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Optimization of Distribution System with hybrid Fuzzy and Opposition based Differential Evolution (FODE) Algorithm

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ABSTRACT

Power delivery performance of the distribution systems has to be enhanced with help of recent technologies. System efficiency can be improved by controlling power loss. The popular techniques adapted to control the power loss are Distribution system reconfiguration and optimal capacitor placement. This paper proposes a method to handle reconfiguration and capacitor placement simultaneously for the effective optimization. It utilizes Opposition based Differential Evolution (ODE) algorithm for efficient searching for the optimal solution. In order to consider the constraints along with the objective, heuristic Fuzzy has been integrated with ODE and the proposed technique is termed as FODE. The effectiveness of the proposed approach is demonstrated by employing the feeder switching operation scheme to 83-Bus Taiwan Power Company Distribution System The proposed algorithm reduces the transmission loss and improve the saving of cost while satisfying power flow constraints.

Keywords - Distribution network reconfiguration, Capacitor placement, Differential evolution, Loss reduction, Switching operation, Volt/Var control.

1. INTRODUCTION

Development of electrical power distribution system performance requires proper plans for increasing utilities efficiency, for instance, losses reduction. Different approaches are used to reduce losses such as optimal use of electrical equipment's optimal loading at the transformers, reconfiguration, and optimal capacitor placement, optimal placement of DG (Distributed Generation) and removal of harmonics. Amongst all, reconfiguration and capacitor placement are comparatively lesser operating cost. 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 feeder reconfiguration problem has been dealt 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. Developments in algorithm design techniques such as simulated annealing [5], heuristic fuzzy [6], Artificial Neural Network [7], population based evolutionary algorithms [8-9] provides much improvement in reconfiguration strategy. The plant growth simulation algorithm (PGSA) is employed to optimize the network configuration of the distribution system [10]. The PGSA provides a detailed description on switch state and decision variables, which greatly contracts the search space and hence reduces computation effort. In [11], harmony search algorithm has been proposed for reconfiguration.

As the nature of capacitor placement problem is complex combinatorial, different techniques have been followed by the authors in the past. The initial contribution was made by Schmill [12] using 2/3 rule for capacitor placement. Dynamic programming with assuming the capacitor sizes as discrete variables adapted by Duran [13]. The capacitor problem was viewed as a nonlinear problem by Grainger et al. [14], where variables were treated as continuous. Optimal capacitor placement was carried out through genetic algorithm by [15]. The number of locations was considered as the total variables for genetic algorithm. The micro genetic concepts involving enhanced genetic algorithm was proposed in [16]. The power flow constraints were handled through fuzzy logic concepts. Optimization procedure through particle swarm optimization principle was adapted in [17]. Optimization through plant growth simulation algorithm (PGSA) was first introduced for feeder reconfiguration in [12]. Later, the PGSA along with loss sensitivity factors was introduced [18] for optimal capacitor placement. Loss sensitivity factors were used to find the optimal location (i.e. identifying weak buses) of capacitor. PGSA was incorporated in order to find out the optimal sizing of the capacitors.

The optimization procedure combining both capacitor placement and reconfiguration was recently introduced. In [19], the ant colony optimization algorithm was introduced for the optimization. The combined usage of deterministic approach and heuristic technique for network reconfiguration and optimal capacitor placement for power-loss reduction and voltage profile improvement in distribution networks [20]. The improved reconfiguration method along with GA used for simultaneous reconfiguration and capacitor placement for distribution network optimization in [21].

In this paper, Opposition based Differential Evolution [22] algorithm has been presented for simultaneous handling of reconfiguration and optimal capacitor placement. Further, heuristic fuzzy has been incorporated to look at constraints with objective. The effectiveness of the proposed approach is demonstrated by employing the feeder switching operation scheme to 83-Bus Taiwan Power Company Distribution System.

