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Comparative Analysis of Cell Balancing Topologies in Battery Management Systems

Abinash Khanal [a], Ashutosh Timilsina [b], Binay Paudyal [c], Saugat Ghimire[d]

[a, b, c, d] *Electrical Engineer* [c] *Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal*
Corresponding Email: [a] bnsh.khnl@gmail.com, [b] ashutoshtimilsina@gmail.com,
[c] vinaypaudyal@gmail.com, [d] g4saugat@gmail.com

Abstract

Unbalancing of cells in a battery pack impacts the overall performance of battery system and can eventually lead to failure of the whole battery system. Hence, an efficient Battery Management System (BMS) must incorporate the feature of cell balancing among other protection and monitoring of the battery pack not just to increase the working capacity of the battery but also to increase its efficiency and overall lifetime. In this paper, brief overview of the existing methods of cell balancing in the BMS has been presented along with the comparative analysis of typical cell balancing topologies based on the MATLAB/Simulink Simulation.

Keywords

Battery Management System, Cell Balancing, Lithium-Ion Batteries, Single Switched Capacitor, Switched Resistance Method

1. Introduction

Battery Energy Storage System (BESS) has been used extensively in various fields including Electric Vehicles (EV), Solar Photovoltaics and other Standalone Renewable Energy systems [1, 2, 3, 4, 5, 6]. Battery and its managing and monitoring system, collectively known as Battery Management System (BMS) is the essential component of such Battery Energy Storage System. Cell Balancing is a major task of BMS among several other functions such as monitoring the system parameters like voltage, current, temperature, State of Charge (SoC), State of Health (SoH) of cells; estimating the Remaining Useful Life (RUL); thermal and charge/discharge management; and protection of the cells[7].

Unbalanced Cells in the battery system affects overall life of the battery system negatively given that the individual cell voltages of the system drift apart over time thus reducing the capacity of the battery pack as a whole and its lifetime. Cell unbalancing in a battery pack results from the difference in internal composition of the cells, initial charge capacities or even from external sources like multi-rank pack protection ICs and thermal difference of the cells, which causes different self-discharge rates of the cells.

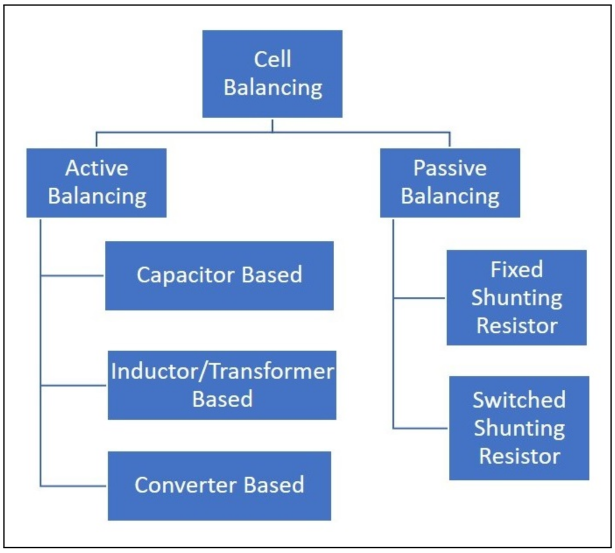

Figure 1: Active and Passive Cell Balancing Topologies

Hence, the differences of charge/discharge rate results in unequal State of Charge in the battery cells, which reduces the battery voltage and capacity of series-connected cells in the battery pack [8, 9]. Therefore, BMS must employ the Cell Balancing circuit to mitigate this issue. A lot of cell-balancing topologies has been proposed in the literatures which can be broadly categorized under Passive Cell Balancing and Active Cell Balancing Methods.

Passive Cell Balancing refers to the mechanism of dissipating the excess charge from cells with higher SoC through passive element, resistance [10, 11, 12, 13]. Active Cell balancing topologies balance the cells in a battery pack by delivering the excess charge from higher SoC cells to those with lower SoCs with the use of active elements that can store energy like Capacitor, Inductor or converters. Cell balancing topologies is shown in Figure 1.

In this paper, general overview of several cell balancing topologies is presented and two topologies have been simulated in MATLAB/Simulink for two different cell voltages and their respective performance have been analyzed.

2. Cell Balancing Topologies

As illustrated in Figure 1, different Cell Balancing Topologies that have found their way into the research are described below:

2.1 Passive Method

Using Passive Element, shunting resistor, the passive method of cell balancing dissipates energy in the form of heat from higher energy cells in a battery pack to bring down their level to the equilibrium of lower energy cells[14]. This method of cell balancing has the advantages of using cheaper components and also a comparatively simpler algorithm. Passive method can be either Fixed Shunt Resistor type or Switched Shunt Resistor type. Both of them are described briefly here.

