A Sensitivity Based Methodology for Optimal Placement of Distributed Generation in Meshed Power Systems

Warid Warid, Hashim Hizam, Norman Mariun, Noor Izzri Abdul-Wahab

Department of Electrical and Electronics Engineering
Universiti Putra Malaysia
43400 UPM Serdang, Selangor, Malaysia.

warid.s.w@ieee.org

Abstract — Distributed generation (DG) plays a considerable role in minimizing power losses in real-world electric power systems. This benefit can be optimally achieved by determining the optimum placement of DG units. The erroneous placement of DG units in electric power networks can lead to high power loss increment and results in lower limit violation of load buses voltages. Hence, this paper suggests a sensitivity-based procedure for the optimal placement of DG in meshed power systems using suitable technologies. The efficacy of minimizing real power loss is considered as a key criterion. The ranking of candidate locations is determined based on two types of active power loss sensitivities along with loss reduction rates that are obtained by different types and capacities of DGs. A correlation parameter is proposed and suitable weighting factors are defined for each sensitivity type, DG type, and DG size. A priority list that includes both the sensitivity indexes of real power loss and used pragmatic indicators is estimated to rank the optimal locations for DG units placement. Moreover, a sorting index is deduced to identify the appropriate DG type(s) for each candidate site. Three rife DG types are used in this paper. The IEEE 30-bus test system is selected to carry out the proposed methodology. Results show that the estimated priority index can attain the best active loss reduction rates. Several buses can be safely precluded as candidate sites using the proposed methodology. The approach can reduce the computational process of identifying the optimal locations for DG placement. Moreover, results point out that certain locations can be selected to set more than one DG type and considerably minimize active power losses instead of accommodating several DG units at different sites with one DG type.

Keywords - distributed generation; sensitivity analysis; power losses reduction; meshed power systems

1. INTRODUCTION

The utilization of distributed generation (DG) technologies in electric power networks has considerably increased [1, 2]. DG technologies provide economical and technical advantages, such as transmission cost reduction, congestion mitigation, and loss minimization [3, 4]. These benefits can be highly achieved by carrying out a comprehensive investigation into the optimal accommodation and sizing of DGs. The recognition of optimal load buses for DG placement has become an important issue, particularly because of the adverse influences of the erroneous placement of DGs on electric power network operation. The choice of optimal location for DG units in electric power systems is a significant challenge and crucial problem because the additional generation from renewable and non-renewable sources could lead to an increase in power losses, which results in voltage magnitudes at load buses that are lower than the permissible limits. Moreover, the incorporation of DGs changes the network from passive to active system, which affects the reliability and operation of the power systems. Identifying the best DG type for each optimal location is an important concern for power systems companies given the diversity of distributed generation technologies that are employed in practical power networks.

Many researchers have examined the optimal allocation of DG units in the distribution and transmission networks to achieve the best loss reduction rates using numerous analytical approaches [5–11] and heuristic optimization techniques [12–17]. Aman et al. [5] proposed a novel power stability index for the optimal placement of DGs in radial distribution networks. A simple analytical method [6] was proposed to identify the optimal location of DG units in a given balanced radial distribution network that could reduce the losses associated with the real and reactive components of DG branch current. A methodology for the placement of DG in distribution networks based on the analysis of power flow continuation was presented [7]. A novel maximum power stability index [8] was developed to recognize the optimum DG locations for power loss minimization and voltage stability enhancement. A dual-index analytical approach [9] based on a combination of real and reactive power loss indices was proposed to verify the optimum location, size, and power factor of DG units toward minimizing power loss and enhancing system load ability.

