Research on Cascade Utilization and Reconfiguration of Decommissioned Power Batteries based on Flexible Control Technology

Yongqiang Zheng¹, Hejie Xue², Fengjuan Wang³,* and Dingyuan Chang⁴

1 Senior R&d Engineer, Affiliation, Zhuhai, China
2 Intermediate R&D Engineer, Affiliation, Zhuhai, China
3 Assistant R&d Engineer, Affiliation, Zhuhai, China
4 Junior R&D Engineer, Affiliation, Zhuhai, China
¹E-mail: watt_ky@163.com; *E-mail: 1776316595@qq.com.

Abstract: With the development and popularization of electric vehicles, the number of decommissioned power batteries increases progressively year after year, urgently requiring the cascade utilization and resource regeneration. In view of the difficulties in assembling decommissioned power batteries, the inflexible system access, and the difficulty in improving the availability of decommissioned batteries, based on the flexible control technology, this paper proposes the architecture of common DC bus for multiple bidirectional DC/DC converters and its energy control technology. Through the supporting source of the DC bus voltage, the coordinated control of the common DC bus architecture is realized. According to the proportion of the capacity of each battery pack, the output depth of each is balanced to realize the energy control between the multiple bidirectional DC/DC converters. In this paper, the multi-port flexible access devices based on flexible control technology is summarized as the research object, the reconfiguration and control strategy of multi-type and multi-cascade decommissioned power batteries are studied, and the prospect of the cascade utilization of decommissioned power batteries is forecasted.

1. Introduction

1.1. Research background and significance
With the vigorous development of the electric vehicle industry in China [1], the installed capacity of the power batteries used in the electric vehicles increases year by year. By 2019, the stock of electric vehicles in China had reached 3.1 million. The large-scale decommissioning of the power batteries launched on the market at the early stage is coming. It is estimated that, by 2025, the decommissioned power batteries will reach 730,000 tons. Unlike the lead-acid batteries characterized by rather high recycling rate, the decommissioned power batteries are faced with such problems as high disassembly and recycling cost and low utilization ratio [2]. How to make full use of the decommissioned power batteries to reduce the waste of resources is a problem to be settled urgently.

At present, there are two main ways for the recycling and utilization of decommissioned power batteries: the first is disassembly and recycling [3-4], but the pretreatment, extraction of metallic oxides, metal recovery, and other steps are complex and expensive; the second is the method for decommissioned power batteries with a capacity of 70% ~ 80% [5-6] , i.e. the cascade utilization used in the fields as power energy storage [7-8] and standby power supply of base station [9]. The cascade
utilization has its unique advantages in environmental protection, resource saving, and some other aspects [10].
However, the decommissioned power batteries are faced with problems such as low availability, difficult configuration, and inflexible system access, which increases the difficulty of the reconfiguration and recycling of cascade utilization and makes it difficult to realize the efficient utilization of the decommissioned power batteries.
In order to solve the problems in the large-scale utilization of the decommissioned power batteries, it is urgently needed to conduct researches of the system-level reconfiguration technology and the energy control technology for realizing high flexibility and high availability. This paper proposes the flexible access and control technology based on the multi-branch topology, which is used together with the local control layer in the control model of energy storage system to improve the control granularity of the energy storage system, thus solving the problems such as difficult reconfiguration and low availability of the decommissioned power batteries, and making it possible for the cascade utilization of the energy storage system to accept the common access of multiple cluster of decommissioned power batteries of different types, brands, cascades, and voltage classes. To sum up, strengthening the research on the system-level reconfiguration and energy control of the cascade utilization can improve the overall utilization efficiency of the energy storage system, realize the multi-type, multi-scenario, and large-scale application of energy storage system, and better boost the cascade utilization of decommissioned power batteries and the rapid development of power energy storage.

