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Combined Scheme of Lithium-ion Battery Equalization with Energy Support Capabilities for Electric Vehicle Applications

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Abstract

The problem of Lithium-ion (Li-ion) battery equalization is examined in this paper and a combined scheme of cell equalization and energy support for high demanding applications such as electric vehicles is proposed. The aforementioned combined scheme is realized with cell-to-cell operating mode. The non-dissipative technique is utilized for the Li-ion battery cell equalization and the respective algorithm controls a matrix switch that connects the battery cells with an auxiliary energy storage system (AESS) which can be consisted by either supercapacitors or Li-ion battery cells of lower energy capacity than the main battery pack. Thus, not only cell equalization is attained but also energy support to any weak or problematic cells for both improving the cell equalization process and protecting the cells' life span of the main battery. Moreover, the AESS can enhance the dynamic performance of the vehicle during fast accelerations and decelerations of the electric vehicle by providing additional energy and absorbing the excess braking energy that cannot be stored in the main battery system so that energy saving is attained. Therefore, a more robust battery storage system is developed that can simultaneously match the requirements of effective non-dissipative cell equalization, cells' energy support, and improvement of the power dynamic performance of the Li-ion battery pack. The functionality and feasibility of the proposed combined system have been verified with several simulation results that validate the operating improvements and demonstrate the enhanced dynamic performance of the battery system.

1 Introduction

An electric vehicle is a highly demanding device with respect to the energy demand by a battery system because it requires high dynamic performance, seamless and reliable operation, and fast charging. On the other hand, protection of the battery system lifespan is required and also highly safe operating conditions [1]. The Li-ion battery technology can satisfactorily meet the aforementioned operating and performance challenges and thus, a Li-ion battery system can be a strong candidate for the energy storage mean in electric vehicle applications [2]. This is the reason that the Li-ion batteries have dominated in electric vehicle applications as well as several other applications, such as zero energy buildings, electric hand tools, electric grid, etc.

Since the nominal voltage of each Li-ion battery cell is relatively low (usually around 3.7V), a high number of cells are usually connected in series to meet the voltage requirement and also, to attain the energy capacity needs [3]. This may cause imbalance issues during charging and discharging, that are owed to discrepancies in the battery cells operating characteristics, such as real-time capacity and internal resistance [4]. These problems may result in the worsening of the battery power performance and reduction of the available energy capacity. Therefore, it is important for the cells to be correctly equalized so that both effective charging/discharging performance in the energy transaction between the Li-ion battery pack and the electric vehicle and protection of the cells' life span are accomplished.

The main technologies that can be applied for battery cell equalization are dissipative and non-dissipative that refer to the energy transfer mode. The dissipative technologies usually use resistors to absorb the equalization energy from cells with higher SoC, while the non-dissipative transfer the equalization energy to other cells of the battery pack [5]. Although the dissipative control schemes are less complicated compared to the non-dissipative, they are less energy efficient [6]. Moreover, they cannot be used during the

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discharging operation of the battery since useful equalization energy is consumed in the parallel resistors that leads in the reduction of the battery efficiency.

On the other hand, the non-dissipative control schemes attain more efficient cell equalization because the equalization energy is not lost, but it is injected to the other cells of the battery [7]. However, they are more complicated and costly, which are in several cases barriers for its broad utilization in electric vehicle applications [14]. The non-dissipative equalization systems may be classified based on their topology as follows: *adjacent-based, nonadjacent-based, direct cell-to-cell* and *mixed topologies*.

Several non-dissipative equalization methods have been proposed in technical literature to alleviate the drawbacks of the non-dissipative cell equalization. These techniques can be categorized according to how the equalization energy is transferred to the other cells and specifically in cell-to-pack [6], pack-to-cells [8], and cell-to-cell [9].

In the cell-to-pack/pack-to-cell, the equalization energy is transferred from the cell with the highest State-of-Charge (SoC) to the whole battery pack and then, from the pack to a potential weak cell. However, the time needed for the equalization is high that makes these techniques ineffective for several applications [10]. The reason for the slow cell equalization process is the fact that the energy transfer is attained by using as intermediate mean the whole battery pack. Contrarily the cell-to-cell is faster and more effective because the equalization energy from the cell with higher SoC is directly transferred to the other cells.

