Network Reconfiguration of Unbalanced Distribution System through Hybrid Heuristic Technique

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***Abstract* - Electrical power distribution systems are critical links between the utility and customer. They are constructed by one of the three types: radial, open loop and network. They are usually arranged to be radial in operation to simplify over-current protection. Usually, distribution systems are designed to be most efficient at peak load demand. Utilities are constantly looking for newer technologies that enhance power delivery performance. One of the several important issues is the control of power loss. Several strategies can be employed to minimize power losses in a distribution network. They are inclusion of capacitor banks, phase balancing, feeder reconfiguration of distribution system, etc. Among these, feeder reconfiguration helps to operate the distribution system at minimum cost and at the same time improves the system reliability and security. Network reconfiguration is the process of changing the topology of distribution system by altering the open/closed status of switches to find a radial operating structure that minimizes the system real power loss while satisfying operating constraints. This paper proposes an efficient algorithm based on Plant Growth Simulation Algorithm (PGSA), Greedy and Fuzzy. The optimization approach based on PGSA provides detailed description on switch states for calculation. The inclusion of Greedy improves the efficiency of optimization by reducing the number of load flow execution. In addition, heuristic fuzzy has been incorporated to handle constraints along with objective. With the use of proposed algorithm, the system loss has been reduced convincingly, composes proper loading at the branches and make up buses voltage within the limit and which provides solution under different conditions such as normal and abnormal conditions of the system. Furthermore, the solution algorithm is implemented through J2EE (Java 2 Enterprise Edition) architecture to reduce software couplings and to achieve software reusability. The effectiveness of the proposed approach is demonstrated by employing the feeder switching operation scheme to unbalanced standard 25- bus distribution system and modified IEEE- 125 bus distribution system.**

***Keywords*: Distribution Network Reconfiguration, PGSA, greedy, Heuristic Fuzzy, Loss Reduction, Switching Operation**

1. Introduction

Feeder reconfiguration is a very important tool to operate the distribution system at minimum cost and improve the system reliability and security. The reconfiguration of a distribution system is a process, which alters the feeder topological structure by changing the open/close status of the switches in the distribution system. The presence of high number of switching elements in a radial distribution system makes the network reconfiguration a highly complex combinatorial, non-differentiable and constrained non-linear mixed integer optimization problem. Also, the number of variables varies with respect to the size of the system. The distribution system with 'n' switches will have 'n' variables. The demand for a radial operation also makes the mathematical model more difficult to represent efficiently and codification of a solution becomes difficult when metaheuristic techniques are employed.

The feeder reconfiguration problem has been dealt with in various papers. Civanlar *et al.* [1] conducted the early work on feeder reconfiguration for loss reduction. In [2], Baran *et al.* defined the problem of loss reduction and load balancing as an integer programming problem. Aoki *et al.* [3] developed a method for load transfer, in which the load indices were used for load balancing. In Shirmohammadi and Hong [4], the solution method starts with a meshed distribution system obtained by considering all switches closed. Then, the switches are opened successively to eliminate the loops. Many other methods, such as mathematical programming techniques [5-7], expert systems [8-11] and optimization algorithm [12] have been proposed in recent years. In [13] and [14], the solution procedures employing heuristic rules and fuzzy multi-objective approach are developed to solve the network reconfiguration problem.

In [15-16], evolutionary computation techniques are employed for optimizing distribution network. The above methods have been successful in solving the problem of distribution network optimization, but the complexity involved in terms of number of variables is more. In addition to the above, the identification of suitable values of cross over rate, mutation and population size are made by trial and error, which also causes computational difficulty. An efficient and faster differential evolution, Hybrid Differential Evolution (HDE) has also been employed for network reconfiguration [17]. In order to avoid the expensive computational costs spent on tuning the control parameters, Self-Adaptive HDE (SaHDE) has been introduced to gradually self-adapt the control parameters by learning from their pervious experiences in generating promising solutions [18].

The plant growth simulation algorithm (PGSA) is employed to optimize the network configuration of the distribution system [19-21]. The PGSA provides a detailed description on switch state and decision variables, which greatly contracts the search space and hence reduces computation effort. Though it reduces the computational effort, the constraint handling was not effective. For unbalanced distribution network reconfiguration problem, simple reconfiguration approaches had been practiced in [22-23].

