Distributed coordinated control of energy storage system in low-voltage distribution network

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Abstract. With the increase of the photovoltaic penetration rate in the low-voltage distribution network, the uncertainty of its output has adversely affected the voltage quality of the power grid. In view of the relatively large R/X characteristics of the low-voltage distribution network, it is proposed to coordinate the active power of the optical storage unit injection system to solve the problem of voltage over-limit of the low-voltage distribution network. Aiming at the imbalance of the energy storage system participating in the voltage control process, a control strategy to coordinate the charging and discharging of each unit of the distributed energy storage system was proposed. At the same time, considering the capacity of the energy storage unit and the coordination of the initial state of charge, the capacity of the energy storage system is utilized to the maximum extent. Finally, the simulation verifies the effectiveness of the proposed coordinated control strategy.

1. Introduction

With the increasing penetration rate of distributed photovoltaics, in order to improve the absorption of photovoltaic energy and improve the system voltage level, more and more scholars have begun to study the combined mode of photovoltaic energy storage. Low-voltage optical storage and distribution networks will increasingly appear in high-permeability distributed photovoltaic low-voltage distribution networks[1]. Therefore, in order to improve photovoltaic consumption and solve the problem of voltage overshoot caused by high-penetration photovoltaic access, it is very important to optimize control for distributed energy storage.

The control strategies for energy storage systems can be roughly divided into two categories[2]. The first category is to build and solve optimization models, and finally give the optimal operation strategy a few days ago[3-4]. Reference [5] adopted a centralized power coordination control strategy for hybrid energy storage system to achieve the suppression of photovoltaic output power fluctuation. Under this control strategy, the stability of the DC bus voltage was achieved, which ensures the reliable operation of the photovoltaic system. Literature [6] proposed a coordinated control scheme for photovoltaic and energy storage systems for voltage control of low-voltage distribution systems. An algorithm based on local droop control was used to control each energy storage unit locally and did not require advanced communication infrastructure. However, since only the local droop control algorithm was used, the problem-solving ability of this technology was very limited, and the utilization rate of energy storage capacity was not well considered. Reference [7] proposed a charge-discharge control strategy considering the current state of charge of the energy storage system. The proposed strategy storage device could be controlled at every moment according to the requirements without being affected by the photovoltaic output. And apply the proposed control strategy to suppress voltage fluctuations. However, all of the above does not take into account the entire coordination. In some cases, the initial
charge state of some energy storage units may be different, which may cause the premature energy storage system to stop participating in the mediation. In this paper, a distributed control strategy for the energy storage systems is proposed for the problem of voltage overrun caused by high-permeability distributed photovoltaic access to low-voltage distribution networks. This strategy is based on ensuring that the voltage does not exceed the limit. Under the premise of considering the energy storage capacity and the state of charge, the charging and discharging power of the energy storage unit is reasonably controlled, so that the capacity of the limited energy storage unit is maximized.

2. Distributed coordinated control strategy of energy storage system

The block diagram of the coordinated control of the charge and discharge of the distributed optical storage unit connected to the bus \( n \) is shown in Figure 1. The solid line in the figure is the power flow signal of the system, and the broken line is the control signal. The distributed coordinated control strategy of the energy storage system is to combine local droop control and distributed consistent control. The local droop control uses the threshold value of the node voltage to determine the initial exchange power of the energy storage system. Distributed uniform control is to coordinate the control of the charge and discharge of the entire energy storage system through the limited data communication between the energy storage units. The power of each energy storage unit participating in the mediation is proportional to the capacity of the energy storage unit, controls the state of charge of each energy storage unit, and prevents the available capacity of the energy storage unit from being prematurely saturated or exhausted. On the premise that the voltage is not exceeded, the available capacity of the energy storage system is effectively used.

\[ P_{d,n} = \begin{cases} m_1(U_n - U_{min}) & \text{if } U_n < U_{min} \\ 0 & \text{if } U_{min} \leq U_n \leq U_{max} \\ m_2(U_n - U_{max}) & \text{if } U_n > U_{max} \end{cases} \]  

(1)

Where \( P_{d,n} \) is the initial exchange power obtained by local droop control; \( U_n \) is the bus voltage of bus \( n \); \( U_{max} \) and \( U_{min} \) are the upper and lower thresholds of bus voltage; \( m_1 \) and \( m_2 \) are the voltage when the voltage lower limit or upper limit droop coefficient. The droop coefficient is related to the two parameters of maximum load and photovoltaic maximum output power, and the charge droop coefficient can be expressed as equations (2) and (3).
\[ m_1 = \frac{P_{\text{PV,max}} - P_{\text{L, max}}}{U_N - U_{\text{min}}} \]  \hspace{1cm} (2)

\[ m_2 = \frac{P_{\text{PV,max}} - P_{\text{L, max}}}{U_{\text{max}} - U_N} \]  \hspace{1cm} (3)

Where \( U_N \) is the standard voltage of the distribution network. \( m_1 \) is the discharge sag coefficient; \( m_2 \) is the charge sag coefficient.

