Optimizing location and size of capacitors for power loss reduction in radial distribution networks

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ABSTRACT

Power radial distribution systems are increasingly more and more important in transmitting the electric energy from power plants to customers. However, total loss in lines are very high. This issue can be solved by allocating capacitor banks. Determining the suitable allocation and optimal sizing of capacitor banks needs an efficient approach. In this study, the diffusion and update techniques-based algorithm (DUTA) is proposed for such reason. The efficiency of DUTA is inspected on two distribution systems consisting of 15-bus and 33-bus systems with different study cases. The solutions attained by DUTA are competed with recently published methods. As a consequence, the method is more effective than the other methods in terms of the quality of solution.

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NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{g,g+1}$</td>
<td>Real power of the branch linking buses $g$ and $g+1$</td>
</tr>
<tr>
<td>$Q_{g,g+1}$</td>
<td>Reactive power of the branch linking buses $g$ and $g+1$</td>
</tr>
<tr>
<td>$V_g$</td>
<td>Magnitude of voltage at bus $g$</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of buses</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>Reactive power of load at bus</td>
</tr>
<tr>
<td>$Q_{CC}$</td>
<td>Compensated reactive power</td>
</tr>
<tr>
<td>$I_c$</td>
<td>Current magnitude of the $c$th branch</td>
</tr>
<tr>
<td>$I_{c,max}$</td>
<td>The maximum current magnitude of each branch</td>
</tr>
<tr>
<td>$Z_{best}$</td>
<td>The global solution</td>
</tr>
<tr>
<td>$C$</td>
<td>Current iteration</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Random number</td>
</tr>
<tr>
<td>$Q_{min}, Q_{max}$</td>
<td>The minimum and maximum rated power of capacitor</td>
</tr>
</tbody>
</table>

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1. INTRODUCTION

Radial distribution systems are transit stations of transferring the electric energy from power plants to customers. Such systems account for large spaces; however, they exist some advantages such as voltage drops, low voltage as well as high power loss. Voltage drops, low voltage and low power quality make a reduction of equipment lifetime, increasing of the energy consumption and the maintenance cost whilst the high-power loss has very economically significant impacts on the overall power system. So far, a solution that has been regarded as the best way for solving such issues, is optimally installing and sizing shunt capacitor units at some buses of radial distribution systems. The work brings a great advantage in minimizing real and reactive power losses, enhancing power factor and voltage profile, and releasing overload of feeders and transformers. Therefore, the optimal capacitor placement and sizing determination problem (OCPSD) is being received more attentions of researchers and operation engineers.

A huge number of researchers have proposed and applied deterministic and meta-heuristic methods for standard radial distribution systems such as 15-bus, 33-bus, 69-bus and 118-bus systems to find the best solution for OCPSD problem. In this paper, we have used 15-bus and 33-bus test systems to implementing an applied method with different study cases. For the first test system, a number of methods as highly efficient method (HEM) [1], particle swarm optimization with time varying inertia weighting (PSO-TV IW) [2], ant colony optimization (ACO) algorithm [3], genetic algorithm (GA) [4] and improved harmony algorithm (IHM) [5] have been recommended. In the studies [2-4], the suitable locations of capacitors have been found by loss sensitivity factor (LSF) technique while the optimal sizes of capacitors have been determined by PSO-TV IW, ACO and GA, respectively. In [5], the mission of determining capacitor placements at candidate buses is assigned to a fuzzy technique while the optimal capacitor size determination is in charge of IHM. For the second test system, many algorithms such as analytical method (AM) [6], grid search algorithm (GSA) [6], golden section search algorithm GSSA [6] and minimization of power losses (MLP) [6], grasshopper heuristic optimization algorithm (GOA) [7], plant growth simulation algorithm (PGSA) [8], two-stage method (TSM) [9], interior point (IP) [10], simulated annealing (SA) [10] and gravitational search method (GSM) [10], flower pollination algorithm (FPA) [11] and ant lion optimizer (ALO) [12] have been successfully applied for implementing the OCPSD problem. In previous method group, the work in [11, 12] has the same manner because the authors have employed FPA and ALO methods to discover both the correct locations and the sizing of capacitor. The combination of K-Mean Clustering and Elbow Technique has been applied for a real distribution network in Vietnam [13]. A dolphin algorithm was suggested in [14] for 16 and 33-buses systems but there has been comparison with previous methods. Distributed generators [15] as well as reconfiguration [16-19] are two solutions for reducing power loss of distribution. Both capacitor placement and reconfiguration were combined to reduce total loss [20]. In addition, static synchronous condenser (STATCOM) was also proposed to improve voltage profile of distribution systems [21]. In general, these proposed solutions could reduce loss and improve voltage; however, the cost of other components is much higher than capacitors.

