Novel Loss-Voltage Sensitivity Factor for Capacitor Placement in Radial Distribution System Using Analytical Approach

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Abstract

An analytical technique is proposed for allocation of shunt capacitor bank in radial distribution system. The objective is formulated to determine the size, number and location of capacitor bank for real and reactive power loss reduction, voltage profile enhancement and annual cost saving. A novel Loss-Voltage Sensitivity Factor (LVSF), has been incorporated in the technique. The value of LVSF decides the candidate bus location.

The achievability of the proposed method (PM) has been demonstrated on IEEE-69 bus test system allowing comparing results with latest optimization techniques in literature. Further application of PM on 130 bus relatively large distribution system shows the effectiveness and robustness of the proposed technique.

Capacitors allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. This development is essential when allocated capacitors in nominal and heavy loading simulations do not include nodes of fixed capacitors.

Keywords: Shunt fixed and switchable capacitor bank; Analytical approach; Distribution system; LVSF; Load flow

Introduction

Placement of capacitor of optimal sizes and at optimal locations not only reduces the power losses, but also improves the voltage stability of the electric power systems. Several meta-heuristic techniques have been used by scientists and researchers over the years to address the problems of capacitor placements. They are very effective and powerful in comparison with conventional methods in solving complex nonlinear constrained optimization problems. Authors [1], used Differential Evolution algorithm, Direct Search Algorithm [2], Artificial bee colony algorithm (ABC) [3], Flower Pollination Algorithm [4], Bacteria Foraging (BF) [5], Ant Colony Search Algorithm (ACO) [6], Cuckoo Search Algorithm (CSA) [7], Harmony Search (HS) [8], Plant Growth Simulation Algorithm (PGSA) [9], Teaching Learning Based Optimization (TLBO) [10], Firefly Algorithm (FA) [11], shark smell optimization algorithm [12], Particle Swarm Optimization (PSO) [13,14], Heuristic Algorithm [15], Fuzzy–GA method [16], Simulated Annealing (SA) [17], Genetic Algorithm (GA) [18], Nonlinear Programming [19], Carpinelli et al. [20] solved the problem of shunt capacitor placement and sizing by approximate power flow method. S Mandal et al. [21] used a new hybrid particle swarm optimization algorithm to determine the best location and size of capacitor units in radial distribution system. The cost of real power losses and cost of capacitors were included in the objective function. However, one of the major difficulties for these methods is the premature convergence.

In this paper a new analytical method has been presented to solve the capacitor allocation problem in distribution system. The objective was formulated to minimize real power loss to its minimum value. A new Loss-Voltage Sensitivity Factor (LVSF), has been proposed here. LVSF incorporated real power loss and voltage of the system. The proposed technique gives best location and size of capacitor banks simultaneously. The efficacy of the proposed methodology has been tested on IEEE 69 bus distribution system. Three loading conditions (Light, Nominal and Heavy) are also considered here.

A further development of the proposed technique, capacitors allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. This development is when allocated capacitors in nominal and heavy loading simulations do not include nodes of fixed capacitors.

The results of proposed technique applied on IEEE 69 bus distribution system are compared with various algorithms to check its supremacy. Further the proposed technique was applied on relatively large 130 bus real distribution system insuring the effectiveness and robustness of the proposed technique.

Paper Contributions

The main contributions of this paper can be defined as

- Proposal of a new technique to solve capacitor location problem especially for large scale system.
- Proposal of a new Loss-Voltage Sensitivity Factor (LVSF), has been incorporated in the technique to decide the candidate bus location.
- The proposed technique outlasts other algorithms in solving the optimal locations and sizing of capacitors in distribution systems. Moreover, it provides a promising and preferable performance over other algorithms in terms of voltage profiles, active and reactive power losses, total cost and net saving.
- Capacitor allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. Capacitors determined

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in nominal and heavy loading simulations are switchable capacitors.

