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Hybrid Battery Management System (BMS) for Lithium Cells Using Supercapacitors and Active Support – A Simulation-Based Comparison of Different BMS Architectures in MATLAB/Simulink R2025a

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Author's affiliations and addresses:

[1] KOMAG Institute of Mining Technology
ul. Pszczyńska 37, 44-100 Gliwice
Poland

[2] University of Žilina
Univerzitná 8215/1
010 26 Žilina,
Slovakia

[3] Missouri University of Science and Technology,
1006 Kingshighway
St. Rolla, Missouri 65409,
USA

*** Correspondence:**

e-mail: wkurpiel@komag.eu

Wojciech KURPIEL[1*], Pavol BOŽEK[2], Greg GALECKI[3]

Abstract:

The article presents the concept of a hybrid battery management system (BMS) that combines active and passive balancing of lithium iron phosphate ($LiFePO_4$) cells using a supercapacitor and an active energy transfer support circuit. The aim of the simulation study was to evaluate the effects of the applied balancing methods on the charging process, cell equalization time, and the potential for improving energy management efficiency in multi-cell battery packs. The simulations were performed in MATLAB/Simulink R2025a using a model of eight cells connected in series (8S), taking into account variations in the initial state of charge (SOC), capacity, internal resistance, and the dynamic and thermal characteristics of the cells. Five BMS configurations were compared: passive, active, hybrid, hybrid with a supercapacitor, and hybrid with a supercapacitor and active support. The results indicate the potential benefits of integrating active and passive balancing with an additional energy storage device in the form of a supercapacitor to improve the charging process and energy management within the battery pack. The proposed concept may be applicable to industrial energy storage systems and battery-powered systems supplying machinery and equipment, including those used in the mining industry. Further simulation and experimental studies are required to confirm the energy-related, thermal, and operational benefits of the proposed solution.

Keywords: battery management system (BMS), lithium batteries, cell balancing, supercapacitor, energy management, MATLAB/Simulink, energy storage, mining industry, electrical energy storage, power grids

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1. Introduction

The growing demand for efficient and reliable electrical energy storage systems is driving the rapid development of battery technologies and battery management systems. Lithium-ion batteries, including lithium iron phosphate ($LiFePO_4$) cells, are particularly important in this field due to their favorable operating characteristics, ability to undergo repeated charging and discharging cycles, and suitability for stationary and mobile energy storage applications. However, the safe and efficient operation of these power sources requires appropriate monitoring of the electrical and thermal parameters of individual cells, as well as effective management of the energy stored in the battery pack.

A significant challenge in multi-cell battery systems is the variation in the parameters of individual cells, resulting from manufacturing tolerances, differences in capacity and internal resistance, and aging and operating processes [1], [2]. Consequently, cells connected in series may reach their voltage limits at different times, even though the same current flows through the entire pack [3]. This limits the utilization of the pack's available capacity, may extend the charging process, and increases the risk of overcharging or excessive discharging of individual cells. Mitigating these effects is one of the primary functions of a Battery Management System (BMS), which monitors operating parameters, estimates the state of charge (SOC), controls the cell balancing process, and implements protective functions [4], [5].

In practical BMS implementations, passive, active, and hybrid balancing systems combining both methods can be used [6], [7]. Passive balancing is characterized by a simple design and relatively low cost; however, excess energy stored in cells with a higher state of charge is dissipated as heat. Active balancing, in contrast, enables energy transfer between cells, reducing energy losses and potentially improving the utilization of the battery pack's capacity. Combining both methods makes it possible to benefit from active energy equalization while retaining the ability to passively limit increases in cell voltage during critical charging phases. This is particularly important in industrial applications, including the mining industry, where operational safety and thermal condition control are as important as energy efficiency [8].

An additional way to enhance the functionality of active balancing systems is to use a supercapacitor as an intermediate energy storage device. It enables temporary storage of energy drawn from cells with a higher state of charge, followed by its transfer to cells requiring additional charging. When combined with a suitably controlled power electronic circuit, this approach enables multi-stage energy transfer and increases the flexibility of energy flow management within the battery pack. However, the actual benefits of using a supercapacitor depend on its parameters, converter efficiency, the adopted control strategy, and the characteristics of the cells used. These benefits therefore require verification through simulation and experimental studies.

The aim of this article is to present the concept of a hybrid BMS that combines active and passive cell balancing, a supercapacitor, and an active energy transfer support circuit, and to evaluate its performance through simulation studies. The analysis was conducted in MATLAB/Simulink R2025a by comparing five BMS configurations using a model of eight $LiFePO_4$ cells connected in series. The model accounts for variations in the initial state of charge, cell capacity and internal resistance, dynamic response, and thermal phenomena. The evaluation focuses primarily on charging time during the constant-current (CC) and constant-voltage (CV) phases, balancing time, and the effect of the selected configuration on the cell equalization process.

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The scope of the study includes a comparison of passive, active, and hybrid systems, as well as two extended hybrid configurations incorporating a supercapacitor, including a system with additional active support. The results make it possible to identify the potential benefits of integrated energy management methods and indicate areas requiring further investigation. Particular attention is given to the potential application of the proposed solution in industrial energy storage systems and battery-powered systems, where reliability, effective utilization of available capacity, and operational safety are essential. The simulation studies provide a basis for further validation of the concept, including analysis of the energy balance, thermal losses, balancing effectiveness, and the impact of the adopted control strategy on battery pack service life.

