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DESIGN OF BATTERY MANAGEMENT SYSTEM FOR ENERGY STORAGE EQUIPMENT OF THE TETHERED AEROSTAT

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Battery management system (BMS, as an integral part of energy storage equipment on a tethered aerostat, is relatively difficult to design owing to its operational environment and design requirement for high reliability. BMS was developed according to technical requirements for the energy storage equipment of the aerostat. With NXP master chips and LAPIS communication chips as its core hardware architectures, it was equipped with independently developed software. After full functional and environmental tests, the high-density energy storage equipment independently developed for the BMS has been stably used for more than 1 year on the tethered aerostat. Its functions such as online charge/discharge and uninterruptible power supply meet design requirements.

Keywords: Tethered Aerostat, Battery Technology, Battery Manage System

1. Introduction

The big data space demonstration platform named “Cloud” delivered for flying in Zun-yi, Guizhou, China, in early 2017, is the first aero big data platform for space of smart cities in China, which uses a tethered aerostat as aero-hub. Generally, this tethered aerostat [1-9] is operated above 1,500m in the air with the electric power and energy is supplied from a AC/DC high-voltage uninterruptible power supply system from ground to the tethered aerostat. To accommodate equipment needs of high energy density, high-altitude adaptation, high-current outputs, high reliability and uninterruptible power supply, the 18650 ternary lithium batteries with high-rate capability were utilized, for the first time, as standby uninterruptible power storage equipment in the aerostat. The

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characteristics of the battery pack are as follows: 1) Many ternary lithium battery cells with the highest energy density are employed at a high altitude. A total amount 180 cells are connected in parallel into 30 groups with 6 cells series in each group. 2) The discharge rate is as high as 1.5 and the maximum discharge current is up to 120A. For uninterruptible power supply, the energy storage equipment is always hung and loaded over the 26V low-voltage DC power distribution bus, and seamlessly supplies power in case of insufficient power supply or power failure.

Fig.1 "Cloud" Tethered Aerostat in Zunyi, Guizhou

The aforementioned technical characteristics of the energy storage equipment bring about following technical difficulties in developing corresponding energy management system [10-14]. 1) It can't be neglected that circuit chips and other electronic components of the BMS would break down under high-altitude and low-pressure conditions. 2) Ternary lithium cells are helpful for effectively reducing curb weight of energy storage equipment. Nevertheless, materials of the ternary lithium battery cells are so active that they are easily thermally decomposed, as a result, the battery pack will catch fire, explode, and threaten safety of aerostats. 3) To a certain extent, 18650 batteries with safety valve and steel shell can reduce the risk of fire from inner of the battery cells. However, battery cells will become more and more inconsistent after a battery pack. It can cause voltage instability, impact life of the battery pack, and bring about safety hazards like over-voltage charging, and so on. 4) The real charge capacity progressively declines with the increasing battery charging& discharging cycles and the extension of the manufacture time of the battery cells. But the primary cells can be hardly replaced by the cells with different parameters, including voltage platforms, discharge curves and capacities. Because of these problems, there are following technical difficulties and requirements for deigning BMS for an energy storage equipment on the tethered aerostat: 1) The BMS will be used in a low air pressure and low temperature environment, so voltage endurance of circuits and elements of BMS shall be corrected for high-altitude operations. 2) It is necessary to strengthen thermal management of the whole battery pack, reasonably equip temperature sensors in different parts of battery pack, effectively acquire information about temperature on key parts of battery cells. 3) Introduce a balance circuit in battery cells and efficiently design a system for balancing cells on the premise of safe operations by both a software active way and a hardware passive way. 4) According to the concept of responsive design, compatible designs are completed based on number of different battery cells connected in series, cell capacity and platform voltage. In addition, discharge curves of different cells are designed with customized software to guarantee commonality of the BMS. 5) Properly manage battery charge and discharge states. Integrate charging and discharging circuits as a whole pursuant to practical needs for low-current charging, high-rate discharging, and uninterruptible power supply.

To follow above technical requirements, BMS was developed for a tethered aerostat as energy storage equipment. After the full functional and environmental tests, the high-density energy storage equipment independently developed for BMS has been stably used for more than 1 year on the tethered aerostat. Its functions, such as online charge/discharge and uninterruptible power supply meet design requirements.

2. Hardware Design for BMS

The BMS for the energy storage equipment of the tethered aerostat is shown in Fig. 2.