Naik et al. [10] suggested an analytical approach for the optimal placement and sizing of DG in radial power distribution networks to reduce real and reactive power losses. An analytical expression [11] was proposed to determine the optimal location of several kinds of renewable DG units that could minimize energy losses in distribution.
The present study presents several contributions to this field, which highlight the advancement of the proposed approach over those of the aforementioned studies. A sensitivity-based procedure for the optimal placement of DG units in meshed power systems involving appropriate technologies is suggested to address the problem. The sensitivity of real power loss to real power injection and the sensitivity of real power loss to reactive power injection are considered in this work. The ranking of the candidate sites is defined based on the two considered types of loss sensitivities along with the loss minimization rates obtained by several types and sizes of DGs. More realistic indicators are employed to rank the optimal locations of DG units. Moreover, a correlation parameter is suggested and appropriate weighting factors are set for each sensitivity type, DG kind, and DG capacity. A priority list for the optimal allocation of DGs is presented, and a sorting index for the selection of the optimal DG type(s) for each candidate site is formulated. The rest of this article is organized as follows. Section 2 introduces the proposed sensitivity-based methodology. Section 3 presents the results and discussions. Section 4 outlines the conclusions.

II. PROPOSED METHODOLOGY

An effective sensitivity-based procedure is demonstrated. In particular, the process of locating the optimal sites for the installation of three types of DGs that could guarantee the optimum real loss reduction rates in meshed power networks is shown. This approach uses new indicators to identify the optimal allocation of DGs and the appropriate types of DGs for the candidate sites. The main notion is to deduce a priority list for the allocation of DGs based on the combination of the rankings estimated with the sensitivities of active power losses to active and reactive power injection, as well as on the ranking gained by considering the efficacy of loss minimization obtained by allocating different kinds and frequently utilized capacities of DGs. Moreover, a sorting index for the placement of common types of DGs at each candidate site can be formulated with the suggested procedure. Using this procedure is aimed at obtaining meaningful and pragmatic findings with high reliability that consider the permanent accommodation of DGs. The common types of DG technologies used in this study are as follows:

Type 1: DG designed for injecting active power only, such as micro turbines, photovoltaic, and fuel cells.

Type 2: DG capable of producing only reactive power, such as synchronous compensators and shunt capacitors.

Type 3: DG that supplies both active and reactive power, such as gas turbines, reciprocating engines, and cogenerating engines.

The basic steps of the proposed methodology for the optimal placement of DG in meshed power networks are outlined below and explained in the flowchart shown in Fig. 1.

Step 1: For the initial case, power flow is performed without DGs, and the overall grid active power loss is estimated as follows:

\[
P_{\text{loss}} = \sum_{i=1}^{N} \sum_{j=1}^{N_a} \frac{G_{ij}}{2} \left[ |V_i|^2 + |V_j|^2 - 2 |V_i||V_j| \cos(\delta_i - \delta_j) \right]
\]  

(1)

Step 2: The active power loss sensitivities to the injection of active and reactive power for each load bus are calculated by formulating the following formula.

\[
\begin{bmatrix}
\frac{\partial P_{\text{loss}}}{\partial P_i} \\
\frac{\partial P_{\text{loss}}}{\partial Q_i}
\end{bmatrix} = [\text{Jac}]^{T,i} \begin{bmatrix}
\frac{\partial P_{\text{loss}}}{\partial \delta_i} \\
\frac{\partial P_{\text{loss}}}{\partial V_i}
\end{bmatrix}
\]  

(2)

with \( i = 2, \ldots, N \) and \( h = 1, 2, \ldots, N_L \).
where $\frac{\partial P_{loss}}{\partial P_i}$ and $\frac{\partial P_{loss}}{\partial Q_i}$ represent the variations in active power loss during the process of equipping the active and reactive power at the $i$th and $h$th bus, respectively. $[J_{ac}]$ is the Jacobian matrix. $\frac{\partial P_{loss}}{\partial \delta_i}$ and $\frac{\partial P_{loss}}{\partial V_k}$ indicate the sensitivities of the active power loss to voltage angle and voltage amplitude for the $i$th and $h$th bus, respectively, which can be estimated by performing an implicit differentiation for (1):

$$\frac{\partial P_{loss}}{\partial \delta_i} = 2 \sum_{j=1}^{N} G_{ij} \left[ |V_i||V_j| \sin (\delta_i - \delta_j) \right]$$ (3)

$$\frac{\partial P_{loss}}{\partial V_k} = 2 \sum_{j=1}^{N} G_{jk} \left[ |V_k||V_j| \cos (\delta_k - \delta_j) \right]$$ (4)

Step 3: The estimated sensitivities are sorted in descending order with the relevant buses. The topmost load buses with considerable sensitivities are candidate sites for DG accommodation. The load bus with high $\frac{\partial P_{loss}}{\partial \delta_i}$ and $\frac{\partial P_{loss}}{\partial V_k}$ is the candidate for the accommodation of DG types 1 and 2, respectively. The load bus with considerable sensitivity of active power loss to the injected active and reactive power is the candidate site for the allocation of type 3 DGs.

