The Eurasia Proceedings of Science, Technology,
Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2022

Volume 19, Pages 47-54

IConTech 2022: International Conference on Technology

Hybrid Battery Balancing System for Electric Drive Vehicles

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Abstract: In electric vehicles, cell and module voltage equalization plays a vital role in Battery Management System (BMS). The capacity, temperature, and aging imbalances in the cells and modules of electric vehicles battery packs restrict the amount of power that can be delivered to the vehicle. Spurred by this issue, we propose a new class of battery balancing systems, called hybrid balancing, capable of simultaneously equalizing battery capacity while enabling cost-effectiveness of cell-level passive balancing and module-level active balancing, modules consist of a number of cells connected in series, with cell-level passive balancing performed in a module, together with the module level switched capacitor that performs active balancing among the modules. The strategy is called hybrid balancing because it pursues goals beyond conventional state-of-charge equalization, including temperature and power capability equalization, and minimization of energy losses. Design details and MATLAB Simulink simulation results are provided for a hybrid balancing system implemented on a lithium-ion battery pack.

Keywords: Electric vehicles, hybrid balancing, battery balancing, automotive systems

Introduction

Rechargeable batteries have been widely used in many fields, including the telecommunications industry, electric vehicles, and renewable energy storage systems to meet the demands for energy storage systems. Due to the individual battery cells low terminal voltage in the majority of applications, a battery bank is often formed by connecting the batteries in series to achieve the desired voltage level. However, there is a commonly known imbalance between battery cells in a battery bank. State-of-Charge (SoC) differences across cells are a well-known imbalance (Aizpuru et al., 2013). Differences between battery cells is caused by both intrinsic and extrinsic reasons (Jonghoon et al., 2012). Intrinsic variances are mostly a result of manufacturing process variation. It is not possible to create two cells with the exact identical properties. Cell performance varies during operation due to differences in capacities, self-discharge rates, and internal resistances. The effects of temperature and extraneous circuitry are extrinsic variables. The characteristics of the cells are impacted by the battery bank's uneven temperature distribution, which can cause performance variations (Belt et al., 2005). Electric-drive vehicles (EV, PHEV, HEV) use high voltage (HV) traction battery packs, which are consist of multiple battery cells linked in series. The capacity, inner resistance, and run-time state-of-charge (SOC) of individual cells differ from one another, hence a battery management system must include cell balancing (BMS) (Smith et al., 2016). In practice, passive balancing is considered the most cost-effective and most commonly used in lithium-ion battery packs for electric vehicles (Chan et al., 2001). The BMS consists of a series of special battery monitoring and passive balancing circuits (ICs) that sense individual cell voltages and activate cell discharge through shunt resistors command from BMS controller. A disadvantage of conventional passive balancing systems is that the available energy capacity of the entire battery pack is determined by the weakest cells (Baumhöfer et al., 2014). The weakest cell issue is getting worse over time due to uneven degradation among cells, causing reduced battery life (Smith et al., 2016).

Mitigating the impact of the weakest cells on a large battery pack requires tight cell binning and efficient thermal control (Chen et al., 2016). On the other hand, active balancing systems became popular nowadays, the weakest-cell effect is mitigated by using high efficiency power converters, supercapacitors, capacitors and inductors to transfer energy from one cell to another. There have been numerous active balancing architectures and realizations examined. However, active balancing strategy needs extra power electronic devices which makes additional costs for applications, this has been a major concern in practical applications (Einhorn et al., 2011; Hopkins et al., 1991).

In this paper, the strategy outlined in Paul et al. (2022), and Pognant-Gros et al. (2014) is expanded in order to determine the optimal trade-off between the advantages of the active balancing with switched capacitor-based circuitry. Fig. 1 presents a proposed circuitry for hybrid balancing strategy. The system concept and the hybrid balancing approach are covered in Section II. The hybrid balancing implementation is covered in Section III, and the simulation results, conclusion and recommendations are covered in Section IV, V and VI.

