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A New Combination of Simulated Annealing, Genetic Algorithm, and Graph Theory Techniques for Multi-Objective Reconfiguration of Distribution System

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ABSTRACT

Reconfiguration of distribution systems is a subject related to operation especially in the presence of automation systems. Reconfiguration of distribution systems can be done with different goals. Ever, various reconfiguration methods presented for unbalanced distribution networks. In this paper, reconfiguration of the unbalanced distribution system in the scheme of multi-objective model proposed to reduce the losses, load imbalances, switching operations and improvement the voltage profile. Simulated annealing algorithm and graph theory implemented in MATLAB software have been used to solve the multi-objective reconfiguration problem, as well as a search method based on genetic algorithm is applied to accelerate problem solving. Three tests with different weighting coefficients are applied on a sample 33 buses and 12.66 KV distribution network to investigate the efficiency of the proposed technique. The obtained results prove the efficient performance of the proposed method for different statuses and demonstrate the operators are able to use the technique for each objective separately or assume an optimal interaction among targets.

KEYWORDS: Distribution system, Graph theory, Simulated annealing algorithm, Genetic algorithm, Multi-objective model, Reconfiguration

1. INTRODUCTION

Distribution system is an intermediate between consumers and transmission network. They are generally utilized with radial structure. This radial configuration has the advantages such as lower short circuit current and easier protection coordination, while lead to reduce the reliability of consumers feeding, increase the total power losses and voltage drop at the load points. Electrical distribution systems have tie and sectionalizing switches. By changing the switches states during operation, the construction of distribution network will change. This change in the distribution system configuration is known as reconfiguration and performed with various objectives such as total losses reduction, voltage profile improvement, load balancing increase and etc [30-31]. Many researches in the literatures have presented several techniques with different goals for the distribution systems reconfiguration. Reconfiguration of distribution network for loss reduction was first offered by Merlin and Back [7] in 1975. They have used a branch and bound optimization technique to determine the status that has the minimum total loss. In this method, all switches are first closed to creation a meshed configuration. The switches are then opened successively to achieve the radial structure. After this method, many algorithms have been proposed with different aims for distribution systems reconfiguration. Goswami and Basu [1] reported a heuristic algorithm for reconfiguration which is implemented using a power flow program. Gomes et al. [2] introduced a heuristic algorithm for the large distribution network that starts by a meshed structure with all switches closed at first. Switches will be opened one by one to achieve the minimum system loss using a power flow program. A novel path to node based modeling to reconfiguration of distribution system has been presented by Ramoset and Exposito [3] in 2005. Schmidt et al. [4] have introduced a technique based on the standard Newton technique for minimization of loss. Zhou et al. [8] have developed two reconfiguration algorithms for load balancing and service restoration. To solve the reconfiguration problem, they used the combination of heuristic rules and fuzzy logics for optimization purposes. An optimization technique to determine the distribution system structure with minimum losses of energy for a given period has proposed by Taleski and Rajicic [9]. Application aspects of optimal distribution system reconfiguration have been offered by Borozan and Rajakovic [10]. A network reconfiguration algorithm using voltage, ohmic, and decision indexes has been introduced by Lin and Chin [11] for switching operations determination. Jeon [12], Augugliaro [13] and their colleagues used artificial intelligence techniques for a minimum loss reconfiguration. Nara et al. [14] used Genetic Algorithm (GA) to solve the distribution reconfiguration problem for minimum loss using. A fuzzy

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multi-objective approach was presented by Das [15] for optimizing distribution network configuration which four goals of load balancing among the feeders, real power loss, deviation of nodes voltage, and branch current constraint violation have been modeled and results obtained are valuable, but selecting criteria of membership functions are not provided. Harmony Search Algorithm (HSA) is used to optimal network reconfiguration of large distribution system by Rao et al. [16].

In this study simulated annealing (SA) algorithm and graph theory are implemented in the Matlab software environment to solve a multi-objective distribution system reconfiguration problem, as well as a search method based on genetic algorithm is applied to accelerate problem solving. The proposed technique is applied on a sample distribution system and the obtained results are presented in numerical studies section. To investigate the sufficiency of proposed method, it is accomplished a comparison between proposed technique and other method results.