Several non-dissipative equalization systems have been proposed for transferring the energy to other cells. This can be attained by using bidirectional power converters [11], [17] and transformers [12]. However, in cases that fast equalization process is needed such as in electric vehicles, this equalization procedure may not meet the requirements of fast charging. Thus, to enhance the equalization process, assistance energy storage media (AESS) are used, such as supercapacitors [13], battery packs of lower energy capacity [14], and electrolytic capacitors [15]. However in these research works, the AESS is devoted only to the cell equalization, it does not provide energy support to potential weak or problematic cells and it does not contribute to the improvement in the dynamic performance of battery.

On the contrary, an AESS which not only assist in the Li-ion battery cell equalization but can provide energy support to any weak or problematic cells and act as an energy reservoir in cases of emergency acceleration/deceleration of an electric vehicle, it can protect the cells' lifespan and enhance the dynamic response of the vehicle. Thus, the AESS's capacity is considered as part of the main battery pack, since its energy is exploitable to provide energy support and to meet emergency energy demands of the electric vehicle in a fast acceleration and also it can absorb the excess energy that cannot stored to the main battery pack in a sudden deceleration. Therefore, without considerably increasing the cost of the battery system, both increase of the active safety of the vehicle and energy saving are attained.

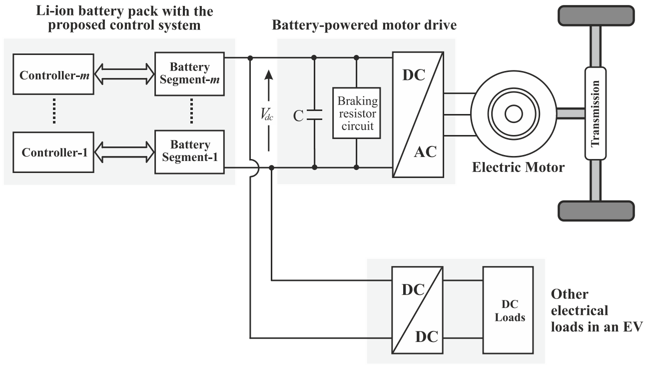

Fig. 1. Overview of the proposed equalizer and energy support technique in an electric vehicle application.

The aim of the paper is to propose a hybrid cell-to-cell non-dissipative equalization system that can provide both cell-to-cell equalization and energy support to problematic and weak Li-ion battery cells as well as enhancement of the dynamic performance of the electric vehicle. An auxiliary energy storage system (AESS) is used in back-to-back connection with the main battery that can be implemented by Li-ion battery or supercapacitors.

Therefore, not only improved and effective balancing of the battery cells is achieved but also protection of their lifespan and extension of the time that the cells are in operation in the battery pack. Moreover, the AESS can serve as an emergency energy reservoir and specifically, it can provide additional energy when it is demanded by the vehicle and also, absorb braking energy that cannot be stored to the main battery pack due to high current and thus, energy saving is attained. Simulation results in MATLAB/Simulink program are provided to validate the functionality and feasibility of the proposed combined energy storage scheme.

2 Construction of the Proposed hybrid Energy Storage System

Fig. 1 illustrates the overview construction of the proposed hybrid equalization and energy support system. The battery pack consists of *m* segments and

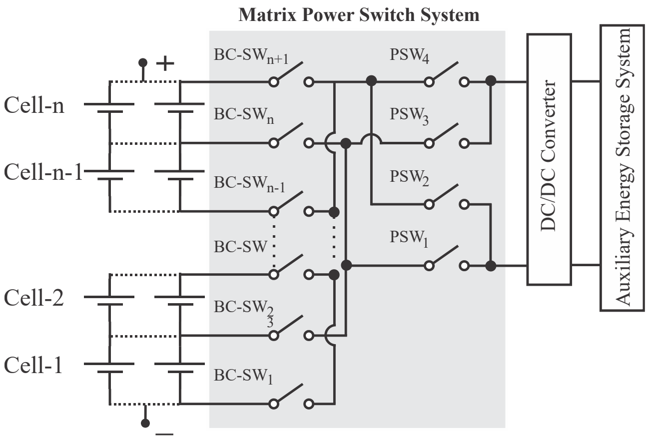

Fig. 2. Power circuit of the matrix switch-based converter of a Li-ion battery segment.

each segment consists of *n* sets of several parallel connected Li-ion battery cells with an AESS per segment. The operation of each battery segment is managed by its individual controller that attains cell equalization as well as energy support and enhancement of the battery dynamic performance. Each battery segment operates individually in respect to the other segments and therefore its performance is not influenced by the others. This means that the proposed combined scheme of Li-ion cell equalization with energy support capabilities can be used as large may be the battery pack of a vehicle.

