Combined Reconfiguration and Capacitor Placement for Distribution System Volt/Var Control through Opposition based Differential Evolution Algorithm

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Power distribution systems must be very effective in power delivery. Utilities are continuously looking for recent technologies to enhance power delivery performance. The control of power loss is one of the most important issues directly related to system efficiency. Distribution system reconfiguration and optimal capacitor placement are the two most popular techniques adapted for the control of power loss. The techniques not only concentrate on power loss control but also control volt/var of the distribution system, and at the same time improve the system reliability and security. Former method 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. Later is the identification of optimal location and size of the capacitors with the objective of minimizing the power loss. This paper combines both reconfiguration and optimal capacitor placement for the effective optimization. Furthermore, it utilizes Opposition based Differential Evolution algorithm for efficient searching for the optimal solution. 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.

Key words: Capacitor Placement, Differential Evolution, Distribution Network Reconfiguration, Loss Reduction, Switching Operation, Volt/Var Control

Integrirani pristup rekonfiguracije i postavljanja kondenzatora za Volt/Var upravljanje distributivnim energetskim sustavima korištenjem na opoziciji baziranog algoritma diferencijske evolucije. Distributivne energetske sustav mora biti vrlo učinkovit u prijenosu energije. Javni sektor neprestano traga za novim tehnologijama ne bi li povećao učinkovitost prijenosa. Upravljanje gubicima energije jedan je od najvažnijih problema koji je direktno povezan s učinkovitošću mreže. Rekonfiguracija distributivne mreže i optimalno pozicioniranje kondenzatora su dvije uvriježene metode koje su prilagođene za upravljanje gubicima energije. Navedene metode se ne koncentriraju samo na upravljanje gubicima već i upravljaju naponsko-reaktivnim prilikama distributivne mreže, i istovremeno povećavaju raspoloživost i pouzdanost sustava. Prva metoda uključuje postupak promjene topologije distributivne mreže promjenom stanja sklopki kako bi se našla radijalna operativna struktura koja minimizira gubitke radne snage u prijenosu uz zadovoljenje operativnih ograničenja. Druga metoda uključuje identifikaciju optimalne lokacije i veličine kondenzatora s ciljem minimizacije gubitaka snage. U ovom radu se kombiniraju obje metode, rekonfiguracije i optimalnog pozicioniranja, s ciljem učinkovite optimizacije. Za postupak optimizacije odabran je na opoziciji baziran genetski algoritam diferencijske evolucije s ciljem učinkovite pretrage optimalnog rješenja. Učinkovitost predloženog pristupa provjerena je primjenom komutacijske sheme srednjenaponske distributivne mreže na IEEE-33 sabirnici baziranim distributivnim energetskim sustavima. Predloženi algoritam smanjuje gubitke prijenosa i upravlja naponsko-reaktivnim prilikama mreže uz zadovoljenje ograničenja na tokove energije.

Ključne riječi: pozicioniranje kondenzatora, diferencijska evolucija, rekonfiguracija distributivne mreže, smanjenje gubitaka, komutacija, volt/var upravljanje

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 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 with in various papers. Civanlar et al.[1] conducted the early work on feeder reconfiguration for loss reduction. In [2], Baran et al. defined the problem of loss reduction and load balancing as an integer programming problem. Aoki et al. [3] developed a method for load transfer, in which the load indices were used for load balancing. In Shirmohammadi and Hong [4], the solution method starts with a meshed distribution system obtained by considering all switches closed. Then, the switches are opened successively to eliminate the loops. 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.

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 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 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.

Ching-Tzong Su et al [19] presented an effective approach to feeder reconfiguration and capacitor settings for power-loss reduction and voltage profile enhancement in distribution systems. The optimization technique of simulated annealing (SA) can be relied on to solve the problem efficiently.

In Zeng et al [20], Minimum Nodal Voltage Method (MNV) and Genetic Algorithms (GA) are chosen to solve the network reconfiguration problem and capacitor placement problem respectively. These two means are combined together so much better effect of loss reduction can be achieved than whichever one method alone.

Zhang et al [21] proposed an improved adaptive genetic algorithm (IAGA) is developed to optimize the capacitor switching. Also, a simplified branch exchange technique is developed to find the optimal network structure for each genetic instance of capacitor optimization algorithm.

In Chang [22], the state of capacitors and branch exchange in each loop are specified by ant colony search algorithm (ACSA), and the branch which must be opened

in each loop is not the optimal branch in primary iterations, when algorithm has not yet converged. Oliveira [23] solved Capacitor placement and reconfiguration by primal-dual interior point technique with considering daily load curves.

In [24], 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 [25]. The improved reconfiguration method along with GA used for simultaneous reconfiguration and capacitor placement for distribution network optimization in [26].

In this paper, Opposition based Differential Evolution [27] 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.

2   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 ($|V_{min}| < |V_i| < |Vmax|$), branch currents ($|I_{jl}| < |I_{max,j\in nl}|$) and radiality constraints. The mathematical description of the above said objective is given in equation (1).

$$Minimize \ C_{total} = C_{capacitor} + C_{energy} \quad (1)$$

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 1 [18].

$$C_{capacitor} = C_{q,fixed} + C_i^{annual} * Q_i \quad (2)$$

Where, $C_{q,fixed}$ is the fixed cost for the capacitor placement \$/year C_i^{annual} is the annual cost for the capacitor installation in \$/(KVAR-year) received from Table

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			

1. (i is the selected buses for capacitor installation) Q_i is the reactive power in (KVAR)

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 Figure 1.
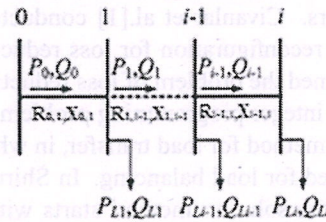

Fig. 1. Single line diagram of a RDS

In Figure 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.

