

# Fault ride-through control strategy of H-bridge cascaded energy storage system

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**Abstract.** The cascaded energy storage system has received extensive attention in areas such as new energy consumption, maintaining stable operation of the power grid, and supporting black start due to its advantages such as high access voltage level, large single unit capacity, and fast dynamic response rate. This paper aimed to improve the fault ride-through capability of the cascaded energy storage system, and proposed a fault ride-through control method. Firstly, the mathematical model of the cascaded energy storage system was established, and then the rapid detection method of the abnormal state of the power grid and the fault ride-through method were analyzed, and finally the simulation analysis was performed. The feasibility and correctness of the control method can be seen from the experiments.

## 1 Introduction

Energy is an important factor for the survival and development of human beings. The continuous increase in population and the continuous development of social economy require a large amount of energy as a driving force [1]. While it has brought huge convenience and benefits to mankind, it also caused many problems, such as energy shortages and fossil energy pollution problems. In recent years, renewable energy power generation technology has continued to advance, the scale of the industry has continued to expand, and it has become more and more important in the power system [2]. At present, energy storage technology has become an important part to promote new energy consumption and support the stable operation of the power grid. The above-mentioned requirements are all eagerly hoped that the battery energy storage systems could develop towards higher voltage level and larger single machine capacity [3].

Compared with the classic low-voltage parallel technology, the energy storage technology based on the multi-level converter does not require a step-up transformer, directly connect to the power grid. The cascaded energy storage system has high conversion efficiency, fewer control levels, and rapid dispatch response, which is more in line with the construction needs of large-capacity energy storage power stations [4]. The multilevel converter technology suitable for 10kV voltage level and above is mainly divided into two types: Cascaded H-bridge converter battery energy storage system (CHBC-BESS) and modular multilevel converter battery energy storage system (MMC-BESS). MMC-

BESS technology and CHBC-BESS technology are all adopt modular design concept, but CHBC-BESS require fewer power electronic devices and control units [5-6]. Therefore, CHBC-BESS is more suitable for engineering construction needs without DC bus. This paper is also based on cascaded storage Energy system as research object.

Voltage imbalance or large value drop faults that occur in the power grid can easily cause overcurrent risk of the energy storage system and threaten stable operation. This article takes the improvement of the fault ride-through capability of the cascaded energy storage system as the starting point, the relationship between the switching state of the energy storage system sub-modules and the AC side variables is analyzed. Output power and current control method under the grid fault state and fast grid voltage amplitude phase angle lock method are purposed to improve the fault ride-through capability of the cascaded energy storage system.

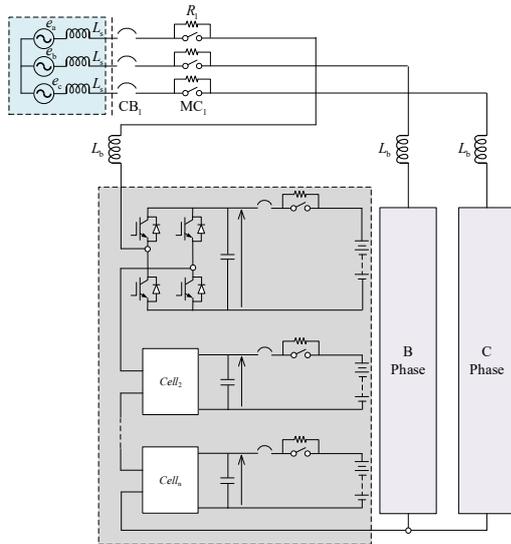
## 2 Mathematical model establishment of H-bridge cascaded energy storage system

The H-bridge cascaded energy storage system is composed of energy storage converters, energy storage batteries, battery management systems and other core components. As shown in Figure 1, the H-bridge cascaded energy storage system is a three-phase symmetric structure, and each phase is composed of N sub-modules, N battery packs and an arm reactor. Sub-module is the basic electric energy conversion unit of the cascaded energy storage system, the battery is the energy

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storage unit, and the arm reactor plays the role of suppressing harmonics and fault current.



