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Safety of operation of lithium batteries with active-passive BMS Systems in mining machinery systems

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Abstract:

The use of lithium batteries in power supply systems for devices and/or machines in mines requires ensuring an appropriate level of work safety. This applies in particular to hard coal mines, and especially methane mines and mines at risk of fire or explosion. For this reason, the lithium cells used must, together with the BMS battery management system, be isolated from the influence of the environment by placing them in special explosion-proof housings. In connection with the above, the operation of cells without the so-called BMS is, as the authors' preliminary research shows, practically prohibited. In practice, various BMSs are used, most often with the so-called passive balancing. However, their use means that the lithium battery is balanced only during charging, which means that the weakest cells in the battery determine its operating time. As for active BMSs, they are used less often due to their rather complicated structure and costs, but their use extends the operation of the lithium battery.

The article presents a new version of the special structure of the BMS system, which will balance the battery cells using the passive and active method. This will extend the battery life and ensure a safe charging process. The BMS system can be used in mining machines and devices and energy storage devices powered by a battery consisting of lithium cells.

Keywords: lithium battery, passive and active cell balancing, battery

1. Introduction

Safe use of lithium batteries as an effective source of battery power for electric drives in mines, especially those at risk of fire or explosion, requires both appropriate selection of the battery's electrical parameters and on-line control of changes in these parameters during operation. From the point of view of the requirements for reducing mine operating costs and ensuring the shortest possible downtimes, it is also important for the battery used to work as long as possible on a single charge/recharge. The development of technology allows the use of commercially available lithium batteries with much better electrical properties and lower weight, which allows for the gradual elimination of difficult to operate and heavy lead-acid batteries. It should be emphasized that underground mining in the world takes place at increasingly greater depths at temperatures exceeding 40°C. Increased temperature usually reduces the safety of mine operation, increasing the failure rate of working machines and devices, also contributing to the damage of lithium batteries. This is caused by the process of electrolyte decomposition at elevated temperature, which increases the internal pressure of the cells and as a result promotes cell ignition and its explosion. In this situation, it is necessary to equip lithium batteries with appropriate electronic monitoring modules designated as Battery Management Systems (BMS) [1]. Their task is both to control the operating state and, above all, to balance (balance) the cells, so as to prevent their damage as a result of overcharging, excessive discharge and/or overheating [2, 3]. Lithium batteries are, above all, very sensitive to complete and/or so-called deep discharge. Left in such a state for a long time, they may be irreversibly damaged. The task of the BMS system is therefore to control the cell parameters online and, in the event of exceeding their limit values (voltage, current, temperature), to alarm or disconnect the battery [4]. The need for energy balancing results from differences in the nominal values of the charge, capacity and/or resistance of individual battery cells. These differences result from manufacturing tolerances and operating conditions of cells of the same type and tend to increase during operation [5].

The article presents and discusses the results of research on the operation of a lithium battery consisting of lithium-iron-phosphate ($LiFePO_4$) cells equipped with a passive and active battery management system (BMS). Due to its intended use in underground mines, the research was conducted with particular attention paid to the efficiency of the cell balancing system when there is a mismatch of one to three cells in the battery. Due to its intended use in underground mines, the tests were conducted both at room temperature (20°C) and with free cooling and with degraded cooling at various mine ambient temperatures (from +5°C to +60°C) at a constant humidity of 75%. The tests were conducted for an example battery consisting of 8 cells connected in series. Such conditions are inevitable in mining applications [6]. Based on conclusions from the conducted research, a new version of the special structure of the BMS system was presented, which will balance the battery cells using the passive and active method. This will allow for extending the battery life and ensuring a safe charging process. The BMS system can be used in mining machines and devices and energy storage devices, the power source of which is a battery consisting of lithium cells.

2. Cell balancing methods

Monitoring and controlling the energy storage process in cell sets should serve to ensure that the cells can function, as the longest, as reliable and stable sources of electrical energy, while being characterized by high efficiency and a high level of safety.

Proper and safe operation of lithium cell batteries requires a BMS (Battery Management System) system that supervises their operating parameters to prevent damage, and balances them to increase efficiency and service life. Balancing methods can be divided into two basic groups (Fig. 1):

- passive - consists in dissipating excess energy into heat using appropriately selected resistors or transistors (less frequently used),

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- active balancing the charges stored in the cells by transferring energy between them. Consists in balancing the energy stored in the cells by using an external system designed to actively transfer energy between them.