Hybrid Balancing Strategy

In the hybrid battery balancing system shown in Fig 1. Battery cells in the battery packs grouped into modules. Active cell balancing is applied at the module level and conventional passive balancing is applied at the cell level within a module.

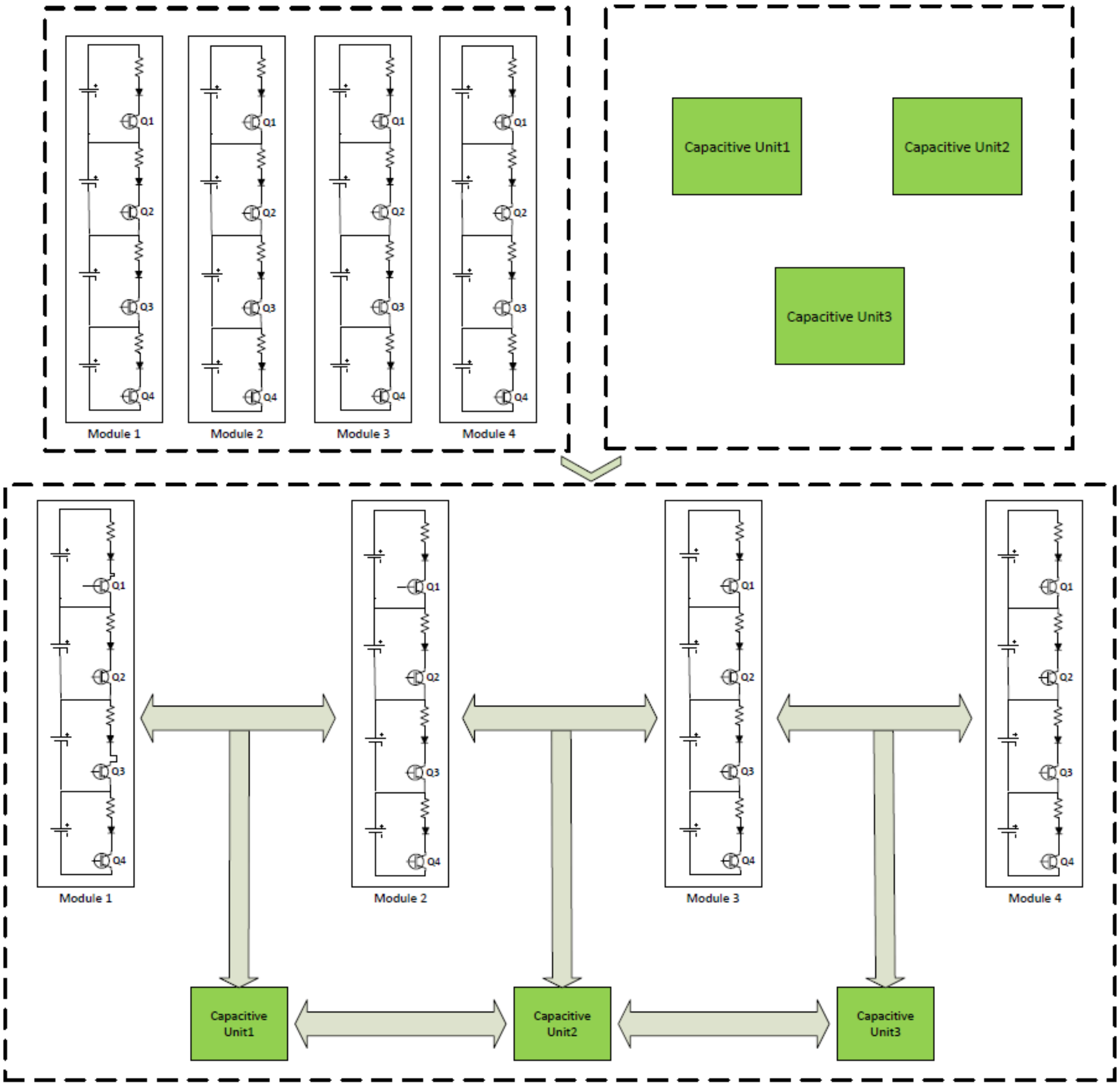

Figure 1. Hybrid balancing system

Cell Level Passive Balancing

This method uses a resistor to dissipate the energy of the cell with the highest voltage in a series module. In general, the weakest cell reaches its maximum voltage threshold earlier when the same current flows through the rest of the cells in the pack. When the cell voltage exceeds the SOA (safe operating area), the switch is turned on and the cell is discharged through a resistance, also called bleeding resistance, lowering the cell voltage and SoC, as shown in Fig. 1. to a safe level. Repeating this procedure allows for the eventual voltage uniformity of all cells. While active module level balancing is performed, additional passive balancing must be used within each module using one of the standard passive balancing algorithms as mentioned (Xiong R et al., 2019).

Module Level Capacitor-Based Active Balancing

One of the most crucial advantages of active balancing in EV/HEV applications is battery life extension. In physically, large EV/HEV battery packs, the temperature fluctuations across the pack lead to uneven aging between the cells, which is one of the main reasons of short battery life. Because nearby cells in a battery pack have lower temperature variations and degrade more gradually, the modular approach described here is driven by this fact (Muneeb Ur Rehman et al., 2016). Thus, passive balancing at the cell level can be carried out inside each module, and nearby cells can be grouped into modules for active balancing at the module level. Capacitor-Based cell balancing has been developed and tested in (Pognant-Gros et al., 2014). This study has been extended and applied at the module level and same strategy followed.

Module Level SOC and SOH

