Lithium-Iron-Phosphate Battery Performance Controlled by an Active BMS Based on the Battery-to-Cell Method

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Abstract—**The article discusses the results of research on the efficiency of a battery assembled with lithium-iron-phosphate (LiFePO₄) cells when managed by an active Battery Management System (BMS) using the "battery-to-cell" energy transfer. This arrangement was especially developed by the authors and is intended for use in a selected suspended mining vehicle. The main emphasis was placed on variation of the two most important factors limiting in practice the effective use of a selected battery: a battery heating during operation and its voltage (power) fade over time. The advantage of the active BMS developed using the "battery-to-cell" energy transfer was compared both with the active BMS based on the cell-to-battery method and with the passive BMS as well. Particular attention was paid to the performance of the BMS balancing effect during the simulated unequal discharging of randomly selected cells (from 12 % to about 40 % of all cells number in the battery). The results obtained allowed for the formulation of appropriate conclusions and practical recommendations.**

Index Terms—**Active BMS system; Battery-to-cell method; Lithium-iron-phosphate cells; Suspended mining vehicle.**

I. INTRODUCTION

The growing demand for electric drives in mines requires the availability of appropriate sources of electricity. They must be safe in work (especially in an environment at risk of fire and/or explosion) and do not create excessive problems under as handling and operation. It is also important to possess the right electrical efficiency to minimize possible power outages of the powered device. In addition, for suspended mine electrical equipment, the small size and weight of a source of electrical energy are a key factor. It is also desirable that the battery lasts as long as possible on a single charge. This reduces the number and time of interruptions in the operation of the powered device necessary to recharge the battery. Thus, it increases the efficiency of its work and the entire production process. Due to significant technological development, it has become

possible to extend the scope of safe use of lithium batteries. They are far more expensive than traditional lead batteries but show much better electrical performance. However, they must be properly managed and protected so that they can be used successfully in an onerous mining environment (risk of methane, coal dust, temperature, water, and/or fire). It should be emphasized that underground mining in the world takes place at ever greater depths with temperatures exceeding 40 °C. The safety of the mine operation is significantly reduced at higher environmental temperatures, and as a result the possibility of failure of the operating machinery and equipment increases. Therefore, the key problem here is to prevent damage to the lithium batteries used so that the electrolyte does not decompose, causing an increase in gas pressure inside the cells. As a result of such a situation, the ignition of the damaged cell and its explosion may appear. It is therefore necessary to employ the lithium batteries strictly within the safe voltage, current, as well as temperature range specified by the manufacturer. To increase the operational safety of lithium batteries and extend their lifetime, it is necessary to use appropriate electronic supervision modules, known as Battery Management Systems (BMS) [1]–[3]. Their task is to control and properly balance cells to prevent overcharging, overdischarge, and overheating [4]–[6]. First, lithium batteries are not very resistant to full and/or the so-called "deep discharge". If left in this state for a long time, they can be irreparably damaged. If the voltage drops below the permissible minimum value U_{min}, the crystal structure of the cell is damaged. Further charging becomes impossible [7]. The task of the BMS system is therefore to control the online parameters of each cell and, in the case that the specified threshold (voltage, current, temperature) is exceeded, to alarm and/or disconnect the battery [8]. BMS is also required to properly balance the energy of the cells used to increase battery efficiency and its lifetime [9]–[11]. The balancing requirement is due to differences in the actual values of charge, capacity, and/or resistance of the

