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Reconfiguration and Capacitor Placement Using Opposition Based Differential Evolution Algorithm in Power Distribution System

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Abstract – *Distribution system is a critical link between customer and utility. The control of power loss is the main factor which decides the performance of the distribution system. There are two methods such as (i) distribution system reconfiguration and (ii) inclusion of capacitor banks, used for controlling the real power loss. 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.Considering the improvement in voltage profile with the power loss reduction, later method produces better performance than former method. This paper presents an advanced evolutionary algorithm for capacitor inclusion for loss reduction. The conventional sensitivity analysis is used to find the optimal location for the capacitors. In order to achieve a better approximation for the current candidate solution, Opposition based Differential Evolution (ODE) is introduced. The effectiveness of the proposed technique is validated through IEEE-33 bus Power Distribution systems.*

***Keywords**: Capacitor Placement, Distribution Network Reconfiguration, Differential Evolution, Loss Reduction, Switching Operation*

Nomenclature

P_i	Real power
Q_i	Reactive power
volt/var	Voltage/Volt Ampere Reactive
$R_{i,j}$	Line resistance
$X_{i,j}$	Line reactance
V_{max}	maximum allowable volage
V_{min}	minimum allowable volage
I_{jl}	branch current

I. 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 equipments, optimal use of 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 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. Even though reconfiguration strategy has above said limitations, it is a most widely recommended and most successful strategy with zero operating cost.

The feeder reconfiguration problem has been dealt within 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].

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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.

Capacitor placement problem has two major concerns in it. The first one is the identification of capacitor location and the second is the amount of capacitor inclusion at the identified location.

The most conventional sensitivity analysis has been followed for finding the optimal location and the conventional searching adapted in order to find the amount of inclusion of capacitors.

Therefore, it provides opportunity for the inclusion of optimization techniques for both the cases. Since 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.

The improvements in advanced optimization techniques such as genetic algorithm, microgenetic, particle swarm optimization, ant colony and differential evolution allowed the optimization procedures comparatively easier than the conventional procedures. 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 microgenetic 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 weak buses which require 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 Big Bang-Big Crunch (BB-BC) optimization is presented to find the optimal placement and size of capacitors in a distribution system. The potentialities of BB-BC are its inherent numerical simplicity, high convergence speed, and easy implementation [20].

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 [21].

The improved reconfiguration method along with GA used for simultaneous reconfiguration and capacitor placement for distribution network optimization in [22].

In this paper, Opposition based Differential Evolution [23] algorithm has been presented for efficient reconfiguration and optimal capacitor placement. The conventional loss sensitivity factors are introduced to identify the optimal location of capacitors in the distribution system and the amount of injection of reactive power through capacitors is fine-tuned with the help of ODE.

The effectiveness of the proposed approach is demonstrated by employing the feeder switching operation scheme to IEEE-33 bus.

II. 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. Additionally, capacitor placement has been involved for the loss reduction through volt/var control.

The primary objective of the proposed technique is to minimize the total annual cost of the distribution system includes capacitor cost and energy loss cost, subject to the power flow constraints such as bus voltage ($|Vmin| < |Vi| < |Vmax|$), branch currents ($|Ij| < |Imax, j \varepsilon nl|$) and radiality constraints. The mathematical description of the above said objective is given in Eq. (1):

$$Minimize\ C_{total} = C_{capacitor} + C_{energy} \tag{1}$$

where:
C_{total} is the total annual cost of the RDS in \$/year
$C_{capacitor}$ is the total capacitor cost of the RDS in \$/year
C_{energy} is the energy loss cost of the RDS in \$/year

The available three phase capacitor sizes in kVAr and costs in \$/kVAr is shown in Table I [18]:

$$C_{capacitor} = C_{q,fixed} + C_i^{annual} \times Q_i \tag{2}$$

where:
$C_{q,\text{fixed}}$ is the fixed cost for the capacitor placement \$/year;
C_i^{annual} is the annual cost for the capacitor installation in \$/(kVAr-year) received from Table I.

The energy loss cost of the distribution system is derived from the power flow equations. The power flow equations are described through assuming the simple distribution system shown in Fig. 1.

In Fig. 1, P_i and Q_i are the real and reactive power flow of the line 'i' , P_{Li} and Q_{Li} are the real and reactive power loads at the bus 'L_i'. 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.