Step 4: For all load buses, the diverse types and capacities of DGs are consecutively placed on the basis of technology and common size. The obtained loss minimization is calculated for each DG type and capacity.

Step 5: According to the tabular ranking, the power network load buses are sorted in descending order based on the minimization of losses along with the corresponding DG type and capacity.

Step 6: A correlation between the sorting of the candidate buses is estimated in the third step, which is based on the sensitivity values. The ranking of load buses (step 5) is sorted based on the loss minimization rates for each DG type and capacity.

Step 7: According to the correlation results and the estimated ranking, an appropriate weighting factor is set for $\frac{\partial P_{loss}}{\partial P_i}$, $\frac{\partial P_{loss}}{\partial Q_i}$, and the loss minimization estimated using the types and capacities of DGs.

Step 8: The priority list is arranged for the optimal locations for DG accommodation and the sorting index for the

$$\text{Sort}_{ij} = W_{\delta} \times R(\text{Capacity C DG, } i) + W_{\delta} \times R(\text{Capacity D DG, } i)$$ (6)

placement of the suitable types of DGs for each candidate load bus. The expressions below present the proposed sorting criteria for the ith load node for the three used types

$$\text{Sort}_{ij} = W_{\delta} \times R(\text{Capacity C DG, } i) + W_{\delta} \times R(\text{Capacity D DG, } i) + W_{\delta} \times R(\text{Capacity E DG, } i)$$ (7)

(i.e., six capacities) of DGs.

For type 1 DG:

$$\text{Sort}_{ij} = W_{\delta} \times R(\text{Capacity A DG, } i)$$ (5)

For type 2 DG:

$$\text{Sort}_{ij} = W_{\delta} \times R(\text{Capacity B DG, } i)$$ (5)

For type 3 DG:

$$\text{Sort}_{ij} = W_{\delta} \times R(\text{Capacity C DG, } i) + W_{\delta} \times R(\text{Capacity D DG, } i) + W_{\delta} \times R(\text{Capacity E DG, } i)$$ (7)

where $R$ indicates the ranking of ith load bus.

Step 9: The top load bus(es) is considered for DG accommodation.
Figure 1. Flowchart of the proposed methodology for the optimal placement of DG in meshed power systems.
III. RESULTS AND DISCUSSIONS

The suggested sensitivity-based methodology for the optimal accommodation of DGs is implemented on the IEEE 30-bus test system [18]. First, the estimated sensitivities and loss minimization rates are sorted in descending order side by side with the corresponding load nodes to distinctly distinguish the candidate sites for DG allocation. This arrangement is beneficial to the determination of the appropriate DG type(s) for each candidate load bus. Hence, many load nodes are excluded as candidate sites for DGs placement. The computational calculations required to recognize optimal DG sites are remarkably reduced. Tables I(a) and I(b) present the correlation between the sensitivities of active power loss to active and reactive power injection and the efficacy in loss minimization of the three different types and six prevalent capacities of DGs. Table I(a) shows this relationship for half of the network load nodes when DGs with 5 MW, 5 MVAR, and 5 MW (0.85 p.f) sizes are utilized. Table I(b) presents the same relationship when DGs with 10 MW, 10 MVAR, and 10 MW (0.85 p.f) sizes are utilized. A remarkable correlation exists between the relevant loss sensitivity and the power loss minimization obtained by the corresponding DG kind. This result shows the validity of considering these sensitivities as indicators for the optimum allocation of DGs. However, a precise inspection is required given that the suggested hypothesis supposes that high sensitivities indicate the nodes at which active or reactive injection is exceedingly effective in minimizing active power loss. Therefore, a parameter named correlation distance is utilized for each load node to estimate the degree of correlation between the suggested sensitivities and the existing rates of active power loss reduction. Based on the sorting of the loss sensitivity index, the correlation distance of the ith load node is stated as the absolute value of the difference between the rank of the ith load node in the \(\frac{\partial P_{\text{losses}}}{\partial P} \) column and the rank of the same node in the loss minimization column of the used DG type. A low correlation distance equates to a considerable degree of correlation. Thus, the suggested approach reveals a high degree of reliability.

