Radial Distribution Network Reconfiguration for Loss Reduction and Load Balancing using Plant Growth Simulation Algorithm

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Abstract: Network reconfiguration is a combinatorial optimization problem because it accounts various operational constraints in distribution systems. Plant Growth Simulation Algorithm has emerged as a useful optimization tool for handling nonlinear programming problems. In this paper, Plant Growth Simulation Algorithm has been proposed with a view to enhance speed and robustness. This method has been applied successfully on some benchmark mathematical problems. The solution for loss reduction through network reconfiguration involves a guiding search over the relevant configurations. The branch load balancing index and system load balancing index are defined for formulation of objective function of load balancing problem. Most of the methods published in the literature require external parameters such as barrier factors, crossover rate etc. The main advantage of the method presented here does not require external parameters. The proposed method is tested to reconfigure 69-node radial distribution system for loss minimization and load balancing.

Keywords: Network reconfiguration, Load balancing, Plant growth simulation algorithm, Radial distribution system

1. Introduction

Optimal distribution planning involves network reconfiguration for distribution loss minimization, load balancing under normal operating conditions and fast service restoration minimizing the zones without power under failure conditions. Network Reconfiguration is the process of operating switches to change the circuit topology so that operating costs are reduced while satisfying the specified constraints.

Distribution systems consist of groups of interconnected radial circuits. Two types of switches, normally closed switches (sectionalizing switches) and normally open switches (tie switches), are used in primary distribution systems for protection and configuration management. Distribution network reconfiguration for loss reduction and load balancing is a complicated combinatorial, non-differentiable, constrained optimization problem since the reconfiguration involves many candidate-switching combinations. The problem precludes algorithms that guarantee a global optimum. Most existing reconfiguration algorithms fall into two categories. In the first, branch exchange, the system operates in a feasible radial configuration and the algorithm opens and closes candidate switches in pairs. In the second, loop cutting, the system is completely meshed and the algorithm opens candidate switches to reach a feasible radial configuration. Merlin and Back [1] introduced the concept of changing the topology of distribution systems for loss minimization. They proposed a branch and bound method, to search for a minimum loss operating spanning tree configuration for urban power distribution system, which was modified later by Shirmohammadi and Hong [2].

Civanlar *et al.* [3] presented a branch exchange method and derived a simple formula to estimate the loss reduction. As an alternative approach, reconfiguration algorithms based on the heuristic optimization techniques such as Genetic Algorithm, Simulated Annealing, Particle Swarm Optimization (PSO), and recently Plant Growth Simulation Algorithm (PGSA) have

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been reported as realistic and powerful solution schemes to obtain the global or quasi global optima [4].

A general formulation of the feeder reconfiguration problem for loss reduction and load balancing is given and a new solution method is presented in [5]. The solution employs a search over different radial configurations created by considering branch exchange type switching. The optimum power flow based heuristic algorithms reported in [6] are developed in [7]. Chen-Ching Liu et al. [8] have constructed a knowledge base which contains rules that implement a solution approach that system operators can use in order to restore as many load zones as possible. A heuristic approach to distribution system feeder reconfiguration for the removal of transformer overloads and feeder constraint problems, while reducing real power losses, is presented in [9].

Simulated annealing methods are developed to solve the network reconfiguration problem in [10] and [11]. Genetic algorithm considering multiobjective [12], a fuzzy mutated genetic algorithm [13] and refined genetic algorithm [14] for optimal network configuration are published in the literature. Artificial neural network based methods [15, 16] are used to optimize the distribution network. Evolution-based algorithms have been developed for distribution network reconfiguration [17, 18]. Das [19] proposed an algorithm based on the heuristic rules and fuzzy multi-objective approach for network reconfiguration. These existing reconfiguration algorithms work with a simplified model of the power system, and they handle voltage and current constraints approximately, if at all. On the other hand the heuristic algorithms have the advantages in terms of less computation time, ease-of-use, and applicability. However, no convergence to a global optimum is guaranteed by the heuristic methods.