TABLE I
CAPACITOR SIZES AND COST

Sl. No.	Q in kVAr	Capacitor cost in \$/kVAr	Sl. No.	Q in kVAr	Capacitor cost in \$/kVAr
1	150	0.500	15	2250	0.197
2	300	0.350	16	2400	0.170
3	450	0.253	17	2550	0.189
4	600	0.220	18	2700	0.187
5	750	0.276	19	2850	0.183
6	900	0.183	20	3000	0.180
7	1050	0.228	21	3150	0.195
8	1200	0.170	22	3300	0.174
9	1350	0.207	23	3450	0.188
10	1500	0.201	24	3600	0.170
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			

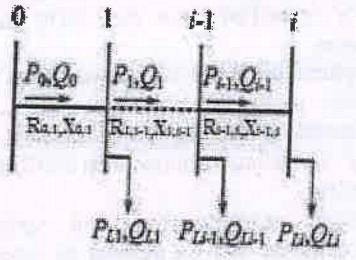

Fig. 1. Single line diagram of a RDS

The power flow equations for the RDS is given by:

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1}\frac{P_i^2 + Q_i^2}{V_i^2} \tag{3}$$

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1}\frac{P_i^2 + Q_i^2}{V_i^2} - V_i^2\frac{y_i}{2} \tag{4}$$

$$V_{i+1}^2 = V_i^2 - 2\left(R_{i,i+1}P_i + X_{i,i+1}Q_i\right) + \left(R_{i,i+1}^2 + X_{i,i+1}^2\right)\frac{P_i^2 + Q_i^2}{V_i^2} \tag{5}$$

After successful calculation of power flow of the individual lines of the RDS using Eqs. (3)-(5), the power loss of the RDS is calculated by using Eq. (6):

$$P_{F,Loss} = \sum_{i=1}^{nl} R_{i,i+1}\frac{P_i^2 + Q_i^2}{V_i^2} \tag{6}$$

The total energy loss cost (E_{cost}) has been calculated as:

$$C_{energy} = P_{F,loss} \times K_p \tag{7}$$

The problem carried out with following assumptions:

(i) Loads are static
(ii) RDS is reactive power compensated
(iii) Operation and maintenance costs of the capacitors are negligible.

III. Proposed ODE Algorithm

III.1. Procedure for Reconfiguration

For reconfiguration, switches present in the distribution network are considered as variables. For instance, closing of S33, S34, S35, S36 and S37 and opening of swithes S6, S11, S14, S27, and S32 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.

In order to reduce the dimension of the variables, Plant Growth Simulation Algorithm (PGSA) has been employed in this paper [19]. 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 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. Thus with the influence of PGSA, the complexity has been greatly reduced. For searching for the optimal solution ODE has been introduced.

III.2. Optimal Capacitor Placement

Optimal capacitor placement process has two major tasks (i) the capacitors location identification and (ii) the search for optimal sizing of capacitors. The capacitors need to be located at the weak buses of the distribution system. The term weak buses refer the buses with least voltage (< *Vmin*) and the associated lines having the most value of rate of change of real power loss with respect to effective reactive power.

The total load connected beyond the associated bus is called as the effective reactive power. The above mentioned procedure is called sensitivity analysis and the relevant buses are called sensitivity buses. The sensitivity analysis is a conventional procedure practiced for many years for identifying the optimal location of capacitors.

The mathematical equations related to formation of sensitivity analysis are described with the Fig. 2.

The Fig. 2 has a distribution line 'm' connected between buses 'i' and 'i+1' with a series impedance of Rm+jXm and an effective load of Peff + jQeff at bus 'i+1'.

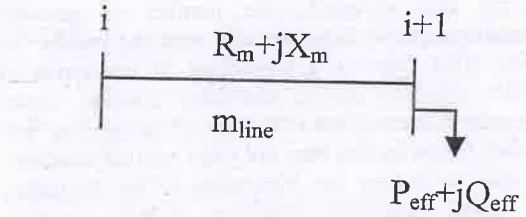

Fig. 2. Single line diagram of a distribution line for loss sensitivity factor

The real power loss of the distribution line (*m*) is given by:

$$P_m = R_m \frac{\left(P_{i+1,eff}^2 + Q_{i+1,eff}^2\right)}{V_{i+1}^2} \quad (8)$$

The loss sensitivity factor can be calculated using Eq. (9):

$$LSF_m = \frac{\partial P_m}{\partial Q_{i+1,eff}} = 2R_m \frac{Q_{i+1,eff}}{V_{i+1}^2} \quad (9)$$

The Loss Sensitivity Factors (*LSF*) of all the lines can be calculated through conducting radial load flow. The calculated values of *LSF* are arranged in non-increasing order. The buses with most *LSF* value and lesser value (ie. < 1.01pu) of normalized voltage (|*V*|/0.95) [19] are selected as the candidate location for capacitor placement.

