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Hybrid Opposition based Differential Evolution algorithm for Distribution System Reconfiguration

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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. Utilities are constantly looking for newer technologies that enhance power delivery performance. One of the several important issues is the control of power loss; it has been controlled through reconfiguration. Distribution system reconfiguration helps to operate the system at minimum cost and at the same time improves the system reliability and security. Under normal operating conditions, optimization of network configuration 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. In this paper, a combination of Opposition based Differential Evolution Algorithm (ODE) and Plant Growth Simulation Algorithm (PGSA) has been introduced to solve the optimization problem. The optimization approach based on PGSA provides a detailed description on switch states and ODE improves the efficiency of optimization by reducing the number of load flow executions. The effectiveness of the proposed approach is demonstrated by employing the feeder switching operation scheme to IEEE-33 bus and 83-bus Taiwan power distribution systems. The proposed algorithm reduces the transmission loss while satisfying the line loading and bus voltage limit constraints.

Key words: Distribution network reconfiguration, PGSA, Differential Evolution, Loss reduction, Switching operation

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. Restoration is the process of providing service to the out-of-service area of the system under single or multiple fault conditions. Several methodologies have been adapted for service restoration. Due to the radial nature of the distribution network and the presence of switches, service restoration can be done through reconfiguration. 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*.(1988) conducted the early work on feeder reconfiguration for loss reduction. In Baran and Wu (1989) defined the problem of loss reduction and load balancing as an integer programming problem. Aoki *et al*. (1998) developed a method for load transfer in which the load indices were used for load balancing. In Shirmohammadi and Hong (1989), 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 (Goswami *et al*., 1992, Ying-Yi *et al*., 2006 and Whei-Min *et al*.,1998) expert systems (Kim, H *et al*.,1993, Salazar,H *et al*.,2006, Liu, C.C *et al*.,1988 and Cheng, H.C *et al*.,1994) and optimization algorithm Venkatesh, B *et al*. (2004) have been proposed in recent years. In Huang and Chin (2002), the solution procedures employing heuristic rules and fuzzy multi-objective approach are developed to solve the network reconfiguration problem.

In Song,Y.H *et al*. (1997) and Delbem *et al*. (2005), 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

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Differential Evolution (HDE) has also been employed for network reconfiguration Su and Lee (2003). 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 Qin and Suganthan (2005).

The plant growth simulation algorithm (PGSA) is employed to optimize the network configuration of the distribution system (Wang and Cheng, 2008). 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.

Even though, the above methods gained encouraging results, the speed for searching optimal configuration was moderate. The concept of Opposition-based Differential Evolution (ODE) for the optimization problems was presented in Rahnamayan *et al*. (2008). ODE has the improved and effective searching characteristics compared with other evolutionary algorithms. In order to utilize the advantages of PGSA and ODE, and to overcome the aforementioned disadvantages, a hybrid technique based on PGSA and ODE has been proposed in this paper. The advantages of the proposed approach concerning previously published algorithms are that it evades heavy numerical computing, the solution procedure is very simple, easy to adapt to any kind of radial distribution network and unambiguous definitions on reconfiguration procedure. The effectiveness of the proposed approach is demonstrated by employing the feeder switching operation scheme to IEEE-33 bus and 83-bus Taiwan Power Distribution systems.

Problem Formulation:

Network reconfiguration 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. In this paper, the objective is to minimize the system power loss under a certain load pattern through network reconfiguration while electrical and operational constraints are met. The objective function of the problem is,

$$\text{Minimize } P_{loss} = \sum_{j=1}^{nl} R_j \frac{P_j^2 + Q_j^2}{V_j^2} \tag{1}$$

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:

$$S_j \le S_{j,max} \quad ; \text{for } j \in 1 \text{ to } nl \tag{2}$$

$$V_{i,min} \le V_i \le V_{i,max} \; ; \text{for } i \in 1 \text{ to } nb \tag{3}$$

where,
R_j is resistance of the j^{th} branch
nl is total number of branches present in the network.
nb is total number of buses present in the network.
Pi and Qi are the real and reactive powers that flow out of bus i;
S_j, $S_{j,max}$ are apparent power and maximum capacity limit of j^{th} branch;
V_i is voltage magnitude of bus i;
$V_{i,min}$ and $V_{i,max}$ are minimum and maximum voltage limits of i^{th} bus.
Furthermore, the radial structure of network must be maintained and all loads must be served.