This paper presents hybrid technology for optimization based on PGSA, Greedy and heuristic fuzzy, which improves the efficiency and provides opportunity of going with more constraints. The highlights of the proposed approach concerning previously published algorithms are that it evades heavy numerical computing, less time consuming, easy to adapt to any kind of radial distribution network such as single and multi feeder system, unambiguous definitions on reconfiguration procedure. The effectiveness of the proposed approach is demonstrated by employing the feeder switching operation scheme to 25 bus and modified IEEE-125 bus Distribution systems.

II. Problem Formulation

In this paper, the objective is to minimize the system power loss under a certain load pattern through network optimization while electrical and operational constraints are met, that is the process of altering the topological structures of distribution network by changing the open/close status of switches so as to minimize total system real power loss. The objective function of the problem is,

$$\min F = \min(P_{T1\,Loss}) \tag{1}$$

where,

P_{T1Loss} is the total real power loss of the system considering all the phases.

The apparent power transported by the branch must satisfy the branch's capacity. The voltage magnitude at each bus must be maintained within limits. These constraints are expressed as follows:

$$S_i \le S_{i,max} \tag{2}$$

$$V_{i,min} \le V_i \le V_{i,max} \tag{3}$$

where,

S_i, $S_{i,max}$ are apparent power and maximum capacity limit of branch i ;

V_i is voltage magnitude of bus i;

$V_{i,min}$ and $Vi_{,max}$ are minimum and maximum voltage limits of bus.

Furthermore, the radial structure of network must be maintained, and all loads must be served.

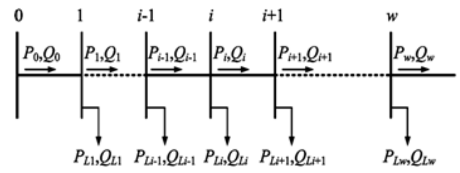

Fig. 1 Single-line diagram of a main feeder

A set of feeder line flow formulations is employed. Considering the single-line diagram in Figure 1, the following set of recursive equations is used to compute power flow:

$$P_{i+1} = P_i - P_{L+1} - R_{i\,i+1}\frac{P_i^2+Q_i^2}{V_i^2} \tag{4}$$

$$Q_{i+1} = Q_i - Q_{L+1} - X_{i\,i+1}\frac{P_i^2+Q_i^2}{V_i^2} - V_i^2\frac{y_i}{2} \tag{5}$$

$$V_{i+1}^2 = V_i^2 - 2(R_{i\,i+1}P_i + X_{i\,i+1}Q_i) + (R_{i\,i+1}^2 + X_{i\,i+1}^2)\frac{P_i^2+Q_i^2}{V_i^2} \tag{6}$$

where,

P_i and Q_i are the real and reactive powers that flow out of bus i;

PL_i and QL_i are the real and reactive load powers in bus i

The resistance and reactance of the line section between buses i and i+1 are denoted by $R_{i,i+1}$ and $X_{i,i+1}$ respectively.

$\frac{y_i}{2}$ is the shunt capacitor connected at bus i

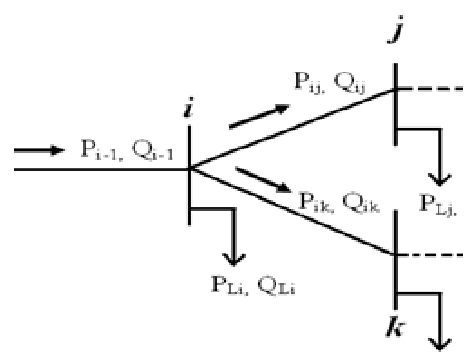

Fig. 2 Single line diagram of a node with two sub feeders

In case of a node with two or more sub feeders as shown in Figure 2, the load flow equations will reflect bus powers including branch powers as given in equations (7) and (8).

$$P_{i-1} = P_{Li} + P_{ij} + P_{ik} \tag{7}$$

$$Q_{i-1} = Q_{Li} + Q_{ij} + Q_{ik} \tag{8}$$

The power loss $P_{Loss(i,i+1)}$ of the line section that connects buses i and i+1 is,

$$P_{Loss}(i,i+1) = R_{i,i+1}\frac{P_i^2+Q_i^2}{V_i^2} \tag{9}$$

The power loss PF,Loss of the feeder may be determined by summing the losses of all line sections of the feeder, given by,

$$P_{F,Loss} = \sum P_{Loss}(i,i+1) \qquad (10)$$

The total system power loss $P_{T,Loss}$ is the sum of power losses of all feeders in the system. In the model, the control variables are the states of all switches in the system. The minimization of total system real power loss is obtained by altering the open/closed status of switches.