2. PROBLEM FORMULATION

The main objective of the optimal capacitor placement is to minimize the total operating cost of the system by reducing the power loss subject to the constraints such as bus voltage ($|V_{min}| < |V_i| < |V_{max}|$), branch currents ($|I_{jl}| < |I_{max}|$) and radiality constraints. The mathematical equation relevant to the objective function of the problem is defined as,

$$F = Minimize(C) \quad (1)$$

Where, the term 'C' represents the total operating cost of the distribution system, it includes the cost for power loss and capacitor cost.

The single line diagram of the balanced distribution system shown in the Figure 1 used to describe the load flow calculations. In Figure 1, P_i and Q_i represents the real and reactive power flow between the sending and receiving end buses, P_{Li} and Q_{Li} denotes the real and reactive power loads. The line resistance and reactance are denoted as $R_{i,j}$ and $X_{i,j}$. $\frac{y_i}{2}$ is the total shunt admittance at bus i.

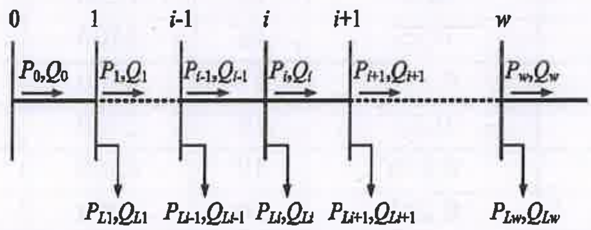

Fig.1 Single line diagram of a main feeder

The following set of equations are used to calculate the power flow,

The power loss $P_{F,Loss}$ of the feeder is determined by summing the losses of all line sections of the feeder and it is given by,

---

The total power loss cost (P_{cost}) has been calculated as,

$P_{cost}=P_{,loss} * K_p$; (3)

where K_p is the equivalent annual cost of power loss in $/(kW-year)

In general, the cost per KVAR varies with respect to their size. The available capacitor sizes and their cost were given in [19]. The total operating cost of the distribution system is given in equation (7).

$C= P_{cost}+ C_{q,cost}$ (4)

where,

$$C_{q,cost} = C_{q,fixed} + C_i^{annual} * Q_I \quad (5)$$

$C_{q,fixed}$ is the fixed cost for the capacitor placement $/year

C_i^{annual} is the annual cost for the capacitor installation in $/(KVAR-year)

Q_i is the reactive power in (KVAR), for capacitor sizing variables, the range for the variables and corresponding cost has been shown in Table 1 [18].

Table 1 Capacitor sizes and cost

Sl.No.	Q inkVAR	Capacitor cost in $/kVAR	Sl.No.	Q in Kvar	Capacitor cost in $/kVAR
1	150	0.5	15	2250	0.197
2	300	0.35	16	2400	0.17
3	450	0.253	17	2550	0.189
4	600	0.22	18	2700	0.187
5	750	0.276	19	2850	0.183
6	900	0.183	20	3000	0.18
7	1050	0.228	21	3150	0.195
8	1200	0.17	22	3300	0.174
9	1350	0.207	23	3450	0.188
10	1500	0.201	24	3600	0.17
11	1650	0.193	25	3750	0.183
12	1800	0.187	26	3900	0.182
13	1950	0.211	27	4050	0.179
14	2100	0.176			

3. SEARCH STRATEGY FOR CAPACITOR SIZING THROUGH ODE ALGORITHM

Opposition based differential algorithm is a recent evolutionary algorithm with enhanced features such as self acceleration, self migration and assured optimal search with least population size. The efficiency of the algorithm can be well proven by applying into complex and/or large problems. In this paper, the purpose of introduction of ODE is to find the optimal location for capacitor placement, optimal capacitor size and optimal configuration. The number of variables for ODE searching is the total of number of loops, number of locations and number of locations (for proper sizing). For instance, the system with 'x' loops and 'y' locations will require 'x+2y' ODE variables. The pseudo code of the ODE algorithm has been given below,

