Optimal Capacitor Allocation for the Reconfigured Network using Ant Lion Optimization Algorithm

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Abstract
This paper presents an Ant Lion Optimization (ALO) algorithm for optimal allocations and sizing of capacitors for the original and reconfigured distribution systems. Feeder reconfiguration is the process of changing the distribution network topology by changing the status of sectional and tie switches. First the candidate buses for installing capacitors are identified using Fuzzy Approach. Then the proposed ALO algorithm is to find the size of capacitors. The main objective is to reduce the total real loss and consequently, to increase the net energy savings per year. The attained results via the proposed ALO algorithm are compared with original network to highlight their benefits. The proposed algorithm is to minimize the losses and total cost and to enhance the voltage profiles and net saving for various distribution systems. The proposed ALO algorithm has been tested on a standard IEEE 33- bus and 69-bus test system for capacitor placement for original and reconfigured network to reduce the power loss and energy savings.

Keywords: Ant Lion Optimization, Energy savings, Optimal Capacitor Placement, Radiality Constraint, Simultaneous Reconfiguration.

INTRODUCTION
In power distribution system (PDS) planning, the major challenge is to supply uninterruptedly power within allowable limits. In primary distribution systems, the sectional switches are used for both protection (to isolate a fault) and for configuration management to reconfigure the network. A power distribution network consists of radial feeders which can be connected together by several tie switches. Power loss reduction major concern of electrical distribution utilities. Among conventional methods, optimal reconfiguration and capacitor placement are the two successful techniques which can be applied on the network. However, the configuration is changed during switching operation by changing the status of sectional and tie switches.

Reconfiguration (RCG) of radial distribution systems is a very successful and efficient approach to reduce losses, improvement of voltage profile and enhance system reliability. Distribution networks are generally structured in mesh but operated in a radial configuration for effective coordination of their protective schemes and to reduce the fault level. The aim of network reconfiguration is to obtain a radial operating configuration that minimizes real power loss while satisfying all the operational constraints without the islanding of any node.

A number of research papers have been emerged on the general topic of feeder reconfiguration, there is still a need to develop more appropriate and effective techniques for the network reconfiguration under reliable operating conditions. Many recent researches on distribution feeder reconfiguration on reducing the power losses. Merlin[1] offered the sequential opening algorithm. Simplicity is the main advantage of heuristic methods. Das[2] proposed a simple and efficient method for solving radial distribution networks, which involves only the evaluation of a simple algebraic expression of voltage magnitudes and no trigonometric functions as opposed to the standard load flow case. Shirmohammadi[3] described a technique for the reconfiguration of distribution networks to reduce their resistive line losses.


Damodar Reddy[13] described an Particle Swarm Optimization (PSO) for maximum savings using capacitor
placements and locations are identified by fuzzy approach. El-Fergany[14] proposed an evolutionary algorithm of optimal capacitor allocation for annual net savings. Sathish[15] proposed Bat Algorithm(BA) and Cuckoo Search (CS) algorithm for the placement of fixed size and variable size of capacitors for real loss minimization and maximum network savings. Hamed[16] proposed an competent algorithm is called graph theory striking a mixed integer programming for reconfiguration problem with radiality constraint. Mostafa[17], described to solve Network reconfiguration problem and capacitor placement are used to decrease real power losses and to maintain voltage profiles within acceptable limits in distribution networks. Gnanasekaran[18], presented a new efficient technique is called Shark Smell Optimization (SSO) algorithm used to find optimal size and position of shunt capacitors with the objective of reducing the cost due to energy loss and reactive power compensation.

This paper proposes(i) Reconfiguration using simultaneous switching (ii) Capacitor installations for the original network. (iii) Capacitor allocations for the reconfigured network using fuzzy and ALO algorithm The proposed ALO algorithm has been tested on a standard IEEE 33- bus and 69-bus test systems.