III. Proposed Technique

A. Search Space Reduction Through PGSA

The PGSA, which characterizes the growth mechanism of plant phototropism, is a bionic random algorithm. 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. The developed model simulates the growth process of a plant, which rapidly grows towards the light source and reaches global optimum solution. The concept of PGSA has been introduced by Wang and Cheng [19].

1. Decision Variables

In distribution network optimization, the switch is usually selected as the decision variable. It can be assigned either a value 0 (zero) or 1, which means open switch or closed switch respectively. Two problems exist during selection of switches, i) the number of possible network states grows exponentially with the number of switches, making the exhaustive search techniques totally unsuitable for the large scale problem; ii) a lot of unfeasible solutions will appear in the iterative procedure, which dramatically decreases the efficiency of calculation and sometimes may not obtain the optimal solution.

Therefore, more sophisticated techniques are required for the selection of decision variable. In a distribution system, 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 open switch for each independent loop so that the system active power loss can be minimized. So, we can employ independent loops rather than switches as decision variables, which can greatly reduce the dimension of the variables in the solved model and lead to a marked decrease of unfeasible solutions in the iterative procedure.

The basic procedure for designing the new decision variable is:

i. Radial distribution system is constructed with open and closed switches.
ii. The open switch of the nth loop is closed to form nth independent loop.
iii. It is assumed that the decision variable of loop n as L_n, and the switches are numbered in loop n using consecutive integers, the numbers of all switches in loop n constitute the possible solution set of L_n.

2. Switch State

The dimension of decision variables is greatly decreased, when independent loops are taken as decision variables. However, it cannot avoid the unfeasible solutions in the iterative procedure. The switches are described in four states so as to reduce the chances of unfeasible solutions in the iterative procedure and to further improve the efficiency of calculation.

i. Open state: a switch is open in a feasible solution.
ii. Closed state: a switch is closed in a feasible solution.
iii. Permanent closed state: a switch is closed in all feasible solutions.
iv. Temporary closed state: switches that have been considered in an earlier loop should be treated as closed switch for the loop under considerations.

After the depiction of the states of all switches, the permanently closed switches can be eliminated from the possible solution sets of the decision variables. Similarly we can monetarily delete the temporarily closed switches.

PGSA reduces the number of control variables by means of selecting individual loops as control variables rather than selecting individual switches. With the introduction of switch state selection by PGSA, unnecessary selection of few switches for optimization also has been avoided. Further the radiality constraint is very well handled within PGSA.

B. Searching through Greedy

For the searching process, loop sequencing has been considered as the most important. The distribution system with ‘n’ loops will produce n! possible loop sequences. The random/incorrect selection of loop sequence on occasion ends with local optimum. To make sure global optimum, in this paper greedy algorithm has been incorporated for identifying the best loop sequence.

As per the heuristic exchange rule (Kun-Yuan Huang and Hong-Chan Chin, 2002) for growth points searching, the loss change resulting from switch exchange between Feeder-I and Feeder-II of the system is given by,

$$\Delta P=2I(x)(E_m-E_n)+R_{loop}[I(x)]^2 \qquad (11)$$

where ΔP is the power loss reduction/increase when it is negative/positive; I(x) is the current distribution along the shortest path; x is the distance from the opened switch to the tie bus; Em is the terminal bus voltage of the Feeder-I before the load transfer; En is the terminal bus voltage of the Feeder-II before the load transfer and Rloop is the series resistance of the path connecting the two substation buses of Feeder-I and Feeder-II. Due to the quadratic nature of ΔP, the optimal distance current $I(x_{opt})$ can be shown and described as follows,

$$I(x_{opt}) = \frac{(E_m - E_n)}{R_{loop}} \tag{12}$$

Therefore the minimum power loss can be obtained by substituting equation (12) in equation (11). It can be established as follows,

$$\Delta P_{min} = \frac{(E_m - E_n)^2}{R_{loop}} \tag{13}$$

From the equation (13), it is clear that larger the value of $I(x_{opt})$ will yield the greatest loss reduction among the candidates. Therefore, for reconfiguration the loops can be sequenced in the decreasing order of $I(x_{opt})$ of each loop.