---

Set Mutation (F), Crossover Rate (CR), maximal iteration number (N_{max}), 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
Z_{opp}(P,V)= Opposite (Z(P,V))
//Calculate the fitness value for all population
Obj(Z_{opp}(P))
//Find the best individual
Z_{best}(P)=best(Obj(Z(P)),Obj(Z_{opp}(P)))
//Execute the following steps for fixed number of iterations(N_{max}) till (count<N_{max})
{
//Mutation operation for the Z_{best}
Z_{plus}(P,V)=Z_{best}(P,V)+F(Z_{best}(P,i)-Z_{best}(P,j))*
// where i and j refers integers (< V) and i≠j
// Crossover operation for the Z_{best}
Z_{plus}(P,V)=Z_{best}(P,V),   if(random()>CR)
// Process to identify best individuals
if(Obj(Z(P))>Obj(Z_{plus}(P)))
Z(P,V)=Z_{plus}(P,V)
//increment the iteration count
count=count+1;
}

---

4. FUZZY OPERATIONS FOR MULTI-OBJECTIVE OPTIMIZATION

The four objectives such as power loss minimization, total cost minimization, bus voltage deviation minimization and branch current deviation minimization are fuzzified and dealt by integrating them into a min-max imperative of fuzzy satisfaction objective function.

In the proposed method for system optimization, the terms μ_{Fj}, μ_{Cj}, μ_{Vj} and μ_{Ij} indicate the membership function for power loss reduction, total cost reduction, bus voltage deviation and branch current deviation respectively of the j^{th} configuration. The higher membership value implies a greater satisfaction with the solution. The membership function consists of a lower and upper bound value together with a strictly monotonically decreasing and continuous function.

4.1 Fuzzy-set model for power loss minimization

The deviation of power loss of the new configuration (P_{nloss}) to the previous configuration loss (P_{oloss}) is to be identified with the objective of minimizing the system power loss.

$$\mu_{Fj} = \begin{cases} \dfrac{X_{max} - X_j}{X_{max} - X_{min}} & \text{for } X_{min} < X_j < X_{max} \\ 1.0 & \text{for } X_j \le X_{max} \\ 0.0 & \text{for } X_j \ge X_{max} \end{cases} \tag{6}$$

where, $X_j = P_{nloss}/P_{tloss}$ In the present work, X_{min}=0.5 and X_{max}=1.0 have been considered.

4.2 Fuzzy-set model for Total cost minimization

The deviation of total cost of the new configuration (C_{new}) to the previous configuration total cost (C_{old}) is to be identified with the objective of minimizing the total cost. The membership function at j^{th} configuration can be expressed as follows,

$$\mu_{Cj} = \begin{cases} \dfrac{Y_{max} - Y_j}{Y_{max} - Y_{min}} & \text{for } Y_{min} < Y_j < Y_{max} \\ 1.0 & \text{for } Y_j \le Y_{min} \\ 0.0 & \text{for } Y_j \ge Y_{max} \end{cases} \tag{7}$$

Where, $Y_j = C_{new}/C_{old}$. In the present work, Y_{min}=0.1 and Y_{max}=0.5 have been considered.

4.3 Fuzzy-set model of the bus voltage deviations

This membership function has been introduced to maintain the deviation of nodes voltage as minimum. The membership function at j^{th} configuration can be expressed as (8). The membership function for nodes voltage deviation is as follows.

$$\mu_{Vj} = \begin{cases} \dfrac{Z_{max} - Z_j}{Z_{max} - Z_{min}} & \text{for } Z_{min} < Z_j < Z_{max} \\ 1.0 & \text{for } Z_j \leq Z_{min} \\ 0.0 & \text{for } Z_j \geq Z_{max} \end{cases} \qquad (8)$$

In the present work, Z_{min}=0.05 and Z_{max}=0.1 have been considered.

