Characterization of Short-circuit Faults Within Battery Modules for Energy Storage Systems

Zhicheng Li
State Grid Fujian Electric Power Co., Ltd.
Electric Power Science Research Institute
Fuzhou, China
565339368@qq.com

Weijun Zhang*
State Grid Fujian Electric Power Co., Ltd.
Electric Power Science Research Institute
Fuzhou, China
14158755@qq.com

Biao Li
State Grid Fujian Electric Power Co., Ltd.
Electric Power Science Research Institute
Fuzhou, China

Shuling Zhang
State Grid Fujian Electric Power Co., Ltd.
Electric Power Science Research Institute
Fuzhou, China

Yuge Chen
State Grid Fujian Electric Power Co., Ltd.
Electric Power Science Research Institute
Fuzhou, China

Chaoping Deng
State Grid Fujian Electric Power Co., Ltd.
Electric Power Science Research Institute
Fuzhou, China

Yeqiang Deng
Wuhan University
School of Electrical Engineering and Automation
Wuhan, China

Xiaolong Gu
Wuhan University
School of Electrical Engineering and Automation
Wuhan, China

Yu Wang
Wuhan University
School of Electrical Engineering and Automation
Wuhan, China

***Abstract*—With the rapid increase in the proportion of new energy installed capacity, in order to solve the problem of new energy output volatility, battery energy storage by virtue of its electrical characteristics and economic advantages of the rapid development, and gradually tend to modularization and large capacity, but also accompanied by battery short circuit, thermal runaway and other safety issues. This paper takes a domestic battery energy storage station as a reference, combines the current decoupling control, builds a complete cascade H-bridge battery energy storage system simulation model, calculates the electrical parameter change rule when short-circuit fault occurs inside the battery module under different operating power, and summarizes the fault characteristics under different fault conditions. The study shows that the battery terminal voltage will fall to different degrees, and under the control of the power module, the system operating power will recover after a short fluctuation. A large short-circuit current will be generated internally, but the short-circuit current remains unchanged with the change of operating power. The battery cluster current has exceeded the maximum allowable current, and failure to remove the fault in time can seriously damage the battery.**

Keywords—Cascade type; Battery storage; Internal short circuit; Fault characterization

I. Introduction

With[1] the rapid development of wind and renewable energy, the demand for energy storage gradually tends to scale and large capacity, gigawatt-hour battery energy storage power plant has become a national strategic development of emerging industries[1-3]. For the high-voltage battery integrated system, the number of batteries is large, the integrated structure is complex, the probability of short-circuit accidents is higher, and the failure triggered accidents is more serious. The current lithium battery energy storage system can not fully realize the early warning function, only when the failure occurs through the smoke, temperature and other information for fault alarm, lack of effectiveness, is still unavoidable to cause economic losses[4-6] .

Literature[7] constructs an active safety system for energy storage power stations is constructed, which establishes the safety defense of the energy storage system from the three perspectives of risk source identification, fault identification and accident identification. Among them, the active risk source identification mainly relies on the battery management system to evaluate the battery state, and the accuracy of the evaluation depends on the mastery of the fault characteristics of the battery pack. In this regard, the literature[8-9] quantitative analysis of battery pack short circuit fault current change law, but it only considered the battery pack static working condition short circuit characteristics, did not consider the energy exchange with the PCS and AC system. However, the research object is the traditional non-cascaded energy storage power station, and it is not necessarily applicable to the research of large-scale energy storage fault characteristics at the GWh level[10-11] .

In the aforementioned research status quo, this paper builds a simulation model of gigawatt-hour cascade H-bridge battery energy storage system, conducts a systematic research on the operating characteristics of battery system under different short-circuit fault types and different operating conditions, and analyzes the

[1] This paper is supported by the science and technology project of State Grid Fujian Electric Power Co., Ltd., the project name is " gigawatt time-class lithium-ion battery energy storage system technology (battery system high voltage integration and fault protection)", and the project code is (52130423000H).

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safety risk of energy storage system under typical faults, so as to provide reference for the safety protection of battery energy storage system..

II. SIMULATION MODELING OF CASCADED H-BRIDGE BATTERY ENERGY STORAGE SYSTEM

A. Structural parameters of cascaded H-bridge battery storage system

The cascaded H-bridge based battery energy storage system (CHB-BESS) connects the battery cells into clusters in series and then connects them to the DC side of the H-bridge power electronic modules, and the series connection of the H-bridge power modules replaces the series connection of the battery cells to increase the voltage, which improves the voltage level and capacity of the storage system and ensures that each power module has a reasonable voltage withstand range. [12-13].