This paper presents a novel design method of the decision variables that remarkably decreases the dimension of the variables in the model employing plant growth simulation algorithm (PGSA) for radial distribution network reconfiguration. This approach minimizes the total system loss and keep load balancing while satisfying its constraints. The proposed method handles objective function and constraints separately, which averts the trouble to determine the barrier factors. The algorithm implements a guiding search direction that changes dynamically as the change of the objective function and does not require any external parameters. The above advantages of PGSA resulted in better searching performance than previously published random algorithms [20]. The validity and effectiveness of PGSA to reconfiguration for loss reduction and load balancing is illustrated with the help of an example.

2. Problem Formulation for Loss Reduction

The objective of the network reconfiguration problem is to minimize the system power loss, subject to operating constraints under a certain load pattern. The objective function can be expressed as:

$$\min F = \min (P_{T,Loss} + \lambda_V S_{CV} + \lambda_I S_{CI}) \tag{1}$$

where $P_{T,loss}$ is the total real power loss of the system. Parameters λ_V and λ_I are the penalty constants, S_{CV} is the squared sum of the violated voltage constraints, and S_{CI} is the squared sum of the violated current constraints. Moreover, the penalty constants are determined as follows:

(i). Constant λ_V (λ_I) is given a value of ‘0’, if the associated voltage (current) constraint is not violated.

(ii). A significant value is given to λ_V (λ_I) if the associated voltage (current) constraint is violated. This makes the objective function to move away from the undesirable solution.

For secure operation, the voltage magnitude at each node must be maintained within its limits. The current in each branch must satisfy the branch capacity. These constraints are expressed as

$$\left|V_{min}\right| \le \left|V_i\right| \le \left|V_{max}\right| \quad (2)$$

$$\left| I_j \right| \le I_{j,max} \quad (3)$$

where $\left|V_i\right|$ is voltage magnitude of node i, $\left|V_{min}\right|$ and $\left|V_{max}\right|$ are minimum and maximum node voltage magnitude limits, $\left|I_j\right|$ and $I_{j,max}$ are current magnitude and maximum current limit of branch j, respectively.

3. Load Balancing

Usually a mixture of residential, commercial and industrial type loads, varying from time to time, appears on distribution lines or line sections. Each of these has different characteristics and requirements. This leads to the fact that some parts of the distribution system become heavily loaded at certain times and less loaded at other times of the day. In order to reschedule the load currents more efficiently for loss minimization, it is required to transfer the loads between the feeders or substations and modify the radial structure of the distribution feeders.

A. Formulation of load balancing problem

An objective function for load balancing is presented which consists of two components. One is the branch load balancing index and the other is the system load balancing index. Branch load index (LB_j) is defined as a measure of how much a branch can be loaded without exceeding the rated capacity of that branch. The objective is to optimize the branch load indices so that the system load balancing index is minimized. In other words, all the branch load balancing indices are set to be more or less the same value and are also nearly equal to the system load balancing index.

The load balancing problem is formulated in the form of branch load balancing and system load balancing indices [21] as

The branch load balancing index, $$LB_j = \frac{S_{(j)}}{S_{(j)}^{max}} \quad (4)$$

The system load balancing index, $$LB_{sys} = \frac{1}{nb}\sum_{j=1}^{nb}\frac{S_{(j)}}{S_{(j)}^{max}} \quad (5)$$

where, nb is the total number of branches in the system.

$S_{(j)}$ is apparent power of branch j

$S_{(j)}^{max}$ is maximum capacity of branch j

Objective function:

$$Minimize \quad F = \frac{1}{nb}\sum_{j=1}^{nb}\frac{S_{(j)}}{S_{(j)}^{max}} \quad (6)$$

The system load balancing index will be minimized when the branch load indices are optimized by rescheduling the loads. In effect, all the branch load balancing indices, (LB_j) are made approximately equal to each other and also closely approximate to the system load balancing index (LB_{sys}).

Representing mathematically,

$$\frac{S_1}{S_1^{max}} \cong \frac{S_2}{S_2^{max}} \cong ..... \cong \frac{S_n}{S_n^{max}} \cong \frac{1}{nb}\sum_{j=1}^{nb}\frac{S_{(j)}}{S_{(j)}^{max}} \tag{7}$$

The conditions taken into consideration are:

(i). The system loss must be minimized.

