Optimum Feeder Routing and Distribution Substation Placement and Sizing using PSO and MST

Ihsan Jabbar Hasan, Chin Kim Gan*, Meysam Shamshiri, Mohd Ruddin Ab Ghani and Rosli Bin Omar

Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia; ckgan@utem.edu.my.

Abstract

A long term distribution network planning consists of several complexity aspects due to the multiple decision variables in objective functions. Optimum placement of distribution substations and determination of their sizing and feeder routing is one of major issues of distribution network planning. This paper proposes an algorithm to find the optimum distribution substation placement and sizing by utilizing the PSO algorithm and optimum feeder routing using modified MST. The proposed algorithm has been evaluated on the distribution network case with 500 consumers which are consisting of residential and commercial loads. The test network is generated by fractal based distribution network generation model software tool. The results indicate the proposed algorithm has been succeeded to find the reasonable placement and sizing of distributed generation with adequate feeder path.

Keywords: Distribution Substation Placement, MST, MV & LV Feeder Routing, OpenDSS, PSO

1. Introduction

The distribution network is a vital part of the electric power system. Distribution planners are always encountered with several difficulties in designing due to the numbers of decision variables which are influenced to distribution networks. Feeder routing in LV network and MV/LV substation placement and sizing are always one of the important challenges in distribution network planner. Meanwhile, it is crucial to reconfigure the existing distribution network due to the high load density and incremental cost of power distribution equipment and significant power losses in LV network (which is 50% of the total losses of power system).

Many researchers discuss about the complexity and difficulty of distribution system planning. In1 the optimal feeder routing problem using the dynamic programming technique and Geographical Information Systems (GIS) facilities has been performed. The total cost of investment, line losses and reliability has been taken to the account with related constraints such voltage drop and thermal issues. In2 GA has been used to solve the optimum planning of large distribution network based on loss characteristics matrix for optimum substation location and graph theory for feeder routing in real size of distribution network. In3 the optimal planning of radial distribution networks using simulated annealing techniques. The paper addressed the minimum capital cost by applying the steepest descent approach as initial solution and improved the obtained cost with simulated annealing method. There are several method for distribution network modeling and planning which reference4 has reviewed the some research work under normal condition and emergency planning and modeling. In reference5 an attempt to reduce the cost of feeders by selecting the optimal conductor type and size of feeders segment. The paper performed a new computer algorithm and heuristic optimization technique.
Power flow solution is one of the important sections of distribution network planning due to the vast of the network. Therefore, this paper has tried to use OpenDSS engine as power flow calculator in distribution network planning in order to extract the voltages and losses of the network during optimization procedures.

This paper performed the PSO algorithm to find the optimal placement of substation and MST algorithm for optimal feeder routing in LV and MV networks.

1.1 Particle Swarm Optimization (PSO)

The swarm intelligent algorithm is one of the evolutionary computation methods which has introduced to solve the optimization problems and since then, their ability to be used in optimization problems has been demonstrated. In this method, the movement towards the optimal position is obtained from the best information of each particle which is included in the initial population (Best Personal Position) and the optimal position that is found by the neighbor's positions (Best Global Position).

Researcher applied PSO algorithm successfully in complex non-linear engineering problem, principally in planning of distribution system, control systems, multi-objective optimization problems with multiple constraints, shape optimization and etc. Since the capacitor installation in distribution system has the non-linear and discrete equation, therefore, this paper utilized PSO algorithm as one of the accurate methods to solve the substation placement and sizing problem. The procedures of this algorithm have been described in. Figure 1 shows the particle movements bases on PSO algorithm.