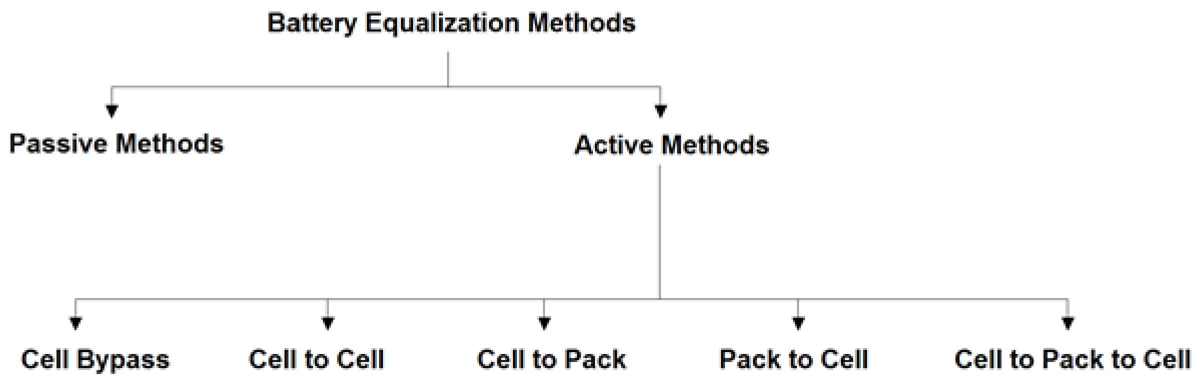

Fig. 1. Battery Cell Balancing Methods

There are several methods of active cell balancing and they are divided in different ways. Due to the energy flow, these methods are grouped into four basic subcategories: cell to cell, cell to battery, battery to cell and combined method cell to battery and from battery to cell [7].

The most commonly used battery management systems built from lithium cells are currently BMS systems using the passive method, based on the principle of dissipating excess electrical energy by converting it into heat. This is an unfavorable method, especially in machines and devices intended for use in mining, which should meet the requirements of the ATEX directive, including temperature limits of elements in contact with the mine atmosphere.

An alternative to the passive method is active cell balancing. The basic idea is to use an external system designed to actively transfer energy between cells. This significantly reduces the unfavorable phenomenon associated with energy dissipation, provides energy savings and creates optimal operating conditions for cells, resulting in extended battery life.

As part of the work carried out earlier [8], research was carried out which showed that regardless of the use of active balancing of the lithium battery during operation, the process of charging the lithium battery when the load is disconnected is also important. In such cases, the best solution is a BMS system with passive balancing, which protects against overcharging of the cells. Considering the functioning of both the BMS system with active and passive balancing and the expectations of hard coal mines in the scope of implementing technical solutions that allow for meeting quality, efficiency and economic requirements, it seems important to develop and build a comprehensive BMS system that functionally combines both types of balancing, i.e. active and passive. Both have their advantages and disadvantages. The active BMS system, which is more technologically complex and more expensive to produce, but ensures better energy management, which causes the battery cells to wear out more slowly, and the passive system, which is cheap and easy to implement, but due to the way it works, it can lead to faster wear of the cells, especially during discharge, because it converts excess electrical energy into thermal energy, equalizing the charge level of individual cells to the level of the weakest cell.

The use of a BMS system that combines both types of balancing can significantly improve the functioning of a device powered by a lithium battery. This is because the battery protection will be ensured at every moment of its use, i.e. during operation, standstill and charging.

3. Research on BMS systems

Research conducted by the authors shows that there is a real [9] chance for the safe and effective use of selected lithium-iron-phosphate batteries to power various mining devices and drives. However, this requires the use of a BMS system to increase both durability, safety and high operational reliability in mining conditions. It is obvious that the use of wireless and zero-emission drives can significantly improve environmental conditions in mines with reduced ventilation requirements.

Since it is extremely difficult to obtain any active BMS system on the market, especially one for specific requirements, the authors developed models of two different active BMS designs. Generally, the active BMS systems offered are quite complex and relatively expensive. Their complexity and price increases as the number of cells increases. Therefore, the authors limited their considerations to a battery set consisting of only eight cells connected in series (Fig. 2). However, the approach to a much larger number of cells and the conclusions drawn from the research are not limited to the size of the battery pack and its voltage level.

Fig. 2. The battery consists of eight lithium-iron-phosphorus cells ($LiFePO_4$)

The first of the two active BMS developed at ITG KOMAG uses the cell-to-battery method and was described in detail in the article [10]. Cell balancing in this BMS system is performed by transferring energy from the most charged cells to the entire battery pack. Thanks to this, the electric charges of individual battery cells are equalized. This means that excess energy from a single, specific overcharged cell is then delivered to the load to keep the battery in a state of top-up. However, when the battery is in a state of charge, this energy is returned to the entire pack. The view of the BMS system installed on the cell pack (battery) and the block diagram of the measurement system are shown in Fig. 3.

Fig. 3. BMS system installed on the cell pack

The second solution of the active BMS system, developed by ITG KOMAG, uses the battery-to-cell method [11]. This balancing method is based on transferring energy from the entire battery to the "weakest" cell. In this way, the charge of individual battery cells is equalized. The developed BMS system consists of a measurement and control module (Fig. 4) and a balancing module (Fig. 5).