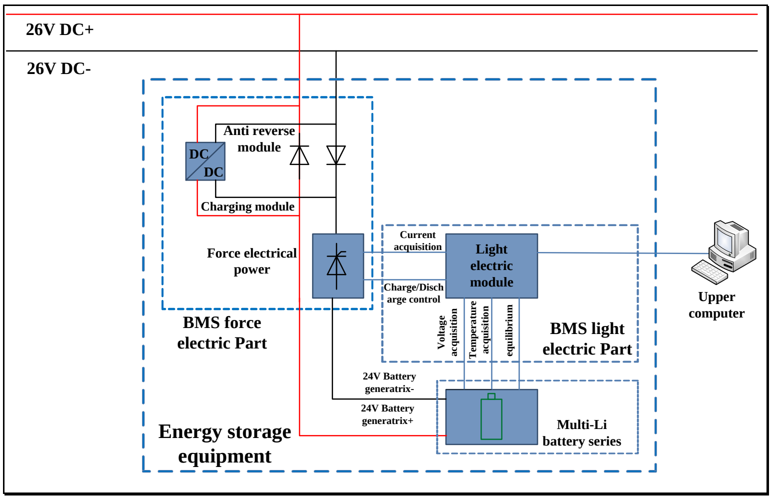


Fig.2 The block diagram of measurement and control system for graphitizing

As shown in the Fig. 3, the BMS of the energy storage equipment is composed of force electricity and weak electricity parts.

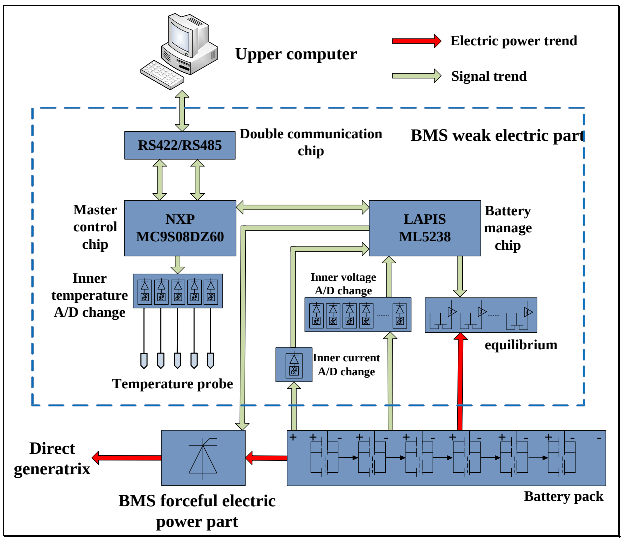


Fig.3 BMS hardware part of the energy storage equipment

2.1. Force electricity Part of BMS

The energy storage equipment, which is directly hung and loaded on the DC bus, will supply uninterruptible power when the AC/DC power supply equipment is disconnected, or the bus voltage fluctuates. The force electricity part integrates DC/DC charging modules, anti-reverse module and force electricity module, which are used for high-current charge/ discharge, current acquisition and charging/discharging control of the battery.

In consideration of costs and circuit board area, the force electricity module is only connected between the batteries and the cathode of the DC bus for controlling disconnection and connection between the batteries and the cathode. This module is made up of MOSFETs connected in parallel. In addition, resistances will be connected to the force electricity module in series, after they are connected in parallel, and current may be sensed by measuring the terminal voltage of the resistances.

2.2. Weak electricity Part of BMS

As the core part of BMS, the weak electricity part is connected to the force electricity part and the battery pack, where the latter supplies power. As shown in Fig. 3, the weak electricity part of BMS, which is made up of the module for master chips, the module for battery management chips, the RS485/RS422 serial communication module, the module for battery equalization, and peripheral circuits, is used for acquiring voltage or temperature of the lithium battery pack, equalizing battery charging, monitoring operating conditions of lithium cells and offering feedbacks to the upper-computer. In consideration of extensive requirements for hardware compatibility, 18650 batteries will be connected in 6 to 16 series for the weak electricity part of BMS for the purpose of general management.

A master chip is employed as master chip and one of core units on the weak electricity part. It is mainly used for data processing, SOC (State of Charge) calculating, control directives downwards sending, data upwards returning and temperatures acquiring of the lithium-battery pack in different part. For operations at a high altitude, electrolytic capacitor is forbidden to applied in the weak or force electricity part of the BMS. Therefore, all the capacitors are ceramic capacitors on the BMS chips. The weak electricity part of the BMS is equipped with indicators connected to I/O ports to indicate voltage of current power supply system, temperature warnings and state of serial communications.