1.2 Minimum Spanning Tree (MST)

This theory is assigned as one of the important part of mathematic sciences which has been introduced in 19s century. A graph is a collection of ordered pairs of branches and nodes that can be written as $G = (V, E)$. Where, V is node and E is branch. In fact, a graph is a diagrammatic model of a system. In general, a graph represents a binary relation between their system components. A single graph can have many different spanning trees that each branch can assign by weight. MST is the graph with the minimum weight on branches. There are a lot of algorithm to solve the MST problems which are Kruskal's algorithm, Prim's algorithm Dijkstra's algorithm and etc. In the MST algorithm has been implemented as feeder routing solution in distribution networks. This paper uses the prim's algorithm to solve the optimum feeder routing on LV and MV networks.

1.3 OpenDSS

The power flow calculation is required in planning of distribution network to evaluate the network. To obtain this reason, the Open Distribution System Simulator (OpenDSS) is a comprehensive electrical system simulation tool for electric utility distribution systems. The OpenDSS is an open source developed by the Electric Power Research Institute. The OpenDSS engine includes the COM interface which can be used in other simulation programs such as MATLAB, VBA, C# and etc. The OpenDSS engine can help the researchers to obtain the variety of significant information about the simulated power system. In this paper, OpenDSS engine is utilized as a power flow solution in order to find the power system parameters such voltage profile, power factor, real and reactive power flowing in each line, power losses and etc. which can be used in optimum substation placement and sizing problem in distribution networks.

2. Methodology

Based on the new prospect of distribution networks planning which is target to bring the small scale of substation beside the load centers in order to reduce the distribution network losses, this paper has tried to introduce the initial adjustments of the algorithm based on this
purpose. Therefore, the minimum numbers of distribution substations are estimated based on the maximum branching rate and number of consumer (load centers) for each branch. In this paper, four branching rate for each substation and maximum 15 consumers have been selected for each branch. Which means; minimum $S_n$ substations are need for a network with $n$ branches and $m$ numbers of consumers for each branch, which $S_n$ can be written as follows:

$$S_n = \frac{N}{m \times n} \tag{1}$$

where, $N$ is the numbers of the consumers. Therefore, the estimation of minimum required substation can be considered as a first step of optimization algorithm that shown in Figure 2.

The optimum substation placement will perform after estimating the number of minimum required substations. For this purpose, the PSO algorithm has been utilized which it will be explained in following sub-section in details. The optimum substation placement and sizing algorithm will generate the coordinates of each substation which has been connected to the particular consumers with adequate substation require sizing based on the number of supplied consumers as shown in Figure 5. The next optimization step will be the optimum LV and MV feeder routing using modified MST algorithm. There are a few constraints and details that will be described in following related section. After indicates the paths of feeders the next algorithm step is power flow calculation using OpenDSS engine. Therefore, the algorithm is generated OpenDSS codes for designing the network to run the power flow and capturing required information for network assessment. The obtained results will be evaluated in the next step. The algorithm will record the captured solution, if the results have satisfied in terms of substation placement standards, desire losses and in range voltage profile. If not, the algorithm will repeat once more time by increasing the number of distribution substation. This loop will continues to find the best possible solution of the substation placement, routing and sizing whenever find the optimum network designing.

2.1 Optimum Substation Placement Using PSO

An adequate placement of distribution substation (MV/LV) can be affected the other parts of distribution planning such as primary/secondary substations and feeders routing in network planning. In other word, if the placement of substation is not done with adequate precision, the technical and economic difficulties will be encountered to MV feeders and other parts of the distribution networks. Therefore, determining the proper placement of distribution substations is crucial. In this paper a comprehensive algorithm for substation placement and determining the number of substation has been utilized. The Particle Swarm Optimization (PSO) method is performed to optimize the best possible placement of distribution substations. The only substation placement problem has considered in this section. Figure 3 illustrates the PSO algorithm flowchart in terms of optimum distribution substation placement in LV network.

Figure 4 shows the consumers and candidate distribution substations with obtained from the fractal based distribution networks generation model tool. Figure 5 shows the numbers of selected substations after optimization, which 16 numbers of distribution substations.
substations has been selected among the 275 candidate substations. Meanwhile, this figure indicates the numbers of consumers which assigned to their particular substation.

