The Research on Optimal Location and Sizing of Distributed Generation Considering Voltage Stability Index and Line Loss Reduction Rate

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Abstract. The continuous growth of power demand poses new challenge to the efficiency of power system. Therefore, distributed generation (DG) is widely concerned because it can provide clean, reliable and economic power. However, the location and sizing of DG connected to the grid shall be properly selected. In this paper, the voltage stability index and the line loss reduction rate are considered synthetically, and the two indexes are transformed into a single index (VSLR) to determine the optimal location of DG. According to this index, the node with high sensitivity and high average power loss reduction rate are selected as the optimum location of DG connected to the power grid, and the optimal access capacity of DG is determined by the algorithm proposed in this paper. The simulation experiments of IEEE30-bus are carried out with MATLAB\Matpower toolbox, and the results are compared with the existing research results. The results show that the method of studying the optimal location and sizing of DG in this paper emerges better performance.

1. Introduction
Under the background of increasing pressure of global resources and increasing awareness of social environmental protection, the technology of using renewable energy to generate electricity has aroused the research and practice of many countries in the world. It is an important way for the future development of renewable energy to connect the small capacity’s DG based on renewable energy to the power grid. DG has great advantages in economy, environmental protection and technology [1]. However, improper location and capacity of DG may lead to reverse flow of power flow, decrease of voltage stability, and increase of fault level and increase of network loss [2]. Therefore, it is necessary to plan the location and capacity of DG in power grid.

Many scholars at home and abroad have conducted the research of DG’s location and capacity [3-7], and have made quite rich achievements. Some people take the minimum power loss as the goal to determine the best DG location [4]; some papers find the most vulnerable node in the power grid through the voltage stability index [5], and selects this node as the best access location of DG. In this paper, the voltage stability index and line loss reduction rate are both considered to determine the optimal access location of DG, and the voltage stability index (L-index) [7] and power loss sensitivity factor (LSF) are compared with VSLR, and the algorithm proposed in this paper is used to determine the optimal capacity of DG. The method of studying the optimal location and capacity of DG in this paper is compared with...
method 1 and method 2 with IEEE30-bus test system. The results show that the method proposed in this paper is effective and reliable.

2. Optimal DG placement

2.1. Voltage stability index

The research of power system voltage stability focuses on identifying the vulnerable or critical nodes. Because DG access to the grid will improve the voltage stability of the network, and the most vulnerable node access to the distributed generation will improve the voltage stability of the power system positively.

In recent years, L-index has been widely used in the study of DG’s access location [7-8]. It can realize the simple and fast online calculation of voltage stability. The value of L-index is between 0 (no load) and 1 (voltage collapse). The closer the value is to 1, the more likely the node is to collapse. L-index is defined as follows:

\[ \text{L} = \max_j \{ \text{L}_j \} = \max_j \left[ 1 - \frac{\sum_{\text{tie}} F_{ji} V_i}{V_j} \right] \]  

where \( \alpha_l \) is the set of load buses, \( \alpha_g \) is the set of generator buses, \( V_l \) and \( V_j \) are the voltage at bus \( l \) and bus \( j \), and \( F_{ji} \) is the element in \( j \)th row and \( i \)th column of matrix \( F \) whose elements are generated from the admittance matrix as (2).

\[ F = -Y_{LL}^{-1} Y_{LG} \]  

And

\[ \begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} V_L \\ V_G \end{bmatrix} \]  

2.2. Power loss index

In the power system, it is very important to transmit the generated power to the users with the highest efficiency. Therefore, determining the best access location of DG can effectively reduce the loss of the system. Loss sensitive factor (LSF) has been widely used in the research of finding the best access capacity of DG, but it is still in the initial stage in the research of the best access location of DG [9]. The target function of this index is to minimize the loss and select the best installation location of DG. The loss sensitivity factor can be defined by the following expression:

\[ \text{LSF}(i) = \frac{P^a_I(i) - P^b_I}{P_{DG}^{inc}(i)} \]  

Where, \( P^a_i \) are the losses after DG placement, \( P^b_i \) are the initial power losses, \( P_{DG}^{inc}(i) \) is the DG size increase of bus \( i \).