Fig. 4. Measurement and control module

Fig. 5. Balancer module

Assessment of the operational efficiency of the newly developed active BMS system also required reference to passive systems available on the market. For this purpose, a technically suitable passive BMS system was selected and adapted for comparative testing. Its operation, as already mentioned, is to dissipate excess energy into heat using appropriately selected resistors. The block diagram of the measurement system is similar to a BMS system with active cell-to-battery balancing. In this case, the voltage values of individual cells are monitored online by a microcontroller using an analog-to-digital converter to which the cell inputs are connected. If the voltage of one of the cells significantly exceeds the value of the others, it is immediately shunted in parallel by a resistor. Discharging continues until the voltage of all cells used in the pack equalizes.

Scope of research

The tests were carried out for batteries (consisting of eight LiFePO4, 10 Ah lithium cells, Headway LFP38120 (S) [12] type) operating both at room temperature (approx. +20°C, humidity approx. 40%), with free heat transfer from the battery to the surroundings. The station was equipped with a temperature and voltage measurement system (DT8873-24 VOLTpoint) and a computer with specialized software (Fig. 6).

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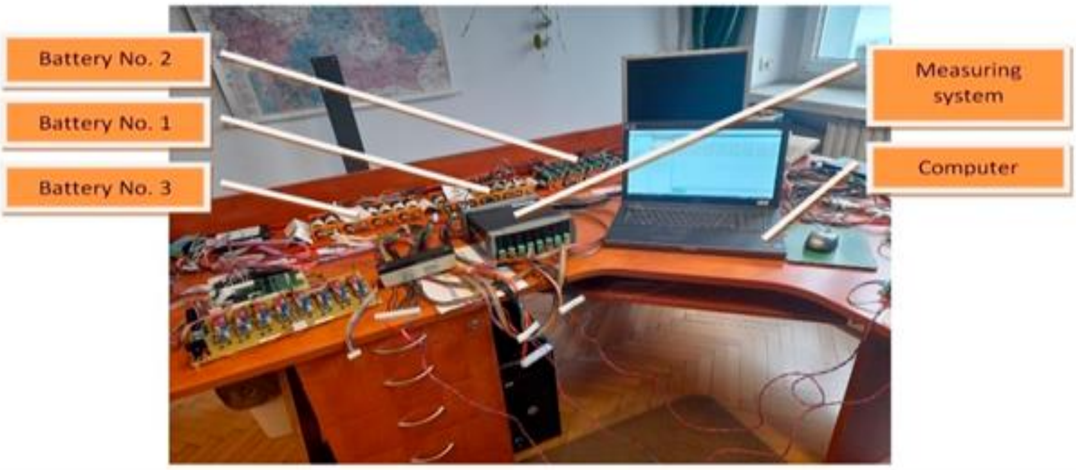

Fig. 6. Station for measuring and recording data (Battery 1 - with a battery for the active BMS battery, Battery 2 - with a battery for the active BMS battery, Battery 3 - with a passive BMS)

The finished battery packs (unloaded) were then connected to the appropriate active/passive BMS system under study. However, the load asymmetry of selected cells (from 1 to 3 tested, respectively) was performed for a discharge current equal to approximately 25% of the standard discharge value (2.5 A) as shown in Fig. 7. Each test began with a fully charged battery (voltage of all cells equal to the rated Un = 3.2 V). The load with a current of 2.5 A lasted until the voltage at the terminals of any of the cells reached the minimum value Umin (equal to 2.5 V).

The research has shown that both the voltage value of individual cells and their temperature may differ from each other even when loaded (discharged) with the same current value. For selected two cells in a battery without a BMS system, it is shown, for example, in Fig. 8. This justifies the need to control the voltage and temperature of all cells, and therefore the need to use a BMS.

