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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: distribution system reconfiguration and 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 study 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.

Key words: Capacitor placement, distribution network reconfiguration, differential evolution, loss reduction, switching operation

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. Civlnar *et al*. (1988) conducted the early research on feeder reconfiguration for loss reduction. Baran and Wu (1989) defined the problem of loss reduction and load balancing as an integer programming problem. Aoki *et al*. (1988) developed a method for load transfer in which the load indices were used for load balancing. In the solution method, starts with a meshed distribution system obtained by considering all switches closed (Shirmohammadi and Hong, 1989). Then, the switches are opened successively to eliminate the loops. Developments in algorithm design techniques such as simulated annealing (Cheng and Kuo, 1994), heuristic fuzzy (Huang and Chin, 2002), artificial neural network (Salazar *et al*., 2006), population based evolutionary algorithms (Hong and Ho, 2005; Qin and Suganthan, 2005) provides much improvement in reconfiguration strategy. The Plant Growth Simulation Algorithm (PGSA) is employed to optimize the network configuration of the distribution system (Wang and

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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. Harmony Search algorithm has been proposed for reconfiguration (Rao *et al*., 2011a, b).

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 researchers in the past. The initial contribution was made by Schmill (1965) using 2/3 rule for capacitor placement. Dynamic programming with assuming the capacitor sizes as discrete variables adapted by Dura (1968). The capacitor problem was viewed as a nonlinear problem by Grainger and Lee (1981) 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 Das (2002). The number of locations was considered as the total variables for Genetic algorithm. The microgenetic concepts involving enhanced genetic algorithm was proposed by De Souza *et al*. (2004). The power flow constraints were handled through fuzzy logic concepts. Optimization procedure through particle swarm optimization principle was adapted by Prakash and Sydulu (2007). Optimization through Plant Growth Simulation Algorithm (PGSA) was first introduced for feeder reconfiguration by Schmill (1965). Later, the PGSA along with loss sensitivity factors was introduced (Rao *et al*., 2011) 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. The Ant Colony Optimization algorithm was introduced for the optimization (Kasaei and Gandomkar, 2010). 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 (Montoya and Ramirez, 2012). The improved reconfiguration method along with GA used for simultaneous reconfiguration and capacitor placement for distribution network optimization by Farahani *et al*. (2012).

In this study, opposition based differential evolution (Rahnamayan *et al*., 2008) 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.

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 ($|V_{min}|<|V_i|<|V_{max}|$), branch currents ($|I_{jl}|<|I_{max,\, jnl}|$) and radiality constraints. The mathematical description is given in Eq. 1:

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

Where:

C_{total} = The total annual cost of the RDS in \$/year
$C_{capacitor}$ = The total capacitor cost of the RDS in \$/year
C_{energy} = 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 (Rao *et al*., 2011b):

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

Where:

$C_{q,\, fixed}$ = The fixed cost for the capacitor placement \$/year
C_i^{annual} = The annual cost for the capacitor installation in \$/(KVAR-year) received from Table 1 (i selected buses for capacitor installation)
Q_i = 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 Fig. 1.

Table 1: Capacitor sizes and cost

Q (kVAR)	Capacitor cost ($/kVAR)
150	0.500
300	0.350
450	0.253
600	0.220
750	0.276
900	0.183
1050	0.228
1200	0.170
1350	0.207
1500	0.201
1650	0.193
1800	0.187
1950	0.211
2100	0.176
2250	0.197
2400	0.170
2550	0.189
2700	0.187
2850	0.183
3000	0.180
3150	0.195
3300	0.174
3450	0.188
3600	0.170
3750	0.183
3900	0.182
4050	0.179

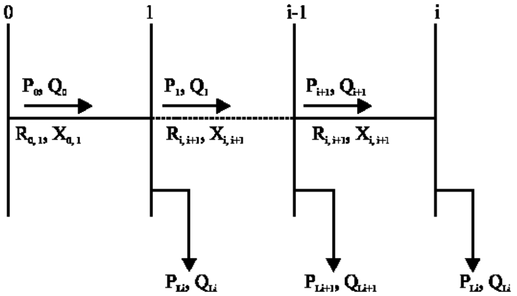

Fig. 1: Single line diagram of a RDS

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 Li. The line resistance and reactance are denoted as $R_{i,j}$ and $X_{i,j}$. $y_i/2$ is the total shunt admittance at bus i. The power flow equations for the RDS is given by:

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

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

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

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

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

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:

- Loads are static
- RDS is reactive power compensated
- Operation and maintenance costs of the capacitors are negligible

PROPOSED ODE ALGORITHM

Procedure for reconfiguration: For reconfiguration, switches present in the distribution network are considered as variables. For instance, closing of S_{33}, S_{34}, S_{35}, S_{36}, 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.