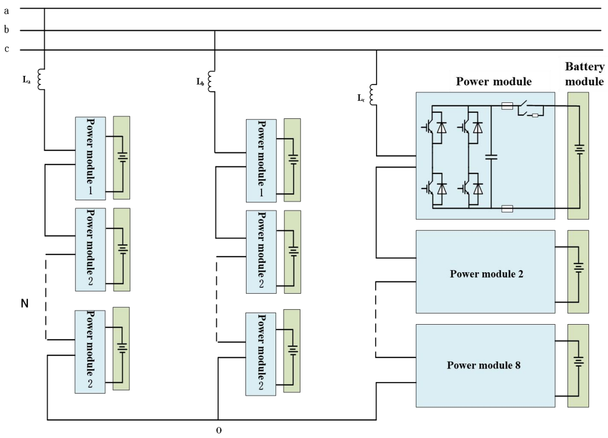

Fig. 1. Structure of cascade H-type energy storage system

The structure and parameters of the large-capacity high-voltage battery energy storage system studied in this paper are based on a pilot demonstration project of a large-scale domestic energy storage power station as a reference. When designing a cascaded battery energy storage system, the number of cascades of each phase power module needs to meet the requirements of grid-connected voltage, system redundancy and equalization function[14]. In this paper, the number of power modules in each phase needs to meet the requirements of grid voltage, system redundancy and equalization. In this paper, we mainly consider from the perspective of grid-connected voltage, to ensure that the battery module voltage can meet the impact of grid voltage fluctuation and voltage unbalance on grid-connected while uninterrupted charging and discharging changes. From this, equation (2.1) can be used to calculate the number of links N for each item.

$$\frac{N \times U_{\text{dcmin}}}{\sqrt{2}} \geq \frac{U_S}{\sqrt{3}} \times K_v \times K_b \times K_L \tag{1}$$

Where U_{dcmin} is the minimum working voltage of the battery module, U_s is the rated voltage of the grid, K_V is the correction factor for the maximum fluctuation of the grid voltage, K_b is the correction factor for the most serious imbalance of the grid voltage, and K_L is the correction factor for the maximum voltage drop of grid-connected reactor. K_V is taken as 1.07, which is mainly referenced to the "Permissible Deviation of Power Supply Voltage for Electricity Quality", which points out that voltage deviation of the power grid of 20kV and below is controlled within 7%. It is stated that the voltage deviation of the grid with 20kV and below is controlled within 7%, so the correction factor of grid voltage in extreme condition is taken to be 1.07. K_b is taken to be 1.02, which can be referred to the requirement of "Allowable imbalance degree of three-phase voltage of power quality", and the imbalance degree of the grid-connected voltage should not be more than 2% under the extreme condition. The battery side voltage of the energy storage station referred to in this paper is 728 to 936 V, so U_{dcmin} is 728 V. The rated voltage of the energy storage system connected to the grid in this project is 10 kV, i.e., U_s is 10,000 V. The voltage drop of the resistor is generally not large, so K_L is 1.1, and then the number of links N needs to satisfy equation (2.2).

$$N \geq \frac{\sqrt{2} \times 10 \times 10^3 \times 1.07 \times 1.02 \times 1.15}{\sqrt{3} \times 728} = 13.46 \tag{2}$$

N needs to be rounded upwards, so in this paper N = 14, i.e., the number of links per phase of the cascade-type battery energy storage system is 14, and the number of battery modules of the whole energy storage system is 42.

The energy storage system consists of 42 subsystems (battery modules), each of which consists of 1 control cabinet and 25 electrical cabinets. A single battery cabinet consists of 5 battery boxes connected in series, and each battery box consists of 52 lithium iron phosphate batteries in series, with a battery monitoring unit inside the battery box. Considering the topology alone, each battery cabinet can be made up of 5 battery boxes connected in series to form a battery cluster, so the internal topology of a single battery module can be used as shown in Figure 2.3. N needs to be rounded upwards, so in this paper N = 14, i.e., the number of links per phase of the cascade-type battery energy storage system is 14.

