White Paper on Active Current Balancing and Intelligent Voltage Balancing of Lithium-ion Batteries

Data Center Facility White Paper 303

HUAWEI

Contents

Preface

Compared with lead-acid batteries, lithium-ion batteries have many advantages, such as high energy density, small size, light weight, many cycles, a long service life, and environment-friendliness. Especially with the rapid development of electric vehicles and mobile phones, lithium-ion batteries are seeing wide commercial application, which drives down lithium-ion battery prices. A large number of data centers have begun to use lithium-ion batteries instead of traditional lead-acid batteries, reducing the footprint and cost through the life cycle of data centers.

Although lithium-ion batteries have many advantages, challenges exist in actual application. This paper analyzes and describes voltage balancing management of lithium-ion battery cells connected in series, intelligent voltage balancing of modules, and active current balancing for battery strings connected in parallel, and provides the corresponding solutions for reference.

1. Features of Data Center Battery Systems

The battery system in a data center has the following features:

- **High voltage:**

  The **battery voltage typically ranges from 400 V DC to 600 V DC** for a high-power UPS.
  Multiple batteries need to be connected in series. The following uses the 480 V DC battery voltage as an example:
  If 3.2 V cells (LFP) are adopted, 150 cells need to be connected in series.
  High cell consistency is required for serial connection of cells.

- **High rate:**

  When the active mains supply is abnormal, the bus tie switch switches the power supply to the standby mains supply or start a diesel generator.
  The normal switchover takes only 1 to 2 minutes. During the switchover, batteries are used to supply power.
  The battery backup time ranges from 5 minutes to 15 minutes. The short-time discharge rate must be high.
  The discharge rate ranges from 4C to 12C. To meet the requirement, lithium-ion batteries with high-rate power cells can be deployed instead of using excessive lead-acid batteries.
  The following uses a 500 kW UPS with 15-minute backup power of 512 V DC as an example:
  If 3.2 V/40 Ah LFP cells are adopted, six battery strings (a total of 960 cells) each with 160 cells connected in series need to be connected in parallel.
  Good battery current balancing consistency is required for high-rate discharge.

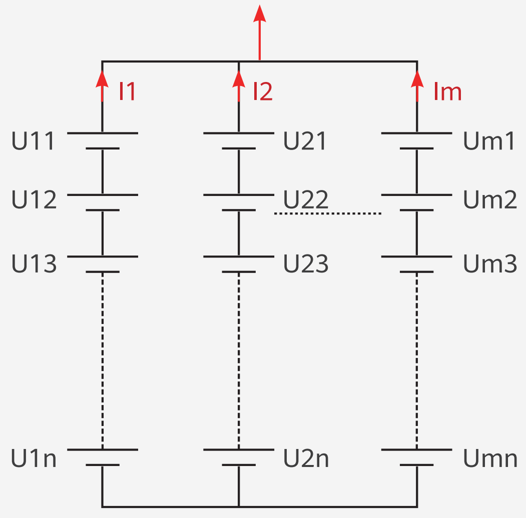


Figure 1-1 Bucket effect of N x M cell configuration

Parallel connection of N strings each with M cells connected in series will cause the bucket effect. The performance of the battery system is determined by the cell with the worst performance.
A single cell affects the entire system. The details are as follows.