individual battery cell. These differences are due to the manufacturing tolerances and working conditions of the same links and tend to increase during operation. It should be noted that due to the volatility of the capacity value over time, "weaker" cells may be overloaded during charging. This can lead to cell failure and ultimately damage to the battery. Therefore, if at least one cell is mismatched and indicates a smaller capacity, the capacity of the completed battery also decreases accordingly [12]–[14]. The problem of safe use of lithium-ion batteries is quite widely analyzed in the literature on the subject. New solutions for BMS systems are also being developed. For example, a new system topology based on passive and active balancing methods is presented in [15]. An active balancing method based on bypass technique was applied to the designed BMS. The applicability of these methods was separately tested as passive- and active-based experimental systems. A new state-of-charge (SOC) balancing method with a parallel and serious output connected battery power modulus in an active BMS is discussed in [16]. To increase both the battery pack and the modularity at the system level, the BMS controls the average SOC of the entire battery pack by regulating the input currents of all BPMs to a common reference. In [17], a review of the most current active battery cell equalization methods is conducted, where it is classified as adjacent-based, non-adjacent-based, direct cell-cell, and mixed topologies. This classification can provide a comprehensive way to analyze and compare the performance of existing active cell balancing methods. The paper in [18] proposes an estimation scheme of enabling state of health (SOH) based on the incremental capacity analysis (ICA) method for real-world electrical vehicles (EVs). The effectiveness of the proposed method is verified using datasets collected from well-controlled laboratory tests and daily operating EVs. The results show that battery cells within a batter pack generally experience similar degradation routes, which means insignificant cell inconsistency development with aging, and the proposed method can realize an accurate pack level SOH estimation for both laboratory battery packs and real-world EVs. The paper in [19] in turn presents a novel approach to extract the equivalent circuit model parameter from a pulse test. The model values obtained from the test of a lithium-ion battery cell correlate with physical parameters and other investigation methods like the calculation of the distribution of relaxation times (DRT). As a result, an accurate equivalent circuit model of the cell was created. However, based on results of their own research, the authors found the possibility of reliable use of a lithium-iron-phosphate battery to power a selected suspended mining vehicle. It meets expectations due to the specially developed active BMS structure [20]. As a new challenging contribution, the authors set out to find an answer to the question of what is the gain in battery life for one charge depending on the number of unevenly loaded cells in the battery when using an active BMS (battery-to-cell).

Therefore, the article presents the results of research on the performance of the battery pack (composed of lithium-iron-phosphate cells (LiFePO$_4$)) when controlled by the active BMS system using the battery-to-cell method. This arrangement was especially developed by the authors and is intended for use in a selected suspended mining vehicle. The main emphasis was placed on variation of the two most important factors limiting in practice the effective use of a selected battery, which is a battery heating during operation and its voltage (power) fade over time. The usefulness of the developed active BMS structure based on the principle of "battery-to-cell" was compared with the active BMS using the cell-to-battery method and with the passive BMS solution commonly used in practice (especially in the automobile industry). Due to the intended use in underground mines, the tests were carried out at both at room temperature (+20 °C), with free heat exchange to the environment, and elevated temperature (up to +60 °C) with a constant humidity of 75 % for restricted heat transfer. Particular attention was paid to performance of the BMS balancing during the simulated unequal discharging of randomly selected cells (from 12 % to about 40 % of all cells number in the battery), which is novelty. Such battery operation conditions are inevitable in the mining environment. Considerations regarding the practical use of a lithium-iron-phosphate battery to power a suspended mining vehicle, along with the selection of an active BMS solution, are presented in Section II. The choice of the method and scope of the research are given in Section III. The results obtained are discussed in Section IV, including representative selected measurements to clarify the essence of the matter. The article ends with an explanatory summary (Section V). On the basis of the obtained research results, appropriate conclusions and practical recommendations have been formulated.

II. SELECTION OF PRACTICAL APPLICATION AND THE METHOD OF BALANCING

The research of the authors shows that it is possible to safely and effectively use lithium-iron-phosphate (LiFePO$_4$) batteries common in vehicles to power selected mining devices and drives [21]. For this purpose, however, it is obligatory to use an appropriate active BMS to increase durability, safety, and high operational reliability in mining onerous conditions [22]. The proposed solution is very beneficial and most desirable because the use of wireless and zero-emission drives significantly improves the environmental conditions in mines with reduced ventilation requirements. Due to the urgent need to implement environmentally friendly advanced technical solutions of any drive with reduced weight and increased safety at work, the authors decided to use a LiFePO$_4$ battery for an overhead mining vehicle type PCA-1 as an example. The view of its installation is shown in Fig. 1.

The selected vehicle (PCA-1) is a transport machine for loads up to approximately 2 tons with slight slopes up to 120 ° in mining excavations. It moves along the route of the suspended monorail with the I 155 profile, with a driving force of up to 3.7 kN when supplied with a DC voltage of 48 VDC. The battery power unit with a resulting energy of 150 kWh will be placed in a special case for protection.