The power loss of the distribution network has been calculated through radial power flow. A single-line diagram of sample power distribution system served from single feeder is shown in Figure 1.

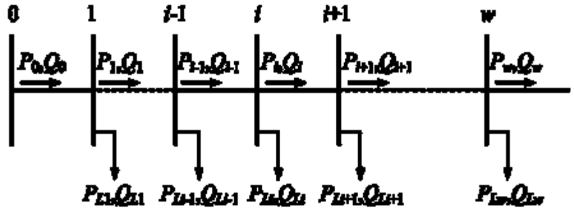

Fig. 1: Single-line diagram of a main feeder

The following set of recursive equations is used to compute power flow,

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

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

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

Where,

P_{Li} and Q_{Li} 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

Proposed Pgsa-Ode Algorithm:

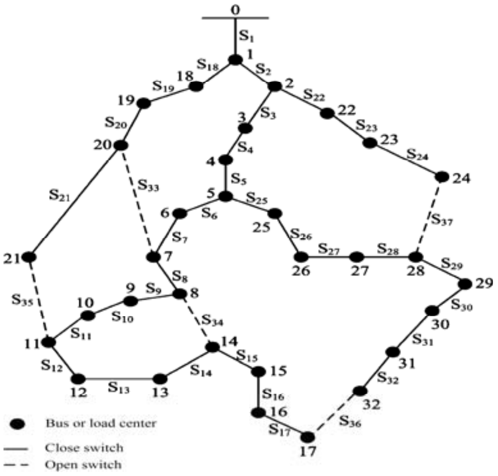

Fig. 2: IEEE 33-bus Test System

The Figure 2 shows the IEEE 33 bus distribution system. It consists of 33 buses, and 32 normally closed switches and five normally opened switches (Rahnamayan *et al*, 2008). The power loss of the test system can be minimized by reconfiguration, i.e., by identifying the optimal combination of tie switches. For reconfiguration, switches present in the distribution network are considered as variables. For instance, closing of S_{33}, S_{34}, S_{35}, S_{36} and S_{37} and opening of swithes S_6, S_{11}, S_{14}, S_{27}, and S_{32} will yield the new confiiguation with new loss. Based on the new configuration loss, the initial configuration may or may not be updated. The similar searching for optimal configuration has to be carried out amongst numerous combinations of tie switches. As per this approach, the number of possible configurations grows exponentially with the number of switches. Also there is a possibility of occurance of unfeasible solutions during searching practice, which dramatically decreases the efficiency of calculation, and sometimes the procedure may not yield optimal solution.

3.1 Variable selection through PGSA:

In order to reduce the dimension of the variables, Plant Growth Simulation Algorithm (PGSA) has been employed in this paper (Rahnamayan *et al*, 2008). In a distribution system, the number of independent loops is the same as the number of tie switches. PGSA handles independent loops rather than switches as decision variables, which greatly reduces the dimension of the variables in the solved model and leads to a marked decrease of unfeasible solutions in the iterative procedure. Therefore, the problem of network reconfiguration is identical to the problem of selection of an appropriate tie switch for each independent loop so that the system power loss can be minimized.

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.

3.1.1 Decision Variables:

The 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 n^{th} loop is closed to form n^{th} 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.

3.1.2 Switch States:

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. Thus with the influence of PGSA, the complexity has been greatly reduced. For searching for the optimal solution ODE has been introduced.

3.2 Search Strategy through Opposition based Differential Evolution (ODE):

For the network reconfiguration, the individual loops are selected as variables and ODE is used to identify the open switches in each loop in order to minimize the power loss. For instance, if the system has ‘n’ identified loops then ODE should have ‘n’ variables. The pseudocode of the ODE algorithm has been given below,

```
Set Mutation (F), Crossover Rate (CR), maximal iteration number (Nmax), variable size (V), population size (P), count=0

    // Initial Population
    Z(P,V)=random()
    // Calculate the fitness value for all population
    Obj(Z(P))

    //Opposite population
    Zopp(P,V)= Opposite (Z(P,V))

    //Calculate the fitness value for all population
    Obj(Zopp(P))

    //Find the best individual
    Zbest(P)=best(Obj(Z(P)),Obj(Zopp(P)))

    //Execute the following steps for fixed number of iterations(Nmax) till (count<Nmax)

    {
    //Mutation operation for the Zbest
    Zplus(P,V)=Zbest(P,V)+F*(Zbest(P,i)-Zbest(P,j))
    // where i and j refers integers (< V) and i≠j
```

```
// Crossover operation for the Zbest
Zplus(P,V)=Zbest(P,V),     if(random()>CR)
 // Process to identify best individuals

if(Obj(Z(P))>Obj(Zplus(P)))
Z(P,V)=Zplus(P,V)

//Opposition based Generation Jumping and selection  best individual for next iteration
Zopp(P,V)=Opposite(Z(P,V))

Z(P,V)=best(Obj(Z(P)),Obj(Zopp(P)))
//increment the iteration count
count=count+1;
}
```

