Research on fault current control method of DC microgrid battery energy storage system

Tianliu Wei  
Guangdong Power Grid Corp Electric Power Research Institute

Weiwei Li  
Guangdong Power Grid Corp Electric Power Research Institute

Fang Guo (fsu_guof@163.com)  
Foshan University  
https://orcid.org/0000-0003-4883-1594

Ruiyang Wang  
Foshan University

Chengzhi Wei  
Guangdong Power Grid Corp Electric Power Research Institute

Bingyao Zheng  
Foshan University

Jiaxi Jiang  
Foshan University

Research Article

Keywords: Battery energy storage system, DC microgrid, Inter-pole short circuit fault, Buck DC/DC, Fault current control

Posted Date: February 3rd, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2464907/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.  
Read Full License
Abstract

Battery energy storage system has become an important link to maintain the stable operation of DC microgrid because of its flexible control and fast response speed. As the battery storage system generally does not have fault current control capability, when a fault occurs between the poles of the system, the battery storage system will provide a great short-circuit current to the fault point, which will cause a great danger to the system operation and equipment safety. At this stage, current-limiting reactors or fault current limiters are generally added to the ports of the energy storage system to reduce the fault current, which has the disadvantage of limited current-limiting effect or high cost and large area, so it is not suitable for wide application in DC microgrid. This paper proposes a fault current control method for DC microgrid battery storage system, which enables the battery storage system to be connected to DC microgrid through Buck DC/DC by increasing the rated voltage of the battery stack. The control mode of the battery storage system is power control mode when the DC microgrid is running on grid, and it will be changed to voltage control mode when the DC microgrid is running off-grid. In case of inter-pole fault, the Buck DC/DC of the battery storage system is controlled to operate with reduced voltage to achieve fault current limit. This scheme does not affect the normal operation of the system, and can quickly limit the peak short-circuit current without adding additional equipment, making the short-circuit current flexible and controllable. Therefore, this scheme has good fault current limiting capability and greatly reduces the technical requirements of DC microgrid for protection. Finally, this paper verifies the feasibility of the proposed scheme and its control strategy through PSCAD/EMTDC modeling simulation.

1 Introduction

With the growing energy crisis and environmental pollution problems, renewable new energy sources have been vigorously developed, and users have put forward higher requirements for distribution networks in terms of distributed power access, load and power demand diversification, power quality, and power supply reliability (Ghareeb et al. 2013; Zhang et al. 2018). As an important approach to improve the efficiency of distributed power consumption research and investigation of DC microgrids are increasingly available (Brivio et al. 2016; Chatzinikolaou et al. 2017). Due to the random and intermittent nature of distributed power sources, battery energy storage systems with flexible regulation capability are essential in microgrids (Dubarry et al. 2019; Gupta et al. 2018). A lot of research had been done at home and abroad on the topology, connection methods, control of grid-connected and islanding operation methods, and energy management of battery energy storage systems. In (Palizban et al. 2015), a decentralized control method for SOC was proposed, based on a modified droop control method in which the SOC of each battery energy storage units was balanced during the discharge process. A high-efficiency grid-tie lithium-ion-battery-based energy storage system was proposed in (Qian et al. 2011), which adopted a highly efficient opposed-current half-bridge-type inverter along with an admittance-compensated quasi-proportional resonant controller to ensure high power quality and precision power flow control. Branco et al. (2018) assessed the possibility of installing battery storage systems into the isolated grid for renewable energy sources integration and the results suggested that the technology considerably
decreased the levels of renewable energy sources curtailment. But when an inter-pole short-circuit fault occurs in DC microgrid, the energy storage battery as a voltage source will provide a great short-circuit current to the fault point, endangering system and equipment safety (Drovtar et al. 2012). These above studies did not take into account this issue.

At this stage of engineering, current-limiting reactors are generally installed to limit the diode current after a short circuit. Zhao et al.(2013) analyzed a short circuit transient process of a distributing network with current limiting reactor derived and an engineering calculation formula of current limiting reactor's impedance. In (Drovtar et al. 2012), proper application of current limiting reactor to high voltage substation was proposed, based on a comprehensive short circuit analysis of 4 well-known substation bus bar arrangements. However, the presence of a current limiting reactor in an electric circuit will lead to a significant increase in the circuit breaker transient recovery voltage, which will also have a greater impact on switching overvoltage and temporary overvoltage. And current limiting reactors are very easy to saturate at high currents and lose their current limiting effect (Chen et al. 2013).

