Distributed Energy Storage Optimization Configuration of Active Distribution Network

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Abstract. With the high proportion of renewable energy access to the distribution network, the volatility and randomness of renewable energy output will have a serious impact on the distribution network, especially at the peak of renewable power output, the reverse trend phenomenon is obvious. The active distribution network displays the "power" characteristics externally, which makes the voltage problem and transmission congestion problem in the distribution network very serious. This paper establishes a distributed energy storage optimization configuration model that takes into account the voltage quality, and considers the energy storage operation strategy optimization in the energy storage site selection and volume model, which makes the energy storage configuration more reasonable, improves the voltage quality and enhances the renewable energy consumption capacity, improve the economics of system operation.

1. Introduction

In the future, renewable energy, especially photovoltaics[1-2], will exist in a distributed form in the distribution network, making the distribution network from the passive acceptance of electrical energy to a certain initiative. After a high proportion of renewable energy is connected to the distribution network, the volatility and randomness of the renewable energy output will have a serious impact on the distribution network[4], especially at the peak of the renewable power output, the reverse trend phenomenon is obvious. The source distribution network displays the "power" characteristics externally, which makes the voltage problem and transmission congestion problem in the distribution network very serious. These will become the key issues restricting the consumption of renewable energy in the context of the significant increase in renewable energy penetration in the future.

The energy storage system can improve the ability of the system to flexibly adjust. In the context of the high-ratio renewable power supply being connected in a distributed form, how the energy storage is configured and in what form is the key to cope with the high-ratio renewable energy grid connection. This paper considers the problem of renewable energy consumption from the distribution network level. Firstly, it analyzes the influence of reverse tidal current on the voltage of renewable energy grid-connected points, and establishes a distributed energy storage optimization configuration model considering voltage quality. Considering the optimization of energy storage operation strategy in the volume model, the energy storage configuration is more reasonable, the voltage quality is improved,
the renewable energy consumption capacity is improved, and the system operation economy is improved.

2. Distributed energy storage optimization configuration model

The first paragraph after a heading is not indented (Bodytext style). Energy storage system as a flexible resource can improve the system's regulation ability and assist the system to absorb renewable energy. The distributed energy storage system existing in the active distribution network can not only improve the system's active power regulation capacity through charge and discharge, but also change the power output adjusts the voltage.

2.1. Distributed energy storage value analysis

After a high proportion of renewable energy is connected in a distributed form, the voltage of the grid-connected point is increased due to the reverse tidal current at the peak of the renewable energy output. The reactive power adjustment capability is limited by the power circle, resulting in the necessity of limiting the renewable energy source contributes to limiting the voltage. Ignore the voltage drop horizontal component. When there is only renewable energy and no energy storage, the voltage of each node can be expressed as

\[ V_{n+} - V_{n-} = U \cdot (R \cdot P + X \cdot Q) \]

In the formula, \( V_{n+} \) and \( V_{n-} \) denote the first and last node voltage column vectors of each branch respectively. For the convenience of analysis, a radial network without branches is considered here; \( U \) is a diagonal matrix, the diagonal elements are \( 1/n \); \( R \) and \( X \) is a diagonal matrix, The corner elements are the resistance and reactance of each branch respectively; \( P \) and \( Q \) is the active power and reactive power column vector of each branch end respectively, wherein it is assumed that node \( n \) has distributed photovoltaic, and its output power is opposite to the original power flow direction.

\[ V_{n+} - V_{n-} = U \cdot (R \cdot P + X \cdot Q) \]

It can be seen from formula (2) that the role of energy storage in improving the capacity of renewable energy absorption, on the one hand, storage energy stores electricity at the peak of renewable power output, and discharges electricity when it is low, to reduce the amount of abandoned wind and light. On the other hand, the energy storage can reduce the amount of terminal voltage increase due to the reverse power, thereby increasing the capacity of renewable energy absorption.