For the reconfiguration problem, the greedy choice properties has been made as, (i) Candidate set, set of loops $\{L_1, L_2, L_3, L_4, L_5\}$ in RDS referring Fig. 2; (ii) Selection function, Sequencing loops in decreasing order of Optimum Transferable Current (Iotc) of each loop; (iii) Feasibility function, Function which checks existence of loops in network and existence of switches in each loop; (iv) Objective function, Traverse all the loops of network one by one in sequence; (v) Solution function, Terminate process after some iteration or condition.

C. Heuristic Fuzzy

In order to address the power flow constraints along with power loss, heuristic fuzzy has been incorporated with PGSA and Greedy. In fuzzy domain, each parameter is associated with a membership function. There are three fuzzy-set models developed for optimization. They are responsible for restricting any configuration from bus voltage deviation, branch current deviation and increase in real power loss.

1. Fuzzy-set Model of the Bus Voltage Deviations

The voltage at the buses must be maintained within the permissible limits for each new configuration. It is defined as,

$V_{min} < V_{new,i} < V_{max}$ for i=1,2,3,…….n ;

where,

n is the total number of buses present in the RDS

$V_{new,i}$ is i[th] bus new configuration voltage

V_{min}=0.9 pu and V_{max}=1pu have been considered

The new configurations bus voltages are compared with the voltage limit. The voltage at the buses has been obtained from radial load flow for each new configuration. Moreover, the amount of the $V_{new,i}$ resulting from any branch exchange can be estimated as 'very close', 'close' or 'not close' to the V_{min}. Therefore, the linguistic terms can be formulated as a membership function by the fuzzy notation. The membership function can be expressed as follows,

$$\mu_{v,n} = \begin{cases} 1 & for\ \Delta V_n = 0 \\ 1 - \frac{\Delta V_n}{\Delta V_{min}} & for\ \Delta V_n > 0 \ \ \&\&\ V_{new,n} < V_{max} \\ 0 & for\ otherwise \end{cases} \tag{14}$$

where,

$\Delta V_n = V_{new,n} - V_{min}$

$V_{new,n}$ is the system voltage at the nth bus after reconfiguration.

The minimum amongst the membership values of voltage of all the bus in the system is obtained after reconfiguration.

$$\mu_v = \min\{\mu_{v},1, \mu_{v,2}........ \mu_{v,n}\} \tag{15}$$

2. Fuzzy-set Model of the Branch Current Loading

The main purpose of this membership function is to determine the branch current loading during each new configuration. Initially, all the branches current capacity are defined as $I_{set,i}$; where, i=1,2,3….n; n is the total number of branches in the RDS. During each new configuration the new value of branch currents are received through Radial Load Flow (RLF) and defined as I_i; where i=1, 2, 3…n; n is the total number of branches.

The small difference between $I_{set,i}$ and Ii are estimated and deviation of $I_{set,i}$ with I_i set as 'very close','close' or 'not close'. The membership function of the n[th] branch $\mu_{B,n}$, can be defined as,

$$\mu_{B,n} = \begin{cases} 1 & for\ \ \Delta I_n = 0 \\ 1 + \frac{\Delta I_n}{I_{set,n}} & for\ \ \Delta I_n < 0 \\ 0 & for\ \ otherwise \end{cases} \tag{16}$$

where,

$\Delta I_n = I_n - I_{set,n}$

The membership function of all the branches can be similarly expressed as equation (18). A large current variation ΔI_n, produce a small value of the membership function $\mu_{B,n}$ and vice versa.

The branch loading level of the selected switch operation can further be defined when all the branches membership values are determined. It can be expressed as follows,

$$\mu_B = \min[\mu_{B,1}, \mu_{B,2},.... \mu_{B,n}] \tag{17}$$

where, μ_B is the membership value after switching.

3. Fuzzy-set Model of the Real Power Loss

The new configurations power loss (P_{nloss}) close to the previous configuration loss (P_{tloss}) to be identified for the objective of minimizing the system power loss. The power loss of the system has been obtained from RLF for each new configuration. Moreover, the amount of the P_{nloss} resulting from any branch exchange can be estimated as 'very close, 'close' or 'not close' to the P_{tloss}.