Over the past few decades, Fault Current Limiters (FCL) have been widely used in engineering as a revolutionary power system device to overcome the problems caused by increased fault current levels (Sushma et al. 2014). The FCL's can be classified as: Superconducting FCL (SFCL), Solid-State FCL (SSFC), Electromagnetic Dynamic Fault Current Limiter (DFCL), Hybrid FCL. SFCL is a novel electric equipment which has the capability to reduce the fault current level within the first cycle of fault current. A DC SFCL was proposed in (Li et al. 2018), which not only limited the peak DC fault current to meet the requirement of reducing the maximum opening capacity of DC circuit breakers, but also limited the fault current rise rate and achieves coordination between the converter, DC circuit breaker and DC SFCL. But because SFCL need to be equipped with expensive cooling systems, they cannot be widely used in DC microgrids where cost requirements are more stringent. Compared to SFCL, SSFC can also achieve a fast response to fault currents with no special requirements for cooling systems. SSFC that limit short-circuit currents by opening IGBTs were discussed in (Fang et al. 2008). However, the control of fault current by IGBT requires high overcurrent resistance of IGBT, and the feasibility and device safety need to be thoroughly investigated. A DFCL is an electromagnetic FCL which automatically and instantaneously adjusts its own impedance depending upon the magnitude of the fault current. There by maintaining the let through current within a narrow range of values. Rubenbauer et al. (2007) proposed a DFCL based on a six-pulse thyristor rectifier which can switch off the limited fault current very fast by blocking the firing pulses. However, the DFCL structure is too complex for DC microgrid and cannot be used in high-power applications, so it has not been widely used in engineering. Prigmore et al. (2014) proposed a hybrid fault current limiter that controls the magnitude of the fault current by pulse-width modulation. This fault current limiter is small in size, but additional components may increase its footprint.

Scholars at home and abroad have done a lot of research on other fault limiting methods. Baran et al. (2007) proposed a protection scheme using a modern voltage-type converter as a fast-acting current-limiting circuit breaker, which effectively limited the fault current by changing the diode in the converter to a fully controlled device. However, this approach will greatly increase the cost and cannot be widely used
in DC microgrids where cost requirements are more stringent. Lu et al. (2018) proposed a virtual impedance-based fault current limiting method, which effectively limited the fault current and did not require additional equipment. However, the current limiting effect still had a gap compared to the fault current limiter. In (Ni et al; 2020), a fault-limiting method based on adaptive control was proposed. This method has a limiting effect on the fault current without adding additional current limiting devices, but the effect is not very obvious, and the control strategy of the converter will become very complicated after the introduction of adaptive control.

The above-mentioned current limiting methods of battery energy storage systems are mostly with the help of current limiting reactors, fault current limiters and other current limiting devices, which are more costly and less effective in promotion. The current limiting effect of the fault current limiting methods without relying on the current limiting device are also not ideal, and they are more difficult to cooperate with the protection. In this paper, a fault current control method for DC microgrid battery storage system is proposed. Unlike the existing current limiting methods, this paper does not add any current limiting device, but increases the rated voltage of the battery stack of the battery storage system, which can be connected to the DC microgrid through a Buck DC/DC converter. In case of inter-pole short-circuit fault, the Buck DC/DC converter can reduce the short-circuit current provided by the battery storage system by buck operation, and the short-circuit current can be controlled transparently. The protection of the DC microgrid is easily achieved by combining with DC circuit breakers.

2 Battery Energy Storage System Access Method

2.1 Fault Current Control Principle

Considering the voltage source characteristics of the battery energy storage system, it can be equated to an adjustable DC voltage source (Amrouche et al. 2015). When an inter-pole short-circuit fault occurs in the system, the equivalent circuit is shown in Fig. 1, which the short-circuit current provided by the battery storage system can be expressed as follows:

\[ i = \frac{U_d}{Z + R_f} \]  \hspace{1cm} (1)

Where: \( U_d \) is the equivalent voltage at the output of the battery storage system, \( Z \) is the impedance between the fault point and the DC/DC converter, and \( R_f \) is the fault transition resistance.