The module level state of charge (SOC) and state of health (SOH) must be known in order to implement module level active balancing. Various advanced cell level SOCs and SOH development methods has been investigated in (Muneeb Ur Rehman et al., 2016), (Plet et al., 2011). The extraction of module-level data needs to be carefully evaluated because the SOC and SOH vary for each cell inside a module. Extra consideration needs to handle if the slow passive balancing action has not completely balanced the module's cells during the balancing time. Passive balancing is applied to the subset of cells in a module; hence the module SOH should be based on that subset's worst-case cell. Eqs. (1) and (2), where n and j are the overall number and the index of cells within a module, respectively, provide the inner resistance and total capacity of Module i (Zhang et al., 2017).

$$R_{modules,i} = n.\max(R_{cell,j}) \tag{1}$$

$$Q_{modules,i} = n.\min(Q_{cell,j}) \tag{2}$$

It takes more careful calculations and consideration to determine a module's SOC. Assume that $SOC_{max} > SOC_{min}$ .Significant considerations are needed when calculating the module SOC. If $SOC_{max} > SOC_{min}$ for the two cells with the highest and lowest SOC values. In the same way that safety restrictions for the SOC_{min} cell may be violated during module discharging if the module SOC is thought to be SOC_{min} , safety limits, for the SOC_{max} cell may be violated during charging if the module SOC is thought to be equal to the highest cell SOC (SOC_{max}). The SOC of module i is determined using the formula presented in Eq (3) and Eq (4), in order to properly accommodate various module-level active balancing strategies under various cell-level passive balancing conditions (Zhang et al., 2017).

$$SOC_{module,i} = \frac{\min(SOC_{cell,j}Q_{cell,j})}{\min(SOC_{cell,j}Q_{cell,j})+\min(1-SOC_{cell,j})Q_{cell,j})} \tag{3}$$

after all cells in a module balanced;

$$SOC_{module,i} \approx \frac{SOC_{cell,j}\min(Q_{cell,j})}{SOC_{cell,j}\min(Q_{cell,j})+(1-SOC_{cell,j})\min(Q_{cell,j})} \approx SOC_{module,k} \tag{4}$$

where index k represents the cell with the least total capacity.

Switched Capacitor Based Hybrid Balancing Strategy

Switched Capacitor based hybrid balancing system is shown in Fig. 1. Basically, it is the mix of the passive and active balancing strategies. A switched capacitor balancing system, it aims at balancing a set of modules in series. In the illustration, a specific module could be substituted by a group of modules operating in parallel, which is a common scenario in EV/HEV batteries. Electrical scheme of the switched capacitor is shown in Fig. 2.