2. Simulated annealing algorithm

Simulated annealing is a meta-heuristic technique for the optimization problem of locating a good approximation to the global optimum of a function in a search space. In SA technique, each "*s*" point of the search space is similar to a status of the certain physical system, and *E(s)* that will be minimized is like to the energy of system for that state. The objective is to bring the system from an arbitrary initial state, to a state with the minimum feasible energy [24, 25].

At each step of the annealing process, an atom moves slightly and leads to change energy of the system. This change is shown by ΔE . If $\Delta E \leq 0$, so this replacement is acceptable and a new structure with displaced atoms will be used as the next starting configuration. If $\Delta E > 0$ then the following probability relation determines the acceptation chance of the new solid construction [24].

$$p(\Delta E) = e^{(-\Delta E/(k_b.T))} \quad (1)$$

Where k_b is the Boltzmann constant and T is the temperature.

In fact, a random number will be selected from (0,1), and compared with $p(\Delta E)$. If the selected number is less than $p(\Delta E)$, the new configuration will be accepted, otherwise it is ineligible. This process continues until the equilibrium level is achieved. Simulated annealing algorithm progress is summarized as following steps:

1. Initial solution selecting from the possible answer set.
2. Initial temperature adopting and number of iterations determination for each temperature.
3. Temperature reduction procedure design.
4. Determine a relation for the number of replacements at each temperature.
5. The temperature change counter equals to zero.
6. Annealing process repetition.
7. Calculation the new temperature (by decreasing the temperature)
8. Replication this algorithm to satisfy the stop condition.

The important SA algorithm parameters should be considered, are :

- Neighborhood space (in this study, a random search technique based on genetic algorithm has been implemented to accelerate problem solving).
- Initial temperature (here, it is considered as a high temperature to consider many initial solutions).
- Temperature change procedure (a geometric relation is used to define the temperature change process: $T_K = \alpha T_{k-1}, (0 < \alpha < 1)$).
- Equilibrium condition (it is defined as a certain number of exchanges for each temperature).
- Stop condition (In this study, a final temperature is assumed for stop condition).

3. Graph theory

A graph is introduced by a binary mixture *G(V,E)*[17], that the vector *V* is the set of nodes in the graph and the vector *E* is the set of unordered pairs of different nodes that each of them is an edge. The degree of each node or vertex is defined by the number of edges meeting it. The connected graph is a graph that there is at least one path between each two vertices of it. Tree graph is a connected graph that there is no cycle in it. In a tree graph, if *V* is the number of vertices and *E* is the number of edges, the following equation is satisfied:

$$V = E - 1 \quad (2)$$

The number of cycles is given by the following equation for each graph:

$$cycle = (E + V) - 1 \quad (3)$$

A graph with *n* nodes can be described by the following adjacency matrix:

$$A = [a_{ij}]_{n \times n} \tag{4}$$

In this matrix, if any two i and j nodes ($i \neq j$) are directly connected together, so a_{ij} element is equal to one, otherwise it is equal to zero.

The graph theory can be used to check whether radial structure of distribution system is retained (tree graph) as well as all loads being in service (connected graph), in the distribution systems reconfiguration.

4. Overview of genetic algorithm

Genetic algorithm has an acceptable characteristic as an optimization tool and present significant advantages more than traditional techniques. This algorithm has the efficiency to search the large solution space containing discrete or discontinuous parameters, without being trapped in local minima [26]. GA may be used to solve the combinatorial optimization problems. GA searches for a solution inside a subspace of the total search space. Thus it is able to give a good solution of a certain problem in a reasonable computation time. The optimal solution is produced from a population of solutions using a random process. A new generation is created by applying the three operators of reproduction, crossover and mutation on the current population. In this study, the genetic algorithm is used to generate the neighborhood space is needed for SA to achieve the solutions with more acceptable speed.

5. Problem formulation

As mentioned in the first section, the reconfiguration of distribution feeders performs with different goals in the normal operating conditions through the change of closed-open switches statuses.