As can be seen, the short-circuit current provided by the battery storage system depends mainly on the magnitude of the equivalent voltage \( U_d \) of the battery storage system. The lower the equivalent voltage, the smaller the short-circuit current provided by the battery storage system. Therefore, when a fault occurs, the short-circuit current provided by the energy storage system can be reduced and controlled by reducing the equivalent voltage of the battery storage system through control means.
2.2 Basic Structure of Battery Energy Storage System

Based on the above fault current control principle, a set of energy storage system access methods with buck operation capability can be designed to realize the fault current control through the access system. Therefore, this paper designs a battery energy storage system access method as shown in Fig. 2. The battery storage system is connected to the DC microgrid through a Buck DC/DC by increasing the number of series-connected cells in the battery stack so that the minimum operating voltage of the port is higher than the bus voltage of the DC microgrid. In case of a fault, the buck DC/DC is controlled to operate at a reduced voltage, which can significantly reduce the fault current.

A typical Buck DC/DC structure is shown in Fig. 3 (Hwu et al. 2012), where the output voltage can be adjusted by controlling the on-off duty cycle of switches S1 and S2 to control the voltage, current, or power.

3 Battery Energy Storage System Control Scheme

Since DC microgrid generally adopt a symmetrical capacitive midpoint grounding method, the fault current is very small in the case of pole-to-pole fault, which does not affect the system operation too much. Therefore, this paper focuses on inter-pole faults in DC microgrid.

In the normal operation of DC microgrid, the fault current control capability of the battery storage system does not affect the normal operation of the system. In addition, this scheme enables fast control of fault currents in the event of a fault, and automatically returns to normal operation after the fault is cleared.

3.1 Normal Operation Control Strategy for Battery Storage System

When the DC microgrid is in grid-connected operation, the battery energy storage systems generally use power control to regulate power, such as smoothing power fluctuations in distributed power sources, peak-to-valley arbitrage or optimizing tides to achieve economic operation, etc.

When the DC microgrid is operated off-grid, the battery storage system is generally used as the main power source, and a voltage control strategy is required to maintain the voltage stability of the DC microgrid.

3.2 Inter-pole Short Circuit Control Strategy for Battery Storage System

After an inter-pole short-circuit fault occurs, the control mode of the battery storage system switches to the buck operation mode, and in order to achieve accurate control of the short-circuit current, the battery storage system can use current control. When the fault is cleared, the battery storage system control mode changes back to voltage or power control.
When an inter-pole short-circuit fault occurs in a system, it is usually accompanied by a rapid decrease in inter-pole voltage and a rapid increase in current. So the amplitude of the inter-pole voltage and the current amplitude can be used as the basis for fault diagnosis and recovery to improve the accuracy of fault diagnosis.

### 3.3 Control Flow

During normal operation of DC microgrid, the control mode of battery storage system is in voltage or power control mode. Short-circuit faults in DC microgrids can occur in a few ms or less, which means that accurate fault diagnosis is essential. Qu et al. (2022) proposed an imbalance-like privacy-preserving federal learning framework for fault diagnosis of decentralized wind turbines, which can maintain high diagnostic performance while enhancing privacy protection. Xu et al. (2019) developed a new framework by combining multi-domain vibration feature extraction, feature selection and cost-sensitive learning methods. When an inter-pole fault occurs, the system voltage or current feedback detects the occurrence of the fault and the control mode switches to current control mode. When the fault is cleared, the control mode is switched back to voltage or power control, and the control process flow chart is shown in Fig. 4.

The control block diagram of the whole process is shown in Fig. 5. Where $U_d$ is the output voltage of the DC/DC low voltage side of the battery storage system, $P_{dc}$ is the output power of the battery storage system. Under normal operation, the voltage between the poles is the rated voltage and the current change is small. The duty cycle $K$ is equal to $K_1$, which is voltage or power control. When the inter-pole voltage is less than the set value $U_{set}$ and the current is higher than the set value $I_{set}$, it is determined that a fault occurs, and the duty cycle $K$ switches to $K_2$ and changes to current control. After the fault is cleared, the voltage between the poles rises, and the duty cycle $K$ switches to $K_1$ and returns to the voltage or power control mode.