**Computation Algorithm**

Following pseudo code summaries the computational process for proposed analytical technique:

- **Computation Algorithm**
  - While $P_{loss_{ic}}$ continue decreasing.
  - Do until a capacitor is allocated
  - a) Set any size (5 kVAR) of capacitor unit at a bus and run load flow program [22].
  - Calculate the $P_{loss_{ic}}$ of the system and LVSF values for each bus.
  - b) Increment the size of capacitor in 5 kVAR steps and repeat ‘i’ and ‘ii’.
  - Store the size of capacitor which gives least amount $P_{loss_{ic}}$ of the system.
  - Store the bus, which has least LVSF value, will be the best location of capacitor unit.
  - Repeat steps ‘d’ to ‘e’ to find more locations and sizes of capacitors as multi-capacitor compensation.
  - End do.
  - Print best capacitor placement.
  - Print $P_{loss_{ic}}, Q_{loss_{ic}}$ Power loss reduction %, and annual $ Saving.

- **Apply this process for Light loading condition to determine best location and size of fixed capacitors.**

- **Next apply this process with allocated fixed capacitors, for nominal and peak loading conditions to determine best location and size of switched capacitors.**

**Algorithm Variables**

The variables in the computation algorithm are defined mathematically as follows:

\[
\text{saving} = K_p \Delta P_{loss} + K_r \Delta P_{loss} T_{loss} \times \left( K_C c_h + K_i \sum Q_c \right) \times CRF \tag{1}
\]

Where

$K_p \Delta P_{loss} = $ Power Loss reduction cost ,

$K_r \Delta P_{loss} T_{loss} = $ Energy loss reduction cost ,

$K_C c_h + K_i \sum Q_c = $ Reactive power compensation cost ,

$C_h$ and $Q_c = $ Optimum number and rating of capacitors,

$CRF = \frac{\left( \frac{r(1 + r')}{(1 + r') - 1} \right)}{(1 + r')}$

\[
\text{Operational Constraints}
\]

The operating constraints are:

- The total reactive power injected is not to exceed the total reactive power demand in radial distribution system.
- The reactive power injection at each candidate bus is given by its minimum and maximum compensation limit.

**Loss-Voltage Sensitivity Factor (LVSF)**

The analytical method incorporating a Loss-Voltage Sensitivity Factor (LVSF), has been proposed to determine the size and location of capacitor units. The LVSF takes the system active power loss with and without capacitors and voltage limits of individual buses with capacitors in account and suggest the best location of the capacitor. The LVSF includes main objectives (power loss reduction and voltage profile enhancement).

\[
LVSF = \frac{V_{min_{ic}}}{V_{max_{ic}}} + \frac{P_{loss_{ic}}}{P_{loss_{base}}} \tag{4}
\]

where,

$P_{loss_{ic}}$ Base case real power loss (kW)

$P_{loss_{ic}}$ Real power loss after capacitor placement at a bus (kW)

$V_{max_{ic}}$ Per unit maximum bus voltage after capacitor placement at a bus

$V_{min_{ic}}$ Per unit minimum bus voltage after capacitor placement at a bus

**Test Results**

In proposed analytical approach, capacitor units are placed to minimize real power loss and to enhance voltage profile. The technique is employed on the IEEE 69 bus distribution system and on relatively large 130 bus real distribution system.

- **The implementation of proposed method for the best capacitor placement problem was done using version (9.0.0) R2016 a of MATLAB language on an Intel Core i7 processor running at 2.20 GHz with 7.95 GB RAM.**

- **The values of various constant used in equation (1 to 2) are: Cost of power loss ($K_p = $0.06/kWh, Cost of energy loss ($K_r = $0.06/kWh), capacitor installation cost for single unit ($K_C = $1000, Cost of per kVAR capacitor bank ($K_b = $5, maximum loss hours = 1500, discount rate (r) = 0.08, and economic life of investment (years) = 10.**

- From simulation results, it is learned that capacitor locations during light loading condition simulation may not repeated in nominal and heavy loading simulations. Therefore, in this paper capacitor allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. Capacitors determined in nominal and heavy loading simulations are switchable capacitors. To the author knowledge this approach was not tackled in previous publications. This approach shall be detailed in the following section.