The purpose of introduction of ODE is to find the optimal capacitor size that need to be included at the optimal locations received at the end of sensitivity analysis. The number of variables for ODE searching is the number of identified locations.

III.3. Search Strategy through Opposition based Differential Evolution (ODE)

The selection of number of variables has been decided based on the three different cases:

i. the network reconfiguration alone, 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 'x' identified loops then ODE should have 'x' variables.
ii. the optimal capacitor placement alone, the number of optimal locations is the number of variables considered for searching. For instance, if the system has 'y' identified locations then ODE should have 'y' variables.
iii. combined reconfiguration and optimal capacitor placement, the sum of number of loops and number of locations are the total number of variables considered for searching. For instatnce, the system with 'x' loops and 'y' locations have 'x+y' variables.

The pseudocode of the Opposition based Differential Evolution algorithm for reconfiguration and optimal capacitor placement problem 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 of 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;
}
```

IV. Simulation Results

The effectiveness of the algorithm has been validated through IEEE 33-bus test distribution systems as described in Wang and Cheng [19]. The proposed scheme has been tested on 33-bus IEEE 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.

Case 1: Reconfiguration only

In this case, reconfiguration was carried out by considering the system 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. As per the PGSA, decision variables are designed for the system, which is shown in Fig. 3.

The description of the switch states is identified as:

i. the open switches are S33, S34, S35, S36, and S37;
ii. the closed switches are S1 to S32;
iii. the permanently closed switches are S1, S2, S3, S18 and S22 (since these switches are near to the feeder);
iv. the temporary closed state switches are S3, S4, S5, S6, S7, S8, S9, S10, S11, S25, S26, S27, and S28 (since these switches are common to more than one loop;

As a result, the solution sets are re-defined as:

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

The Eq. (10) reveals that the system has five 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 7,6,4,7 and 8 defines the range for the variables.

Therefore, the range for the searching process is selected as (1-7), (1-6), (1-4), (1-7) and (1-8) for the variables L1, L2, L3, L4 and L5 respectively. For instance for variable L1, by the control strategy "DE/current-to-rand/1" the value generated is 3 then S6 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 S7, S9, S14, S32 and S37. The final configuration current at the branches and voltage at the buses are within the limits.

Case 2: Capacitor Placement only

In this case, optimal capacitor placement process starts with finding the optimal location through sensitivity analysis. The sensitivity factors with Normalized voltage at the buses are shown in Table II.

The buses 5, 27 and 28 are identified as candidate locations for capacitor location through sensitivity analysis.

