Distributed Energy Storage Optimization Location Method Based on Improved Voltage Distribution

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Abstract. Aiming at the problem of voltage overrun caused by large-scale distributed generation (DG) access to distribution network, a distributed energy storage optimization location method based on improved power quality is proposed. Firstly, the voltage governance mechanism of distributed energy storage access to distribution network with large-scale distributed generation is analyzed. Secondly, a distributed energy storage optimization site selection model is proposed, which can be solved in two stages: In the first stage, the power flow calculation is performed based on the typical time section, and the set of energy storage grid-connected nodes is determined by using the weighted voltage sensitivity. In the second stage, the distribution network voltage offset and active power loss optimization are taken as the objective functions. Each node in the set is selected as a parallel node for power flow calculation to determine the final grid-connected node by using the enumeration method. Finally, the improved IEEE33 node distribution network system is taken as an example to verify the correctness of the proposed model. The results of the example show that the distributed energy storage access can effectively support the voltage, and the proposed location model has good practicality.

1. Introduction

With the depletion of global stone energy and the application of clean energy, distributed generation (DG) is continuously connected to the distribution network due to its flexible control and high energy utilization. However, due to its characteristics of volatility and intermit and the application of power electronic devices, problems such as voltage over-limit and harmonic pollution often occur in the distribution network [1]. When a node in a system accesses a DG and its output power exceeds the node’s own capacity, the voltage is more likely to be exceeded [2]. Distributed energy storage has the characteristics of fast power throughput and flexible access points. Reasonable selection of energy storage access location can realize voltage regulation of distribution network on the basis of over-consumption of DG [3].

In recent years, domestic and foreign scholars have already had some research results on the issue of optimal storage site selection. According to the typical daily load curve of the main transformer of each substation, [4] proposed the evaluation index of peak-shaving suitability and optimized the site selection of energy storage on the power grid side. [5] establishes a two-layer optimization model for location and volume, and solves the model through intelligent algorithms. In [6], the energy storage location constant volume optimization model is established with the system node voltage fluctuation,
load fluctuation and total energy storage capacity as the target. An improved multi-objective particle swarm optimization algorithm is proposed to solve the model. Sensitivity method is widely used in distributed energy storage site selection [7]. In [7,8], a storage energy optimization location algorithm based on network loss sensitivity is proposed, and the node with the highest sensitivity coefficient is used as the energy storage grid point. [9] proposed a heuristic optimization algorithm based on clustering and voltage sensitivity for site selection research. In [10], a node sensitivity analysis method for power quality management of high power density distributed PV access distribution network is proposed, which realizes the fast solution of the location and capacity of composite energy storage device.

This paper aims at the problems existing in the optimal site selection of distributed energy storage. Firstly, a model of distributed energy storage access's influence on the voltage of distribution network containing DG is established, and then a distributed energy storage location model is proposed. The results of the example show that distributed energy storage has better voltage support capability. The proposed location method is actually more operability. At different PV penetration rates, the use of two grid-connected points for power quality control is better than a grid-connected point.

2. Analysis of influence of distributed energy storage access on distribution network voltage with DG

The radiant distribution network structure shown in figure 1. The line impedance between adjacent nodes is $R+jX$. The load capacity of node $i$ is $P_L+jQ_L$. At node $i$, a PV system with a capacity of $P_{PV}+jQ_{PV}$ and an ESS with a rated power of $P_{ESS}$ are proposed. Load, PV and energy storage all adopt constant power model.

$$U_{i-1} - U_i = \frac{(P_L + P_{ESS} - P_{PV})R + (Q_L - Q_{PV})X}{U_{i-1}}$$

Figure 1. Radial distribution network structure

Distributed energy storage has the characteristics of strong power handling capacity and flexible access position, which can play a role in absorbing DG on the side of distribution network. This paper intends to improve the voltage distribution of the distribution network by accessing distributed energy storage. The voltage drop relationship after accessing the ESS is as follows:

$$U_{i-1} - U_i = \frac{(P_L + P_{ESS} - P_{PV})R + (Q_L - Q_{PV})X}{U_{i-1}}$$

According to equation (1), when the PV output is too large, part of the PV power can be absorbed through energy storage charging, making $P_L + P_{ESS} - P_{PV}$ positive and avoiding voltage over-limit problem. When the PV output is insufficient but the load power is large, the energy storage can be discharged to avoid the problem of voltage drop being too large.