In the module for battery management chips, a communication chip is used as another core unit of the weak electricity part. It is mainly utilized for acquiring data of the voltages and currents, controlling charging and discharging, protecting short circuits, communicating with master chips and executing directives. The battery management chips control charging and discharging of lithium cells.

The current acquisition module works as follows: The in-built A/D conversion module of the battery management chips is used. Resistors are connected in series to the chip circuit. When the current flows through the resistor, voltage is acquired from the sides of resistors, and converted into the current as follows:

$$I_{\mathrm{tst}} = G\frac{V_{tst}}{R_{tst}} = 1000GV_{tst} \tag{1}$$

Where, I_{tst} is the acquired current, V_{tst} is the acquired voltage, and G is the gain of the in-built A/D converter.

The temperature acquisition module is made up of NTC temperature sensors. R_v of NTC and the measured resistance R_m (precision resistance) make up a simple series-connected voltage divider circuit. After the reference voltage (V_{Ref}) is divided, the new voltage obtained varies with temperature, acquired and transferred to the chip register through the in-built A/D module in the master chip. The values of this voltages reflect the values of the NTC resistances, namely the values of corresponding temperatures. The formula of the relationships between the acquired voltage (V_{adc}) and the NTC resistance is as follows:

$$V_{adc} = V_{ref} \times \frac{R_m}{R_v + R_m} \tag{2}$$

As shown in Fig. 4, temperature sensors are placed on 5 temperature sensitive positions inside the battery pack, namely at the communication port, at the port of charge/discharge, in the middle of the box, on the chipboard of the weak electricity part, and on the control board of the weak electricity part, in order to fully understand the temperature conditions of the battery pack on each sensitive position.

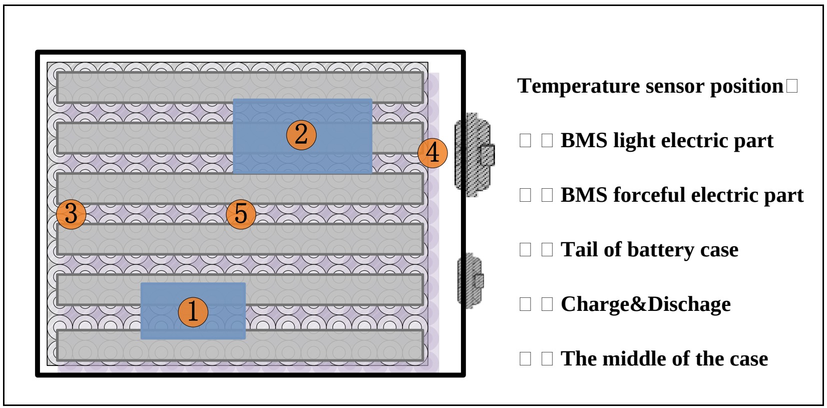


Fig.4 Position of the temperature probe

In the equalization module, passive equalization (lossy equalization) is chosen for the hardware, where the cost is relatively low. An equalization module is made up of shunt resistors and MOS tubes, connected to the battery stack in parallel. The software of this module is controlled by master chips and the control directives are executed by the power management chips. When the acquired maximum and minimum voltage of batteries (V_{max}& V_{min}) are in line with the formula as follows:

$$V_{max} - V_{min} \geq 100mV \tag{3}$$

The battery management chips will have the MOSFETs which are connected to the battery stack with the highest voltage in parallel gate connected, and the current will be effective for equalization after it goes through shunt resistors. The equalization current shall be reasonably chosen, because the effects will be not obvious if the current is too low, while the energy loss will be considerable provided that the current is extremely high, thus leading to poor equalization efficiency. Besides, the serial communication modules support two communication modes, namely RS485 and RS422, which are used for transmitting data about battery status to the upper-computer.

3. Software Design for BMS

3.1 Software Processes

Fig. 5 shows the software flowchart of the BMS. The software is designed for the BMS for the purpose that a complete control system is available to energy storage equipment to acquire voltage, current or temperature of batteries, estimate the state-of-charge of batteries, equalize voltage of cells, protect over-charge/over-discharge, and communicate with the upper-computer. The concept of software design for BMS is in line with the purpose of modular and hierarchical design. Software fulfils tasks of a system by constantly jumping out of and returning to cycles.

