A Novel Control Method of Low-voltage-ride-through Technique for Asymmetrical Hybrid Energy Storage System

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Abstract. Low-voltage-ride-through (LVRT) capability is an important criterion for the stability of cascaded multilevel energy storage system (ESS). Based on asymmetrical hybrid ESS, a coordinated operating method is proposed to maintain the phase angle of positive-sequence-voltage of battery cells and capacitor cells. To deal with the asymmetrical chains among three phases, its influence on the power distribution is eliminated by modifying the command of battery cells, then the traditional zero-sequence-voltage injection is feasible for asymmetrical situations. Proposed methods can stabilize the dc-side voltage of capacitor cells, maintaining the output current. Finally, the correctness and effectiveness of proposed methods are proved by experiment.

1. Introduction

Cascaded multilevel converters are widely used in energy storage systems due to their characteristics of modularization, low harmonic, and low switching stress [1-2]. Cascade multilevel energy storage system can be matched with different energy storage devices on the DC side, which can be mainly divided into battery energy storage system (BESS) with battery as the DC side, static synchronous compensator (STATCOM) with capacitor as the DC side and hybrid energy storage system [3-4]. The hybrid energy storage system based on batteries and capacitors has been applied to off-grid energy storage and motor drive [5-6]. This structure can maximize the use of each link, improve equipment efficiency and save costs.

Low voltage crossing is a key technical problem in cascaded multilevel converters. The control methods of low voltage crossing for cascaded multilevel converters connected with star can be divided into zero sequence voltage injection and negative sequence current injection. Literature [7] proposed a control method based on zero sequence current and voltage injection to realize the phase-to-phase average active power of h-bridge converter is zero, but the influence of unbalanced power network is not considered, so the balanced control of three-phase DC side voltage cannot be realized. Literature [8] proposes that the average active power control, DC voltage control and reference current tracking control can be realized under unbalanced power network by injecting appropriate phase voltage. However, this control method is based on ABC coordinate system, so the control system is more complex and requires a large amount of calculation. Literature [9] established a zero-sequence voltage compensation model based on coordinate system, and constructed a virtual vertical voltage vector participating in coordinate transformation to simplify the calculation process. Literature [10] further converted to DQ coordinate system for modeling, making the calculation process more simple. For hybrid cascaded multilevel circuits, especially when the three-phase system is asymmetric, its control targets are many, coupling terms are complex, and its low voltage crossing control is difficult.
In this paper, a low voltage crossing control method is proposed for the asymmetric hybrid energy storage system consisting of a three-phase asymmetric cascade multilevel hybrid energy storage system. By separating the zero-sequence components of the rated order of the battery, the three-phase asymmetric system can use zero-sequence voltage injection to cross the unbalanced power grid. The reliability of the method is verified by experiments to ensure the stable operation of the system under complex faults.

2. A Symmetric Cascaded Multilevel Hybrid Energy Storage System

The asymmetric cascade multilevel hybrid energy storage system studied in this paper is shown in Figure 1. Each phase is composed of battery chain and capacitor chain. The total number of each phase is the same, but the number of each phase battery and capacitor chain is different. \( L \) is the filter inductance, \( V_S \) and \( I_S \) are the grid voltage and grid-connected current respectively, \( m_1,m_2,m_3 \) and \( n_1,n_2,n_3 \) are the number of battery chains and capacitor chains respectively, and \( V_{bat} \) and \( V_{cap} \) are their DC side voltages respectively.

![Figure 1. Hybrid energy storage system structure](image)

The same type of link in each phase converter can be modeled by merging the DC side. The three-phase converter with cascaded topology as independent is controlled by split phase, which further simplifies the analysis of the three-phase hybrid energy storage system.

When the system is running normally, the vector relationship of each phase is shown in Figure 2. \( V_{r1} \) and \( V_{r2} \) are respectively the output voltage of the battery and capacitor chain, \( V_S \) is the grid voltage, and \( V_L \) is the inductance voltage. \( I_S \) is the grid-connected current, which has a close vertical relationship with \( V_{r2} \) to ensure the active power balance at the DC side of the capacitor chain. \( V_L \) and \( V_{r2} \) are combined into vector \( V_q \). \( \delta \) and \( \delta_1 \) are the angles between \( V_{r1}/V_{r2} \) and \( V_S \).
3. Low Voltage Crossing Control Method for Asymmetric Hybrid System

To realize the low voltage crossing of three-phase asymmetric hybrid energy storage system, the control method for symmetric hybrid energy storage needs to be extended. In order to maintain the pre-fault output current of the symmetric hybrid energy storage system under the unbalanced grid, the battery chain output voltage $V_{r1}$ needs to track the grid voltage $V_s$. In the case of asymmetric equipment, the three-phase $V_{r1}$ tracking $V_s$ is shown in Equation (1). $K$ is the rated modulation ratio of the battery chain; $V_p$ and $V_n$ are the positive sequence and negative sequence components of $V_s$, respectively.