**Case 1: 69 bus system**

The IEEE 69 bus has 12.66 kV and 100 MVA base values. The base case real power loss and minimum bus voltage are 224.7893 kW and 0.9092 pu [23].

- Generally Capacitor bank size, location and control are determined based on reactive load curve usually approximated by a steps ladder function. In this work, three steps functions are used. Thus, calculation
of energy losses requires power losses in peak (160% of nominal load), nominal and light (50% decrement in load) load levels.

Simulation results for the three operating conditions are summarized in Table 1. The voltage profile after compensation compared to base case is shown in Figure 1 for nominal operating condition and in Figure 2 for heavy operating condition.

Meaning beside \((175/17+260/50)\) kVar/node fixed capacitors, \((1267/61+303/50)\) kVar/node switched capacitors are required at nominal load operating condition and additional \((844/61+54/50)\) kVar/node switched capacitors are required at heavy load operating condition.

The results of proposed method are compared with latest optimization technique like Fuzzy-GA [16], Direct Search Algorithm [2], PSO [13], Heuristic [15], and Flower Pollination Algorithm [24]. The comparative analysis is shown in Table 2. It is noticed from table that the proposed approach give maximum loss reduction on lesser size of capacitor bank and percentage saving in cost exceeds those in other technique. The bus voltage profile of 69 bus system is also improved due to proposed approach. DE [2] and FPA [24] searched lesser size

<table>
<thead>
<tr>
<th>Before Capacitor Placement</th>
<th>Light Load (50%)</th>
<th>Nominal Load (100%)</th>
<th>Heavy Load (160%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Loss (kW)</td>
<td>51.6150</td>
<td>224.7893</td>
<td>651.9646</td>
</tr>
<tr>
<td>Min. bus voltage (pu)</td>
<td>0.9567</td>
<td>0.9092</td>
<td>0.8445</td>
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<table>
<thead>
<tr>
<th>After Capacitor Placement</th>
<th>Capacitor Size in kVar and location</th>
<th>Power Loss (kW)</th>
<th>Min. bus voltage (pu)</th>
<th>% Loss reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>175/17</td>
<td>34.6352</td>
<td>0.9680</td>
<td>32.8969</td>
</tr>
<tr>
<td></td>
<td>260/50</td>
<td>145.9182</td>
<td>0.9316</td>
<td>35.0867</td>
</tr>
<tr>
<td></td>
<td>Total kVar</td>
<td>2468</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Total kVAR                 | 435                                | 1570            | 2111/61               |
| Total kVAR                 | 303/50                             | 357/50          | 410.1286              |
| % Loss reduction           | 32.8969                            | 35.0867         | 37.0934               |

Table 1: Simulation results for 69 bus system after capacitor installation.

**Figure 1:** Voltage profile before and after capacitor placement for 69 bus system in nominal loading condition.

**Figure 2:** Voltage profile before and after capacitor placement for 69 bus system in heavy loading condition.
Figure 3: Tree graph of 130 bus radial distribution system.
of capacitor bank, however resulting in lower loss reduction and percentage saving.

**Case 2: 130 bus system**

The system under consideration is 11 kV, 130 bus radial distribution system. The system load is 1911.6 kW and 1423.8 kVAR. The line and load data are given in Appendix and the tree graph of the feeder is shown in Figure 3. The real power loss of the system is 365.1864 kW and minimum bus voltage is 0.9243 pu without compensation. The procedure of proposed approach, as detailed for IEEE 69 bus system is