The power circuit of each battery string is presented in Fig. 2. As can be seen, it consists of the Li-ion battery cells of the main battery pack, two sets of matrix switches, a bidirectional DC/DC converter, and the AESS of supercapacitors or battery cells. The cells of the battery string are connetected with the AESS through the matrix switch system and the DC/DC converter.

The matrix switch system consists of two sets of switches, the Batter Cell switches (BS-SW) and the pollarity switches (PSW). Both BS-SW and PSW consist of MOSFETS switches and the role of the BC-SWs is to block the current flow in both directions while the role of the PSWs is to block the current in only one direction. The BS-SWs are at the battery cells‘ side of the system and they regulate both the equalization current between the cells of the main battery pack and the support current by the AESS. The switches PSWs are at the AESS side of the system and manage the connection of the cells of th ebattery string with the DC/DC converter and the AESS. Thus, the BC-SWs manage both the equalization and energy support processes while the PSW regulates the connection of the AESS with the exact cell that needs energy support which is selected through the proper control of the BC-

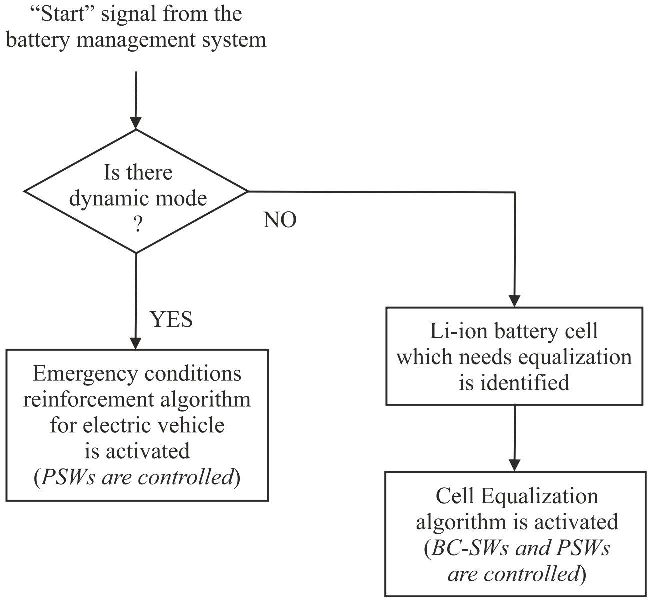

Fig. 3. Overview of the proposed cell equalization and energy support algorithm.

SW switches. Therefore, the BC-SW matrix switch operates during both cell equalization and energy support while the PSWs are activated only when energy support and improvement of the battery dynamic performance is required.

The AESS with the DC/DC converter and the matrix switches operate during both charging and discharging of the battery and therefore, cell equalization, energy support, and improvement of the dynamic performance is attained in the whole operation of the battery pack. Since the role of the AESS is supportive to the equalization and the dynamic operation of the battery pack, its energy capacity is lower than that of the main battery pack. The exact nominal capacity and rated power of the AESS depend on the desired energy support that it should be capable provide to the battery cells and the anticipated dynamic response capability that it should provide to the electric vehicle as well as the potential energy saving level that can be attained by absorbing as much as possible generated energy during an abrupt braking of the electric vehicle. Thus, the optimal values of the energy capacity and rated power of the AESS are determined experimentally and considering the technical characteristics of the battery system and the electric vehicle for searching an appropriate balance between the above goals.

The rated values of the power switches of the matrix switch system and the switching frequency of the DC/DC converter should be properly selected so that both satisfactory energy support and cell-to-cell equalization are provided depending on the nominal values of the Li-ion battery cells. As for the nominal

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values of the AESS, they are selected experimentally. Moreover, the switching frequency of the DC/DC converter should be much higher than that of the matrix switch system so that effective energy regulation of the energy flow to/from the AESS is accomplished.

A typical value for the DC/DC converter switching frequency is 250kHz [18]. The switching frequences of the BC-SWs and PSWs vary depending of the health conditions of the cells, the equalization needs, and the potential dynamic operating conditions of the electric vehicle. It is expected that they are at the range of 1Hz up to a few Hz.