$$
egin{align*}
V_{r1A} &= m_A V_{batA} \cdot K_A \cdot (V_{psA} + V_{nsA}) e^{-j\delta_A} \\
V_{r1B} &= m_B V_{batB} \cdot K_B \cdot (V_{psB} + V_{nsB}) e^{-j\delta_B} \\
V_{r1C} &= m_C V_{batC} \cdot K_C \cdot (V_{psC} + V_{nsC}) e^{-j\delta_C} \\
K'_x &= \frac{V_x}{V_{rated}} \quad x = A, B, C
\end{align*}
$$

The rated modulation ratio $K$ of $V_{r1}$ under the balanced grid is independently adjusted by the three phases according to the number of each battery chain. At this point, the sum of the three-phase $V_{r1}$ modulated waves is no longer 0, and the amplitude and phase of the zero-sequence component also change with the change of the unbalanced degree of the power grid. Since $V_s$ does not contain a zero sequence in the star circuit, the zero sequence component of $V_{r1}$ will act on the capacitor chain and make $V_{r2}$ contain an undesired zero sequence component, which will be interfered with by the zero sequence of $V_{r1}$ regardless of the latter's low voltage crossing mode.

The positive sequence component of three-phase $V_{r1}$ is shown in Equation (2). $V_{r1pA}$ is obtained by the rotation and vector superposition of three-phase $V_{r1}$, and the relationship between $V_{r1pA}$ and $V_{psA}$ and $V_{nsA}$ is further decomposed. The positive sequence is affected by both the positive sequence and negative sequence of grid voltage.

$$
\begin{align*}
v_{r1pA} &= (v_{r1A} + v_{r1B} e^{j\frac{\pi}{3}} + v_{r1C} e^{-j\frac{\pi}{3}}) / 3 \\
&= (k_1 v_{psA} e^{j\delta_1} + k_2 v_{psB} e^{j\delta_2} + k_3 v_{psC} e^{j\delta_3}) / 3 \\
&+ (k_1 v_{nsB} e^{j\delta_1} + k_2 v_{nsC} e^{j\delta_2} + k_3 v_{nsC} e^{j\delta_3}) / 3 \\
v_{r1pA} &= v_{r1pA} e^{j\frac{\pi}{3}} \\
v_{r1pC} &= v_{r1pC} e^{-j\frac{\pi}{3}}
\end{align*}
$$

So that the vector of arbitrary tracking three-phase $V_s$ in a balanced power grid satisfies the relation shown in Equation (3) for $V_{sA}$, it has the relation shown in Equation (4) for $V_{naA}$ in an unbalanced power grid.

$$
\begin{align*}
&k_1 v_{psA} e^{-j\delta_1} + k_2 v_{psB} e^{-j\delta_2} + k_3 v_{psC} e^{-j\delta_3} = 0 \\
&k_1 v_{nsA} e^{-j\delta_1} + k_2 v_{nsB} e^{-j\delta_2} + k_3 v_{nsC} e^{-j\delta_3} = 0 \\
&k_1 v_{psB} e^{-j\delta_1} + k_2 v_{psC} e^{-j\delta_2} + k_3 v_{psC} e^{-j\delta_3} = 0
\end{align*}
$$

Equation (4) is the second term of $V_{r1pA}$ in Equation (2). Therefore, $V_{r1P}$ is only determined by the positive sequence component $V_p$ of the grid voltage, regardless of whether $V_{r1}$ contains zero sequence.
or not, as long as the component of the tracking grid voltage does not contain zero sequence. If the phase of \( V_{r1p} \) is unchanged, then the corresponding \( V_{r2p} \) in Equation (5) also remains unchanged. In this case, the degree of imbalance of \( V_r2 \) is the same as that of \( V_S \).

\[
v_{px} = v_{r1px} + v_{r2px}, \quad x = A, B, C
\]

(5)

To sum up, when the battery chain tracks the unbalanced power network in the case of equipment asymmetry, the zero-sequence component in the rated state of \( V_r1 \) can be separated to avoid the influence of the amplitude and phase of \( V_{r1p} \) on the positive sequence \( V_p \) and negative sequence \( V_n \) of the power network simultaneously, as shown in Equation (6). At this point, the positive sequence phase of the battery chain and the capacitor chain is a constant value no matter how the imbalance of the power grid changes.

\[
\begin{align*}
V_{r1z\text{ rated}} &= \frac{1}{3} (V_{r1A\text{ rated}} + V_{r1B\text{ rated}} + V_{r1C\text{ rated}}) \\
v_{r1z\text{ inc}} &= V_{r1z\text{ rated}} - V_{r1z\text{ rated}} \\
&= m_{v_{pu}} K_e \left( v_{pu} + v_{nu} \right) e^{-j\theta_i} \\
v_{r1z} &= V_{r1z\text{ inc}} + V_{r1z\text{ rated}} \\
&= \frac{V_z}{V_{\text{rated}}} \\
x &= A, B, C
\end{align*}
\]

(6)

