Research on Inconsistency of Echelon-Use Batteries and Flexible Group Energy Storage Converter

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Abstract. In this paper, fifty-five echelon-use batteries were tested and the capacity inconsistency of the batteries are analyzed. The flexible group technology of batteries is studied, and the characteristics and application scenarios of different topologies of energy storage converters are analyzed. Aiming at the problems of high current stress, high loss and high cost in full power control mode, a new energy storage converter topology with integrated primary power control is proposed, and the control method of the topology structure is given. The modeling and Simulation of MATLAB proves that the topology can realize independent control of the charging and discharging current of battery module under highly integrated conditions.

1. Introduction

Because of its energy-saving and environmental protection, electric vehicles have become the main direction of the future development of the automotive industry. With the commercialization of new energy vehicles will be further commercialized, in the next few years a large number of vehicle power batteries will reach their service life and be eliminated, so it is necessary to make rational use of retired electric vehicle batteries.

Retired electric vehicle batteries are commonly echelon-used in energy storage systems for distributed energy access and other occasions [1-2]. However, the consistency of the echelon-use batteries is poor, and the life of the batteries is greatly shortened due to the interaction of traditional batteries. Flexible grouping technology is an effective way to solve the inconsistency of batteries in cascade utilization [3-5]. Flexible group energy storage system can control charge and discharge current independently according to each battery module, which can reduce the requirement of battery capacity consistency and the cost of regrouping, and improve the utilization rate of battery capacity while meeting the requirements of energy storage system.

In order to solve the problem of inconsistent capacity of returned batteries, the capacity tests of 55 batteries with cascade utilization were carried out. The characteristics and application scenarios of the topology structure of cascade battery flexible group energy storage converter are studied. The topology of the original integrated partial power control energy storage converter is proposed, and the control method of the topology is given. The effectiveness of the energy storage converter is verified by MATLAB modeling and simulation.
2. Capacity inconsistency analysis of Echelon-use batteries

2.1. Capacity test of echelon-use batteries
In this paper, a certain type of retired electric vehicle batteries from an electric bus have been used for more than three years. The nominal voltage/capacity of single battery is 3.2V/20Ah, the upper limit of voltage is 3.65V, the lower limit of voltage is 2V, the specifications of modules are 4 series and 8 parallel, and the nominal voltage/capacity of single module is 12.8V/160Ah. Charging and discharging are carried out at 0.1C. The voltage of any battery module reaches the upper/lower limit of the voltage and stops charging and discharging.

55 battery modules are grouped into 11 groups according to capacity approximation, and the results of capacity testing are shown in Table 1.

| Group | Module1     | Module2     | Module3     | Module4     | Module5     |
|-------|-------------|-------------|-------------|-------------|-------------|
| 1     | 121.560     | 125.022     | 126.955     | 126.957     | 127.265     |
| 2     | 127.962     | 128.234     | 128.475     | 129.209     | 129.770     |
| 3     | 131.286     | 131.460     | 132.063     | 133.656     | 134.874     |
| 4     | 134.919     | 135.279     | 135.693     | 135.919     | 136.019     |
| 5     | 136.063     | 136.073     | 136.090     | 136.529     | 136.695     |
| 6     | 136.761     | 137.237     | 137.605     | 137.699     | 137.900     |
| 7     | 138.265     | 138.297     | 138.326     | 138.712     | 138.786     |
| 8     | 138.851     | 139.260     | 139.460     | 139.595     | 139.827     |
| 9     | 139.984     | 140.030     | 140.182     | 140.337     | 140.528     |
| 10    | 140.690     | 140.804     | 140.853     | 140.992     | 141.014     |
| 11    | 141.101     | 141.897     | 142.006     | 142.814     | 144.214     |

2.2. Analysis of capacity inconsistency between battery modules
There are 55 battery modules in this test. After a long period of use, the battery is aging and capacity declines. The inconsistency of the battery manufacturing process leads to the difference in the initial characteristics of the battery. The difference in the temperature, vibration level and connection between the batteries makes the battery more inconsistent. The inconsistency of battery modules can be obtained by measuring capacity.

