Capacitor Placement Using Bat Algorithm for Maximum Annual Savings in Radial Distribution systems

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ABSTRACT
This paper presents a two stage approach that determines the optimal location and size of capacitors on radial distribution systems to improve voltage profile and to reduce the active power loss. In first stage, the capacitor locations can be found by using loss sensitivity method. Bat algorithm is used for finding the optimal capacitor sizes in radial distribution systems. The sizes of the capacitors corresponding to maximum annual savings are determined by considering the cost of the capacitors. The proposed method is tested on 15-bus, 33 bus, 34-bus, 69-bus and 85-bus test systems and the results are presented.

Keywords - capacitor placement, loss sensitivity method, Bat algorithm, radial distribution system

I. Introduction
Distribution System is that part of the power system which connects the high voltage transmission system to low voltage consumers. 70% of the total losses are occurring in the primary and secondary distribution system, while the remaining 30% in transmission and sub transmission lines. Distribution losses are 15.5% of the generation capacity whereas the target level is 7.5%. Therefore the primary and secondary distribution system must be properly planned to ensure losses within the tolerable limits.

Distribution systems have more losses and poor voltage regulation. Almost 13% of the generated power is wasted as I^2R losses. Loss reduction in distribution systems by applying the optimization methods is the current potential area of research. The basic requirements of a good distribution system are good voltage profile, availability of power on demand and reliability. The efficiency of the distribution system can be improved by adopting Reactive power compensation, Network Reconfiguration, Distributed generation and Hybrid methods. Each method has its own advantages and disadvantages.

Capacitors are commonly used to provide the reactive power compensation in distribution systems. Shunt capacitors placement is the simple and efficient method in distribution networks to reduce losses, improve voltage profile, maximize transmitted power in cables and transformer, increase the thermal capacities of the distribution lines and transformers and improve power factor. However, shunt capacitor installation in distribution networks requires an appropriate location and size of the capacitors. Thus, optimal capacitor placement plays an important role in minimizing the losses through proper installation and sizing which can be achieved by using optimization techniques.

Su et al. (2005) introduced meta heuristic algorithm called ant colony search algorithm to solve the capacitor placement problem. Venkatesh and Ranjan. (2006) proposed a new dynamic structure for an evolutionary programming algorithm with fuzzy modeling to solve the capacitor placement problem. Khalil et al. (2006) proposed binary particle swarm optimization method for placing the fixed capacitor banks in the distribution systems. Prakash and Sydulu. (2006, 2007) proposed two methods to solve the capacitor placement problem. Particle Swarm Optimization method and α-coefficients method to find the size of the capacitors to be installed.

Das. (2008) proposed a method which is designed as a multi objective approach using both genetic algorithm and fuzzy. Damodar Reddy and Veera Reddy. (2008) presented a new methodology to solve the capacitor placement problem. Fuzzy approach is used to find the locations and real coed genetic algorithm is used to find the capacitor sizes to reduce the losses and improve the voltage profile based on the net savings. Srinivasa Rao and Narasimham. (2008) proposed a new and efficient plant growth simulation algorithm which is used to determine the sizes of the capacitors.

methodology using new membership functions in fuzzy and simulated annealing technique to solve the capacitor placement problem.

Segura et al. (2010) presented a heuristic algorithm to solve the capacitor placement problem in distribution systems. Abdelaziz et al. (2010) introduced two methods. First method determines the locations and sizes of the capacitors and the loss reductions are calculated. Second method finds the solution for optimal placement of voltage regulators problem by determining the location and tapping ratio of the regulators keeping the voltage within the limits. Abbas Babazadeh et al. (2011) proposed particle swarm optimization for transportation network design problem. Paul and Jewell (2012) presented the power loss index and sensitivity approach using fuzzy. Sizes of the capacitors are determined by genetic algorithms. Dong et al. (2013) presented a mixed integer programming model and the cost is evaluated by adopting the net present value criterion. Dinakara Prasad Reddy P et al. (2011, 2012 and 2013) proposed two methods for loss reduction in distribution systems using optimal capacitor placement i.e. differential evolution and hybrid genetic algorithms. X.S. Yang. (2013) proposed a bat algorithm for optimization problems. In this paper bat algorithm is used to find the optimal capacitor size.