Therefore, the linguistic terms can be formulated as a membership function by the fuzzy notation. The proposed membership function μ_p has been depicted using equation (18). A small difference between P_{nloss} and P_{tloss} possesses a larger membership value. The membership function can be expressed as follows,

$$\mu_p = \begin{cases} 1 & for \quad \Delta P = 0 \\ 1 + \dfrac{\Delta P}{P_{tloss}} & for \quad \Delta P < 0 \\ 0 & for \quad otherwise \end{cases} \qquad (18)$$

where, $\Delta P = P_{nloss} - P_{tloss}$; P_{tloss} is the system power loss before switching.

The purpose of the feeder reconfiguration can be achieved by the decision fuzzy set D, which is derived from the intersection of the three membership functions μ_V, μ_B and μ_P. However, the optimal decision is the highest membership value of μ_D. Thus, an optimal decision fuzzy set D can be designated as follows,

$$\mu_D = \max\{\min[\mu_V, \mu_B, \mu_P]\} \qquad (19)$$

The complete flow of operation for reconfiguration through the co-ordination of PGSA and SaHDE has been revealed by the flowcharts shown in Figure 3.

IV. Simulation Results

The effectiveness of the algorithm has been validated through two test distribution systems; Test System I and Test System II.

A. Test System I

The test system I [22] is an unbalanced distribution system with base of 4.16KV and 25 Nodes. The initial condition of the system is identified by the open switches S_{25}, S_{26}, S_{27}; the closed switches S_1 to S_{24}. The corresponding power loss is 450.38kW. As per the PGSA, decision variables are designed for the Test System I. As per the proposed approach all the switches of the loops are considered as closed. Test System I with decision variables is shown in the Figure 4.

The possible solution sets are,

$$\left.\begin{array}{l} L_1 = \{S_8, S_9, S_{11}, S_{17}, S_{26}\} \\ L_2 = \{S_4, S_5, S_6, S_{20}, S_{22}, S_{27}\} \\ L_3 = \{S_2, S_3, S_4, S_7, S_9, S_{10}, S_{11}, S_{13}, S_{14}, S_{15}, S_{17}, S_{23}, S_{24}, S_{25}, S_{26}\} \end{array}\right\} \qquad (20)$$