When it comes to BMS solutions, in the literature, two practical methods of balancing cells in a battery are highlighted, i.e., the so-called "active" and "passive" [23].

The third method of selecting cells of close electrochemical parameters is, firstly, expensive and, secondly, does not ensure the maintenance of constant parameters of the cells during operation. The most commonly used in practice (especially in the mobile industry) is passive balancing. It is a relatively simple and, therefore, inexpensive way. It is based on dissipation of excess energy of a given cell into heat over appropriately used resistors. From a mining point of view, it is disadvantageous because it starts to activate only after disconnecting the battery from work and starting to charge it. In addition, machinery and equipment intended for use in mines must meet the requirements of the ATEX directive. It defines *inter alia* the limit values of the temperature of elements that are in direct contact with the mine environment [24]. Therefore, an alternative to passive balancing is only the active one. It can be implemented in several ways [25]. However, all of these structures are based on the transfer and distribution of energy between cells [26]. This reduces energy losses related to the dissipation of excess energy into heat, creating optimal working conditions for the cells throughout their service life. As a result, the battery lifetime is extended. Because ,there is no suitable active BMS available on the market (especially for particular applications), the authors developed and tested two different solutions of active structures for powering PCA-1-type suspended vehicles. These BMS models are not intrinsically electric sparking - safe and must therefore be placed (together with the battery) inside a special metal housing to meet the requirements of the ATEX directive. Therefore, like cells, they are exposed to the same onerous temperature conditions. In truth, the active BMS solutions are quite complex, and their price increases with increasing number of cells. Therefore, to reduce the costs of investigations under preliminary testing, the authors limited the research to battery sets consisting of a limited to eight series-connected cells (see Fig. 2). However, note that the significant increase in the number of cells and the conclusions drawn from the tests are not limited only to the size of the tested battery pack and its voltage level.

Fig. 1. General view of the installation of a selected suspended battery vehicle (PCA-1).

Fig. 2. Battery pack arranged of eight lithium-iron-phosphate (LiFePO$_4$) cells for testing.

A block diagram of the measurement system of one of the two active BMS solutions developed in the KOMAG Institute of Mining Technologies (Gliwice, Poland) is shown as an example in Fig. 3. The cell-to-battery method was used here, i.e., the energy transfer takes place from the most charged cells to the entire battery pack. This solution is described in detail in the article [27]. On the contrary, for the second active BMS solution, the battery-to-cell method was employed. This method uses energy transfer from the entire battery to the "weakest" cell. As a result, the charge of particular cells is equalized. The developed BMS, whose block diagram of the measuring system is shown in Fig. 4, consists of a measurement and control module (Fig. 5) and a balancing one (Fig. 6). Measurement data are available for reading and recording using a Secure Digital (SD) MultiMedia Card (MMC).
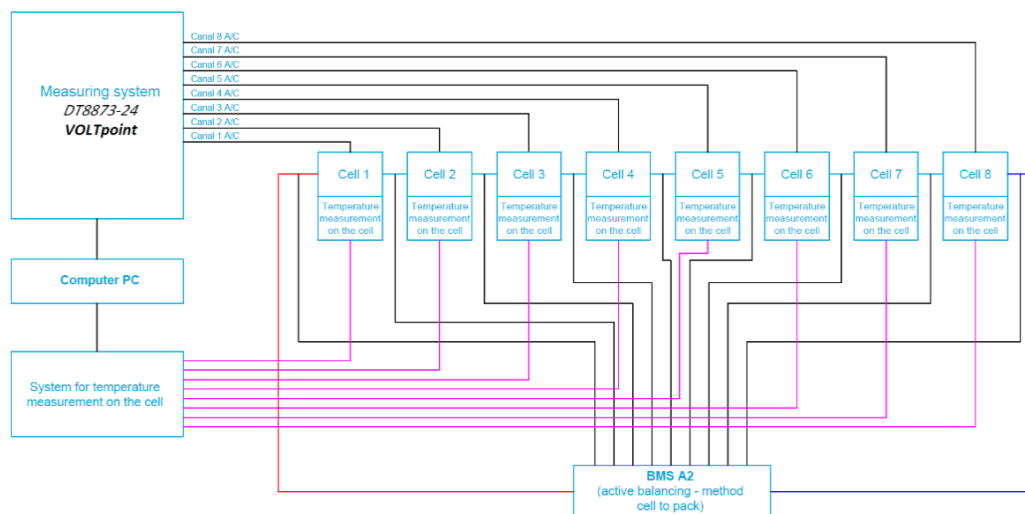

