Energy storage locating and sizing method in grid-connected micro-grid

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Abstract. In micro grid, the distributed generations have a large proportion and the energy storage system is the fundamental structure of the micro grid. Wind and photovoltaic power generation contain intermittent and uncertain characteristics. Energy storage system in micro grid can smooth the volatility of distributed power and supply power to important loads in case of the insufficiency of distributed power generation. In this paper, a location and capacity planning method of energy storage system is proposed. The energy storage installation points are the key points of the system, which are identified based on the electrical distance. Further, the capacity is optimized and solved on these basics. Finally, the effectiveness of the proposed method is verified through case studies.

1. Introduction

With the large consumption of fossil energy and the warming of the climate caused by greenhouse gases, the development of renewable energy power generation is the focus of energy transformation. Research and practice show that the most effective way to develop distributed power supply is to connect the distributed power supply into the grid in the form of micro-grid[1]. However, large-scale grid integration of distributed power supply will bring problems of grid safety and economic operation.

The energy storage system is characterized by its fast power absorption and supply capability, which can provide active and reactive power, stabilize voltage fluctuation and improve power supply reliability. It is a significant means to deal with the uncertainty of distributed generation.

Reference [2] summarized the research status of large-capacity energy storage technology applied to power grid peak regulation and the energy storage system planning methods for centralized and distributed access mode. Reference [3] built a cost-benefit calculation model for the whole life cycle of battery energy storage. Further it built a capacity configuration model of secondary frequency modulation with battery energy storage participation. Reference [4] analyzed different scheduling modes of photovoltaic energy storage power station and built an energy storage optimization model with the objective of net earnings, which can provide reference information for the selection of energy storage capacity under different scheduling modes and different market environments. According to the different wind power stabilize strategies, reference [5-6] built different capacity optimization models, in which the locations of energy storage are selected at the wind power connection points. In reference [7], considering the correlations among wind speed, light intensity and load, the opportunity constrained planning method was used to establish the distributed generation location and capacity planning model aiming at the minimum annual comprehensive cost. Reference [8-10] established a
two-layer decision model, and the outer optimization model was responsible for solving the planning problem of energy storage system, including the location selection and capacity allocation of energy storage. The inner optimization model is responsible for solving the operation problems of the energy storage system, including generator control and energy storage charge and discharge strategy. Most of the above researches are on the energy storage locating and sizing optimization models in distribution grid, but rarely of them are applied in micro grid. Moreover, the synchronous energy storage location and capacity optimization will cause the installation location is scattered and the capacity is small at each point. In this paper, an energy storage location and capacity optimization model in the micro grid is proposed. A location determination method of energy storage based on the electrical distance connection coupling degree is provided, which is the first step and followed by capacity optimization. Through the comparison of network loss and voltage fluctuation under different planning schemes different planning schemes, the validity of the proposed method is verified.

2. Planning of the single point

2.1. Energy storage locating
In this paper, the energy storage locating and sizing are determined separately due to the mixed integer nonlinear functions are difficult to solve. Furthermore, the characteristic identification model of complex power network based on electrical coupling connection degree can reflect the heterogeneous structural characteristics of power grid [11].

In power system the electrical distance between node i and node j can be defined as equivalent impedance \( Z_{ij,\text{equ}} \) between the two points, which is equal to the voltage \( U_{ij} \) between node i and node j under unit current from node i shown in Equation (1).

\[
Z_{ij,\text{equ}} = \frac{U_{ij}}{I_i} = U_{ij}
\]  

(1)

where, \( Z_{ij,\text{equ}} \) can be expressed as Equation (1) and \( Z_{ij} \) is the element in row i and column j of the node impedance matrix.

\[
Z_{ij,\text{equ}} = (Z_{ij} - Z_{ij}^\text{r}) - (Z_{ij} - Z_{ij}^\text{l})
\]  

(2)

In an N-node power network, the electrical coupling connection degree of node i is:

\[
D_{e,i} = \sum_{j=1,j\neq i}^{N} |Z_{ij,\text{equ}}|
\]  

(3)

where the importance of node i in the power network is represented by the sum of the electrical distance between node i and other nodes in the system. This index can quantitatively describe the strength of the electrical coupling connection between a node and other nodes in the system. The smaller the value of \( D_{e,i} \) is, the stronger the electrical coupling effect between node i and other nodes is, and the failure at this node is more likely to cause the overall accident of the system.

![Figure 1. Electrical coupling connectivity index.](image-url)
The electrical coupling connectivity index of each node in IEEE 33-node network is shown in Figure 1. The index of $D_{ei}$ of each node is distributed as follows. The value of $D_{ei}$ of node 6 is the smallest, that is, the coupling degree of node 6 and other nodes is the strongest. The battery energy storage should be installed at node 6.