3 Equalization and Energy Support Algorithms

Since the battery system perormance may degrade when residual discrepancies occur between the cells, equalization is required. However, this can be realized only when the electric vehicle is in steady state operation. On the contrary, during a transient condition either extra energy should be provided so that the vehicle can satisfactorily respond in a fast acceleration or as many as possible braking energy should be absorbed by the battery during a deccelaration. In both cases, the battery should have the required capabilities to provide high dynamic performance so that satisfactory safety and energy saving performance, respectively, are attained. Thus, during a transient condition, the performance of the battery management system is focused at the dynamic response and consequently, the battery should be able ot accordingly react.

The overview flowchart of the proposed cell equalization and energy support algorithm is shown in Fig. 3. The algorithm is energized when a "start" signal is sent by the battery management system. The first step is to identify if the electric vehicle is in steady-state or dynamic mode. This is identified by examining the amplitude of the dc-link current of the battery system I_{dc} (Fig. 1). Specifically, if the dc-link current is lower than a threashold value $I_{dc_{th}}$ $(I_{dc} \le I_{dc_{th}})$, it is considered that the electric vehicle is in steady-state mode and thus, the cells' equalization algorithm is energized, otherwise it is decided that the vehicle is in dynamic mode and the respective energy support algorithm is activated. The flow chart of the proposed combined scheme of cell equalization, energy support and emergency conditions reinforcement algorithms is illustrated in Fig. 4.

In case of steady-state mode, the equalization algorithm periodically checks the value of the parameter SOH_{flag}. If it is equal to 1, the State-of-Health (SOH) of each cell is recalculated and the values of the n cells of a string are stored in a array as given below

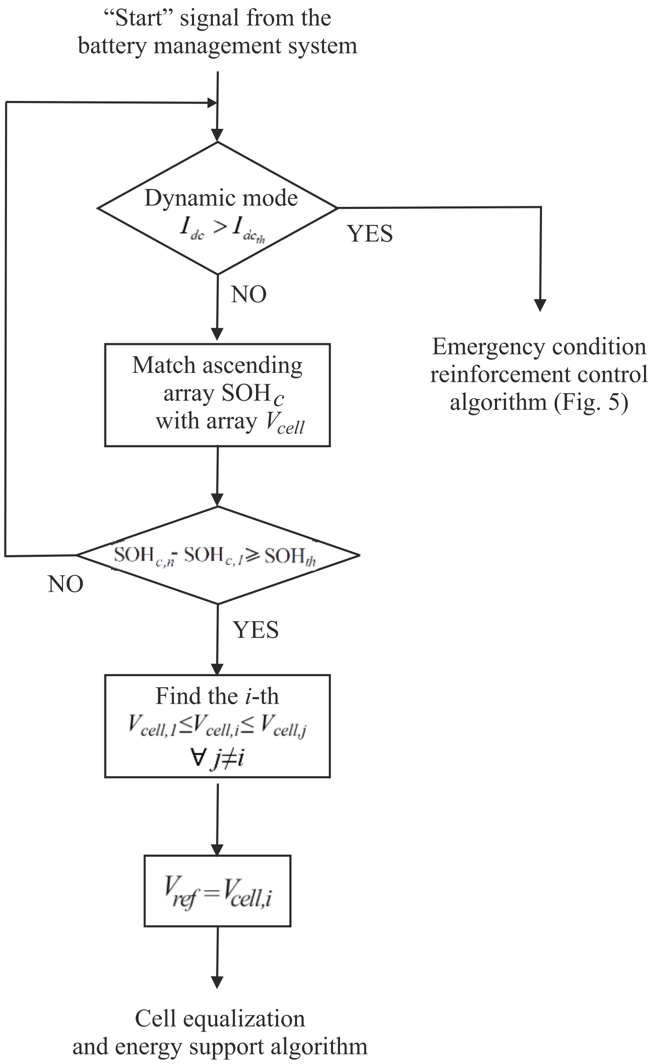

Fig. 4. Flowchart of the proposed combined scheme of cell equalization, energy support and emergency conditions reinforcement algorithms.