3. Weighted node voltage sensitivity based on typical time profile

3.1 Node voltage sensitivity

When a node is connected to a PV system, the relationship between the amount of change in the node voltage and the amount of change in input power is derived as follows [12]:

$$\begin{bmatrix} J_{rP} & J_{rQ} \\ J_{qP} & J_{qQ} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta U \end{bmatrix} = \begin{bmatrix} J_{rP} \Delta \delta + J_{rQ} \Delta U \\ J_{qP} \Delta \delta + J_{qQ} \Delta U \end{bmatrix}$$

(2)
In the formula, $\Delta P$ and $\Delta Q$ represent the amount of change in active and reactive power, respectively. $\Delta \delta$ and $\Delta U$ represent the voltage phase angle and the amount of change in amplitude, respectively. $J_{P6}$, $J_{P7}$, $J_{Q6}$, and $J_{Q7}$ represent the Jacobian matrix parameters, respectively. Make $\Delta Q = 0$, available:

$$
\Delta U = \frac{1}{(J_{P6} - J_{P7}J_{Q6}^{-1}J_{P7})} \Delta P = J \Delta P
$$

(3)

In the formula, $J$ is the node voltage-active sensitivity.

According to equation (4), the node voltage-active self-sensitivity coefficient $\lambda_{ii}$ and the mutual sensitivity coefficient $\lambda_{ij}$ are defined. Where $\lambda_{ii}$ indicates a change in the voltage of the node $i$ when the node $i$ is injected with power, and $\lambda_{ij}$ indicates a change in the voltage of the node $i$ when the power of the node $j$ is injected.

$$
\lambda_{ii} = \frac{\Delta U}{\Delta P_i},
\lambda_{ij} = \frac{\Delta U}{\Delta P_j}
$$

(4)

When there are multiple node injection powers in the system, the voltage sensitivity of node $i$ should be the result of self-sensitivity and mutual sensitivity. The functional relationship is as follows:

$$
\lambda_i = f(\lambda_{ii}, \lambda_{ij})
$$

(5)

Existing research on location selection based on conventional node voltage sensitivity generally selects the operating section with the largest PV output or the least load according to the static typical daily curve. In fact, due to the uncertainty of PV output and the volatility of the load, the selection of the running section in the above study did not consider the timing matching problem.

3.2 Weighted node voltage sensitivity based on typical time profile

Since both PV output and load power have volatility and uncertainty, it is not representative to select a certain time as a section based on typical daily power data. Based on the typical section acquisition method, this paper proposes a weighted node voltage sensitivity based on typical time profile.

3.2.1 Typical time section method

This paper takes a time series of 8760h a year as the research object. Assume that the initial peak power of load and power is set to 1.0 pu, calculate the PV power permeability at each moment, and select the moment with the highest permeability as the typical time section. Considering the PV output period, the load is generally at the peak period. In order to eliminate the interference of individual data, the typical time section should select the moment when the load power is higher than 0.5 pu.

$$
\max R_{P_{tPV},t} = \frac{P_{PV,t}}{P_{load,t}} \text{ for } t = 1,2,\ldots,8760 \quad \text{st. } P_{load,t} \geq 0.5 \text{pu}
$$

(6)

In the formula, $R_{P_{tPV},t}$ represents the PV power permeability at time $t$; $P_{PV,t}$, $t$ and $P_{load,t}$ are the PV output and load power at time $t$, respectively.

According to the formula (6), the time $t_0$ at which the PV permeability in 8760h is the largest can be calculated. The $t_0$ time is selected as a typical time section to calculate the power flow.

3.2.2 Weighted node voltage sensitivity

Since the conventional voltage sensitivity can only measure the magnitude of the voltage change when the power change occurs at the node. However, from the perspective of network loss, the energy storage grid connection point should try to choose the PV system on the grid connection node. In addition, although some nodes are not equipped with PVs, due to the influence of power injection by adjacent nodes, the node voltage changes at the node voltage of the PV system. Therefore, depending
on whether the node is equipped with a PV system to construct a weighted node voltage sensitivity, the functional relationship is as follows:

\[ Z_i = \omega \lambda_{i,0} \]  

In the formula, \( Z_i \) represents the weighted voltage sensitivity of node \( i \); \( \omega \) represents the weighting coefficient of node \( i \). When node \( i \) is equipped with a PV system, its value is 1, otherwise it is 0.8.

4. Distributed energy storage location model and process

4.1 Alternative grid-connected nodes

According to the above method, the weighted node voltage sensitivity \( Z_i \) of each node is solved under a typical time section. For the node of \( Z_i > Z_0 \), it is regarded as the node set \( \Omega_c \) of the energy storage grid. Since the voltage sensitivity matrix uses a linear representation of the power equation [13], there is a certain error between the result and the true value. Therefore, the grid-connected node set \( \Omega_c \) obtained according to the weighted sensitivity method should be further analyzed to determine the final grid-connected node.

4.2 Final grid-connection node

On the basis of the alternative grid-connected nodes, the final grid connection point of the ESS should be the node that minimizes the voltage deviation of the whole system, and the active network loss of the distribution network should be minimized. Therefore, this paper selects the two parameters of node voltage deviation and network loss as the objective function.