2. Balancing Methods in BMS

Balancing methods, in general, can be divided into the following three groups (Fig. 1) [8, 9]:

- Passive balancing – involves dissipating excess energy as heat using appropriately selecteesistors, impedance elements, and/or transistors.
- Active balancing – involves using an external balancing circuit to equalize the energy
- stored in the cells by transferring energy between individual cells (a less frequently used approach).
- Hybrid balancing – combines the features of active and passive systems; it involves active energy transfer between cells and passive protection against overcharging during the charging process.

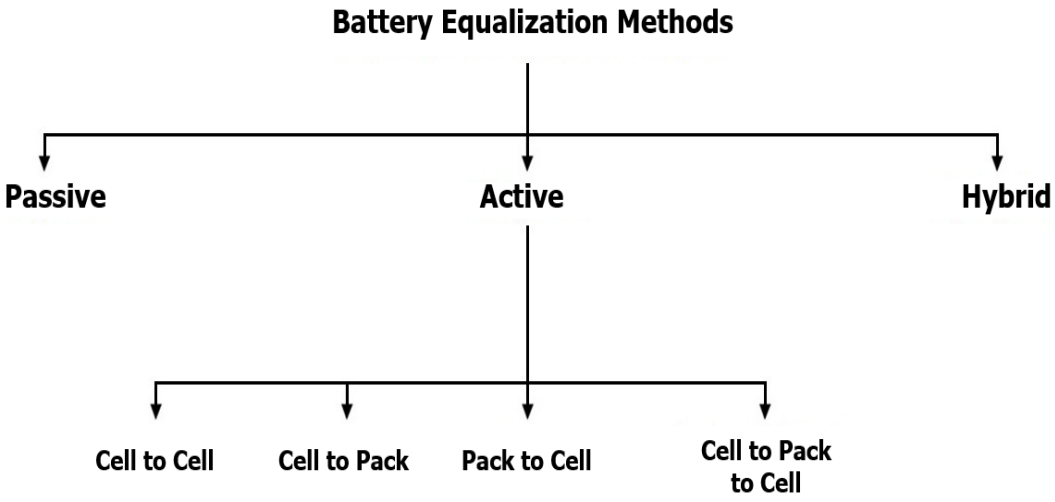


Fig. 1. Methods of balancing battery cells

Several active cell balancing methods are available. Based on the direction of energy flow, they can be divided into four basic subcategories: cell-to-cell, cell-to-battery, battery-to-cell, and the combined cell-to-battery/battery-to-cell method [10].

In practice, BMSs most commonly use passive balancing, which dissipates excess energy as heat. This solution is simple and inexpensive; however, it results in energy losses and may pose challenges in

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mining applications subject to ATEX Directive requirements concerning limits on the temperature of equipment components.

An alternative is active balancing, which enables energy transfer between cells, thereby reducing energy losses and improving battery operating conditions. However, the authors' previous studies have shown that the additional use of passive balancing during charging effectively reduces the risk of cell overcharging.

For this reason, implementing a hybrid BMS that combines the advantages of active and passive balancing is justified. Such a solution provides effective cell protection during operation, idle periods, and charging, while meeting the technical, operational, and economic requirements of modern battery systems.

3. Concept of a Hybrid BMS Equipped with Supercapacitors and Active Support

Previous studies have shown that, regardless of whether an active balancing system is used for lithium cells during operation, the proper implementation of the charging process is also crucial for the safety and service life of a battery pack. The final charging phase is particularly important, as differences in the state of charge (SOC) and voltage of individual cells may become apparent when no load is present. Under these conditions, an additional passive balancing circuit can reduce voltage differences between cells and protect cells with the highest state of charge against overcharging.

Based on these findings, a hybrid battery management system (BMS) concept was developed, combining active and passive balancing methods with an additional energy storage device in the form of a supercapacitor. The proposed solution aims to increase the utilization of the available battery pack capacity, reduce energy losses during balancing, improve energy efficiency, and enhance the safety of charging and discharging processes. The use of a supercapacitor also enables temporary energy storage and transfer between cells, potentially reducing the need to dissipate energy in balancing resistors.

The structure of the proposed hybrid BMS (Fig. 2) consists of five interacting modules:

- Measurement and control module, responsible for continuously measuring the voltage and temperature of individual cells, estimating their state of charge (SOC), identifying cells with the highest and lowest SOC, and controlling the operation of the balancing and protection circuits;
- Passive balancing module, consisting of balancing resistors connected in parallel with individual cells. Its purpose is to limit excessive increases in cell voltage during charging by dissipating excess energy as heat in a controlled manner. This module plays a particularly important role during the final charging phase, when the risk of overcharging cells with the highest SOC must be reduced;
- Active balancing module, which enables controlled energy transfer from cells with a higher SOC to cells with a lower SOC. Unlike passive balancing, energy is not directly dissipated as heat, allowing greater balancing efficiency and more effective utilization of the available battery pack capacity;
- Supercapacitor module, serving as an additional, fast-response energy storage device. This module enables temporary storage of energy drawn from cells with a higher SOC and its controlled transfer to cells requiring additional charging. Energy flow between the cells and the supercapacitor is controlled by a power electronic circuit supervised by the measurement and control module;

