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A New Fault-tolerant Control of Battery Energy Storage Grid-connected System Based on Cascaded H-Bridge

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***Abstract*-- Cascaded H-Bridge (CHB) converter has high output power quality, which can be used in energy storage grid connected systems to control charging and discharging of batteries. But this system contains a large number of switching devices and energy storage batteries, increasing the probability of failure. The traditional fault-tolerant control is not suitable when the state-of-charge (SOC) initial values of the battery modules are not the same. Therefore, a new control strategy is proposed in this paper, which only needs to inject zero-sequence voltage once and makes system control simpler and more efficient. Through MATLAB/Simulink and experiments, it has been proven that the proposed fault-tolerant control can not only maintain normal operation in the event of system failure, but also greatly improve the SOC balance speed.**

***Index Terms*-- Cascaded H-bridge, fault-tolerant control, SOC balancing, zero-sequence voltage injection.**

I. INTRODUCTION

In order to improving the conversion efficiency of battery modules and reducing the impact of circulating currents, a kind of topology structure for battery module separate governance strategy(BSGS)is widely adopted, as shown in Fig.1. This structure divides a large battery pack into several small battery modules, and each battery module is connected to an H-bridge unit which can achieve independent charge and discharge control. However, in this case, the probability of battery module or power switch devices failure greatly increases, and it is urgent to study corresponding fault-tolerant control to ensure the reliability and stability of the energy storage grid-connected system.

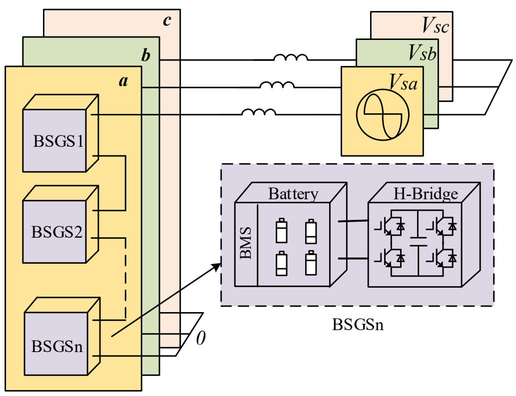

Fig. 1. Topological structure of BSGS.

When a battery module or switch device in the energy storage grid-connected system malfunctions, the faulty unit should be immediately cut off. The output voltage of this unit is 0, which will cause the three-phase voltage output of CHB to be unequal, resulting in an asymmetry in the output current. It will affect the normal operation of the system. In severe cases, it can cause frequency fluctuations in the power grid, which cannot meet the requirements for grid connection. In general, faulty units can only be replaced when the system is allowed to shut down. Therefore, when the system malfunctions, it is very important to take necessary fault-tolerant control, which can timely avoid risks and maintain the normal operation of the energy storage grid-connected system. Fault-tolerance control can be divided into hardware redundancy control and software fault tolerance control. Comparatively speaking, the former is easier to implement, but the system cost will significantly increase. Software fault-tolerant control is technically challenging, but it will not increase additional costs and is more flexible and diverse, which can maximize the energy utilization rate of the remaining healthy modules after a fault [1]-[4].

II. TRADITIONAL FAULT-TOLERANT CONTROL

Due to the star configuration adopted by the cascaded H-bridge converter, the neutral point is in a suspended state. Zero-sequence voltage injection will causes the neutral point potential of the CHB to be different from that of the AC side power supply. This neutral shift can change the output voltage of each phase and making the CHB output a symmetrical three-phase line voltage. Because the actual energy storage grid-connected system is mostly a three wire three-phase system, the zero-sequence component in the output voltage of the cascaded H-bridge converter does not affect the control of grid-connected current. But it can change the output phase voltage. In other words, injecting zero sequence voltage components to generate additional power can adjust the active power of each phase of the cascaded H-bridge converter, without affecting the total power of the system.

In the following, it is assumed that the number of cascaded H-bridge in each phase respectively is N. When the grid-connected system runs normally, the output voltage of each H-bridge is expressed as follows:

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$$\begin{cases} u_{an} = mU_{dc}\cos(\omega t) \\ u_{bn} = mU_{dc}\cos(\omega t - \frac{2}{3}\pi) \quad n = 1\cdots N \\ u_{cn} = mU_{dc}\cos(\omega t + \frac{2}{3}\pi) \end{cases} \tag{1}$$

where m is the modulation ratio, and U_{dc} is the DC side voltage of each H-bridge.