In this paper, the process for determining both the suitable positions and the ratings of capacitor has been resolved by diffusion and update techniques-based algorithm (DUTA). DUTA was formed by three phase including diffusion phase and two other update phases for creating solutions [22]. The first phase’s mission is to explore search spaces by using many new solutions whereas two other phases are in charge of exploit the search space. The experienced results of DUTA method are very promising via executing on 15-bus and 33-bus standard distribution systems. Subsequently, this paper offers some contributions as follows:

- Clearly analysis the structure of DUTA
- Solve OCPSD problem with many study cases by using DUTA
- DUTA can offer favorable solutions

2. OCPSD PROBLEM FORMULATION

2.1. Load flow

Power flow calculation in the distribution network is very essential to analyze or assess the operating state of the distribution system. From here, we can determine voltage at buses, calculate the current running on branches and compute active power losses between two nodes. For this work, a single line diagram of the simple distribution system as displayed in Figure 1 is considered, where \( g \) is the sending bus and \( g + 1 \) is the receiving bus. From Figure 1, equations for the power flows can be established as follows:

\[
V_{\text{min}}, V_{\text{max}} \\
Z_{e1}, Z_{e2}, Z_{e3}, Z_{e4}, Z_{e5} \\
K
\]

- The minimum and maximum rated voltage of bus
- Randomly selected solutions
- Penalized factor
Optimizing location and size of capacitors for power loss reduction in radial... (Thuan Thanh Nguyen)
problem [25] and optimizing distributed database queries [26]. The searching power of DUTA is based on three phases including diffusion the first update and the second update phases. The mission of such phases is described as follows:

Diffusion mechanism-based search algorithm (DMBSA) is implemented by:

\[
Z_{d_{new}} = \text{Gaussian}(Z_{best, d}) + \delta(Z_{best} - Z_d); \quad d = 1, \ldots, P_d
\]

\[
Z_{d_{new}} = \text{Gaussian}(Z_{d, \theta})
\]

\[
\delta = |(Z_{best} - Z_d) \cdot \log(c)| / c
\]

To use shown in (12) or (13), a comparison between a random number (\(\theta\)) and a walk factor (\(\omega\)) is determined. If \(\theta < \omega\), shown in (12) is assigned and otherwise, shown in (13) is given. Clearly, the value of \(\omega\) plays a key role in selecting two previous equations. If \(\omega\) is fixed to \(1\), new solutions are created by (12). If \(\omega\) is fixed to \(0\), new solutions are generated by (12). Otherwise, both as shown in (12) and (13) are used for producing new ones. After performing DMBSA, the first and second updates are implemented by the two following equations:

\[
Z_{d_{new}} = Z_{r_1} + \delta(Z_{r_2} - Z_d)
\]

\[
Z_{d_{new}} = \begin{cases} 
Z_{d_{new}} + \delta(Z_{r_3} - Z_{r_4}) & \text{if } \alpha > 0.5 \\
Z_{d_{new}} - \delta(Z_{r_5} - Z_{best}) & \text{else}
\end{cases}
\]

4. THE IMPLEMENTATION OF DUTA TO OCPSD PROBLEM

In OCPSD problem, the location and size of capacitors are also controlled by variables corresponding to a solution of DUTA. Such variables are dependent on the number of capacitors added to the system. For calculating the power loss and the voltage at each bus, we run the power flow program using forward–backward sweep technique [27]. The fitness function for assessing solutions is specified by using as shown in (17);

\[
\text{Fitness} = \sum P_{\text{loss}} + K(\Delta V + \Delta I)
\]

Steps to implement the DUTA for OCPSD problem are presented by the flowchart provided in Figure 2.