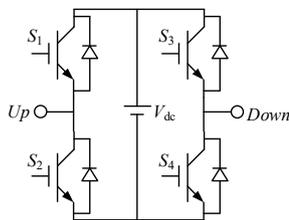
**Figure 1.** Topology structure of H-bridge cascaded energy storage system

The sub-module of the cascaded energy storage system mentioned in this article is H-bridge topology. As shown in Figure 2, the switching state of the sub-module can be defined as three states of P, O, and N. The output voltages of sub-module  $V_{sm}$  are  $V_c$ , 0, and  $-V_c$ . The corresponding power device conduction state  $S_{sm}$  is shown in formula (1),

$$S_{sm} = \begin{cases} +1 & (\text{P state}) \\ 0 & (\text{O state}) \\ -1 & (\text{N state}) \end{cases} \quad (1)$$

$$V_{sm} = S_{sm} \times V_c$$

If  $S_1$  and  $S_4$  switching devices are on,  $S_2$  and  $S_3$  switching devices are off, the sub-module is in the P operating state. Elseif  $S_1$  and  $S_4$  switching devices are off,  $S_2$  and  $S_3$  switching devices are on, the sub-module is in the N operating state. Else  $S_1$  and  $S_3$  are on, or  $S_2$  and  $S_4$  are on, the sub-module is in the O operating state.



**Figure 2.** Power sub-module topology structure

Based on Kirchhoff's voltage and current law, the equations of sub-module switching states, sub-module DC voltage and grid side voltage and current can be constructed as

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} + R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

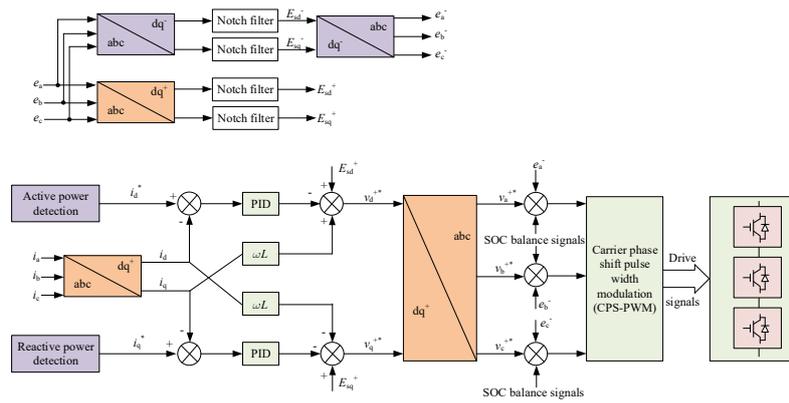
### 3 Fault ride-through control strategy of H-bridge cascaded energy storage system

Normally, asymmetrical faults or unbalanced system parameters in the power grid could cause the three-phase unbalance of the system voltage. When the system voltage unbalance is large, the traditional control strategy will still be used, which will cause the converter device to generate a negative sequence current.

#### 3.1 Control method of cascade energy storage system under unbalanced grid voltage

Therefore, an unbalanced control strategy can be adopted to add a component equal to the negative sequence voltage of the system in the voltage modulation signal, thereby suppressing the negative sequence current of the device.

The purposed unbalanced control strategy is shown in Figure 3. The grid voltages  $e_a$ ,  $e_b$ , and  $e_c$  are changed through the positive sequence coordinate transformation and the notch filter to obtain the positive sequence components  $E_{sd}^+$ ,  $E_{sq}^+$ . The negative sequence components  $E_{sd}^-$ ,  $E_{sq}^-$  are obtained through the negative sequence coordinate transformation and the notch filter. Then, three-phase negative sequence voltage components  $e_a^-$ ,  $e_b^-$ ,  $e_c^-$  can be obtained through negative sequence inverse coordinate transformation, and further the final voltage modulation signal can be synthesized.



**Figure 3.** Control block diagram of unbalanced voltage fault ride-through

The proposed notch filter is directly converted from the analog low-pass prototype filter through the s-plane to the z-plane of the digital band-stop filter. The transformation relationship from analog low pass to analog band stop is:

$$s = \frac{\omega_0^2 p}{p^2 + \omega_0^2} \quad (3)$$

As shown in formula (3),  $s$  and  $p$  are the Laplacian variable of the simulated low-pass prototype and the Laplacian variable of the simulated band stop. Respectively,  $\omega_0$  is the geometric center frequency of the simulated band stop filter.

The following equation can be obtained by bilinear transformation:

$$\begin{cases} p = \frac{2z-1}{Tz+1} \\ \omega_0 = \frac{2}{T} \tan(\Omega_0/2) \\ s = \frac{D(1-z^{-2})}{1-Fz^{-1}+z^{-2}} \end{cases} \quad (4)$$

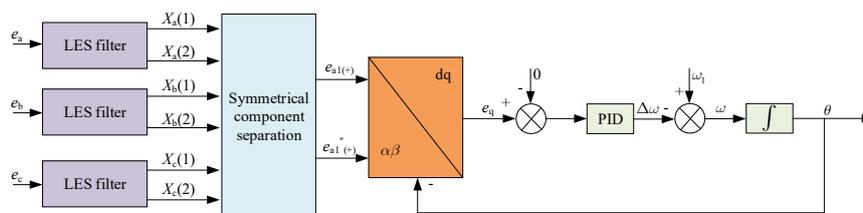
$\omega_c$  is the cutoff frequency of the analog low-pass filter. When the normalized prototype low-pass filter is used as the transformation prototype,  $\omega_c=1$ .  $\Omega_1$  and