ODE tunes for the optimum capacitor size for the identified locations. The proposed method reduces the power loss from 202.67kW to 159.89kW, and maintains the bus voltages well above minimum value.

The kVAr at the buses 5, 27 and 28 are 2210, 47 and 687 respectively. With the effective influence of capacitors at the optimal locations the total operating cost of the system has been reduced from 34,049.75 $/Year to 28,392.12 $/Year. Thus the proposed algorithm has achieved 16.61 % of cost saving with optimal capacitor placement. The bus voltages are maintained within the limit.

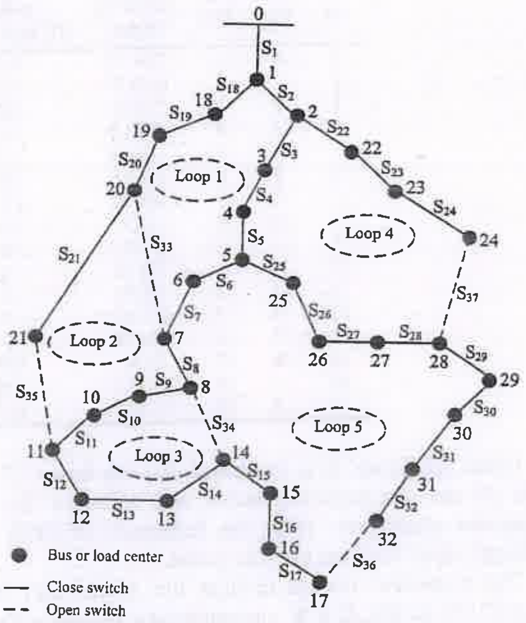

Fig. 3. IEEE 33-bus RDS with state variable sketch

Case 3: Combined Reconfiguration and Capacitor placement

This case combines both reconfiguration and capacitor placement.

As per this case, Optimization process starts from reconfiguration and completes with capacitor placement. As per the reconfiguration, the system has been restructured by making the switches S7, S9, S14, S32 and S37 are opened. The reconfigured system has been considered for the optimal capacitor placement.

The sensitivity analysis has been carried out for the reconfigured system in order to identify the optimal locations for the capacitor placement. Loss Sensitivity Factor along with Normalized voltage at the buses is given in Table III.

TABLE II
LOSS SENSITITY FACTOR FOR THE IEEE 33-BUS RDS

Line no	Start Bus	End Bus	Loss Sensitivity Factor	Normalized voltage (|V| in pu / 0.95)	Line no	Start Bus	End Bus	Loss Sensitivity Factor	Normalized voltage (|V| in pu / 0.95)
1	0	1	266.19	1.05	17	16	17	43.82	0.96
2	1	2	1324.40	1.03	18	1	18	32.97	1.05
3	2	3	763.17	1.03	19	18	19	228.46	1.05
4	3	4	766.25	1.02	20	19	20	41.52	1.04
5	4	5	1677.15	1.00	21	20	21	35.99	1.04
6	5	6	133.08	1.00	22	2	22	264.16	1.03
7	6	7	410.75	0.99	23	22	23	473.76	1.02
8	7	8	455.70	0.98	24	23	24	237.98	1.02
9	8	9	437.52	0.98	25	5	25	267.93	1.00
10	9	10	76.85	0.98	26	25	26	367.21	0.99
11	10	11	130.51	0.98	27	26	27	1364.15	0.98
12	11	12	442.93	0.97	28	27	28	1030.98	0.97
13	12	13	136.18	0.97	29	28	29	603.49	0.97
14	13	14	78.92	0.97	30	29	30	303.13	0.97
15	14	15	88.85	0.96	31	30	31	64.53	0.97
16	15	16	115.60	0.96	32	31	32	20.26	0.96

TABLE III
LOSS SENSITIVITY FACTOR FOR THE RECONFIGURED IEEE 33-BUS RDS

Line no	Start Bus	End Bus	Loss Sensitivity Factor	Normalized voltage (|V| in pu / 0.95)	Line no	Start Bus	End Bus	Loss Sensitivity Factor	Normalized voltage (|V| in pu / 0.95)
1	0	1	266.17	1.05	17	19	20	285.70	1.02
2	1	2	1029.37	1.04	18	20	21	225.57	1.02
3	2	3	539.40	1.03	19	2	22	261.98	1.04
4	3	4	526.85	1.03	20	22	23	469.79	1.03
5	4	5	1124.98	1.02	21	23	24	235.97	1.02
6	5	6	25.00	1.02	22	5	25	247.26	1.02
7	7	8	209.52	1.01	23	25	26	338.31	1.01
8	10	9	5.29	1.01	24	26	27	1252.23	1.00
9	11	10	25.20	1.01	25	27	28	943.69	0.99
10	11	12	228.35	1.01	26	28	29	549.62	0.99
11	12	13	58.70	1.01	27	29	30	234.69	0.99
12	14	15	123.45	1.00	28	30	31	44.05	0.99
13	15	16	178.78	1.00	29	20	7	673.33	1.01
14	16	17	81.40	1.00	30	8	14	357.09	1.00
15	1	18	126.07	1.05	31	21	11	538.14	1.01
16	18	19	1118.01	1.03	32	17	32	27.82	1.00

From the Table, it is identified that the buses 27, 28 and 29 are the sensitive buses and effective for the capacitor placement. With the influence of ODE the optimal capacitor sizes are fine tuned.