In the next parts of this section, four different objectives have been introduced for the multi-objective reconfiguration problem and each of them will be formulated separately in the form of mathematically model.

5.1. Minimization of active power losses

Reduction of power losses is considered as the most important objective function. In this study, power losses objective function is expressed as following mathematically equation:

$$f_l = \sum_{k=1}^{n} r_k . I_k^{\ 2} \tag{5}$$

Where:

n: Total number of sections.

r_k : The conductor resistance value of section *k*.

I_k : Current flowing through section *k*.

5.2. Minimization of load unbalancing

There are different reasons that lead to unbalancing on the feeder load such as heterogeneous and none uniform distribution of single phase subscribers among the three phases of a feeder or random and asynchronous treatment of the single phase consumers.

The overall goal of this objective function is reduction of active and reactive power imbalance for all sections, so it is formulated as follows:

$$f_i = Variance\left[\frac{S_1}{S_{1\max}}, \frac{S_2}{S_{2\max}}, ..., \frac{S_k}{S_{k\max}}, ..., \frac{S_n}{S_{n\max}}\right] \tag{6}$$

Where:

S_k : Is the apparent power value flowing through the section *k*.

$S_{k\max}$: Is the maximum permissible apparent power value for the section *k*.

5.3. minimization of voltage offsets

The basic purpose of this objective function is that the deviation of nodes voltage should be minimized and it is evaluated as:

$$\min\ f_d = \max\left|V_k - V_r\right| \quad k = 1,2,\ldots,n_l \tag{7}$$

Where:

n_l : Total number of buses.

V_k : The actual voltage of bus *k*.

V_r : The rated voltage of bus *k*.

5.4. Minimization of the switching operations number

In order to perform the shift from the initial to the optimal configuration by minimum switch operations, an efficient switch designation needs to be developed such that dispensable switch operations can be avoided. Minimizing the number of switch operations can be considered as follows:

$$\min\ f_s = \sum_{k=1}^{n}\left|SW_k - SW_{ak}\right| \tag{8}$$

Where:

SW_k : The new status of switch *k*

SW_{ak} : The original status of switch *k*

6. Problem solution based on simulated annealing, genetic algorithm and graph theory

In this study, reconfiguration is used to achieve four minimization goals including power losses, load unbalancing, voltage deviation and number of switching operations. The mathematical model of this multi-objective function is defined as follows:

$$E = Minimum\left\lfloor a_1.(f_l - f_{l\min}) + a_2.(f_i - f_{i\min}) + a_3.(f_d - f_{d\min}) + a_4.(f_s - f_{s\min}) + P\right\rfloor, \sum_{i=1}^{4} a_i = 1 \tag{9}$$

Where problem constrains are:

$1: V_{k\min} \le V_k \le V_{k\max} \quad k = 1,2,\ldots n_l$

$2: I_k \le I_{k\max} \quad k = 1,2,\ldots n$

3: Network Radial configuration should be maintained.

4: All available nodes should be fed for the distribution system.

In the suggested multi-objective function, a_i is a weighting coefficient for each objective function and *B* is defined as follows:

$$P = T_{cycle(number)} + M_{isolated-loads(number)} \tag{10}$$

In the above equation, $T_{cycle(number)}$ and $M_{isolated-loads(number)}$ values are the penalty coefficients for wrong solutions that lead to form cycles or establish the isolated loads. By placing *p* in the multi-objective function, the possible wrong solutions of search space have been neglected gradually and solutions will be converged to the optimal answers with the more acceptable speed. 1-4 above constraints represent voltage and current permitted limitations, maintain the radial structure of distribution system and being all loads in service for the reconfiguration problem solving.

Reconfiguration of distribution system procedure using the simulated annealing, genetic algorithm and graph theory is described as this flowchart: (The distribution system power flow is performed using the method presented in [18].)

Step1. Read bus, load, and branch data of distribution system.

Step 2. Create the initial solution(x).

Step 3. Run the power flow program [18]. Compute the multi -objective function value (E_{best}).

Step 4. Create neighborhood solution(y) using GA.

Step 5.Run the power flow program. Compute the multi -objective function value for the new structure (E_{new}).