1.1 Voltage Balancing in a String of Lithium-ion Batteries Connected in Series

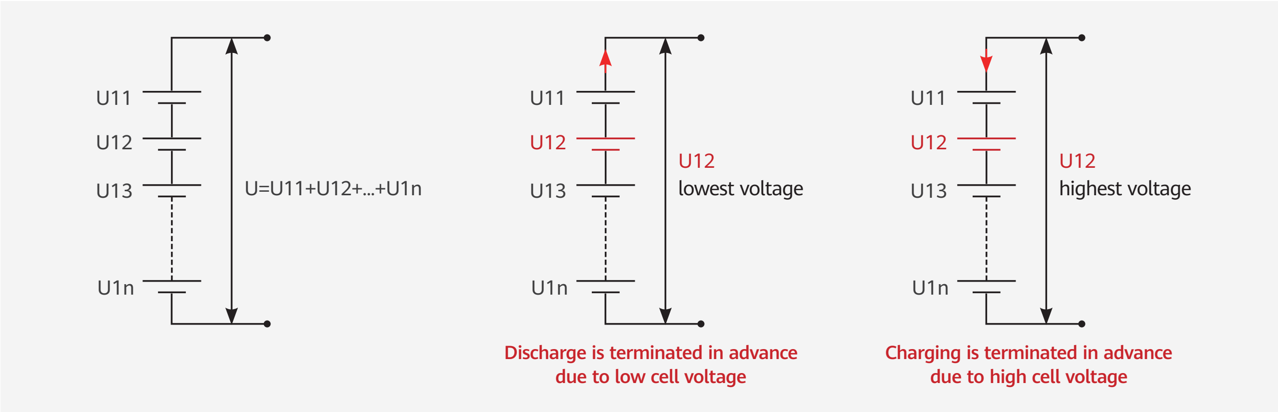


Figure 1-2 Voltage inconsistency in serial connection of cells

The voltage of a single lithium-ion battery cell is low. If 3.2 V LFP cells are adopted, 160 cells need to be connected in series to provide the battery voltage of 512 V DC. The charge and discharge currents (I) of the cells connected in series are the same. Due to cell differences in parameters such as capacity, internal resistance, connection impedance, and initial voltage, the voltage of each cell is different though the charge current is the same. If more cells are connected in series, the differences increase, which causes a gap between cell voltages. The battery management system (BMS) for lithium-ion batteries provides charge and discharge protection for the voltage of each cell. If the voltage of a cell is too high or low, the system will stop charging or discharging earlier, which affects the performance of batteries in serial connection. For example, if the SOH of cell U12 is low and the discharge current is the same, the voltage of the cell decreases to the EOD voltage first during discharging, and the voltages of other cells are higher. To protect cell U12 from being damaged due to overdischarge, the entire battery system needs to stop discharging earlier. In this case, all cells except U12 are not completely discharged, which **wastes the capacity of the entire system. U12 is the shortest stave in the bucket effect of discharge voltage balancing for serial connection**.

Similarly, if the SOH of U12 is low and the charge current is the same, U12 is charged to the full level first during charging. To prevent U12 from being damaged due to overcharge, the entire battery system in series connection has to stop charging earlier. **All cells except U12 are not fully charged, and the capacity of the entire system is insufficient, generating the bucket effect in charge voltage balancing for serial connection**.

1.2 Current Balancing Between Lithium-ion Battery Strings Connected in Parallel

Similar to the bucket effect in voltage balancing for batteries connected in series, the bucket effect exists in current balancing of multiple battery strings connected in parallel. As shown in Figure 3, current imbalance exists between parallel battery strings due to battery parameters (such as SOC, SOH, and internal resistance) discreteness and connection differences (such as cable length). The issue is more severe in capacity expansion scenarios where old and new battery strings are connected in parallel. The **current imbalance between parallel battery strings may reach 20% or even higher**. The current difference can decrease the effective capacity of the parallel system, or even trigger current limiting protection for the battery string with a higher discharge current. For example, when multiple battery strings are connected in parallel, the battery string with a higher current will first reach the EOD level and stop discharging. After the battery string exits from the parallel battery system, all loads are carried by the other battery strings.

The batteries with the highest current in other parallel battery strings will also be stopped earlier, causing the domino effect. The battery string that exits last cannot discharge properly due to overcurrent protection. As a result, the discharge time of the entire parallel battery system cannot meet the design requirements, and the battery system capacity cannot be fully used. To ensure the required discharge time of the system, the problem of insufficient backup time caused by current imbalance has to be resolved by **excessive battery capacity configuration**, which increases the cost and footprint.