$\Omega_2$  are the cutoff frequencies of the two passbands of the band-stop digital filter.

$$\begin{cases} D = \omega_c \tan \frac{\Omega_1 - \Omega_2}{2} \\ F = \frac{2 \cos \frac{\Omega_1 + \Omega_2}{2}}{\cos \frac{\Omega_1 - \Omega_2}{2}} \end{cases} \quad (5)$$

### 3.2 Fast locking method for amplitude and phase angle of unbalanced power grid

When the grid voltage amplitude drops or frequency fluctuates, the converter device needs to be able to respond quickly to compensate for the grid voltage. The fast and accurate phase-locked loop detection algorithm is the decisive factor. Figure 4 shows the principle diagram of fast phase-locked loop detection using the LES filter and the symmetric component method. LES The filter filters out the interference components, and the symmetric component method can quickly and effectively extract the positive sequence component of the fundamental frequency, thereby ensuring the accuracy and speed of the phase-locked loop.



**Figure 4.** Control block diagram of inter-phase SOC equalization

When the grid voltage is distorted, the grid voltage can be expressed as:

$$\begin{aligned} u_a(t) &= \sum_{n=1}^{\infty} U_{an} \sin(n\omega_0 t + \theta_{an}) \\ u_b(t) &= \sum_{n=1}^{\infty} U_{bn} \sin(n\omega_0 t + \theta_{bn}) \\ u_c(t) &= \sum_{n=1}^{\infty} U_{cn} \sin(n\omega_0 t + \theta_{cn}) \end{aligned} \quad (6)$$

To facilitate analysis and deduction, assume that the grid voltage contains a certain amount of voltage

$$\begin{aligned} u_a(t) &= U_{a1} \sin(\omega_0 t + \theta_{a1}) + U_{a5} \sin(5\omega_0 t + \theta_{a5}) \\ &= U_{a1} \cos \theta_{a1} \sin \omega_0 t + U_{a1} \sin \theta_{a1} \cos \omega_0 t + U_{a5} \cos \theta_{a5} \sin 5\omega_0 t + U_{a5} \sin \theta_{a5} \cos 5\omega_0 t \end{aligned} \quad (7)$$

It can be seen from equation (1) that there are 4 unknowns in the equation, and the equations can be set

$$\begin{aligned} A &= \begin{bmatrix} \sin \omega_0 t & \cos \omega_0 t & \sin 5\omega_0 t & \cos 5\omega_0 t \\ \sin \omega_0(t - \Delta t) & \cos \omega_0(t - \Delta t) & \sin 5\omega_0(t - \Delta t) & \cos 5\omega_0(t - \Delta t) \\ \sin \omega_0(t - 2\Delta t) & \cos \omega_0(t - 2\Delta t) & \sin 5\omega_0(t - 2\Delta t) & \cos 5\omega_0(t - 2\Delta t) \\ \sin \omega_0(t - 3\Delta t) & \cos \omega_0(t - 3\Delta t) & \sin 5\omega_0(t - 3\Delta t) & \cos 5\omega_0(t - 3\Delta t) \end{bmatrix} \\ X_a &= [U_{a1} \cos \theta_{a1} \quad U_{a1} \sin \theta_{a1} \quad U_{a5} \cos \theta_{a5} \quad U_{a5} \sin \theta_{a5}]^T \\ U_a &= [u_a(t) \quad u_a(t - \Delta t) \quad u_a(t - 2\Delta t) \quad u_a(t - 3\Delta t)]^T \end{aligned} \quad (8)$$

By analyzing and calculating each element of  $X_a$ , the amplitude and initial phase angle of each component can be obtained.

## 4 Simulation results of fault ride-through control strategy for H-bridge cascaded energy storage system

### 4.1 Fault ride-through control simulation under unbalanced grid voltage

The cascaded energy storage system which contains 42 sub-modules works in 35kV voltage level. As shown in Figure 5, voltage unbalance is set to 11%.