The proposed method reduces the power loss from 202.67 kW to 101.42 kW, and maintains the bus voltages well above minimum value. The kVAr at the buses 27, 28 and 29 are 149 727 and 149 respectively. With the effective influence of capacitors at the optimal locations the total operating cost of the system has been reduced from 34,049.75 $/Year to 18,198.96 $/Year.

Thus the proposed algorithm has achieved 46.55 % of cost saving with the combined reconfiguration-optimal capacitor placement case. Furthermore, the bus voltages are maintained within the limit. The results of the three cases are compared in Table IV along with the results of the previous published work [20].

TABLE IV
SUMMARY OF RESULTS FOR 33-BUS RDS

Parameters	Initial Configuration	Reconfiguration Only	Capacitor Placement Only	Reconfiguration and Capacitor Placement [20]	Proposed Reconfiguration and Capacitor Placement
Loss (kW)	202.67	139.54	159.89	101.499	101.42
Min. bus Voltage (pu)	0.913	0.9378	0.933	0.957	0.959
Total Capacitor size (kVAr)	-	-	2940	1685	1027
Power Loss Cost ($/(kW-yr))	-	23444.62	26861.59	17038.56	17039.03
Capacitor Cost ($/yr)	-	-	1529.87	722.84	159.94
Total Annual Cost ($/yr)	34049.75	23444.62	28,391.46	18761.4	18198.96
%saving	-	31.14	16.61	44.9	46.55

From the Table, it is understood that the annual operating cost and power loss has been greatly reduced with the combined reconfiguration and capacitor placement approach.

V. Conclusion

An efficient approach for power loss reduction and bus voltage improvement has been proposed in this paper. The location identification for the capacitor placement has been carried through the sensitivity factor.

The incorporation of ODE increases the speed of the searching process. 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 shown that the introduction of the algorithm with ODE 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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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:

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

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

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.

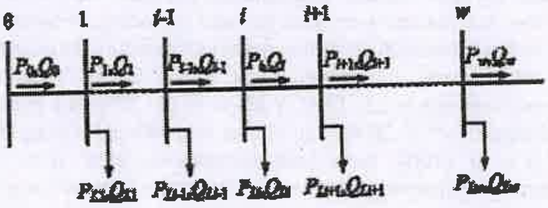

Fig. 1: Single-line diagram of a main feeder

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

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

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

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

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:

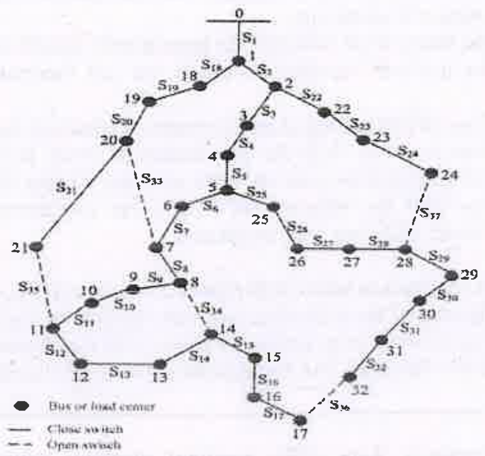

Fig. 2: IEEE 33-bus Test System

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

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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.

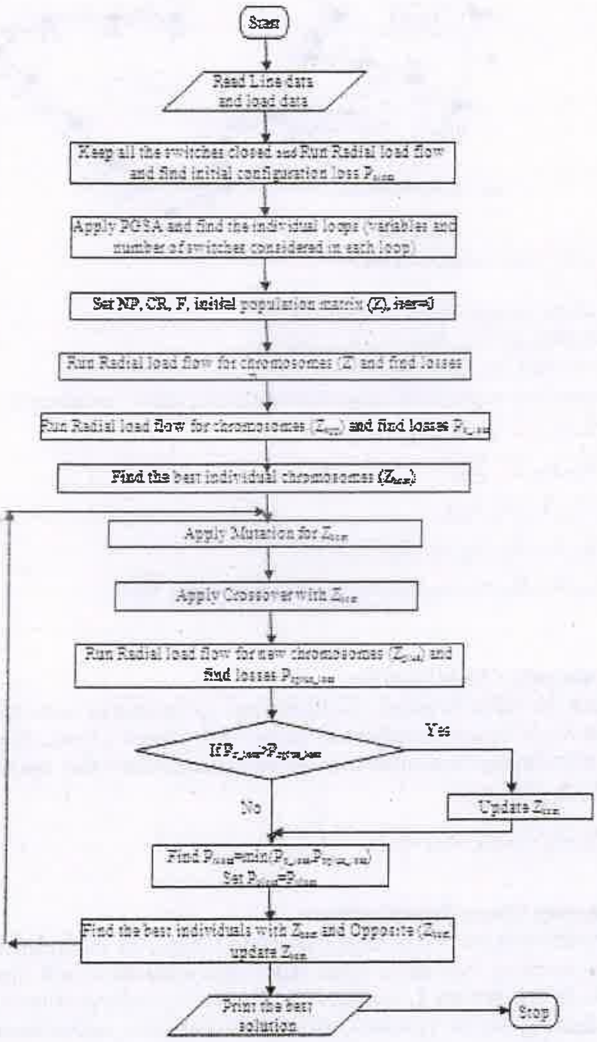

Fig. 3: Flowchart for reconfiguration through hybrid PGSA-ODE under normal conditions

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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.

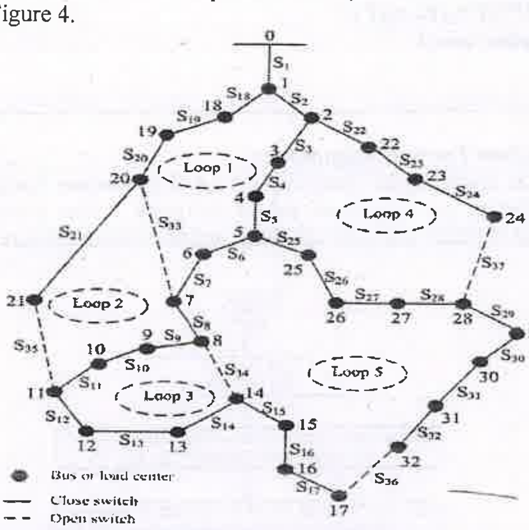

Fig. 4: Test System I with state variable sketch

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,

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

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,