PROBLEM FORMULATION
The complex power injected into the bus n is given [13] by
\[ S_{L,n} = P_{L,n} + jQ_{L,n} = V_n I_{n} \]
The load current at any bus n is given by
\[ I_{L,n} = \frac{P_{L,n} + jQ_{L,n}}{V_n} = \frac{P_{L,n} - jQ_{L,n}}{V_n^*} \]

Figure 1: A Simple 6-bus radial distribution system

B. Load Flow Solution:
The relation[14] between load currents and branch currents can be found by using KCL equations as follows.
\[ I_{b1} = I_{L2} + I_{b2} \]
(2)
\[ I_{b2} = I_{L3} + I_{b3} + I_{b5} \]
(3)
\[ I_{b3} = I_{L4} + I_{b4} \]
(4)
\[ I_{b4} = I_{L5} \]
(5)
\[ I_{b5} = I_{L6} \]
(6)

Thus, the relationship between load currents and branch currents can be expressed in matrix form as shown below.
\[ [I_L] = [BIBC][I_b] \]
(7)

C. Forward sweep
The receiving end voltages can be premeditated by forward sweeping across the line by subtracting the line section drop from the sending end voltages of the line section.
\[ V_q(k) = V_p(k) - I_n(k) * Z_p(k) \]
(8)

D. Radiality constraint
All load buses must be connected to the source node. According to graph theory a tree satisfies the following equation.
\[ N_{br} = N_{no} - 1 \]
(9)
Where, \( N_{br} \) is the number of branches and \( N_{no} \) is the number of nodes.
The proposed ALO algorithm is used for solving distribution network reconfiguration based on switching loops LSW33 [10] and LSW69 [11] for the checking radial structure of distribution network has been used in this approach.

E. Power losses:
The power losses in the distribution systems are real power loss and reactive power loss. The total real power loss in a balanced radial distribution system consisting of \( B \) branches can be written as
\[ P_{L} = \sum_{k=1}^{B} I_k^2 R_k \]
(10)

F. Objective Function:
The objective function of the problem is formulated to exploit the power loss reduction in the radial distributed system, which is given by
\[ \text{Fitness Function} = \min \{ P_{L,\text{loss}} \} \]
(11)
The cost related to capacitor compensation for the original and reconfigured network are calculated. On the other hand, the benefits due to peak power loss reduction of transmitted power in cables and transformers are neglected. Here, switching losses in the reconfiguration process are also neglected. The maximum annual savings per year is given by
\[ S_k = C_1 * \Delta P_{L} * T - C_2 * N_{dim} - C_3 * \sum_{k=1}^{dim} Q_c(k) \]
(12)
Where, \( S_k \) is the net savings in $/year, \( C_1 \) is a factor the energy losses converted into dollars, \( C_2 \) is the installation cost of capacitors in dollars, \( C_3 \) is a factor to convert the rating of capacitors into dollars, \( T \) is the Total time period for an year in hours, \( \Delta P_{L} \) is the system real power loss reduction in KiloWatts, \( N_{dim} \) is the number of candidate buses for capacitors, \( Q_c(k) \) is the capacitor bank rating at bus \( k \) .
NETWORK RECONFIGURATION

The fundamental loops are determined for the meshed distribution network by closing all tie or secure switches. The number of fundamental loops on the meshed distribution network is equal to the number of tie-switches of the system and are given by the relation [3].

\[ N_l = N_{ele} - N_{be} + 1 \]  \hspace{1cm} (13)

Where, 

- \( N_l \) is the total number of links (tie switches) for the distribution network. \( N_{ele} \) is the total number of elements i.e., sectionalizing plus tie-switches. \( N_{be} \) is the total number of branches. From Table 1, switching loops is designed by considering the real power loss constraint.

Basic configuration for 33-bus system = \([33 \ 34 \ 35 \ 36 \ 37]\) and Basic configuration for 69-bus system = \([69 \ 70 \ 71 \ 72 \ 73]\).