2.2. Distributed energy storage site selection and capacity optimization model

Cost is an important trade-off indicator in energy storage planning. From the perspective of distribution network, this paper considers energy storage investment cost, power loss cost, electricity purchase cost to main network (sales revenue), and establishes energy storage site selection and capacity optimization. The comprehensive model of the strategy: determine the energy storage capacity of each node by site selection and volume, and perform the time series production simulation according to the actual load curve and the renewable energy prediction curve, with the line loss cost and the purchase cost to the main network (the sales revenue) the minimum. The goal is to optimize the energy storage and discharge strategy to promote the recovery of renewable energy while ensuring voltage quality.

\[ \min C = C_{\text{investment}} + C_{\text{operation}} \]

\[ C_{\text{investment}} = \frac{\delta(1+\delta)^{N_{\text{ems}}}}{(1+\delta)^{N_{\text{ems}}} - 1} \left[ C_{\text{pcs}} \cdot P_{\text{pcs}} + C_{\text{eau}} \cdot E_{\text{eau}} \right] \]
The total cost \( C \) includes: annualized investment cost \( C_{\text{invest}} \), including investment cost of power capacity and energy capacity, \( P_{\text{pc},k} \) and \( E_{\text{esu},k} \) is the power capacity and energy capacity of the energy storage, respectively. \( C_{\text{pc},k} \) is its unit cost coefficient, and \( N_{\text{esu}} \) is used for energy storage device years, \( \delta \) represents the discount factor; annualized operating cost \( C_{\text{operation}} \), including the cost of purchasing electricity to the main network (sales revenue) and line loss costs, \( \Delta t \) is the time interval (this paper takes 1h), \( P_{\text{change}}^l \) is the network root node and the main network exchange power, \( C_{\text{esu}} \) is the system electricity price at that time, \( C_{\text{loss}} \) is the unit loss power cost (yuan), and \( \text{Line} \) is the total number of lines.

Including constraints:

1) each node installs a capacity constraint:
\[
0 \leq P_{\text{pc},k} \leq P_{\text{pc},\max}\tag{6}
\]
\[
0 \leq E_{\text{esu},k} \leq E_{\text{esu},\max}\tag{7}
\]

In the formula, \( P_{\text{pc},\max} \) and \( E_{\text{esu},\max} \) is the maximum energy capacity and energy capacity of the energy storage allowed for each node.

2) power equation constraint:
This paper utilizes the accurate AC flow equation DistFlow model applicable in radial distribution networks.
\[
P_{ij}^t - r_y \frac{(P_{ij}^t)^2 + (Q_{ij}^t)^2}{(U_{ij}^t)^2} = \sum_{k(i,j)} P_{ik}^t + (P_{ij}^t - P_{ij}^{t,v} + P_{ij}^{t,l})
\tag{8}
\]
\[
Q_{ij}^t - x_y \frac{(P_{ij}^t)^2 + (Q_{ij}^t)^2}{(U_{ij}^t)^2} = \sum_{k(i,j)} Q_{ik}^t + (Q_{ij}^t - Q_{ij}^{t,v} + Q_{ij}^{t,l})
\tag{9}
\]
\[
(U_{ij}^t)^2 = (U_{ij}^t)^2 - 2(x_y P_{ij}^t + r_y Q_{ij}^t) + (r_y^2 + x_y^2) \frac{(P_{ij}^t)^2 + (Q_{ij}^t)^2}{(U_{ij}^t)^2}
\tag{10}
\]

Each variable superscript \( t \) represents a time; \( P_{ij}^t \), \( Q_{ij}^t \), \( r_y \), \( x_y \) represents the active power, reactive power, resistance, and reactance between the node and the node; \( \phi(j) \) represents a set of nodes connected to the node but not on the path of the node \( j \) to the root node; \( P_{ij}^{t,v} \), \( Q_{ij}^{t,v} \) respectively represents the active and reactive load; \( P_{ij}^{t,l} \), \( Q_{ij}^{t,l} \) respectively represents the active and reactive power of the renewable power supply on the node; \( P_{ij}^{t,esu} \), \( Q_{ij}^{t,esu} \) is the active and reactive power absorbed by the node energy storage device, and negative if the power is emitted; \( U_i^t \), \( U_j^t \) is \( i \) and \( j \) Node voltage.