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- Active support module, enabling coordinated control of energy transfer between the cells and the supercapacitor. Its operation involves drawing energy from a cell with a higher SOC, transferring it to the supercapacitor, and then delivering it in a controlled manner to a cell with a lower SOC. The sequence and intensity of these operations depend on the current state of the battery pack, differences in SOC, permissible current and voltage limits, and the control algorithm. This module enables multi-stage energy transfer, allowing the supercapacitor to serve not only as an intermediate energy storage device but also as a component supporting dynamic energy management within the pack. Functionally, the active support module can be implemented as part of the active balancing system; however, identifying it separately in the BMS architecture emphasizes its role in controlling energy flow through the supercapacitor.

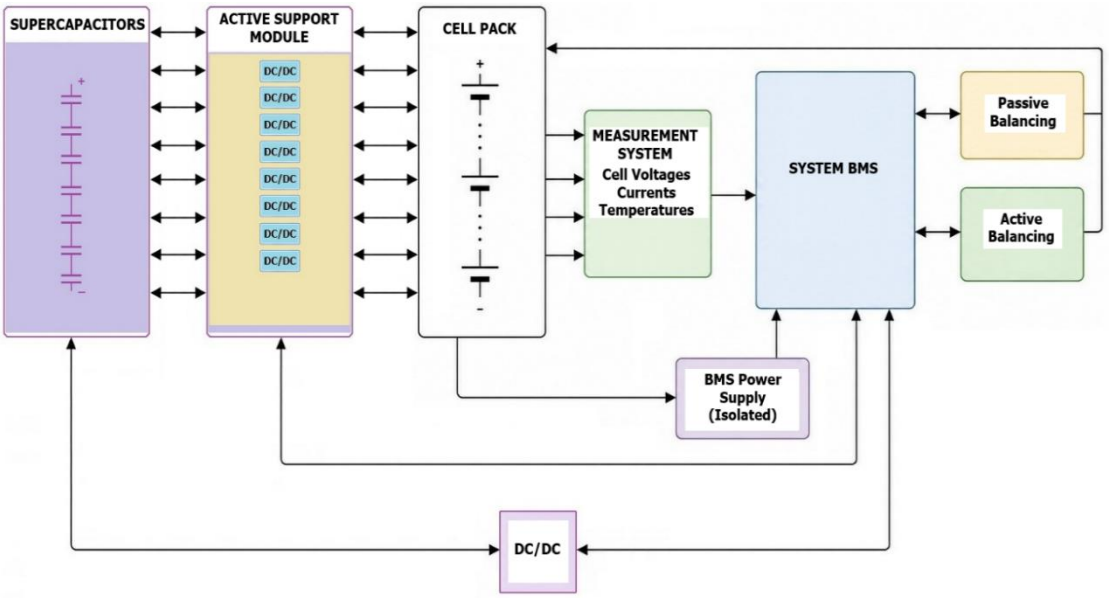


Fig. 2. Block diagram of a hybrid BMS equipped with supercapacitors and active support

The individual modules of the hybrid BMS interact according to the current operating state of the battery pack. The measurement and control module analyzes cell voltages, temperatures, current, and estimated SOC values, and then selects the appropriate balancing method and intensity. The choice of method depends, among other factors, on the magnitude of the differences between cells, the operating phase of the battery pack, current and voltage limits, and thermal conditions. During charging, monitoring the voltages of individual cells is particularly important. If a cell approaches its permissible voltage limit, the BMS may activate passive balancing, reduce the charging current, or terminate charging, depending on the adopted control strategy and the state of the battery pack. At the same time, active balancing can be used to transfer energy from cells with a higher SOC to those with a lower SOC, reducing charge imbalance and potentially lowering energy losses. In the extended hybrid configuration, the supercapacitor acts as an intermediate energy storage device, increasing the flexibility of the balancing process. Energy drawn from a cell with a higher SOC can be stored in the supercapacitor and subsequently transferred to a cell with a lower SOC. This approach separates the energy extraction stage from the energy delivery stage in time. It may be particularly beneficial when direct cell-to-cell energy transfer is limited by converter parameters or balancing current requirements.

However, the use of a supercapacitor does not, by itself, guarantee faster balancing or lower energy losses under all operating conditions. Achieving these benefits depends on the appropriate selection of

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supercapacitor capacitance, converter topology, control parameters, and the efficiency of the entire energy transfer path. Therefore, the effectiveness of the proposed solution should be verified through theoretical analysis and experimental studies, including assessments of balancing time, energy transfer efficiency, thermal losses, and the degree of battery pack capacity utilization. It should be emphasized that the supercapacitor and balancing circuits support energy management but do not replace the fundamental protective functions of the BMS. Ensuring safety requires independent monitoring of cell voltages, temperature, and current, as well as sufficiently rapid responses to any exceedance of permissible limits. If a potentially hazardous condition is detected, the system should limit or terminate charging or discharging in accordance with the adopted protection strategy.