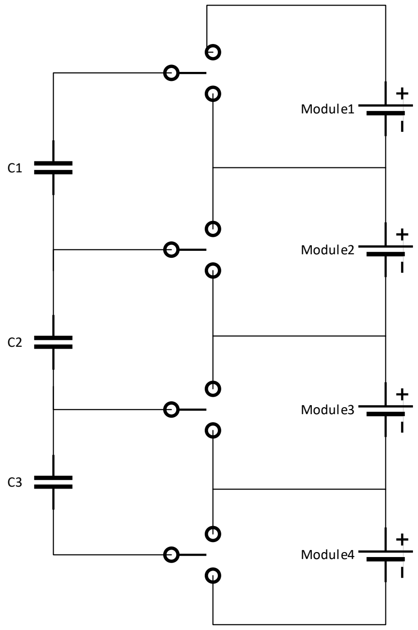

Figure 2. Electric scheme of the switched capacitor-based module balancing system

The switches are interlocked and alternately connected to the top and bottom contacts. Switching the capacitor back and forth gives the exact same voltage across the battery modules. Physically, the dynamics depend on the capacitance C, the equivalent resistance including cells inside the module, switches and capacitors and the chemistry of the cells inside the module.

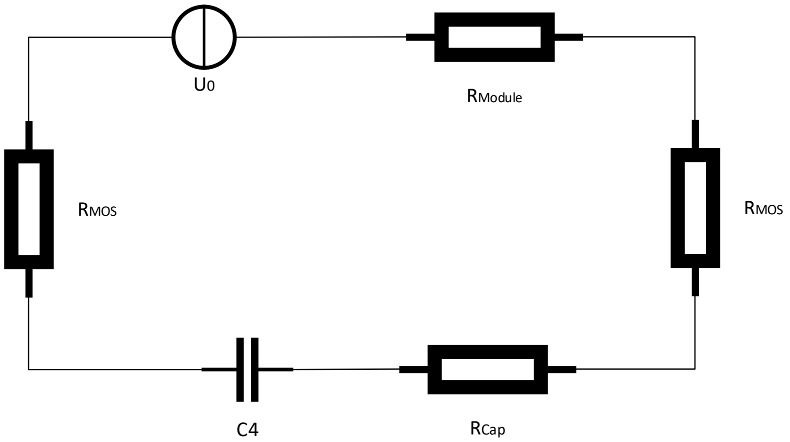

Figure 3. Module level electric equivalent scheme of each module while switching

The circuit depicted in Fig. 3 is taken into consideration without losing generality. The electrical connection between a capacitor and a module is shown in the figure during the switching period, which is $[t_k, t_{k+1}]$, with $t_{k+1} - t_k = T_s$. The Eqs. (5) and (6), regulating the electric circuit can be described as follows in the continuous time domain.

$$C\frac{dv}{dt} = I = \frac{U_{0_i}-V}{R_{tot}} \qquad (5)$$

$$\frac{dQ_i}{dt} = -I = -\frac{U_{0_i}-V}{R_{tot}} \qquad (6)$$

where V is the capacitor voltage (in V), Q_i is the cell discharge/charge (in C) and, symmetrically, the capacity charge/discharge, U0i is the cell open circuit voltage (in V), function of the cell charge Q_i, R_{tot} is the sum of module, capacitor and MOSFETs resistances (in W).

Simulation Results

The hybrid battery balancing strategy has been tested in MATLAB/Simulink. A battery pack composed of 4 module and each module consist of 4 cells connected in series was considered with a uniform initial dispersion of charge between 10% and 100%. The evolution of voltage and charge for the cells, modules and capacitors has been also collected, in order to verify that the imposed thresholds were respected. The figures below summarized the results. In details, Figure 4 compares the module open circuit voltage dispersion before and after the balancing. Figures 5, 6 and 7 show the evolution of, respectively, cells state of charge during the balancing, cells voltage equalization with passive balancing and voltage difference between load and 4 modules highlighting that, accordingly to the imposed condition, the balancing is achieved in the expected time. Li-ion cell and capacitive unit parameters are given in Table1.

