Sensitivity Based Capacitor Placement with Self-Adaptive Differential Evolution with Neighborhood Search Algorithm

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Abstract—This paper presents comparative study of two sensitivity based methods namely loss sensitivity method and bus sensitivity method, for the optimal capacitor placement problem. These methods will give best capacitor locations for the reactive power compensation. Self-adaptive Differential Evolution with Neighborhood Search (SaNSDE) algorithm is used to find the optimal capacitor sizes. The performance of these two methods is compared on the basis of the active losses and voltage profile of the bus systems after optimal capacitor placement. The methods have been implemented on IEEE 15-bus, IEEE 34-bus and IEEE 69-bus radial distribution systems. The results obtained clearly indicate that bus sensitivity method based capacitor placement gives better results in comparison to the loss sensitivity method.

Index Terms—capacitor placement, bus sensitivity method, loss sensitivity method, self-adaptive differential evolution with neighborhood search

I. INTRODUCTION

In the past few decades the distribution systems were facing several persistent problems. Presently many electric companies in a number of countries experiencing very high losses. Studies shows that 13% of total power generated is wasted in the form of losses at the distribution level. To reduce these losses, shunt capacitor banks are installed on radial distribution feeders. With active power loss reduction and voltage profile improvement as objectives, the optimal capacitor placement problem aims to determine the optimal capacitor location and capacitor sizes in radial distribution systems. Efficient methods are required to determine the best location and sizes. The early approaches were based on heuristic optimization algorithms.

In previous methods the problem the problem are taken as a nonlinear programming model and considered both location and capacitor sizes as continuous variables [1]-[5].

Sundharajan and Pahwa [6] proposed the genetic algorithm approach to determine the optimal placement of capacitors. Das et al. [7] presented a simplified load flow technique for distribution systems. A simple heuristic numerical algorithm that is based on the method of local variation is proposed in [8], [9]. Ng et al. [10], [11] proposed an approach to the capacitor placement problem based on fuzzy expert system. This system containing a set of heuristic rules used to determine the capacitor placement suitability index of each node in the distribution system. Capacitors are placed on the nodes with the highest suitability index.

Das [12] proposed the genetic algorithm approach for reactive power compensation in distribution systems to reduce the energy loss under varying load conditions. Prakash and Sydulu [13] proposed the particle swarm optimization method to size the capacitors in distribution system capacitor placement problem. Papers [14], [15] and [17]-[20] presented a two stage methodology using Practical swarm optimization method, real coded genetic algorithm and differential evolution algorithm, Hybrid genetic algorithm and Bat algorithm with combination of Fuzzy approach for optimal capacitor sizing and location respectively. This paper presents comparative study of two sensitivity based methods. These methods will give best capacitor locations for the reactive power compensation. Self-adaptive differential evolution with neighborhood search (SaNSDE) algorithm is used to find the optimal capacitor sizes.

II. PROBLEM FORMULATION

Capacitor placement in the distribution system is to minimize active power loss of the system, subjected to voltage constraints. The three phase system is considered here as balanced and loads are assumed as time invariant.

Mathematically, the objective function of the problem is described as:

\[ \text{Minimize } f = \min(P_{T, Loss}) \]

Subjected to \( V_{\text{min}} \leq |V_i| \leq V_{\text{max}} \)

where \( P_{T, Loss} \) is the total real power loss of the system, \( |V_i| \) voltage magnitude of bus \( i \), \( V_{\text{min}} \) and \( V_{\text{max}} \) are bus minimum and maximum voltage limits.

III. CAPACITOR LOCATIONS USING SENSITIVITY ANALYSIS

Capacitor locations can be found from sensitivity analysis. In this paper two methods are employed to find
the capacitor locations. Both these bus sensitivity [17] and loss sensitivity [13] methods will give the best capacitor locations for reactive power compensation. Both these methods are discussed in below sections.

A. Bus Sensitivity Method

Bus sensitivity method is the sensitivity of buses based on reactive power (Q) and voltage (V) at the buses. It suggest to provide reactive compensation mainly on those buses where the reactive power demand is high and the bus voltages are the below nominal value. For the bus the bus sensitivity index \( SB_i \) is defined as:

\[
SB_i = \frac{Q_i}{V_i}
\]  

Based on \( SB_i \), 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 capacitor locations for 15 bus, 34 bus and 69 bus from bus sensitivity method are \{15, 6, \} 4\}, \{20, 21, 22, 23, 24, 25, 26\} and \{61, 50\} respectively.