Step 6.If $\Delta E = E_{new} - E_{best} \leq 0$, then accept solution(y), otherwise calculate the chance of accepting it by this probability function: $p(\Delta E) = e^{(-\Delta E/(k_b.T))}$ and replace it by E_{best}.

Step7.If the equilibrium condition is not satisfied, go to step 4.

Step 8.If the stop condition is not satisfied, decrease temperature: $T_k = \alpha T_{k-1}$, $0 < \alpha < 1$ and go to step4.

Step 9.Use the graph theory using the following method to investigate the radial structure and feeding all loads of distribution system meanwhile the reconfiguration process:

A. Establish the adjacency matrix according to the obtained SA solution in the step 8 and name it asA1 matrix. This matrix shows the connection between the buses of feeder.

B. Calculate matrix A2 by eliminating the repeated elements of A1. None zero elements number of the matrix A2 will be compared with the bus numbers, so one of the two following states will be concluded: these two numbers are not equal (status 1) or they are equal with together (status 2).

Status 1: it means that the distribution system graph is not connection, so there are some isolated loads in the network.

Status 2: by eliminating the first column of A1, if a row is generated with all zero elements, so there are some isolated loads. These buses are connected to the feeder. If there are no isolated loads, then the numbers of cycles are calculated by equation (3). If the cycle numbers is equal to zero, the graph is a tree, so the distribution system is radial and all its loads are in service, else multi-objective function should be penalized using new *P* factor and process repeat again from step4. Checking procedure by graph theory is shown as a flowchart in the figure1.

Step 10.The final proposed configuration.

7. Numerical Studies

To evaluate the performance of the suggested method, a sample distribution feeder is selected for test. Single line diagram of the sample feeder is shown in the figure2. It is a 12.66 kV grid and includes one feeder, 33 buses, 32 sectionalizing, and 5 tie switches. Electrical information of the sample network is presented in the table1. It is considered that all sections have switches. Three different tests have been applied to investigate the performance of the proposed technique:

First test: In this test, unequal weighting coefficients are assumed in multi-objective function, $a_1 = 0.4$, $a_2 = 0.4$, $a_3 = 0.1$, and $a_4 = 0.1$

Second test: All four goals of the scheme are considered by similar coefficients in this test, in other words, $a_1 = a_2 = a_3 = a_4 = 0.25$.

Third test: Only one target (minimization of feeder load unbalancing) is assumed for reconfiguration and other goals are not considered in the objective function, so: $a_1 = 0$, $a_2 = 1$, $a_3 = 0$ and $a_4 = 0$

The obtained results are presented in the table2. As can be seen in this table, the amount of loss reduction is significant for both tests. This reduction is 34.113%, 33.335% and 20.454 for first, second and third tests respectively. The feeder load unbalancing has been improved about 41.176% for first, 36.974% for second and 46.218% for third test. Voltage deviation is reduced for all tests, although further improvement has been seen for second test. The obtained objective function values for the number of switching operations are 6, 4 and 8 in first, second and third tests respectively. The convergence process of f_l, f_i and f_d objective functions have been shown in figures 3, 4 and 5 for all tests. The loss reduction for the proposed method has been compared with other works in table3. The performance of SA is satisfactory using the parameter values have been shown in the table4.

The results indicate that different weighting coefficients values lead to different solutions. It is observed that the proposed model is a sensitive multi-objective function and able to adapt itself with the new status of the project.