When a faulty occurs, the faulty unit should be bypassed. Maharjan et al. [5] proposes that the modulation ratio of healthy H-bridges in the fault phase can be directly improved to keep the output voltage unchanged. Assuming N_a, N_b and N_c modules are respectively faulty in each phase, the modulation ratio of the remaining healthy modules must be increased to $N/(N\text{-}N_a)$, $N/(N\text{-}N_b)$ and $N/(N\text{-}N_c)$ times to achieve the output of three-phase symmetrical line voltage and maintain the same as before the fault. Due to the different three-phase modulation ratio, the power exchange of the H-bridge unit in normal operation of the three-phase is inevitably different, resulting in the unbalanced SOC of the energy storage battery. SOC is usually defined as the ratio of the remaining battery capacity to the maximum available capacity, used to quantify the current amount of remaining power inside the battery. An important factor affecting the service life of batteries is overcharging and overdischarging caused by the imbalance of SOC between battery modules. Therefore, after bypassing the faulty unit, the fault-tolerant control can maintain the three-phase symmetrical current that meets the grid connection requirements and ensures the SOC balance of the remaining battery modules in CHB to extend the service life of the system. By injecting zero-sequence voltage to achieve neutral shift, the remaining healthy modules are evenly distributed in power, realizing SOC balancing. The essence of this method is to use the principle that zero-sequence voltage can adjust the power between the three phases of CHB. Zero-sequence voltage injection is used to increase the output voltage of the each phase, thereby enabling the cascaded H-bridge converter to output three-phase symmetrical current. In addition, this method can adjust the modulation ratio of the healthy H-bridge unit in the faulty phase to avoid over modulation.

The zero-sequence voltage injection u_{0f} is given by:

$$u_{0f} = U_{0f}\cos(\omega t + \theta_f) \tag{2}$$

In order to maintain the SOC balance of the energy storage battery in the remaining healthy H-bridge unit, the power of each H-bridge unit should be consistent, and the amplitude and phase of the zero-sequence voltage injection can be calculated as follows,

$$U_{0f} = \frac{\sqrt{2\left[(N_a - N_b)^2 + (N_b - N_c)^2 + (N_c - N_a)^2\right]}}{3N - N_a - N_b - N_c} \tag{3}$$

$$\theta_f = \begin{cases} \arctan\frac{\sqrt{3}(N_c - N_b)}{N_b + N_c - 2N_a} & N_b + N_c - 2N_a \neq 0 \\ \frac{\pi}{2} & N_b + N_c - 2N_a = 0 \square N_c - N_b > 0 \\ -\frac{\pi}{2} & N_b + N_c - 2N_a = 0 \square N_c - N_b < 0 \end{cases} \tag{4}$$

III. NEW FAULT-TOLERANT CONTROL

When the SOC of all energy storage modules is balanced before the fault occurs, traditional fault-tolerant control can be used. However, the SOC of the energy storage battery cannot be guaranteed to be exactly the same in fact. The literatures [6]–[7] propose injecting another zero-sequence voltage to solve this problem and using the unbalance degree of three-phase SOC.to calculate it. But this calculation is relatively complex and it will result in the superposition of two zero sequence voltages, which may cause over modulation in the system. From the above analysis, it can be seen that the traditional fault-tolerant control improves the modulation ratio of the faulty phase after removing the faulty unit, causing the SOC imbalance of the energy storage module too. Therefore, the essence of fault-tolerant control is also to achieve SOC balance control. In the literature [8], a fast SOC balancing control is proposed that injecting zero sequence voltage can limit the amplitude of the modulation wave corresponding to the maximum amplitude in the three-phase modulation wave to 1. This enables fast SOC balancing while achieving grid-connected control. On this basis, considering the unequal initial values of SOC, this paper applies fast SOC balancing control to achieve both fault-tolerant control and SOC balancing control simultaneously.

Zero-sequence voltage injection u_0 using fast balancing control is as follows,

$$u_0 = U_0\cos(\omega t + \theta_0) \tag{5}$$

Assuming the amplitude of phase a is maximum after injecting zero-sequence voltage, the amplitude of the zero-sequence voltage is calculated by (6),

$$\begin{cases} U_0 = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \\ A = 1, B = -2U_{an}\cos\theta_0, \; C = {U_{an}}^2 - \frac{1}{(\frac{N}{N - N_a})^2} \end{cases} \tag{6}$$

The phase difference of three-phase modulation waves is $2\pi/3$. The calculation results of phase b and phase c are similar to that of phase a, except for B and C corresponding adjustments required. The specific calculation formula is shown in the appendix.