(ii). The voltage magnitude of each node must be within permissible limits, i.e., $\left|V_{min}\right| \le \left|V_i\right| \le \left|V_{max}\right|$

(iii). Current capacity of each branch, $\left|I_j\right| \le I_{j,max}$

When the load balancing index, LB_j of the branch is equal to 1then the condition of that branch will become critical and the branch rated capacity will be exceeded if it is greater than 1. The system load balancing index, LB_{sys} will be low if the system is lightly loaded and its value will be closer to zero, and the individual branch load balancing indices will also be low. If the loads are unbalanced, the load balancing indices of individual branches will differ widely, whereas, the balanced load will make the load balancing indices of all the branches nearly equal. It is not practically possible to make all the branch load balancing indices, LB_j exactly equal. However, it is possible that by reconfiguration the load balancing indices of the branches will be adjusted, and hence the load balancing in the overall system improved.

The proposed method uses a set of simplified feeder-line flow formulations for power flow analysis to prevent complicated computation.

4. Implementation of PGSA to Network Reconfiguration for Loss Reduction and Load Balancing

The plant growth simulation algorithm is a bionic random algorithm which characterizes the growth mechanism of plant phototropism. It looks at the feasible region of integer programming as the growth environment of a plant and determines the probabilities to grow a new branch on different nodes of a plant according to the change of the objective function, and then makes the model, which simulates the growth process of a plant, rapidly grow towards the light source (global optimum solution).

A. Growth Laws of a Plant

The following facts have been proved by the biological experiments.

1. In the growth process of a plant, the higher the morphactin concentration of a node, the greater the probability to grow a new branch on the node.
2. The morphactin concentration of any node on a plant is not given beforehand and is not fixed; it is determined by the environmental information of the node, and the environmental information of a node depends on its relative position on the plant. The morphactin concentrations of all nodes of a plant are allotted again according to the new environment information after it grows a new branch.

B. Probability Model of Plant Growth

By simulating the growth process of plant phototropism, a probability model is established. In the model, a function g(Y) is introduced for describing the environment of the node Y on a plant. The smaller the value of g(Y), the better the environment of the node Y for growing a new branch. The main outline of the model is as follows: A plant grows a trunk M from its root B_0. Assuming there are *k* nodes B_{M1}, B_{M2}, B_{M3} .... B_{Mk} that have better environment than the root B_0 on the trunk M, which means the function g(Y) of the nodes B_{M1}, B_{M2}, B_{M3} .... B_{Mk} and B_0 satisfy $g(B_{Mi}) < g(B_0)$ *(i=1, 2, 3….k)*, then the morphactin concentrations C_{M1}, C_{M2}, C_{M3} .... C_{Mk} of the nodes B_{M1}, B_{M2}, B_{M3} .... B_{Mk} can be calculated using,

$$C_{Mi} = \frac{g(B_0) - g(B_{Mi})}{\Delta_1} (i = 1,2,3 \dots k) \tag{8}$$

$$\Delta_1 = \sum_{i=1}^{k} (g(B_0) - g(B_{Mi}))$$

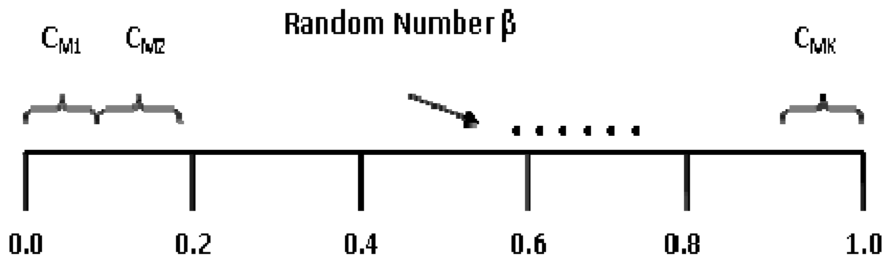

Figure 1. Morphactin concentration state space

The significance of (8) is that the morphactin concentration of a node is not dependent on its environmental information but also depends on the environmental information of the other nodes in the plant, which really describes the relationship between the morphactin concentration and the environment.