Local droop control is simple and easy to implement, but the energy storage unit connected to the bus at the end of the line will participate more in voltage regulation. On the other hand, due to differences in the capacity of each energy storage unit, and the initial state of charge is different, factors such as unpredictable photovoltaic output and load cause individual energy storage units to be fully charged and discharged during the voltage regulation process.

2.2. Distributed weighted coordinated control algorithm

As a distributed control strategy, the weighted uniform control algorithm can complete the coordinated control of all subunits without a central controller. According to the system's topology diagram, the mathematical expression of the directed graph is:

\[
\begin{align*}
G(V, E) \\
V &= \{v_1, v_2, \ldots, v_n\} \\
E &\subseteq V \times V
\end{align*}
\]  \hspace{1cm} (4)

In the formula, \( V \) represents the set of network communication nodes; \( E \) represents the set of connected edges between nodes. Define \((v_i, v_j)\) as the directed edge from node \( i \) to node \( j \) to represent the communication link between \( v_i \) and \( v_j \). Therefore, \((v_i, v_j) \in E\) is needed, and there is the possibility of data communication between \( v_i \) and \( v_j \).

\( P_{\text{C, i}} \) is the exchange power that the \( i \)-th energy storage unit at time \( t \). Define a weight coefficient \( \mu_i \) according to the control target to modify the initial exchange power determined by the local droop control, As shown in equation (5):

\[ \frac{P_{\text{C, i}}^t}{\mu_i} = \eta \quad i = 1, 2, 3, \ldots, n \]  \hspace{1cm} (5)

\[ \eta = \sum_{i=1}^{n} \mu_i + \cdots + \mu_n \]  \hspace{1cm} (6)

A correction value \( v \) is introduced to correct the exchange power, and \( t \) represents a discrete control step taking time \( T \) as a cycle. In each control cycle, the update rule is:

\[ P_{\text{C, i}}^{t+1} = P_{\text{C, i}}^{t} + v_i^t \]  \hspace{1cm} (7)

\[ v_i^t = \sum_{(v_i, v_j) \in E} \lambda_{ij}^t + \sum_{(v_j, v_i) \in E} \lambda_{ji}^t \]  \hspace{1cm} (8)

\[ \lambda_{ij}^t = \frac{p_{\text{C, i}}^t}{\mu_i} - \frac{p_{\text{C, j}}^t}{\mu_j} \]  \hspace{1cm} (9)

The implementation of the above weighted uniform control algorithm is to share the total initial exchange power calculated by the droop control through distributed control, and to modify the exchange power of each energy storage unit so that each energy storage unit participates in proportion to its capacity Voltage regulation.

2.3. Distributed dynamic consistent control algorithm

Each energy storage unit can only receive information about itself and its neighbors. In order to estimate the average state of charge of the entire system, the designed system average state of charge observer is shown in Equation (10).
\[ \overline{SOC_i} = SOC_i + \sum_{j \in N_i} a_{ij} (SOC_j - SOC_i) d\tau \]  

(10)

After obtaining the average state of charge of the energy storage. When the i-th energy storage unit is in charging mode and discharging mode, the correction factors are:

\[ \varepsilon_{LC} = \begin{cases} 
0 & \text{SOC}_i \geq SOC_{max} \\
1 - k \times \left( \frac{SOC_i - SOC_{100}}{100} \right) & \text{SOC}_i < SOC_{max} 
\end{cases} \]  

(11)

\[ \varepsilon_{Ld} = \begin{cases} 
1 + k \times \left( \frac{SOC_i - SOC_{100}}{100} \right) & \text{SOC}_i > SOC_{min} \\
0 & \text{SOC}_i \leq SOC_{min} 
\end{cases} \]  

(12)

Where \( k \) is the acceleration convergence constant, which is the empirical value. Therefore, after adding dynamic consistent control, the exchange power value of the energy storage unit can be updated to:

\[ P_{bat,i} = \varepsilon_i \times P_{C,i} \]  

(13)

The addition of the correction factor \( \varepsilon \) in this section further corrects the exchange power of the energy storage unit, so that in the process of voltage adjustment, all energy storage units obtain the same SOC.