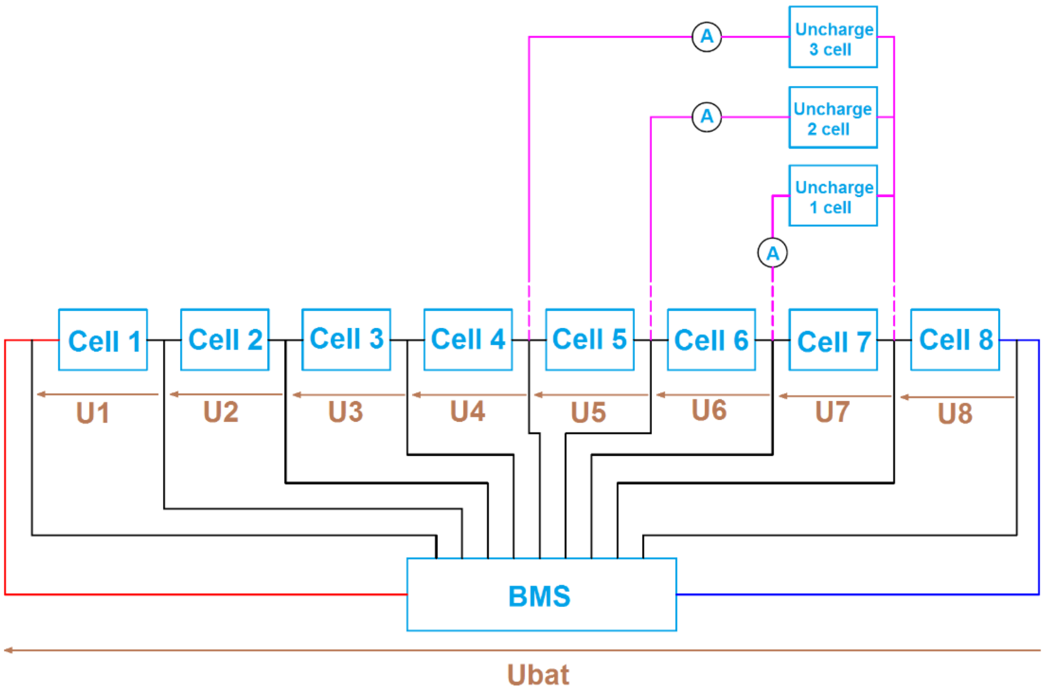

Fig. 7. Block diagram of the BMS system testing system during battery load simulation

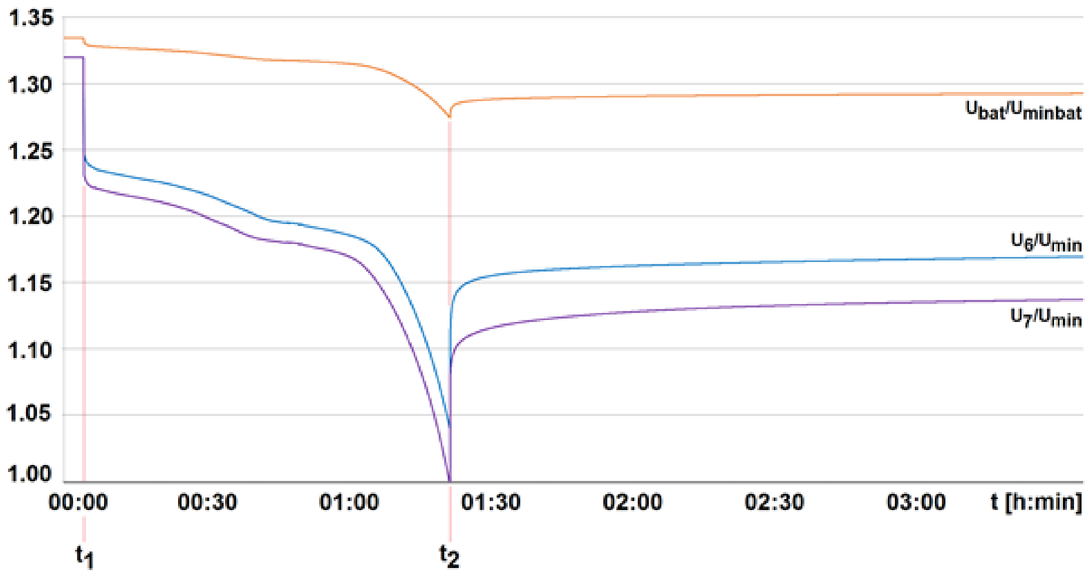

Fig. 8. Graph of the voltage value on two loaded cells without a BMS system connected

In order to compare the performance of the developed active BMS systems, their technical parameters were configured accordingly. Therefore, for both active systems, balancing is activated when the cell voltage drops below 3.05 V (U/U_n = 0.95). Balancing is interrupted when the voltage on the terminals of any of the cells used is lower than U_{min} = 2.5 V or higher than 3.65 V (U/U_n = 1.14) (Fig. 9 and Fig. 10). The balancing current value was set at 2 A (approximately 40% of the standard charging current). However, for a commercial BMS system with passive balancing, the value of the balancing current was set arbitrarily by the manufacturer and is 350 mA. However, other technical parameters could be determined by configuration using computer software. As a result of the configuration, passive cell balancing starts during charging, when the cell voltage value is between U_n = 3.2 V and 3.65 V (1.14 U_n). However, it turns off when the voltage at the terminals of any of the cells is lower than U_{min} = 2.5 V and/or above 1.14 U_n (3.65 V) (Fig. 11).