II. Capacitor Locations Using Loss Sensitivity Method

In this paper loss sensitivity method is to find capacitor locations. It is a logical process of computing the extreme effect on the real power losses of the system with respect to the nodal reactive power. The connection for calculating the loss sensitivity for any bus can be obtained as follows

Consider a distribution line with an impedance $R + jX$ and a load of $P_{eff} + jQ_{ref}$ connected between ‘i’ and ‘j’ buses as given below in Figure.1.

![Fig1. A distribution line with impedance and a load.](image)

The active power losses ($P_{loss}$) and reactive power loss ($Q_{loss}$) in the distribution line are given as

$$P_{loss}[j] = \frac{(P_{ref}^2[j] + Q_{ref}^2[j])R[k]}{(V[j])^2}$$  \hspace{1cm} (1)

$$Q_{loss}[j] = \frac{(P_{ref}^2[j] + Q_{ref}^2[j])X[k]}{(V[j])^2}$$  \hspace{1cm} (2)

Loss sensitivity $SL_j$ for any bus $j$ can be given as

$$SL_j = \frac{2*Q_{eff}[j]*R[k]}{(V[j])^2}$$  \hspace{1cm} (3)

Based on $SL_j$, the buses are ranked in descending order of its values. The bus having highest numeric value is ranked top in the priority list and is considered first for capacitor placement. The buses having high value of the loss sensitivity $SL$, along with voltage $(V)$ in p.u. at each bus satisfying the condition $V/0.9>1.1$ are selected as candidate buses for capacitor placement.

Candidate location vector of 15, 33, 34, 69 and 85 bus radial distribution system contains set of sequence of buses given as $\{6, 3\}, \{6, 28, 29, 5\} \{19, 20, 22\}, \{57, 58, 61\}$ and $\{8, 57, 5, 7, 57\}$ respectively.

III. Bat Algorithm

Bat Algorithm (BA) is a nature inspired metaheuristic algorithm developed by Xin She Yang in 2010. This paper presents the application of BA for finding the optimum sizes of capacitors after the optimum locations are determined using loss sensitivity method.

Metaheuristic algorithms use certain trade-off of randomization and local search. Randomization provides a good way to move away from local search to the search on the global scale. Therefore, almost all the metaheuristic algorithms intend to be suitable for global optimization. This algorithm is based on the echolocation behavior of micro bats. These bats can emit a very loud and short sound pulse, the echo that reflect back from the surrounding objects is received by their extraordinary big auricle.

Bat algorithm is developed by idealizing some of the characteristics of micro bats. The approximated or idealized rules are:

a) All bats use echolocation to sense distance and they also know the difference between prey and barriers.

b) Bats fly randomly with velocity $V_i$ at position $x_i$ with a fixed frequency $f_{min}$ varying wavelength $\lambda$ and loudness $A_0$ to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and the rate of pulse emission $r$ $\in [0,1]$ depending on the proximity of the target.

c) Loudness varies from a large positive $A_0$ to a minimum constant value.

The steps of Bat Algorithm is as follows.

3.1 Population

The initial population i.e., number of virtual bats for BA (n) is generated randomly using equation (4). Where $Q_{min}$ and $Q_{max}$ are lower and upper bounds of capacitive compensation. After finding the initial fitness of the population for given objective function, the values are updated based on movement, loudness and pulse rate.

$$X_{ij} = Q_{min} + (Q_{max} - Q_{min}) * rand (1, d)$$  \hspace{1cm} (4)
3.2 Movement of Virtual Bats

The rules for updating the positions \( X_i \), Frequency \( f_i \), and velocities \( V_i \) of the virtual bats are given as

\[
\begin{align*}
    f_i &= f_{\text{min}} + (f_{\text{max}} - f_{\text{min}}) \beta \\
    V_i &= V_{i-1} + (X_{i-1} - X_i) f_i \\
    X_i &= X_{i-1} + V_i
\end{align*}
\]

(5) (6) (7)

Where \( \beta \in [0,1] \) is a random vector and \( X_i \) is current global best solution. \( f_{\text{min}} \) and \( f_{\text{max}} \) are frequency minimum and frequency maximum.