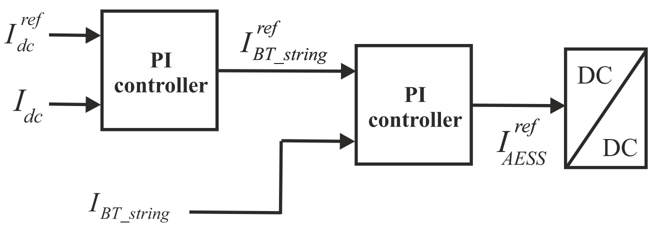

Fig. 5. The emergency conditions reinforcement control algorithm that regulates the *DC/DC* converter of the auxiliary energy storage system (AESS).

$$SOH_c = \begin{bmatrix} SOH_1 & SOH_2 & \cdots & SOH_n \end{bmatrix} \tag{1}$$

Then, the algorithm searches for the cell that needs equalization and the BC-SWs and PSWs switches are properly controlled so that equalization by the others

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cells of the string and energy support by the AESS through the control of the DC/DC converter is accomplished. The combined scheme of cell equalization and energy support can be realized by adopting several control algorithms, such as particle swarm optimization (PSO) technique, fuzzy logic method, etc.

When the energy support algorithm starts, the SOH_c array is ascending, and the corresponding cells' voltage array is created as follows

$$V_{cell} = \begin{bmatrix} V_{cell,1} & V_{cell,2} & \cdots & V_{cell,n} \end{bmatrix} \quad (2)$$

The decision for initializing the energy support process is obtained with respect to the amplitude of the difference between the highest SOH cell ($SOH_{c,n}$) and the lowest SOH cell ($SOH_{c,1}$)

$$\Delta SOH_c = SOH_{c,n} - SOH_{c,1} \quad (3)$$

If ΔSOH_c is greater than a threshold value SOH_{th}, the reference voltage value of the PI controller is set to the nearest cell voltage value $V_{cell,i}$ that satisfies the condition $V_{cell,1} \le V_{cell,i} \le V_{cell,j}$, $\forall\, j \ne i$. It is worth noted that, due to the fact that the cut-off voltage of a cell affects the power performance of the whole battery pack, the voltage value of the weakest cell is chosen as variable in the energy support process, and not the SOC or the residual available capacity.

In case of dynamic operating mode, the emergency conditions reinforcement algorithm is activated (Fig. 5). It comprises two proportional-integral (PI) controllers in cascaded connection. The first PI controller has inputs the reference and the measured dc-link voltage of the battery system and determines the reference battery string current. Then, by considering the measured battery string current and the respective reference current determined by the first PI, the reference current of the AESS is regulated by controlling the DC/DC converter.

4 Simulation results

For the validation of the effectiveness and the operating improvements of the proposed monitoring and equalizion system for an electric vehicle application, a battery pack of 6 Li-ion cells has been considered. The parameters of the battery cells and the supercapacitors (SC) of the AESS are given in Table I. The verification has been carried out through simulation analysis by utilizing the MATLAB/Simulink program.

Figs. 6 and 7 illustrate the performance of the proposed and the conventional battery management system (BMS), respectively, for the steady-state and the dynamic operation of the motor drive of the electric vehicle. To be more evident the validation of the proposed system, an unbalanced case in the battery string has been considered. Specifically, the capacities of the 6 Li-ion battery cells are 7Ah, 6.95Ah, 6.9Ah, 6.85Ah, 6.8Ah and 6.2Ah while the voltage of the SC-bank is 7V. Both the proposed and conventional algorithms initiate when SOC is 12% and expire when the voltage of at least one cell of the battery string drops below the cut-off value of 2.775V.

TABLE I

PARAMETERS OF THE LI-ION BATTERY AND THE SC-BASED AESS

Li-ion battery parameters	
Nominal Capacity	7 Ah
Nominal Voltage	3.7 V
Internal Resistance	5.2 mΩ
SC-Bank parameters	
SC-bank equivalent capacitance	C_{SC}=200 F
SC-bank rated voltage	8.1 V
SC-bank max continouus current (ΔT=15°C)	50 A (RMS)

The battery string is considered as balanced when the discrepancy between the highest and the lowest residual available capacity of the cells is lower than 0.002Ah. The above equalization threshold can be selected by the user of the application while both the charging and the discharging balancing current of the battery cells are selected by the proposed algorithm.