3. Example analysis
Select a 7-bus low-voltage distribution network in a certain place as shown in Figure 4. The distribution network supplies power to user loads through 11/0.4kV step-down transformers with a capacity of 185kVA. The cable used for the line is LV cable, and the cable parameters are shown in Table 1. The secondary voltage of the transformer of the distribution network is the reference voltage (1.0 p.u), and the maximum allowable voltage deviation along the distribution network is ±5%.
Use the historical data of real photovoltaic output and user load in a certain place and day as the original data. The output power curve of the photovoltaic unit and the curve of the load are shown in Figure 3. The peak output of all photovoltaic units is concentrated at 10-15 points; while the peak load time of the day is 19-22 points. Figure 4 is the voltage curve of each bus of the system without considering the energy storage system. It can be seen that in the peak phase with the photovoltaic output, due to the injection of photovoltaic power generation, the voltage across the buses 3, 4, 5, 6, and 7 has occurred. Among them, the bus 7 is located at the end of the distribution network. The upper voltage limit is the most serious.

3.1. Application analysis of local droop control
After joining the energy storage unit, the energy storage unit participates in the balance of photovoltaic output power and load power to solve the problem of node voltage over-limit. The local droop control is used to control the energy storage unit. According to the photovoltaic and load data, the corresponding droop control coefficients of each photovoltaic unit can be calculated as shown in Table 1.

| Photovoltaic number | PV1 | PV2 | PV3 | PV4 | PV5 | PV6 |
|---------------------|-----|-----|-----|-----|-----|-----|
| \( m \)             | 522 | 478 | 478 | 370 | 400 | 350 |

Table 1. Droop factor

![Figure 5. Local sagging control of energy storage system (a)24h Voltage curve; (b) SOC curve](image)

From the above figure 5 (a), during the process of energy storage participation adjustment, the voltage values of the bus bar 4, bus bar 5, and bus bar 6 are basically stable within the threshold range. It can be seen that around 12 o'clock, due to the connection of the energy storage to withdraw from operation, the voltage of the bus has exceeded the limit. As can be seen in Figure 5 (b), since the voltage of bus 2 has not exceeded the limit, the SOC value of the energy storage unit it is connected to remains unchanged. When the SOC value of the energy storage unit reaches 80, the energy storage unit will withdraw from operation and lose its voltage regulation capability. Therefore, local droop control cannot fully utilize the effective capacity of energy storage.

3.2. Application analysis of distributed coordinated control strategy
In this section, the basic data of the simulation is unchanged, and the premature overcharge or overdischarge of each energy storage unit in the energy storage system is prevented by controlling the charge and discharge rate. \( \mu \) is determined by the capacity of the battery, as shown in Table 2:

| Energy storage serial number | BES1 | BES2 | BES3 | BES4 | BES5 | BES6 |
|-----------------------------|------|------|------|------|------|------|
| \( \mu \)                   | 6    | 5.5  | 5.5  | 4    | 5    | 4.5  |

Table 2. Weighting coefficient of each energy storage unit
As shown in Figure 6 (a), under the distributed coordinated and consistent control, the bus voltage does not exceed the limit within 24 hours, effectively solving the voltage drop of the network. The expected results have been achieved in terms of voltage control. Figure 6 (b) shows that although the initial state of charge of each energy storage unit is not the same at the beginning, in the process of voltage regulation, by modifying the exchange power, on the premise of meeting the voltage limit, each energy storage unit's state of charge gradually tends to be consistent. After reaching agreement, it participates in voltage control at the same rate of change of state of charge according to its energy storage capacity, and continues to operate with a consistent SOC value, making full use of the available capacity of each energy storage unit. The simulation results fully verify the effectiveness of the distributed coordinated control strategy.

Figure 6. Distributed coordinated control strategy of energy storage system. (a) 24h Voltage curve; (b) SOC curve

4. Conclusion
Aiming at solving the problem of voltage overrun caused by high penetration of distributed photovoltaic access to low voltage distribution network, a distributed coordinated and consistent control strategy for energy storage system is proposed. The results of simulation analysis show that under coordinated and consistent control, during the process of voltage regulation of each energy storage unit, the charge and discharge power of the energy storage is closely related to its rated capacity and state of charge, so that the energy storage capacity is fully used. It solves the problem of voltage over-limit of low-voltage distribution network, improves the distribution network photovoltaic capacity, and verifies the effectiveness of distributed coordinated and consistent control strategy.

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