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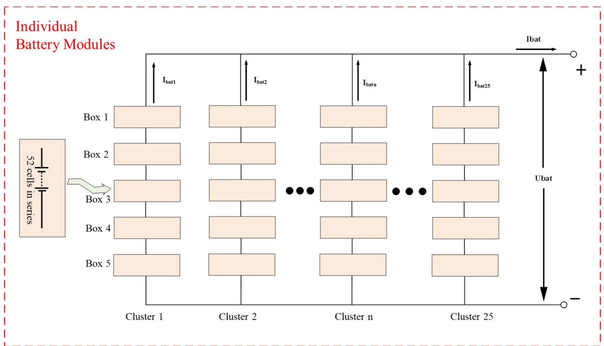


Fig. 2. Internal structure of a single battery module

B. Cascade H-bridge power control

Fig.3 shows the overall flow of grid-connected power control of cascaded battery storage system. Firstly, the three-phase voltages U_a , U_b , U_c and currents I_a , I_b , I_c of the grid-connected point need to be collected, and the phase of the grid-connected point voltage is obtained through the phase-locked-loop PLL link, and the Pike transform is applied to it, so that the three-phase voltages and currents of the grid-connected point are transformed to the dq rotating coordinate system, and the intermediate control quantities U_d , U_q , and I_d , I_q are obtained.

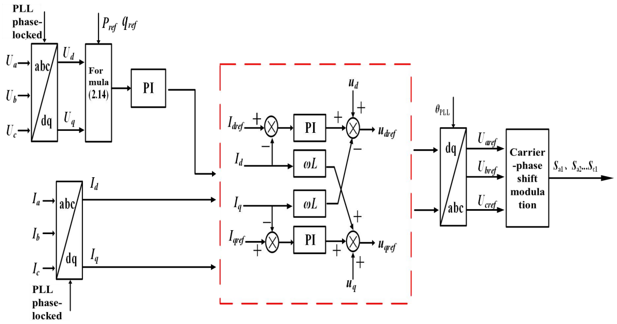


Fig. 3. Power control structure of cascade battery energy storage system

This is followed by the power outer loop control, which calculates the grid-connected current component references I_{dref} and I_{qref} in d-axis and q-axis according to the instantaneous power calculation formula, through the dc voltage and the set reference values of active and reactive power, and then by using the PI control and negative feedback link.

Secondly, the reference component of the current is introduced into the current inner-loop control, which is involved in the calculation of the active current I_d and the reactive current I_q , respectively, to obtain the reference values of the d-axis component and the q-axis component of the voltage at the parallel network point U_{dref} and U_{qref} through the feed-forward decoupling control as described before.

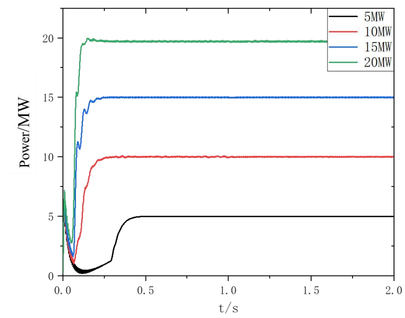
Finally, the Pike inverse transform is performed on the reference value of the grid-connected point voltage to obtain the reference values of the three-phase AC voltage, U_{aref} , U_{bref} , U_{cref} , and the carrier-phase shifting method is used to modulate the reference value of the AC voltage, and the control signals generated from these signals, S_{a1} , S_{a2} ... S_{c1} , are used as the control signals of the cascaded power devices, which ultimately realizes the power control for the grid-connected battery energy storage system. The control signals S , S ...S are used as the control signals of the cascaded power devices to realize the power control of the battery storage system on the grid[15-16].

III. Simulation Study of Fault Characteristics of Lithium-ion Battery Packs

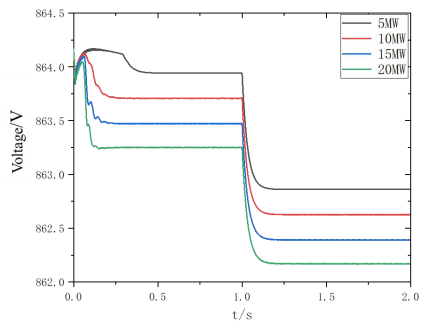
A. Short-circuit faults within the battery cluster

Set the simulation time as 2s and the fault moment as 1s, i.e., the battery system operates normally during 0~1s, and the battery is in the short-circuit fault state during 1~2s. Taking the case of SOC=60% as an example, we analyze the discharge multiplier of the battery system in the battery cluster at 0.125C, 0.25C, 0.375C, 0.5C, i.e., the operating power of 5MW, 10MW, 15MW, and 20MW. No. 1 monomer and No. 16 monomer short-circuit failure occurs.