3) line constraint:
\[
P_{\text{loss},l}^t = r_y \frac{(P_{ij}^t)^2 + (Q_{ij}^t)^2}{(U_{ij}^t)^2}, l \in i,j
\tag{11}
\]
\[
(P_{ij}^t)^2 + (Q_{ij}^t)^2 \leq (S_{ij})^2
\tag{12}
\]

Equation (11) is the line loss constraint, nodes \( i \) \( j \) are the first and last nodes of line \( l \); Equation (12) is the line capacity constraint, and \( S_{ij} \) is the branch transmission capacity.

4) voltage constraint:
\( U_{\min} \), \( U_{\min} \) is the voltage upper limit and lower limit, and the root node \( i = 1 \) voltage is the reference value.
\[
U_{\min} \leq U_i^t \leq U_{\max}, i \neq 1
\tag{13}
\]

5) renewable power supply constraints:
\[(P_{i,v}^r)^2 + (Q_{i,v}^r)^2 \leq (S_{i,v})^2\]  
\[0 \leq P_{i,v}^r - P_{i,v}^r' \leq Q_{i,v}^r \leq S_{i,v}\]  
\[(14)\]  
\[(15)\]  
Equation (14) is the renewable power power circle constraint, \(S_{i,v}\) is the apparent power; Equation (15) is the active and reactive power constraints, and \(P_{i,v}^r'\) is the predicted value of the renewable power output.

6) distributed energy storage system constraints:
\[-x_{i,v} \cdot P_{pcs,i} \leq P_{i,ch} \leq x_{i,v} \cdot P_{pcs,i}\]  
\[(16)\]  
\[P_{i,ch}^2 + (Q_{i,ch}^r)^2 \leq (P_{pcs,i})^2\]  
\[(17)\]  
\[E_{esu,i}^0 = E_{esu,i}^{i-1} + \eta \cdot \Delta t \cdot P_{i,ch} \cdot \eta = \begin{cases} \eta_{ch} \cdot P_{i,ch}' \geq 0 \\ \eta_{dis} \cdot P_{i,ch}' \leq 0 \end{cases}\]  
\[(18)\]  
\[x_{i,v} \cdot \alpha_{low} \cdot E_{esu,i} \leq E_{esu,i} \leq x_{i,v} \cdot \alpha_{high} \cdot E_{esu,i}\]  
\[(19)\]  
\[E_{esu,i}^0 = E_{esu,i}^{24}\]  
\[(20)\]  
Equation (16), Equation (17) is the energy storage power constraint, \(P_{pcs,i}\) is the energy capacity of the energy storage device; Equation (18)–Equation (20) is the energy storage energy constraint, and \(E_{esu,i}\) is the energy storage. The energy capacity of the device, \(\eta\) is the energy conversion efficiency coefficient, \(\eta_{ch} \cdot \eta_{dis}\) is the charging and discharging efficiency coefficient, respectively, and \(\alpha_{low} \cdot \alpha_{high}\) is the upper and lower limit coefficients of the energy storage state. Equation (20) is to ensure the continuity of the state of charge storage, \(E_{esu,i}^0\) is the initial value, and \(E_{esu,i}^{24}\) is the energy state of the last time energy storage.

In summary, the distributed energy storage location constant volume and operation strategy optimization model is a Mixed-Integer NonLinear Programming (MINLP) problem involving 0,1 quantities, which is difficult to solve and linearized for calculation.

3. Example
This chapter adopts the IEEE33 node distribution network example. The wiring diagram is shown in Figure 1. There are a total of 32 branches in the tie line. The data of each node and the resistance reactance of each branch are shown in the appendix. According to the actual data, distributed photovoltaics account for a large proportion of distributed power sources[8]. For comparison analysis, it is assumed that nodes 13 to 18 each have distributed photovoltaics with a capacity of 1 MW. The maximum network load is 3715+j2300 kvar and the reference voltage is 12.66 kV.