1.2. Development status quo at home and abroad
The researches on cascade utilization of decommissioned batteries are mainly divided into three types. The first type is the research conducted by the electric vehicle manufacturers such as BYD and BAIC BJEV. For example, BYD builds the 15 MW ~ 30 MW power stations based on cascade utilization in its factories. The second type is the research conducted by the companies such as China Tower Corporation Limited and grid companies. For example, China Tower Corporation Limited started the trials of cascade utilization of batteries in the standby power supplies of base stations in 2015, and Guangzhou Power Supply Bureau of China Southern Power Grid put the first cascade energy storage system into operation in 2019, which solved the problems of the power grid such as high load and trip caused by the daily power utilization of the residents. The third type is the research conducted by the companies engaged in the energy storage technology. For example, Global Mainstream Dynamic Energy Technology Ltd. built a power station based on cascade utilization in Liyang City, Jiangsu Province, which realized the peak-load shifting.
In the foreign countries, some automobile manufacturers have conducted the researches on the cascade utilization of batteries. For example, General Motors Corporation cooperated with ABB to use five cascade battery cluster to construct an energy storing device as short-time power supply for ordinary families, and Bayerische Flugzeugwerke AG utilized the decommissioned batteries to realize the partial energy storage and supply for Leipzig plant in 2017.
To sum up, the present researches on cascade utilization of decommissioned power batteries at home and abroad are still at an early stage, there are rather few relevant researches on the scale utilization of large-scale energy storage system, and it is difficult to solve the problems such as difficult scale configuration and inadequate fine control capability, making it difficult to conduct the large-scale cascade utilization of decommissioned power batteries.

2. Flexible reconfiguration technology
Based on the flexible control technology, the multi-port flexible access devices with multi-branch common DC bus topology are used to realize the system-level reconfiguration of decommissioned power batteries, and the researches on DC bus voltage control strategy are conducted to improve the stability of DC bus voltage, thus realizing the energy storage system with high flexibility and under multi-branch cascade utilization.
2.1. Multi-branch topology

Decommissioned power batteries come from different manufacturers and have diversified brands, cascades, and capacities, making it difficult to configure the decommissioned power batteries. The battery cluster configured in a group may have different voltage classes and capacities. If the commonly used direct multi-cluster parallel structure is adopted, there will be a ring current problem between different battery cluster, as illustrated in Figure 1(a). If the AC/DC converters with rather small capacity are configured, it is required to arrange rather many AC/DC converters in parallel on the AC side, which will easily cause the resonance on the AC end, as illustrated in Figure 1(b). Therefore, the design of multi-port flexible access devices with high flexibility and high availability is the key link to the scale utilization of decommissioned power batteries.

![Figure 1. Common energy storage system topology.](image1)

This paper proposes the multi-branch topology based on the common DC bus for multiple bidirectional DC/DC converters, as illustrated in Figure 2. In the multi-branch topology, each group of energy storage units are equipped with several bidirectional DC/DC converters. Such bidirectional DC/DC converters can make it possible to access the decommissioned power batteries of different types, brands, cascades, and voltage classes to the energy storage system and to form the battery cluster of different voltage classes and different cascades, thus avoiding the ring current and resonance problems among the battery cluster.

![Figure 2. Multi-branch topology based on common DC bus for multiple bidirectional DC/DC converters.](image2)
The multi-port flexible access devices based on the common DC bus for multiple bidirectional DC/DC converters can solve the flexible access problem of decommissioned power batteries, utilize the more flexible reconfiguration capability, and connect new energy equipment, charging stations, and some other equipment to the energy storage system in the DC form, forming a DC micro-grid with lower energy conversion loss. More importantly, in the energy storage system with multi-branch topology and under cascade utilization, it is possible to cut off the energy storage unit in abnormal operation without overall shutdown, thus increasing the equipment operation time and reducing the losses caused by equipment shutdown.