4. Simulation of a Hybrid BMS Equipped with Supercapacitors and Active Support Compared with Other Systems in MATLAB/Simulink

To evaluate the operational characteristics and effectiveness of the proposed hybrid battery management system (BMS), simulation studies were conducted in MATLAB/Simulink R2025a. The primary objective of the simulations was to compare different methods of managing the state of charge of lithium iron phosphate ($LiFePO_4$) cells and to determine the effects of active energy transfer, passive balancing, and a supercapacitor on the battery pack charging process, cell state-of-charge equalization, energy losses, and thermal operating conditions.

The studies accounted for physical phenomena occurring during the operation of lithium iron phosphate ($LiFePO_4$) batteries, including variations in individual cell parameters, changes in the state of charge (SOC), voltage drops caused by internal resistance, the dynamic response of cells, and thermal processes. The model included both charging and discharging of the battery pack, with the main focus on the charging process and cell balancing effectiveness. The discharge phase served as a preparatory stage, bringing the pack to a predefined initial state to ensure comparable starting conditions for subsequent test cycles. This approach helps reduce the influence of random variations in the initial state of charge on the results obtained when comparing different BMS methods.

A particularly important aspect of the study was the analysis of battery pack behavior under cell imbalance conditions. In real-world battery systems, differences in capacity, internal resistance, and initial SOC cause individual cells to reach their voltage limits at different times. In a series-connected configuration, one cell reaching its voltage limit may necessitate reducing the charging or discharging current of the entire pack, even when the remaining cells still have usable capacity available.

From the perspective of industrial applications, particularly machinery and equipment used in the mining industry, this phenomenon has significant implications for the safety and reliability of power supply systems. Therefore, a BMS must not only ensure the most efficient possible use of available energy but, above all, monitor the electrical and thermal parameters of individual cells and prevent them from operating outside their permissible limits. This is particularly important in underground mining applications, including methane mines and locations where fire or explosion hazards exist. In such applications, the BMS should form part of a comprehensive battery power supply safety system designed in accordance with the requirements applicable to the specific operating environment.

As part of the study, models of eight independent $LiFePO_4$ cells and models of the individual BMS configurations were developed. This enabled a direct comparison of passive balancing, active balancing, and a hybrid solution incorporating a supercapacitor. The analysis included, among other parameters, individual cell voltage profiles, SOC, balancing currents, cell equalization time, energy losses, and thermal load.

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4.1. Model of the Battery Pack Under Investigation and Individual Cell Models

The subject of the simulation study is a battery pack consisting of eight lithium iron phosphate ($LiFePO_4$) cells connected in series in an 8S configuration. Each cell was represented by an independent electrothermal model that enables the determination and monitoring of voltage, current, state of charge (SOC), and temperature. The nominal voltage of a single cell was set to 3.20 V, its capacity to 10 Ah, and its operating voltage range to 2.50–3.65 V. These parameters correspond to a nominal total pack voltage of 25.6 V and a capacity of 10 Ah.

To reproduce real-world differences between cells, different initial SOC values, capacities, and internal resistances were assigned to individual cells. The electrical model incorporates the open-circuit voltage characteristic OCV(SOC), internal resistance, and a dynamic R_1–C_1 element that represents transient voltage variations and voltage relaxation following a change in current or the end of charging or discharging. Consequently, the cell terminal voltage depends on the current SOC and OCV characteristic, as well as the voltage drop across the internal resistance and the dynamic response of the model.

Additionally, a thermal model was implemented for each cell, taking into account power losses and heat exchange with the surroundings. This model enables the analysis of temperature variations resulting primarily from resistive losses and the operation of balancing circuit components. This is particularly important when comparing BMS methods, since passive balancing dissipates part of the energy as heat, whereas the use of active energy transfer and a supercapacitor can reduce energy losses and thermal load. The adopted model therefore enables a realistic assessment of the effects of cell parameter variations, voltage dynamics, and the selected balancing method on the operation of the entire battery pack.

4.2. Initial Conditions, Operating Cycle, and Balancing Strategies

To ensure realistic simulation conditions, different initial parameters were assigned to the eight $LiFePO_4$ cells, primarily including the state of charge (SOC), capacity, and internal resistance. The initial cell imbalance makes it possible to evaluate the effectiveness of individual balancing methods and reproduces the actual parameter variations found in multi-cell battery packs. These parameter variations affect the voltage and SOC profiles of individual cells, causing them to reach their limiting values at different times. This phenomenon is particularly important during the final stage of charging, when the risk of any cell exceeding its permissible voltage limit must be minimized.

The test cycle consists of three consecutive stages: battery pack discharge, a rest period, and charging using the constant-current/constant-voltage (CC–CV) method. Since the primary focus of the study is the charging and cell-balancing process, the discharge stage serves as a preparatory step to establish a repeatable initial point for the test cycle. Discharging is terminated when the voltage of any cell reaches the lower limit of 2.50 V. After discharging is completed, a rest period follows, after which the charging process begins.