4.2.1 Objective function

1) Node voltage deviation. Since the grid-connected node determined by the weighted sensitivity analysis is the node with the most severe voltage offset, it is necessary to weigh the voltage deviation of the grid-connected node and the voltage deviation of other nodes. Therefore, the weight coefficient is used to select the sum of the voltage deviation of the grid-connected node and the voltage deviation of other nodes as the objective function. The mathematical relationship is as follows:

\[ f_1 = \alpha_1 \sum_{i \in \Omega_c} |U_i - U_N| + \alpha_2 \sum_{j \in \Omega_o} |U_j - U_N| \]  

In the formula, \( \alpha_1 \) and \( \alpha_2 \) represent weight coefficients, which range from 0 to 1, and satisfy \( \alpha_1 + \alpha_2 = 1 \); \( \Omega_c \) represents a set of grid-connected nodes; \( \Omega_o \) represents a set of other nodes.

2) The system has active network loss. Since the storage point selection of different access points has a great influence on the active network loss of the distribution network, it is necessary to consider the system network loss size. The calculation formula is as follows:

\[ f_2 = \sum_{l=1}^{L} P_{\text{loss},l} \]  

In the formula, \( P_{\text{loss},l} \) represents the active network loss of the branch \( l \); \( L \) represents the total number of branches in the distribution network.

Considering the node voltage deviation and the active network loss of the distribution network, the objective function of the energy storage site selection is as follows:

\[ \min f = \beta_1 f_1 + \beta_2 f_2 \]  

In the formula, \( \beta_1 \) and \( \beta_2 \) represent weight coefficients, which range from 0 to 1, and satisfy \( \beta_1 + \beta_2 = 1 \).

4.2.2 Restrictions

The constraints mainly consider system power flow constraints and energy storage constraints.
In the formula, $P_{\text{grid}, t}$ and $P_{\text{loss}, t}$ represent the power and line active loss provided by the grid at time $t$. $U_{\max}$ and $U_{\min}$ represent the upper and lower limits of the node voltage, respectively. $P_{\max}$ and $P_{\min}$ represent the upper and lower limits of the stored energy, respectively; SOC represents the state of charge of the stored energy, and $SOC_{\max}$ and $SOC_{\min}$ represent the upper and lower limits of the state of charge, respectively.

### 4.3 Determining energy storage

Since the power flow calculation is based on a typical time section, this paper only considers the power level of the energy storage. Under the condition where economic factors are not taken into account and only energy storage is used to absorb the excess PV power, the energy storage power required for the entire distribution network is the difference between PV output and load power under the typical time section. Calculation method of energy storage power is as follows:

$$P_{\text{ESS}} = P_{\text{PV}, t} - P_{\text{load}, t}$$

(12)

### 5. Case analysis

#### 5.1 Introduction to the study

In this paper, the improved IEEE33 node distribution network system is taken as an example to verify the above method, as shown in figure 2. The reference voltage of the system is 12.66kV, while the total system load is 3715kW+j2300kvar. The bus 0 is the balance node, whose voltage is set to 1.0pu, and the system voltage upper limit is set to 1.05pu. It is planned to access 1MW of distributed PV systems at each of nodes 4, 5, 11 and 17. The load and PV power use actual grid data in a region with a higher light intensity. The load fluctuation in this region is less affected by seasonal changes. The power curve is shown in figure 3.

![Figure 2. Improved IEEE33 node system](image)

![Figure 3. Actual power curve](image)

#### 5.2 Result analysis

The IEEE33 node system is built in MATLAB, and the power flow calculation is performed according to the requirements of the example. The voltage, conventional sensitivity, and weighted sensitivity parameters proposed by each node after accessing the PV system are shown in the table 1.

When $Z_0=0.08$ is selected, the energy storage grid-connected candidate node set is {11,16,17} three nodes. The power flow calculation is performed by using these three nodes as energy storage grid
points. Where \( \alpha_1 = 0.2, \alpha_2 = 0.8; \beta_1 = 0.5, \beta_2 = 0.5 \). The objective function calculation results are shown in Table 2.