3.3. Computational Flowchart For Reconfiguration:

The complete flow of operation for reconfiguration and restoration through the co-ordination of PGSA andODE has been revealed by the flowcharts shown in Figure 3. The proposed algorithm is implemented through Java programming to reduce software couplings and to achieve software reusability.

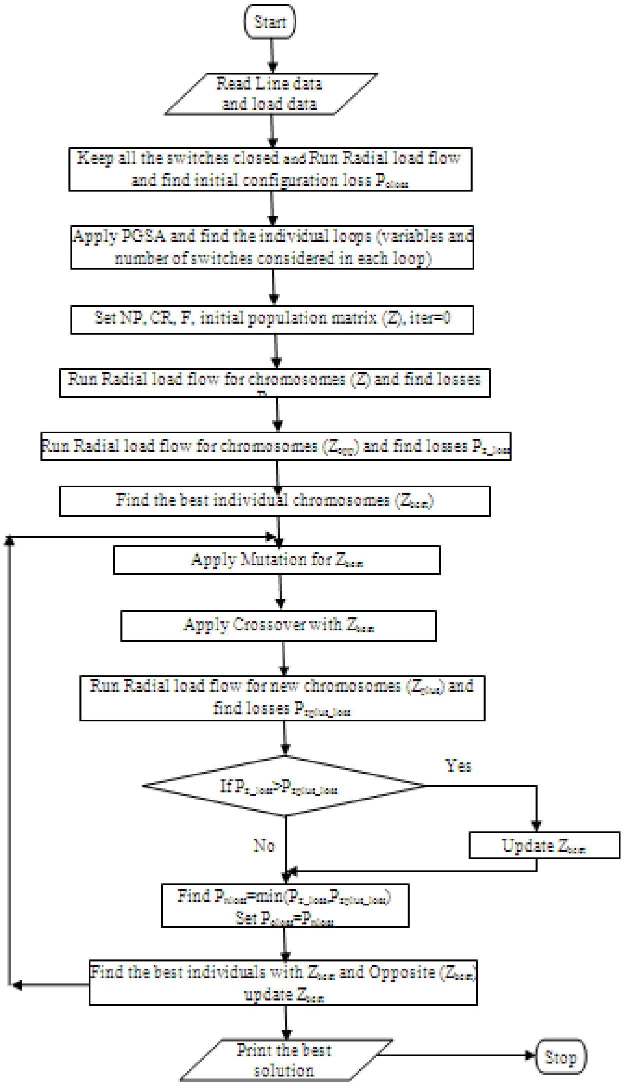

Fig. 3: Flowchart for reconfiguration through hybrid PGSA-ODE under normal conditions

Simulation Results:

The effectiveness of the algorithm has been validated through two test distribution systems; Test System I and Test System II as described in Wang and Cheng (2008). In this case, reconfiguration was carried out by considering both the systems working under normal conditions, i.e., all the branches are being loaded without violating its limits, voltage at the buses is within limit and the phases are balanced.

Test System I:

The proposed scheme has been tested on 33 bus radial distribution system, which has 5 normally opened switches, 32 normally closed switches with 33 buses and it is assumed as balanced three-phase with 12.66kV. The corresponding power loss is 202.7kW. As per the PGSA, decision variables are designed for the Test system I which is shown in Figure 4.