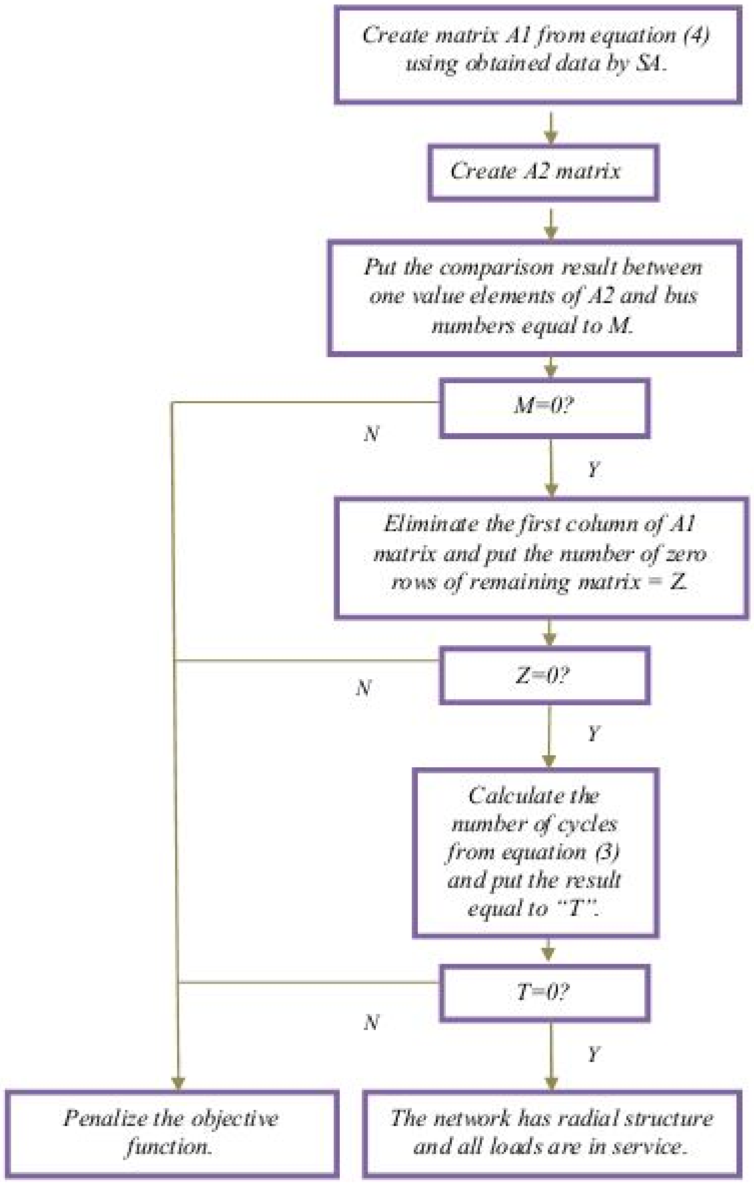

Figure 1: Investigation of radial structure and being all loads in service using graph theory.

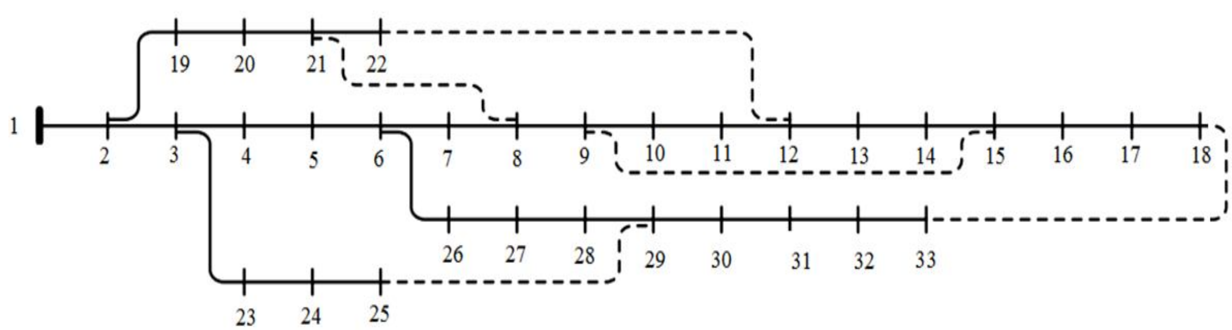

Figure 2: single line diagram of sample studied feeder.

Table1: Electrical information of sample studied feeder.