Fig. 3. Block diagram of the cell measurement system for the battery with a connected BMS with active balancing, the cell-to-battery method.
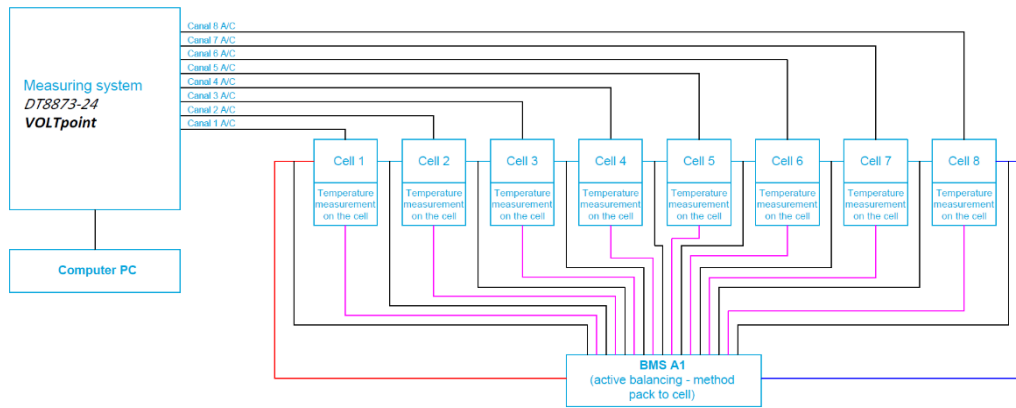
Fig. 4. Block diagram of the cell measurement system for the battery with a connected BMS with active balancing, the battery-to-cell method.
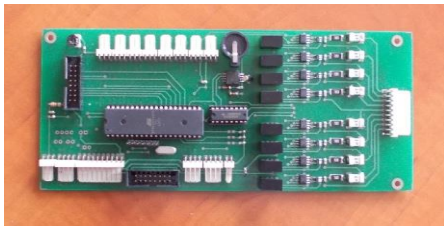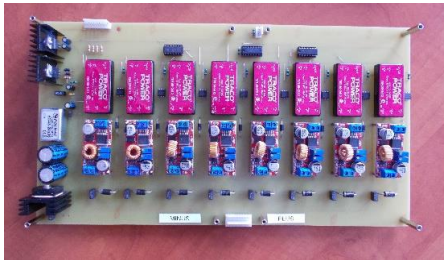

Fig. 5. Measurement and control module.

Fig. 6. Balancing module.

III. METHOD AND SCOPE OF RESEARCH

The tests were carried out for Headway LFP38120 (S) lithium-iron-phosphate cells of the basic technical data as follows [28], [29]:

- Voltage: 3.2 V,
- Capacity: 10 Ah,
- Internal resistance: < 6 mΩ,
- Charging voltage: 3.65 V ± 0.05 V,
- Energy density: 105 Wh/kg,
- Technology: lithium-iron-phosphate ($LiFePO_4$),
- Maximum discharge voltage: 2.5 V–2.0 V,
- Range of operational temperatures:
    - Charging: 0 °C–45 °C,
    - Discharging: -20 °C–65 °C,
- Life: over 2000 cycles (80 % of capacity when loading with 10 A current).

Because it is obligatory to control the temperature of each cell during BMS operation, it was necessary to determine the location of the measuring point of the highest temperature. Therefore, analog device temperature sensors were used as indicated in Fig. 7.

The test results show that the highest temperature appears at the positive (+) pole of the cell, which for discharging with 4.9 A current (about 50 % of the standard discharge current value) is illustrated, e.g., in Fig. 8, whereas the smaller one is at point T_4, respectively.