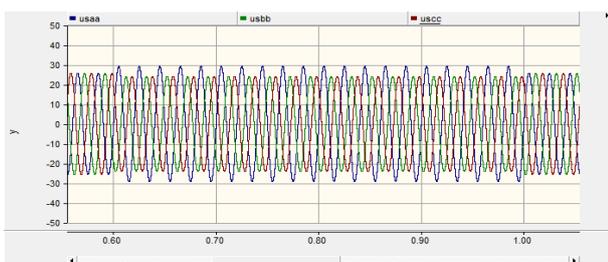


Figure 5. Three-phase grid voltage waveform (kV)

Figure 6 shows the output active power of the system. As shown in the figure, the active power is set as 5MW.

harmonics of the 5th order. Taking phase A as an example, the voltage of phase A can be expressed as:

simultaneously based on the 4 consecutive sampling results of

At 0.6s, voltage unbalance fault occurs in the power grid, the system quickly switches to the fault ride-through control state, and the output active power is continuously maintained at 5MW without fluctuations. At 1s, the power grid is restored to a healthy state again, and the energy storage system continues to maintain stability.

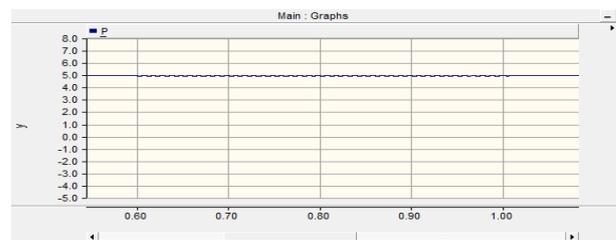
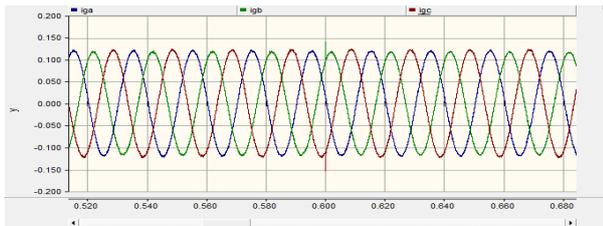


Figure 6. Output power waveform of cascaded energy storage system (kW)

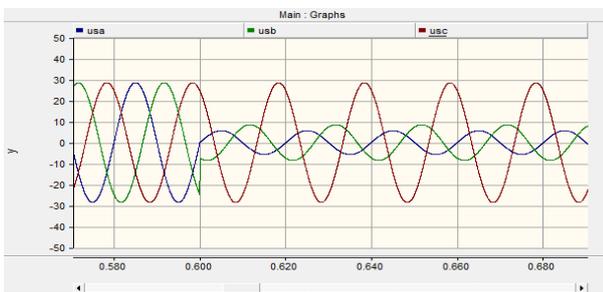
Figure 7 shows the system output ABC three-phase currents. As shown in the figure, during the entire fault ride-through process, the output currents of the cascaded energy storage system has good sine without fluctuations and distortions, which proves that the proposed control strategy is effective in the unbalanced state of the grid.



**Figure 7.** Output three-phase current waveform of cascaded energy storage system (kA)

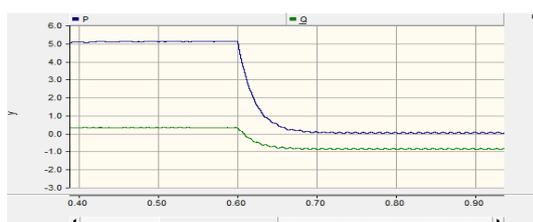
#### 4.2 Fault ride-through control simulation under two phase low voltage

The system is worked in the rated state, and the power is set as 5MW. As shown in Figure 8, at 0.6s, the voltage of phase A drops to 20%, and the voltage of phase B drops to 30%.

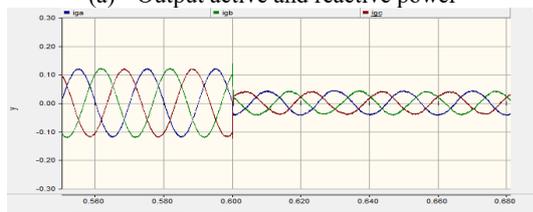


**Figure 8.** Three-phase grid voltage waveform (kV)

As shown in figure 9, when a large two-phase voltage drop occurs in the power grid, the cascaded energy storage system can automatically identify the fault state, recalculate the operating range, and supplement the reactive power. At the same time, the system can maintain the symmetry of the three-phase current and the stability of the output power.



(a) Output active and reactive power



(b) Output three phase current

**Figure 9.** The output power and current waveform of the energy storage system when the two-phase voltage of the power grid drops sharply (kW/kVA) (kA)

## 5 Conclusion

This paper has established the mathematical model of the cascaded energy storage system, and then the rapid detection method of the abnormal state of the power grid and the fault ride-through method are analyzed, and finally the simulation analysis is performed. The feasibility and correctness of the control method can be seen from the experiments. The research content of this paper can provide new ideas for fault ride-through control of large-capacity energy storage systems.

## Acknowledgment

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