The sizing and siting of Distributed Generation for mitigating voltage sags

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Abstract. Voltage sags have a major concern in the distribution systems. With the large number of distributed generations connected to the distribution networks, the complexity of distribution networks increases gradually. Thus, how to ensure the minimum damage caused by voltage sags has been the focus of research. In order to effectively mitigate voltage sags and satisfy the grid-connection control requirements of distributed generations, the sizing and siting optimization model of distributed generations is proposed in this paper. The investment and operation cost of distributed generations and mitigating voltage sags on sensitive load are comprehensively considered in this model. To reasonably evaluate economic losses of sensitive load caused by voltage sags in a grid, a novel voltage sags frequency indicator is proposed and the line faults are considered in this indicator. The proposed method is validated by IEEE 33 system and its correctness and reliability are also proved.

1. Introduction

As an important way of electric energy productions, Distributed Generation (DG) is used more and more widely now. DG [1] has many advantages, such as flexible generation modes, low investments and environmental friendliness, etc. DG can be installed independently and dispersedly around the users to meet the specific needs of the users. DG adopts the principle of on-site energy acquisition and on-site consumption. And it does not aim to transmit power with high power and long distance. The access of DG can change the structure and operation mode of Low and Medium Voltage Distribution Network. The impact of DG on safe power supply is closely related to the access capacity and access point of DG. Thus, the sizing and siting of DG in distribution network have attracted extensive attention from researchers all over the world.

The sizing and siting of DG has been researched extensively from two aspects of optimization objectives and optimization algorithms. Literature [2] proposes a distribution generation (DG) allocation strategy for radial distribution networks under uncertainties of load and generation using adaptive genetic algorithm (GA). The optimal locations for DG integration and the optimal amount of generation are determined by minimizing the network power loss and maximum node voltage deviation. Literature [3] considers the multi-objective optimization of DG with equivalent loss factor proposed based on active and reactive power loss incremental factors. Through calculating these factors and comparing them, the node of the maximal factor is chosen and viewed as the optimal location. Literature [4] discusses the correlation between uncertainties and establishes the multi-objective optimization model of DG to minimize the operation risk and the annual comprehensive cost of power grid.
Voltage sag is one of the most complained power quality problems in distribution networks. Thus, mitigating voltage sags on sensitive load [5,6] should be one of the optimization objectives for the sizing and siting of DG. Literatures [7,8] show that DG can provide dynamic reactive power support for power grid quickly and effectively in a certain level of voltage sags when DG keeps running without disconnection in case of power grid failure, and installing a DG with suitable capacity at an appropriate node can improve node voltages. Literature [9] uses the recently proposed concept of PV-STATCOM that utilizes photovoltaic(PV) inverter as STATCOM. To relieve the enormous economic losses caused by the inefficiency in voltage recovery scenario, the reactive power fast response characteristic of PV is adequately considered in optimal sizing and siting of DG. In [9], a modified optimal siting and sizing model is proposed for the targets of minimizing the total annual cost associated with DG to be planned.

Reliable and safe power supply, high power quality, and economic operation are the basic requirements for power systems. According to these basic requirements in this paper, a multi-objective optimization model for the sizing and siting of DG is established to minimize the investment and operation cost of DG and economic losses caused by voltage sags on sensitive loads. An indicator to evaluate the frequency of voltage sags on sensitive load is also proposed. The correctness and feasibility of the optimization model are verified by the calculation and analysis of IEEE 33 system. This paper provides a reference for the sizing and siting of DG and helps the system to realize safe and economic operation.

2. Evaluation indicator of voltage sags frequency for buses

2.1. Analysis on voltage sags caused by faults

To analyze voltage sags caused by faults, the method of fault point is used to calculate voltages of buses in this paper. Assuming that there are \( W \) branches and \( Q \) buses in power grid (where \( W \) denotes the total number of branches). Each branch of power grid can be divided into \( d \) equal parts. Assuming that there are four types of short-circuit faults occurring at \( d-1 \) equal points of each branch and the terminal nodes of each branch respectively, so each branch has \( d \) fault points. The branch \( r \) shown in Figure 1 is taken as an example. The node numbers at both ends of the branch are \( c \) and \( g \). Here has a hypothesis that it can replace an \( m \)-type fault at any point of the part of \( c-1 \) with an \( m \)-type fault at node 1. Similarly, it can replace an \( m \)-type fault at any point of the part of 1-2 with an \( m \)-type fault at node 2. And so on, it can replace an \( m \)-type fault at any point of the part of \((d-1)-g \) with an \( m \)-type fault at node \( g \). (\( m = 1, 2, 3, 4 \) denotes respectively single-phase to ground fault, two-phase short-circuit fault, two-phase to ground fault and three-phase short-circuit fault.)