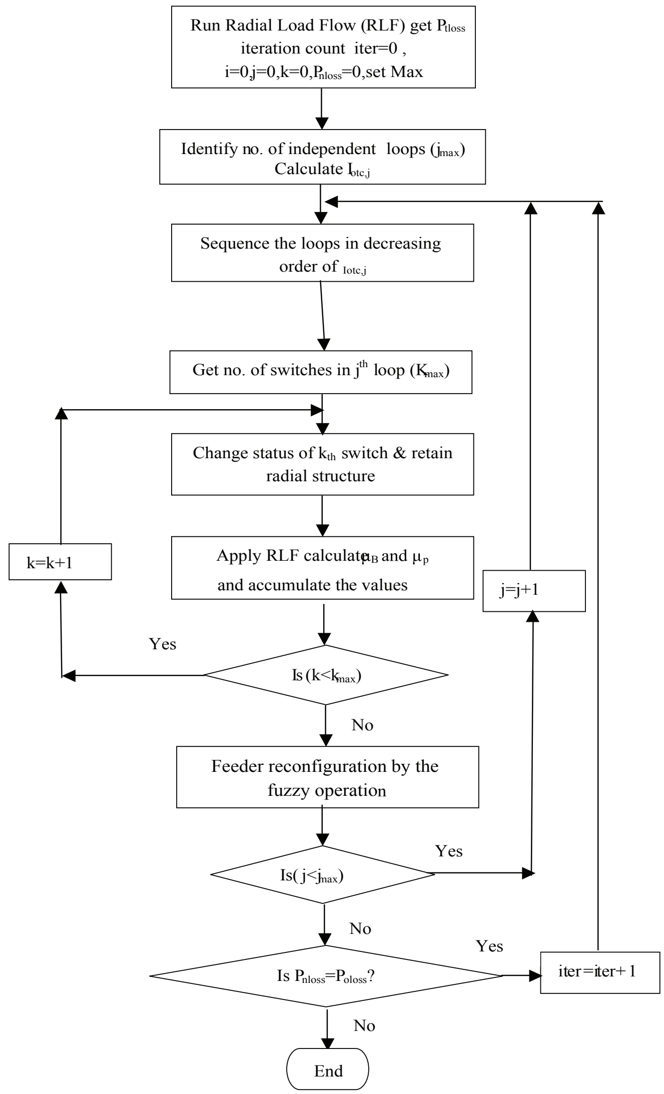

Fig. 3 Radial Distribution System Reconfiguration through Hybrid Technique

After describing the switches in four states, the chance for the unfeasible solutions in the iterative procedure have been eliminated. By closing some switches permanently closed, the search space was reduced as follows,

$$L_3 = \{S_4, S_7, S_9, S_{10}, S_{11}, S_{13}, S_{14}, S_{15}, S_{17}, S_{23}, S_{24}, S_{25}, S_{26}\} \qquad (21)$$

Then the inclusion of the concept of temporary closed state avoids finding the unfeasible solutions due to the interrelation of some switches.

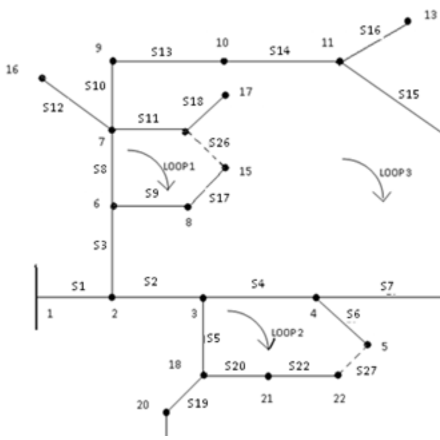

Fig. 4 The 25-bus unbalanced distribution system with loop numbers (Test System I) [22]

As a result, the possible solution sets shown in equation (20) and (21) were reduced. The search space reduced to,

$$\left.\begin{array}{l} L_1 = \{S_8, S_9, S_{11}, S_{17}, S_{26}\} \\ L_2 = \{S_4, S_5, S_6, S_{20}, S_{22}, S_{27}\} \\ L_3 = \{S_7, S_{10}, S_{13}, S_{14}, S_{15}, S_{23}, S_{24}, S_{25}\} \end{array}\right\} \quad (22)$$

From the above equation, it is clear that the Test system 1 has three variables (L_1, L_2, and L_3). The I_{otc} of loops are calculated as per equation (12). The values of $I_{otc,i}$ [for i ε 1-3] are 28.15A, 23.98A and 58.20A respectively. As per the greedy algorithm, the loop sequence has been made from the largest I_{otc} to smallest I_{otc}. It is identified that I_{otc} value of loop 3 is largest. Therefore, searching begins from third loop. Search over RDS starts from L_1 which yields 5 different combinations of open/close pair. The membership values of the switching operations significant to the different combinations are calculated. According to the min-max imperative new and better configuration has been arrived. The same process has been repeated for the fixed number of iterations. The loss has been reduced to 400.47kW from its initial configuration loss. The identified switches to be opened are S_{15}, S_{17} and S_{22}. The final configuration bus voltages and branch currents are maintained within the limit.

The results obtained through proposed methodology have been compared with other technologies proposed earlier for reconfiguration in Table II for Test system I. The proposed algorithm obtains the global optimum within 3.21sec. while PGSA takes 110 sec. for Test System I.

Table I Simulation results of Test system I

Items	Initial state (normal condition)	Proposed method (PGSA-Greedy-Fuzzy)	Wang and Cheng (2008)	Goswami and Basu (1992)	Ying-Yi and Saw-Yu (2006)
Loss (kW)	450.38	400.47	400.47	410.22	410.22
Time (sec.)	-	3.21	110.23	420.22	386.34

B. Test System II

The IEEE 123 node system shown in Figure 5, is an unbalanced distribution system with base kV of 4.16 kV and base MVA of 100 MVA. It is characterized by overhead and underground line segments, four step- type voltage regulator, and shunt capacitors and switching to provide alternate paths of power flow. The initial loading at the phases a, b and c are 331.28A, 207.86A and 313.53A respectively. It consists of 125 lines and 2 loops with 26 and 9 switches in respective loops. For the loops, solution sets are named sequentially from L1 to L2. As per the PGSA, decision variables are designed for the system shown in Figure 5. The maximum current capacity of the branches is 400A. The bus voltage limits are fixed as Vmin=0.9 pu and Vmax=1.02 pu. After applying the proposed methodology, the real power loss is reduced from 87.56 kW to 64.73. kW. The feeder currents and bus voltages are maintained within the limit. The final configuration branch currents and bus voltages are shown in Figure 6 and Figure 7. The identified switches to be opened at the final configuration are S_2 and S_3.