### 4 Simulation Verification

In this paper, simulation analysis is carried out for a typical DC microgrid structure as shown in Fig. 6, in which the parameters of each power source and load are shown in Table 1. The simulation assumes that an inter-pole short-circuit fault occurs at the $f_1$ position at 0.3s, and sets the fault current control target to 0.3kA, which is 1.15 times the rated current $I_N$ of the energy storage system. The short-circuit fault is cleared after a duration of 0.1s.
Table 1
Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Numerical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power of resistive load/kW</td>
<td>100</td>
</tr>
<tr>
<td>DC bus voltage/kV</td>
<td>0.75</td>
</tr>
<tr>
<td>Rated power of charging pile/kW</td>
<td>120</td>
</tr>
<tr>
<td>Rated power of resistive load/kW</td>
<td>100</td>
</tr>
<tr>
<td>Photovoltaic power generation system capacity/kW_p</td>
<td>120</td>
</tr>
<tr>
<td>Battery stack port nominal voltage/kV</td>
<td>0.85</td>
</tr>
<tr>
<td>Energy storage system nominal power/kW</td>
<td>200</td>
</tr>
<tr>
<td>Nominal capacity of energy storage system/kWh</td>
<td>200</td>
</tr>
<tr>
<td>Energy storage system nominal current I_N/kA</td>
<td>0.26</td>
</tr>
<tr>
<td>Fault current control target/kA</td>
<td>0.3</td>
</tr>
<tr>
<td>C_1&amp;c_2/uF</td>
<td>6000</td>
</tr>
<tr>
<td>C_3/uF</td>
<td>1000</td>
</tr>
<tr>
<td>L/uH</td>
<td>100</td>
</tr>
<tr>
<td>Voltage PI controller</td>
<td>K_p=1,K_i=0.001</td>
</tr>
<tr>
<td>Power PI controller</td>
<td>K_p=1,K_i=0.001</td>
</tr>
<tr>
<td>Current PI controller</td>
<td>K_p=1,K_i=0.001</td>
</tr>
<tr>
<td>Switching frequency/Hz</td>
<td>3000</td>
</tr>
</tbody>
</table>

Considering that different control strategies are generally used for energy storage systems when DC microgrid is grid-connected and off-grid., in order to verify that the short-circuit current provided by the battery storage system can be effectively controlled regardless of whether the DC microgrid is in the grid-connected or off-grid state at the time of fault, the following simulation analysis will be conducted for two states of DC microgrid grid-connected operation and off-grid operation respectively.

### 4.1 Grid-connected Operation

The grid-connected switch is closed and the DC microgrid is in grid-connected operation. The battery storage system adopts power control during normal operation and current control under fault conditions. In order to verify the good current control effect of the energy storage system before the fault, no matter it
is in the discharging or charging state, the following simulation analysis will be conducted for the two states of discharging and charging respectively.

### 4.1.1 Discharge State

Assume that the DC microgrid is in grid-connected operation before the fault, and the battery storage system is discharged at a constant power of 100kW and the charging pile is charged at full power. The voltage and current waveforms of the battery storage system before and after the occurrence of inter-pole short circuit fault $f_1$ shown in Fig. 6 are shown in Fig. 7 and Fig. 8. The switching states of switching devices $S_1$ and $S_2$ before and after fault are shown in Fig. 9. The switch state of 1 is on, the state of 0 is off.

As can be seen from the above figure, when the battery energy storage system is connected to the DC microgrid through a Boost DC/DC, the inter-polar voltage of the battery storage system continues to drop after the fault occurs, and the fault current rises rapidly. The inter-pole voltage drops to about 0.35kV after 100ms and the fault current rises to a maximum value of 3.62kA after 100ms, which is about 13.92 times the rated operating current. At this point, the DC/DC starts the blocking protection and the storage battery discharges to the fault point via the diode. The fault is cleared after a duration of 0.1s, the inter-pole voltage of the battery storage system rises rapidly and the fault current falls rapidly. The inter-polar voltage rises to the maximum value of 1.91kV after 21ms of fault clearing, and then recovers to 0.75kV after about 70ms of oscillation; the fault current is restored to 0.13kA after 125ms oscillation.