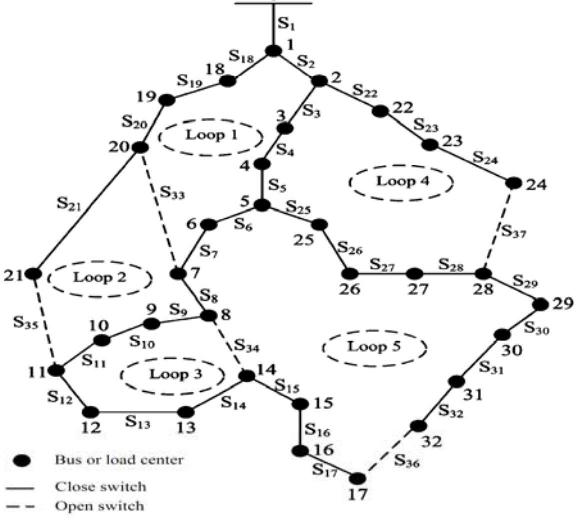

Fig. 4: Test System I with state variable sketch

The description of the switch states is identified as,

i. The open switches are S_{33}, S_{34}, S_{35}, S_{36}, and S_{37};

ii. The closed switches are S_1 to S_{32};

The possible solution sets as per PGSA algorithm for test system I are given by,

$$\left.\begin{aligned}
L_1 &= \{S_2, S_3, S_4, S_5, S_6, S_7, S_{33}, S_{20}, S_{19},\ S_{18}\}\\
L_2 &= \{S_8, S_9, S_{10}, S_{11}, S_{35}, S_{21}, S_{33}\}\\
L_3 &= \{S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{34}\}\\
L_4 &= \{S_3, S_4, S_5, S_{25}, S_{26}, S_{27}, S_{28}, S_{37}, S_{22}, S_{23},\ S_{24}\}\\
L_5 &= \{S_6, S_7, S_8, S_{34}, S_{15}, S_{16}, S_{17}, S_{36}, S_{32}, S_{31}, S_{30}, S_{29}, S_{28}, S_{27}, S_{26}, S_{25}\}
\end{aligned}\right\} \tag{7}$$

Identification Of Permanently Closed Switches:

In order to maintain the radial structure, switches close to the source node should be permanently closed. The switches S_2, S_3 and S_{18} of L_1 are considered as permanently closed. Hence, they can be eliminated from the solution set. Similarly eliminating the permanently closed switches from other solution sets,

$$\left.\begin{aligned}
L_1 &= \{\ S_4, S_5, S_6, S_7, S_{33}, S_{20}, S_{19}\}\\
L_4 &= \{S_4, S_5, S_{25}, S_{26}, S_{27}, S_{28}, S_{37}, S_{23},\ S_{24}\}
\end{aligned}\right\} \tag{8}$$

Identification Of Temporary Closed State Switches:

Some switches, which belong to 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 test system 1, switches S_9, S_{10} and S_{11} belong to both loops 2 and 3, so they are interrelated. If the solution of L_2 is the switch S_9, then the solution of L_3 cannot be the switch S_{10} or S_{11}. In other words, the switches S_{10} and S_{11} must be temporarily closed while switch S_9 is in open state. Inclusion of the concept of temporary closed state avoids finding the unfeasible solution due to the interrelation of some switches.

As a result, the solution sets are,

$$\left.\begin{aligned} L_1 &= \{S_4, S_5, S_6, S_7, S_{20}, S_{19}, S_{33}\} \\ L_2 &= \{S_8, S_9, S_{10}, S_{11}, S_{21}, S_{35}\} \\ L_3 &= \{S_{12}, S_{13}, S_{14}, S_{34}\} \\ L_4 &= \{S_{25}, S_{26}, S_{27}, S_{28}, S_{23}, S_{24}, S_{37}\} \\ L_5 &= \{S_{15}, S_{16}, S_{17}, S_{32}, S_{31}, S_{30}, S_{29}, S_{36}\} \end{aligned}\right\} \tag{9}$$

From the above equation, it is clear that the Test system 1 has five variables (L_1, L_2, L_3, L_4 and L_5) and those variables have 7,6,4,7 and 8 number of switches respectively. For an instance for variable L_1, by the control strategy "DE/current-to-rand/1" the value generated is 3 then S_6 is the switch assumed as opened in the loop 1 and the same process is continued for the rest of the variables. The initial population and their respective losses were calculated and stored. With the initial values of F=0.8 and CR=0.6 searching was done for the fixed number of iterations. The loss has been reduced to 139.54kW from its initial configuration loss. The identified switches to be opened are S_7, S_9, S_{14}, S_{32} and S_{37}. The final configuration current at the branches and voltage at the buses are within the limits.

The results obtained through proposed methodology have been compared with other technologies proposed earlier for reconfiguration in Table 1 for Test system I. From the table it is realized that reconfiguration made through proposed algorithm receives global optimum.