In both examined cases, the system initially operates in cell equalization mode whicht is interrupted at 80s due to the high dynamic of the vehicle. In the proposed system (Fig. 6), the lower residual available capacity of the cells at the time that the emergency reinforcement algorithm is activated (at 80s) is 0.459Ah and the SOC of the backup SC-bank of the AESS alternates with a small range at around 7.4%. Then, the proposed BMS assists the operation of the lowest SOH battery cell and ensures satisfactory performance during the dynamic operation which ends at 99.5s, where the voltage of this cell reaches the cut-off voltage (2.775V). Note that during the equalization process, the SC-bank's SOC is kept almost constant equals to 60.125% and thus, it has the necessary capacity for a potential new energy support of a weak battery cell or to satisfactorily respond in case of a new dynamic condition of the electric vehicle.

The performance of a SOC-based equalization system

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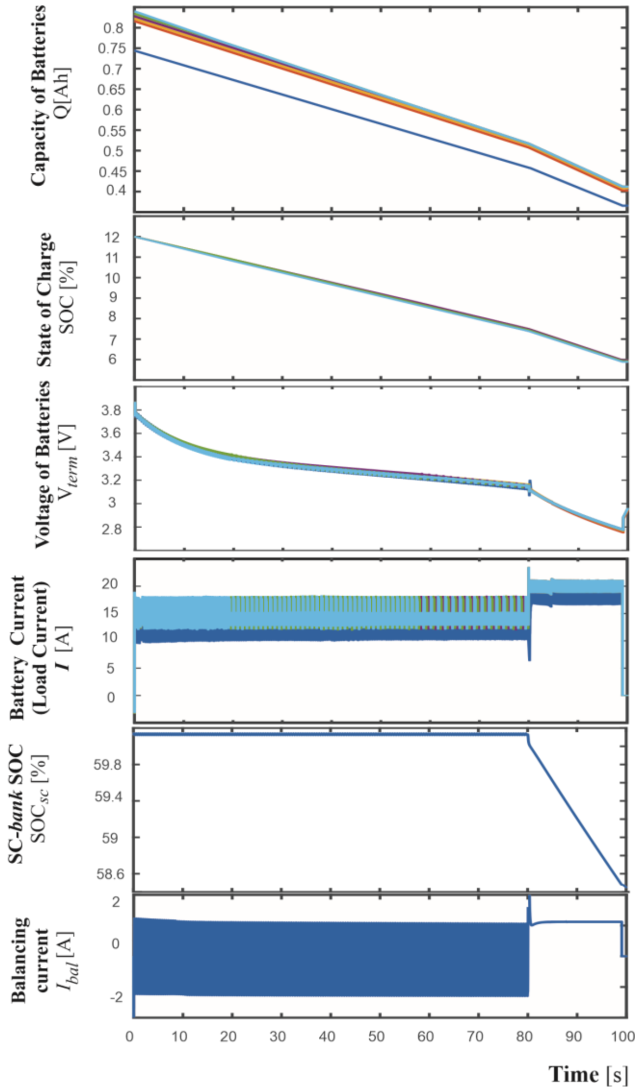

Fig. 6. Performance of the proposed algorithm at a 6-cell Li-ion battery pack with a supercapacitor-bank as AESS.