Figure 2. The flowchart of DUTA for implementing OCPSD problem

5. COMPARISON AND DISCUSSION

In this paragraph, an actual performance of DUTA is studied by making the result comparisons of such method to other previous reported methods. Two distribution test systems are employed for solving the optimal capacitor placement problem with two the following intentions:

- Distribution system of 15 buses and 33 buses are used as the basic models for accessing the ability of DUTA.
- Such test systems are regarded as the expediency for surveying different compensated capacitor placements.

5.1. The 15-bus network

The IEEE 15-bus test distribution system has a total load of 1.2264 MW and 1251.2 MVAr. The investigated system is suffered an active power loss of 61.8 kW [1]. Clearly, such power loss is significant that
needs to be reduced by adding capacitors. However, a determination of location, the number and size of capacitors has to be selected carefully because it can lead to over compensation. It is for that reason that DUTA is applied for this task with two cases for capacitor placements. Namely, Case 1 install two capacitors while Case 2 adds three capacitors to the system. With each optimization problem, investigating parameters to access the efficacy, sturdiness and stability of the search process of DUTA are extremely important. Wherein population sizes \((P_s)\) and the maximum number of iterations \((C_{\text{max}})\) are two parameters to be investigated.

For case 1, Table 1 shows that the best power loss is 32.306 kW corresponding with \(P_s = 10\) and \(C_{\text{max}} = 30\). Clearly, the \(P_s\) value is impossible to decrease although \(C_{\text{max}}\) is increased. However, the standard deviation (STD) value of subcase 1.1D is smaller than that of subcase 1.1C. Figure 3 provides the power loss results of 50 runs from subcase 1.1A to subcase 1.1C whilst Figure 4 shows the best power loss and STD of these subcases.

### Table 1. The power loss (kW) obtained from different values of \(P_s\) and \(C_{\text{max}}\) over 50 runs

<table>
<thead>
<tr>
<th>No</th>
<th>Subcase 1.1A</th>
<th>Subcase 1.1B</th>
<th>Subcase 1.1C</th>
<th>Subcase 1.1D</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_s)</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>(C_{\text{max}})</td>
<td>10</td>
<td>15</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Min loss</td>
<td>32.524</td>
<td>32.312</td>
<td>32.306</td>
<td>32.306</td>
</tr>
<tr>
<td>Aver loss</td>
<td>34.668</td>
<td>34.204</td>
<td>32.719</td>
<td>32.515</td>
</tr>
<tr>
<td>Max loss</td>
<td>37.563</td>
<td>41.295</td>
<td>37.095</td>
<td>34.678</td>
</tr>
<tr>
<td>STD</td>
<td>1.508</td>
<td>1.841</td>
<td>0.898</td>
<td>0.477</td>
</tr>
</tbody>
</table>

Figure 3. The best power loss of 50 runs from sub-case 1.1A to sub-case 1.1D

Figure 4. The best power loss and STD for case 1 from sub-case 1.1A to sub-case 1.1D

The results of DUTA are compared to other methods for Case 1 as shown in Table 2. Seeing the table can recognize that DUTA and ACO [3] find the same positions of capacitors but different positions with HEM [1] and PSO-TVIW [2]. However, power loss of DUTA is the smallest while that of ACO [3] is the highest. For Case 2, the process for investigating these mentioned parameters of DUTA is again implemented with the results obtained as displayed in Figure 5. From the figure, the power loss of 31.280 kW is corresponding to \(P_s = 5\) and \(C_{\text{max}} = 10\), that of 30.378 kW is corresponding to \(P_s = 5\) and \(C_{\text{max}} = 20\). That of 30.338 kW, which is considered as the best power loss, is corresponding to \(P_s = 10\) and \(C_{\text{max}} = 40\). If \(C_{\text{max}}\) is continuously increased to 60, the best power loss does not still change but STD is better. Table 3 shows the optimal results obtained from DUTA and IHA [5] in term of capacitor positions and sizes, total compensation, power loss and minimum voltage. It can be proven that DUTA is superior to IHA. Figure 6 is plotted to illustrate improvement of the first system voltages due to connected capacitors.