Charging is performed using the CC–CV method, which comprises a constant-current (CC) phase and a constant-voltage (CV) phase. During the CC phase, the charging current is set to 5 A, with the balancing circuits initially disabled. The transition to the CV phase occurs when the voltage of any cell reaches the upper limit of 3.65 V. During the CV phase, the voltage is maintained at the specified level, while the charging current gradually decreases as the cells' ability to accept charge diminishes. Voltage hysteresis is introduced to prevent frequent switching of the charging process near the voltage limit. Once the voltage reaches 3.65 V, charging may be suspended and resumed when the voltage of the

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corresponding cell drops to 3.40 V. Implementing this mechanism requires monitoring the voltages of all cells and enforcing an overriding safety condition whereby the voltage of no cell may exceed its permissible upper limit.

During the CV phase, the balancing strategies appropriate to the BMS configuration under investigation are activated. In a passive BMS, excess energy is dissipated in balancing resistors. An active BMS transfers energy between cells, with the maximum balancing current set to 2 A. A hybrid BMS combines active energy transfer with passive balancing, enabling both mechanisms to be used simultaneously to equalize cell parameters. In the most advanced configuration, comprising a hybrid BMS with a supercapacitor and active support, an additional energy transfer path using a supercapacitor is implemented, together with direct energy transfer through a DC/DC converter from a cell with a higher state of charge to a cell with a lower SOC. The objective of this solution is to improve SOC equalization and reduce differences between cells during the final stage of charging.

During the simulations, the voltage and SOC of each cell, charging and balancing currents, cell temperature, and energy associated with the equalization process are recorded. This enables analysis of both charging dynamics and the effectiveness and energy efficiency of the implemented balancing strategies.

Discharging is terminated when the voltage of any cell reaches 2.50 V. Charging, in turn, is completed when the specified final SOC criterion and the applicable voltage conditions for all cells are satisfied. This criterion should also account for the permissible end-of-charge current if it is used in the CV-phase control model. Regardless of the selected charging termination criterion, any cell exceeding its permissible voltage limit must trigger an appropriate protective response from the BMS.

The adopted methodology enables different BMS configurations to be compared in terms of charging time, degree of SOC equalization, voltage distribution, energy used for balancing, and cell operating conditions. This makes it possible to evaluate not only the average state of charge of the battery pack but also the quality of cell-to-cell equalization, the energy efficiency of the process, and the level of operational safety.

4.3. Cell Parameter Heterogeneity

One of the fundamental assumptions of the simulation model is that the parameters of individual cells in the $LiFePO_4$ 8S battery pack are not identical. In a real battery pack, cells do not have perfectly identical characteristics. Differences may already exist at the manufacturing stage and may subsequently increase as a result of aging, the number of charge–discharge cycles, temperature variations, and different operating conditions.

For this reason, controlled differences between individual cells were deliberately introduced into the simulation model. The main parameters varied were capacity, internal resistance, initial state of charge (SOC), and the parameters of the RC elements describing the dynamic characteristics of the cells. This approach makes it possible to reproduce conditions resembling those of a real battery pack and to reliably evaluate the performance of individual balancing methods. The parameters adopted for the eight cells are presented in Table 1.

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Table 1. Parameters adopted for the eight cells

Cell	Capacity [Ah]	Initial SOC [%]	R_0 [mΩ]
Cell 1	10,00	82	3,0
Cell 2	9,90	78	3,2
Cell 3	10,10	85	2,9
Cell 4	9,80	80	3,3
Cell 5	10,00	88	3,0
Cell 6	9,95	76	3,1
Cell 7	10,05	84	2,8
Cell 8	9,85	79	3,2

For example, cell C5 has an initial SOC of 88%, whereas cell C6 has an SOC of only 76%. This corresponds to an initial SOC difference of 12 percentage points. At the same time, the cell capacities range from 9.8 Ah to 10.1 Ah, while the internal resistances range from 2.8 mΩ to 3.3 mΩ. These variations cause individual cells to exhibit different voltage drops when the same current flows through them, while their SOC values change at different rates.

Differences in internal resistance are particularly important during dynamic changes in current. A cell with higher internal resistance exhibits a greater voltage drop during discharge and a greater voltage rise during charging. As a result, it may reach its voltage limit earlier, even though its actual SOC is not necessarily the lowest or highest in the entire pack. Differences in capacity, in turn, cause SOC to change at different rates under the same current flowing through all cells connected in series.

The use of heterogeneous parameters is particularly important when evaluating a BMS. If identical models were used for all cells, the balancing process would be considerably less demanding and would not reflect the actual operating conditions of a battery pack. Introducing controlled parameter variations makes it possible to observe the development of voltage and SOC differences and determine the effectiveness of individual compensation methods.

The adopted initial SOC range of 76–88% enables a clear assessment of balancing system performance. In particular, cell C5, which has the highest initial SOC, represents a source of excess energy that needs to be redistributed, whereas cells with lower SOC values require appropriate charging. In subsequent experiments, the initial SOC difference can be reduced, for example, to a few percentage points, allowing BMS effectiveness to be evaluated under conditions involving a more balanced battery pack.

The model configured in this way makes it possible to reproduce a situation in which one cell reaches its voltage limit earlier than the others during charging. The BMS must then respond appropriately by limiting the charging process or activating a suitable balancing method. This enables the effectiveness of the four BMS configurations under investigation to be compared under conditions involving realistic variations in cell parameters.