From (8), we can derivate $\sum_{i=1}^{k} C_{Mi} = 1$, which means that the morphactin concentrations C_{M1}, C_{M2}, C_{M3} .... C_{Mk} of the nodes B_{M1}, B_{M2}, B_{M3} .... B_{Mk} form a state space shown in Figure 1. Selecting a random number β in the interval [0, 1], β is like a ball thrown to the interval [0, 1] and will drop into one of C_{M1}, C_{M2}, C_{M3} .... C_{Mk} in Figure 1, then the corresponding node that is called the preferential growth node will take priority of growing a new branch in the next step. In other words, B_{MT} will take priority of growing a new branch if the selected β satisfies $0 \le \beta \le \sum_{i=1}^{T} C_{Mi} (T = 1)$ or $\sum_{i=1}^{T-1} C_{Mi} < \beta \le \sum_{i=1}^{T} C_{Mi}$ (*T=2, 3 ... k*). For example, if random number β drops between an interval [1 2], which means $\sum_{i=1}^{1} C_{Mi} < \beta \le \sum_{i=1}^{2} C_{Mi}$, then the new branch *m*, will grow at node 2.

5. Network Optimization Based on PGSA

A. Design of Decision Variables

The switch is usually considered as the decision variable and can be assigned either a value 0 (zero for open switch) or 1 (for closed switch) in the distribution network optimization problem. However, two problems exist: (1) the number of possible network states grows exponentially with the number of switches, making rudimentary techniques such as exhaustive search totally unsuitable for the large-scale problem; (2) optimal solution may not be obtained since a lot of unfeasible solutions will appear in the iterative procedure. More sophisticated techniques are required for the design of decision variable to overcome the above problems. In a distribution system, the independent loops can be selected as decision variables since the number of independent loops is the same as the number of tie switches, the problem of network optimization is identical to the problem of selection of an appropriate tie switch for each independent loop so that the system active power loss can be minimized. This can greatly reduce the dimension of the variables in the solved model and leads to a marked decrease of unfeasible solutions in the iterative procedure. To illustrate the new decision variables, consider the IEEE 16-bus distribution system shown in Figure 2, which consists of 13 sectionalizing switches and 3 tie switches. The initial tie switches are represented by dotted lines and sectionalizing switches by thick lines. The following steps are involved in the basic procedure for designing the new decision variable.

1. Form an initial radial network with all of the sectionalizing switches in Close and open all of the tie switches
2. Close the first tie switch (S_5) and form the first independent loop (nominated loop 1)
3. Assume the decision variable of loop-1 as x_1, and number the switches in loop 1 using consecutive integers, then the numbers of all switches in loop-1 constitute the possible solution set of x_1. For example, number the switches S_1, S_2, S_5, S_9, S_8, S_6 in loop-1 using 1, 2, 3, 4, 5, 6 then the possible solution set of x_1 is integral set [1 6]. In the same way, define other decision variables as x_2 for loop 2, x_3 for loop 3, and get their respective possible solution sets.

B. *Description on Switch State*

By taking independent loops as decision variables, the cases to appear unfeasible solutions in the iterative procedure cannot be avoided. Here, the switches are described in four states so as to reduce the chance to appear the unfeasible solutions in the iterative procedure and/or further improve the efficiency of calculation.

1. Open state: which means a switch is open in a feasible solution.
2. Closed state: which means a switch is closed in a feasible solution.
3. Permanent closed state: which means a switch is closed in all feasible solutions.
4. Temporary closed state: which means a switch must be closed in a feasible solution because another switch is open in the feasible solution, and the switch will be open or closed state when the opened switch is closed in another feasible solution.

With the above description on switch state, no need to number the switches of permanent closed state while forming the possible solution sets of decision variables and the number of the switches of temporary closed state in the possible solution set of the corresponding variable can be temporarily deleted. Taking Figure 2 for instance to make this easily understood, some illuminations about permanent closed state and temporary closed state of switch is as follows.

1. A switch, which is close to source node, should be closed in any feasible and reasonable solution. In Figure 2, switches S_1, S_6, and S_{12} belong to such case. Some needless search can be avoided by introducing the concept of permanent closed state which also enhances the efficiency of calculation. For example, defining switches S_1, S_6, and S_{12} to be in permanent closed state make no need to number switches S_1, S_6, and S_{12} while forming the possible solution set of each decision variable, which reduces the search domain.
2. Some switches, which belong to the same two or three independent loops, are interrelated. In a feasible solution, only one of the interrelated switches may be in open state; otherwise, there will appear isolated islands in the corresponding network. In other words, the possible switches corresponding to two independent loops must be temporarily closed while only one switch is in open state. Finding the unfeasible solution due to the interrelation of some switches can be avoided by introducing the concept of temporary closed state.