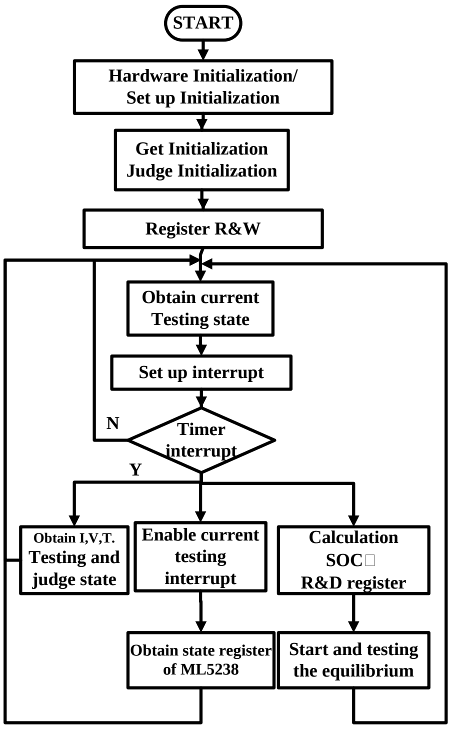


Fig.5 Software Flowchart

3.2. Interrupt Responses

Serial communications are realized by responding to serial port interrupts. In addition to serial ports, timer interrupts and current detection interrupts are also set in programs. The master chip of this system, is interrupted as follows, as shown in Table 1.

Table 1

Interrupt Priority

Type of interrupt	Priority (from high to low)
DOG/BDM/External pin	1
TPM	2
SPI	3
SCI	4
Port pin	5
ADC	6

The upper-computer communication protocol is modified from MODBUS protocol. After codes are received and calibrated by chips, data values of the register are transmitted to the upper-computer, in order that monitoring personnel may observe state on a real-time basis. According to the communication protocols, content of the chip register can be read. Likewise, default initial values of the register can be modified, in order that upper and lower limits can be revised according to different application status.

3.3. Control and Estimation of SoC

The energy storage equipment, which is hung and loaded on the DC bus, needs to be comprehensively controlled to protect battery pack from losing control. Table 2 shows control blocks of battery packs for controlling cut-off voltage, cut-off current, high& low temperature and cell equalization. Control variables shall be controlled when they go beyond their limits, and such control shall not be deregulated until the variables are restored to their allowable values.

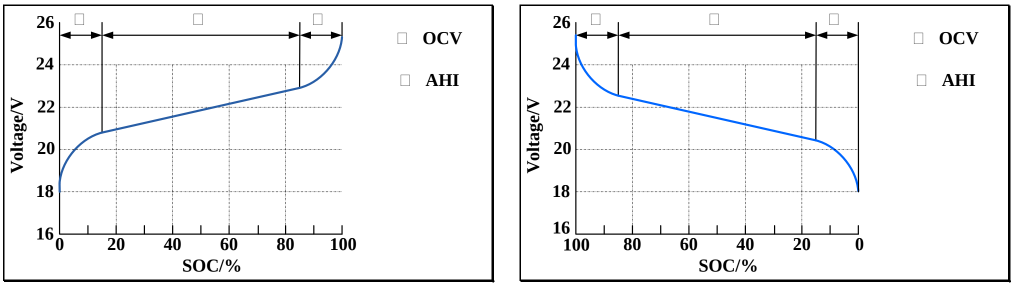
Table 2

Battery Control Table

Battery control table		
Control variable	Limited Value	Control method
Over charge voltage	4.25V	Charge cut off
Over discharge voltage	2.95V	Discharge cut off
Over charge current	40A	Charge cut off
Over discharge current	200A	Discharge cut off
Low temperature	-10℃	Charge cut off
Low temperature	-20℃	Charge & discharge cut off
High temperature	50℃	Charge cut off
High temperature	60℃	Charge & discharge cut off
Cell Equilibrium	100mV	Start the equilibrium when charging

Control over voltage and charging current is dependent upon cell performances. Discharge over current is controlled to avoid cell over-discharge when the DC bus is somewhere short-circuited. High and low temperature control is imposed to determine protective values ranging from -10℃ to 50℃ based on actual operational environment of the energy storage equipment.

Battery equalization is effective for solving voltage unbalance of batteries. At present, estimating battery state-of-charge (SOC) [15-19] is one of difficulties in battery research. In view of practicality and customization, SOC of the energy storage equipment is estimated on three parts as follows: The battery pack is charged and discharged repeatedly to obtain its charge and discharge curves, based on which, the voltage on the battery sides is divided into three segments. The SOC is estimated according to open circuit voltage algorithm and ampere-hour integration algorithm, as shown in Fig. 6.