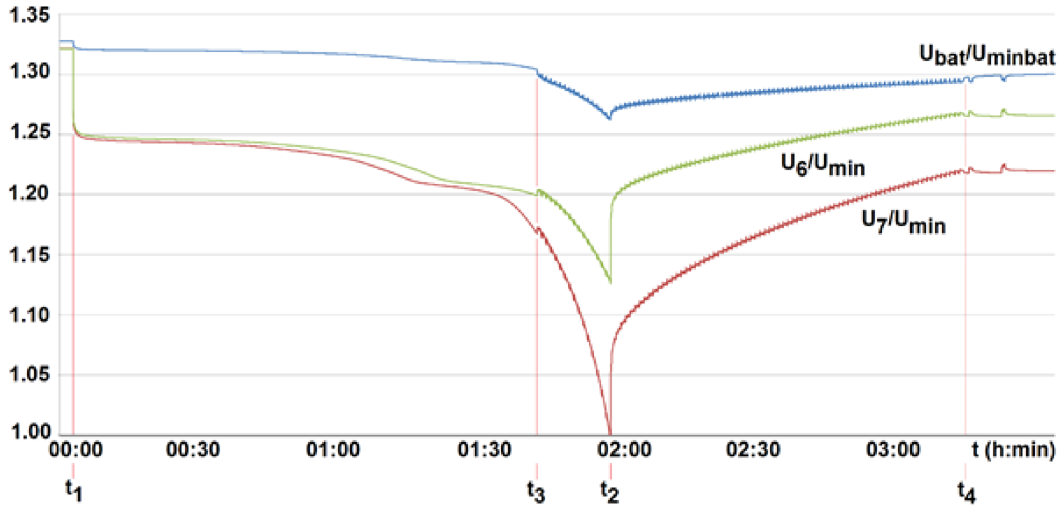

Fig. 9. Graph of the voltage value on two loaded cells for a BMS system with active balancing (cell-to-battery method). Voltages U_6/U_{min} and U_7/U_{min} over time for two cells loaded in series in an unloaded battery without a BMS system (room temperature T_o = 20°C, free cooling, t_1, t_2 - moment of switching on and off the load current, t_3, t_4 - moment of turning on and off the balancer, U_{min} - minimum cell voltage equal to 2.5 V)

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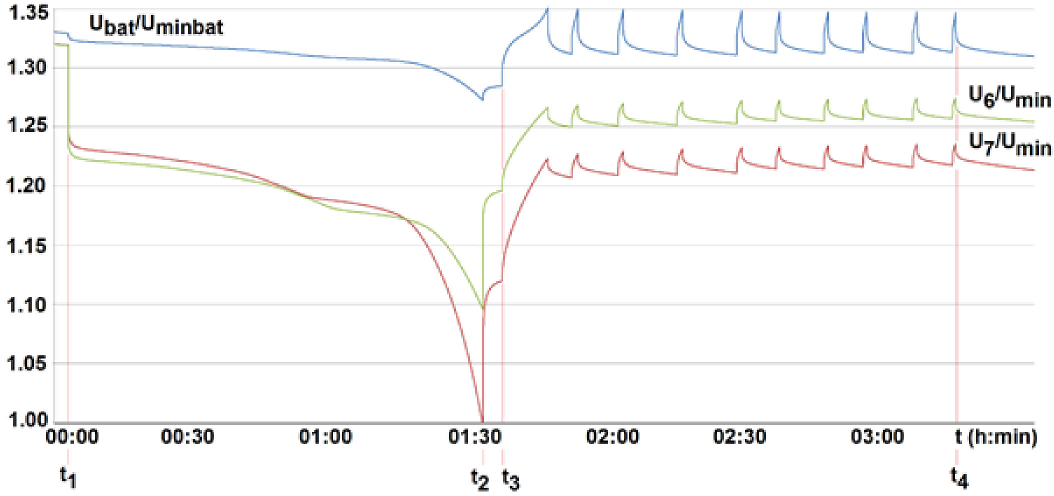

Fig. 10. Graph of the voltage value on two loaded cells for a BMS system with active balancing (battery-to-cell method). Voltages U_6/U_{min} and U_7/U_{min} over time for two cells loaded in series in an unloaded battery without a BMS system (room temperature T_o = 20°C, free cooling, t_1, t_2 - moment of switching on and off the load current, t_3, t_4 - moment of turning on and off the balancer, U_{min} - minimum cell voltage equal to 2.5 V)