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5. Simulation Results

Simulations of five battery management system (BMS) configurations were conducted in MATLAB/Simulink R2025a: passive, active, hybrid, hybrid with a supercapacitor (SC), and hybrid with a supercapacitor and active support. The analysis covered voltage profiles, charging and discharging times, balancing duration, and the contribution of individual cell-balancing mechanisms. The timing results are summarized in Table 2.

Table 2. The timing results of simulation

Parametr	Passive BMS	Active BMS	Hybrid BMS	Hybrid BMS + SC	Hybrid BMS + SC + active support
CC charging time [min]	104,675	104,675	104,675	104,675	104,675
CV charging time [min]	126,750	115,817	112,067	112,000	109,775
Balancing time [min]	126,750	21,558	112,067	112,000	109,775
Active balancing during CV [min]	0,000	21,558	1,242	1,992	1,992
Active support during CV [min]	0,000	0,000	0,000	0,000	0,200
Passive balancing during CV [min]	126,750	0,000	112,067	112,000	109,775

For all configurations analyzed, the charging time during the constant-current (CC) phase was 104.675 min, indicating that the use of different BMS configurations did not affect the duration of this phase under the adopted simulation conditions. Differences were observed during the constant-voltage (CV) phase, where the selected solution had a noticeable effect on the charging process.

The longest CV phase, lasting 126.750 min, was obtained with the passive BMS. For the active system, this time decreased to 115.817 min, a reduction of 10.933 min, corresponding to approximately 8.6%. The hybrid system achieved a CV duration of 112.067 min, shortening the phase by 14.683 min, or approximately 11.6%, compared with the passive solution. Adding a supercapacitor to the hybrid system resulted in a further, albeit small, reduction in CV duration to 112.000 min. The best result was obtained with the hybrid system incorporating a supercapacitor and active support, for which the CV phase lasted 109.775 min. Compared with the passive system, this represents a reduction of 16.975 min, or approximately 13.4%.

These results indicate that active and hybrid energy management can help reduce charging time, with the greatest improvement achieved by the configuration combining a hybrid system, a supercapacitor, and additional active support.

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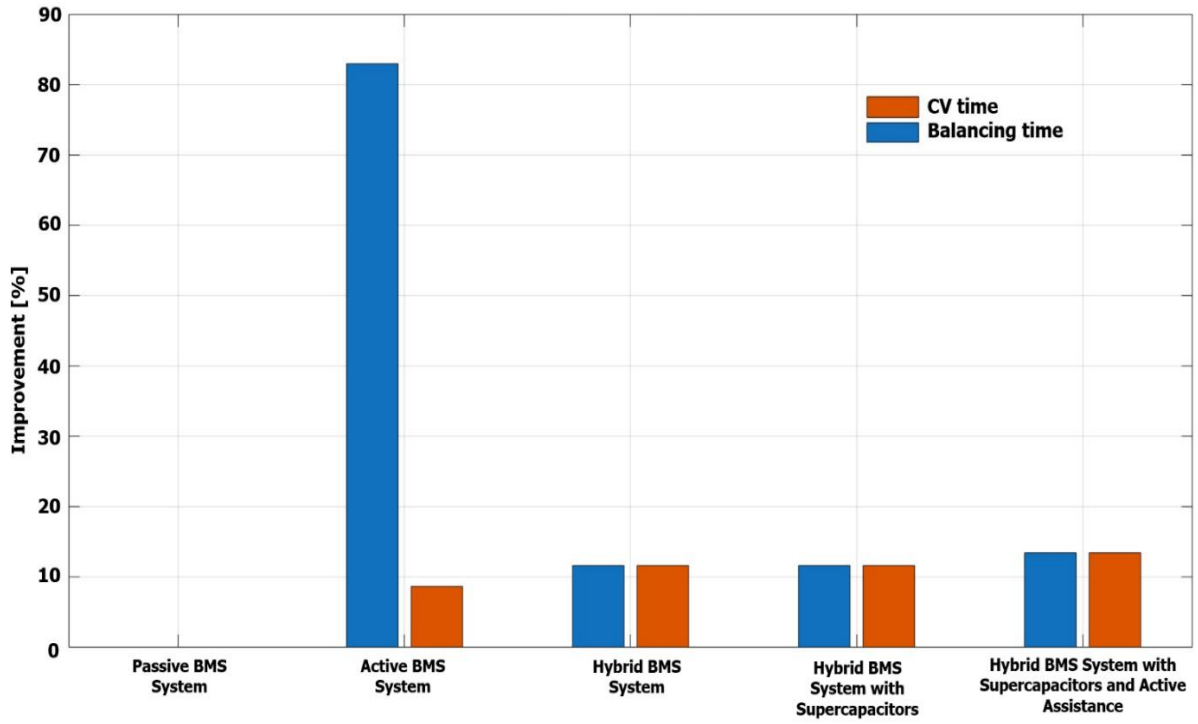


Fig. 3. Example simulation plot illustrating the improvement in balancing time

The analysis of balancing duration (Figs. 3 and 4) showed that balancing in the passive BMS lasted 126.750 min, corresponding to the entire CV phase. This results from the operating principle of passive balancing, in which excess energy stored in higher-voltage cells is dissipated as heat. In the active system, balancing lasted 21.558 min, indicating a shorter operating period for the energy-equalization mechanism compared with the passive solution.