<table>
<thead>
<tr>
<th>Items</th>
<th>Un-compensated</th>
<th>Compensated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss reduction (%)</td>
<td>30.4</td>
<td>32.7</td>
</tr>
<tr>
<td>Exminum voltage</td>
<td>0.9092</td>
<td>0.9369</td>
</tr>
<tr>
<td>Optimal location and size in kVAR (Node/kVAR)</td>
<td>59/100</td>
<td>61/700</td>
</tr>
<tr>
<td></td>
<td>64 800</td>
<td>57/150</td>
</tr>
<tr>
<td></td>
<td>58/50</td>
<td>61/1000</td>
</tr>
<tr>
<td></td>
<td>60/150</td>
<td>59/100</td>
</tr>
<tr>
<td></td>
<td>67/241</td>
<td>47/365</td>
</tr>
<tr>
<td></td>
<td>50/1015</td>
<td>8/600</td>
</tr>
<tr>
<td></td>
<td>58/150</td>
<td>60/1050</td>
</tr>
<tr>
<td></td>
<td>61/1350</td>
<td>61/1267</td>
</tr>
<tr>
<td>Total kVAR</td>
<td>1600</td>
<td>1450</td>
</tr>
<tr>
<td>Annual cost ($/year)</td>
<td>118,204.8</td>
<td>90119.5</td>
</tr>
<tr>
<td>Net saving ($/year)</td>
<td>28085.3</td>
<td>29291.4</td>
</tr>
<tr>
<td>% saving</td>
<td>23.8</td>
<td>24.8</td>
</tr>
</tbody>
</table>

Table 2: Comparison of annual loss saving for various techniques at nominal load for 69 bus system.

**Figure 4:** Voltage profile before and after capacitor placement for 130 bus system in nominal loading condition.

**Figure 5:** Voltage profile before and after capacitor placement for 130 bus system in heavy loading condition.
repeated for this relatively large system to determine the best location and size of capacitor bank.

Simulation results for the three operating conditions are summarized in Table 3. The voltage profile after compensation compared to base case is shown in Figure 4 for nominal operating condition and in Figure 5 for heavy operating condition.

Meaning beside (10/5 kVAR/node) fixed capacitors, (1085/89+115/128+65/3 kVAR/node) switched capacitors are required at nominal load operating condition and additional (585/320/+25/6 kVAR/node) switched capacitors are required at heavy load operating condition.

Table 3: Simulation results of the 130 bus distribution system.

<table>
<thead>
<tr>
<th>Capacitor Placement</th>
<th>Light Load (50%)</th>
<th>Nominal Load (100%)</th>
<th>Heavy Load (160%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Loss (kW)</td>
<td>185.4599</td>
<td>365.9583</td>
<td>979.0706</td>
</tr>
<tr>
<td>Min. bus voltage (pu)</td>
<td>0.9562</td>
<td>0.9242</td>
<td>0.8760</td>
</tr>
<tr>
<td>Capacitor Size in kVAR and location</td>
<td>10/5</td>
<td>1085/89</td>
<td>340/20</td>
</tr>
<tr>
<td>Total kVAR</td>
<td>10</td>
<td>1510</td>
<td>2510</td>
</tr>
<tr>
<td>Power Loss (kW)</td>
<td>64.0474</td>
<td>241.8028</td>
<td>633.9606</td>
</tr>
<tr>
<td>Min. bus voltage (pu)</td>
<td>0.9682</td>
<td>0.9376</td>
<td>0.8992</td>
</tr>
<tr>
<td>% Loss reduction</td>
<td>65.4656</td>
<td>33.9261</td>
<td>35.3367</td>
</tr>
</tbody>
</table>

Conclusion

In this paper, an analytical technique is proposed for allocation of shunt capacitor bank in radial distribution system for real and reactive power loss reduction, voltage profile enhancement and annual cost saving. A new Loss-Voltage Sensitivity Factor (LVSF), has been incorporated in the technique to decide the candidate bus location.

Capacitors allocated (size and location) during light loading condition simulation are forced as fixed capacitors in nominal and heavy loading simulations. This development is when allocated capacitors in nominal and heavy loading simulations do not include nodes of fixed capacitors.

A large scale and small scale distribution systems are used to demonstrate the performance of the new formulation. The proposed algorithm provides an efficient solution since it provides a promising and preferable performance over other algorithms in terms of voltage profiles, active and reactive power losses, total cost and net saving.

References