Table1. Li-ion cell and capacitive unit parameters

Parameter	Value	Unit
Cell Capacity	2,3	Ah
Nominal Cell Voltage	3,3	V
Fully Charged Voltage	3,748	V
Cell Series Resistance	30	Ω
Capacitive Unit	0.033	F

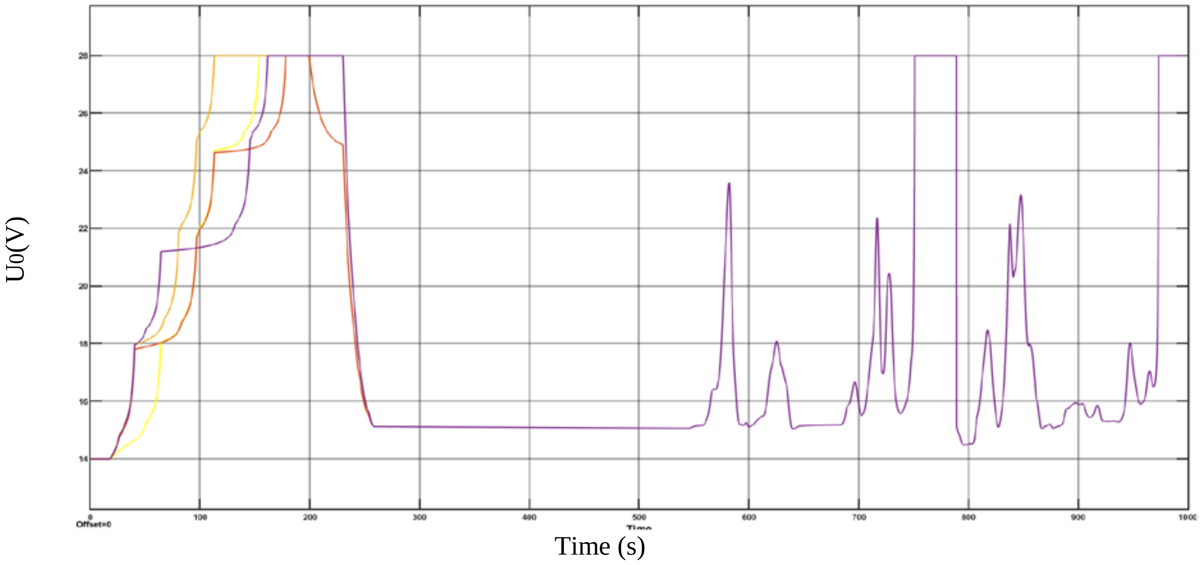

Figure 4. Module voltage equalization with fluctuated charging current

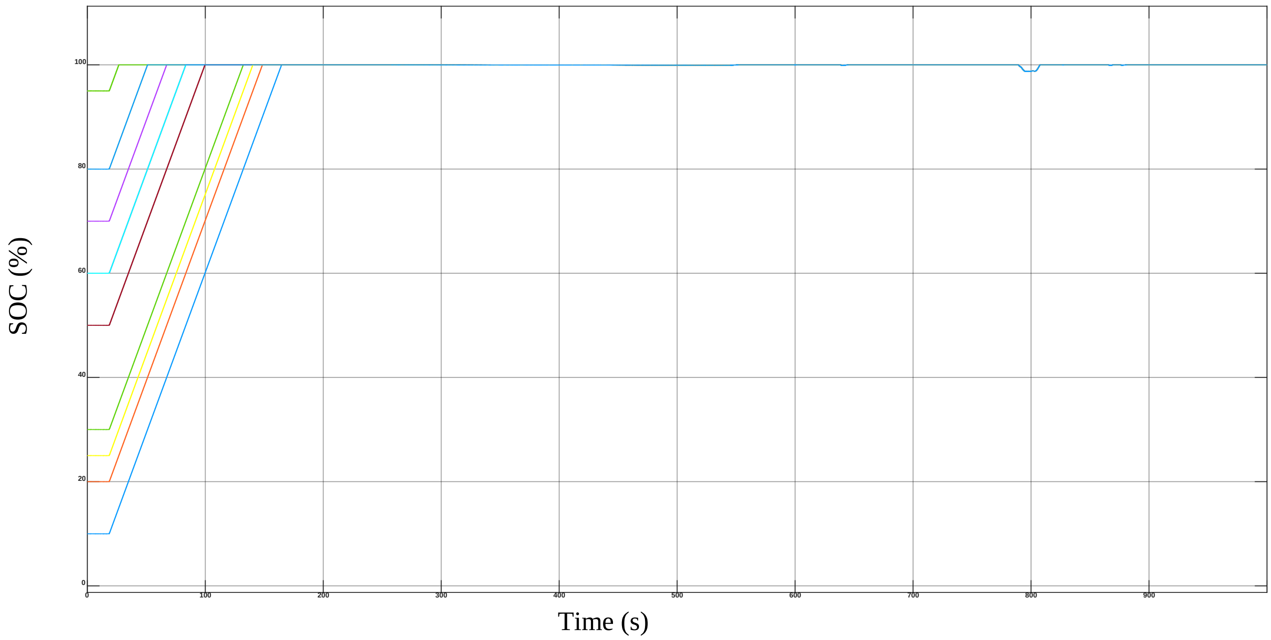

Figure 5. Cell SOCs equalization during charging

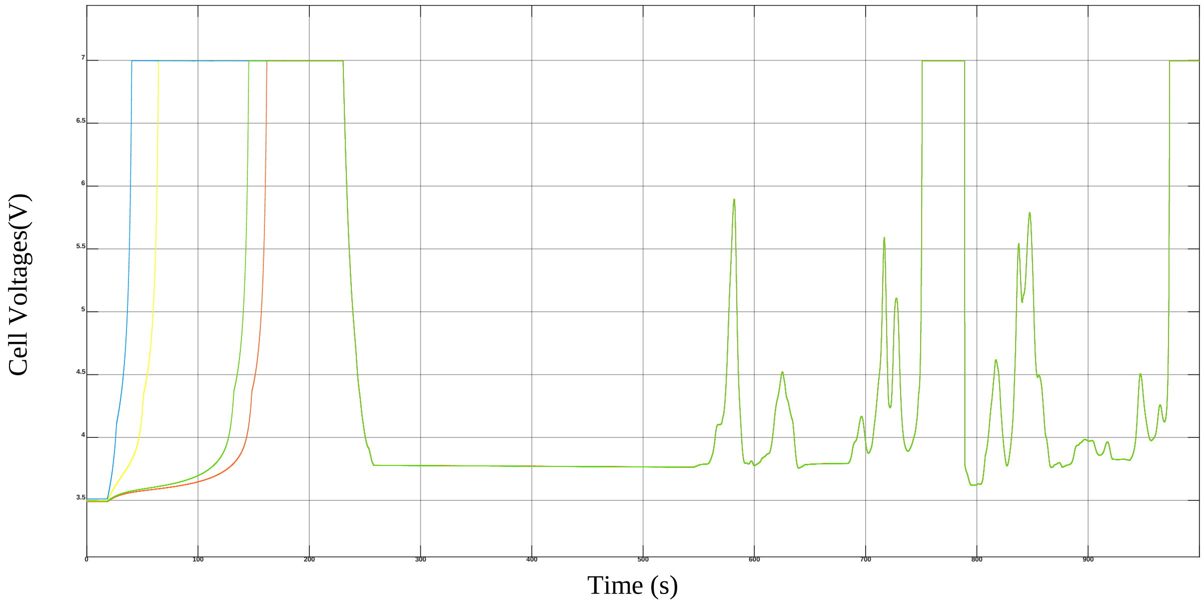

Figure 6. Cell Voltage equalization via passive balancing in Module1 during charging with fluctuated charging current

Conclusion

Cell balancing is a crucial function of the battery management system. It prolongs battery pack life time, improves the safety of the battery system and maximizes the battery pack total capacity. Hybrid battery balancing system has been investigated and simulated with the aid of MATLAB/Simulink. A novel hybrid balancing system has been proposed and designed with module level active balancing and cell-level passive balancing is presented in this paper. The advantages of the proposed control strategy are: reducing the system size, cost as well as the balancing time. Module-level active balancing is performed by switched capacitors. The hybrid system features favorable cost/performance tradeoffs and is capable of implementing a range of system and module-level control strategies. The system simulation results demonstrated on a Lithium-ion battery pack, which composed of 4 module and each module consist of 4 cells connected in series.