When the Buck DC/DC with the fault current control strategy is used to access the energy storage system, after the inter-pole fault occurs, the inter-pole voltage of the battery storage system drops rapidly and the fault current rises rapidly. The inter-pole voltage drops to about 0.08kV after about 17ms, and the Buck DC/DC switches to the current control mode. During the fault, the maximum fault current is 0.38kA, which is about 1.46 times of the rated operating current, with a duration of about 0.2ms. About 25ms after the $f_1$ fault occurs, the fault current is controlled at a set value of about 0.3kA. After 0.1s, the fault is cleared and the Buck DC/DC switches to power control mode, the inter-pole voltage of the battery storage system rises and the fault current falls. The inter-pole voltage rises to 0.7kV after about 12ms and recovers to 0.75kV after about 65ms; the fault current recovers to 0.13kA after 100ms oscillation.

It can be seen that under the access method and control method designed in this paper, the battery storage system can reduce the maximum fault current from 13.92 times the rated current to 1.46 times the rated current in the discharged state during grid-connected operation, and can control the fault current to be stable at about 1.15 times the rated current. Therefore, this scheme has good fault current control effect and good rapid automatic recovery capability for transient faults.

### 4.1.2 Charging State

Assume that the DC microgrid is in grid-connected operation before the fault, and the battery storage system is charged at a constant power of 100kW and the charging pile is charged at full power. The
voltage and current waveforms of the battery storage system before and after the occurrence of inter-pole short circuit fault $f_1$ shown in Fig. 6 are shown in Fig. 10 and Fig. 11. The switching states of switching devices $S_1$ and $S_2$ before and after fault are shown in Fig. 12.

As can be seen from the above figure, when the battery energy storage system is connected to the DC microgrid through a Boost DC/DC, the inter-polar voltage of the battery storage system continues to drop after the fault occurs, and the fault current rises rapidly. The inter-pole voltage drops to about 0.35kV after 100ms and the fault current rises to a maximum value of 3.71kA after 100ms, which is about 14.27 times the rated operating current. At this point, the DC/DC starts the blocking protection and the storage battery discharges to the fault point via the diode. The fault is cleared after a duration of 0.1s, the inter-pole voltage of the battery storage system rises rapidly and the fault current falls rapidly. The inter-polar voltage rises to the maximum value of 1.91kV after 75ms of fault clearing, and then recovers to 0.75kV after about 70ms of oscillation; the fault current is restored to 0.13kA after 200ms oscillation.

When the Buck DC/DC with the fault current control strategy is used to access the energy storage system, after the inter-pole fault occurs, the inter-pole voltage of the battery storage system drops rapidly and the fault current rises rapidly. The inter-pole voltage drops to about 0.1kV after about 21ms, and the Buck DC/DC switches to the current control mode. During the fault, the maximum fault current is 0.36kA, which is about 1.38 times of the rated operating current, with a duration of about 0.5ms. About 15ms after the $f_1$ fault occurs, the fault current is controlled at a set value of about 0.3kA. After 0.1s, the fault is cleared and the Buck DC/DC switches to power control mode, the inter-pole voltage of the battery storage system rises and the fault current falls. The inter-pole voltage rises to 0.7kV after about 15ms and recovers to 0.75kV after about 65ms; the fault current recovers to 0.13kA after 60ms oscillation.

It can be seen that under the access method and control method designed in this paper, the battery storage system can reduce the maximum fault current from 14.27 times the rated current to 1.38 times the rated current in the charged state during grid-connected operation, and can control the fault current to be stable at about 1.15 times the rated current. Therefore, this scheme has good fault current control effect and good rapid automatic recovery capability for transient faults.

### 4.2 Off-grid Operation

When the grid-connected switch is disconnected, the DC microgrid is in off-grid operation. The battery storage system adopts voltage control during normal operation, and adopts current control under fault conditions to control the charging pile to operate at reduced power, so that the load can operate at rated power.