B. Loss Sensitivity Method

The loss sensitivity method is a systematic procedure of computing the maximum impact on the real power losses of the system with respect to the nodal reactive power. The relationship for computing the loss sensitivity for any bus can be derived as follows:

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

![Figure 1. A distribution line with an impedance and a load.](image)

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

\[
P_{loss}[j] = \frac{(P_{ij}^2 + Q_{ij}^2)R[j]}{(V[j])^2}
\]

\[
Q_{loss}[j] = \frac{(P_{ij}^2 + Q_{ij}^2)X[j]}{(V[j])^2}
\]

Loss sensitivity \( SL_j \) for any bus \( j \) can be given as:

\[
SL_j = \left( \frac{2\cdot Q_{ij}[j] \cdot R[j]}{(V[j])^2} \right)
\]

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 \( SL_j \) 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, 34 and 69 bus radial distribution system contains set of sequence of buses given as \{6, 3\}, \{19, 20, 22\} and \{57, 58, 61\} respectively.

IV. SELF-ADAPTIVE DIFFERENTIAL EVOLUTION WITH NEIGHBORHOOD SEARCH (SANSDE)

Differential Evolution (DE) has become a popular algorithm in global optimization. DE mainly depends on three parameters i.e. population size \( NP \), Scale parameter \( F \) and crossover rate \( CR \). Here \( NP \) parameter is common in all other evolution algorithms. Mutation strategy selection, \( F \) and \( CR \) parameter selection is important issues in DE algorithm.

Self-adaptive Differential Evolution with Neighborhood Search (SaNSDE) is a population based optimization algorithm developed by Z. Yand, K. Tang and X. Yao [16]. In order to overcome local optimas and to get better convergence this algorithm mainly uses the features of self-adaptive DE (SaDE) and DE with neighborhood (NSDE) search algorithms.

The proposed SaNSDE as follows:

A. Initial Population

It is a set of pop number of particles generated between \((0, 1)\) for each generation \( G \) represented as \( x(G) = \{x_1, x_2, \ldots, x_n\} \).

B. Mutation Strategies

There are several schemes in mutation strategies. The first strategy is given by (5) and second strategy is given by (6):

\[
v_i = x_i + F.(x_{best} - x_i) + F.(x_{rand} - x_i)
\]

(5)

\[
v_i = x_i + F.(x_{best} - x_i) + F.(x_{rand} - x_i)
\]

(6)

where \( i_1, i_2, i_3 \in \{1, NP\} \) are random and mutually different integers, and they are also different with the vector index \( i \). The probability of selecting mutation strategy (8) is initially set to 0.5 and updated (every 50 generation) by (7):

\[
P = \frac{n_{s1}.(n_{s2}+n_{f2})}{n_{s2}.(n_{s1}+n_{f1})+n_{s1}.(n_{s2}+n_{f2})}
\]

(7)

C. Scale Factor

A self-adaptation of the scale factor \( F \) is also performed. For each individual a scale factor \( F_i \) is associated. Each scale factor is updated according:

\[
F_i = \begin{cases} 
N(0.5,0.3), & \text{if } U(0,1)-c_p > \delta, \\
\delta_i, & \text{otherwise}
\end{cases}
\]

(9)

where \( N(0.5,0.3) \) is a number sampled normal distribution with mean value of 0.5 and standard deviation equal to 0.3, \( rand \) is a random number...
generator from uniform distribution, \( \delta_i \) is a random sample from Cauchy distribution with a scale parameter equal to 1. \( fp \) will be self-adapted as \( p \) is done in according to (7), but related to the success of the scale factor.

D. Crossover Rate (CR)

In order to perform the crossover the SaNSDE employs the weighted crossover rate CR self-adaptation. But whenever we record a successful CR value in array CRrec, we will also record the corresponding improvement on fitness value in array \( \Delta \text{frec} \), where

\[
CR_m = \sum_{k=1}^{[\text{CR}_{\text{rec}}]} w_k \cdot CR_{\text{rec}}(k)
\]

\[
w_k = \Delta f_{\text{rec}}(k) / \left( \sum_{k=1}^{[\Delta \text{frec}]} \Delta f_{\text{rec}}(k) \right)
\]

here \( [\text{CR}_{\text{rec}}]=\sum\Delta \text{frec} \). The weighted self-adaptation scheme for CR is denoted as SaCRW.

E. Crossover

To eliminate duplicates in population crossover is to be done.

\[
u_i(j) = \begin{cases} v_f(j), & \text{if} \ U(0,1) \& < CR_m \\ v_m(j), & \text{otherwise} \end{cases}
\]

The crossover probability \( CR_m \) is obtained from crossover rate.

F. Selection

If the trial vector \( u_i \) has an equal or lower objective function value than that of its target vector it replaces the target vector in the next generation otherwise the target retains its place in the population for at least one more generation.

\[
x_i^{(t+1)}(j) = \begin{cases} u_i(j), & \text{if} \ f(u_i) \leq f(x_i) \\ x_i(j), & \text{otherwise} \end{cases}
\]

Once the new population is generated the process of mutation, crossover and selection is repeated until the optimum capacitor sizes are obtained or a pre specified termination criterion is satisfied i.e. the number of generations reaches a preset maximum \( g_{\text{max}} \).