The rated capacity of batteries is 160Ah, the average capacity of cascade batteries is 136.146 Ah, and the capacity decline rate is 14.91%. The capacity of batteries after the decline varies greatly. The maximum available capacity of batteries is 144.214Ah, the minimum available capacity of batteries is 121.56Ah and the range of battery capacity is 22.654Ah. The capacity scatter plot, capacity distribution and fitted statistical distribution curves of batteries module for cascade utilization are shown in Figure 1 and 2, respectively. Combining the two graphs, it can be seen that the capacity of battery modules is basically distributed between 125 and 145 Ah, and only one module's capacity falls within the range of 125 Ah. Generally speaking, the distribution of battery module's capacity is relatively centralized. The non-parametric test of the capacity data of 55 battery modules shows that the capacity basically obeys the normal distribution.
3. Research on flexible group energy storage converter

Traditional energy storage system grouping technology is to connect series and parallel batteries to the grid through high-power converters. This grouping method has poor redundancy and obvious short board effect. As can be seen from the above section, after long-term use of batteries, there are obvious differences among batteries. The difference of battery capacity and initial SOC seriously affects the capacity and energy utilization of batteries, and reduces the service life of batteries.

In order to solve this problem, the flexible grouping technology is studied in this paper. Large-scale series-parallel monomer batteries are decomposed into several low-voltage battery modules to form a separate energy storage module. Each module is connected to the grid by flexible group energy storage converter [3-6]. Balanced control is carried out for battery capacity and SOC status within the module, which improves capacity utilization.

3.1. H-bridge cascaded flexible group energy storage converter

Figure 3 is the topology of H-bridge cascaded flexible group energy storage converter. The characteristic of this topology is three-phase AC output structure. Each phase is cascaded by n identical energy storage sub-modules. The DC side of each sub-module is an independent battery module. After the respective H-bridge DC-AC converter, the low voltage AC voltage is generated.
After the modules are connected in series, the high voltage AC voltage required for grid connection is generated. The filter is directly connected to the three-phase AC network.

The topology can independently control the charging and discharging current of the module. Cascade mode can reduce the switching frequency and switching loss. The structure of the system is flexible. It can be directly connected to the AC network to facilitate large-scale centralized energy storage. But its low-voltage application efficiency is low, the cost increases with the total power, the number of modules is large, there are three-phase unbalance problems, and the control is complex. Therefore, H-bridge cascade energy storage system is suitable for high voltage, large capacity, complex battery type, large differential current, high reliability requirements, large-scale centralized energy storage applications.

![Figure 3. H-bridge cascaded flexible group energy storage converter.](image)

### 3.2. Modular multilevel flexible group energy storage converter

Figure 4 is the topology of modular multilevel flexible group energy storage converter, which consists of three phase clusters. The two ends of the phase cluster are connected with the common DC bus, and the midpoint of the phase cluster is connected with the AC terminal, which can connect the AC load or the AC network. Each phase cluster consists of two upper and lower bridge arms, inductance of bridge arms and equivalent impedance of line in series. Each bridge arm contains n sub-modules. Each sub-module consists of a half-bridge structure, a supporting capacitor, a bypass switch and a battery module.

This energy storage system can control the current of battery module independently. Its structure can be connected to DC and AC power grids at the same time, realize three-port energy transfer, effectively reduce cost, and have certain fault redundancy function, high reliability. However, its cost and volume increase with the total power. The current of the sub-module contains various frequency components, which makes the power devices lose a lot, and there are circulation problems, and the control strategy is complex. Therefore, modular multilevel battery energy storage system is suitable...
for high voltage, large capacity, high reliability requirements, AC/DC hybrid microgrid, flexible DC transmission and energy storage applications.

Figure 4. Modular multilevel flexible group energy storage converter.

3.3. DC-DC cascaded flexible group energy storage converter
Figure 5 is the topology of DC-DC cascade flexible group energy storage converter. The left side of the topology is composed of $n$ identical DC-DC energy storage modules, which can be connected to the intermediate DC bus or to the AC network through the traditional grid-connected converter. The input side of each energy storage module is an independent battery module. After parallel filter capacitor is connected to DC-DC converter, the controllable DC-DC voltage can be generated. The DC-DC converter can be in the form of Buck-Boost circuit in the figure or other DC-DC converters.

This topology can control module current independently, with fewer switches, simple control and high reliability. Because of the cascade structure, the switch frequency is low, the efficiency is high, and the fault redundancy function can be realized. However, the absolute loss of battery charge and discharge power is large through each conversion module, and its cost and volume increase with the total power. Therefore, this energy storage system is suitable for medium power, medium voltage level, high reliability and redundancy requirements, and complex battery types.
4. Modular independent control energy storage converter with primary integrated

4.1. Topology
The three energy storage systems mentioned above have relatively simple structure and high fault redundancy, which can realize independent control of modules and effectively improve the utilization of battery energy. However, the above three topologies, each module converter for full power control mode, resulting in greater current stress, loss, cost increases accordingly.