Table 1: Simultaneous Reconfiguration for 33 Bus

<table>
<thead>
<tr>
<th>Test System</th>
<th>Loops corresponding to Possible Switchings</th>
<th>SW1</th>
<th>SW2</th>
<th>SW3</th>
<th>SW4</th>
<th>SW5</th>
</tr>
</thead>
<tbody>
<tr>
<td>33 Bus System</td>
<td>SW1</td>
<td>33 35 36 37 34</td>
<td>6 8 15 22 12</td>
<td>7 9 16 23 13</td>
<td>-- 10 17 24 14</td>
<td>-- 11 29 25 --</td>
</tr>
<tr>
<td>69 Bus System</td>
<td>SW1</td>
<td>72 71 73 69 70</td>
<td>46 11 21 9 15</td>
<td>47 12 22 10 16</td>
<td>48 13 23 -- 17</td>
<td>49 14 24 -- 18</td>
</tr>
</tbody>
</table>

Here, LSW is used for the optimal switching corresponding to minimum loss in each loop while maintain the radial structure in the distribution systems [13].

ANT LION OPTIMIZATION (ALO)

This manuscript also proposed a new algorithm called Ant Lion Optimizer [9] as an alternative approach for solving optimization problems. As its name implies, the ALO algorithm imitates the intelligent exploits of antlions in hunting ants in environment.

Antlions (doodlebugs) belong to the Myrmeleontidae family and Neuroptera order (net-winged creatures). The lifecycle of antlions includes two main phases: larval and adult. A natural total lifespan can take up to 3 years, which mostly occurs in larvae (only 3–5 weeks for adulthood). Antlions undergo metamorphosis in a cocoon to become adult. They mostly hunt in larvae and the adulthood period is for reproduction.

The ALO algorithm mimics relations between antlions and ants in the trap. To mould such dealings, ants are essential to move over the search space, and antlions are authorized to hunt them and grow to be fitter using traps. Since ants travel stochastically in nature when searching for food, a random walk using rolette wheel is chosen for modelling ants movement. In order to keep the random walks inside the search space, they are normalized min–max normalization using the following equation.

\[ X = \begin{cases} 
0, & \text{CumSum}(2*\text{rand}(\text{max_iter},1)>0.5) - 1 \\
\end{cases} \]

\[ RW(i) = X(i) = \frac{(X - a) \cdot (d - c)}{(b - a)} + c \]  \hspace{1cm} (14)

Where \( a = \min(\text{RandomWalk}) \)

\( b = \max(\text{RandomWalk}) \)

\( c = lb(dim) \)

\( d = ub(dim) \)

Implementation of the Projected ALO Algorithm:

Step 1: Initialize the parameters. Initialize the positions of antlions and ants.

Step 2: Set boundaries (upper bound and lower bound) and dimensions to the parameters that are to be optimized.

Step 3: Initialize variables to save the position of elite, sorted antlions to the parameters.

Step 4: Calculate the fitness of initial antlions and sort them.

Step 5: Run the basic load flow to obtain the real and reactive power losses and voltage profile before optimization.

Step 6: Calculate the initial fitness for ants and sort them.

Step 7: Main loop started from the second iteration since the first iteration was dedicated to calculating the fitness of antlions.

Step 8: Main loop is simulate random walks. Select ant lions based on their fitness i.e., the better antlion having the higher chance of catching ant.

Step 9: The ant position can be calculated as

\[ ant\_position(i) = \frac{RA(C_n) + RE(C_n)}{2} \]  \hspace{1cm} (14)

Where, RA is the random walk around the selected antlion and RE is the random walk around the elite by rolette wheel.
Step 10: Check the Boundaries for position. Bring back the antlions of ants inside search space, if they go beyond the boundaries. Update the ant position by eq.(15).

\[
ant_{-} \text{position}(i) = \left( \text{ant}_{-} \text{position}(i) \times \left( (\text{Flag}_{ub} + \text{Flag}_{lb}) \right) \right) + \text{ub} \times \text{Flag}_{ub} + \text{lb} \times \text{Flag}_{lb}
\]

Step 11: Update antlion positions and fitnesses based on the ants, if an ant becomes fitter than an antlion we assume it was caught by the antlion and the antlion update goes to its position to build the trap.

Step 12: Update the Convergence curve upto max iterations.

Step 13: Display the best score which gives the optimum result with respect to best ant position.