Assume that the DC microgrid is in off-grid operation before the fault, and the battery storage system controls the DC microgrid grid-side voltage to be stable at 0.75kV. The charging pile is charging at 60kW. The voltage and current waveforms of the battery storage system before and after the occurrence of inter-pole short circuit fault $f_1$ shown in Fig. 6 are shown in Fig. 13 and Fig. 14. The switching states of switching devices $S_1$ and $S_2$ before and after fault are shown in Fig. 15.
As can be seen from the above figure, when the battery energy storage system is connected to the DC microgrid through a Boost DC/DC, the inter-polar voltage of the battery storage system gradually decreases after the fault occurs, and the fault current rises rapidly, the inter-polar voltage drops to about 0.31kV after 100ms; the fault current rises to the maximum value of 4.82kA after 100ms, which is about 18.54 times of the rated system current. At this point, the DC/DC starts the blocking protection and the storage battery discharges to the fault point via the diode. The fault is cleared after a duration of 0.1s, the inter-polar voltage of the battery storage system rises rapidly and the fault current falls rapidly. The inter-polar voltage rises to the maximum value of 1.67kV after 75ms of fault clearing, and then recovers to 0.68kV after about 65ms of oscillation; the fault current is restored to 0.19kA after 41ms oscillation.

When the Buck DC/DC with the fault current control strategy is used to access the energy storage system, after the inter-pole fault occurs, the inter-pole voltage of the battery storage system drops rapidly and the fault current rises rapidly. The inter-pole voltage drops to 0kV after 50ms, and the Buck DC/DC switches to the current control mode. During the fault, the maximum fault current is 0.39kA, which is about 1.5 times of the rated operating current, with a duration of about 0.5ms. About 40ms after the f1 fault occurs, the fault current is controlled at the set value of about 0.3kA. The fault is cleared after a duration of 0.1s, the Buck DC/DC is switched to constant voltage control mode. The inter-pole voltage rises rapidly and the fault current falls rapidly. The inter-pole voltage rises to 0.7kV after about 3ms and recovers to 0.75kV after about 30ms; the fault current recovers to 0.19kA after 75ms oscillation.

It can be seen that with the above access method and control method, the off-grid battery storage system can also have good fault current control effect. The maximum fault current is reduced from 18.54 times the rated current to 1.5 times the rated current, and the fault current can be controlled to be stable at about 1.15 times the rated current. Besides, it has good automatic recovery capability for transient faults.

5 Conclusion

This paper proposes a fault current control method based on the battery storage system access scheme and without additional current limiting devices. In the event of a short-circuit fault, the current-limiting control strategy is immediately activated to significantly reduce the rate of rise of the fault current and control it at the set value. The effectiveness of the method is further demonstrated by simulating the DC microgrid with PSCAD/EMTDC. The simulation results under DC short-circuit fault show that, compared with the current common control strategies, the fault current limiting method proposed in this paper can reduce the charging and discharging fault currents of the energy storage system from 3.62 kA and 3.71 kA to 0.3 kA when grid-connected, and from 4.82 kA to 0.3 kA when off-grid. In addition, the set value of fault current is flexible and controllable, which makes it better compatible with DC circuit breakers and makes DC microgrid protection simpler and easier to achieve cascade coordination. In turn, it verifies the feasibility and effectiveness of the control method proposed in this paper, which has obvious engineering application value and practical significance.

Declarations
Author contributions


Founding

This work was supported by State Key Laboratory of HVDC, grant number SKLHVDC-2021-KF-15.

Data availability

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Competing interests

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

References


**Figures**

![Figure 1](attachment:image.png)

**Figure 1**

Equivalent circuit of battery energy storage system.
Figure 2

Schematic diagram of access mode structure of energy storage system with fault current control function.

Figure 3

Typical buck DC/DC structure diagram
Figure 4

Flow chart of control process.
Figure 5

Control block diagram of battery energy storage system.
Figure 6

Structure diagram of DC microgrid

Figure 7

Voltage waveform diagram of grid-connected battery energy storage system in discharge state
**Figure 8**

Current waveform diagram of grid-connected battery energy storage system in discharge state

**Figure 9**

The switching states of switching devices
Figure 10

Voltage waveform diagram of charging state of grid-connected battery energy storage system

Figure 11

Current waveform diagram of charging state of grid-connected battery energy storage system
Figure 12

The switching states of switching devices
Figure 13

Voltage waveform diagram of off-grid battery energy storage system
Figure 14

Current waveform diagram of off-grid battery energy storage system
Figure 15

The switching states of switching devices