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Table 2. Result comparison between DUTA and other methods for case 1

<table>
<thead>
<tr>
<th>Methods</th>
<th>Capacitor node</th>
<th>Size (kVAR)</th>
<th>Total KVAR</th>
<th>Total loss (kW)</th>
<th>Minimum Voltage (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEM [1]</td>
<td>3, 6</td>
<td>805, 388</td>
<td>1193</td>
<td>32.6</td>
<td>0.96504</td>
</tr>
<tr>
<td>PSO-TVIV [2]</td>
<td>3, 6</td>
<td>871, 321</td>
<td>1192</td>
<td>32.7</td>
<td></td>
</tr>
<tr>
<td>ACO [3]</td>
<td>4, 6</td>
<td>630, 410</td>
<td>1040</td>
<td>36.81</td>
<td>0.95</td>
</tr>
<tr>
<td>DUTA</td>
<td>4, 6</td>
<td>438.46, 702.64</td>
<td>1141.1</td>
<td>32.306</td>
<td>0.9604</td>
</tr>
</tbody>
</table>

Figure 5. The best power loss and STD for case 1 from sub-case 1.2A to sub-case 1.2D

Table 3. Result comparison between DUTA and other methods for case 2

<table>
<thead>
<tr>
<th>Methods</th>
<th>Capacitor node</th>
<th>Size (kVAR)</th>
<th>Total KVAR</th>
<th>Total loss (kW)</th>
<th>Minimum Voltage (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IHA [5]</td>
<td>6, 11, 15</td>
<td>350, 300, 300</td>
<td>950</td>
<td>31.12</td>
<td>0.9658</td>
</tr>
<tr>
<td>DUTA</td>
<td>4, 6, 11</td>
<td>488.24, 408.08, 300.1</td>
<td>1197.14</td>
<td>30.34</td>
<td>0.96955</td>
</tr>
</tbody>
</table>

Figure 6. The influence of compensated capacitors on the voltage of 15 bus system

5.2. The 33-node network

This system without compensation has the minimum bus voltage of 0.9038 p.u at bus 18 and total active power loss of 210.97 kW [13]. For purposing loss reduction of such system, DUTA is utilized to seek the correct positions and optimal sizes of capacitors with two survey cases. Single and three capacitors are considered, where two cases are reported in Table 4 and Table 5. For each study case of the system, we also analyze $P_s$ and $C_{max}$to find the best optimal results achieved by DUTA for comparisons. As a result, $P_s = 10$ and $C_{max} = 50$ are selected for the case with one capacitor and $P_s = 10$ and $C_{max} = 70$ are set for the case with three capacitors. It is seen from Table 4 that DUTA gives capacitor placement, total power loss and minimum voltage like other five methods. This demonstrates that all methods can result in the same as a solution quality.

In case of locating three capacitors, DUTA identifies the optimum positions as bus numbers 13, 24, and 30 and optimal sizes as 387.92, 544.21 and 1037.03 kVAR, respectively. Total loss is lessened to 138.372 kW from the base case of 210.97 kW corresponding 34.41% of active power loss rate and the minimum voltage is improved to be 0.9567 pu. As shown in Table 5, total loss from GSA [10] is the smallest but it is easily recognized that GSA uses $P_s = 2000$ and $C_{max} = 400$, leading to number of solution generations $(P_s \times C_{max})$ is 800,000. Clearly, this value is very high. From this view, that of DUTA of 138.266 kW is considered as the best result as compared to other methods. This illustrates the performance and effectiveness of DUTA. Furthermore, the voltage profile significantly has been enhanced with installation capacitors as shown Figure 7. The Figure shows the influence of compensated capacitors on the voltage of 33 bus system before and after compensation cases.