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

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,

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

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.

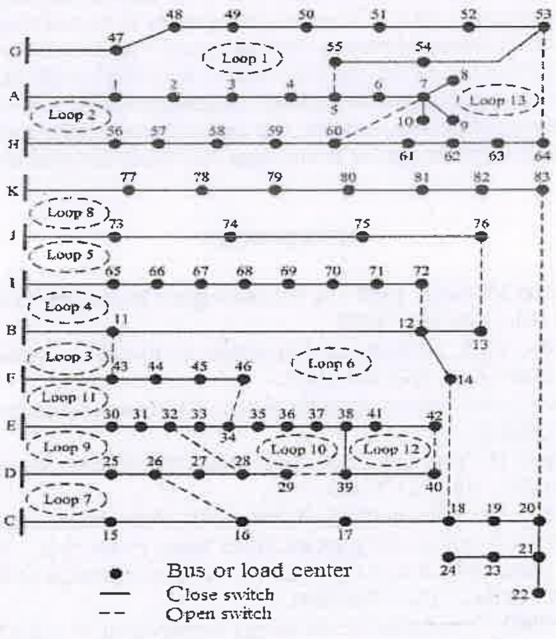

Fig. 5: Test System II with state variable sketch

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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Capacitor Placement and Reconfiguration of Distribution System with hybrid Fuzzy-Opposition based Differential Evolution Algorithm

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Abstract: *Distribution system reconfiguration and optimal capacitor placement are the two techniques adapted for the control of power loss. These techniques not only control the power loss but also control volt/var of the distribution system, and improve the system reliability and security. This paper proposes a method to handle reconfiguration and capacitor placement simultaneously for the effective optimization. In order to consider the constraints along with the objective, heuristic fuzzy has been integrated with ODE. The effectiveness of the proposed approach is demonstrated by employing the feeder switching operation scheme to IEEE-33 bus Power Distribution systems. The proposed algorithm reduces the transmission loss and controls volt/var while satisfying power flow constraints.*
Keywords *-Capacitor placement, Differential evolution, Distribution network reconfiguration, Loss reduction, Switching operation*

I. 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 equipments, optimal use of 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 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. Even though reconfiguration strategy has above said limitations, it is a most widely recommended and most successful strategy with zero operating cost.

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. The improvements in advanced optimization techniques such as genetic algorithm, micro genetic, particle swarm optimization, ant colony and differential evolution allowed the optimization procedures comparatively easier than the conventional procedures. 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 microgenetic 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 weak buses which require 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 IEEE-33 bus.

II. Problem Formulation

The main objective of the optimal capacitor placement is to minimize the total annual cost of the system subject to the power flow constraints such as bus voltage ($|V_{min}| < |V_i| < |V_{max}|$), branch currents ($|I_{ji}| < |I_{max,j\in nl}|$) and radiality constraints. The mathematical equation relevant to the objective function of the problem is defined as,

$$F=\text{Minimize}(C) \tag{1}$$

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

The problem carried out with following assumptions.

(i) Loads are static
(ii) Distribution system is perfectly balanced
(iii) Well reactive power compensated system
(iv) Operation and maintenance costs of the capacitors are negligible.

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

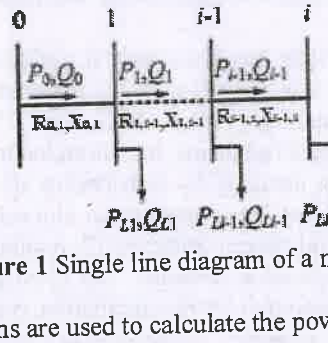

Figure 1 Single line diagram of a main feeder

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