2.2. Operation strategy of energy storage
During the peak period of electricity consumption, if the renewable power is larger than load, the excess power will be sent to the higher power grid priority, and the remaining power will be used to the energy storage system charging. If the renewable power is less than load, the energy storage discharge priority to supply power, and the insufficient part is provided by the grid.

During the period of electricity throughs, when the renewable energy power is larger than load, the excess power will be provided to the energy storage charging. If the energy storage is not fully charged, the superior power grid will continue to provide power to the energy storage system. If the power of renewable energy is less than the load, it purchases power from the superior power grid priority and the insufficient part is provided by the energy storage system.

2.3. Optimization of energy storage capacity
Under the premise that the energy storage installation location is known, the optimization of the energy storage capacity is conducted, shown as follows.

$$C = C_{bess} + C_{pline} + C_{pb}$$

(4)

$$C_{bess} = \frac{1}{365} \cdot \frac{d(1+d)^{y_1}}{(1+d)^{y_2}-1} \cdot k \cdot S \cdot E_b$$

(5)

$$C_{pb} = \sum_{t=1}^{N_t} c_{pt} \cdot P_{bt}$$

(6)

$$C_{pline} = \sum_{t=1}^{N_t} c_{pt} \cdot P_{line_t}$$

(7)

where, $C_{bess}$ is the installation cost of energy storage; $k$ is the installation cost of per unit capacity; $S$ represents the number of energy storage batteries installed at node 6; $E_b$ is the rated capacity of a single battery; $C_{pb}$ is the arbitrage benefit of energy storage peak and valley; $N_t$ is the number of time periods in a day; $c_{pt}$ is the electricity price; $P_{bj,t}$ is the charging and discharging power of the battery, where, discharging is positive and charging is negative; $C_{pline}$ is the revenue from buying and selling electricity to the bulk power system; $P_{line_t}$ is the power exchanged with the bulk power system, where buying electricity from the grid is positive and selling is negative.

The constraints include the power balance of network nodes, voltage amplitude and phase angle constraint, tie line power constraint, charging and discharging constraints and SOC constraint of energy storage.

(1) Node voltage constraint:

$$u_{ij}^{\min} \leq u_{ij,t} \leq u_{ij}^{\max} \quad j \in 1..n, t \in 1..N_t$$

(8)

where, $u_{ij}^{\min}$ and $u_{ij}^{\max}$ is the upper and lower limit of node voltage amplitude, respectively.

(2) Phase Angle constraint:

$$\theta_{ij}^{\min} \leq \theta_{ij,t} \leq \theta_{ij}^{\max} \quad j \in 1..n, t \in 1..N_t$$

(9)

where, $\theta_{ij}^{\min}$ and $\theta_{ij}^{\max}$ is the upper and lower limit of node phase Angle, respectively.

(3) Node power balance equation:

$$P_{i,t} = U_{i,t} \sum_{j \in N_t} U_{i,t} \left( G_{ij} \cdot \cos \theta_{ij,t} + B_{ij} \cdot \sin \theta_{ij,t} \right)$$

(10)

$$Q_{i,t} = U_{i,t} \sum_{j \in N_t} U_{i,t} \left( G_{ij} \cdot \sin \theta_{ij,t} - B_{ij} \cdot \cos \theta_{ij,t} \right)$$

(11)
where, $P_{i,t}$, $Q_{i,t}$ is the active and reactive power injected into node $i$ at time $t$, respectively. ; $U_{i,t}$, $U_{j,t}$ is the voltage of node $i$ and $j$ ; $G_{i,j}$, $B_{i,j}$ are the real and imaginary parts of row $i$ and column $j$ of node admittance matrix, respectively.

(4) Battery charging and discharging constraints:

$$-S * p_n \leq p_t \leq S * p_n$$ (12)

where, $p_n$ is the rated power of a single battery and $S$ is the number of installations to be optimized.

(5) Battery capacity constraint:

$$0.3 * S * E_b \leq E_t \leq 0.95 * S * E_b$$ (13)

$$E_{t-1} - p_t = E_t \quad t \in 1..N_t$$ (14)

$$E_{24} - p_t = E_t$$ (15)

where, $E_t$ is the capacity of the battery at time $t$; $E_b$ is the rated capacity of a single battery; In addition, to ensure the continuous working capacity of the energy storage battery, it is necessary to ensure the consistency of the initial SOC during a day.

(6) Tie line constraint:

$$0 \leq |P_{line,t}| \leq P_{line}^{max}$$ (16)

where, $P_{line}^{max}$ is the upper limit of power exchange with large power grid.

(7) Branch constraint:

$$R_{ij} = |V_i V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) - V_i^2 G_{ij}| \leq p_{ij}^{max}$$ (17)

where, $p_{ij}^{max}$ is the upper limit of branch capacity.