**TABLE I. CORRELATION BETWEEN ACTIVE POWER LOSS SENSITIVITIES AND EFFECTIVENESS IN LOSS MINIMIZATION FOR THREE DIFFERENT TYPES AND CAPACITIES OF DG FOR THE IEEE 30-BUS SYSTEM**

<table>
<thead>
<tr>
<th>No.</th>
<th>(\frac{\partial P_{\text{losses}}}{\partial P} )</th>
<th>Load Bus</th>
<th>(\frac{\partial P_{\text{losses}}}{\partial Q} )</th>
<th>Load Bus</th>
<th>Losses Minimization (%) using 5 MW DG</th>
<th>Load Bus</th>
<th>Losses Minimization (%) using 5 MVAR DG</th>
<th>Load Bus</th>
<th>Losses Minimization (%) using 5 MW DG (0.85 p.f)</th>
<th>Load Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.1451</td>
<td>30</td>
<td>-0.0564</td>
<td>26</td>
<td>10.7287</td>
<td>30</td>
<td>3.4577</td>
<td>26</td>
<td>11.8435</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>-0.1212</td>
<td>26</td>
<td>-0.0413</td>
<td>30</td>
<td>8.4572</td>
<td>29</td>
<td>2.3098</td>
<td>30</td>
<td>10.8723</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>-0.1172</td>
<td>24</td>
<td>-0.0387</td>
<td>29</td>
<td>7.97445</td>
<td>26</td>
<td>2.1209</td>
<td>24</td>
<td>9.657</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>-0.1045</td>
<td>29</td>
<td>-0.0354</td>
<td>24</td>
<td>7.60254</td>
<td>24</td>
<td>1.988</td>
<td>29</td>
<td>8.9108</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>-0.0964</td>
<td>18</td>
<td>-0.0322</td>
<td>27</td>
<td>7.3778</td>
<td>18</td>
<td>1.9056</td>
<td>25</td>
<td>8.1124</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>-0.0906</td>
<td>19</td>
<td>-0.0289</td>
<td>25</td>
<td>7.0354</td>
<td>19</td>
<td>1.8676</td>
<td>27</td>
<td>7.9565</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>-0.0897</td>
<td>25</td>
<td>-0.0266</td>
<td>22</td>
<td>6.9876</td>
<td>20</td>
<td>1.7343</td>
<td>22</td>
<td>7.7099</td>
<td>23</td>
</tr>
<tr>
<td>8</td>
<td>-0.0872</td>
<td>23</td>
<td>-0.0232</td>
<td>23</td>
<td>6.8303</td>
<td>25</td>
<td>1.6711</td>
<td>21</td>
<td>7.5622</td>
<td>19</td>
</tr>
<tr>
<td>9</td>
<td>-0.0808</td>
<td>20</td>
<td>-0.0224</td>
<td>21</td>
<td>6.6932</td>
<td>23</td>
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<td>23</td>
<td>7.4326</td>
<td>21</td>
</tr>
<tr>
<td>10</td>
<td>-0.0779</td>
<td>15</td>
<td>-0.0208</td>
<td>19</td>
<td>6.3055</td>
<td>21</td>
<td>1.3542</td>
<td>19</td>
<td>7.1543</td>
<td>20</td>
</tr>
<tr>
<td>11</td>
<td>-0.0752</td>
<td>22</td>
<td>-0.0195</td>
<td>18</td>
<td>5.9845</td>
<td>22</td>
<td>1.2114</td>
<td>18</td>
<td>6.9552</td>
<td>27</td>
</tr>
<tr>
<td>12</td>
<td>-0.0734</td>
<td>21</td>
<td>-0.0185</td>
<td>20</td>
<td>5.8992</td>
<td>15</td>
<td>1.1734</td>
<td>20</td>
<td>6.852</td>
<td>22</td>
</tr>
</tbody>
</table>