2.1.1 Fixed Shunt Resistor

This method employs equal number of resistors connected to each cell preventing it from being overcharged. Simple design marks low cost for such system but results in continuous thermal losses in BMS, thus considered inefficient cell balancing method & mainly used in Lead-Acid and Ni-Batteries.

2.1.2 Switched Shunt Resistor

This method involves controlled energy dissipation using switches or relays by deciding which resistor should be shunted based on cell voltages. Passive cell balancing circuit requires separate thermal management system and is bound to reduce the battery's run time. It is typically implemented for the low power applications [7].

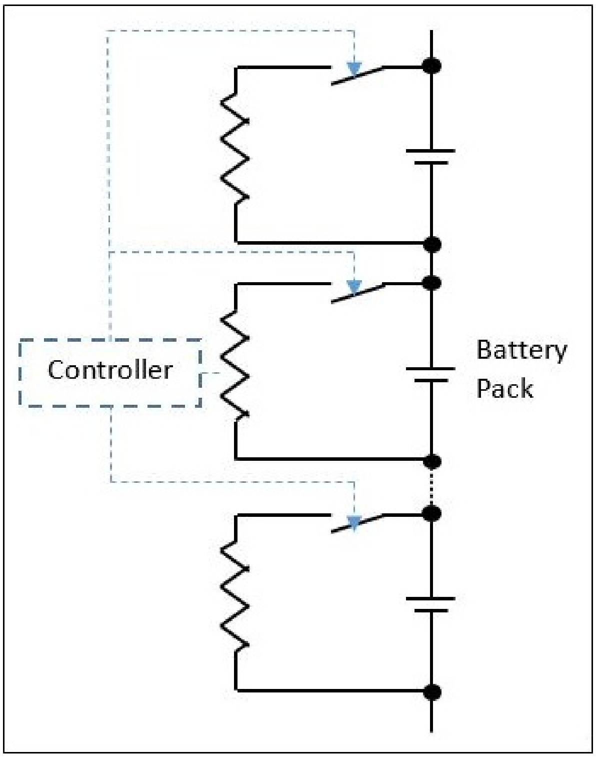

Figure 2: Switched Shunt Resistor topology of Passive Cell balancing

2.2 Active Cell Balancing Method

An Active cell balancing circuit transfers the energy from higher energy cells to lower energy ones through active elements using a power electronic interface[15]. This method has higher efficiency than passive balancing but the control algorithm is complex, resulting in higher cost. The active cell balancing can be of Capacitive, Inductive or Converter type.

2.2.1 Capacitive Cell Balancing

Capacitive cell balancing methods, also referred to as Shuttling Capacitor Balancing methods, utilize capacitors as external energy storage devices for shuttling the energy between the cells [13] to balance their SoC to the same level. Active cell balancing using Capacitor are shown in Figure 3. They are briefly described here.

Switched Capacitor (SC) balancing topology requires n-1 capacitors and 2n switches to balance n cells. As it operates in only two states, its control strategy is simple: to shuttle between the whole cells sequentially, switches are frequently moved from upper to lower position and again to upper position with smaller delay in each transition. It can work in both charging and discharging modes and has high

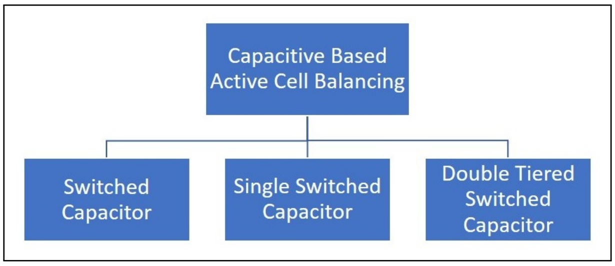

Figure 3: Active Cell Balancing Topologies using Capacitor

efficiency but its relatively higher equalization time and higher cost are the major disadvantage.

Single Switched Capacitor (SSC) topology is the derivation of the Switched Capacitor topology and makes use of only one capacitor as shown in the Figure 4. This topology requires n+5 bidirectional switches to balance n cells and hence it is employed in the battery system with more than 4 cells, making it more cost efficient than its counterparts. Its control strategy is also simpler where a controller is employed which selects the cells with higher and lower SoCs and operates the corresponding switches to shuttle the energy between the cells. More complex strategies can also be used for increasing the balancing speed.