Table 1: Simulation results of Test System I

Items	Initial state (Normal condition)	Proposed method (PGSA-ODE)	Goswami and Basu (1992)	Ying-Yi and Saw-Yu (2006)
Open switches	S_{33}, S_{34}, S_{35}, S_{36}, S_{37}	S_7, S_9, S_{14}, S_{32}, S_{37}	S_7, S_{10}, S_{14}, S_{32}, S_{37}	S_9, S_{28}, S_{33}, S_{34}, S_{36}
Loss (kW)	202.7	139.54	141.5	140.6

4.2 Test System II:

The proposed methodology has been applied next to the Test System II. The system is assumed balanced three-phase with 11.4 kV. It consists of 11 feeders, 83 normally closed switches, 13 normally open switches and 13 loops. For the loops, solution sets are named sequentially from L_1 to L_{13}. As per PGSA, the switch states are defined, as shown in Figure 5. The maximum current capacity of the branches is 600A. The bus voltage limits are fixed as V_{min}=0.9 pu and V_{max}=1.0 pu.

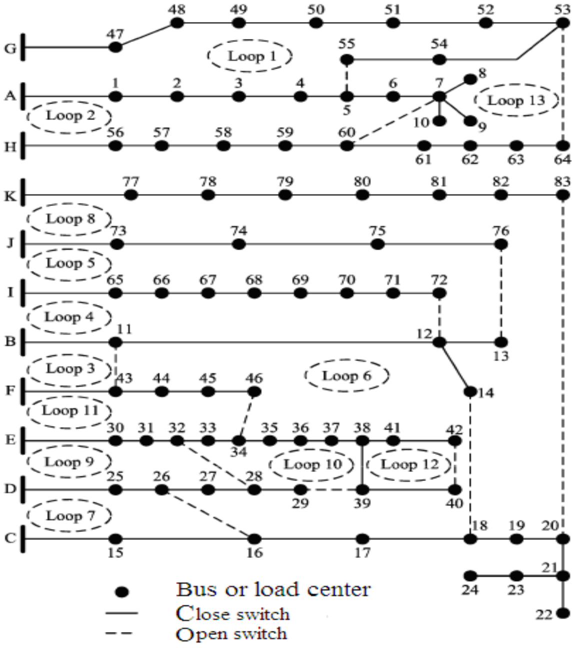

Fig. 5: Test System II with state variable sketch

After applying the proposed methodology, the system loss is reduced from 542.55 kW to 469.88 kW. The feeder currents are maintained under limit which is compared with the initial configuration feeder currents and it is tabulated in Table 2. The final configuration branch currents and bus voltages are maintained within the limit. The identified switches to be opened at the final configuration are S_7, S_{13}, S_{32}, S_{35}, S_{63}, S_{72}, S_{82}, S_{84}, S_{86}, S_{89}, S_{90}, S_{92}, and S_{95}. The final configuration current at the branches and voltage at the buses are within the limits.

The results obtained through proposed methodology have been compared with other technologies proposed earlier for reconfiguration in Table 3 for Test system II. From the tables, it is realized that reconfiguration made through proposed algorithm receives global optimum with minimum time consumption and has taken multiple constraints.

Table 2: Final configuration feeder currents under normal condition through hybrid PGSA-ODE

Sl. No.	Start Bus	End Bus	Initial configuration Current in Amps.	Final configuration Current in Amps.
1	0	1	388.7269	245.6431
2	0	11	296.1750	226.7297
3	0	15	396.7751	445.3161
5	0	25	245.9921	264.1416
6	0	30	429.5862	254.9461
7	0	43	118.8916	266.0495
8	0	47	293.2296	364.8648
9	0	56	162.1575	223.7966
10	0	65	308.3686	282.6937
11	0	73	167.6652	259.1616
12	0	77	404.9000	351.4395

Table 3: Simulation results of Test System II

Items	Initial state (Normal condition)	Proposed method (PGSA-ODE)	Wang and Cheng (2008)	Ying-Yi and Saw-Yu (2006)
Loss (kW)	531.99	469.88	469.88	469.88
CPU time (second)	-	1.44	113.25	303.66

Conclusion:

An efficient approach that employs hybrid technology as optimal means has been presented for the reconfiguration of 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 ODE increases the speed up the searching process. The proper use of PGSA and ODE improves the efficiency in terms of reduced number of load flow executions, reduced computational executions and removal of unfeasible solutions in the search space.

The results obtained with the present approach, when compared with the previous methods proposed by the authors will show that the introduction of the algorithm with hybrid PGSA-ODE 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 and can be applied to any large real radial distribution system supplied from both single and multi feeders.

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