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Based on the findings shown in Tables I(a) and I(b), the correlation distance is calculated for the three considered types of DGs. Each type has two prevalent capacities. Table 2 presents the average correlation distances for the different kinds of DGs. The tabulated results demonstrate a significant correlation between the ranking according to the sensitivity of the active power loss to active power injection \( \frac{\partial P_{\text{losses}}}{\partial P_i} \) and the ranking based on the loss minimization rates gained by placing DG types 1 and 3 (i.e., the four diverse capacities of DGs). The average correlation distance is < 1 row in the sorted Table I, which points out the reliability of the suggested approach. A low correlation (< 3 rows) is observed between the ranking according to \( \frac{\partial P_{\text{losses}}}{\partial P_i} \) and the ranking based on the loss minimization rates gained by placing type 2 DG. These findings express the validity of employing the ranking based on sensitivity \( \frac{\partial P_{\text{losses}}}{\partial P_i} \) as a credible sign for the accommodation of DG types 1 and 3. Similarly, a remarkable correlation (i.e., low average correlation distance ≈ 1 row) is observed between the ranking based on \( \frac{\partial P_{\text{losses}}}{\partial Q_i} \) and the sorting according to the loss minimization rates gained by placing type 2 DG. A low correlation is noted between the ranking of \( \frac{\partial P_{\text{losses}}}{\partial Q_i} \) and the ranking according to the loss minimization rates obtained by allocating DG types 1 and 3. These findings validate the idea of considering sensitivity \( \frac{\partial P_{\text{losses}}}{\partial Q_i} \) as an indicator for the accommodation of DG type 2. Moreover, a high correlation (low average correlation distance < 1 row) is noticed between the considered capacities for each kind of DG. For instance, the average correlation distance between 5 MW DG and 10 MW DG (type1) is 0.7113.

### TABLE II. AVERAGE CORRELATION DISTANCE FOR THREE TYPES OF DG (CONTINUED)

<table>
<thead>
<tr>
<th>Sensitivity Type</th>
<th>DG Type 1</th>
<th>DG Type 2</th>
<th>DG Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity A (5 MW)</td>
<td>Capacity B (10 MW)</td>
<td>Capacity C (5 Mvar)</td>
</tr>
<tr>
<td>real power losses sensitivity with injected real power</td>
<td>0.634</td>
<td>0.634</td>
<td>2.562</td>
</tr>
<tr>
<td>Average correlation distance</td>
<td>2.896</td>
<td>2.8454</td>
<td>0.745</td>
</tr>
</tbody>
</table>
Based on the results in Tables I and II, the diverse meaningful weighting factors are selected for each loss sensitivity and actual loss minimization rates gained by the types and capacities of DGs used. The goal is to define the optimum ranking of load nodes as candidate sites for the permanent placement of the three considered types of DGs. The ranking procedure includes ranking according to the sensitivity magnitude and based on the loss minimization rates gained by considering several types and capacities of DGs. Rational weight factors, which lead to meaningful outcomes, are considered to obtain a reliable priority list. To sort the optimal sites for DGs types 1 and 2 placement, a 0.5 weighting factor \( W_e \) is assigned to each of \( \frac{\partial P_{\text{loss}}}{{\partial P}_{\text{h}}} \) and \( \frac{\partial P_{\text{loss}}}{{\partial Q}_{\text{h}}} \). A weighting factor of 0.25 is assigned to the loss minimization rates that are satisfied by the two prevalent capacities of the corresponding DG kind. For the sorting of the optimal location for DG type 3 placement, the selected weighting factors for \( \frac{\partial P_{\text{loss}}}{{\partial P}_{\text{h}}} \) is 0.4, and the factor considered for \( \frac{\partial P_{\text{loss}}}{{\partial Q}_{\text{h}}} \) is 0.1. Equal weighting factors are selected for the loss minimization gained with the two prevalent capacities of type 3 DG.