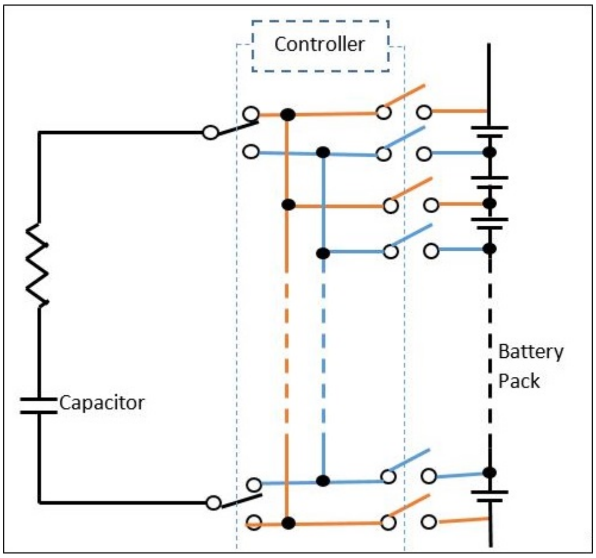

Figure 4: Single Switched Capacitor topology of Active Cell Balancing

Double Tiered Switched Capacitor (DTSC) derived from the switched capacitor method, this topology of cell balancing utilizes two tiers of capacitor for shuttling the energy between the cells. It requires n capacitors and 2n switches to balance n cells with its advantage being reduced balancing time than switched capacitor method due to the added second capacitor tier by almost 3/4th time [13] and also can operate in both charging and discharging modes. More tiers result in more path between batteries which reduces the impedance for shuttling energy over the cells in the pack.

2.2.2 Inductor-based Cell balancing methods

This type of cell balancing circuit balances battery cells with inductors or transformers. Balancing time in this topology can be reduced by increasing cell balancing current. Since the switching frequency is high, each cell in the pack also requires a filtering capacitor and there is magnetic losses involved in transformer, making it relatively costlier and unfeasible. It utilizes single/multiple inductors or transformers along with MOSFETs for switching and transferring energy between cells in the battery pack.

2.2.3 Converter-based Cell Balancing

Converter based cell balancing topologies employs the suitable converters for balancing unequal cells. This cell balancing circuit has higher energy transfer efficiency but in the mean time, it can be bulky and might require complex control algorithm because of additional passive components and active switches [7]. The methodologies of cell balancing using converter are shown in Figure 5. Depending on which converter

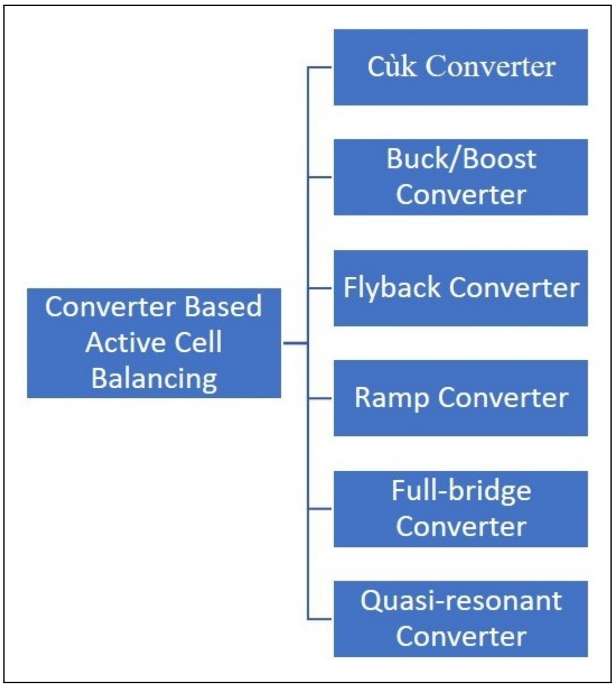

Figure 5: Active Cell Balancing Topologies using Converters

is used for cell balancing, the cell balancing topologies can be different including Cúk Covnerter, Buck-Boost Converter, Flyback Converter, Ramp Converter, Full Bridge Converter, Quasi-Resonant converter.

Buck-Boost Converters are widely used for cell balancing in Battery Management systems. Buck-Boost Converter is used to remove the excess energy from the cells with higher SoC to the auxiliary battery system and then again transfer to the energy to the cells with lower SoC. An intelligent controller and voltage sensing device is required for the operation of such topology. Even though this topology is expensive and complex in operation, provided their higher efficiency and their modular applications, they can be regarded as the robust and rugged cell balancing topology in existence for the BMS.