The power flow equations for the RDS is given by,

$$P_{i+1} = P_i - P_{L_{i+1}} - R_{i,i+1}\frac{P_i^2 + Q_i^2}{V_i^2} \quad (3)$$

$$Q_{i+1} = Q_i - Q_{L_{i+1}} - X_{i,i+1}\frac{P_i^2 + Q_i^2}{V_i^2} - V_i^2\frac{y_i}{2} \quad (4)$$

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

After successful calculation of power flow of the individual lines of the RDS using equations (3-5), the power loss of the RDS is calculated by using equation (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,

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

The problem carried out with following assumptions.

1. Loads are static

2. RDS is reactive power compensated

3. Operation and maintenance costs of the capacitors are negligible.

3 PROPOSED ODE ALGORITHM

3.1 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 configiuation 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 [18]. 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.

1. Open state: a switch is open in a feasible solution.

2. Closed state: a switch is closed in a feasible solution.

3. Permanent closed state: a switch is closed in all feasible solutions.

4. 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.

3.2 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 ($< V_{min}$) 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 Figure 2. The Figure 2 has a distribution line m connected between buses i and $i + 1$ with a series impedance of $R_m + jX_m$ and an effective load of $P_{eff} + jQ_{eff}$ at bus $i + 1$.
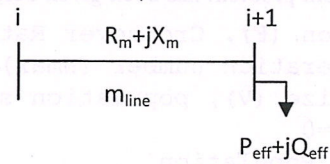

Fig. 2. *Single line diagram of a distribution line for loss sensitivity factor*

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

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

The loss sensitivity factor can be calculated using equation (9),

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

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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 high LSF value and lesser value (ie. $< 1.01pu$) of normalized voltage ($|V|/0.95$) [17] 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.

3.3 3.3 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 instance, 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;
}
```

4 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 Figure 3.

The description of the switch states is identified as,

1. the open switches are S_{33}, S_{34}, S_{35}, S_{36}, and S_{37};

2. the closed switches are S_1 to S_{32};

3. the permanently closed switches are S_1, S_2, S_3, S_{18} and S_{22} (since these switches are near to the feeder);

4. 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;

Table 2. Loss Sensitivity 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
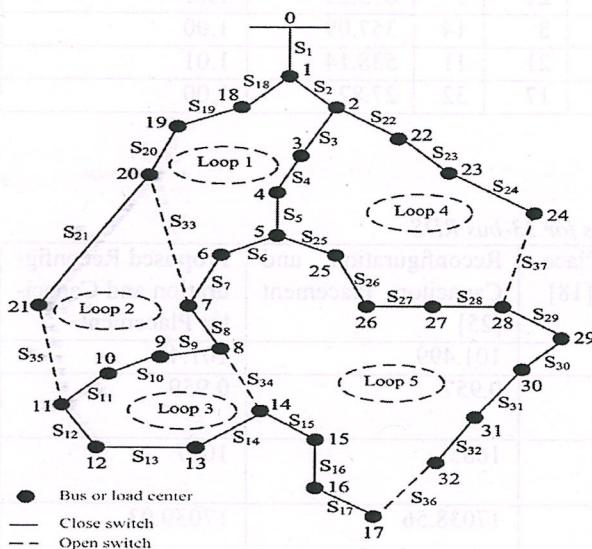
Fig. 3. IEEE 33-bus RDS with state variable sketch

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

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

The equation (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 L_1, L_2, L_3, L_4 and L_5 respectively. 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 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.

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 2. 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

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Table 3. 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

Table 4. Summary of results for 33-bus RDS

Parameters	Initial Configuration	Reconfiguration Only [11]	Capacitor Placement Only [18]	Reconfiguration and Capacitor Placement [25]	Proposed Reconfiguration and Capacitor Placement
Loss (kW)	202.67	139.54	139.57	101.499	101.42
Min. bus Voltage (pu)	0.913	0.9378	0.9300	0.957	0.959
Total Capacitor size (kVAR)	-	-	1731	1685	1027
Power Loss Cost ($/(KW-yr))	-	23444.62	23,447.76	17038.56	17039.03
Capacitor Cost ($/yr)	-	-	1327.37	722.84	159.94
Total Annual Cost ($/yr)	34049.75	23444.62	24,775.13	18761.4	18198.96
%saving	-	31.14	27.23	44.9	46.55

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. **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 S_7, S_9, S_{14}, S_{32} and S_{37} 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 3. 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 4 along with the results of the previous published work [20].

From the Table 4, it is understood that the annual operating cost and power loss has been greatly reduced with the combined reconfiguration and capacitor placement approach.

5   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. 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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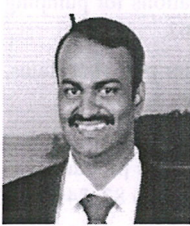
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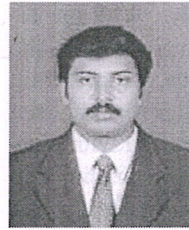
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