It is assumed that ΔSOC is unbalance degree, and the calculation results for each phase are as follows,

$$\begin{cases} \Delta SOC_a = SOC_a - SOC \\ \Delta SOC_b = SOC_b - SOC \\ \Delta SOC_c = SOC_c - SOC \end{cases} \tag{7}$$

where SOC=1/3(SOC_a+SOC$_b$+SOC$_c$).

Through PARK transformation, unbalance degree between phases ΔSOC_m and phase angle θ can be obtained by (8) and (9),

$$\Delta SOC_m = \sqrt{\Delta SOC_\alpha^{\ 2} + \Delta SOC_\beta^{\ 2}} \tag{8}$$

$$\theta_0 = \arctan(\Delta SOC_\alpha / \Delta SOC_\beta) \tag{9}$$

This new fault-tolerant control flowchart is shown in Fig. 2.

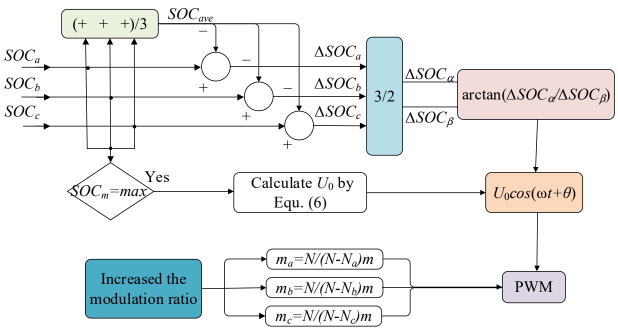

Fig.2. New fault-tolerant control flowchart.

IV. SIMULATION RESULTS AND ANALYSIS

In Simulink, the model of energy storage grid-connected system is built. The rated power of the system is 5,6000W, with 5 H-bridge units cascaded for each phase. The simulation parameters are set as follows: DC bus capacitance C_1=C_2=470μF, switching frequency is 10 *kHz*, output voltage frequency of CHB is 50*Hz*, and filter inductance L=10mH. It is assumed that the initial values of three-phase SOC are respectively, 39.4% (phase *a*), 39.6% (phase *b*) and 40% (phase *c*). Assuming that the fifth module of phase *a* is faulty, the fault unit is removed and the new fault-tolerant control strategy is taking effect.

The grid-connected current and voltage waveform of phase *a* is shown in Fig.3. The current and voltage are in the same phase, and the cascaded H-bridge energy storage system can realize grid-connected and discharge.

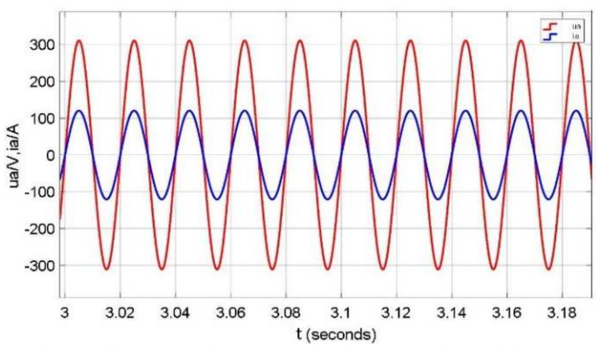

Fig.3. Grid-connected current and voltage waveform of phase *a*.

The output current waveform of CHB is shown in Fig.4. It can be seen that when the new fault-tolerant control proposed in this paper is adopted, CHB can output three-phase symmetrical current, which also enables the energy storage system to operate stably and meet with grid connection conditions.

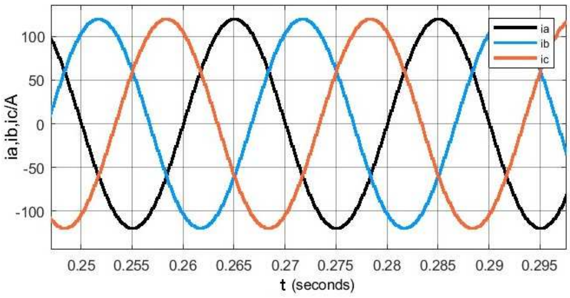

Fig.4. Output current wave of CHB.