| Node number | Voltage /pu | \( \lambda_i \) | Z_i | Node number | Voltage /pu | \( \lambda_i \) | Z_i | Node number | Voltage /pu | \( \lambda_i \) | Z_i |
|-------------|-------------|----------------|-----|-------------|-------------|----------------|-----|-------------|-------------|----------------|-----|
| 0           | 1.000       | 0.000          | 0.000 | 11          | 1.032       | 0.105          | 0.105 | 22          | 0.997       | 0.018          | 0.012 |
| 1           | 1.000       | 0.003          | 0.002 | 12          | 1.037       | 0.116          | 0.074 | 23          | 0.990       | 0.017          | 0.011 |
| 2           | 1.001       | 0.018          | 0.018 | 13          | 1.039       | 0.120          | 0.077 | 24          | 0.987       | 0.018          | 0.012 |
| 3           | 1.001       | 0.026          | 0.016 | 14          | 1.042       | 0.125          | 0.080 | 25          | 1.001       | 0.053          | 0.034 |
| 4           | 1.003       | 0.035          | 0.022 | 15          | 1.046       | 0.130          | 0.083 | 26          | 0.999       | 0.054          | 0.035 |
| 5           | 1.003       | 0.050          | 0.050 | 16          | 1.053       | 0.139          | 0.089 | 27          | 0.988       | 0.054          | 0.034 |
| 6           | 1.002       | 0.056          | 0.036 | 17          | 1.058       | 0.145          | 0.145 | 28          | 0.980       | 0.054          | 0.034 |
| 7           | 1.008       | 0.067          | 0.043 | 18          | 0.999       | 0.002          | 0.001 | 29          | 0.977       | 0.055          | 0.035 |
| 8           | 1.017       | 0.082          | 0.053 | 19          | 0.996       | 0.003          | 0.002 | 30          | 0.973       | 0.055          | 0.035 |
| 9           | 1.026       | 0.097          | 0.062 | 20          | 0.995       | 0.003          | 0.002 | 31          | 0.972       | 0.055          | 0.035 |
| 10          | 1.028       | 0.100          | 0.064 | 21          | 0.994       | 0.002          | 0.001 | 32          | 0.972       | 0.055          | 0.035 |

Table 2. Grid-connected node target function calculation value

| Node number | \( f_1 \) | \( f_2 \) | \( f \) |
|-------------|---------|---------|-------|
| 11          | 0.346   | 0.135   | 0.240 |
| 16          | 0.273   | 0.112   | 0.193 |
| 17          | 0.271   | 0.106   | 0.188 |

Table 3. Objective function calculation result when the number of grid points is different

| Number | Location | Power/kW | \( f_1 \) | \( f_2 \) | \( f \) |
|--------|----------|----------|---------|---------|-------|
| 1      | 17       | 850      | 0.271   | 0.106   | 0.188 |
| 2      | 16, 17   | 425      | 0.267   | 0.108   | 0.187 |
| 3      | 11, 16, 17 | 283     | 0.280   | 0.114   | 0.197 |

Table 2 shows that node 17 is the best grid-connected node for energy storage, and node 16 is the second best grid-connected node.

Figure 4. IEEE33 node distribution network voltage and voltage distribution

Figure 4 shows the original voltage distribution of IEEE33 node, the voltage distribution after access to DG, and the voltage distribution after access to distributed energy storage on node 17.

As can be seen from figure 4, the distributed energy storage access can effectively suppress the voltage over-limit problem and make the voltage deviation of the entire system small.

Next, analyze the impact on the objective function when the number of connected points is different. This paper does not consider the optimal allocation of energy storage power. The average
allocation principle is adopted for the convenience of research. The calculation results of the objective function when different number of grid points are shown in Table 3.

It can be seen from Table 3 that when the number of energy storage grid points is 2, although the system network loss increases, the system voltage deviation can be reduced to some extent. The final objective function value is lower than the case where the number of energy storage grid points is one.

When the number of energy storage grid points is 3, the system network loss and voltage deviation increase, so the objective function value is higher than the case where the number of energy storage grid points is 1.

The above conclusions are based only on the specific PV penetration rate. The following will change the PV penetration rate and continue to explore the energy storage location problem. Based on the original example, two different penetration scenarios are set up, namely:

Scene 1: Each node of nodes 2, 5, 11 and 17 is connected to a 0.5 MW PV system;
Scene 2: Each node at nodes 2, 5, 11 and 17 is connected to a 1.5 MW PV system.

Nodes 16 and 17 are still the best grid-connected nodes for calculation. The calculation results of the objective functions in each scenario are shown in Table 4.

| Node number | Original case | Scene 1 | Scene 2 |
|-------------|---------------|---------|---------|
| 1           | 0.188         | 0.413   | 0.321   |
| 2           | 0.187         | 0.404   | 0.308   |

It can be seen from Table 4 that in the case of different PV penetration rates, the effect of selecting two energy storage grid points is better than the single point access method.

6. Conclusions
Aiming at the problem of voltage overrun caused by large-scale distributed power access distribution network, this paper proposes a distributed energy storage optimization location method based on improved power quality. Through analysis and numerical example verification, the following conclusions are obtained:

The distributed energy storage access can support the entire distribution network voltage, and has a good voltage regulation effect in the scene of large-scale DG grid connection.

The proposed distributed energy storage location model is improved on the basis of the original voltage sensitivity, which not only greatly reduces the calculation amount, but also makes up for the deficiency of using the sensitivity coefficient as the location index.

Compared with the single-point access method, distributed energy storage multi-point access has better effect on voltage management.

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