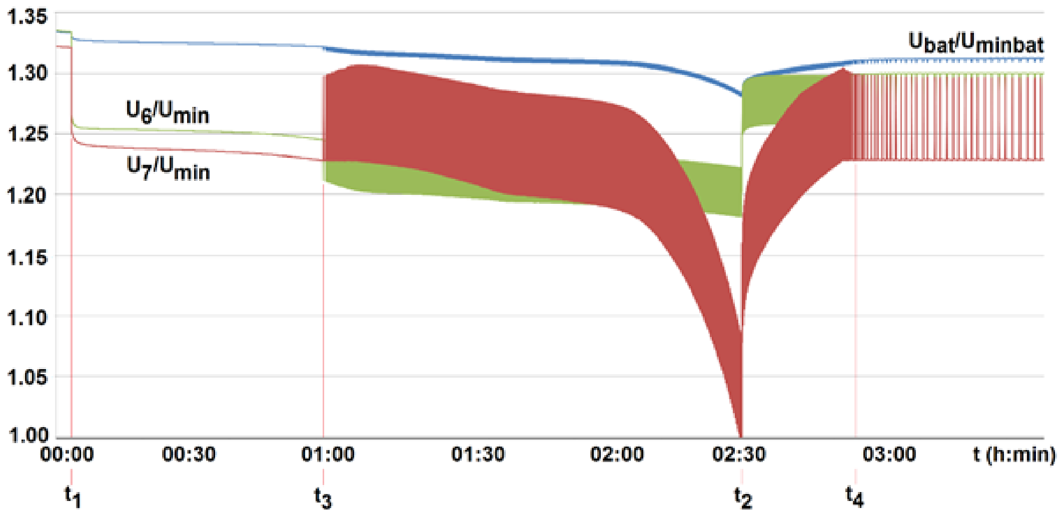

Fig. 11. Graph of the voltage value on two loaded cells for a BMS system with passive balancing. Voltages U_6/U_{min} and U_7/U_{min} over time for two cells loaded in series in an unloaded battery without a BMS system (room temperature T_o = 20°C, free cooling, t_1, t_2 - moment of switching on and off the load current, t_3, t_4 - moment of turning on and off the balancer, U_{min} - minimum cell voltage equal to 2.5 V)

Findings

The research shows that active balancing systems (BMS) contribute to extending battery life, especially when cells are discharged to the minimum voltage (Umin = 2.5 V). The improvement in battery life is particularly noticeable as the number of cells in the system increases, but these effects remain effective only until the number of cells exceeds 50%. The increase in lifespan results from better management of cell discharge, which improves their efficiency. However, in the case of passive balancing systems, the charging process of cells occurs only after the load is disconnected, allowing for the equalization of energy differences between cells, preventing overcharging, and protecting the battery from damage. The passive method ensures safety but does not result in the same significant improvements in lifespan and efficiency as active systems. Therefore, based on the research findings, it can be concluded that active balancing systems offer a clear advantage in terms of battery lifespan and efficiency, especially as the number of cells increases. While passive balancing is effective in terms of safety, it does not provide the same benefits in performance and system durability.

4. Description of the concept of the new solution

Previous research has shown that regardless of the use of active balancing of the lithium battery during operation, the process of charging the lithium battery when the load is disconnected is also important. In this case, a BMS with passive balancing works best, protecting against overcharging the cells, because they dissipate excess energy in the form of heat. On the other hand, a BMS with active balancing is more effective in energy management, because it does not dissipate excess energy in the form of heat, but transforms it and balances it between the cells. This is especially important in a situation where the battery cells being charged are already fully charged and the charging process is not fully completed. In such conditions, a BMS with active balancing allows for more precise energy management by transferring excess energy from overcharged cells to less charged ones. This type of balancing ensures evenly distributed voltage in the cells, which allows for their longer durability and also reduces the risk of damage caused by uneven charging. On the other hand, a passive BMS system works less efficiently in such cases, because excess energy from overcharged cells is dissipated in the form of heat. Although it is a protective mechanism against overcharging, the generation of excess heat can lead to unnecessary energy loss and an increase in temperature, which in turn can reduce the life of the battery. In the context of charging lithium batteries, when the cells are almost fully charged, active balancing offers a clear advantage, as it ensures an even distribution of energy between the cells, which increases the efficiency of the charging process. This reduces the risk of overheating and damage to the cells, and the battery itself is able to withstand more charge and discharge cycles. However, it is worth noting that in the actual use of lithium batteries, the use of a BMS system in which both types of balancing, i.e. active and passive, are used, is beneficial, as it will be possible to achieve both safety and high energy efficiency. Active balancing can be used in more demanding conditions, while passive balancing can play a protective role during charging, especially in the absence of load.

The concept of a passive-active BMS system

In the developed concept of a mixed BMS system, two balancing methods will be used: active and passive. The system will consist of three modules (Fig. 12):

- measurement and control module - a control system used to measure the voltages of connected cells and control the operation of the entire BMS system and supervise battery operating parameters,
- passive balancing module - assigned to each cell, they allow for the physical implementation of the balancing process, i.e. dissipation of excess energy into heat using resistors connected in parallel to the cells,
- active balancing system module - assigned to each cell, they allow for the physical implementation of the balancing process, i.e. transfer of energy to other cells using the battery-to-cell method.

