Improved Droop Control Strategy Based on SOC Power Exponent with Secondary Voltage Compensator

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Abstract: Aiming at the problem of over-charge and over-discharge caused by different state-of-charge (SOC) of multi-energy storage units in traditional droop control, an improved droop control strategy based on the SOC power exponent of lithium battery with secondary voltage compensator was proposed. First, based on the relationship between the SOC of the lithium battery and the charge and discharge current, a controller with the power index of SOC compensation sag coefficient is designed to balance the charge and discharge speed of lithium battery. At the same time, in order to reduce the DC bus voltage deviation during system disturbance, a secondary voltage regulator is added. Finally, the Matlab/Simulink simulation model is built to verify the proposed strategy under the load switching environment. The results show that the control strategy can control the charging and discharging current of the energy storage unit according to the SOC real-time state quantity, ensuring the safe and stable operation of the DC microgrid.

1. Introduction

With the rapid development of DC microgrid and droop control technology, the application of distributed energy storage technology was born, which increased the capacity of DC microgrid system and ensured the power supply reliability of the system[1-3]. However, in the traditional droop control, the energy storage unit absorbs or releases energy according to a fixed droop coefficient, resulting in overcharge, over discharge and early exit of different SOC lithium batteries[4], which seriously affect the safe operation of the DC microgrid.

In response to this problem, literature [5] proposes an SOC adaptive control to ensure the stability of the bus voltage while effectively achieving the distribution of load power; literature [6] proposes an SOC-I droop control method, which can be based on the SOC state, The power distribution of the energy storage unit is realized by the quantity, which ensures the safe and stable operation of the system. This paper proposes an improved droop control strategy based on the SOC power exponent of lithium battery with secondary voltage compensator, which can adjust the droop coefficient online in real time according to the SOC state of the lithium battery. The problem of large voltage deviation of DC bus in droop control is solved. The simulation results show that the proposed strategy can achieve the goals of energy storage unit current distribution and bus voltage regulation.

2. Equivalent model of energy storage unit

Figure 1 shows the parallel equivalent model of two sets of energy storage units with the same capacity.
In Figure 1, $r$ is the equivalent line impedance, $u_{dc}$ is the output voltage of the lithium battery, $u_{dcref}$ is the rated value of the bus voltage, $R$ is the fixed droop coefficient, and $i_{dc}$ is the output current of the lithium battery. $u_{PCC}$ is the common point voltage. The traditional droop control method can be expressed as:

$$u_{PCC} = u_{dcref} - R_i i_i - r_i i_i$$

(1)

According to equation (1), the output current relationship between two sets of lithium battery cells is:

$$\frac{i_{dc1}}{i_{dc2}} = \frac{R_1 + r_1}{R_2 + r_2}$$

(2)

It can be seen from equation (2) that when the line impedance is ignored, the current distribution is affected by the droop coefficient $R$.

3. Improved droop control strategy

3.1. Sagging control based on correlation SOC power exponent

Considering that the SOC of each energy storage unit may be different, the load current needs to be provided according to the actual situation[7-8], so the droop coefficient can be related to the SOC, and the remaining capacity of each energy storage unit is expressed as:

$$SOC_i = SOC_{i0} - \frac{1}{C_{bat}} \int i_L dt$$

(3)

In equation (3), $SOC_i$ represents the charge capacity of the lithium battery, $SOC_{i0}$ is the initial charge of the lithium battery, $C_{bat}$ is the lithium battery capacitance, and $i_L$ is the output current of the lithium battery. It can be seen from equation (3) that SOC is calculated in the form of indefinite integrals, so the rate of change is very low, which has a certain impact on the SOC balance effect. To improve the balance effect, this paper proposes a droop control method based on the SOC power exponent of lithium batteries, Which can be expressed as:

$$u_{dc} = u_{dcref} - i_{dc} \times R_0 k_{Di}$$

(4)

Where,

$$k_{Di} = \begin{cases} 
\exp[p(SOC_i^n - A^n)] & i_{dc} < 0, SOC_i \neq A \\
\exp[-p(SOC_i^n - A^n)] & i_{dc} > 0, SOC_i \neq A \\
1 & SOC_i = A
\end{cases}$$

In equation (4), $R_0$ represents the given initial droop coefficient, $k_{Di}$ is the compensation factor coefficient of the interconnected SOC power exponent, $A$ is the average state of charge of the two sets of lithium batteries, $n$ is the power index coefficient, and $p$ is the SOC convergence rate factor. The overall structure of the improved droop control system is shown in Figure 2.
It can be seen from equation (3) and (4) that the proposed control strategy can be divided into two states: lithium battery charging and discharging. \( i_{dc}^c < 0 \) during charging, if the SOC value of the lithium battery is greater than \( A \), then \( R_0 K_{D_i} > R_0 \), which means that the lithium battery of this group will absorb a smaller current than when no SOC control is added; if the SOC value is less than \( A \), then \( R_0 K_{D_i} < R_0 \), droop Decreasing the coefficient increases the current it absorbs. Similarly, the output characteristics of the discharge state and the charge state are opposite. In this process, if the SOC of the two sets of lithium batteries is the same, the compensation factor \( K_{D_i} \) is adjusted to 1.