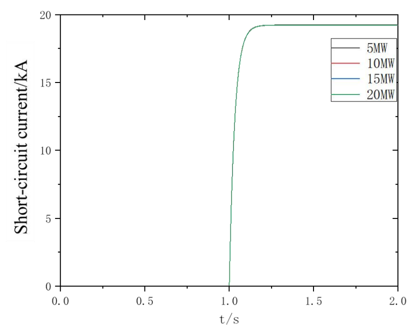
From Fig. 4, it can be seen that the transition time from startup to stabilization of the system becomes shorter while the battery discharge power increases. From Fig. (a), it can be seen that the system tends to stabilize from startup to the time when the power reaches the reference power during the period from 0 to 1s. The higher the power, the shorter the transition time of startup, but the amplitude of transient fluctuations increases slightly. the failure occurs at the moment of 1s, and the battery operating power hardly fluctuates, which shows that the system can be stabilized under the control of the power module. From Fig. (b), it can be seen that when the fault occurs, the overall terminal voltage of the battery module will fall to different degrees, and the final steady-state value of the voltage will become lower with the increase of the power, and the final steady-state value of the voltage is 862.86V, 862.62V, 862.39V, 862.17V in order under the 5-20MW. from Fig. (c), it can be seen that the short-circuit current at the moment of 0-1s is almost 0, and the short-circuit current is about 18kA when the fault occurs. moment reaches about 18kA, and the steady-state value of the short-circuit current is almost unchanged with the increase of the operating power, which is due to the fact that the operating power does not affect the short-circuit circuit.



(a) Battery module power change



(b) Battery module terminal voltage change



(c) Short circuit fault current

Fig. 4. Variation of the main parameters of the battery module

Figure 5 shows the change rule of each battery cluster current under 20MW, Ibat1 and Ibatn indicate the current of faulty battery cluster and normal battery cluster. Before the fault occurs, the current of each battery cluster is in the normal state, about 0.9kA. When the fault occurs, the polarity of the two is reversed, in which Ibat1 rises rapidly and finally stabilized at about 24kA, much larger than the normal operating conditions, Ibatn is also a little higher than the normal, stabilized at about 1.7kA, the discharge current is less than 1C, which is still in the safer state.

From the above analysis, it can be seen that when the short-circuit fault occurs inside the battery box, although the battery pack external output power, voltage and current and other parameters do not change significantly, but the short-circuit circuit has generated a very high short-circuit current, generating a large amount of heat, which for a long time will lead to thermal runaway of the battery or even fire and explosion, and the battery clusters will inevitably form a loop current between the battery clusters, and the entire battery pack of batteries are in an abnormal state, and the operation of the system is seriously The operation of the system is seriously affected.

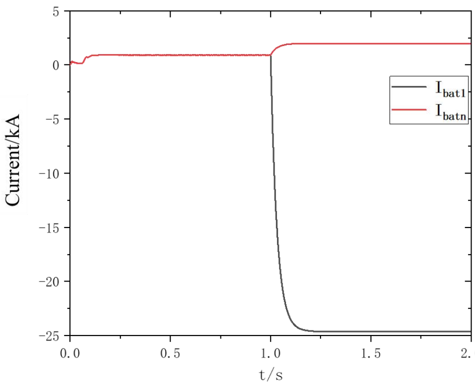


Fig. 5. Current variation of each battery cluster

B. *Short-circuit failures between cell clusters*

According to Fig. 6, it can be seen that the transition time of the system from startup to stabilization becomes shorter with the increase of battery discharge power. From Fig. (a), it can be seen that the fault occurs at the moment of 1s, and the power curve shows obvious fluctuation, after which it returns to stability, which is different from the short-circuit fault inside the battery box, indicating that the fault between the battery clusters causes larger fluctuations in the system, but the system quickly returns to stability under power control. From Fig. (b), it can be seen that the overall terminal voltage of the voltage module will drop to different degrees when the fault occurs, and the final steady-state value of the voltage will become lower with the increase of the power, and the final steady-state value of the voltage is 848.89 V, 848.66 V, 848.42 V, and 848.19 V in order under 5-20 MW. From Fig. (d), it can be seen that the short-circuit current doesn't change with the change of the operating power, and the At this time, the steady-state value of short-circuit current has reached about 63kA, which seriously affects the safe operation of the battery pack.

