Coordinated Control of Independent Microgrid Based on SOC Deviation Rate

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Abstract. System failure due to high failure rate of independent microgrid energy management system (EMS) in high altitude and cold area, considering the difference in charge state (SOC) between multiple energy storage devices in the system, a power coordinated control strategy based on the SOC deviation rate of energy storage devices is proposed, adjust the output power of the energy storage converter according to the difference in SOC of each energy storage device, reduce the difference in SOC of each energy storage device, after the system EMS fails, the operation status of the energy storage equipment is consistent to ensure the normal operation of the system. The RT-LAB simulation platform is used to establish a simulation model and design a digital control system. The control system can quickly carry out power coordination control according to the SOC state of energy storage devices, so it makes the devices output power differently according to the SOC level, reduces the SOC difference of energy storage devices, makes the devices SOC reach the same, and verifies the feasibility and effectiveness of the coordination control strategy.

1 Introduction

Microgrids located at high altitudes and in harsh cold regions have high failure rates and inconvenient maintenance of energy management systems (EMS) due to environmental impacts, causing the microgrid system to lose its coordination mechanism to collapse. Therefore, a coordinated control strategy for energy storage devices after EMS failure should be sought for Coordinate control to ensure proper operation of the microgrid system.

To avoid damage to battery life caused by deep charging and discharging, the battery's state of charge (SOC) should be taken into account when designing the control strategy of the microgrid³. Set upper and lower limit values for the battery SOC, and stop charging when the SOC reaches the upper limit, and stop discharging when it reaches the lower limit²⁴. The literature [4] uses the SOC as an input to the droop control and adjusts the battery output power in real time according to the SOC, so that the SOC of multiple parallel batteries converge during operation. Although the optimized design of energy storage capacity ratios can effectively reduce the probability of SOC exceeding the operating limit,
the battery faces the risk of deep charging and discharging when there is a long time mismatch between supply and demand regulation [6]. The literature [7] proposes an improved sag control method based on the energy storage unit SOC, which dynamically adjusts the sag coefficient by setting it inversely proportional to the \( n \)th power of the energy storage unit SOC in order to achieve the power distribution of the energy storage device, and the control will become more complex and difficult to achieve as the number of energy storage units increases.

Therefore, it is necessary to find a simple and effective control strategy for the SOC consistency of multi-storage devices, which is essential to ensure the safety of microgrids. Stable operation is of great significance. In this paper, we propose a power coordination method based on SOC deviation rate, which is simple and adaptable in principle and easy to implement. The EMS system effectively maintains stable system operation in the event of failure, and can better solve the energy storage device's inefficiency caused by SOC differences. The utilization of the problem to achieve the balance between the output power of the energy storage device and the SOC.

2 Independent microgrid and sag control

2.1 Independent microgrid

Independent microgrid consists of distributed power supply, energy storage system and load, and its structure is shown in Figure 1. The distributed power supply and energy storage system are connected to the AC bus of the micro-grid via power electronic converters [8]. Each distributed unit in an independent microgrid is responsible for its own voltage and frequency control, and together they maintain the power balance and system stability [9-10]. When the power generation capacity of renewable energy is greater than the power demand of the load, the microgrid operating frequency is close to the rated value, and the energy storage devices charge their own batteries; when the output power of renewable energy is insufficient, the grid frequency decreases, energy storage devices inject energy into the grid according to the load demand, effectively supporting the grid voltage and frequency, until the power supply of renewable energy is greater than the load demand, the grid frequency rises, energy storage devices exit compensation [11]. In order to ensure the continuous and consistent operation of each energy storage device and maintain its effective compensation capacity, the output power of each energy storage device needs to be adjusted in real time to achieve a consistent state of charge (SOC) of the batteries in each energy storage device [12].

![Figure 1. Structure chart of independent microgrid.](image-url)
2.2 Traditional sag control

The storage converter in an independent microgrid operates in VSG mode with active-frequency (P-f) sag control, and the principle of P-f sag control is shown in Figure 2. The relationship between active power and frequency is shown in equation (1), and the P-f sag control characteristic curve is shown in Figure 3a), which is determined by the rated frequency \( f_0 (\omega_0 / 2\pi) \), reference power \( P_0 \) and sag coefficient \( m \), i.e., the frequency corresponding to point A on the curve in Figure 3 a) is the frequency \( f_0 \), and the corresponding power is the active power \( P_0 \) given by the VSG mode of the converter.

\[
\omega - \omega_0 = m(P - P_0)
\]  

(1)

![Figure 2. Active power -frequency droop control block diagram.](image)

a) Traditional sag control  b) Improved sag control

Figure 3. Droop control characteristic diagram.