2.2. DC bus voltage control strategy

In the multi-branch common DC bus topology, the stability of the DC bus voltage is crucial. The bidirectional flow of energy can be realized in both AC/DC converters and DC/DC converters. Therefore, if the coordination and control are not conducted efficiently, there will be a ring current among the bidirectional units, and the systems will be out of control. In order to avoid this problem, this paper proposes a strategy to determine the supporting source of the DC bus voltage based on the grid-connected operation and off-grid operation status of the energy storage system, thus maintaining the stability of the DC bus voltage, and avoiding the voltage drop of DC bus and the ring current among different battery cluster. The flow of the DC bus voltage control strategy is illustrated in Figure 3.

Figure 3. Flow diagram of DC bus voltage control strategy.

When the system starts up normally, the bidirectional DC/DC converter establishes the DC bus. After the bidirectional AC/DC converter starts up normally, the supporting source of the DC bus voltage is determined according to the current operation mode of the system.

1) In the grid-connected status, the DC bus control is switched to the mode in which the bidirectional AC/DC converter provides the support for DC bus voltage and plays the role of constant voltage source for the bidirectional output. The bidirectional DC/DC converter operates in the charging/discharging mode as required. When the DC bus voltage rises/drops, based on the DC bus voltage droop control, the bidirectional AC/DC converter automatically adjusts the energy
output/input, thus maintaining the stability of DC bus voltage.

(2) In the off-grid status, since the bidirectional AC/DC converter operates in a unidirectional mode, it cannot provide the energy required for supporting the DC bus voltage. Therefore, according to the State of Health (SOH) of individual battery cluster, the battery cluster with the optimal SOH is selected, and the DC/DC converter configured for such battery cluster acts as the “master” DC/DC converter to provide the support for DC bus voltage. The “slave” DC/DC converter operates in the charging/discharging mode as required. When the DC bus voltage rises/drops, based on the DC bus voltage droop control, the “master” bidirectional DC/DC converter automatically adjusts the energy output/input, thus maintaining the stability of DC bus voltage. Although this method solves the problem of DC bus voltage stability in the off-grid status, it is only applicable to the conditions with rather small fluctuation of DC bus voltage or load because of the restrictions of the rated power of bidirectional DC/DC converter and the charging discharging capacity of such battery cluster.

To sum up, this paper proposes the multi-branch topology based on the common DC bus for multiple bidirectional DC/DC converters, which realizes the system-level flexible reconfiguration of multi-type and multi-cascade decommissioned power batteries, solves the problems of difficult configuration and inflexible access related to the cascade utilization of the decommissioned power batteries, and improves the availability of decommissioned power batteries. Meanwhile, in order to avoid the out-of-control of the system caused by the unstable DC bus voltage, according to the grid-connected/off-grid operation status of the system, different supporting sources of the DC bus voltage and control strategies are selected to ensure the stability of the DC bus voltage.

3. Local energy control technology

Based on the local control layer in the control model of energy storage system, the local energy control technology is used to realize the system control and energy management, propose the new control and operation strategy, and realize the simultaneous decommissioning goals of multi-type and multi-cascade decommissioned power batteries.

3.1. Management and control of energy storage system

When there are multiple battery cluster in an energy storage system, it is difficult to use the conventional control methods to achieve the energy coordination and control among such battery cluster since such battery cluster are different. Existing cloud management methods pay more attention to the remote centralized control on a large time scale. For cascade utilization scenarios, the control strategies are not flexible enough, and the system response time is limited because of the limited communication channels and bandwidths, making it difficult to meet the needs of the practical applications. Based on this, this paper proposes to add a local control layer in the control model of energy storage system and provides local energy control strategy to energy management, coordination, and control of the energy storage system using the multi-branch topology, as illustrated in Figure 4. Through the coordination and control of the bidirectional AC/DC converters and the bidirectional DC/DC converters, the local energy storage controller realizes the fine energy control of the energy storage system under cascade utilization.