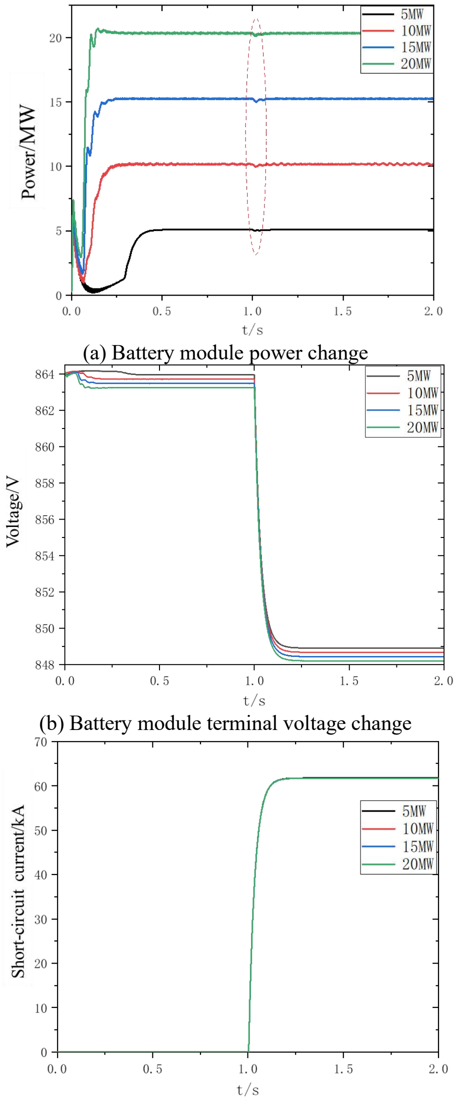


Fig. 6. Changes in the main parameters of the battery module

Inter-cluster short-circuit fault will make two clusters in an abnormal state, at this time the inter-cluster loop current is more serious, so it is necessary to study the characteristics of each cluster current change. Let each battery cluster current be Ibat1, Ibat2 ......Ibatn, where Ibatn denotes the current of the non-faulty battery cluster.

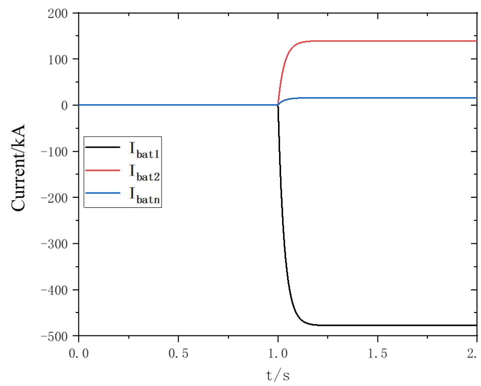


Fig. 7. Current change rule of each cell cluster during inter-cluster failure

As shown in Fig. 7, the current change of each battery cluster when the output power of the system is the rated discharge multiplier (20 MW), in which due to the short circuit between battery clusters 1 and 2, the currents of the two, I_{bat1} , I_{bat2} , change significantly, with opposite polarity and very large amplitude. Since the batteries of battery cluster 1 at both ends of the short-circuit circuit are at a high potential and the batteries of battery cluster 2 are at a low potential, the current of battery cluster 1 is negative, and the whole is in a clearly discharged state, which supplies power to all the other clusters. Battery cluster 2, on the other hand, is in a charging state, and the cluster current is significantly higher than other normal clusters, indicating that the energy from battery cluster 1 is mainly flowing to battery cluster 2. I_{batn} The current is also positive, with an amplitude of about 16 kA, indicating that the other normal clusters are less affected, but that the current values of the entire battery module have significantly exceeded the normal operating values.

CONCLUSION

In this paper, according to the internal integration structure of the actual battery module, short-circuit faults are categorized into intra-cluster short-circuit and inter-cluster short-circuit faults, and then based on the battery energy storage simulation model constructed in the previous section, the operation characteristics of the system under the two kinds of faults are systematically investigated. The main conclusions are as follows:

(1) Under the control of the power module, the short-circuit fault within the battery cluster does not significantly affect the operating power and steady-state current of the battery module, while the battery terminal voltage drops to different degrees and the internal short-circuit current reaches 18 kA. In the case of a short-circuit fault between the battery clusters, the fault moment will cause a large fluctuation in the power and current, and the power will be restored to the reference power value, and the steady state value of the current at this time will be slightly larger than that during normal operation. during normal operation.

(2) different faults under different rules of change of battery cluster current, non-fault battery cluster current and fault battery cluster current polarity opposite, and the latter far more than the normal operating state, the formation of loop current between the battery cluster. Battery box failure non-fault battery cluster current of 1.7kA, is still in a relatively safe range, between the battery box and the short circuit between the cluster failure, the battery cluster current has exceeded the maximum allowable current, do not timely excise the fault will seriously damage the battery.

ACKNOWLEDGMENT

This paper is supported by the science and technology project of State Grid Fujian Electric Power Co., Ltd., the project name is " gigawatt time-class lithium-ion battery energy storage system technology (battery system high voltage integration and fault protection)", and the project code is (52130423000H).

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