The three-phase modulation wave is shown in Fig.5. Because the SOC value of phase *c* is the largest, to avoid over modulation and maximize utilization, the maximum amplitude of the phase *c* modulation wave is limited to 1 and maintained until balance between phases is achieved.

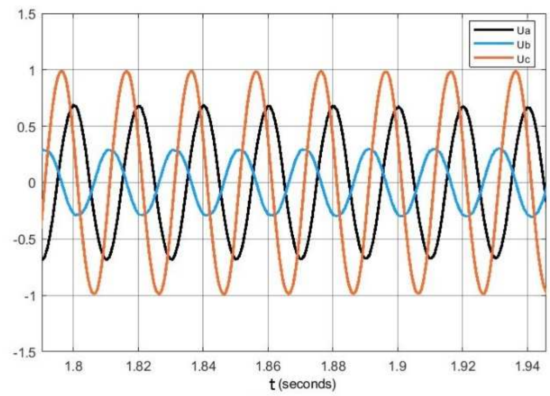

Fig.5. Three-phase modulation wave of CHB.

Fig.6 is output power of CHB. Because the SOC of phase *c* is the largest, it needs to release the most energy. Under the new fault-tolerant control, P_c is approximated to a constant value for maximum regulation. After a few seconds, the three-phase power is balanced and the system can be transformed into traditional fault-tolerant control. At this time, the remaining 14 modules work properly. In order to maintain the SOC balance, each module has an output power of 4,000W.

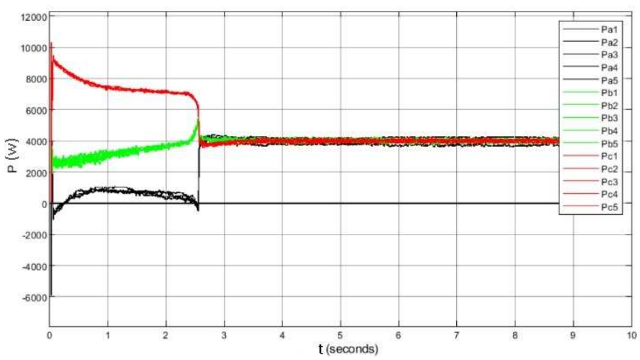

Fig.6. Three-phase output power of CHB

The variation trend of ΔSOC_m is shown in Fig.7. When the amplitude of the zero-sequence voltage injection remains unchanged, ΔSOC_m linearly decreases until SOC equalization is achieved. After that, traditional fault-tolerant control continues to maintain SOC equalization.

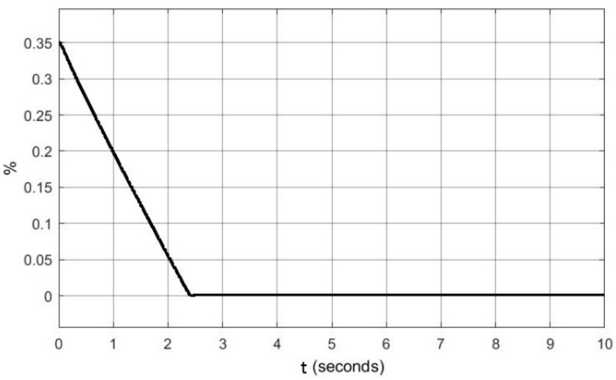

Fig. 7. Unbalance degree between phases (ΔSOC_m)

Fig.8 shows the waveform of three-phase SOC. When the battery discharge, SOC decreases. Because the SOC of phase *c* is the largest, its downward trend is also the most obvious.