3. Simulation and Analysis of typical Cell Balancing Topologies

In this paper two cell balancing topologies, one passive and one active have been studied for two different Cell Voltages. The analyzed system consisted of three cells, each with capacity of 2.3 Ah and rated voltage of (i) 3.3V and (ii) 7.1 V, connected in series. The initial SoCs of the cells were set as follows:

Cell 1: 100% SoC, 2.3 Ah,

Cell 2: 90% SoC, 2.3 Ah,

Cell 3: 60% SoC, 2.3 Ah.

Simulations were performed on MATLAB/Simulink, first for Passive Switched Resistor Balancing and then for Active Single Switched Capacitor Balancing for two sets of cell modules. For the reference of this paper, cells are considered to be balanced when their SoC is within 5% of each other. The simulation results are presented in figures 6-21.

3.1 Passive Cell Balancing Technology using Switched Shunt Resistance Method

3.1.1 Cell Voltage 3.3V

The simulation is run for 3000 seconds. Cell balancing is achieved between cells after about 2200 seconds as shown in Figure 6. Energy content of each cell and the total energy of the battery pack is presented in Figure 9. Energies of higher SoC cells 1 and 2 are dissipated through the shunt resistors until the SoCs of all cells are essentially equal. Overall energy of the system dropped by 7.1 mWh in the balancing process.

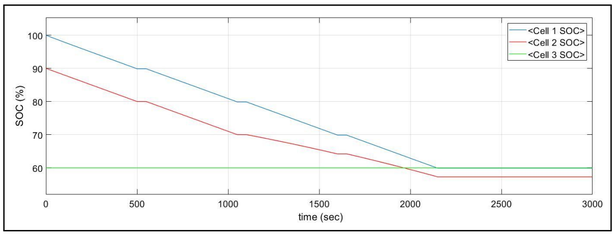

Figure 6: SoC of Cells in Passive Balancing for 3.3V

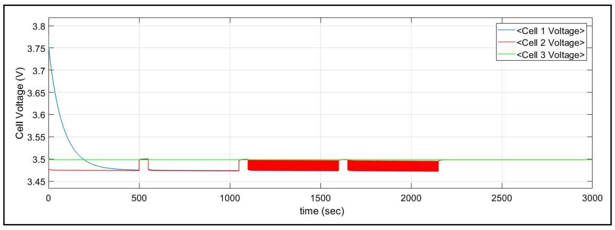

Figure 7: Cell Voltage in Passive Balancing for 3.3V

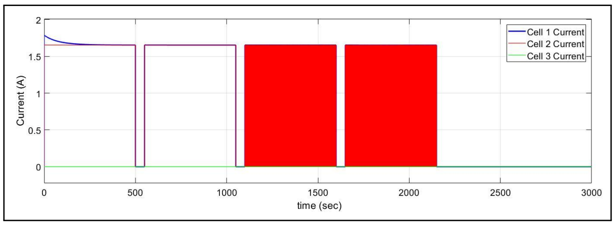

Figure 8: Resistor Current in Passive Balancing for 3.3V

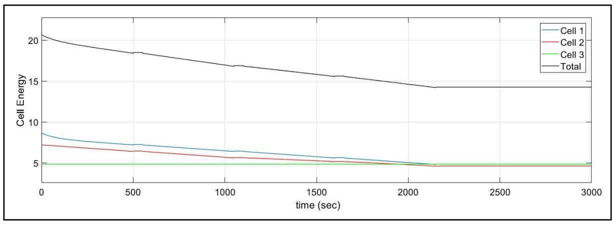

Figure 9: Energy Content of Cells in Passive balancing for 3.3V

3.1.2 Cell Voltage 7.1V

Simulation is run for 3000 seconds. Cell balancing is achieved between cells after about 950 seconds as shown in Figure 10. Energy content of each cell and the total energy of battery pack is presented in Figure 13. Energies of higher SoC cells 1 and 2 are dissipated through the shunt resistors until the SoCs of all cells are essentially equal. Overall energy of the system dropped by 11.5 mWh in the balancing process.