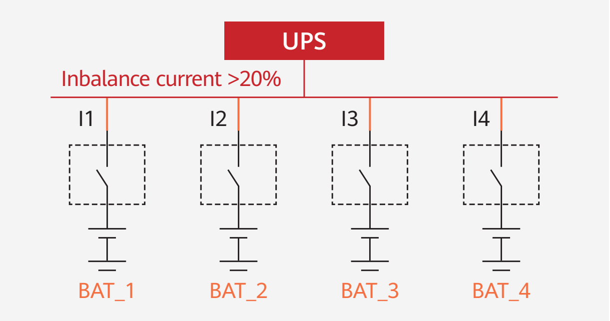
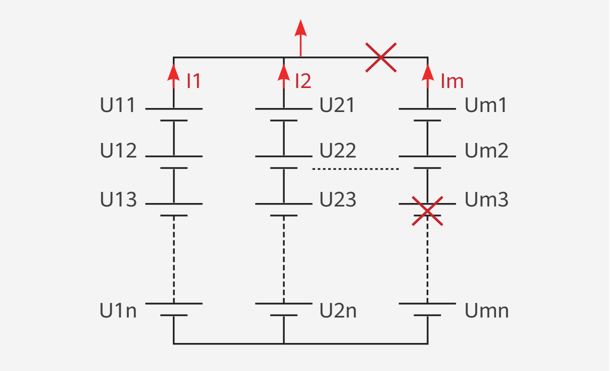


Figure 1-3 Current balancing between multiple battery strings connected in parallel

1.3 Voltage Balancing Between Lithium-ion Battery Strings Connected in Parallel

In actual application scenarios, when multiple battery strings are connected in parallel, the number of batteries in each string must be the same. Otherwise, cross current will occur between the battery strings, which will cause energy wasting or even switch tripping. In data centers, if a single battery is faulty, it cannot be used until being replaced with a spare part. Before the replacement, the battery has to be removed from the system. As a result, the backup time and redundancy of the system are greatly reduced. If the load rate is too high, other battery strings may fail to carry all loads, causing system switch tripping due to overcurrent.



1.4 Summary of Voltage Balancing in a String of Batteries Connected in Series, Current and Voltage Balancing Between Battery Strings Connected in Parallel

To sum up, the problems in voltage and current balancing of batteries connected in series and parallel have the following consequences:

1. **The backup time is shortened:** The equivalent capacity of the entire system decreases due to the bucket effect of batteries connected in series and parallel, and the backup time is shortened. Excessive battery configuration will increase the system cost.
2. **Battery capacity cannot be expanded by phase:** The SOC/SOH of new and old batteries differ greatly. If the new and old batteries are directly connected in parallel, the bucket effect of current balancing will be obvious. Severe current imbalance will cause a failure in the parallel battery system. Therefore, new and old batteries cannot be used together.
3. **If one battery fails, the entire battery string cannot be used:** Strings with different numbers of batteries cannot be connected in parallel. The battery replacement period is long. Before the replacement, the battery cabinet where the faulty battery module is located cannot work, and the entire system has to work with fewer batteries. The backup time is shortened, and the redundancy reliability is reduced.

Therefore, voltage and current balancing should be considered in the design of a parallel battery system.

2. Solutions

2.1 Voltage Balancing Solution for a String of Batteries Connected in Series

2.1.1 Cell Selection

To solve the problems in voltage and current balancing, most manufacturers adopt the in-factory selection method. They select cells that are produced in the same period, from the same batch, and have specifications close to each other to minimize inconsistency in cell voltage in a string of batteries connected in series.

This method solves the problem of voltage imbalance in a string of batteries connected in series by means of capacity sorting and grouping. However, if the selection is not accurate or batteries of different batches are installed onsite and therefore the capacity of a cell (or a battery module) in a string is lower than that of another cell, the capacity of the entire string is limited by the cell. Currently, there is no cost-effective technical solution in the industry to solve this problem.

Cell selection or module grouping greatly reduces voltage imbalance caused by uneven voltage and capacity in a string of batteries connected in series. However, cell parameters (internal resistance) change with time and cannot keep consistency with the initial values. Especially, if some battery modules are replaced due to faults during operation, and new and old cells are used together, it is highly possible that the initial SOC is inconsistent with that of other cells or modules in the battery string, which will also cause the bucket effect. The following technologies can be used to solve the problem of voltage balancing in a string of batteries connected in series.