In order to reduce the dimension of the variables, Plant Growth Simulation Algorithm (PGSA) has been employed in this study (Kasaei and Gandomkar, 2010). 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:

- Open state: a switch is open in a feasible solution
- Closed state: a switch is closed in a feasible solution
- Permanent closed state: a switch is closed in all feasible solutions

- 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, researchers 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.

Optimal capacitor placement: Optimal capacitor placement process has two major tasks the capacitors location identification and 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 Fig. 2. 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. The real power loss of the distribution line (m) is given by:

$$P_m = R_m \frac{(P^2_{i+1,\,eff} + Q^2_{i+1,\,eff})}{V^2_{i+1}} \tag{8}$$

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

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

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 (i.e., <1.01 p.u.) of normalized voltage (|V|/0.95) (Kasaei and Gandomkar, 2010) 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.

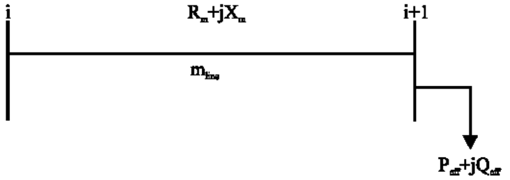

Fig. 2: Single line diagram of a distribution line for loss sensitivity factor

Search strategy through Opposition based Differential Evolution (ODE): The selection of number of variables has been decided based on the three different cases. 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.

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. 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 as:

```
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;
}
```

SIMULATION RESULTS

The effectiveness of the algorithm has been validated through IEEE 33-bus Test Distribution Systems as described by Kasaei and Gandomkar (2010). 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 12.66 kV. The corresponding power loss is 202.7 kW.

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:

- The open switches are S_{33}, S_{34}, S_{35}, S_{36} and S_{37}
- The closed switches are S_1-S_{32}
- The permanently closed switches are S_1, S_2, S_3, S_{18} and S_{22} (since these switches are near to the feeder)
- 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:

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

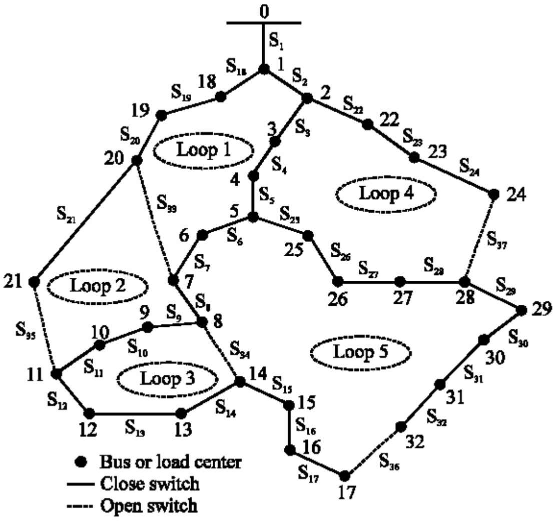

Fig. 3: IEEE 33-bus RDS with state variable sketch

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 139.54 kW 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 202.67-159.89 kW 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 34,049.75-28,392.12 \$/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 3, it is identified that the buses

Table 2: 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 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	Capacitor placement only	Reconfiguration and capacitor placement (Montoya and Ramirez, 2012)	Proposed reconfiguration and capacitor placement
Loss (kW)	202.670	139.5400	159.890	101.499	101.420
Min. bus voltage (pu)	0.913	0.9378	0.933	0.957	0.959
Total capacitor size (kVAR)	-	-	2940.000	1685.000	1027.000
Power loss cost ($/(kW-year))	-	23444.6200	26861.590	17038.560	17039.030
Capacitor Cost ($/year)	-	-	1529.870	722.840	159.940
Total annual cost ($/year)	34049.750	23444.6200	28,391.460	18761.400	18198.960
Saving (%)	-	31.1400	16.610	44.900	46.550

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 202.67-101.42 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 34,049.75-18,198.96 $/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 earlier published research (Montoya and Ramirez, 2012). 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.

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 study. 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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