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

$$Q_{i+1}=Q_i - Q_{Li+1} - X_{i,i+1}\frac{P_i^2+Q_i^2}{V_i^2} - V_i^2\frac{y_i}{2} \tag{3}$$

$$V_{i+1}^2=V_i^2 - 2(R_{i,i+1}P_i + X_{i,i+1}Q_i) + (R_{i,i+1}^2 + X_{i,i+1}^2)\frac{P_i^2+Q_i^2}{V_i^2} \tag{4}$$

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,

$$P_{F,Loss} = \sum_{i=1}^{nl} R_{i,i+1} \frac{P_i^2+Q_i^2}{V_i^2} \quad (5)$$

The total energy loss cost (E_{cost}) has been calculated as,

$$E_{cost}=P_{T,loss} * K_p; \quad (6)$$

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 (K) were given in [19]. The total cost of the distribution system is given in equation (7).

$$C=E_{cost}+ C_{q,cost} \quad (7)$$

where,

$$C_{q,cost} = C_{q,fixed} + C_i^{annual} * Q_i$$

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

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

(i is the selected buses for capacitor installation)

Q_i is the reactive power in (KVAR)

III. 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.

IV. Fuzzy Operations For Multi-Objective Capacitor Placement

In fuzzy domain, each objective is associated with a membership function. The membership function indicates the degree of satisfaction of the objective. In the crisp domain, either the objective is satisfied or it is violated, implying membership values of unity and zero, respectively. When there are multiple objectives to be satisfied simultaneously, a compromise has to be made to get the best solution. 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. The power loss of the system has been obtained from radial load flow for each new configuration. Moreover, the amount of the P_{nloss} resulting from capacitor inclusion can be estimated as 'very close, 'close' or 'not close' to the P_{oloss}. Therefore, the linguistic terms can be formulated as a membership function by the fuzzy notation. The membership function μ_{Fj} has been depicted using Equation (8). A small difference between P_{nloss} and P_{oloss} possesses a larger membership value. The membership function at j^{th} configuration can be expressed as follows,

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$$\mu_{Fj} = \begin{cases} \dfrac{X_{max} - X_j}{X_{max} - X_{min}} & \text{for } X_{min} < X_j < X_{max} \\ 1.0 & \text{for } X_j \le X_{max} \\ 0.0 & \text{for } X_j \ge X_{max} \end{cases} \tag{8}$$

where, $X_j = P_{nloss}/P_{tloss}$

V. Simulation Results

The effectiveness of the algorithm has been validated through IEEE 33-bus test distribution system [19]. The system 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. It has been carried out by considering the system 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.

The optimization process starts with identifying the total variables, such as number of locations for capacitor placement and loops present in the distribution system. For the test system, it has been considered as 5 loops and 3 locations for the capacitor placement based on experience and earlier studies. Therefore, total number of variables required for ODE searching is 11(ie. 5 for loops, 3 for locations and 3 for sizing).

5.1 Variable Size

For the 5 loops, as per the PGSA [10], decision variables are designed for the system, which is shown in Fig. 2.