(8) Reserve constraint:

According to the trial measures for promoting the construction of grid-connected micro-grid, the micro-grid should guarantee the continuous power supply of important loads longer than 2 hours under the independent operation, shown in Equation (18).

$$(\text{Soc}_t - 0.1) * S * E_b \geq P_{cl} * T$$ (18)

where, the limit of SOC during charging in independent operation is 0.1; $P_{cl}$ represents the important load and $T$ represents the continuous operating time.

2.4. Experiment analysis

The improved IEEE 33-node system was used for example analysis. In the system, the rated voltage of the system is 10 kV and the allowable voltage offset is plus or minus 7%. The maximum interactive power of the tie line is 1MW, critical load is 15% of the base load and the island operation time is 2 hours. The service life is 15 years and the discount rate is 8%. Battery related parameters are shown in table 1, the peak valley price information is shown in table 2.

| Table 1. Battery related parameters. |
|--------------------------------------|
| Rated capacity                       | 40kW·h               |
| Rated charging-discharging power     | 5kW                  |
| Installation cost of per unit capacity | 3000RN / (kW·h)      |
| soc operating range                  | 0.3 – 0.95           |

Taking wind power, photovoltaic power and load power of a typical day as examples, the wind power, photovoltaic power and load power curves of a typical day are shown in figure 2.
Table 2. The peak valley price.

| Period of time       | The unit price [RNB/(KW·h)⁻¹] |
|----------------------|-------------------------------|
| 06:00-08:00          | 0.744                         |
| 08:00-12:00          | 1.197                         |
| 12:00-15:00          | 0.744                         |
| 15:00-21:00          | 1.197                         |
| 21:00-22:00          | 0.744                         |
| 22:00- next day 06:00| 0.356                         |

Figure 2. Typical data curve of wind power PV and load.

The result of optimization is that the number of installations is 317, equal to 1.585MW, which met the design specification for access of distributed energy storage system to distribution network and the grade table recommended in technical regulations for access of electrochemical energy storage system to power network.

Figure 3. Charging and discharging curve of battery.

Figure 3 shows that the photovoltaic output is larger than the load demand at 12:00-15:00, during which the energy storage battery is charged, and the energy storage battery is discharged at other peak
periods. Although it is in the load trough period from 2:00 to 6:00, the energy storage battery is charged due to the large wind power. Wind power and tie line power are less than load power at 22:00-24:00, during which the energy storage battery is discharged, which conforms to the operation strategy of energy storage system.

If there is no additional constraints on the installation location of energy storage, the optimization results are shown in Figure 4.

![Figure 4](image-url)  
**Figure 4.** Optimization results of energy storage location without constraint scheme.

The energy storage installation optimization results of each node is not much different and the energy storage installation locations are scattered, and the installation capacity is small at each point. According to the design specification for access of distributed energy storage system to distribution network, the access power of a single point energy storage is between [400kW, 6MW] at the voltage level of 10kV. In Figure 4, the energy storage power of a single point in this scheme is far less than 400kW, thus this scheme is not feasible.

### 3. Comparison of different planning schemes

On the premise of meeting the design specification for access of distributed energy storage system to distribution network, the network loss and voltage fluctuation are compared under the three schemes of single-point planning, three-point planning and five-point planning, shown in Figure 5.

Under the three planning schemes, the installation positions of energy storage batteries are all located on the feeder line at the node with high electrical connection degree. Under the three schemes, the network loss are all small and the tendency of the three curves are very close. Only in a few time periods, the result of single-point planning is slightly larger than that of the other two schemes.
The voltage fluctuation curve of node 9 and node 20 are shown in Figure 6 and Figure 7, respectively.

**Figure 5.** Network loss comparison curve.

**Figure 6.** Voltage fluctuation curve of the node9.
In the comparison of voltage fluctuation, it can be seen that under the three planning schemes, the voltage fluctuation is less than the 7% upper limit. In the node near the energy storage installation location, such as node 9 in Figure 6, the voltage fluctuation range is large. During the period of large power charging and discharging of energy storage, the voltage fluctuation under the single-point planning scheme is slightly larger than the other two schemes. At the node far away from the energy storage access point, such as node 20 in Figure 7, the voltage fluctuation almost coincides in the three schemes.

4. Conclusion
Due to the characteristics of short transmission distance and low voltage level of micro grid, the energy storage installed capacity is small. The energy storage equipment configured on a node can not only meet the requirements of national standards, but also reduces the installation workload of the corresponding plant lines. In addition, the investment cost of the energy storage inverter required is also decreased correspondingly. According to the comparison of different schemes, the network loss and voltage fluctuation are far less than the upper limit under the single-point planning scheme. This scheme provides a reference for energy storage planning of micro grid.

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