![Figure 1. a branch \( r \) divided by \( d \) equal parts](image)

The \( m \)-type voltage sags matrix of bus \( j \) can be got as follows when there is an \( m \)-type fault occurring at each node of branch \( r \).

\[
U_{l,j}^{(m)} = [u_{l,j}^{(m)}(1) \ u_{l,j}^{(m)}(2) \ \ldots \ u_{l,j}^{(m)}(d-1)]_{1x3d}
\]

\( U_{l,j}^{(m)} \) denotes the three-phase voltages of bus \( j \) when an \( m \)-type fault occurs at node \((d-1)\) of branch \( r \). If any one of the values in \( U_{l,j}^{(m)} \) is lower than the threshold \( U_{thre,j} \), it is considered that voltage sags occur on the bus \( j \) and let \( v_{l,j}^{(m)} \) = 1. If voltage sags do not occur on bus \( j \), let \( v_{l,j}^{(m)} \) = 0. So, the \( m \)-type
voltage sags area matrix of bus $j$ can be established as follows when an $m$-type fault occurs at each node of branch $r$.

$$

V_{i,j}^{(m)} = \begin{bmatrix}
V_{i_{1j}}^{(m)} & V_{i_{2j}}^{(m)} & \ldots & V_{i_{r-1j}}^{(m)} & V_{i_{dj}}^{(m)}
\end{bmatrix}

$$

(2)

The frequency occurring voltage sags on bus $j$ is determined by the following equation when an $m$-type fault occurs on branch $r$.

$$

V_{i,j}^{(m)} = \frac{1}{n} \left( V_{i_{1j}}^{(m)} + V_{i_{2j}}^{(m)} + \ldots + V_{i_{r-1j}}^{(m)} + V_{i_{dj}}^{(m)} \right)

$$

(3)

The $m$-type voltage sags area matrix $V_{i}^{(m)}$ can be established as follows when an $m$-type fault occurs on branch $r$.

The information analyzed from the $i$'th row in an $m$-type voltage sags area matrix $V_{i}^{(m)}$ reflects the frequency occurring voltage sags on each bus when an $m$-type fault occurs on branch $i$. And the information analyzed from the $j$'th column in the matrix $V_{i}^{(m)}$ reflects the frequency occurring voltage sags on bus $j$ when all the branches have a $m$-type faults in sequence.

$$

V_{i}^{(m)} = \begin{bmatrix}
V_{i_{11}}^{(m)} & V_{i_{12}}^{(m)} & \ldots & V_{i_{1j}}^{(m)} & \ldots & V_{i_{1Q}}^{(m)} \\
V_{i_{21}}^{(m)} & V_{i_{22}}^{(m)} & \ldots & V_{i_{2j}}^{(m)} & \ldots & V_{i_{2Q}}^{(m)} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
V_{i_{r1}}^{(m)} & V_{i_{r2}}^{(m)} & \ldots & V_{i_{rj}}^{(m)} & \ldots & V_{i_{rQ}}^{(m)} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
V_{i_{dj}}^{(m)} & V_{i_{d2}}^{(m)} & \ldots & V_{i_{dj}}^{(m)} & \ldots & V_{i_{dQ}}^{(m)} \\
\end{bmatrix}_{r \times Q}

$$

(4)

Similarly, a voltage sags matrix and voltage sags area matrix can be established when an $m$-type fault occurs on the branches.

2.3. The voltage sags frequency indicators of buses

Voltage sags are mainly caused by branch faults. Therefore, the voltage sags frequency of buses can be determined by voltage sags area matrix of branch $V_{i}^{(m)}$.

The total number that bus $j$ occurs voltage sags is denoted by $F_{j}^{(m)}$ when $m$-type faults occur in the grid.

$$

F_{j}^{(m)} = \sum_{i=1}^{n} V_{i,j}^{(m)}

$$

(5)

With the four types of short-circuit faults considered, the average frequency that bus $j$ occurs voltage sags also can be got and it is denoted by $F_{j}$. (where $\lambda_{m}$ denotes the probability that an $m$-type fault occurs in the system.)

$$

F_{j} = \sum_{m=1}^{4} \lambda_{m} F_{j}^{(m)}

$$

(6)

3. Analysis on the sizing and siting optimization model of DG

The access of DG has a certain impact on the operation states of power grid. Although the investment and operation cost can be incurred when DG is connected to the distribution networks, the reasonable access of DG can reduce the number of voltage sags on sensitive loads and the economic losses of voltage sags. Thus, the sizing and siting of DG are optimized from two aspects in this paper: the investment and operation cost of DG and economic losses caused by voltage sags on sensitive loads.
3.1. Objective function
The purpose of the optimization for the sizing and siting of DG is to minimize the total costs of investment and operation cost and economic losses of voltage sags under relevant constraints in this paper. Thus, a multi-objective optimization function \( E \) can be proposed here and the access capacity and access point of DG are taken as variables in the objective function \( E \).

\[
E = \min( E_{DG} + E_{sl} )
\]  

(7)

Where \( E \) denotes the sum of economic costs that includes the investment and operation cost of DG, the economic cost of network losses and the economic losses of voltage sags.