From the second section of this paper, it can be seen that there are differences among the battery modules, but within a certain range, it is not necessary to control all the charging and discharging currents independently, only part of the differential current control is needed to achieve the purpose of improving the battery energy utilization. Partial power control has less absolute loss and lower cost than full power control. According to the difference of battery capacity, it can be designed as 10%-20% of the main current. In this paper, a modular independent control energy storage converter with primary integrated is proposed, as shown in Figure 6.

In the middle part of the topology, the batteries are directly connected in series. On the right side, the power control system (PCS) is the main converter. On the left side, the multi-module DC-DC auxiliary converter is the main converter. The battery module interacts with the power grid through PCS, realizes the bidirectional flow of energy between the battery and the grid side, and achieves the functions of "peak shaving and valley filling". The middle part of the energy storage system is composed of cascade batteries connected in series, which can be used as the basis for balanced control of the whole energy storage system through the combination of voltage and current acquisition, SOC estimation and protection control. Left auxiliary converter can be divided into primary side winding converter and multiple secondary side winding converter. One winding is integrated on the primary side and connected to the DC side through the power electronic converter. The secondary side is composed of several sub-conversion modules.

The topology has obvious modularization advantages. The auxiliary converter can be used in many traditional energy storage systems to adjust the total voltage of DC side by changing the number of modules of secondary windings. The total current of the battery is controlled by independent control of the differential current of each module. It not only reduces the cost and loss obviously, but also has low control power and absolute loss, high efficiency, higher utilization rate of battery energy, and
prolongs the service life of battery. It is suitable for medium and high power and medium voltage applications.

Figure 6. Modular independent control energy storage converter with primary integrated.

4.2. Control method

From the previous analysis, it can be seen that there is a significant difference between the capacity of battery modules and SOC. In order to make each battery module work in the best state, it is necessary to control its current independently. When considering the control strategy of the whole energy storage system, the battery module, PCS and auxiliary converter are integrated. The control block diagram is shown in Figure 7 below.

The control method of the modular energy storage system with primary integrated is as follows:

- PCS charges and discharges series batteries according to grid side demand, and its current value is $I_{M1}$
- After $I_{M1}$ superimposes the primary current $I_{P}$, it acts as the main circuit current $I_{M}$ of the series battery pack. After $I_M$ superimposes the differential current $I$ of the secondary modules of the assist converter, the total current $I_B$ of the different battery modules will be the total current $I_B$ of the different battery modules
- Battery Management System (BMS) estimates the state of charge (SOC) of each module by collecting current $I_B$ and voltage $U$
- The errors of SOC and average SOC of each module are closed-loop controlled respectively, and the output results are taken as the given value of differential current
- After calculating the error between the given value of differential current and the sampled value, the relative phase-shifting angle of each module can be given through current closed-loop control, so as to control the phase-shifting pulse. The relative phase-shifting angle of the pulse determines the magnitude and positive or negative of the transmission power and differential current of the module, thus forming a double closed-loop control
In summary, after considering the capacity difference between each battery module and SOC, the energy storage system realizes the independent control of the total current of the battery module by controlling the 10%-20% differential current in the main current of the battery. After the positive and negative power of the secondary module is offset, the original power can be neglected. The total control power of the auxiliary converter is small, the absolute loss is small, most of the power is borne by PCS, and the efficiency of the whole machine is low. It is high and easy to control. It can realize grid-connected AC side.

4.3. Simulation verification
This project is based on the modular energy storage system with primary integrated. Matlab/Simulink is used to verify the principle. As shown in Figure 8, When the module 1 changes from the discharge mode to the charging mode, the original side current, the average current and the differential current are shown in Figure 8 below. The new steady state value of the original winding and module 1 current can be obtained, and the remaining modules remain independent control. The independent control of the topology is proved. At the same time, compared with the traditional full power modular control energy storage system, the control current of the system is small and the loss is small.
5. Conclusion
By controlling each power converter module, the flexible group energy storage converter described in this paper realizes the independent control of the charging and discharging current of the battery module and improves the usable energy of the battery pack. The first three topologies belong to the full-power independent control system. They are relatively simple, high fault redundancy, high reliability and large independent regulation range. However, the loss, cost and volume of the converter also increase. They are suitable for applications with high voltage, large capacity and large battery difference. The modular independent control energy storage converter with primary integrated proposed in this paper belongs to a part of power independent control system. It realizes module separation and controls the differential current of the battery module independently. It has low cost and small volume. The original power is the sum of all the secondary edges. After the positive and negative power offset, the original power can be neglected, and the efficiency is high. It is suitable for the battery energy storage system of medium and high power and medium voltage level.

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