The control block diagram of the VSG mode storage converter power outer loop using P-f droop control is shown in Figure 4.

![Figure 4. P-f droop control power outer loop control diagram.](image)

2.3 SOC calculation

The SOC of an energy storage battery characterizes the charge state of the storage unit, i.e., the ratio of the existing charge of the storage unit to its rated capacity, due to the nonlinearity of the energy storage battery, calculating the SOC of the battery is a very difficult task, so this paper adopts the SOC estimation method given in the literature[8] to calculate the SOC of the battery in simulation and experiments, see equation (2).

\[
SOC = SOC_{ini} - \left( \int i_a dt \right) / C_e \approx SOC_{ini} - \left( \int p_{out} dt \right) / (V_e C_e)
\]  

(2)
where: $SOC_{ini}$ is initial SOC of the energy storage unit, $i_b$ is battery current, $C_e$ is the capacity of the energy storage unit, $V_{dc}$ the DC voltage, $p_{out}$ is the output power of the energy storage converter, from equation (2) we can see that the SOC of the storage battery is mainly determined by the initial value and the active power output of the converter.

3 Coordinated control based on SOC deviation rate

To maintain stable operation of the stand-alone microgrid system after an EMS failure and to keep the energy storage system from overcharging and over-discharging that would affect its useful life. In this paper, a coordinated control approach considering the energy storage SOC deviation rate is proposed. Specifically, it refers to the power coordination control by adopting the corresponding improved sag control method according to the energy storage SOC deviation rate to achieve improved energy storage SOC differences to keep the system running reliably.

3.1 Improved sag control strategies

This paper adopts an improved sag control strategy for energy storage devices in VSG mode, the core of the strategy is to determine the actual active power to be emitted from the energy storage devices by the SOC deviation rate, and then adjust the active power-frequency sag curve (P-f curve) of the energy storage devices to make the energy storage devices emit the corresponding actual active power.

To more visually illustrate the improved sag control strategy, two energy storage devices are used as examples. As shown in Fig. 3 b), in the conventional droop control mode, both energy storage devices run on the P-f curve 0 and both converters run at operating point A. The power at point A is $P_1$, the system frequency is $f_1$. That is, regardless of the SOC high and low unified issued the same active power, the SOC difference between equipment always exists, SOC low battery early discharge, SOC high battery full in advance, the battery life damage is greater. With the improved sag control strategy, the converter with high SOC runs on P-f curve 2 and the converter with low SOC runs on P-f curve 1. Low SOC converters operate at operating point B at a power of $P_{11}$, high SOC converters operate at operating point C at a power of $P_{22}$, and $P_{11} + P_{22} = 2P_1$, the system frequency is $f_2$. The higher SOC converter emits more power and the lower SOC converter emits less power, which gradually reduces the SOC difference of the battery, so that the battery SOC is gradually balanced.

3.2 SOC interval classification

In order to avoid the shortening of battery life caused by emptying or full charging, the upper and lower limits of battery SOC are set, and the upper limit is 90 and the lower limit is 20 in this paper. In this paper, the energy storage power is uniformly set as positive for discharge and negative for charge. When the total power $P$ of the energy storage device is positive and the SOC of the single energy storage device in operation is below the lower limit, it is necessary to adjust the actual power of the device to 0 and prohibit discharge. The rest of the SOC is between 20 and 100 and the energy storage devices in operation are called effective devices, which bear the total power $P$. When the total power of the energy storage device is negative, the single energy storage device in operation SOC is higher than
the upper limit value, it need to adjust the actual power of the device to 0, prohibit charging, the rest of the SOC between 0-90 and the energy storage device in operation is called effective device, assume the total power $P_t$.

### 3.3 SOC deviation rate calculation

(1) SOC average calculation

The average value of SOC of effective energy storage devices is calculated as in equation (3)

$$SOC_{\text{avg}} = \frac{1}{n} \sum_{i=1}^{n} SOC_i$$

where: $SOC_{\text{avg}}$ is the average SOC of the effective energy storage device, $SOC_i$ is the SOC of the effective energy storage device, and $n$ is the number of effective energy storage devices.