4.4 Fuzzy-Set model of the branch current deviations

This membership function has been introduced to maintain the deviation of branch current as minimum. The membership function at j^{th} configuration can be expressed as (9).

$$\mu_{Ij} = \begin{cases} \dfrac{I_{max} - I_j}{I_{max} - I_{min}} & \text{for } I_{min} < I_j < I_{max} \\ 1.0 & \text{for } I_j \leq I_{min} \\ 0.0 & \text{for } I_j \geq I_{max} \end{cases} \qquad (9)$$

In the present work, I_{min}=0.05 and I_{max}=0.1 have been considered.

The purpose of the feeder reconfiguration can be achieved by the decision fuzzy set D, which is derived from the intersection of the four membership functions μ_{Fj}, μ_{Cj}, μ_{Vj} and μ_{Ij}. However, the optimal decision is the highest membership value of μ_D. Thus, an optimal decision fuzzy set D can be designated as follows,

$$\mu_D = \max\{\min[\mu_{Fi}, \mu_{Cj}, \mu_{Vj}, \mu_{Ij}]\} \qquad (10)$$

where,

i=1,2,….np ;

For optimal searching, hybrid Fuzzy-Opposition based Differential Evolution (FODE) has been practiced by considering Equation (10) as fitness function.

5. SIMULATION RESULTS

The effectiveness of the algorithm has been validated through 83-Bus Taiwan Power Company Distribution System shown in figure 2. The system is a balanced three-phase system with 11.4 kV. It consists of 11 feeders, 83 normally closed switches and 13 normally open switches. It's the branch capacity is 600A and voltage limits are V_{min}=0.9 pu and V_{max}=1.0 pu.

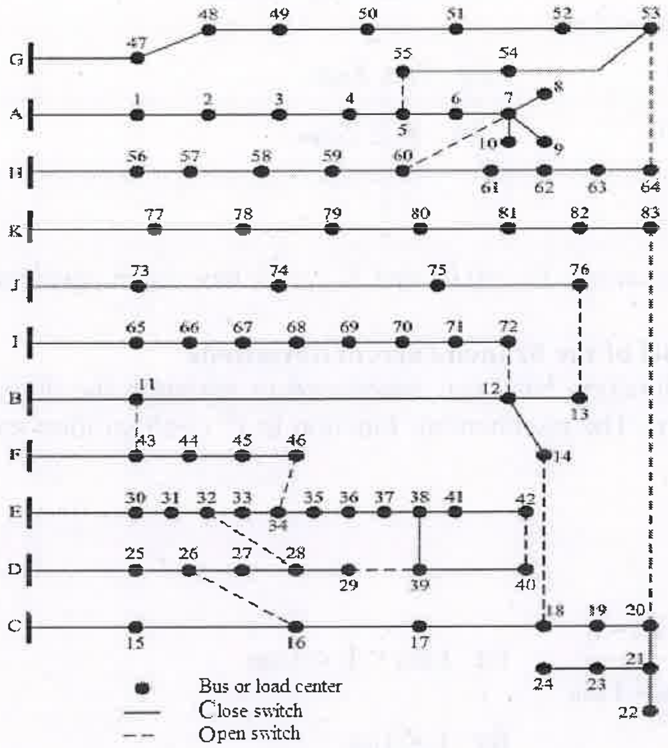

Fig. 2 83-bus RDS with state variable sketch

The optimization process starts with identifying the total variables, such as number of locations for capacitor placement and loops present in the distribution system. This system has total number of variables required for ODE searching is 19 (i.e. 13 for loops, 3 for capacitor locations and 3 for capacitor sizing). The proposed algorithm has been programmed using Java programming.

5.1 Variable Size

Variable size for the 13 loops is decided by the status of the switches. Based on the experience three locations are identified with help of sensitivity analysis to locate capacitors, variable size for the capacitor value is varying from 150Kvar to 4050kvar.

The description of the switch states is identified as,

i. The open switches (ie switches open for an feasible solution)

ii. The closed switches (ie switches closed for an feasible solution)
iii. The permanently closed switches (ie switches closed in all feasible solution)
iv. The temporary closed state switches (ie previously opened switch is closed for the loop under consideration)

The switches are opened and closed in order to maintain radiality.
The initial solution set for the system is given in equation 13.

