, genes are randomly altered and this causes some variations in population. These variations must be very small to avoid losing individuals that are available for fitness values. Therefore, mutation rate is selected small and calculated via an equation like (1/individual length) [12]. When the best solution is obtained, the algorithm is ended. If the solution is not true, algorithm must continue to work until optimum solution is obtained.

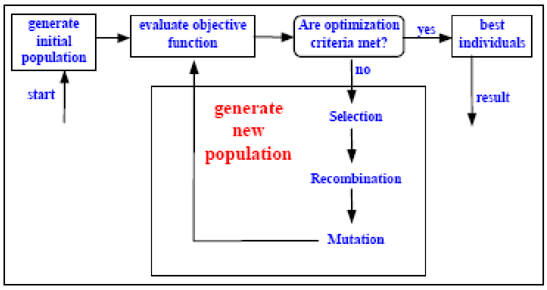

Figure 1. Evolutionary algorithm structure

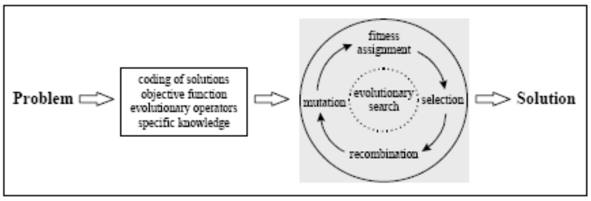

Figure 2. Problem solution via evolutionary algorithm

MATHEMATICAL MODEL

Objective Functions

First objective function is to maximize the supply of power as many loads as possible, giving importance to critical loads, which is taken care of by the equation stated below

$$\max \sum_{i=1}^{n} W_i . I_i \qquad (1)$$

where I is the load current at node i, n is the total number of nodes in the system and W is the weight associated with each load according to its importance.

The second objective is to maximize the load feeding;

$$\max \sum_{k \in R}^{n} L_k . y_k \qquad (2)$$

where L_k is the load at bus k, y_k is the decision variable. If restoration is processed at bus k, its value equals to 1 otherwise 0. R is the set of de-energized loads.

Constraint Functions

First constraint is to minimize the system losses;

$$\min \sum_{i=1}^{n_b} k_i . r_i . \frac{P_i^2 + Q_i^2}{|V_i|^2} \qquad (3)$$

where n_b is the total number of branches, k_i is the decision variable like expressed above, P_i an Q_i is the active and reactive powers of branch i,

V is the voltage and r_i is the resistance of branch i.
Second constraint is the available power source capacity;

$$\sum_{e \in F_e} P_e . X_e \leq G_q \quad q \in S \qquad (4)$$

where P_e is the power on branch e and it is assumed higher than zero. X_e is the decision variable of branch e, G_q is the restoration power from the energized bus q and S is the set of energized buses.
Third constraint is the Power balance between supply and demand;

$$\sum_{k \in T_i} P_k - \sum_{k \in F_i} P_k - L_i . y_i = 0 \quad i \in N \qquad (5)$$

where T_i is the set of branches incident to bus i, F_i is the set of branches with originating from bus i, L_i is the load at bus i, and N is the set of busses.
Fourth constraint is the branch power limit;

$$P_k - U_k . X_k \leq 0 \qquad (6)$$

where P_k is the power flow of branch k, U_k is the power capacity of branch k and B is the set of branches.
Fifth constraint is; the system voltage must always be within the allowed limits;

$$V_{i\min} \leq V_i \leq V_{i\max} \quad i \in N \qquad (7)$$

The last constraint is the radiality requirement. The obtained optimum system operating configuration must be radial after restoration. To insure a radial configuration, total number branches connected to bus must be at most unity.

EXAMPLE APPLICATION

The proposed algorithm has been tested on an example radial distribution system like specified in section 2. The studied system is given in figure 4 [3]. The three of its branches that are called tie-switch is open because of avoiding mesh structure. This system is operated at 15,0kV voltage level and consists of three source nodes, 16 load nodes/busbars, 16 lines and three of lines are tie switches. System data and parameters are listed on the figure 4. The system is initially configured radial with switches 14, 15, 16 open. For the algorithm, MATLAB's "Genetic Algorithm and Direct Search Toolbox" was used for evolutionary coding. Moreover, there is needed a load flow analysis to compare whether results are suitable for objectives and constraints or not. Therefore, a load flow program was written.
For applied method, first of all, the genetic string of switches is coded on binary system like given below;

1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0

According to initial topology, load flow analysis is done and results are registered to compare with last results.