If the LSF value is strictly negative, the system losses are reduced, else, the DG integration has the effect of increasing system losses. Therefore, the buses having lowest LSF values are selected for DG Placement.

2.3. Proposed index for DG units’ Allocation

In this paper, considering the influence of the distributed power station on the voltage and system loss after connecting to the power grid, an index (VSLR) based on voltage variation and average power loss reduction rate is proposed, which is defined as follows:
\[
VSLR(i) = \lambda VSL(i) + \mu LRR(i)
\]  \hspace{1cm} (5)

Where,

\[
VSL(i) = \frac{\sqrt{\sum_{k=1}^{n}(v_k^b - v_k)^2}}{\beta v_i^b}
\]  \hspace{1cm} (6)

\[
LRR(i) = \frac{p_l^b - p_l^a(i)}{N p_l^b}
\]  \hspace{1cm} (7)

The first \(VSL(i)\) represents the fluctuation of all node’s voltage caused by DG connecting to the grid from node \(i\). The larger the value is, the more sensitive the node \(i\) is; where \(i\) is the load node, \(k\) is the \(k^{th}\) node of the system, \(V_k\) is the node’s voltage after DG connecting to the power grid, \(V^b\) is the initial voltage under the stable state of the system, \(\beta\) is the correction factor [10], \(\beta = 1 - (\max(V_m - |V_i|)^2). \ V_m\) and \(V_i\) are the highest and the lowest voltage under the stable state of the system. The second term \(LRR(i)\) represents the average power loss reduction rate of the system after the DG is connected to the grid from node \(i\). The larger the value is, the better the result is in reducing the system loss when the DG is connected to the grid from this node. Where \(P_l^b\) and \(P_l^a\) are the power loss of the system before and after the DG is connected, and \(N\) is the number of lines.

However, because the first \(VSL(i)\) and the second \(LRR(i)\) in this paper have different dimensions, it is necessary to convert the objective functions of different dimensions into dimensionless objective function to make the objective function comparable. First, \(VSL(i)\) and \(LRR(i)\) are normalized, and the normalized objective function is between 0 and 1. \(\lambda\) and \(\mu\) are weight coefficients respectively, but considering the greater impact of voltage stability on the safe operation of the power grid, \(\lambda\) and \(\mu\) are taken as 0.8 and 0.2, 0.7 and 0.3, 0.6 and 0.4 respectively in multiple test systems. The results show that different values of \(\lambda\) and \(\mu\) lead to different ranking of nodes, but the nodes ranking in the first two places are not changed. In other words, different values of \(\lambda\) and \(\mu\) will not affect finding the node with the maximum value of the objective function. In the next simulation experiment, \(\lambda\) and \(\mu\) are 0.8 and 0.2 respectively, so the value of VSLR is between 0 and 1. In addition, according to the actual situation, DG should be connected to the grid from the load nodes, so DG should be connected to the grid from the load node whose value of VSLR is closest to 1.

3. Optimal DG capacity

3.1. Constraint conditions

For a safe operation of the distribution system, DG planning must be subjected to the following constraints:

\[
0 \ll P_{dg} \ll P_{load}
\]  \hspace{1cm} (8)

\[
V_{min} < V < V_{max}
\]  \hspace{1cm} (9)

\(P_{dg}\) And \(P_{load}\) are the total power of DG and load, \(V_{min}, V_{max}\) are minimum and maximum acceptable bus voltages respectively.

3.2. Proposed algorithm

After the optimal location of DG is determined, the active power of DG is gradually increased from 0% to 100% of the total active load. In this paper, the step size is kept at 1% of the total load. Although
smaller steps can be used, the calculation will take longer. The calculation process of DG optimal power is shown in Figure 1.

**Figure 1.** Flow chart of proposed algorithm.

4. Simulation results and discussion

4.1. Test system
This section carries on the simulation experiment on the IEEE30-bus test system. The IEEE 30 system consists of 24 load nodes, 6 generator nodes and 41 transmission lines, with a total load of 283.4 MW. The system topology is shown in Figure 2.