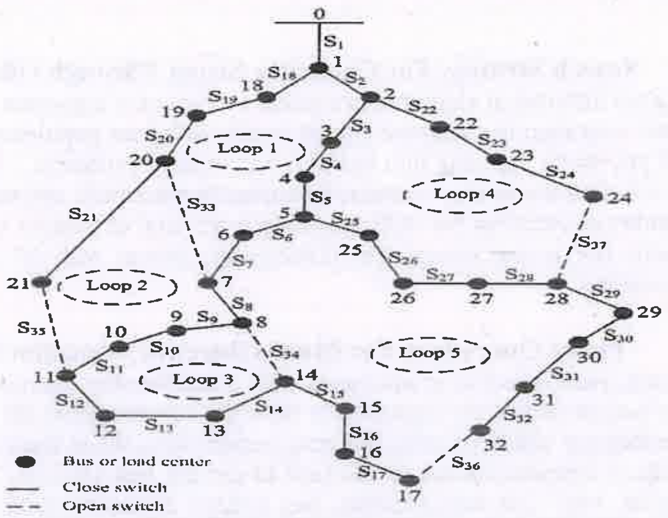

Figure 2 IEEE 33-bus RDS with state variable sketch

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};
iii. the permanently closed switches are S_1, S_2, S_3, S_{18} and S_{22} (since these switches are near to the feeder);
iv. the temporary closed state switches are S_3, S_4, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{25}, S_{26}, S_{27}, and S_{28} (since these switches are common to more than one loop;

As a result, the solution sets are re-defined as,

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

The equation (9) reveals that the system has five 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 7,6,4,7 and 8 defines the range for the variables. Therefore, the range for the searching process is selected as (1-7), (1-6), (1-4), (1-7) and (1-8) for the variables L_1, L_2, L_3, L_4 and L_5 respectively.

For location variables, total number of buses except feeder bus has been considered as the maximum range for the variables. For 'n' bus system, the maximum value of the variable has to be 'n-1'.

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 in kVAR	Capacitor cost in $/kVAR	Sl. No.	Q in kVAR	Capacitor cost in $/kVAR
1	150	0.500	15	2250	0.197
2	300	0.350	16	2400	0.170
3	450	0.253	17	2550	0.189
4	600	0.220	18	2700	0.187
5	750	0.276	19	2850	0.183
6	900	0.183	20	3000	0.180
7	1050	0.228	21	3150	0.195
8	1200	0.170	22	3300	0.174
9	1350	0.207	23	3450	0.188
10	1500	0.201	24	3600	0.170
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			

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_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 proposed method reduces the power loss from 202.67 kW to 101.42 kW, and maintains the bus voltages well above minimum value. The kVAR at the buses 27, 28 and 29 are 149, 727 and 149 respectively. With the effective influence of capacitors at the optimal locations the total operating cost of the system has been reduced from 34,049.75 $/Year to 18,198.96 $/Year. Thus the proposed algorithm has achieved 46.55 % of cost saving with the combined reconfiguration-optimal capacitor placement case. Furthermore, the bus voltages are maintained within the limit. The results of the three cases are compared in Table 2 along with the results of the previous published work [20]. From the Table, it is understood that the annual operating cost and power loss has been greatly reduced with the combined reconfiguration and capacitor placement approach.

Table 2 Summary of results for 33-bus RDS

Parameters	Initial Configuration	Reconfiguration Only [10]	Capacitor Placement Only [18]	Reconfiguration and Capacitor Placement [20]	Proposed Reconfiguration and Capacitor Placement
Loss (kW)	202.67	139.54	159.89	101.49	101.42
Min. bus Voltage (pu)	0.913	0.9378	0.933	0.957	0.959
Total Capacitor size (kVAR)	-	-	2940	1685	1027
Power Loss Cost ($/(KW-yr))	-	23444.62	26861.59	17038.56	17039.03
Capacitor Cost ($/yr)	-	-	1529.87	722.84	159.94
Total Annual Cost ($/yr)	34049.75	23444.62	28,391.46	18761.4	18198.96
% saving	-	31.14	16.61	44.9	46.55

VI. 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

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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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