If there is fault on bus 11, the switch 8 must be open to isolate the fault from the system. After that, the optimal feeding or switching strategy is tried to evaluate with proposed algorithm and solution method. At algorithm stage, initial population is generated randomly on binary coding system and fitness assignment is done among individuals. After that, a matrix is created as a size of [population size x line number]. Population size is given 50 and line number is 16 in this study. Hence, matrix is written as a code like initbp(50,16) in MATLAB. Then line matrixes, which correspond to each individual in population, are created automatically by being written codes. Following that, iteration for each loop is given 20 according to specified system topology and population. Each individual is sent to load flow one by one and active, reactive, loss power values are obtained as many as individual number. These results are registered in MATLAB memory.
Second part is evolutionary stage. Elitisizm, crossover whose rate is 0.8, tournament selection, two point crossover and the rate of mutation (1/16=0.06) are done. Genetic Algorithm Toolbox was taken advantage of the coding part of evolutionary algorithm stage. There is a part of written algorithm in MATLAB given below as a MATLAB format;

```
gaoptimset('PopulationType',
'bitstring',
'PopulationSize',50,
'EliteCount', 1,
'CrossoverFraction', 0.8,
'Display','iter',
'Generations',                100,
'StallGenLimit',100,'TimeLimit',   300,
'StallTimeLimit', 300,
'SelectionFcn',{@selectiontournament,2},
'CrossoverFcn', {@crossovertwopoint},
'MutationFcn',{@mutationuniform, 0.06}
'PlotFcns', {@gaplotbestf});
```

This is done as many as iteration number. New individuals are sent to load flow. Individuals that are available for objectives and constraint are taken as the best results. Best result is given in figure 3. If initial and last results are compared, loss power should be lower at last results and load maximization should be higher then initial results. Furthermore, last results are satisfied objectives and constraints mentioned in section "mathematical model".

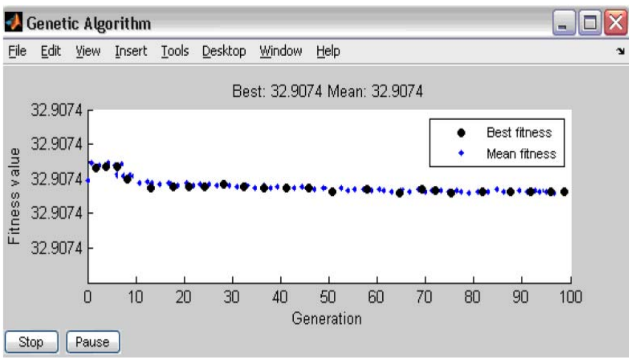

Figure 3. Restoration results in MATLAB graphic plot

According to figure 3, best fitness value is found after 100 generations are created. End of applied algorithm, switches