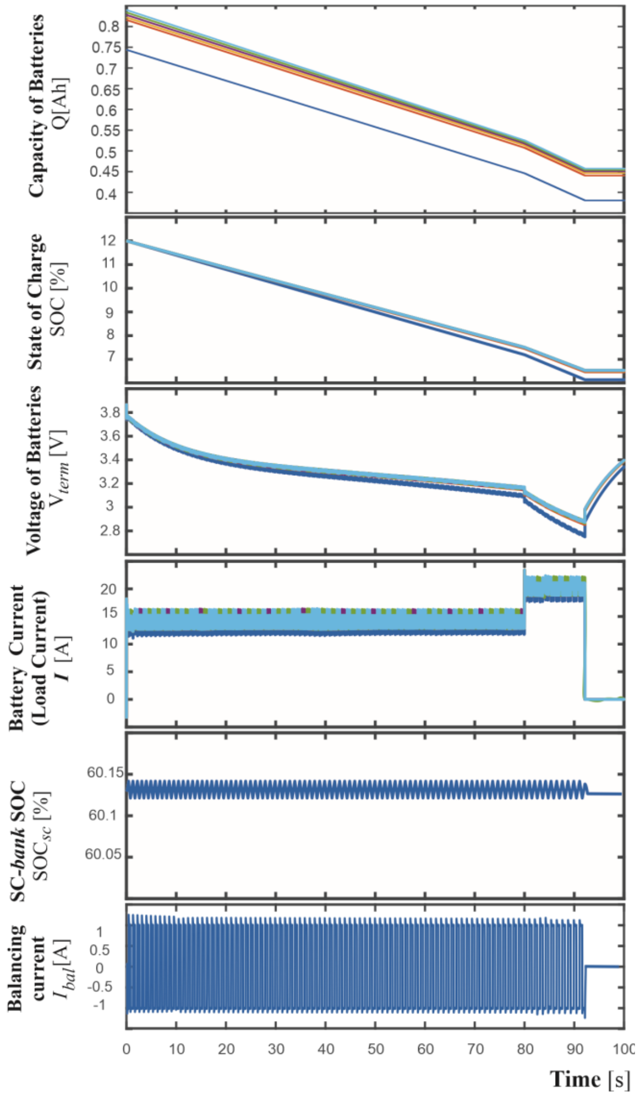

Fig. 7. Performance of the conventional algorithm at a 6-cell Li-ion battery pack with a supercapacitor-bank as AESS.

without the proposed algorithm is illustrated in Fig. 7. Both the charging and discharging balancing current of the battery cells are selected arbitrary by the user at 1A. The equalization algorithm is activated when the discreapancy between the maximum and the minimum SOC of the cells exceeds the value of 0.01. Comparing the first diagrams of Figs. 6 and 7, you can see that, when the dynamic operation is initiated, the lower residual capacity is 0.446Ah which is lower than the 0.459Ah of the proposed system.

During the dynamic operation of the conventional control system of Fig. 7, the voltage of the problematic battery cell has dropped lower than the cut-off voltage (of 2.775 V) at 92s. Due to the above, this battery cell could not continue its operation and thus, the whole battery string is disconnected to protect the lifespan of all the cells. This results to deterioration of the energy storage system performance, because the battery string cannot provide the required energy during the dynamic operation of the electric vehicle that may result to dangerous conditions for the driving of the vehicle. On the other hand, as you can see in the 5th diagram of Fig. 7, although the SC-bank of the AESS has the required energy capacity (SOC around 60.13%), it remains inactive without providing any support to the battery string and thus, without reinforcing in the emergency condition of the electric vehicle.

From the above it is concluded that the proposed battery management system, not only can attain satisfactory cell equalization, but also it can provide energy support to any potenial weak and problematic cells. Additionally, it can reinforce the dynamic performance of the battery for satisfactorily respond to fast accelerations and decelerations of the electric

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vehicle by providing additional energy and absorbing the excess braking energy that cannot be stored in the main battery system so that energy saving is attained.

5 Conclusions

A novel battery management system that consists of a combined scheme of a non-dissipative direct cell-to-cell equalization algorithm of a Li-ion battery and an energy support algorithm has been presented in this paper, that enhances the performance and protects the lifespan of the Li-ion battery system in an electric vehicle. The above is accomplished by utilizing a SC-based AESS that is controlled through a matrix switch and a DC/DC converter. Moreover, the AESS can enhance the dynamic performance of the electric vehicle during fast accelerations and decelerations of the electric vehicle by providing additional energy and absorbing the excess braking energy that cannot be stored in the main battery system so that energy saving is attained.

Therefore, a more robust battery storage system is developed that can simultaneously match the requirements of effective non-dissipative cell equalization, cells' energy support, and improvement of the power dynamic performance of the Li-ion battery pack. The effectiveness and the operating improvements of the suggested combined control scheme of Li-ion battery equalization with energy support capabilities control scheme have been verified with simulations in the MATLAB/Simulink environment. Several selective simulation results are provided to demonstrate the accomplishment of the above objectives.

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7 References

[1] Yi Xie, et. al., "An MPC-Based Control Strategy for Electric Vehicle Battery Cooling Considering Energy Saving and Battery Lifespan", *IEEE Trans. Vehicular Technology*, vol. 69, no. 12, pp. 14657-14673, Dec. 2020.

[2] X. Gong, R. Xiong, and C. Chris Mi, "Study of the Characteristics of Battery Packs in Electric Vehicles with Parallel-Connected Lithium-Ion Battery Cells", *IEEE Trans. Ind. Appl.*, vol. 51, no. 2, pp. 1872-1879, March/Apr. 2015.

[3] K. W. See, K. C. Lim, S. Batternally and N. Zhang, "Charge-Based Self-Equalization for Imbalance Battery Pack in an Energy Storage Management System: Developing a Time-Based Equalization Algorithm," IEEE Consum. Electron. Mag., vol. 8, no. 2, pp. 16 - 21, 2019.