2.1.2 Cell Balancing Management

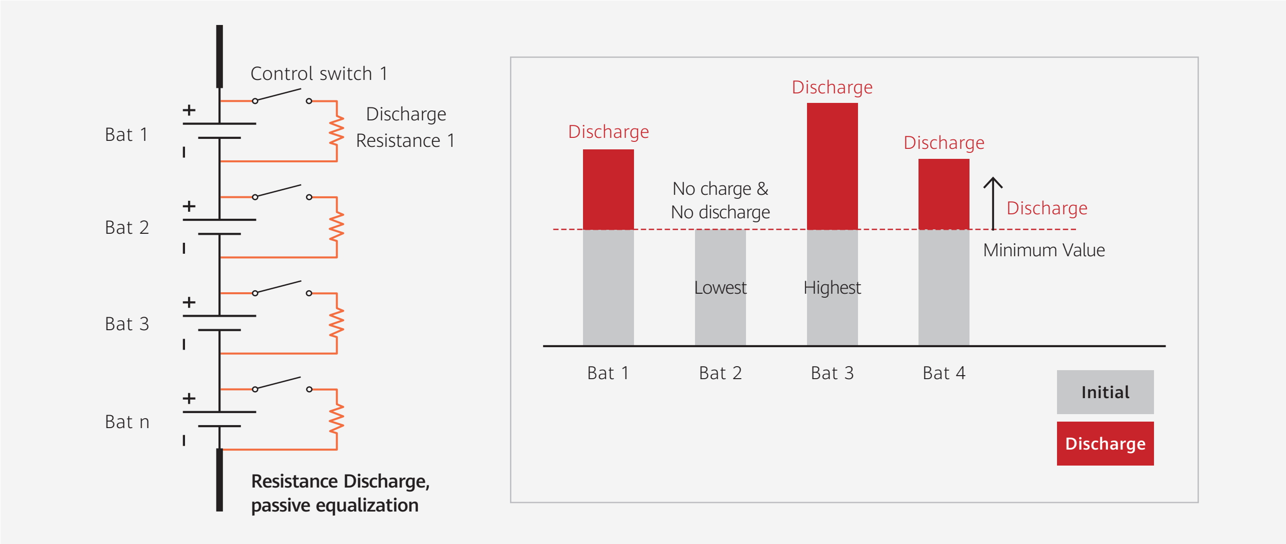


Figure 2-1 Cell balancing management solution

Figure 2-1 shows a resistor-based voltage balancing circuit. In this circuit, each cell is connected to a switch (transistor or MOSFET) and a discharge resistor in parallel. After the switch is turned on, the resistor discharges the cell to reduce voltage. For N batteries connected in series, the lowest voltage is used as a reference, and all cells whose voltages are higher than the lowest voltage are discharged until the voltages of all cells are the same as the lowest value, which achieves voltage balancing.

2.1.3 Summary of the Voltage Balancing Solution

The common solution used in the industry is cell selection and passive consumption.

	Advantage	Disadvantage	Applicable Scenario
Cell selection	Consistent in SOH	High cost in selection and grouping	A small number of cells are connected in series.
Cell balancing management	Simple, reliable, and cost-effective Consistent in initial SOH	Energy loss, which can be ignored	The power grid quality is good, but the charge and discharge frequency is low.

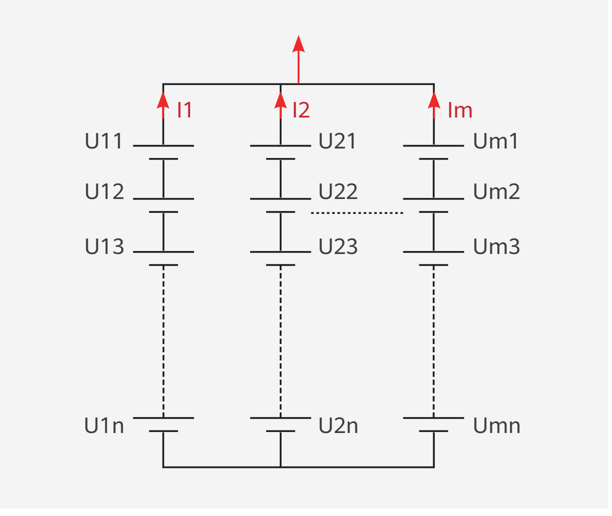
Table 2-1 Comparison between voltage balancing solutions

2.2 Current Balancing Solution for Battery Strings Connected in Parallel

As described in section 1.2, if multiple battery strings are directly connected in parallel, large current imbalance will cause the bucket effect. When the battery string with a higher discharge current reaches the cutoff voltage first, the entire system stops discharging though the energy of battery strings with lower discharge currents is not completely released. This will shorten the backup time, so excessive batteries have to be configured to ensure the required backup time. Excessive configuration increases the cost. Currently, there are two solutions in the industry to solve the problem of current balancing between battery strings connected in parallel: **passive selection and active current balancing.**