The unit power capacity cost of the energy storage system is 4,000 yuan/kW, the unit energy capacity cost is 3,500 yuan/kWh, the service life is 20 years (full charge and full discharge), the discount rate is 10%, and the energy storage efficiency of the energy storage device is charged. The discharge efficiency is 0.8, the installation node is allowed to be 2-33 nodes, the maximum allowable installation power capacity of each node is 300kW, the maximum allowable installation energy capacity is 1000kWh, and the maximum number of installed energy storage devices is 10.

![Figure 1. IEEE33 node system](image-url)
The domestic industrial electricity time-sharing electricity price period is divided into: 8:00-12:00, 17:00-21:00 is the peak period; 12:00-17:00, 21:00-24:00 is the flat period; 0:00-8:00 is the valley time. According to this division mode, there will be a small peak load during the flat period, that is, the time division of the time-of-use electricity price is not completely divided according to the load level. Therefore, if the storage energy is charged and discharged according to the time-sharing electricity price, there may be a “peak”. The phenomenon of "adding peaks", so the time-of-use electricity price data used in this paper comes from the literature [89]. Assume that the daily time-of-use electricity prices are consistent throughout the year, as shown in Table 1.

| t/h               | Electricity price data /yuan/kWh |
|------------------|----------------------------------|
| 0:00~8:00        | 0.4                              |
| 8:00~12:00       | 1.0                              |
| 12:00~15:00      | 0.6                              |
| 15:00~21:00      | 1.0                              |
| 21:00~24:00      | 0.6                              |

The energy storage capacity and energy capacity of each node obtained by the distributed energy storage optimization configuration model are shown in Table 2.

| Node | Power Capacity /kW | Energy capacity /kWh |
|------|--------------------|----------------------|
| 24   | 238                | 573                  |
| 25   | 295                | 718                  |
| 29   | 300                | 720                  |
| 30   | 300                | 720                  |
| 31   | 257                | 720                  |

To compare and analyze the impact of the energy storage configuration on the operating cost of the distribution network, consider the total annual operating cost and the cost of each part in the scenario of configuring energy storage and unconfigured energy storage, and obtain the results as shown in Table 3.

| Cost/104         | Unconfigured ESS | Configured ESS |
|------------------|------------------|----------------|
| Investment cost  | 0                | 365.6          |
| Electricity purchase cost | 1563.2          | 1128.9         |
| Line loss        | 603.4            | 492.7          |
| total cost       | 2166.6           | 1987.2         |
For the analysis, take the active power exchange between the root node and the main network in a scenario of 24 hours in a typical day. Figure 2 shows the total active power of the energy storage device. Figure 3 shows the time sharing. During the low price period (0:00-8:00) and the price period (12:00-15:00, 21:00-24:00), the energy storage device absorbs electric energy, and the distribution network purchases electricity from the main network (selling electricity, Reduced); during the peak hours of time-of-use tariffs (8:00-12:00, 15:00-21:00), the energy storage device releases electricity, especially at 9:00-12:00, the PV output is large, so At this time, the network sells electricity to the main network. During the rest of the period, due to energy storage and storage of electrical energy, the distribution network purchases electricity from the main network. In summary, after the energy storage device is configured, the system greatly reduces the cost of purchasing electricity. After calculation, the energy storage device transfers 3.12 GWh per year, accounting for 11.98% of the total load.

At the same time, the energy storage device can generate reactive power, so that the reactive power flow of the branches 24, 25, 26-30 is reduced, and the line loss cost is also reduced.

4. Conclusion
This paper analyzes the example, the high-proportion distributed photovoltaic access distribution network, its active output peak time, the reverse power flow phenomenon is serious, resulting in the voltage increase of the photovoltaic access point, limiting the outward transfer of photovoltaic active power, and distributed storage. The energy device not only can directly reduce the light rejection rate by charging and discharging active power, but also can reduce the line voltage drop by adjusting the reactive power, maintain the voltage of the photovoltaic access point, facilitate the active power delivery, and improve the system operation economy.
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