After the temperature tests were completed, further research was conducted for eight-cell battery packs. They were sequentially connected to the appropriate active and/or passive BMS system for comparison. Performance at room temperature (about + 20 °C, humidity 40 %) with free heat transfer from the battery to the environment was studied primarily. The view of the test stand equipped with both a temperature and voltage measurement system (DT8873-24 VOLT point) and a computer with specialized software is shown in Fig. 9. However, to evaluate the operation of battery systems with BMS, when they are mounted in a closed housing on suspended vehicle, the tests were also carried out for distorted cooling and at elevated temperature (up to + 60 °C, humidity around 75 %). These studies were carried out in a climatic chamber and the results of the battery sets are presented in [30].
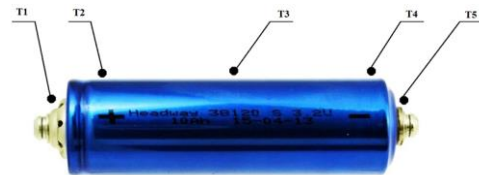

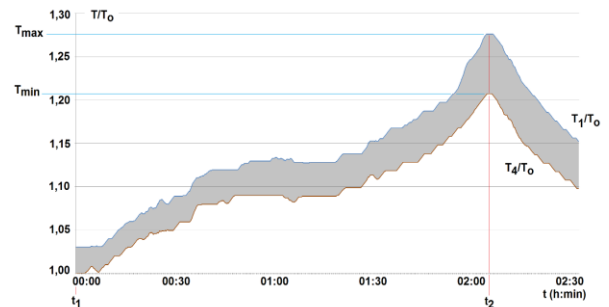Fig. 7. Arrangement of temperature sensors on the tested cell.

Fig. 8. Variation of cell casing temperature with time, at different measuring points ($T_1…T_5$) under discharge with current 4.9 A (around 50 % of the standard discharge value), room temperature $T_o = 21$ °C.

To test the balancing effectiveness of the BMS, an asymmetric loading of completed cells was needed. Therefore, for an unburdened battery, randomly selected cells (from 1 to 3; that is, from 12.5 % to 37.5 % of the total number of cells) were loaded independently, as shown in Fig. 10. The load current was assumed to be 2.5 A, which is 25 % of the value of the standard cell discharge current. Both the voltage and the temperature of the battery and

individual cells were controlled.

Each test was initiated for a fully charged battery (voltage of all cells equal to the rated $U_n = 3.2$ V). The loading (with a current of 2.5 A) lasted until the voltage of any of the cells reached the minimum value ($U_{min} = 2.5$ V) stated by the producer. The tests carried out have shown that both the voltage values of the same-type cells and their temperature may differ from each other even when loaded (discharged) with the same current value. For selected 3 cells (37.5 % of all cell numbers of the battery) of the battery working without BMS, it is clearly visible in Fig. 11. This justifies the importance of using an appropriate active BMS.
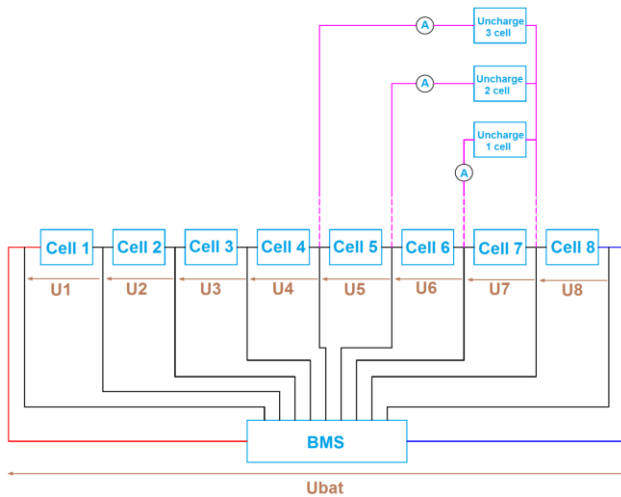

Fig. 9. View of the measuring stand.