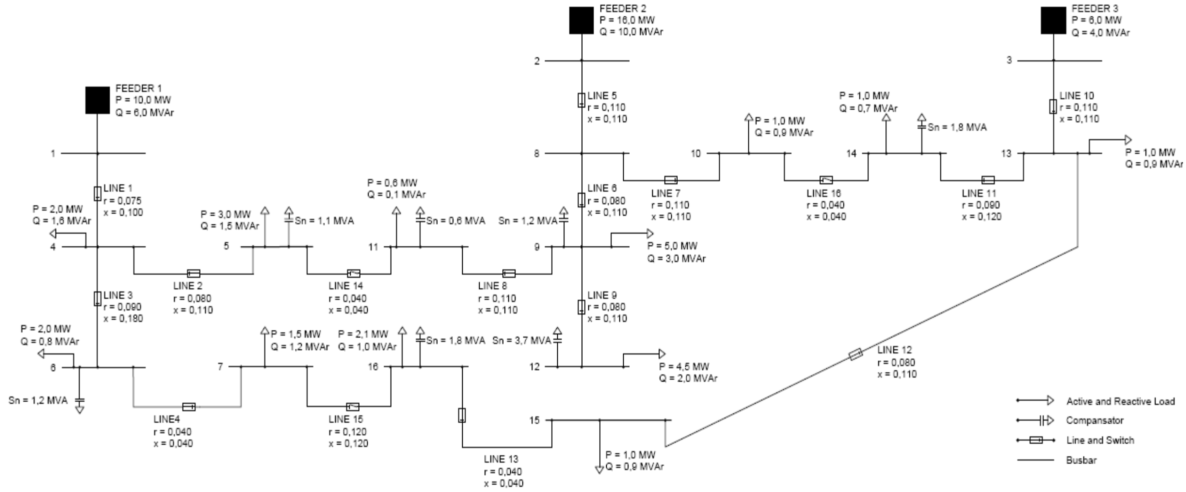

Figure 4. Example distribution system [3]

on 7, 8, 14 and 15 are open, other switches are closed. The genetic string of switches on binary system is obtained as below;

1 1 1 1 1 1 0 0 1 1 1 1 1 0 0 1

At first topology, when load flow was run, total losses were found like $\sqrt{0.515^2 + 0.593^2} = 0.785\,MVA$. At obtained optimal system after restoration, total losses were calculated as $\sqrt{0.469^2 + 0.548^2} = 0.721\,MVA$.

CONCLUSION

An evolutionary algorithm approach to multi objective distribution restoration is presented in this paper. Unlike other studies done before, objective number is increased in this study. This provides computing the more optimum solution and making an opportunity to examine for all side of the system in terms of restoration strategy. Although this has an advantage to find optimal topology, the computational time goes up because all objectives are investigated. All characteristics and properties of restoration strategy and its mathematical model were tried to explain in detail. Then, described restoration problem has been solved by means of an evolutionary strategy on an example distribution system given figure 4.

In the future, the algorithm used in this study will improve to achieve economical analysis for restoration problems by providing all economic data of electrical elements of the system. Besides, this algorithm can be applied to high and low voltage radial distribution systems if it will be developed.

REFERENCES

[1] Su, C. T., Lee, C. S., 2001, "Feeder Reconfiguration and Capacitor Setting for Loss Reduction of Distribution Systems," Electric Power System Research, no. 58, 97–102.

[2] Civanlar, S., Grainger, S., and Yin, H., 1988, "Distribution Feeder Reconfiguration for Loss Reduction," IEEE Transactions on Power Delivery, vol. 3, no. 3, 1217–1223.

[3] Mendiola, M. C., Chang, C. S., and Elangovan, S., 1995, "Fuzzy Expert System for Distribution System Restoration and Contingency Operation," IEEE Explore Catalogue, no. 95TH8130, 73–79.

[4] Sakaguchi, T., 1983, "Development of a Knowledge Based System for Power System Restoration," IEEE Transactions on Power Apparatus & Systems, vol. PAS–102, no. 2, 320–329.

[5] Nagata, T., 1995, "Power System Restoration by Joint Usage of Expert System and Mathematical Programming Approach," IEEE Transactions on Power Systems, vol. 10, no. 3, 1473–1479.

[6] Lee, S., 1998, "Service Restoration of Primary Distribution Systems Based on Fuzzy Evoluation of Multi-criteria," IEEE Transactions on Power Systems, vol. 13, no. 3, 1156–1163.

[7] Nara K, 1997, "Genetic Algorithm for Power Systems Planning," in Proc. 1997 The 4th International Conference on Advances in Power System Control, Operation and Management,60–65, Hong Kong.

[8] Baran, E., Wu, F., 1989, "Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing," IEEE Transactions on Power Delivery, vol. 4, no. 2, 1401–1407.

[9] Liu C. C., Vittal V., Tomsovic K., 2009, "Development and Evaluation of System Restoration Strategies from a Blackout," Power Systems Engineering Research Center.

[10] Pohlheim, H., 2010, "GEATbx Genetic and Evolutionary Algorithm Toolbox for MATLAB Version 3.8 User's Manual," retrieved.

[11] Venkatraman, S., 2005, "A Generic Framework for Constrained Optimization Using Genetic Algorithms," IEEE International Conference on Evolutionary Computation, vol. 9, no. 4, 579–584.

[12] Solanaki, J. M., Khushalani, S., and Schulz, N. N, 2007, "A Multi-Agent Solution to Distribution Systems", *IEEE Transactions on Power Systems*, vol. 22, no. 3, 1026–1033.