In the hybrid system, the active-balancing duration during the CV phase was 1.242 min, increasing to 1.992 min when a supercapacitor was introduced. The same value was obtained for the configuration with additional active support. Meanwhile, the passive-balancing duration during the CV phase was 112.067 min for the hybrid system, 112.000 min for the hybrid system with a supercapacitor, and 109.775 min for the configuration with active support. These data indicate that both balancing mechanisms contribute to the operation of the hybrid systems. However, assessing their actual effectiveness also requires consideration of the voltage differences between cells, the amount of energy transferred between them, and the associated energy losses.

The effect of the supercapacitor on charging time was small, as the reduction in CV duration compared with the hybrid system without an SC was only 0.067 min, or approximately 4 seconds. A more noticeable improvement was achieved by introducing additional active support, which shortened the CV phase by a further 2.225 min compared with the hybrid system with a supercapacitor. The active-support operating time during the CV phase was 0.200 min, or 12 seconds.

This result suggests that short-duration active support may positively affect the charging process. However, a comparison of operating times alone is insufficient to determine its impact on the overall energy efficiency of the system.

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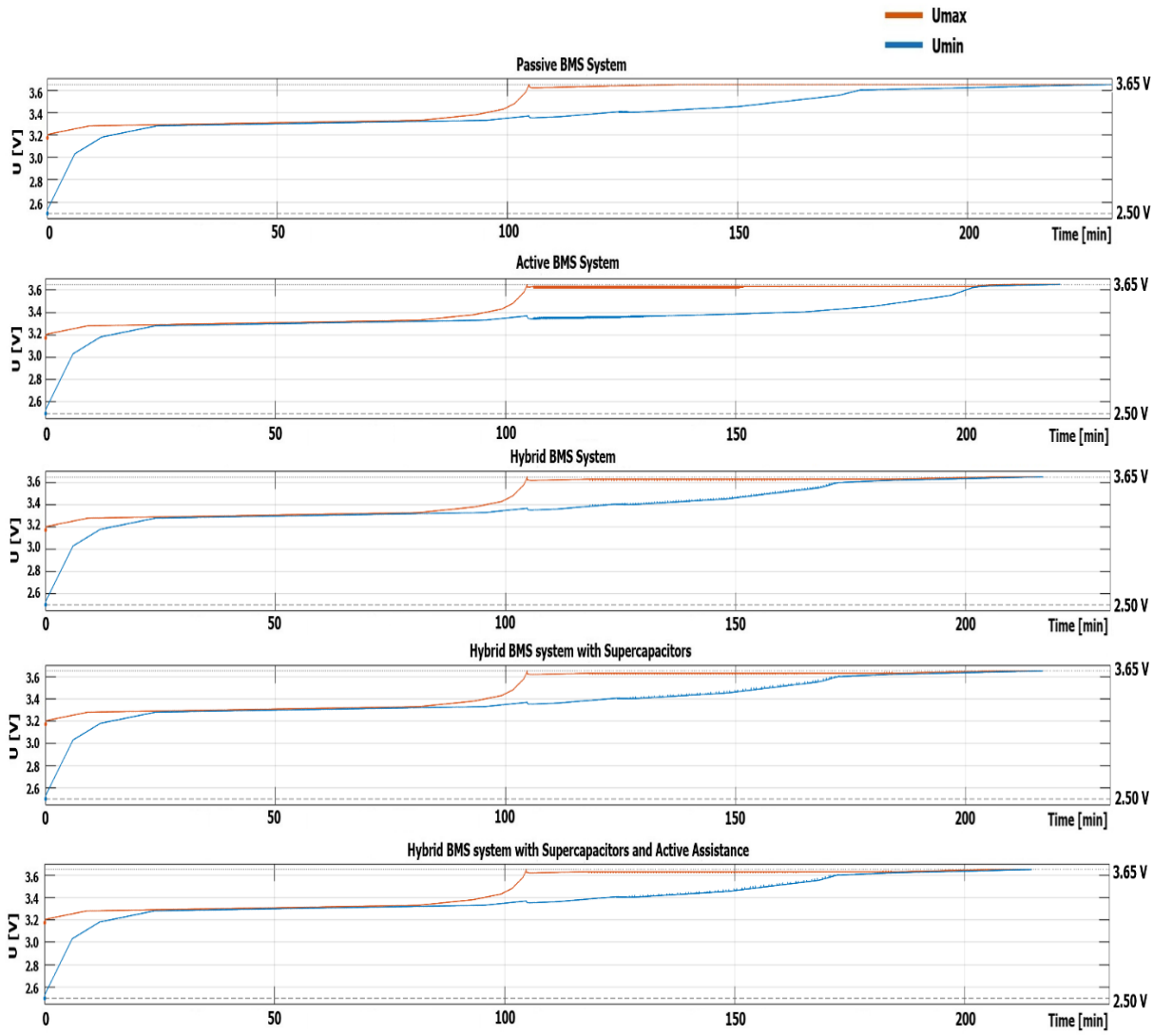


Fig. 4. Example simulation plot showing the variation in U_{min} and U_{max} during charging

This requires comparing the energy drawn from the power source, the energy stored in the cells, and the losses occurring in each configuration.