2.2.1 Cell Selection

Current imbalance in batteries connected in parallel is mainly caused by differences of cell parameters such as SOC, SOH, and internal resistance. To solve this problem, most manufacturers adopt the in-factory selection method. They select cells that are produced in the same period, from the same batch, and have specifications close to each other to minimize current imbalance. This method can only reduce the probability of current imbalance, but cannot solve the problem. After the battery system runs for a period of time, the cell parameters (internal resistance) change with time and cannot keep consistency with the initial values. Especially when some cells are replaced due to faults during operation, new and old cells are used together, which cannot ensure the consistency. The newly added cells or battery strings have to be derated based on the old battery strings, causing serious waste and reliability problems.



2.2.2 Active current balancing

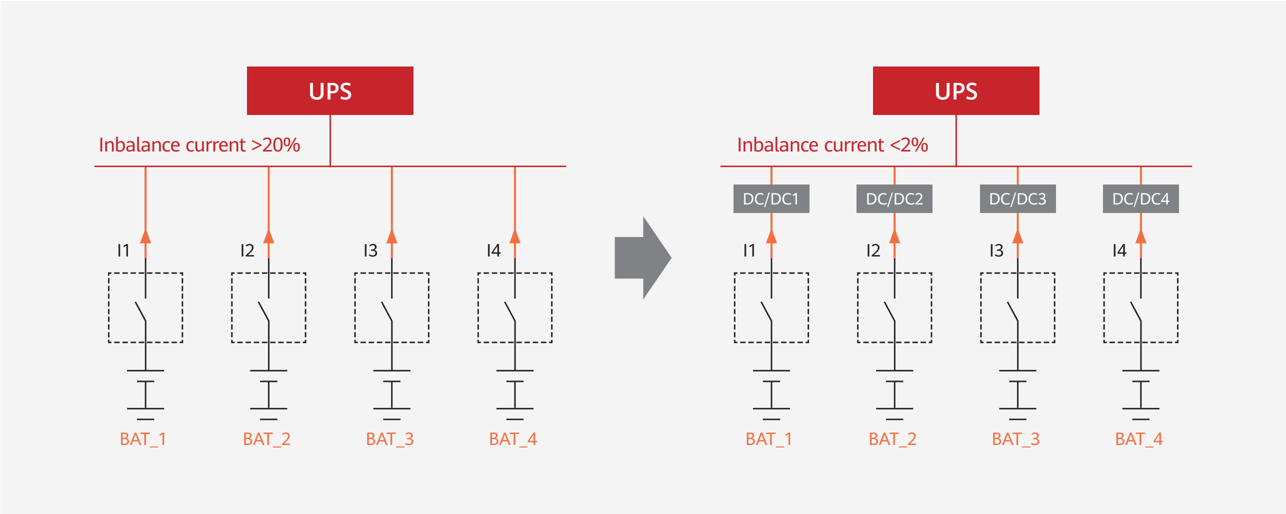


Figure 2-2 Direct parallel connection → Active current balancing

As shown in the right part of Figure 8, a **bidirectional power control** circuit is added to each battery loop, and the duty cycle of the power circuit may be adjusted by power circuit regulation to control the balance of cell charge and discharge currents (I1, I2, ...) of each battery string. For new batteries of a same batch, after bidirectional power control is added, the cell current **imbalance decreases from 20% to 2%, which can be completely decoupled from cell parameters. Strings with different voltages, different numbers of batteries, or different capacities can be connected in parallel, which reduces the redundancy configuration cost and improves reliability**.

Using this function, a new battery string and an old battery string can be connected in parallel.