Section number	Beginning	End	R(Ohm)	X(Ohm)	P(KW)	Q(KVAR)
1	1	2	0.0922	0.0470	100	60
2	2	3	0. 4930	0.2511	90	40
3	3	4	0. 3660	0.1864	120	80
4	4	5	0. 3811	0.1941	60	30
5	5	6	0. 8190	0.7070	60	20
6	6	7	0. 1842	0.6188	200	100
7	7	8	0. 7114	0.2351	200	100
8	8	9	1. 0300	0.7400	60	20
9	9	10	1. 0440	0.7400	60	20
10	10	11	0. 1966	0.0650	45	30
11	11	12	0. 3744	0.1238	60	35
12	12	13	1. 4680	1.0550	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.5910	0.5260	60	10
15	15	16	0.7463	0.5450	60	20
16	16	17	1.2890	1.7210	60	20
17	17	18	0.7320	0.5740	90	40
18	2	19	0.1640	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	3	23	0.4512	0.3083	90	40
23	23	24	0.8980	0.7091	420	200
24	24	25	0.8960	0.7011	420	200
25	6	26	0.2030	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.0590	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9742	0.9630	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.3410	0.5320	60	40
33*	21	8	2.0000	2.0000	-	-
34*	9	15	2.0000	2.0000	-	-
35*	12	22	2.0000	0.5000	-	-
36*	18	33	0.5000	0.5000	-	-
37*	25	29	0.5000	0.5000	-	-
			***Open branches**			

Table 2: Obtained results for all tests.

proposed technique (third test)	proposed technique (second test)	proposed technique (first test)	Initial configuration	Obtained parameters
161.263	135.148	133.572	202.730	**(KW)** f_l
20.454	33.335	34.113	-	**Active power loss reduction (%)**
8	4	6	-	f_s
5	5	5	5	**Number of open switches**
7-9-14-32-36	34-32-21-7-10	32-14-13-8-7	33-34-35-36-37	**Section of tie switches**
0.064	0.075	0.070	0.119	f_i
46.218	36.974	41.176	-	**Load unbalancing improvement (%)**
0.0839	0.0543	0.0607	0.0962	**(p.u)** f_d
0.9161	0.9457	0.9393	0.9038	**Worst voltage (p.u)**

Table 3: Comparison between the obtained results by the proposed method and other researches for the active power losses.

Method	Tie switches	Power loss(KW)
Original configuration[23]	33-34-35-36-37	202.730
Shirmohammadi and Hong (1989)[22]	7-10- 14- 32- 37	140.26
Goswami and Basu (1992)[1]	7-9- 14- 32- 37	139.53
Vanderson Gomes et al. (2005)[21]	7- 9- 14- 32- 37	139.53
proposed method (first test)	32-14-13-8-7	133.572

Table 4: SA selected parameters.

Initial temperature	200K
Cooling rate	0.95
Temperature steps	30
iterations	450

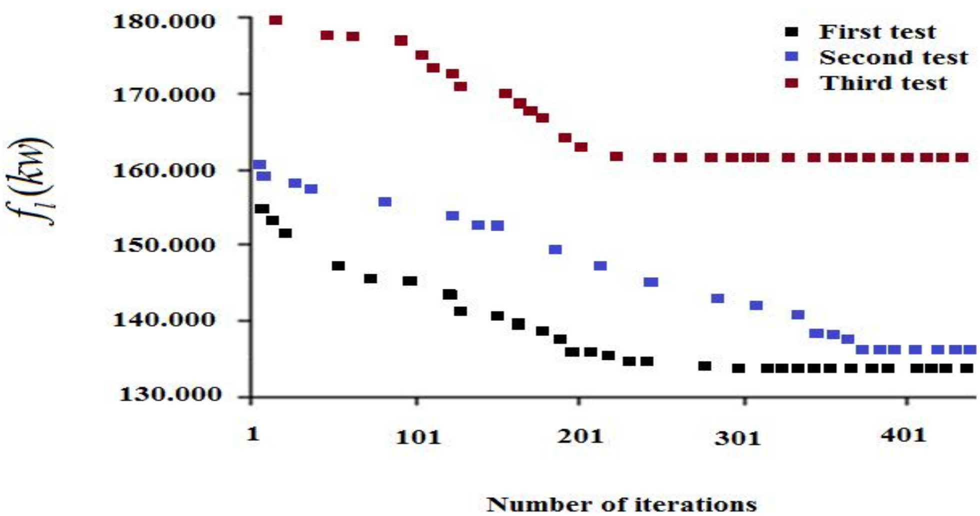

Figure 3: f_l objective functions convergence procedure.