2.2 Optimum Feeder Routing using MST

As explained in introduction the prim’s algorithm has been utilizes in this paper to find the optimum feeder routing of LV and MV networks. But the only prim’s algorithm cannot carry out our desire optimal routing. The modified prim algorithm needs to be performed because of some technical requirement such as, open loop feeders and not allowed branches pass through each other. Figure 6 shows the proposed modification algorithm using prim’s algorithm in MST in order to find the optimum feeder routing in distribution network.

Figure 7 shows the obtained results after LV and MV feeder routing using modified MST algorithm. It depicts the LV feeder path with purple line color and MV conductors by black line color. The LV feeders are connected adequately without passing each other as shown in figure. It demonstrated the modified algorithm has succeeded to solve the feeder routing problem by considering the problem constraints.

3. Problem Formulation

In distribution system planning, the geographical distribution of loads density and allocation of feasible candidate substations are the important information in the study year. Based on optimization point of view,
bus, c) Maximum load capacity of all substation, and
d) cost minimization of new substation construction.
Accordingly, the objective functions of substation place-
ment and sizing can be formulated as follows:

\[ CL = C_L \cdot \sum_{j=1}^{nlb} P_{Loss}^j \cdot 8760 \]  

where, \( CL \) is the total losses cost for a study year, \( C_L \) [$/kWh] is the cost of real power losses which is provided
in \(^2\) \( P_{Loss}^i \) [kW] is the real power
losses at consumer \( i \) and \( nlb \) is the number of consumers.

The investment cost of substation should be annui-
tized to able to accumulate with other network costs\(^3\).
Thus, to annuitize the investment cost of distribution net-
work, the following economical consideration should be
performed.

\[ VC_S = \sum_{j=1}^{ns} C_{var} (j) \left( \sum_{i=1}^{nlb} d_{ij}(j,i) \right) \]  

\[ FC_S = \sum_{j=1}^{ns} C_{fix} (j) \]  

\[ C_S = VC_S + FC_S \]

where \( VC \) is the total substation variable cost, \( C_{var} (j) \) is
the cost of substation \( j \) per MVA, \( d_{ij}(j,i) \) is the consumer
demand \( i \) which connected to substation \( j \). \( FC \)
represents the total fixed cost of substations and \( C_{fix} (j) \) is the
fixed cost of substation \( j \). The variable cost of substation
included the cost of operation and maintenance, and the
fixed cost consists of installation and other related fix cost
of substation such as land and equipment prices and etc.

\[ IC = \sum_{j=1}^{ns} C_S^j \cdot C_i \]  

\[ CC = IC \cdot \frac{d(1+d)^T}{(1+d)^T - 1} \]

where \( IC \) stand for Investment Cost [\$, \( C_S \) is the total
substation installation and operation costs [\$, \( C_i \) is the
total cost of the lines [\$, \( CC \) is the annuitized capital cost
[\$/year], \( d \) is the discount rate and \( T \) is the number of operation years.

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**Figure 6.** The flowchart of modified MST algorithm in
order to solve the optimum feeder routing in distribution
network.

**Figure 7.** Obtained network after optimum feeder routing
for LV and MV in 164 consumers distribution network.
Thus, the main objective function that needs to be minimized can be written as follows:

$$\text{Min } Z = CL + CC + PF$$  \hspace{2cm} (8)

where $Z$ is the total cost function and $PF$ is the penalty factor which is calculated by the optimization constraints. For instance, if the voltage is out of the defined range, therefore the violation amount of voltage will multiply to the constant fine rate ($Beta$) which can be written as follows:

$$PF = \sum_{i=1}^{nv} (\beta \times \text{Violation}_i)$$  \hspace{2cm} (9)

where, $nv$ is number of violations and $\beta$ is the fine rate.