The local energy storage controller, as the comprehensive control center of the energy storage system under cascade utilization, performs the dynamic power distribution according to the preset energy management strategies when receiving the dispatch command, and conducts the local real-time optimization of the energy management strategies and improve the overall operation efficiency of the system according to the real-time status of the system. Meanwhile, the local energy storage controller can realize the real-time monitoring of the system operating status through the comprehensive monitoring of the battery management units, the energy storage converters (AC/DC converters and DC/DC converters), and other auxiliary equipment, upload the data to the dispatching layer, and ensure that the energy storage system is in the good working conditions. In addition, the local energy storage controller can preset the communication protocols for different upstream and downstream manufacturers, realize the external uniform data interfaces, solve the problems of difficult access and control of the energy storage system, and realize the “plug and play”.
3.2. Operation strategy for simultaneous decommissioning

At present, the general practice is to equally distribute the output power of individual battery cluster. The reason is that the reconfiguration method causes the differences among the battery cluster. The battery cluster may have inconsistency in capacities and cascades, causing the difference in the output capacities. When the battery cluster have the same output power, such difference may cause the excessive proportion of the current output of the battery cluster with lower capacity in the total capacity of the system. If things continue this way, the degree of deterioration of such battery cluster will increase, causing the early decommissioning of such battery cluster. Based on the difference of nominal capacity and State of Charge (SOC), during the power distribution, the new control strategy is proposed, that is, the output power will be determined according to the capacities of individual battery cluster, the battery cluster with rather low residual capacity will have low output power, and the battery cluster with rather high residual capacity will have corresponding increased output power:

If we suppose the nominal capacity of the battery cluster as $C_i$, the residual capacity as $Q_i$, and the SOC as $SOC_i$, the relationship between total capacity $Q_{sum}$ and $Q_i$ of the system is as follows:

$$Q_i = C_i \times SOC_i \quad (1)$$

$$Q_{sum} = \sum_{i=1}^{n} Q_i \quad (2)$$

According to Formula (1.2), the formula for calculating the proportionality coefficient $K_i$ of the residual capacity of the battery cluster $i$ in the current total capacity of the system is as follows:

$$K_i = \frac{Q_i}{Q_{sum}} \quad (3)$$

Therefore, the relationship between the output power $P_i$ distributed to a battery cluster and the total demand power $P_{total}$ of the system is as follows:

$$P_i = K_i \times P_{total} \quad (4)$$

It can be seen from Formula (1.4) that the actual distributed output power of a battery cluster is in direct proportion to $K_i$, that is, the higher the residual capacity of the battery cluster, the higher the output power distributed to the battery cluster. This strategy effectively balances the output capacities of individual battery cluster, makes the depth of discharge of individual battery cluster basically the same, minimizes the inconsistency of battery cluster caused by the mode of operation, and realizes the
simultaneous decommissioning of battery cluster in the energy storage system under cascade utilization.

To sum up, the local energy storage controller, as the control unit of the energy storage system, plays a vital role in the system energy control and the energy management strategy optimization. Because of the application of local energy storage controller, different types of battery cluster can seamlessly access to the energy storage system, realizing the coordinated management of multi-branch flexible topology and the control of the energy storage system.

4. Conclusions

Based on the problems of low availability, difficult configuration, and inflexible system access in the cascade utilization of decommissioned power batteries, this paper proposes the flexible access technology for the system-level reconfiguration and the local control technology for the energy storage system. Multiple bidirectional DC/DC converters and common DC bus form the multi-branch flexible access topology to realize the flexible access of batteries of different cascades, capacities, and brands and to improve the availability of decommissioned power batteries. In order to improve the energy management and control capability of the multi-branch energy storage system, the local energy storage control technology is proposed, and the energy management strategy for multi-branch simultaneous decommissioning is adopted to realize the coordination and control of multi-branch energy storage system. To sum up, the energy storage system composed of multi-branch flexible access topology and local energy storage controller has the advantages of high reliability, high flexibility, and easy capacity expansion. Therefore, it can meet the requirements for diversified application scenarios and large-scale applications of energy storage system, and promote the rapid development of the cascade utilization of decommissioned power batteries and the power energy storage.

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