4.2. Comparison of simulation results of different indexes
In order to verify the rationality of the index of identifying the optimal access location of DG proposed in this paper, the values of VSLR are compared with L-index and LSF index respectively. LSF is calculated under the condition that DG accesses the grid with 25% of the load demand, and L-index is 1.6 times of the original load node power in the following calculation, the value of VSLR in this paper is calculated when DG is connected to the power grid with 25% of load demand. The specific experimental comparison results are shown in Table 1:
### Table 1. Comparison results of different index for IEEE 30-bus.

| Rank | Proposed index Bus No. | Value | L-index Bus No. | Value | LSF Bus No. | Value |
|------|------------------------|-------|----------------|-------|------------|-------|
| 1    | 26                     | 0.82  | 30             | 0.839 | 7          | -0.1008 |
| 2    | 30                     | 0.74  | 26             | 0.7783| 6          | -0.0962 |
| 3    | 25                     | 0.7266| 29             | 0.7651| 9          | -0.0923 |
| 4    | 27                     | 0.7051| 25             | 0.7568| 26         | -0.0908 |
| 5    | 29                     | 0.6588| 27             | 0.7496| 28         | -0.0902 |
| 6    | 24                     | 0.656 | 24             | 0.7348| 10         | -0.0869 |
| 7    | 19                     | 0.6377| 19             | 0.732 | 30         | -0.0869 |
| 8    | 20                     | 0.5962| 18             | 0.7179| 4          | -0.0824 |
| 9    | 18                     | 0.5779| 20             | 0.7134| 29         | -0.081 |
| 10   | 21                     | 0.5596| 23             | 0.7111| 21         | -0.0798 |
| 11   | 22                     | 0.5594| 28             | 0.6954| 22         | -0.078 |
| 12   | 28                     | 0.538 | 22             | 0.6934| 24         | -0.0753 |
| 13   | 23                     | 0.5277| 21             | 0.6908| 19         | -0.074 |
| 14   | 15                     | 0.4995| 15             | 0.6677| 18         | -0.0735 |
| 15   | 10                     | 0.4617| 17             | 0.6612| 17         | -0.0733 |
| 16   | 17                     | 0.4317| 14             | 0.6536| 25         | -0.0728 |
| 17   | 14                     | 0.4132| 10             | 0.6435| 23         | -0.0724 |
| 18   | 6                      | 0.3692| 16             | 0.6351| 20         | -0.0719 |
| 19   | 7                      | 0.3691| 12             | 0.584 | 12         | -0.0709 |
| 20   | 9                      | 0.357 | 7              | 0.4791| 15         | -0.0664 |
| 21   | 4                      | 0.347 | 9              | 0.4568| 27         | -0.0659 |
| 22   | 16                     | 0.3454| 4              | 0.3464| 14         | -0.0642 |
| 23   | 3                      | 0.2891| 6              | 0.3203| 16         | -0.062 |
| 24   | 12                     | 0.2545| 3              | 0.2797| 3          | -0.0593 |

It can be seen from table 1, from the perspective of voltage sensitivity index L-index, the 30th node of IEEE30 system are the most sensitive nodes, which are the most suitable DG access node, and 26 nodes are the second most sensitive node; and the power loss sensitivity factor LSF shows that node 7 is the most suitable DG access node, but the voltage sensitivity index of this node is small; although the voltage sensitivity of node 26 is not as good as node 30, the loss caused by connecting DG from the 26th node can be reduced much. In this paper, considering the voltage sensitivity index and power loss reduction rate, it is concluded that the 26th node is the most suitable access node of DG for IEEE30 system.

To sum up, L-index and LSF are not in the same order in this paper. L-index and LSF evaluate the optimal location through voltage stability and power loss respectively, and it has certain limitations to determine the grid access position of DG with a single index, while the index in this paper is to determine the optimal grid access position of DG by comprehensively considering the influence of these two aspects, so it is more reasonable.
4.3. Comparison of VSLR values of DG with different capacities