In summary, the simulations indicate that the greatest improvement in charging time during the CV phase was achieved by the hybrid BMS equipped with a supercapacitor and active support. Compared with the passive solution, the duration of this phase decreased by approximately 13.4%, while the charging time during the CC phase remained unchanged. The results support further investigation of hybrid energy management methods that combine active and passive balancing with additional energy storage devices.

A comprehensive assessment of the effectiveness of the analyzed solutions should, however, consider not only charging time but also energy efficiency, thermal losses, final cell-voltage equalization, and the impact of the implemented mechanisms on battery service life.

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6. Significance of the Solution in Industrial Applications

From the perspective of applying the proposed solution to industrial machinery and equipment, particularly equipment used in the mining industry, the primary task of the Battery Management System (BMS) remains ensuring the safe operation of the battery pack. This requires continuous monitoring of cell voltages, temperature, current, and state of charge (SOC), as well as the detection of abnormal operating conditions and the implementation of appropriate protective measures.

In mining applications, especially in methane-rich mines and areas at risk of fire or explosion, safety requirements apply not only to the BMS itself but also to the entire power supply system, including the battery, power converters, electrical connections, enclosures, and thermal management system. The equipment design must take into account the relevant explosion protection requirements, resistance to environmental conditions, and functional safety. Meeting these requirements necessitates the appropriate selection of technical solutions and the implementation of suitable conformity assessment procedures.

7. Conclusions

Simulations of five BMS configurations for an 8S $LiFePO_4$ battery pack, performed in the MATLAB R2025a environment, demonstrated that the adopted energy management configuration primarily affects the duration of the constant-voltage (CV) phase, balancing effectiveness, and energy losses associated with cell equalization.

The most promising results in terms of shortening the CV phase and achieving final SOC equalization were obtained with the hybrid BMS incorporating a supercapacitor and active support. Compared with the passive system, the CV phase duration was reduced by approximately 13.4%, while the duration of the constant-current (CC) phase remained unchanged. The active balancing system, in turn, achieved the shortest balancing time.

The results indicate that the hybrid BMS with a supercapacitor and active support has the potential to shorten the CV phase and improve SOC equalization. However, a comprehensive assessment of the effectiveness of these solutions requires further research, including an energy balance analysis, validation of the thermal model, investigation of the effects of cell parameters and operating conditions, and experimental evaluation of balancing performance and the impact of the implemented mechanisms on battery lifetime.

References

[1] Cao J., Schofield N., Emadi A.: Battery Balancing Methods: A Comprehensive Review. *IEEE Vehicle Power and Propulsion Conference*, VPPC, September 3-5, 2008, Harbin, China. DOI: 10.1109/VPPC2008.4677669

[2] Jamasmie C.: Miners should adopt next generation values to battle reputation crisis. Mining, com:, 2020, https://www.mining.com/miners-need-to-adopt-next-generation-values-to-battle-reputation-crisis-says-anglo-american-boss/ (accessed on July 10, 2025).

[3] Battery University. Lithium-ion Safety Concerns, 2016; https://batteryuniversity.com/article/lithium-ion-safety-concerns (accessed on July 10, 2025).

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[4] Junling Wang, Konghao Yu, Peng Xiao, Li Li, Chunlin Wang, Zhirong Wang, Dongliang Guo, Yuen Kwok Kit Richard, Yawei Lu: Killing two birds with one stone strategy inspired advanced batteries with superior thermal safety: A comprehensive evaluation. Chemical Engineering Journal, 2025,515,163272.

[5] Kurpiel W., Polnik B., Orzech l., Lesiak K., Miedzinski B., Habrych M., Debita G., Zamłynska M., Falkowski-Gilski P.: Influence of operation conditions on temperature hazard of lithium-iron-phosphate (LiFeP04) cells. *Energies,* 2021 pp 2-12, No 14, 6728, https://doi.org/10.3390/en 14206728.

[6] Kurpiel W., Deja P., Polnik B., Skóra M., Miedzinski B., Habrych M., Debita G., Zamłynska M., Falkowski-Gilski P.: Performance of passive and active balancing system of lithium batteries in onerous mine environment. *Energies,* 2021, No 14 (22) 7624; https://doi.org/10.3390/en14227624

[7] Kurpiel W., Polnik B., Miedzinski B., Habrych M., Debita G.: Lithium-iron-phosphate battery performance controlled by an active BMS based on the battery-to-cell method, *Elektronika ir Elektrotechnika*, 2022 vol 28, No4, pp35-41.

[8] Kurpiel W., Miedziński B., Polnik B.: The influence of the balancing system on the durability and operational safety of lithium cell batteries in a selected mining machine power supply system. Monograph (in polish) 2025, pp. 152, https://www.komag.eu/images/maszynygornicze1/monografie/MonografieNaukowe/Monografia_W_Kurpiel/Monografia_Nr_59_open.pdf

[9] Kurpiel W., Miedziński B., Habrych M., Polnik B.: The Integration of Passive and Active Methods in a Hybrid BMS for a Suspended Mining Vehicle. *Energies* 2025, *18*(24), 6465; https://doi.org/10.3390/en18246465

[10] Kurpiel W.: Research on balancing BMS systems in a climatic chamber. Min. Mach. 2020, 53-63.

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