<table>
<thead>
<tr>
<th>Table 2: Control Parameters for ALO algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>parameters</td>
</tr>
<tr>
<td>SearchAgents</td>
</tr>
<tr>
<td>Max no of iter</td>
</tr>
<tr>
<td>No.of dim</td>
</tr>
<tr>
<td>Lower Bound</td>
</tr>
<tr>
<td>Upper Bound</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Best Score</td>
</tr>
<tr>
<td>Best Position</td>
</tr>
</tbody>
</table>

RESULTS

Optimal locations of capacitors are identified using fuzzy approach and ALO method is used to find the sizes of the capacitors for original and reconfigured networks. These methods are applied to standard IEEE 33-bus and 69-bus systems. In all calculations the control parameters are, \( C_1 = \$0.06 / kWh; C_2 = \$1000 / each \_ Location; C_3 = \$3 / kVAr \) \( T = 8760 \text{hours} / \text{year} \).

Optimal Location of Shunt Capacitor:

Fuzzy approach is used to identify the capacitor locations[8]. For the 33-bus system, the capacitor placement suitability index (CPSI) value greater than or equal to 0.75 are considered for capacitor location. Node 30 is selected for the optimal capacitor placement. For the 69-bus system, the capacitor placement suitability index (CPSI) value greater than or equal to 0.75 are considered for capacitor location. Node 61 is selected for the optimal capacitor placement for the original and reconfigured network.

IEEE 33-Bus test system:

The 33 bus system of 100MVA, 12.66KV, IEEE 33-bus test system with 37 branches, 32 sectionalizing switches and 5 tie switches. The total substation loads for the basic configuration are 4715 kW and 2300 kVAr [8]. By using fuzzy approach, the top ten locations obtained according to the CPSI values are [30, 32, 31, 8, 29, 7, 14, 18, 33, 6]. Here, the capacitors are installed based on CPSI values which is greater than or equal to 0.75 for 33-bus system, which are shown in Table 3. The simultaneous reconfiguration results for 33-bus system are shown in Table 4.

<table>
<thead>
<tr>
<th>Table 3: Capacitor Results for 33 bus system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Number</td>
</tr>
<tr>
<td>Capacitor Size in kVAr</td>
</tr>
<tr>
<td>Total Real Power Loss before capacitor placement in kW</td>
</tr>
<tr>
<td>Loss Reduction</td>
</tr>
<tr>
<td>% Loss Reduction</td>
</tr>
</tbody>
</table>

From Table 2, the real power loss for the original network was 369.2558 kW and after capacitor placement by using the projected ALO algorithm, power loss is reduced to 297.9886 kW. From Table 3, the real power loss for reconfigured network was 238.2888 kW and after capacitor placement for the reconfigured network the power loss is reduced to 203.1939 kW. The comparison of loss reduction, Energy savings[14] and net savings of capacitor placement for the original and reconfigured network are shown in Table 5. The annual energy savings are $ 37,458 and $ 87,282 with capacitor installations for the original and reconfigured network are shown in Table 5. The annual energy savings are $ 37,458 and $ 87,282 with capacitor installations for the original and reconfigured network for 33-bus system. Moreover, the annual net benefits are $ 32,513 and $ 82,944 with capacitor installations for the original and reconfigured network for 33-bus system.
### Table 5: Final Results of 33-Bus System

<table>
<thead>
<tr>
<th>Point of comparison</th>
<th>Capacitors for original network</th>
<th>Capacitors for reconfigured network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Loss</td>
<td>369.2558 kW</td>
<td>238.2888 kW</td>
</tr>
<tr>
<td>Final Loss</td>
<td>297.9886 kW</td>
<td>203.1939 kW</td>
</tr>
<tr>
<td>Loss Reduction</td>
<td>71.2672 kW</td>
<td>166.0619 kW</td>
</tr>
<tr>
<td>Energy Savings</td>
<td>$37,458</td>
<td>$87,282</td>
</tr>
<tr>
<td>Compensation</td>
<td>$4,945</td>
<td>$4,338</td>
</tr>
<tr>
<td>Net Savings</td>
<td>$32,513</td>
<td>$82,944</td>
</tr>
</tbody>
</table>