The first constraint of distribution network planning is acceptable voltage drop at receiving bus ($V_i$) which voltage should be within the specified range.

$$0.95 \leq V_i \leq 1.05$$  \hspace{2cm} (10)

The next constraint of distribution network planning is the longest distance of each consumer from the distribution substation which introduced by substation radius based on standard. To consider this constraint the following condition must be considered:

$$D_j^i \leq R_{\text{max}}$$  \hspace{2cm} (11)

where $D_j^i$ is stand for distance between substation $j$ to consumer $i$ and $R_{\text{max}}$ is the maximum acceptable radius of substation $j$ that can supply the consumers. Based on the standard, in LV feeder the maximum length of feeder can be up to 0.5–1 km. In urban networks, the length of 11 kV feeders in generally up to 3 km and for rural networks is up to 20 km.

### 4. Result and Discussion

The fractal based distribution networks generation model tool has been utilized in this paper to generate a distribution network test system. The initial assumptions of the utilized distribution network model are as, 275 MV/LV candidate distribution substations and 500 consumers. Table 1 shows the distribution network consumer demands which generated by the prescribed tool. This case has been used in this paper in order to demonstrate the functionality of proposed algorithms of substation placement and sizing in distribution network and feeder routing in both LV and MV networks.

<table>
<thead>
<tr>
<th>Type of consumer</th>
<th>Percentage</th>
<th>No.of Customers</th>
<th>Maximum Load [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential (Double Story house)</td>
<td>90%</td>
<td>450</td>
<td>5</td>
</tr>
<tr>
<td>Residential (Bungalow house)</td>
<td>10%</td>
<td>50</td>
<td>7</td>
</tr>
</tbody>
</table>

As shown in Figure 5 the number of selected distribution substation is 16 numbers after optimum placement through 275 substation candidates. Table 2 shows the optimization procedure to select the number of required substations with considering the acceptable voltage drop and minimum losses of networks. Table 3 indicates the selected the substation size of transformers after optimization. The voltage drop based on distance for all distribution substations and 500 consumers are shown in Figure 8. It indicates all the buses allocated within the standard range of voltage drop which stated in previously sections. In Figure 8, the dotted line and continuous line indicates LV and MV voltage profiles, respectively. An MV/MV substation (secondary substation 33/11 kV) is placed at the fix position which as shown in Figure 7 and the selected substation size is shown in Table 4. To select the size of substation sizing has been tried to follow the standard of distribution transformer by IEEE/ANSI C57.12.0014.

<table>
<thead>
<tr>
<th>Number of transformer</th>
<th>Minimum Voltage [p.u.]</th>
<th>Total Losses [KW]</th>
<th>Best Cost [$/year$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0.90492</td>
<td>93.11</td>
<td>2351657</td>
</tr>
<tr>
<td>9</td>
<td>0.89132</td>
<td>87.59</td>
<td>2558751</td>
</tr>
<tr>
<td>10</td>
<td>0.91855</td>
<td>76.68</td>
<td>2784625</td>
</tr>
<tr>
<td>11</td>
<td>0.8682</td>
<td>71.64</td>
<td>3004456</td>
</tr>
<tr>
<td>12</td>
<td>0.88147</td>
<td>67.23</td>
<td>3223352</td>
</tr>
<tr>
<td>13</td>
<td>0.87815</td>
<td>77.24</td>
<td>3466781</td>
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<tr>
<td>14</td>
<td>0.9315</td>
<td>59.01</td>
<td>3681601</td>
</tr>
<tr>
<td>15</td>
<td>0.91676</td>
<td>50.74</td>
<td>3927347</td>
</tr>
<tr>
<td>16</td>
<td>0.95365</td>
<td>41.33</td>
<td>4142015</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Consumer Demand Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of consumer</td>
<td>Percentage</td>
</tr>
<tr>
<td>Residential (Double Story house)</td>
<td>90%</td>
</tr>
<tr>
<td>Residential (Bungalow house)</td>
<td>10%</td>
</tr>
</tbody>
</table>
Table 3. Selected size of MV/LV transformers after optimization