A Charge SOC estimate B Discharge SOC estimate

Fig.6 3 Stage Charge and Discharge SOC Estimation Curve

The SOC is controlled within 0 to 15% and 85% to 100% for charging and discharging respectively. In view that voltage is fast-changing and generally exhibits linear changes, the SOC is estimated pursuant by OCV. When the SOC ranges between 15% and 85%, it is estimated by ampere-hour integration(AHI) algorithm, on the grounds that discharge voltage fluctuates slowly in a platform-shaped form. Compared with the OCV under the state of discharge, the OCV under the state of charge is about 0.4V higher, so state of charge and discharge shall be treated separately.

4. Tests and Practical Applications

4.1. Tests of Energy Storage Equipment

The circuit board of the BMS was placed inside an aging test chamber for 48h to test its aging. It is assembled together with a battery pack and a casing and so on. The test is made up of two parts, including environmental and functional tests.

The environmental simulation test is carried out according to actual operational environment of energy storage equipment and in combination with corresponding technical requirements. The test conditions are as follows.

Table 3

Test Conditions of the Energy Storage Equipment

Test condition	
Temperature/℃	-10~55
Atmospheric pressure /kPa	61.5~101.3
Vibration	Low-frequency, random

Table 3 and Table 4 shows environmental test results of the energy storage equipment. From Table 4, it is known that state of charge& discharge is in line with the software logics, communications are normal, and equipment can be normally used under four types of environments.

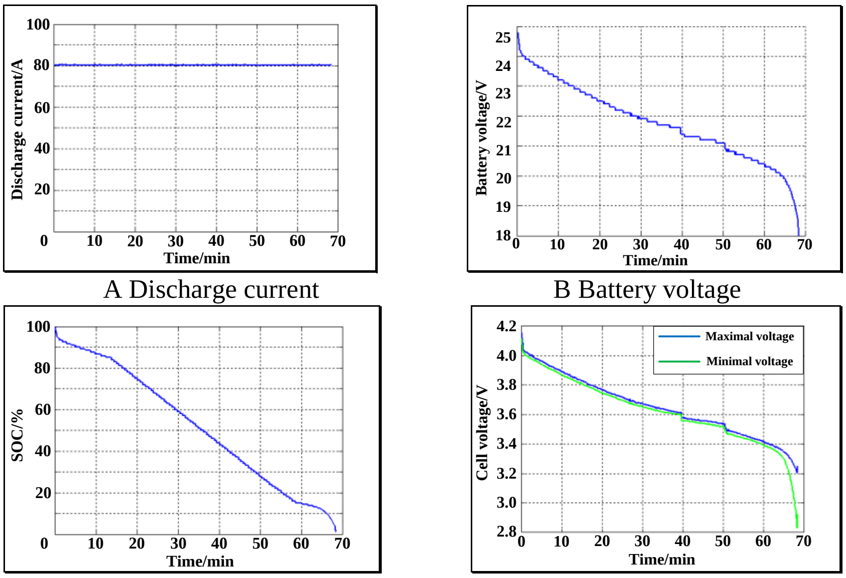
Table 4

Environment Test Results of the Energy Storage Equipment

Environment test results				
Type of test	AMFC	BMFC	ALFC	BLFC
Test time	8h	8h	8h	8h
Charge state	Chargeable	Charge cut off	Chargeable	Charge cut off
Discharge state	Dischargeable	Dischargeable	Dischargeable	Dischargeable
Equipment state	Normal	Normal	Normal	Normal
Signal communication state	Normal	Normal	Normal	Normal

Notice: A for low temperature, B for high temperature, M for low atmospheric pressure, L for normal temperature, Fc for vibration

The energy storage equipment is discharged under an environment with atmospheric temperature and pressure at a discharge rate of 1.5. However, to protect the life of the battery pack, the batteries are discharged at a single rate (80A) with electronic DC load. Data are acquired through RS422 serial port of the energy storage equipment. Fig. 7 shows discharge-related data of the energy storage equipment in classical tests.