G. Algorithm for Capacitor Placement Using Sensitivity Analysis Methods and SaNSDE

1. Read the system data.
2. Run the base case distribution load flow and determine the active power loss \( (P_{\text{Loss}}) \).
3. Identify the Candidate buses for placement of capacitors using sensitivity analysis methods.
4. Generate randomly \( n \) number of particles, where each particle is represented as:

\[
Q_c[i] = Q_{\text{min}} + (Q_{\text{max}} - Q_{\text{min}}) \cdot \text{rand}(i)
\]

where \( i=1, 2, \ldots, n \), where, \( \text{rand}(i) \) is a random number between \((0,1)\).
5. Initialize the candidate bus vector and gen=1.
6. Initialize the count \( i=1 \).
7. Determine the mutant vector \( v_i \) using equations (5) and (6).
8. if \( U_i(0,1) < p \) then assign \( v_i[i] = (5) \) else (6).
9. Check the \( v_i[i] \) within \( q_{\text{max}} \) and \( q_{\text{min}} \) limits.
10. Crossover the population in order to eliminate the duplicate using (11).
11. Assign \( Q_{\text{comp}} = x[i] \).
12. Run the load flows by placing the \( Q_{\text{comp}} \) at the candidate bus vector.
13. Evaluate the fitness value \( f[i] = P_{\text{Loss}} \).
14. Store the best fitness value among all the fitness values using (12).
15. Repeat the steps from 7 to 14 until \( i \) reaches to maximum generations.
16. Print the results and stop.

<table>
<thead>
<tr>
<th>Table I. Comparison of Results for 15 Bus System. Base Case Active Power Loss=61.79kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>Bus No</td>
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<tr>
<td>------</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>Total kvar placed</td>
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<td>Active Power loss (kW)</td>
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<tr>
<th>Table II. Comparison of Results for 34 Bus System. Base Case Active Power Loss=221.723kW</th>
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<td>-------------------------</td>
</tr>
<tr>
<td>Bus No</td>
</tr>
<tr>
<td>------</td>
</tr>
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<td>24</td>
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<tr>
<td>17</td>
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<tr>
<td>12</td>
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<tr>
<td>----</td>
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<tr>
<td>Total kvar placed</td>
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<tr>
<td>Active Power loss (kW)</td>
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</tbody>
</table>
TABLE III. COMPARISON OF RESULTS FOR 69 BUS SYSTEM, BASE CASE: ACTIVE POWER LOSS=225kW

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>PSO based [13] Placed</th>
<th>Proposed SaNSDE Based &amp; BSM</th>
<th>Proposed SaNSDE Based &amp; LSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>214</td>
<td>61</td>
<td>1330</td>
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<td>47</td>
<td>365</td>
<td>50</td>
<td>521</td>
</tr>
<tr>
<td>50</td>
<td>1015</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Total kvar Placed</td>
<td>1621</td>
<td>Total kvar Placed</td>
<td>1851</td>
</tr>
<tr>
<td>Active Power Loss (kW)</td>
<td>152.48</td>
<td>Active Power Loss (kW)</td>
<td>151.2</td>
</tr>
</tbody>
</table>

V. RESULTS

Optimal capacitor placement problem is performed using proposed algorithm on IEEE test systems. The proposed method for loss reduction by capacitor placement is tested on IEEE 15 bus, 34 bus and 69 bus radial distribution systems. The algorithm has been implemented in Matlab 2012. The various constants used in the proposed algorithm are $Q_{min}=100\, \text{kvar}$, $Q_{max}=1500\, \text{kvar}$, pop=40, $t_{max}=1000$. The test results for 15 bus system is shown in Table I, for 34 bus system is shown in Table II and for 69 bus system is shown in Table III. The proposed methods have been compared with various previous algorithms. The proposed SaNSDE algorithm based capacitor placement with sensitivity analysis methods gives better results when compared to previous methods.

VI. CONCLUSIONS

In this paper, optimal capacitor placement problem is solved using sensitivity analysis methods with SaNSDE algorithm to achieve minimum power loss and voltage profile improvement in distribution systems. SaNSDE a population based algorithm is used to find the optimal capacitor sizes.

In this paper, comparison of two sensitivity based capacitor placement methods Loss Sensitivity Method (LSM) and Bus Sensitivity Method (BSM) is performed. Bus sensitivity method is simple and gives capacitor locations with less effort. The detailed analysis shows that implementation of BSM for the placement of the capacitors, results in considerable more reduction of power losses in the system, leading to improved system efficiency and voltage profile, as compared to LSM.

The proposed method is tested on IEEE 15, 34 and 69 bus radial distribution systems. The proposed method places capacitors with optimal capacitor sizes which will give more real power loss reduction when compared other methods also.

REFERENCES

Dinakara Prasad Reddy P., is a graduate in Electrical and Electronics Engineering from JNTU Hyderabad and M.Tech in Power Systems Operation and Control from S.V. University College of Engineering, Tirupati. Presently he is pursuing Ph.D. from JNTU, Kakinada. Currently he is working as Lecturer in S.V. University, Tirupati.