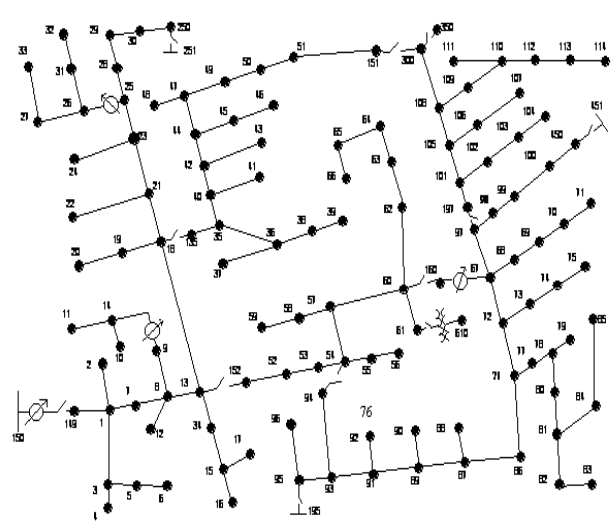

Fig. 5 IEEE-125 bus unbalanced distribution system (Test System II)

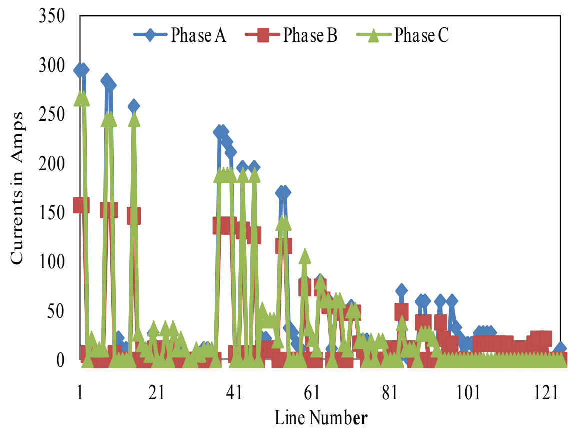

Fig. 6 Final configuration branch currents of Test System II

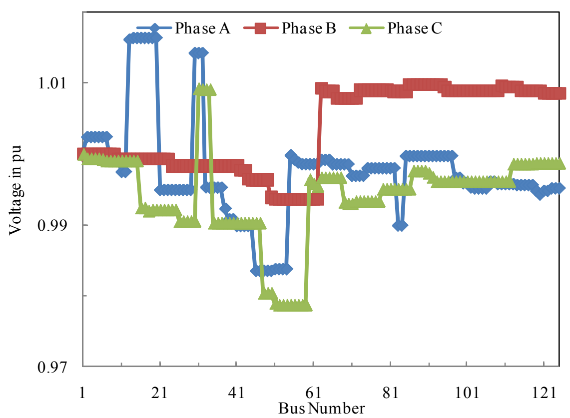

Fig. 7 Final configuration bus voltages of Test System II

V. Conclusion

An efficient approach that employs hybrid technology as optimal means has been presented for the reconfiguration of unbalanced radial distribution system, where the objective is loss reduction and subjected under constraints like branch currents limit violation and bus voltages limit violation. The results have shown that reconfiguration has been attained with multi constraints of radial distribution system. Thus the introduction of PGSA reduce dimension of variables. The incorporation of Greedy technique will speed up the searching process. With the inclusion of heuristic fuzzy constraints were handled simultaneously along with objective.

The results obtained with the present approach, when compared with the previous methods proposed by the authors will show that the introduction of the proposed algorithm has contributed to reduce the number of power flows and has incorporated the network constraints. Hence with the effective introduction of the proposed reconfiguration algorithm, loss reduction was done subjected under constraints such as bus voltage limit and branch current limit. This can be further improved to address minimization of phase currents deviation in future.

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