$L_1=\{S_1,S_2,S_3,S_4,S_5,S_6,S_7,S_{47},S_{48},S_{49},S_{50},S_{51},S_{52},S_{53},S_{54},S_{55},S_{84}\}$
$L_2=\{S_1,S_2,S_3,S_4,S_5,S_6,S_7,S_{56},S_{57},S_{58},S_{59},S_{60},S_{85}\}$
$L_3=\{S_{11},S_{43},S_{86}\}$
$L_4=\{ S_{11},S_{12},S_{65},S_{66},S_{67},S_{68},S_{69},S_{70},S_{71},S_{72},S_{87}\}$
$L_5=\{S_{13},S_{65},S_{66},S_{67},S_{68},S_{69},S_{70},S_{71},S_{72},S_{87},S_{73},S_{74},S_{75},S_{76},S_{88}\}$
$L_6=\{S_{12},S_{14},S_{89},S_{90},S_{17},S_{18},S_{27},S_{28},S_{29},S_{93},S_{40},S_{95},S_{41},S_{42},S_{35},S_{36},S_{37},S_{38},S_{94},S_{44},S_{45},S_{46},S_{86}\}$
$L_7=\{S_{15},S_{16},S_{25},S_{26},S_{90}\}$
$L_8=\{S_{19},S_{20},S_{77},S_{78},S_{79},S_{80},S_{81},S_{82},S_{83},S_{91},S_{89},S_{13},S_{14},S_{88},S_{73},S_{74},S_{75},S_{76}\}$
$L_9=\{S_{25},S_{26},S_{27},S_{28}, S_{30},S_{31},S_{32},S_{92}\}$
$L_{10}=\{S_{29},S_{33},S_{34},S_{35},S_{36},S_{37},S_{38},S_{39},S_{92},S_{93}\}$
$L_{11}=\{S_{31},S_{32},S_{33},S_{34},S_{43},S_{44},S_{45},S_{46},S_{86}\}$
$L_{12}=\{S_{40},S_{41},S_{42},S_{95}\}$
$L_{13}=\{S_{54},S_{55},S_{84},S_6,S_7,S_8,S_9,S_{10},S_{61},S_{62},S_{63},S_{64},S_{85},S_{96}\}$ (11)

The equation (11) reveals that the system has thirteen loops with set of switches. The searching for the best set of open switches from each loop has been carried out with ODE. The number of switches present in each loop such as 8,6,0,7,1,7,1,8,3,6,4,3 and 4 defines the range for the variables. Therefore, the range for the searching process is selected as (1-8), (1-6), (0), (1-7),(1-1),(1-8), (1-3),(1-6),(1-4),(1-3)and (1-4) for the variables L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, L_9, L_{10}, L_{11}, L_{12} and L_{13} respectively. After eliminating open, permanently closed and temporarily closed switches, the final solution set for the system is given in equation 12.

$L_1=\{S_{48},S_{49},S_{50},S_{51},S_{52},S_{53},S_{54},S_{55}\}$
$L_2=\{S_2,S_3,S_4,S_5,S_6,S_7\}$
$L_3=\{\}$
$L_4=\{S_{66},S_{67},S_{68},S_{69},S_{70},S_{71},S_{72}\}$
$L_5=\{S_{13}\}$
$L_6=\{S_{12},S_{14},S_{17},S_{18},S_{44},S_{45},S_{46}\}$
$L_7=\{S_{16}\}$
$L_8=\{S_{19},S_{20},S_{78},S_{79},S_{80},S_{81},S_{82},S_{83}\}$
$L_9=\{S_{26},S_{27},S_{28}\}$
$L_{10}=\{S_{29},S_{35},S_{36},S_{37},S_{38},S_{39}\}$
$L_{11}=\{S_{31},S_{32},S_{33},S_{34}\}$
$L_{12}=\{S_{40},S_{41},S_{42}\}$
$L_{13}=\{S_{61},S_{62},S_{63},S_{64}\}$ (12)

5.2 Implementation

For instance for variable L_1, by the control strategy "DE/current-to-rand/1" the value generated is 3 then S_{50} 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 proposed method reduces the power loss from 542.55 kW to 411.96kW and maintains the bus voltages well above minimum value. The feeder currents are maintained under limit which is compared with the initial configuration feeder currents and it is shown in the Figure 3.