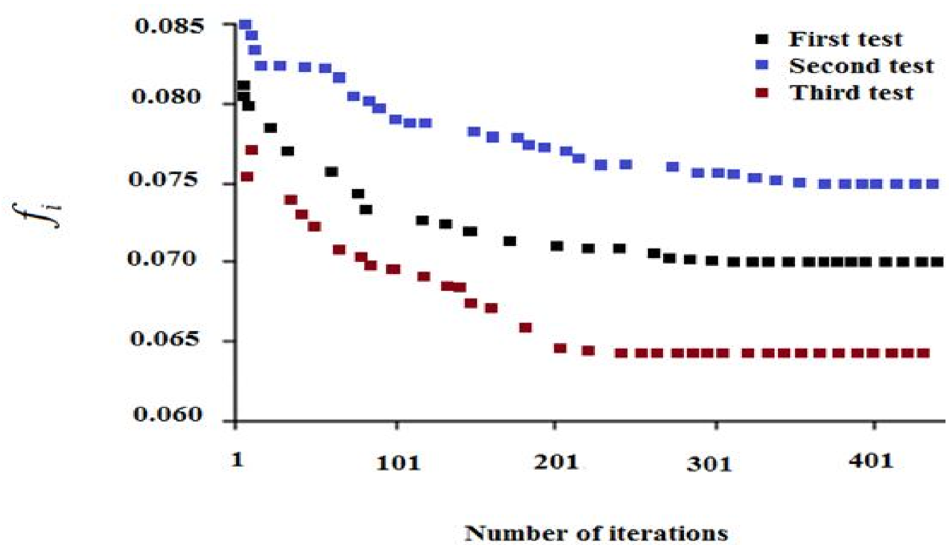

Figure 4: f_i objective functions convergence procedure.

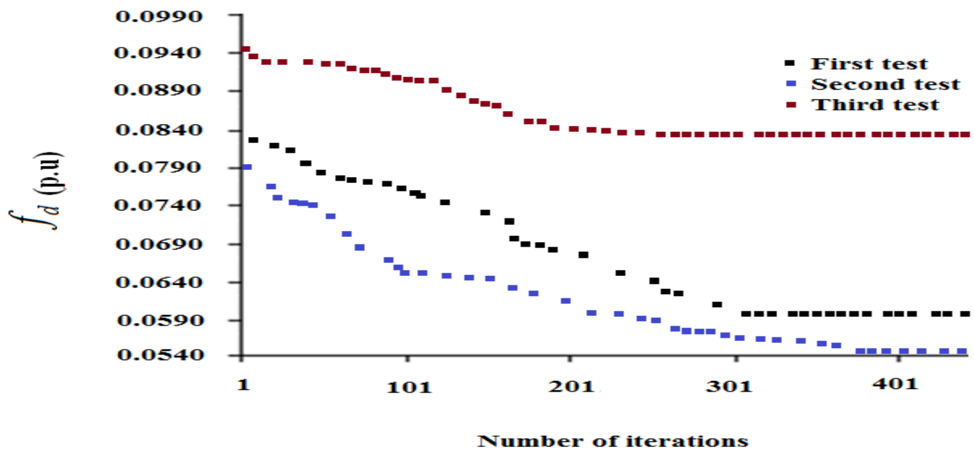

Figure 5: f_d objective functions convergence procedure.

8. Conclusion

In this paper, a new technique of combining the simulated annealing, genetic algorithm and graph theory has been introduced to solve the multi-objective reconfiguration problem in the distribution systems. Four goals including the minimization of active power losses, load unbalancing, voltage deviation and the number of switching operations have been considered in the proposed multi-objective model. Simulated annealing and genetic algorithms implemented in MATLAB software are used to find the best solutions of problem as well as graph theory investigates the radial structure and being all loads in service. Three tests with different weighting coefficients are applied on a sample distribution network to investigate the efficiency of the proposed technique. The obtained results prove the efficient performance of the proposed method for different statuses. Among the other benefits of this method is that operator can use each objective separately or assume an optimal interaction among targets.

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