[4] Y.S. Lee and M.W. Cheng, "Intelligent control battery equalization for series connected lithium-ion battery strings", *IEEE Trans. Industrial Electronics*, vol. 52, no. 5, pp. 1279-1307, Oct. 2005.

[5] B. Agrawal, et. al., "Non-dissipative battery cell balancing using half-bridge switching circuit", in Proc. *Int. Conf. IEEE ITEC*, 2016.

[6] A. M. Imitiaz and F. H. Khan, "'Time shared flyback converter' based regenerative cell balancing technique for series connected li-ion battery strings", *IEEE Trans. Power Electron.,* vol. 28, pp. 5960-5975, Dec. 2013.

[7] N. Jabbour, E. Tsioumas, M. Koseoglou and C. Mademlis, "Highly Reliable Monitoring and Equalization in a Hybrid Energy Storage System with Batteries and Supercapacitors for Electric Motor Drives in Building Applications," in IEEE Int. Conf. SPEC'2018.

[8] M. Uno and A. Kukita, "Double-switch equalizer using parallel- or series-parallel-resonant inverter and voltage multiplier for series connected supercapacitors", *IEEE Trans. Power Electron.*, vol. 29, no.2, pp. 812- 828, Feb. 2014.

[9] V. Pham, T. Nguyen, D. Tran, V. Vu, and Woojin Choi, "A new cell-to-cell fast balancing circuit for Lithium-Ion batteries in Electric Vehicles and Energy Storage System," Int. Conf. IEEE-ECCE Asia*,* 2016.

[10] F. Feng, X. Hu, J. Liu, X. Lin, and B. Liu, "A review of equalization strategies for series battery packs: variables, objectives, and algorithms," *Renewable and Sustainable Energy Reviews*, *Elsevier,* vol. 116, pp. 109464, 2019.

[11] S. Wang, S. Yang, W. Yang, and Y. Wang, "A New Kind of Balancing Circuit With Multiple Equalization Modes for Serially Connected Battery Pack," *IEEE Trans. Industrial Electronics*, vol. 68, no. 3, pp. 2142–2150, 2021.

[12] K.-M. Lee, S.-W. Lee, Y.-G. Choi, and B. Kang, "Active Balancing of Li-Ion Battery Cells Using Transformer as Energy Carrier," *IEEE Trans. Industrial Electronics*, vol. 64, no. 2, pp. 1251–1257, 2017.

[13] N. Jabbour, E. Tsioumas, N. Karakasis, and C. Mademlis, "Improved monitoring and battery equalizer control scheme for electric vehicle applications", in Proc. *2017 IEEE 11th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, 2017, pp. 380–386.

[14] S. Jinlei, L. Wei, T. Chuanyu, W. Tianru, J. Tao, and T. Yong, “A Novel Active Equalization Method for Series-Connected Battery Packs Based on Clustering Analysis With Genetic Algorithm,” *IEEE Trans Power Electronics,* vol. 36, no. 7, pp. 7853–7865, 2021.

[15] Y. Shang, B. Xia, F. Lu, C. Zhang, N. Cui, and C. C. Mi, “A Switched-Coupling-Capacitor Equalizer for Series-Connected Battery Strings,” *IEEE Trans. on Power Electronics*, vol. 32, no. 10, pp. 7694–7706, 2017.

[16] N. Ghaeminezhad, Q. Ouyang, X. Hu, G. Xu, and Z. Wang, “Active Cell Equalization Topologies Analysis for Battery Packs: A Systematic Review,” *IEEE Trans Power Electronics*, vol. 36, no. 8, pp. 9119–9135, 2021.

[17] S. Yarlagadda, T. T. Hartley and I. Husain, "A Battery Management System Using an Active Charge Equalization Technique Based on a DC/DC Converter Topology," *IEEE Trans. Ind. Appl.,* vol. 49, no. 6, pp. 2720-2729, Nov.-Dec. 2013.

[18] S. Jinlei, L. Wei, T. Chuanyu, W. Tianru, J. Tao, and T. Yong, “A Novel Active Equalization Method for Series-Connected Battery Packs Based on Clustering Analysis With Genetic Algorithm,” *IEEE Trans Power Electronics*, vol. 36, no. 7, pp. 7853–7865, 2021.