When the battery chain is operated by this method, the working state of the capacitor chain is shown in Figure 3. \( N \) is the center of gravity of the voltage triangle, and the three-phase vector starting from this position does not have a zero sequence. \( F \) is Fermat point, and the Angle between the three vectors starting from this position is 120° of each other. \( V_z \) is the zero-sequence voltage used by the symmetric system to cross the unbalanced power grid. As shown in Formula (7), \( V_{n2} \) is the effective value of the negative sequence component of \( V_{r2} \), and \( \phi_p \) and \( \phi_n \) are the phases of the positive sequence and negative sequence components of the power grid respectively. This voltage transfers the star connection neutral point potential of the capacitance chain from \( N \) to \( F \). In the unbalanced state, the capacitor chain node should also subtract the built-in zero-sequence \( -V_{r1z} \) to transfer the neutral point potential from \( P \) point to \( N \), and then combine with \( V_Z \) to make the output voltage of the three-phase capacitor chain node be perpendicular to \( I_s \) is before each phase fault, so as to ensure the constant grid-connected current and active power balance of the capacitor chain node.

\[
\begin{cases}
V_z = V_{n2} \\
\phi_z = \phi_p - \phi_n + \delta_i = \Delta \phi + \delta_i
\end{cases}
\]

(7)

The battery chain is controlled by open-loop voltage. \( V_{r1\text{trc}} \) tracking imbalance \( v_{s} \) is obtained after separating the rated zero-sequence component, and its output voltage is adjusted. The separated \( V_{r1} \) zero-sequence component is modified according to the change of positive sequence amplitude during grid sag to obtain \( V_{r1Z \text{ Add}} \), so as to ensure that the system maintains a working state similar to the rated grid during symmetrical grid sag. The modulated battery chain wave is obtained by combining with \( V_{r1\text{TRC}} \). Due to the different control targets on the DC side of the asymmetric three-phase capacitor, the capacitor chain adopts the split current control. According to the imbalance degree of the
power network, the corresponding VZ balance power of the three phases is calculated to maintain the dc side voltage and output current unchanged. This builds up the overall control method for the three-phase asymmetric hybrid energy storage system.

4. Experimental Verification

The effectiveness of the proposed low voltage crossing method is verified by rT-LAB based hardware on the loop experimental platform. The experimental parameters are shown in Table 1. The system is simplified in the experiment.

The low voltage crossing process of asymmetric hybrid system is shown in Figure 4. In case of unbalanced power network, the positive sequence component drops from 20.2kV to 15kV at time T1, accompanied by additional negative sequence component. The grid-connected current is restored to the state before the power grid failure after 0.1s. Each phase voltage controller independently regulates the DC side voltage of the capacitor chain, and the voltage is stabilized at the reference value of 19.6kV, 21.1kV and 23.5kV during the fault.

Table 1. Experimental parameters of three-phase asymmetric hybrid energy storage system

|                              | Phase A | Phase B | Phase C |
|------------------------------|---------|---------|---------|
| Number of battery links m    | 20      | 18      | 15      |
| DC side voltage of the battery $m \cdot V_{bat}$ (kV) | 15.7    | 14.1    | 11.7    |
| Number of battery links n    | 25      | 27      | 30      |
| Rated DC side voltage $n \cdot V_{cap}$ (kV)   | 19.6    | 21.1    | 23.5    |
| DC side link voltage $V_{bat}, V_{cap}$ (V)     | 783     |         |         |
| Filter inductance L (mH)     | 60      |         |         |
| DC side capacitor C (mF)     | 5       |         |         |
| Number of links per phase $m+n$ | 45      |         |         |
| Rated RMS value of phase voltage $V_{s}$ (kV)  | 20.2    |         |         |
| Magnitude of Current $I_{sm}$ (A) | 100    |         |         |

(a) Grid voltage
Instead of adopting the low voltage crossing mode of the asymmetric system presented in this paper, the current waveform of direct injection of zero sequence voltage is shown in Figure 5. At this point, the positive sequence of each physical quantity in the system is affected by V_s negative sequence, the closed-loop control and the calculation of zero sequence voltage are affected, and zero sequence voltage injection fails. The voltage controllers of each phase alone generate inaccurate active current instructions, so that the sum of the three phase current instructions is not zero, which causes the current controller instruction conflict in the star circuit. Even if the regulated current can achieve active power balance within a period and keep the voltage stable, the current waveform is no longer sine, and the harmonics contained in it will seriously damage the power quality. The experimental results verify the effectiveness of the proposed low voltage crossing method.

Figure 4. Asymmetric hybrid energy storage system low voltage crossing waveform

Figure 5. The asymmetric system low voltage crossing method is not used
5. Conclusions
This paper studies the low voltage crossing control of three-phase asymmetric hybrid energy storage system under unbalanced power grid. By making the battery link track the grid voltage, the battery and capacitor link can work together in case of grid failure and maintain the positive sequence phase invariance of each link. By separating the zero-sequence components in the battery control instructions, the system can operate stably in the case of three-phase asymmetry and cross the unbalanced power grid with zero-sequence voltage injection. The proposed method can maintain the dc side voltage and grid-connected current of the capacitor chain at the time of voltage sags and cross the unbalanced condition. Experimental results verify the correctness and effectiveness of the proposed method.

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