Fig. 10. Block diagram of a cell test system for batteries with connected BMS when simulating unbalanced load of one, two, and/or three cells .
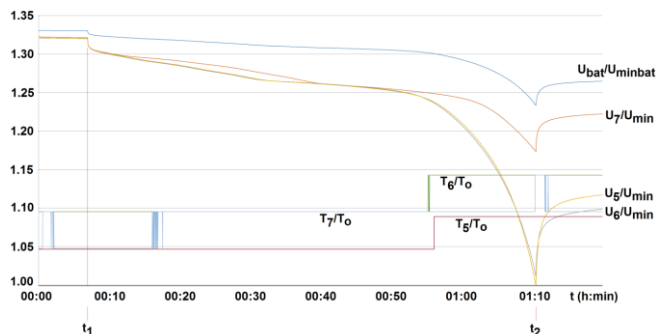

Fig. 11. The voltage U_5/U_{min}, U_6/U_{min} ,U_7/U_{min} and the temperature T_5/T_o, T_6/T_o, T_7/T_o as a function of time for three series-loaded cells (cells no. 5, no. 6, and no. 7 - see Fig. 10) of the unburdened battery without any BMS (room temperature $T_o = 21$ °C, free cooling, t_1, t_2 - on and off the load current of 2.5 A with respective recharging, U_{min} - minimum cell voltage equal to 2.5 A, U_{minbat} - minimum battery voltage 20 V, U_{bat} - battery voltage (maximum 29.2 V)).

IV. RESULTS AND DISCUSSION

To compare performance of the developed active BMS systems (both battery-to-cell and cell-to-battery), their technical parameters were respectively matched such that

balancing is activated when the voltage of any of the cells drops below 95 % of the rated U_n value (i.e., below 3.05 V). Then it is turned off when the voltage is lower than the minimum U_{min} value ($U_{min} = 2.5$ V) or higher than $U/U_n = 1.14$ (3.65 V). For BMS using the battery-to-cell method, it is shown in Fig. 12. The value of the balancing current was set at 2 A (approximately 40 % of the standard charging current). The differences in voltage waveforms (seen in Figs. 11 and 12) result only from the method of measurement and data recording. It does not deteriorate in any way the accuracy of the measurement and hence the assessment of the analyzed balancing effect. For example, the temperature records of the loaded cells when employing the active BMS (battery-to-cell) as in Fig. 12 are shown in Fig. 13. It is seen that cell temperature is not equal and gradually increases with the battery life. However, its values do not differ much from each other without and with the BMS at room temperature for free heat exchange.
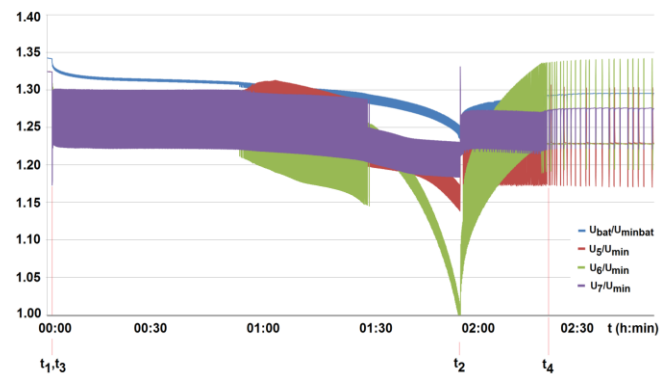

Fig. 12. The voltage U_5/U_{min}, U_6/U_{min}, and U_7/U_{min} as a function of time for three series-loaded cells (cells no. 5, no. 6, and no. 7 - see Fig. 10) of the unburdened battery with the BMS using the battery-to-cell method (room temperature $T_0 = 20$ °C, free cooling, t_1, t_2 - moment of switching on and off the load current of 2.5 A, U_{min} - minimum cell voltage equal to 2.5 A, U_{minbat} - minimum battery voltage 20 V, U_{bat} - battery voltage (maximum 29.2 V), t_3, t_4 - on and off the active balance).
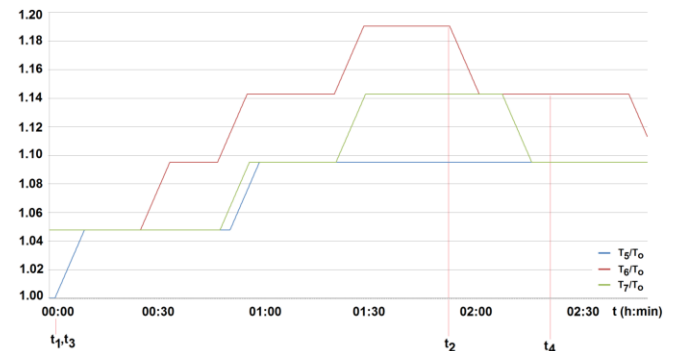