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Table 4. Result comparison between DUTA and other methods with single capacitor

<table>
<thead>
<tr>
<th>Methods</th>
<th>Capacitor node</th>
<th>Size (kVAR)</th>
<th>Total loss (kW)</th>
<th>Minimum Voltage (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM [6]</td>
<td>30</td>
<td>1229.8</td>
<td>151.40</td>
<td>0.9162</td>
</tr>
<tr>
<td>GSA [6]</td>
<td>30</td>
<td>1265</td>
<td>151.38</td>
<td>0.9165</td>
</tr>
<tr>
<td>GSSA [6]</td>
<td>30</td>
<td>1258</td>
<td>151.38</td>
<td>0.9165</td>
</tr>
<tr>
<td>MPL [6]</td>
<td>30</td>
<td>1258</td>
<td>151.38</td>
<td>0.9165</td>
</tr>
<tr>
<td>GOA [7]</td>
<td>30</td>
<td>1250</td>
<td>151.38</td>
<td>0.916</td>
</tr>
<tr>
<td>DUTA</td>
<td>30</td>
<td>1258.01</td>
<td>151.379</td>
<td>0.91648</td>
</tr>
</tbody>
</table>

Table 5. Result comparison between DUTA and other methods with three capacitors

<table>
<thead>
<tr>
<th>Methods</th>
<th>Capacitor node</th>
<th>Size (kVAR)</th>
<th>Total KVAR</th>
<th>Total loss (kW)</th>
<th>Minimum Voltage (p.u)</th>
<th>( P_s )</th>
<th>( C^{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOA [7]</td>
<td>13, 24, 30</td>
<td>375, 550, 1050</td>
<td>1975</td>
<td>138.27</td>
<td>0.931</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>PSGA [8]</td>
<td>6, 28, 29</td>
<td>1200, 760, 200</td>
<td>2160</td>
<td>151.98</td>
<td>0.946</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TSM [9]</td>
<td>7, 29, 30</td>
<td>850, 25,900</td>
<td>1775</td>
<td>144.042</td>
<td>0.9251</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IP [10]</td>
<td>9, 29, 30</td>
<td>450, 800, 900</td>
<td>2150</td>
<td>171.78</td>
<td>0.9501</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SA [10]</td>
<td>10, 30, 14</td>
<td>450, 350,900</td>
<td>1700</td>
<td>151.75</td>
<td>0.9591</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GSA [10]</td>
<td>13, 15, 26</td>
<td>450, 800, 350</td>
<td>1600</td>
<td>134.5</td>
<td>0.9672</td>
<td>2000</td>
<td>400</td>
</tr>
<tr>
<td>FPA [11]</td>
<td>13, 24, 30</td>
<td>450, 450, 900</td>
<td>1800</td>
<td>139.08</td>
<td>0.933</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>ALO [12]</td>
<td>13, 24, 30</td>
<td>350, 600, 1050</td>
<td>2000</td>
<td>138.372</td>
<td>0.9304</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>DUTA</td>
<td>13, 24, 30</td>
<td>387.92, 544.21, 1037.03</td>
<td>1969.16</td>
<td>138.2660</td>
<td>0.94568</td>
<td>10</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 7. The influence of compensated capacitors on the voltage of the 33bus system

6. CONCLUSION

This work is to use DUTA for the most appropriate location and sizing of fixed capacitor banks in order to reduce total loss as well as improve the voltage profile of the radial distribution network. The applied method is verified on standard 15-bus and 33-bus networks with different study cases. Results achieved from DUTA show that the power losses are decreased while the voltage profile is enhanced. Also, the comparisons of solutions obtained by DUTA with those by recently reported methods indicate that the method can attain approximate or better power loss for all test cases. Therefore, it is possible to imply that the method should be regarded as an effective method for solving OCPSD problem.

REFERENCES