For local search part once the solution is generated among the current best solution a new solution of each bat is generated using random walk.

\[
X_{\text{new}} = X_{\text{old}} + \varepsilon A_i
\]

(8)

Where \( \varepsilon \in [-1,1] \) is a random number.

3.3 Loudness and Pulse Emission

The loudness \( A_i \) and the rate of pulse emission \( r_i \) are updated accordingly as the iterations proceed. The loudness decreases and rate of pulse emission increases as the bat closes on its prey i.e., the equations for convergence can be taken as

\[
\begin{align*}
    A_{i+1} &= A_i \alpha \\
    r_{i+1} &= r_i (1 - \exp(-\gamma t))
\end{align*}
\]

(9) (10)

Where \( \alpha \) and \( \gamma \) are constants. For any \( 0<\alpha<1 \) and \( \gamma>0 \), we have

\[
A_i \to 0, \quad r_i \to r_i^0 \quad \text{as} \quad t \to \infty
\]

The initial loudness \( A \) can typically be 0.9, while the initial emission rate \( r_i^0 \) can be [0, 1]. In this paper \( r_i^0 = 0.5 \).

3.4 Algorithm for Capacitor Placement and Sizing Using Loss sensitivity method and Bat Algorithm

After identifying the \( n \) number of candidate locations using loss sensitivity method, the capacitor sizes in all these \( n \) candidate locations are obtained by using the Bat algorithm. Based on the above three rules, the basic steps of the Bat algorithm are framed.

Step 1: Initially \([\text{pop} \times n]\) number of nest population are generated randomly within the limits \( Q_{\text{min}} \) and \( Q_{\text{max}} \) where \( \text{pop} \) is the population size and \( n \) is the number of capacitors

\[
X_{ij} = Q_{\text{min}} + (Q_{\text{max}} - Q_{\text{min}}) \cdot \text{rand}(1,d)
\]

Step 2: By placing all the \( n \) capacitors of each nest at the respective candidate locations and load flow analysis is performed to find the total real power loss \( P_i \). The same procedure is repeated for the \( n \) number of particles to find the total real power losses. Fitness value corresponding to each nest is evaluated using the below equation for maximum annual savings. Fitness function for maximum savings (considering the capacitor cost) is given by

\[
S = K_{\text{p}} \Delta P + K_{\text{e}} \Delta E - K_{\text{c}} Q_c
\]

Where \( S \) is the savings in $/year, \( K_{\text{p}} \) is a factor to convert peak power losses to dollars, \( K_{\text{e}} \) is a factor to convert energy losses to dollars, \( K_{\text{c}} \) is the cost of capacitors in dollars, \( \Delta P \) is the reduction in peak power losses, \( \Delta E \) is the reduction in energy losses and \( Q_c \) is the size of the capacitor in kvar.

The capacitor sizes corresponding to maximum savings are required. For any one nest, the negative \( S \) value indicates that savings are negative and \( S \) is fixed at \( S \) (minimum) and capacitor sizes corresponding to that particle are fixed at \( Q_c \) (minimum).

Step 3: Start iterations

Step 4: Generate new population (solution) by using (5), (6) and (7) equations.

Step 5: If the random number is greater than the rate of pulse emission then select a solution among the best solution and generate a local solution around the best solution using equation (8). Otherwise new solution will be same as in step 4.

Step 6: Evaluate the fitness of new solution. If the fitness is greater than the current best solution, then replace the current best solution with the present obtained value and update loudness and pulse rate using equations (9) and (10). Here the value of \( A_i \) decreases and \( r_i \) increases.