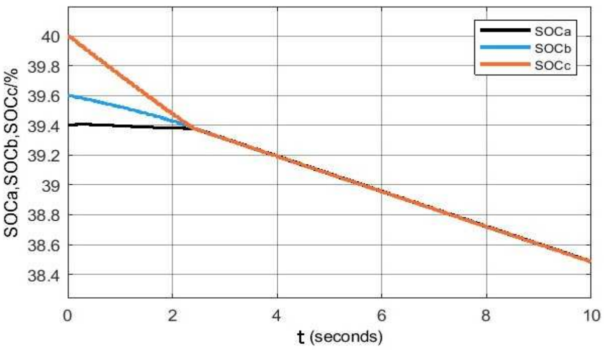

Fig. 7 Waveform of three-phase SOC

V. CONCLUSIONS

The cascaded H-bridge converter has been widely used in energy storage grid connected systems due to its own advantages, but it also makes the system architecture more complex and increases the possibility of faults, requiring corresponding fault-tolerant control to maintain its stable and efficient operation. After cutting off the faulty unit, traditional fault-tolerant control increases the modulation ratio of the remaining healthy units in the faulty phase to output three-phase symmetrical voltage, but it also causes unequal SOC values of battery modules in the energy storage grid connected system, requiring the injection of new zero sequence voltage to maintain balance. When the initial SOC values of the battery modules are not equal, it is necessary to inject another zero sequence voltage for regulation, which not only easily leads to over-modulation but also consumes more time.

This paper proposes a new fault-tolerant control. Even if the initial SOC values of the battery modules in the energy storage grid connected system are not equal, zero-sequence voltage only needs to be injected once.to maintain the maximum amplitude of the three-phase modulation wave at 1. It can ensure system normal operation and achieve SOC balance faster. A calculation formula for new zero-sequence voltage injection has been provided in this paper. Through simulation experiments, it has been verified that the new fault-tolerant control has a significant effect, which can ensure the safe and stable operation of the system even after a fault occurs. It greatly improves the speed of SOC balancing and extends the service life of the energy storage grid connected system.

APPENDIX

Assuming the amplitude of phase b is maximum after injecting zero-sequence voltage. The expression for B and C is given by (10),

$$B = U_{bn}\cos\theta_0 + 1.732U_{bn}\sin\theta_0, C = U_{bn}{}^2 - \frac{1}{\frac{N}{N-N_b}} \quad (10)$$

Assuming the amplitude of phase c is maximum after injecting zero-sequence voltage. The expression for B and C is given by (11),

$$B = U_{cn}\cos\theta_0 - 1.732U_{cn}\sin\theta_0, C = U_{cn}{}^2 - \frac{1}{\frac{N}{N-N_c}} \quad (11)$$

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REFERENCES

[1] Xiao Q, Chen L, Jin Y, et al, “An improved fault-tolerant control scheme for cascaded H-bridge STATCOM with higher attainable balanced line-to-line voltages,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 4, pp. 2784-2797, March. 2021.

[2] Hao Xue, Jinwei He, Yongfeng Ren, “Seamless Fault-Tolerant Control for Cascaded H-bridge Converters Based Battery Energy Storage System,” *IEEE Transactions on Industrial Electronics*, vol. 70, no. 4, pp. 3803-3813, June. 2023.

[3] Paul Gistain Ipoum-Ngome, Rodolfo César Costa Flesch, “Fault-Tolerant Model-Free Predictive Controller for Multilevel Cascaded H-bridge converters With Faulty Cells,” *IEEE Transactions on Industrial Electronics*, vol. 69, no. 12, pp. 12225-12236, Nov. 2022.

[4] Yousef Neyshabouri, Kourosh K. Monfared, “Symmetric Cascaded H-Bridge Multilevel Inverter With Enhanced Multi-Phase Fault Tolerant Capability,” *IEEE Transactions on Industrial Electronics*, vol. 69, no.6, pp. 8739-8750, Sep. 2022.

[5] Maharjan, L, T Yamagishi, “Fault-Tolerant Operation of a Battery-Energy-Storage System Based on a Multilevel Cascade PWM Converter With Star Configuration” *IEEE Transactions on Power Electronics*, vol. 25, no.9, pp. 2386 -2396, Sep. 2010.

[6] Herzog M, Ebentheuer A W, “State Of Charge Balancing during Fault Tolerant Operation of Battery Storage Systems Based on Cascaded H-Bridge Multilevel Inverter” The 2019 *14th International Conference on Ecological Vehicles and Renewable Energies* (EVER-Monaco 2019), Monaco, May 2019.

[7] Xing L, Rui L,“Control of a Battery-Energy-Storage System Based on a Cascaded H-Bridge Converter under Fault Condition” The 2012 *7th International Power Electronics and Motion Control Conference* (IPEMC-Harbin), Harbin(China),June 2012.

[8] Hu Huihui;Liu Kaixuan;Wu Mingbo, “Research on SOC Equalization Control Strategy of Cascaded Inverter for Grid-connected Energy Storage System, “The 2022 5th International Conference on Power and Energy Applications (ICPEA-Guangzhou), Guangzhou(China), November 2022.