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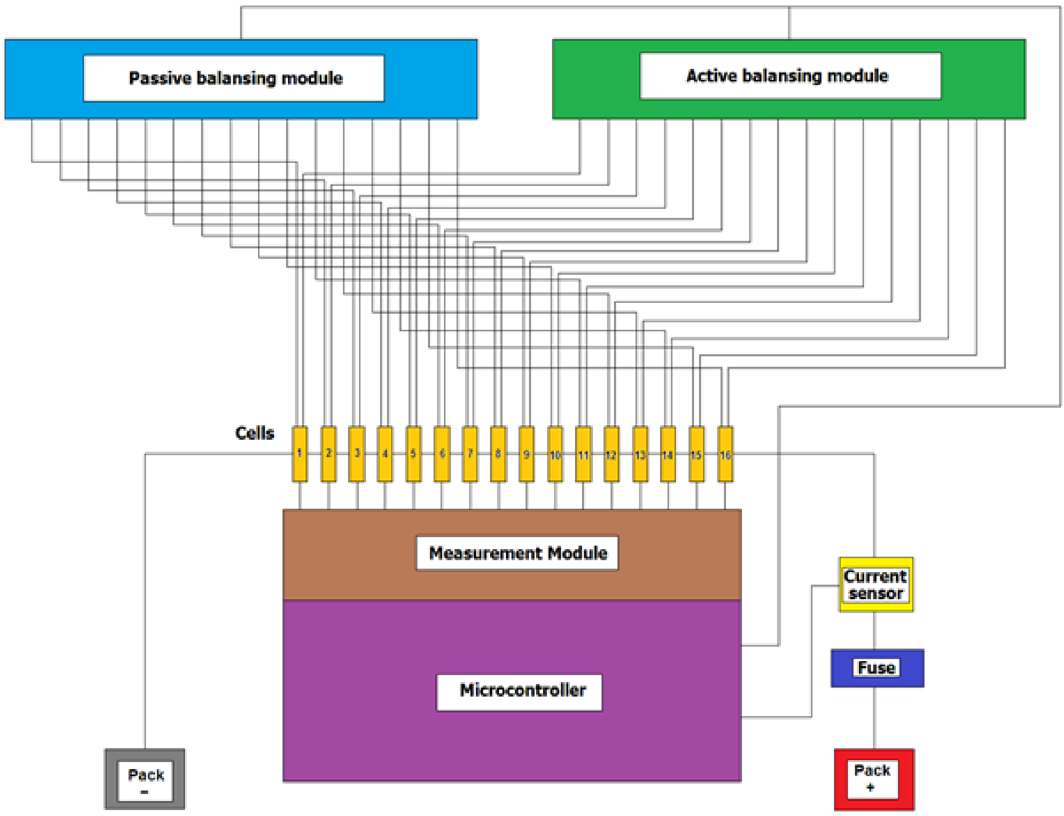

Fig. 12. An example of a mixed BMS system designed to manage battery operation

Measurement module

In the measurement module, the voltage values of individual cells will be monitored in the microcontroller via analog-to-digital converters to whose input individual cells will be connected. Additionally, temperature measurements of individual cells will be performed via the microcontroller's analog-to-digital converter.

If overload, overvoltage, undervoltage or overheating and/or any other dangerous situation occurs, the battery will be disabled. Maintaining an unsafe situation is both undesirable and dangerous. It shortens the battery life and may affect the safety of its use.

The measuring module also performs the function of checking the battery charge level. This value will be calculated on the basis of data from measuring the voltage value on individual battery cells.

Active balancing module

Balancing in the battery-to-cell method involves transferring energy from the entire battery to the weakest cell. The balancing process equalizes the state of charge of individual cells in the battery and aims to maximize the use of its capacity and extend its service life. Typically, the cells that make up the battery do not differ much in capacity, but after several charging-discharging cycles without balancing, this difference becomes significant and may lead to a situation in which the voltage on one of the cells drops below the safe operating limit recommended by the manufacturer. Continued use may be dangerous and may damage the battery. This situation means that the maximum energy obtained from the battery is limited by the cell with the smallest capacity.

The discrepancy in the amount of energy stored in the cells in the battery system is very important in relation to the life expectancy of the battery. Without a BMS system, the voltage values on

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individual cells may differ significantly from each other after some time. The capacity of the entire battery may also decrease rapidly during operation, resulting in the battery system becoming completely unusable.

Passive balancing module

The operation of this system is based on the dissipation of excess energy into heat using resistors. If the voltage of any cell significantly exceeds the voltage of the others, it is short-circuited by an appropriate switch. This results in the discharge of a given cell through an element of the passive balancing circuit - a resistor, connected in parallel with each cell and continues until the voltage of the overcharged cell equals the voltage of the remaining cells. The package loading then continues.

Operation of the passive-active BMS system

The passive-active BMS system will measure the voltage and temperature on each battery cell and, depending on the measured value and type of operation, activates one of the two balancing modules or both at the same time. There are two types of work: discharging and charging.