Step 7: The iteration count is incremented and if iteration count is not reached maximum then go to step 4.

Step 8: The capacitor sizes corresponding to maximum fitness gives the optimal capacitor sizes in \( j \) capacitor locations and the results are printed.

Step 9: The capacitor sizes corresponding to maximum savings gives the optimal capacitor sizes in \( n \) capacitor locations and the results are printed.

IV. Results

The proposed method for loss reduction by capacitor placement is tested on IEEE 15,33,34,69 bus and 85 bus radial distribution systems. Loss sensitivity method is used to find the optimal capacitor locations and Bat algorithm is used to find the optimal capacitor sizes for maximum annual savings. When the proposed method is tested on 15 bus, 33 bus, 34 bus, 69 bus and 85 bus systems the total real power losses before and after placement of capacitors and annual saving are shown in tables. The data used for finding the optimal capacitor sizes are \( \text{nop}=50, \quad Q_{\text{min}}=100 \text{ kvar}, \quad Q_{\text{max}}=1500 \text{ kvar}, \quad p_a=0.25, \quad K_{\text{p}}=150 \text{ $/kW}, \quad K_{\text{e}}=-0.06 \text{ $/kWh}, \quad K_{\text{c}} = 5 \text{ $/kVAR} \text{ and } I_{\text{max}}=1000 \).
Table 1. Results for 15 Bus System

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Size (kvar)</th>
<th>Total kVAR placed</th>
<th>Total Power loss in kW (before)</th>
<th>Total Power loss in kW (after)</th>
<th>Savings in dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>827</td>
<td>987</td>
<td>61.7944</td>
<td>34.5376</td>
<td>$ 13,398</td>
</tr>
</tbody>
</table>

Table 2. Results for 33 Bus System

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Size (kvar)</th>
<th>Total kVAR placed</th>
<th>Total Power loss in kW (before)</th>
<th>Total Power loss in kW (after)</th>
<th>Savings in dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>113</td>
<td>1567</td>
<td>369.2543</td>
<td>291.6287</td>
<td>$ 38,678</td>
</tr>
</tbody>
</table>

Table 3. Results for 34 Bus System

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Size (kvar)</th>
<th>Total kVAR placed</th>
<th>Total Power loss in kW (before)</th>
<th>Total Power loss in kW (after)</th>
<th>Savings in dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1152</td>
<td>1919</td>
<td>221.7235</td>
<td>169.2287</td>
<td>$ 25,713</td>
</tr>
</tbody>
</table>

Table 4. Results for 69 Bus System

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Size (kvar)</th>
<th>Total kVAR placed</th>
<th>Total Power loss in kW (before)</th>
<th>Total Power loss in kW (after)</th>
<th>Savings in dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>71</td>
<td>1280</td>
<td>225</td>
<td>151.9464</td>
<td>$ 42,737</td>
</tr>
</tbody>
</table>

Table 5. Results for 85 Bus System

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Size (kvar)</th>
<th>Total kVAR placed</th>
<th>Total Power loss in kW (before)</th>
<th>Total Power loss in kW (after)</th>
<th>Savings in dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1065</td>
<td>2092</td>
<td>225</td>
<td>168.9813</td>
<td>$ 87,761</td>
</tr>
</tbody>
</table>

V. Conclusion

In this paper, a two stage methodology of finding the optimal locations and sizes of shunt capacitors for reactive power compensation of radial distribution systems is presented. Loss sensitivity method is proposed to find the optimal capacitor locations and Bat algorithm is proposed to find the optimal capacitor sizes. By installing shunt capacitors at all the potential locations, the total real power loss of the system has been reduced significantly and at same time annual savings are increased and bus voltages are improved substantially. The proposed method is tested on IEEE 15, 33, 34, 69 and 85 bus radial distribution systems. The proposed Bat algorithm iteratively searches the optimal capacitor sizes for the maximum annual savings. Bat algorithm is less complex because less parameters are there when compared to other algorithms.

References