TABLE III. LIST OF ACCOMMODATION PRIORITY FOR THREE KINDS OF DG UNITS

<table>
<thead>
<tr>
<th>Location Rank</th>
<th>DG Type 1</th>
<th>DG Type 2</th>
<th>DG Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( W_e = 0.5 )</td>
<td>( W_e = 0.5 )</td>
<td>( W_e = 0.4 )</td>
</tr>
<tr>
<td></td>
<td>( W_e = 0.25 )</td>
<td>( W_e = 0.25 )</td>
<td>( W_e = 0.1 )</td>
</tr>
<tr>
<td></td>
<td>( W_e = 0.25 )</td>
<td>( W_e = 0.25 )</td>
<td>( W_e = 0.25 )</td>
</tr>
</tbody>
</table>

The accommodation priority list gained by the proposed sorting formula for the three kinds of DGs used is demonstrated in Table III. This study presents the estimated ranking for the topmost 12 load buses from the most to the least efficient in relation to real power loss reduction. The priority list shows that the top four sites for the placement of all the used types of DGs are nodes 30, 29, 26, and 24. Thus, a considerable group of load nodes can be exempted from consideration to reduce the computational processes toward recognizing the optimal sites for DGs. From an economic viewpoint, the outcomes reveal that specific load nodes are appropriate for the placement of more than one kind of DG with high size and considerable effect than accommodating many DGs at different sites with one type of DG. Based on these outcomes, a sorting index for the placement of three types of DGs at each candidate load node is presented for the topmost twelve load nodes (Table IV). Consequently, the appropriate DG type(s) can be selected when a candidate node for DG accommodation is considered. For example, DG type 3 is the most appropriate DG type for node 30, whereas DG type 2 is the appropriate type for node 29.

TABLE IV. SORTING INDEX FOR THE PLACEMENT OF THREE KINDS OF DGs AT EACH CANDIDATE BUS

<table>
<thead>
<tr>
<th>No</th>
<th>Location</th>
<th>Accommodating Rank of DG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Type 1</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>3</td>
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<tr>
<td>3</td>
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<td>1</td>
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<tr>
<td>4</td>
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<tr>
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<tr>
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<td>10</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>21</td>
<td>2</td>
</tr>
</tbody>
</table>

IV. CONCLUSIONS

A sensitivity-based procedure was suggested to ensure the optimal placement of the diverse types of DGs in meshed power networks. The real power sensitivity to the injection of real power and the real power sensitivity to the injection of reactive power were considered. Moreover, more realistic indicators were incorporated in the ranking process based on the obtained loss reduction rates using different types and kinds of DG. The correlation between the sorting of the candidate locations was estimated and rational weighting factors were given for each sensitivity type, DG type, and DG size. Credible and realistic results were obtained by combining the ranking based on loss sensitivities and the sorting depends on the efficacy in loss minimization gained by the placement of the three prevalent types and frequently utilized capacities of DGs. The findings validate the consideration of the sensitivity of real power loss to real power injection as a reliable indicator for the placement of type 1 DG. The sensitivity of real power loss to reactive power injection is validated as a reliable indicator for the placement of type 2 DG. Moreover, the results reveal that specific load buses are more suitable for accommodating more than one type of DG with high capacity compared with using many DGs at different locations with one type of DG. Hence, an extra considerable number of load nodes can be safely precluded from consideration, which reduces the required execution time. Moreover, a sorting index for choosing the optimal type(s) of DG for each candidate site was deduced. This is an important contribution given the diversity of DG.
technologies in the electricity markets. The findings of the obtained ranking demonstrate that few topmost load nodes were appropriate for the placement of all the used kinds of DG. An advantage of the proposed approach over the previous method is the employment of pragmatic indicators in identifying the optimum permanent allocation of DG units. However, the proposed approach needs to be combined with an optimization technique to estimate the optimal DG size. To sum up, the suggested methodology can be utilized in practical power systems as a guide for the optimal placement of DGs and for the identification of the optimal kind(s) of DGs for each candidate location. In future studies, the effect of load variation should be considered in the proposed procedure to determine the most trusted sites for DG placement. The obtained priority list and ranking index for DG placement can be effectively included with the optimal power flow problem to satisfy higher optimality.

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