In the event of discharge during operation or standstill of a device or machine powered by a lithium battery, when the voltage drops below a set threshold (e.g. 3 V), the active balancing system will be activated, while the passive balancing system will be inactive. Cell balancing will continue until the voltage levels on all battery cells are equal or if the voltage on any cell drops below the minimum value set by the manufacturer.

When charging battery cells, both balancing systems are activated. In this situation, the active balancing system adds additional energy to the weakest link. However, when the voltage on any cell approaches the maximum limit set by the manufacturer, the passive balancing system is activated to prevent the cell from overcharging by dissipating excess heat using resistors. If there is a situation in which there is more energy in the charging process than can be dissipated into heat, the controller turns off the charger and switches to the state of measuring cell voltages. As soon as the cell voltages drop below the maximum value, the controller turns on the charger and both balancing systems again. If the voltages on the cells are already close to the maximum voltage, then only the passive balancing system will be turned on, while the active balancing system will be turned off. The operation of the mixed BMS system will be completed when the voltages on all cells have the same value (close to the maximum voltage consistent with the voltage specified by the manufacturer).

This operation of the passive-active BMS system should shorten the time needed to charge a lithium battery, because downtime caused by turning off the charger due to energy saturation of the strongest cells will occur less often. An example simulation of the operation of a passive-active BMS system is presented in Fig. 13.

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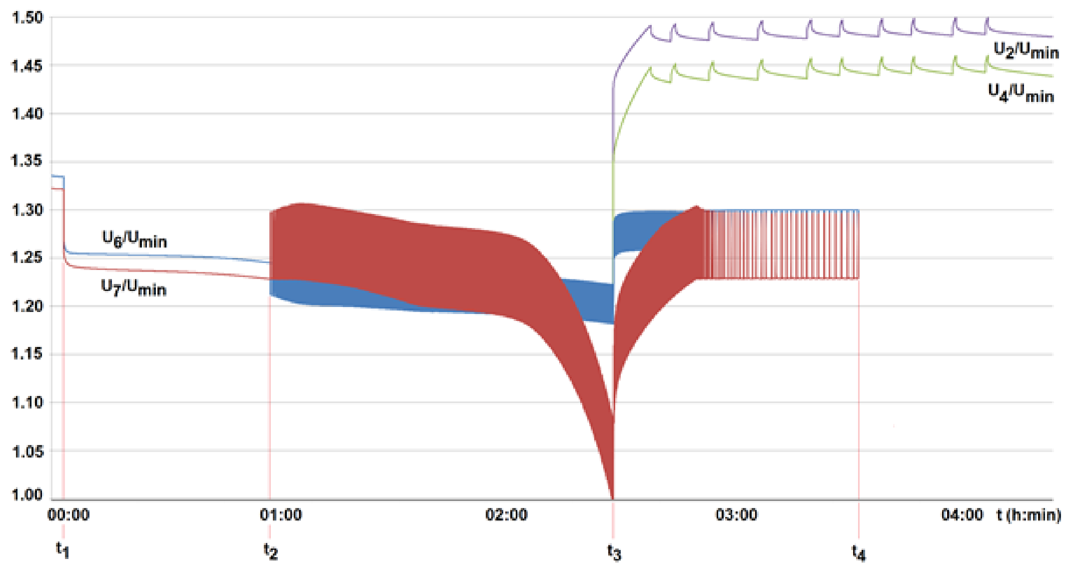

Fig. 13. Example of theoretical simulation of the voltage waveform on two loaded cells for a passive-active BMS system

5. Conclusions

An analysis of BMS systems with active and passive balancing of lithium cells was carried out. On this basis, the concept of a passive-active BMS system was proposed, which by combining active and passive balancing in one system will increase the possibility of effective and safe operation of batteries made of lithium cells.

The proposed solution will extend the operating time of a machine or device powered by a lithium battery because balancing battery cells is a key issue in managing the batteries of electrically powered vehicles, increasing the efficiency of the battery pack while extending its life cycle and ensuring safe operation at all times.

The benefit of a BMS system constructed in this way is that the active part of the balancing system will equalize the voltages on all cells and extend the battery life, while the passive part will ensure a safe charging process by leveling the differences between cells with lower and higher energy levels, protecting the battery against overcharging the cells.

The operation of the passive-active BMS system will shorten the time needed to charge a lithium battery, because downtime caused by turning off the charger due to energy saturation of the strongest cells will occur less often.

The use of such a solution can significantly improve the functioning of a device powered by a lithium battery. The battery will be protected at every moment of its use, i.e. during operation, parking and charging. The efficiency of the battery results from the efficiency of individual cells, especially the weakest ones.

Currently, energy storage is a dynamically developing industry, especially in connection with photovoltaic installations. The use of active balancing allows you to extend the battery life, as well as the use of recycled batteries that were no longer suitable for cooperation with passive balancers due to their insufficient performance. An active balancing system, the use of which will be economically justified, will constitute a market innovation.

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