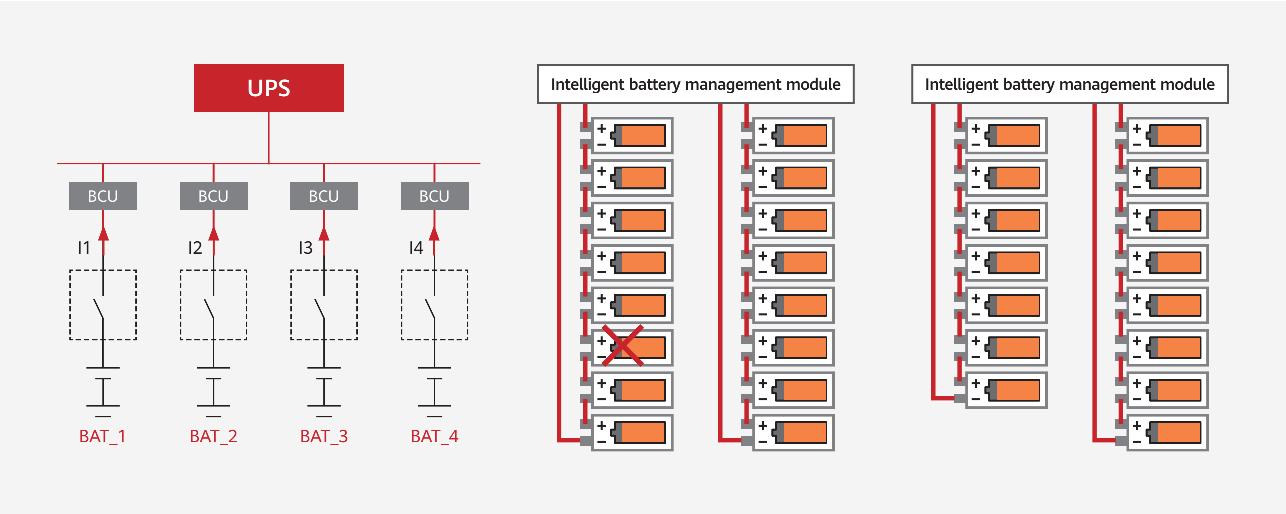
The bidirectional power conversion circuit in the intelligent battery management module enables parallel connection of battery strings with different SOHs. The power conversion controls current distribution between battery strings based on (Vbat – Veod) x SOH. The current balancing function ensures that the cells of parallel battery strings with different SOHs reach the EOD threshold at the same time. The ultimate goal is to discharge more energy from new battery strings and less energy from old battery strings to fully utilize energy.

2.2.3 Summary of the Current Balancing Solution

Item	Traditional Solution (Direct Parallel Connection)	New Solution (Parallel Connection with Power Control)	Customer Benefit
Current balancing	20%	2%	Utilization improved by 18%
Parallel connection of old and new battery strings	Not supported	Supported	Battery reuse and online capacity expansion
Number of strings connected in parallel	4 to 6	Unlimited	Low configuration cost

Table 2-2 Comparison between current balancing solutions

2.3 Intelligent Voltage Balancing Solution for Battery Strings Connected in Parallel



If a battery module in a battery string is abnormal in a parallel battery system, remove the battery module and connect the remaining battery modules in series.

The bidirectional power conversion circuit in the intelligent battery management module enables parallel connection of strings with different numbers of batteries. However, the battery strings are not directly connected in parallel, but are isolated by using a bidirectional power conversion circuit in the intelligent battery management module. With this management module, strings with different numbers of batteries can have the same battery string voltage to support parallel operation. The power conversion controls current balancing between battery strings based on (Vbat – Veod). In fact, the current balancing function ensures that the cells of each battery string in the parallel battery system reach the EOD threshold at the same time to fully utilize energy. To achieve the same output power as normal, the system current is slightly greater than the original current when strings with different numbers of batteries are connected in parallel.

3. Conclusion

After a large number of lithium-ion batteries are connected in series and then in parallel, problems of cell voltage and current balancing occur, causing the bucket effect. The performance of the entire system is determined by the worst cell, consequently reducing system capacity and reliability. This paper first elaborates on the solution of cell balancing management in a string of batteries connected in series. Then, the paper describes the intelligent voltage balancing and active current balancing technologies. These technologies can greatly reduce the current imbalance and waste of redundant configurations. With the technologies, new and old battery strings can be connected in parallel, and even after a battery is removed, battery strings with different voltages can still be connected in parallel, which greatly improves the reliability and availability of lithium-ion batteries.

HUAWEI TECHNOLOGIES CO., LTD.
Huawei Industrial Base
Bantian Longgang
Shenzhen 518129, P. R. China
Tel: +86-755-28780808
www.huawei.com