3.2. DC bus voltage deviation compensation control

In the traditional droop control, in addition to affecting the current sharing effect, another drawback is that the charging and discharging of the energy storage unit will cause the DC bus voltage to deviate from the given value[9-10]. In order to solve this problem, this strategy adds a DC bus voltage secondary regulation device, which can be expressed by equation (5). The block diagram of its control structure is shown in Figure 2.

\[
    u_{dc} = u_{dcref} - i_{dc} R_p k_{D_i} + \left( k_p + \frac{k_i}{s} \right) (u_{dcref} - u_{dc}) \tag{5}
\]

In equation (5), \( k_p \) and \( k_i \) represent proportional and integral coefficients respectively. The secondary voltage adjustment device compares \( u_{dcref} \) and \( u_{dc} \) and sends it to the PI controller to obtain the real-time secondary compensation, and adds it to \( u_{dcref} \) to weaken the DC bus voltage deviation.

4. Simulation verification

The control system model shown in Figure 2 is built, and the proposed control strategy is simulated and analyzed under load switching conditions. In the simulation of this paper, the nominal value of the DC bus voltage is 400V, and the output power of the photovoltaic system is constant at 20kw. Load power setting: the first 5s is the same as the photovoltaic output power, which drops to 18kw at 5s and increases to 22kw at 30s The parameters of the two sets of lithium batteries are shown in Table 1. Figure 3 is the variation curve of the two sets of lithium battery sag coefficients in the strategy proposed in this article, Figure 4 is the DC bus voltage variation waveform, Figure 5 is a comparison chart of SOC curves of two groups of lithium batteries, and Figure 6 is a comparison waveform chart of output currents of two groups of lithium batteries.

| Parameter         | Nominal voltage(V) | Rated capacity (Ah) | Initial SOC (%) |
|-------------------|---------------------|---------------------|-----------------|
| No. 1 lithium battery | 200                 | 1                   | 61              |
| No. 2 lithium battery | 200                 | 1                   | 50              |
Figure 3. Comparison graph of droop coefficient change curve

Figure 4. SOC curve comparison chart

Figure 5. Comparison graph of output current

Figure 6. DC bus voltage variation waveform

It can be seen from Figure 3 that the droop coefficients of the two sets of lithium batteries can be updated in real time according to the SOC state value to ensure that the energy storage unit is charged and discharged according to the SOC; from Figures 4 and 5, it can be obtained that before 5s, the SOC of the two groups of lithium battery cells was basically unchanged and the output current was close to 0 because the photovoltaic output power was equal to the load requirement; 5-30s, the photovoltaic output power is higher than that required by the load, and the lithium battery is in the charging stage. Compared with the No. 2 lithium battery, the No. 1 lithium battery's SOC only increased from 61% to 62.5%, and the rate of rise was small, so its charging current was small. 30-60s, the photovoltaic output power is lower than that required by the load, and the lithium battery is in the discharge stage. The SOC of the No. 2 lithium battery is reduced from 54% to 51%, which is smaller than the No. 1 lithium battery, so the discharge current is smaller. That is, regardless of the lithium battery charging or discharging stage, the proposed strategy can achieve the goals of SOC balance and reasonable current distribution according to the real-time SOC value. As can be seen from Figure 6, when the load is switched on and off, although there will be a sudden rise or sag of the DC bus voltage, the bus always runs within a reasonable range (±5%) to ensure the stable operation of the system.

5. Conclusion
Aiming at the problem of over-charge and over-discharge of different SOC energy storage units caused by the droop control of traditional DC microgrid, this paper proposes an improved droop control strategy based on the SOC power exponent of lithium battery with secondary voltage compensator, which achieved the goal of allocating output current reasonably for each energy storage unit according to its own state quantity, and at the same time improved the anti-disturbance capability of the DC bus to ensure the stable operation of the system. Simulation results verify the effectiveness of the proposed strategy.
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