### IEEE 69-Bus test system

The final configuration of the 100MVA, 12.66kV, IEEE 69-bus test system with 73 branches, 68 sectionalizing switches and 5 tie switches as shown in fig 4. The total substation loads for the basic configuration are 3.8022 MW and 2.6946 MVAr [4]. By using fuzzy approach, the top ten locations obtained according to the CPSI values are [61, 64, 59, 65, 62, 58, 25, 17, 18, 19]. Here, the capacitors are installed based on CPSI values which is greater than or equal to 0.75, which are shown in Table 6. The simultaneous reconfiguration results are shown in Table 7.

### Table 6: Capacitor Results for 69 bus system

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Capacitor Size in kVAR</th>
<th>Total Real Power Loss before capacitor placement in kW</th>
<th>Total Real Power Loss before capacitor placement in kW</th>
<th>Loss Reduction</th>
<th>% Loss Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>1329.9980</td>
<td>225.0044</td>
<td>152.0446</td>
<td>72.9598</td>
<td>32.43 %</td>
</tr>
</tbody>
</table>

### Table 7: Simultaneous Reconfiguration for 69 bus system

| Total real power loss of the original network | 225.0044 kW |
| Optimal Switchings for Reconfiguration        | 57,14,61,69,70 |
| Total real power loss of the reconfigured network | 99.6216 kW |
| Loss reduction after optimal reconfiguration | 55.72 % |
| Location of capacitors for RCG network       | 61 |
| Size of capacitor (kVAR)                     | 1049.9715 |
| Total real power loss after capacitor placement for the reconfigured network | 73.5478 |
| % Loss reduction after capacitor placement for the reconfigured network | 67.31 % |

From Table 5, the real power loss for the original network was 225.0044 kW and after capacitor placement by using the projected ALO algorithm, power loss is reduced to 152.0446 kW. From Table 6, the power loss for reconfigured network was 99.6216 kW and after capacitor placement for the reconfigured network the power loss reduced to 73.5478 kW. The comparison of loss reduction, Energy savings[14] and net savings of capacitor placement for the original and reconfigured network are shown in Table 8.

### Table 8: Final Results of 69-Bus System

<table>
<thead>
<tr>
<th>Point of comparison</th>
<th>Capacitors for original network</th>
<th>Capacitors for reconfigured network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Loss</td>
<td>225.0044 kW</td>
<td>99.6216 kW</td>
</tr>
<tr>
<td>Final Loss</td>
<td>152.0446 kW</td>
<td>73.5478 kW</td>
</tr>
<tr>
<td>Loss Reduction</td>
<td>72.9598 kW</td>
<td>151.4566 kW</td>
</tr>
<tr>
<td>Energy Savings</td>
<td>$38,348</td>
<td>$79,606</td>
</tr>
<tr>
<td>Compensation</td>
<td>$4,990</td>
<td>$4,150</td>
</tr>
<tr>
<td>Net Savings</td>
<td>$33,358</td>
<td>$75,456</td>
</tr>
</tbody>
</table>

The annual energy savings are $38,348 and $79,606 with capacitor installations for the original and reconfigured network for 69-bus system. Moreover, the annual net benefits are $33,358 and $75,456 with capacitor installations for the original and reconfigured network for 69-bus system.

### CONCLUSION

In this paper, Reconfiguration using simultaneous switching is implemented. The Capacitor installations for the original and reconfigured network applied successfully. The reduction in power losses leads to energy savings with capacitor placement for the original and reconfigured network. In this paper, the Ant Line Optimization algorithm is successively applied to capacitor allocation for original and reconfigured network. The power loss reduction for the original network is 19.3% and 32.43% with capacitor installation for 33-bus and 69-bus respectively. The power loss reduction is 44.97% and 67.31% with capacitor installation for the reconfigured network of 33-bus and 69-bus respectively. Results show the considerable reduction in losses and significant increase in the energy savings of the original and reconfigured network.

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