C. Treatment of Constraints

In PGSA, the constraints are treated in the following ways:

1. The radial characteristic of the network is enforced by adopting independent loops as decision variables.
2. The other constraints including network connectivity, branch capacity, and bus voltage are executed by checking every found possible solution.

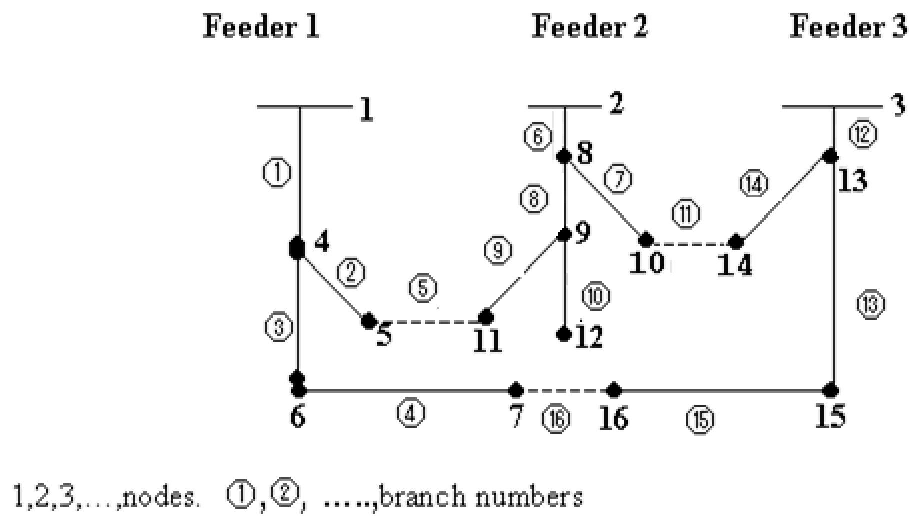

Figure 2. Single line diagram of IEEE 16-node system

The flow chart for network reconfiguration using PGSA is shown in Figure 3.

A complete algorithm for the proposed method of network reconfiguration is given below:

1. Input the system data such as line and load details of the distribution system, constraints limits etc.; set iteration count N=0 and N_{max}.
2. Form the search domain by giving possible tie-line switches available which corresponds to the length of the trunk and the branch of a plant;
3. Give the initial solution X_0 (X_0 is initial configuration) which corresponds to the root of a plant, and calculate the initial value objective function (power loss or load balancing index);
4. Let the initial value of the basic point X_b, which corresponds to the initial preferential growth node of a plant, and the initial value of optimization X^{best} equal to X_0, and let F^{best} that is used to save the objective function value of the best solution X^{best} be equal to f(X_0), namely, $X_b = X^{best} = X_0$ and F^{best} = f(X_0);
5. For k=1: n (n is the no. of tie lines)
6. For *j=1: m (m is the* maximum no. of possible switches for k^{th} tie line)
7. Get a possible solution (configuration) X_p from basic point X_b (initial or updated configuration) by replacing k^{th} element in the basic point X_b with j^{th} possible switch of k^{th} tie line.
8. Calculate the corresponding objective function (power loss or load balancing index) for X_p (new configuration).
9. Check for limit constraints and if the objective function f(X_p) < f(X_b), then save the X_p in feasible solution set, otherwise abandon the possible solution X_p.
10. From the set of all feasible solutions find the minimal solution.
11. Calculate the individual and cumulative probabilities of all the elements in the feasible solution set.
12. Select a random number β from the interval [0, 1] and check for the value lies in between the two consecutive cumulative probabilities.
13. Set the upper limit as the new basic point for the next iteration.
14. Check for $N >= N_{max}$, if yes go to next step else set N=N+1 and go to step number 6 by replacing X_b and F^{best} with new growth point and its corresponding objective function respectively.
15. Print the results for the optimal configuration obtained above.
16. Stop.