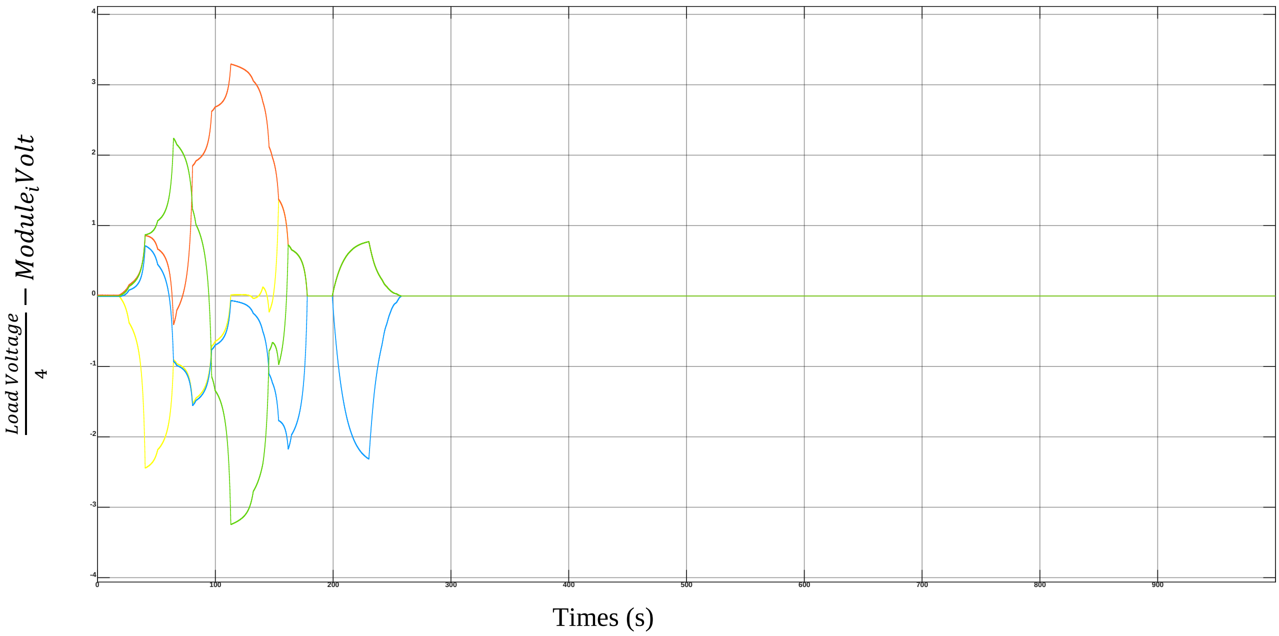

Figure 7. Difference between (Load Voltage/4)-(Module i Voltage) results

Recommendations

This structure is probably the easier way to design an active balancing system at the module level, but its convergence is intrinsically governed by the lithium chemistry, capacitor size and switching frequency. The selection of switching frequency and capacitor size is an optimization problem in switched balancing capacitors to maximize the energy transfer rate among high charge module capacitor to low charge module. The proposed structure can be extended by using supercapacitors at the module level. This will help to reduce balancing time.

Scientific Ethics Declaration

The authors declare that they are responsible for the scientific, ethical, and legal aspects of the paper published in EPSTEM.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Technology (www.icontechno.net) held in Antalya/Turkey on November 16-19, 2022.

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To cite this article:

Kocyigit, D. & Ayten, U. E. (2022). Hybrid battery balancing system for electric drive vehicles. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 19,* 47-54.