(2) Calculation of SOC deviation rate

The effective energy storage device SOC deviation rate is calculated as in equation (4).

$$\lambda_i = (SOC_i - SOC_{\text{avg}}) / SOC_{\text{avg}}$$

### 3.4 Power distribution

In this paper, the total power $P_t$ to be generated by the energy storage equipment is explained as positive, and the specific power allocation method is as follows:

Calculation of the average SOC $SOC_{\text{avg}}$ and deviation rate $\lambda_i (1 \leq i \leq n)$ of an effective energy storage device according to the method in section 2.3 $SOC_{\text{avg}}$, constructing the SOC deviation rate matrix. The deviation power matrix is shown in Eq. (5), the deviation power matrix is shown in Eq. (6), and the actual power target value assigned by each energy storage device is shown in Eq. (7).

$$E = \begin{bmatrix} \lambda_1 & 0 & 0 & \ldots & 0 \\ 0 & \lambda_2 & 0 & \ldots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \ldots & \lambda_n \end{bmatrix}$$

$$\begin{bmatrix} P_{\Delta_1} \\ P_{\Delta_2} \\ \vdots \\ P_{\Delta_n} \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 & \ldots & 0 \\ 0 & \lambda_2 & 0 & \ldots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \ldots & \lambda_n \end{bmatrix} = (P_t / n)$$
(7)

where: \( n \) is the number of effective energy storage devices, \( P_i \) is total power of energy storage equipment, \( P_i / n \) is the average power, \( \lambda_i \) is deviation power, \( i \) is positive, SOC is above average SOC, deviation power is positive, the actual power target value assigned by the device is higher than the average power; \( \lambda_i \) is negative then the SOC is lower than the average SOC, the deviation power is negative, and the actual power target assigned by this energy storage device is lower than the average power.

Subject to the power limit of the actual energy storage device, if the SOC difference is large, the assigned actual power target value exceeds the power limit of the energy storage device, then the actual power target value assigned by the energy storage device is the upper limit value, and the remaining effective energy storage device is redistributed according to the rule.

### 3.5 Coordinated control

The actual power target value for each effective energy storage device can be obtained from the above steps, using this power target as the set value and the actual power of the device as the feedback value, the PI adjustment is performed, the output of the PI adjustment as a change in the active power reference value \( P_0 \) of the PF curve of the energy storage device. This change value is summed with the \( P_0 \) value from the previous step to obtain the \( P_0 \) value. By dynamically adjusting the P-f curve, the actual power of the energy storage device can be stabilized at the active power target value. In this way, the active power is distributed according to the SOC deviation rate, so that the SOC difference between energy storage devices gradually decreases and finally equilibrates.

The power coordination strategy control block diagram is shown in Figure 5.

![Figure 5. Coordinated control block diagram.](image)

### 4 Simulation verification

Based on RT-LAB real-time simulation platform, an independent microgrid model containing PV, energy storage, and load was established. The two energy storage converters in the system operate in VSG mode. The test conditions were 80% and 75% of the initial SOC of the two energy storage converters and 600kw load power. Before coordinated control, the two converters had the same power, both 340 kW, and the SOC difference between the two energy storage devices persisted during operation, as shown in Figures 6 and 7.
The active power of the energy storage device with high SOC increases to 349kw and the active power of the energy storage device with low SOC decreases to 331kw after the power coordination control, as shown in Figure 8. The SOC changes of the two energy storage devices are shown in Figure 9, and after a period of adjustment, the SOCs of the two energy storage devices reach the same level.

During continuous discharge, the SOC of the energy storage device is reduced to the lower limit value, the actual active power should be adjusted to 0 according to the adjustment strategy, the adjustment process is shown in Figure 10.

If the difference in SOC between the two energy storage devices is large during operation or when the microgrid starts up in its initial state, with one SOC of 90 and one SOC of 30 and a load of 700kw, the power of the two energy storage units is the same before power coordination control is performed. After performing power coordination control, the actual power that should be emitted by the energy storage device with high SOC is 570kw, according to the control strategy the maximum power emitted by a single energy storage device is limited to 500kw, and the remaining power is allocated to the energy storage device with low SOC, according to the control strategy, the adjustment process is shown in Figure 11, the power of both devices before adjustment is 385kw, and
after adjustment, the power of high SOC device is 500kw and the power of low SOC device is 270kw.

From the simulation test, it can be seen that the power distribution method based on the SOC deviation rate can effectively realize the reasonable power distribution among the energy storage units, and finally achieve the SOC balance. It effectively solves the problem of lack of coordination mechanisms for energy storage devices causing system collapse after EMS failure, it plays an effective role in maintaining stable operation of the system and extending the life of the energy storage device. The method only needs to adjust the P-f sag curve of energy storage device, without modifying the original control algorithm of energy storage, the algorithm is simple and adaptable.

5 Conclusion

In this paper, we propose a method for power coordination control applicable to stand-alone microgrids, assigning different target powers based on energy storage SOC deviation rates, and adjusting the power of VSG-mode energy storage devices by adjusting their active-frequency curves (P-f curves). The method is simple and easy to implement, with good regulation effect, and can ensure the SOC equalization of energy storage devices in the microgrid system in the absence of a coordination mechanism in the EMS fault system to ensure the normal and smooth operation of the microgrid system.

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