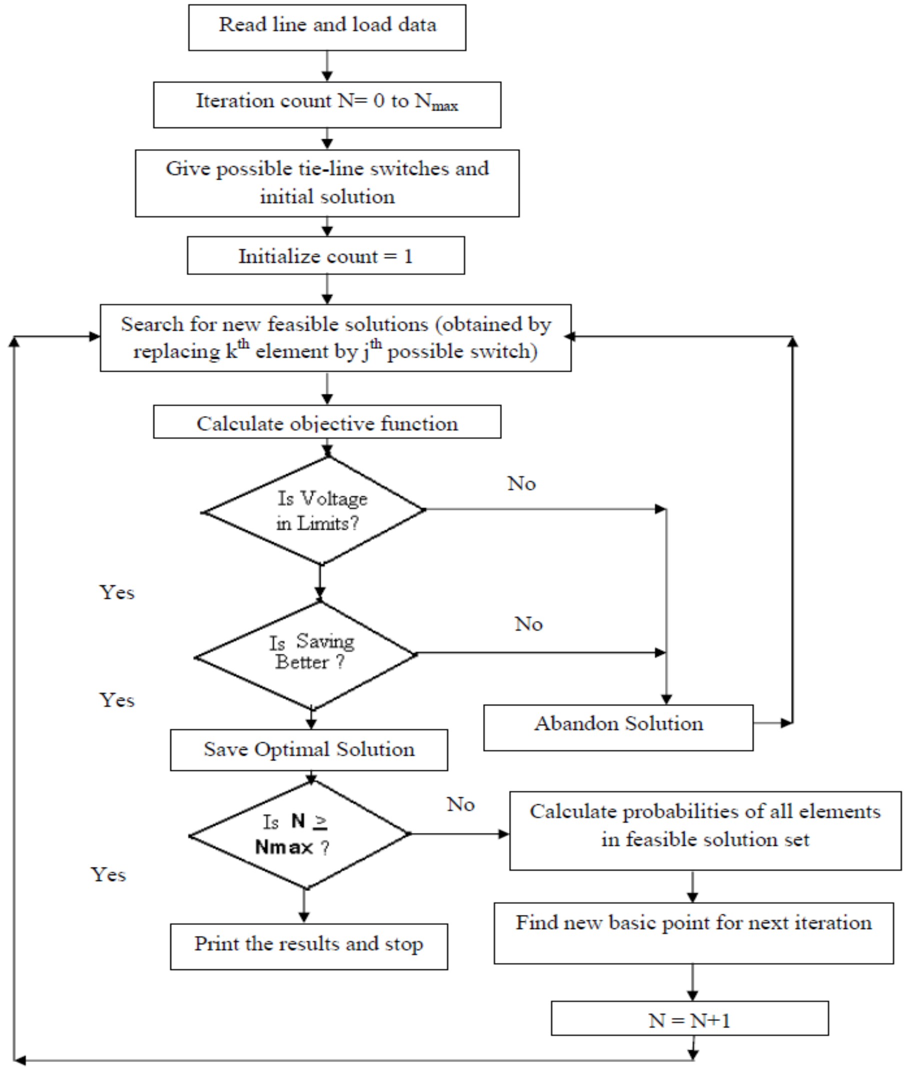

Figure 3. Flow Chart for network reconfiguration using PGSA

6. Results and Analysis

The proposed method is illustrated with two different cases as follows:

Case-I: Illustrates the loss reduction through network reconfiguration of a test system consisting of 69-node radial distribution system.

Case-II: Illustrates the Load Balancing through network reconfiguration of a test system consisting of 69-node radial distribution system.

Case-I

A. Example - 1:

To assess the efficiency of the proposed PGSA, it has been applied to 69 node radial distribution systems for loss reduction. The results obtained from the PGSA are compared with the results of genetic algorithm (GA) [22] in Table 1. It shows that the PGSA has succeeded in finding the global solution with a high probability. Since the algorithm is based on random number generating probability that may create different sequence of tie switches, to show the average performance of the algorithm, it is run for 100 times out of which PGSA converged to optimum solution 97 times with an average loss reduction of 55.52%, where as genetic algorithm converged 79 times with an average loss reduction of 51.15%. The convergence characteristics are shown in Figure 4.