A Discharge current B Battery voltage

C SOC D Cell voltage

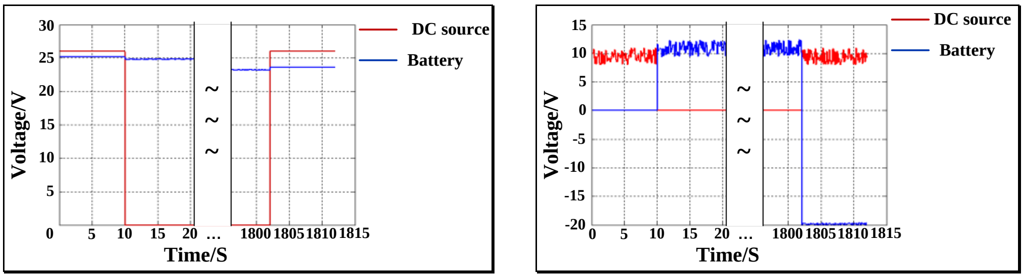
Fig.7 Typical Test Discharge Curve of the Energy Storage Equipment

From Fig. 7, it can be known that: (1) The discharge current recorded by the BMS is 80A. (2) The discharge lasts more than 68 minutes, and the cumulative discharge capacity is 90.6AH, which is higher than 80AH (i.e. the default value), with relatively good performances. The cumulative discharge capacity will gradually decline with the use of the battery pack and increase in the charge/discharge cycles. (3) The voltage on the side of the battery pack slowly declines from 24.8V to 18V with discharging process. The voltage apparently tends to vary in the shape of a platform in the middle part, but the voltage shows a drastic linear decline on both ends. (4) The waveform of SOC is smooth and continuous, which suggests that it is relatively reliable for calculating SOC in combination with terminal voltage and ampere-hour integration algorithm. Furthermore, the errors in SOC arising from life attenuation of lithium cells may be calibrated online via complete charge and discharge. (5) At the beginning of discharge, there is only very small difference between the maximum and minimum voltage of cells. However, such difference progressively increases to about 200mV at the end of discharge. It will gradually contribute to battery equalization when batteries are charged.

Furthermore, charging process of the energy storage equipment is tested at room temperature and under atmospheric pressure with 20A current. The results are generally inversely related to discharge, which will be not discussed in details in this paper.

4.2. Practical Applications

Up till now, the BMS of the energy storage equipment has been continuously operated on the tethered aerostat for more than 1 year. The AC power supply from the ground to the aerostat has been disconnected for more than 100 times. Fig. 8 shows voltage and current waveforms of DC power supply and energy storage equipment on the tethered aerostat which are generated when ground power is turned off for 1,800s (30 mins) according to the equipment maintenance plan.



A Voltage waveform B Current waveform

Fig.8 Voltage and Current Curves of the DC Source and the Energy Storage Equipment

From Fig. 8, it is known that AC power outage occurs at 10s on the aerostat, where the AC power supply is restored at 1,800s, in which period, the output of the AC/DC power supply to the DC bus is disconnected. Battery standby power is supplied to the energy storage equipment, and switch time is 0. The voltage of DC power supply is 26V, and after switching, the voltage of the energy storage equipment gradually decreases with time. After its power supply is restored, the energy storage equipment is charged at about 20A.

4.3. Comparison with another BMS

A certain type of BMS used on the ground was adopted to compare with the BMS used in the aerostat by using the same type of ternary lithium battery cells, as shown in the Table 5.

Table 5

Economic and performance analysis of the ground use BMS and the aerostat use BMS

Economic and performance analysis		
BMS type	Ground use	Aerostat use
Self-power consumption(A)	0.1	0.025
Adopt altitude(m)	1000	4000
Cost ($)	400	550
Weight(g)	315	215
Permissible voltage(V)	60	72

From the Table 5 it can be known that 1) the aerostat BMS has advantages of the self-power consumption, adopt altitude, weight and permissible voltage, compared with the certain type of BMS used on the ground, 2) it also has a disadvantage of the higher cost with the BMS used on the ground. It is apparently more superior for the aerostat BMS than the ground BMS, even it takes more cost than the ground BMS.

5. Conclusions

There are relatively many difficulties and requirements for designing BMS for energy storage equipment of a tethered aerostat. After they underwent adequate environmental and functional tests, BMS and its energy storage equipment, which were designed in accordance with special requirements, have exhibited stable and reliable parameters over the past 1 year when the tethered aerostat was flying outdoors. Being applicable to several kinds of batteries and highly reliable with low requirements for operational environment, the BMS of the energy storage equipment is fairly pragmatic and universal in the field of aerospace.

In addition, the high cost of the aerostat battery BMS can be controlled by reducing the capability of the BMS. The ternary lithium battery cells are used in the aerostat by using the special designed aerostat BMS, with higher safety, lower weight, higher adopt altitude, higher permissible voltage. The aerostat battery BMS can also be used in other aircraft in the aerospace field, such as the UAV, the helicopter, the airship and the near space aircraft.

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