The final configuration bus voltages and branch currents are shown in the Figures 4 and 5 respectively. The identified switches to be opened at the final configuration are S_7, S_{13}, S_{34}, S_{39}, S_{42}, S_{55}, S_{62}, S_{72}, S_{83}, S_{86}, S_{89}, S_{90}, and S_{92}. Buses 27, 28 and 29 are selected as optimal locations for the capacitor placement The optimal size of the capacitors at the locations 27, 28 and 29 are 149 Kvar, 38 Kvar and 900 Kvar.

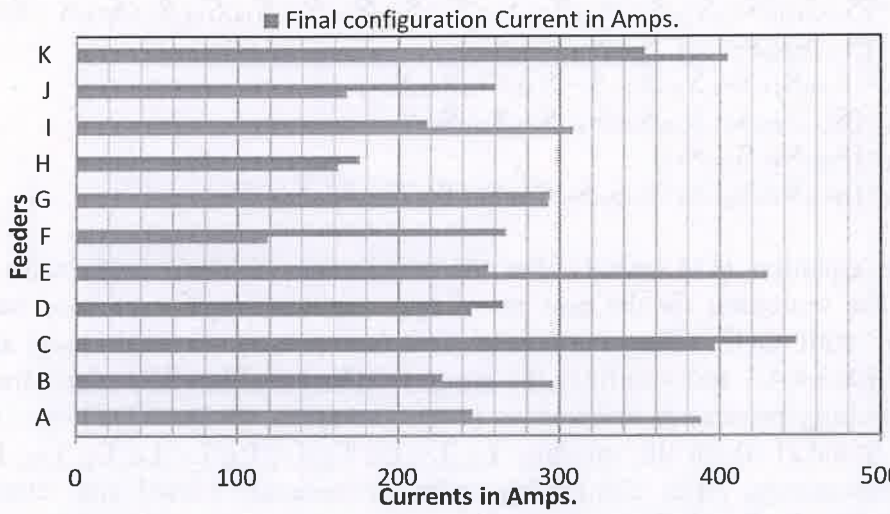

Figure 3 Feeder Currents Under Base Load Condition Through FODE Algorithm

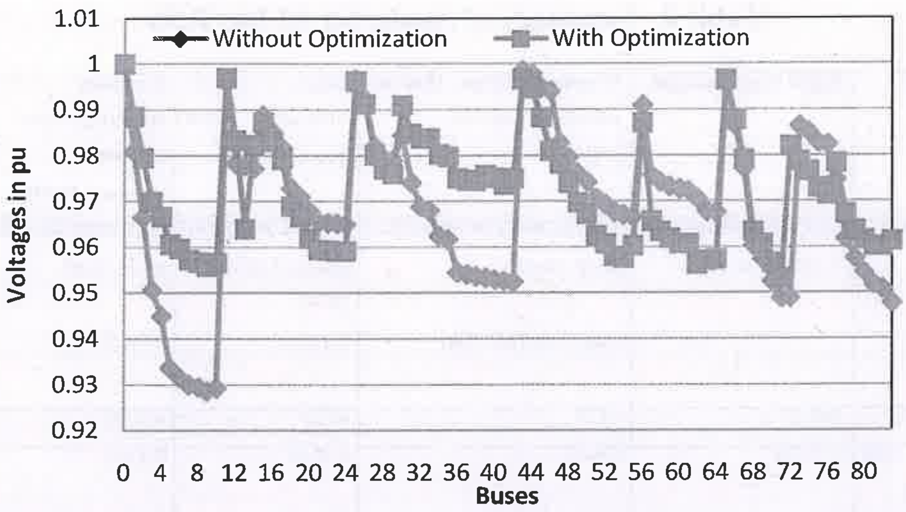

Figure 4 Bus voltages under base load condition through FODE algorithm

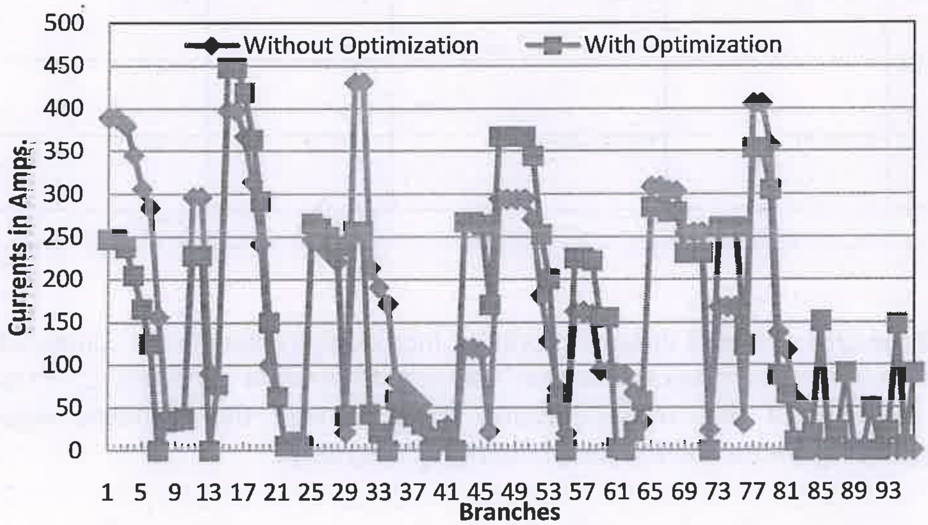

Figure 5 Branch currents under base load condition through FODE algorithm

Table 2 Summary of results for 83-bus RDS

Parameters	Initial Configuration	Hossein Dehghan Dehnavi and Saeid Esmaeili (2013)	Diana P. Montoya and Juan M (2012)	Proposed Reconfiguration and Capacitor Placement Through FODE
Open Switches	84-85-86-87-88-89-90-91-92-93-94-95-96	7-13-34-39-42-54-62-72-83-86-89-90-92	7-13-34-39-42-55-62-72-83-86-89-90-92	7-13-34-39-42-55-62-72-83-86-89-90-92
Capacitor Locations	-	16&20/DSTATCOM	3-16-20	7-70-53
Loss (kW)	542.55	447.8	442.3	411.96
Min. bus Voltage (pu)	0.95573	0.9481	0.9556	0.9561
Total Capacitor size (kVAR)	-	4887.3	4682	5529
Power Loss Cost ($/yr)	91148.40	75230.4	74306.4	69210.26
Capacitor Cost ($/yr)	-	-	1136.35	1038.67
Total Annual Cost ($/yr)	91148.40	Not Considered	76442.75	71248.93
% saving	-	-	16.13	21.84

The results obtained through proposed methodology have been compared with the other technologies proposed earlier for reconfiguration in Table 2. From the tables, it is realized that reconfiguration made through the proposed algorithm receives global optimum and has taken multiple constraints.

6. CONCLUSION

An efficient approach that combines the reconfiguration and optimal capacitor placement for power loss reduction and bus voltage improvement has been proposed in this paper. ODE has taken care of reconfiguration, optimal capacitor location and capacitor sizing. With the effective inclusion of heuristic fuzzy, the power flow constraints were considered along with loss reduction. The proper use of 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 shows that the introduction of the algorithm with hybrid FODE has contributed to reduce the number of power flows and has incorporated the network constraints. Hence with the effective introduction of the proposed 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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