Table 1. Results of 69-node radial distribution network reconfiguration for loss reduction

Description		Initial Configuration	Genetic Algorithm	Proposed PGSA
Tie switches		69,70,71,72,73	9,18,14,58,63	69,70,14,56,61
Total power loss (kW)	Best	225.44	108.40	99.63
	Worst		118.52	134.08
	Average		110.12	100.27
Average power loss reduction (%)		-----------	51.15	55.52
Min. voltage magnitude(p.u)		0.9083	0.9414	0.9428
No. of switches changed		-----------	5	3
No. of times best solution occurred		------------	79	97
Average execution time (s)		-----------	40.5797	23.2633

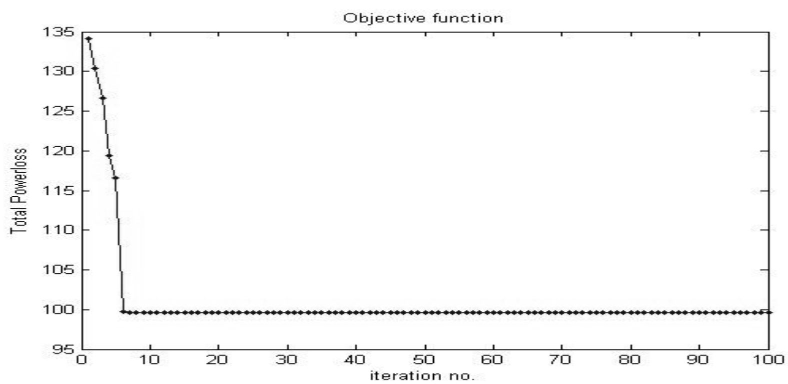

Figure 4. Convergence characteristics for loss reduction of 69 node system

Case-II

B. Example - 2:

For testing the effectiveness of load balancing, consider 69-node radial distribution network [23]. The results obtained from the PGSA are compared with GA. The obtained results and their convergence characteristics are given in Table 2. and Figure 5. To show the average performance, the algorithm is run for 100 times out of which PGSA converged to same solution for 94 times with an average system load balancing index of 0.5667, whereas genetic algorithm converged to same solution for 59 times, with average system load balancing index of 0.6187.

Table 2. Results of 69-node radial distribution network for load balancing

Description		Original Configuration	Genetic Algorithm	Proposed PGSA
Tie Switches		69, 70, 71, 72, 73	10,20,13,57,25	10,20,13,55,25
Load Balancing Index	Best	0.9438	0.5692	0.5692
	Worst		0.6597	0.6294
	Average		0.6187	0.5667
Average LB_{sys} Reduction (%)		-	39.656	39.654
No. of switches changed		-	5	5
No. of times best solution occurred		-	59	94
Average execution time (seconds)		-	45.7687	27.3468

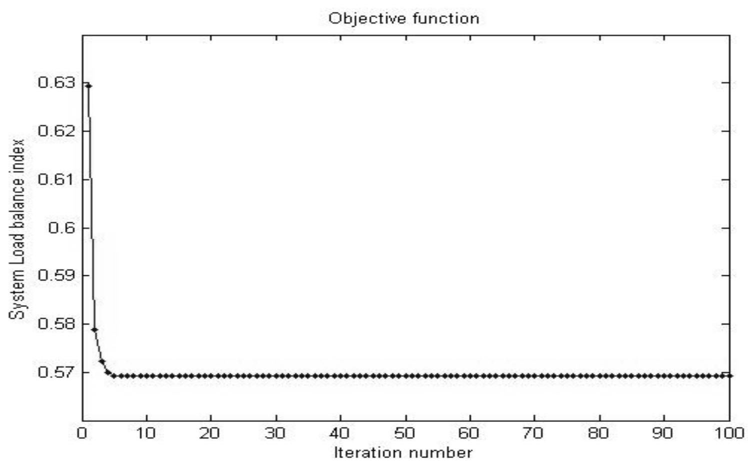

Figure 5. Convergence characteristics for 69 node system for load balancing

7. Conclusion

In this paper, a plant growth simulation algorithm has been proposed to reconfigure distribution network for loss reduction and to keep load balancing. A novel model has been used to simplify the distribution network. The problem is formulated as a non-linear optimization problem with an objective function of minimizing system losses and load balancing index subject to security constraints. Test results have been presented, which shows that using the PGSA method, the feeder reconfiguration problem can be solved efficiently for loss reduction as well as improving the load balancing index when compared to genetic algorithm.

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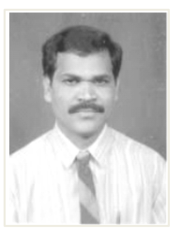

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