<table>
<thead>
<tr>
<th>Sub. Name</th>
<th>Xs</th>
<th>Ys</th>
<th>MV/LV Sub. capacity [kVA]</th>
<th>Numbers of consumers</th>
<th>Supplied consumer [kVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>718.77</td>
<td>413.42</td>
<td>300</td>
<td>31</td>
<td>159.5</td>
</tr>
<tr>
<td>S2</td>
<td>463.61</td>
<td>890.43</td>
<td>225</td>
<td>23</td>
<td>122.4</td>
</tr>
<tr>
<td>S3</td>
<td>943.48</td>
<td>331.06</td>
<td>300</td>
<td>32</td>
<td>164.7</td>
</tr>
<tr>
<td>S4</td>
<td>516.17</td>
<td>320.09</td>
<td>500</td>
<td>43</td>
<td>227</td>
</tr>
<tr>
<td>S5</td>
<td>438.00</td>
<td>154.33</td>
<td>500</td>
<td>37</td>
<td>201.2</td>
</tr>
<tr>
<td>S6</td>
<td>947.26</td>
<td>480.25</td>
<td>500</td>
<td>37</td>
<td>204.8</td>
</tr>
<tr>
<td>S7</td>
<td>195.69</td>
<td>452.21</td>
<td>500</td>
<td>44</td>
<td>236</td>
</tr>
<tr>
<td>S8</td>
<td>250.07</td>
<td>846.54</td>
<td>300</td>
<td>28</td>
<td>146.6</td>
</tr>
<tr>
<td>S9</td>
<td>485.23</td>
<td>967.16</td>
<td>225</td>
<td>18</td>
<td>95.4</td>
</tr>
<tr>
<td>S10</td>
<td>859.07</td>
<td>8.74</td>
<td>225</td>
<td>21</td>
<td>114.7</td>
</tr>
<tr>
<td>S11</td>
<td>647.27</td>
<td>712.35</td>
<td>500</td>
<td>39</td>
<td>210.7</td>
</tr>
<tr>
<td>S12</td>
<td>160.42</td>
<td>821.21</td>
<td>500</td>
<td>42</td>
<td>220.6</td>
</tr>
<tr>
<td>S13</td>
<td>434.28</td>
<td>486.68</td>
<td>500</td>
<td>44</td>
<td>235.4</td>
</tr>
<tr>
<td>S14</td>
<td>925.38</td>
<td>975.84</td>
<td>112.5</td>
<td>10</td>
<td>55.9</td>
</tr>
<tr>
<td>S15</td>
<td>246.28</td>
<td>136.59</td>
<td>300</td>
<td>35</td>
<td>188.5</td>
</tr>
<tr>
<td>S16</td>
<td>371.55</td>
<td>495.52</td>
<td>225</td>
<td>16</td>
<td>86.4</td>
</tr>
</tbody>
</table>

Table 4. Selected size of secondary transformer (33/11) kV after optimization

<table>
<thead>
<tr>
<th>Substation name [33/11]kV</th>
<th>X</th>
<th>Y</th>
<th>Substation capacity [kVA]</th>
<th>Numbers of supplied MV/LV substations [11/0.4]kV</th>
<th>Total apparent power demand [kVA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES1</td>
<td>54</td>
<td>58</td>
<td>5000</td>
<td>16</td>
<td>2669.8</td>
</tr>
</tbody>
</table>

5. Conclusion

In conclusion, this paper has proposed the algorithm based on combination of PSO and MST to solve the distribution network planning in terms of substation placement, sizing and feeder routing. The proposed algorithm has performed on the test distribution network model with 500 consumers and 275 candidate distribution substations. The results demonstrate the proposed algorithm has succeeded to find the suitable placement and sizing of distributed generation with adequate feeder path.

6. Acknowledgement

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7. References