3.2. The investment and operation cost of DG
The investment and operation cost of DG includes the initial investment cost, annual operation cost of DG.

\[
E_{DG} = \sum_{i=1}^{N_{DG}} (\xi_{i1} + \xi_{i2})P_{DGi}
\]  

(8)

Where \( E_{DG} \) denotes the total cost of DG. \( \xi_{i1} \) denotes the installation cost of DG unit capacity at node \( i \). \( \xi_{i2} \) denotes the operation cost of DG unit capacity at node \( i \). \( P_{DGi} \) denotes rated capacity of DG installed at node \( i \). \( N_{DG} \) is the total number of DG installed in distribution network.

3.3. Economic losses caused by voltage sags on sensitive load
The economic losses of voltage sags are the economic losses of sensitive load caused by voltage sags. The economic losses of voltage sags consist of two parts, including the average economic losses of sensitive load caused by a single voltage sags event and the number of voltage sags on sensitive load.

\[
E_{sl} = \sum_{j=1}^{\chi} \tau_{j}F_{j}
\]  

(9)

Where \( E_{sl} \) denotes the total economic losses of voltage sags. \( F_{j} \) denotes the frequency of occurring voltage sags at node \( j \). \( \tau_{j} \) denotes the average economic losses of sensitive load caused by a single voltage sags event at node \( j \). \( \chi \) denotes the total number of buses that sensitive loads are connected to.

3.4. Constraints

3.4.1. The inequality constraints of voltages

\[
U_{\text{min}} \leq U_{i} \leq U_{\text{max}}
\]  

(10)

In inequality (10), \( U_{\text{min}} \) denotes minimum allowable voltage at node \( i \) and \( U_{\text{max}} \) denotes maximum allowable voltage at node \( i \).

3.4.2. The inequality constraints for the power transmission limit

\[
P_{ij} \leq P_{j\text{max}}
\]  

(11)

In inequality (11), \( P_{ij} \), \( P_{j\text{max}} \) are transmission power and maximum transmission power of the branch from node \( i \) to node \( j \) respectively.
3.4.3. The constraint on penetration of DG

\[ \sum_{i=1}^{n} S_{DG_{i}} \leq \eta S \]  

(12)

The total installation capacity of DG should not exceed 10%~25% of the maximum capacity of the power grid, which \( \eta \) is a constant and equal to 0.25. \( S \) denotes the total capacity of the system load.

4. The simulation and discussion

To mitigate voltage sags, an optimization algorithm for selecting optimal access capacity and access point of DG is proposed. An example of IEEE 33 system illustrated in Figure 2 is given. The system consists of 33 buses, 32 transmission lines and 5 transmission lines with loop switches. The five dotted lines in Figure 2 are the lines with loop switches. The 5 loop switches are usually opened and IEEE 33 system operates as a radial network. Here is a hypothesis that buses that sensitive loads are accessed to are 11 and 30. The unit capacity installation cost, operation cost of DG installed are 0.63×10^6 CNY/MVA and 0.18×10^6 CNY/MVA respectively. The electricity charge per kilowatt-hour is 0.6 yuan (CNY). The average economic losses caused by single voltage sags event of sensitive load on bus 11 is 1.5 million yuan (CNY) and the average economic losses caused by single voltage sags event of sensitive load on bus 30 is 3.2 million yuan (CNY). The probabilities that four types of short-circuit faults [10] occur in the grid respectively (single-phase to ground fault, two-phase short-circuit fault, two-phase to ground fault and three-phase short-circuit fault) are 0.83, 0.08, 0.05 and 0.04 respectively.

4.1. Analysis for selecting the optimal access capacity and access point of DG

To verify the proposed optimization method for the sizing and siting of DG, a corresponding program is written by MATLAB language. The program includes the power flow calculation subprogram, the short-circuit calculation subprogram, the voltage sags frequency indicator calculation subprogram of sensitive load, and the sizing and siting optimization main program of DG.

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The access capacities and access points of DG are shown as follows:

- Access bus is 11 and the capacity is 0.6MW.
- Access bus is 16 and the capacity is 0.15MW.
- Access bus is 30 and the capacity is 0.3MW.
- Access bus is 33 and the capacity is 0.2MW.

5. Conclusion

This paper optimizes the sizing and siting of DG from three aspects: the investment and operation cost of DG, economic cost caused by network losses, and economic losses caused by voltage sags on sensitive loads. Thus, a multi-objective sizing and siting optimization model of DG based on \( p\% \) elite
sampling is proposed in this paper. The main research results are shown as follows. The reasonable access of DG can improve operating voltages of buses in the system, effectively reduce network losses, mitigate voltage sags of sensitive load, and improve the security and economy of system operation. The voltage sags frequency indicator proposed in this paper provides a new way to evaluate economic losses of sensitive load caused by voltage sags.

In general, the multi-objective sizing and siting optimization model of DG provides a reference for selecting optimal access capacity and access point of DG.

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