Connecting the DG to the power grid with 5%, 15% and 25% of the load demand respectively, calculate the value of VSLR under different DG access power, the comparison results are shown in Table 2:

| Rank | Bus No. | Value  | Bus No. | Value  | Bus No. | Value  |
|------|---------|--------|---------|--------|---------|--------|
| 1    | 26      | 0.928305 | 26      | 0.911919 | 26      | 0.82   |
| 2    | 30      | 0.712647 | 30      | 0.856543 | 30      | 0.74   |
| 3    | 29      | 0.616011 | 27      | 0.825815 | 25      | 0.7266 |
| 4    | 25      | 0.600846 | 29      | 0.809835 | 27      | 0.7051 |
| 5    | 27      | 0.555042 | 24      | 0.74718  | 29      | 0.6588 |
| 6    | 24      | 0.511805 | 25      | 0.696986 | 24      | 0.656  |
| 7    | 19      | 0.505958 | 19      | 0.691652 | 19      | 0.6377 |
| 8    | 20      | 0.45434  | 20      | 0.645913 | 20      | 0.5962 |
| 9    | 18      | 0.443523 | 18      | 0.638141 | 18      | 0.5779 |
| 10   | 22      | 0.397089 | 21      | 0.613522 | 21      | 0.5596 |

It can be seen from table 2 that although the VSLR values obtained by different access powers of DG are slightly different, the top six nodes in the VSLR values of IEEE30 network are the same, and the top two are 26th node and 30th node, so the different access powers of DG will not affect the determination of the optimal access location of DG, which further explains the reliability of the indicators in this paper. To sum up, the optimal access location of IEEE30 network DG is node 26.

4.4. Results of single DG capacity

According to the algorithm proposed in this paper, the optimal access capacity of DG for the IEEE30 network is calculated. The relationship between the capacity of the DG and the total power loss is shown in Figure 3:
As can be seen from the above figure, in the IEEE30 system, when the access power of DG is 20MW, the real line loss of the network is the minimum, so the optimal access power of the IEEE30 network is 20MW.

4.5. Comparison of results of different papers

In order to further explain the rationality and reliability of the index and algorithm proposed in this paper, take IEEE30 system as an example, compare the results obtained in this paper with the results obtained in methods 1 and 2 in references [8] and [11], and the specific results are shown in Table 3:

| Method        | DG’s location | DG size (MW) | PLR (%) |
|---------------|---------------|--------------|---------|
| Method 1      | 26            | 3.3          | 4.05    |
| Method 2      | 5             | 9.89         | 11.29   |
| Proposed method | 26            | 20           | 9.9     |

It can be seen from table 3 that the real loss reduction rate obtained by the algorithm in method 2 is the largest, which has the greatest impact on improving the power quality of the power grid. However, the node 5 is the generator node. According to the actual situation, DG is connected to the power grid from the user end (i.e. the load node), so method 2 are not suitable for the actual power grid planning; The optimal location of DG by method 1 and the method in this paper network both are node 26, but the access capacity of DG is different. Table 3 shows that using the results of the algorithm in this paper to access DG can get a larger real loss reduction rate, which shows that the method in this paper has better performance in reducing real loss. The following uses the voltage performance improvement index (VPI) [12] to compare the effect of improving voltage performance with method 1 and the method in this paper.

The voltage performance improvement index (VPI) is defined as follows:

$$VPI\% = \left( \frac{\sum_{i=1}^{N}(V_{i}L_{i})_{w/DG} - \sum_{i=1}^{N}(V_{i}L_{i})_{wo/DG}}{\sum_{i=1}^{N}(V_{i}L_{i})_{wo/DG}} \right) \times 100\%$$

In the formula, $VPI\%$ is the percentage of voltage distribution improvement; $V_{i}$ is the node voltage; $L_{i}$ is the node load; $n$ is the total number of nodes; $w/DG$ presents access to DG; $wo/DG$ is not connected to DG.

After the simulation calculation, the VPI\% of method 1 is 26%, and the VPI\% of this method is 33%, which shows that this method has better effect in improving the voltage distribution.
5. Conclusion

This paper proposes a new method considering the voltage sensitivity index and the line loss reduction rate to determine the optimal location of DG. According to the above simulation and comparison results, the method in this paper is more comprehensive than that of using voltage stability index or power loss sensitivity factor to determine the optimal location of DG. And from the aspect of reducing the real loss and improving the voltage distribution, compared with other methods, the results obtained by using this method have better effect in reducing the real loss and improving the voltage distribution. To sum up, the method of studying the optimal location and power of DG in this paper has better performance.

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