Fig. 13. Temperature $T_5…T_7$ change diagram of three loaded cells (37.5 % of total cell number) under operation with active BMS when using the battery-to-cell method as in Fig. 12 ($T_0 = 20$ °C).

The research conducted shows that the use of any of the two developed active BMS extends the battery voltage fading time t_2 on one (single) charge compared to work without BMS or with a passive BMS. Therefore, the battery life is accordingly increased. However, much better results are found to be provided by an active BMS using the battery-to-cell method (compare Figs. 11 and 12).

Extending the battery life on a single charge can be significant and several times exceed its fading time t_2, compared to operation without BMS and/or with a passive

BMS. For a case of the tested number of loaded cells, it was found to be not less than 100 %. However, provided that the relative number of non-uniformly loaded cells does not exceed 50 %.

However, this effect is non-linear and the relative gain of working time t_2/t_{2o}, for a single charging is the highest when the number of unevenly loaded cells of the battery is around 25 %, which can be seen from Fig. 14.
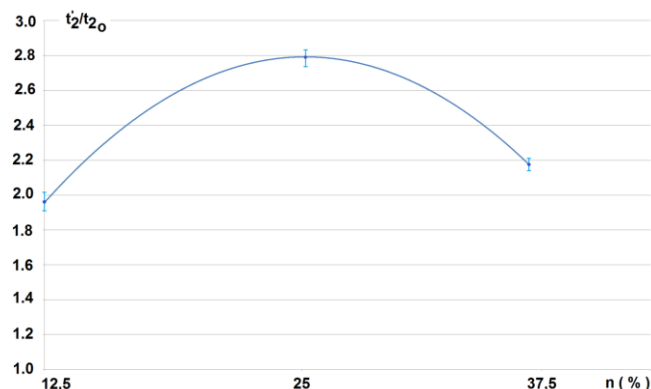

Fig. 14. Variation of the gain in the battery life t_2, for one charge due to the application of the active BMS (battery-to-cell), on the percentage share (n%) of series loaded cells in the battery (t_2, t_2' - time of switching off the load without and with the BMS, respectively).

V. CONCLUSIONS

For lithium-iron-phosphate cells to work long-term and reliably, their temperature and voltage variation during operation should be controlled online. This requirement is due to the limited cooling conditions and the significant thermal inertia of the cells used. As a result, cell temperature (even under room conditions around 20 °C and with free heat exchange with the environment) may increase to a significant and unacceptable value for safety reasons. This can happen not only when the cell is deeply discharged. The tests carried out showed that particular cells of the same type show different changes in temperature and voltage fading, even when loaded with the same current value. Therefore, it is necessary to balance them during operation. So, the lithium-iron-phosphate cells ($LiFeP0_4$) recommended by the authors can be used to power selected suspended mining vehicles, provided that the right active BMS is used.

The BMS systems available on the market, mainly passive ones, are not suitable for mining applications. This is due to the effect of undesirable heat dissipation by the applied equalizing resistors. In this situation, the values of the equalizing current would have to be significantly limited. This would adversely extend the balancing times and, as a result, would significantly reduce the efficiency of the supplied electrical device. The results obtained from the research carried out by the authors showed that the developed BMS system using the "battery-cell" energy transfer is the most advantageous for controlling and balancing lithium-iron-phosphate batteries to power a selected suspended mining vehicle. The voltage fading for a single (one) charge increases by at least 100 % and depends on the number of unevenly loaded cells. This effect is non-linear and is the greatest for the number of cells not exceeding 25 % of the total number of cells in the battery. It

should also be noted that although an increase in ambient temperature significantly reduces voltage fading, it does not significantly affect the cells overheating.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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