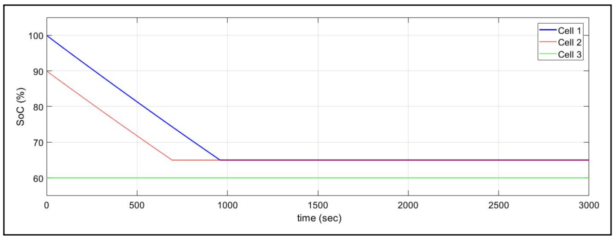

Figure 10: SoC of Cells in Passive Balancing for 7.1V

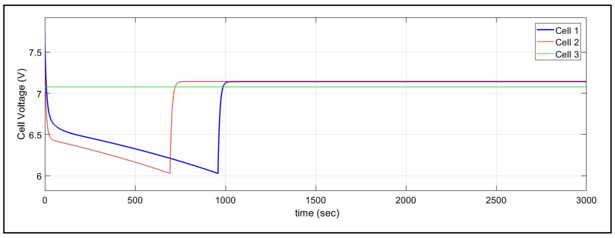

Figure 11: Cell Voltage in Passive Balancing for 7.1V

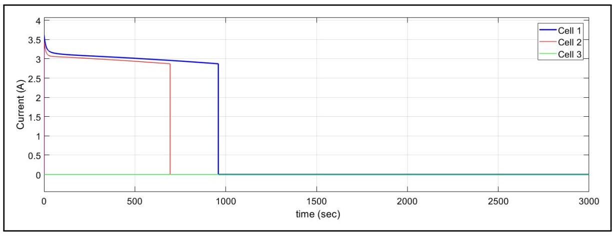

Figure 12: Resistor Current in Passive Balancing 7.1V

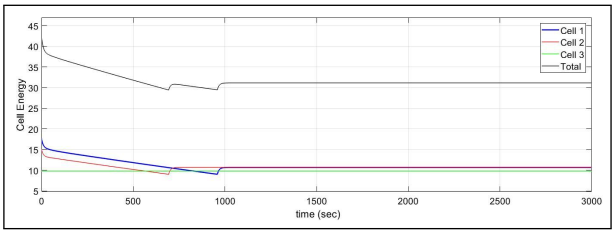

Figure 13: Energy Content of Cells in Passive balancing for 7.1V

3.2 Active Cell Balancing using Single Switched Capacitor

3.2.1 Cell Voltage: 3.3V

Cell balancing (5% SoC difference) was not achieved between the cells even after 12 hours of simulation as shown in Figure 14. But considering the pattern of the graph, it is observed that the algorithm works and cell balancing will be achieved eventually. Figure 17 displays Energy content of each cell and the total energy of the battery. The energy from high SoC cells 1 and 2 is transferred to the low SoC cell 3 through a balancing capacitor. Energy is lost in the equivalent series resistance between the cells and the capacitor during cell balancing. Energy lost during the balancing process in the 12 hours of simulation is 0.5 mWh.

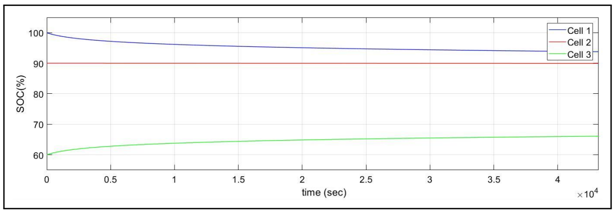

Figure 14: SoC of Cells in Active Balancing for 3.3V

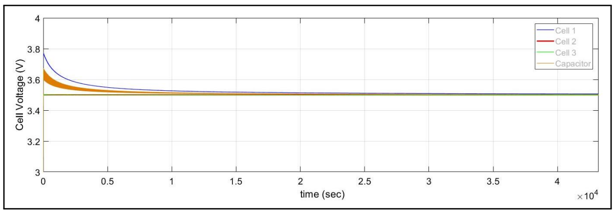

Figure 15: Voltages in Active Balancing for 3.3V

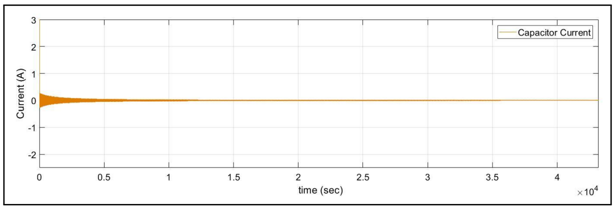

Figure 16: Capacitor Current in Active Balancing for 3.3V

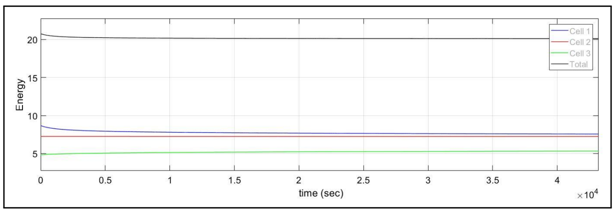

Figure 17: Energy Content of Cells in Active Balancing for 3.3V

3.2.2 Cell Voltage: 7.1V

Cell balancing is achieved between the cells after about 40000 seconds as shown in Figure 18. Figure 21 displays Energy content of each cell and the total energy of the battery. The energy from high SoC cells 1 and 2 is transferred to the low SoC cell 3 through a balancing capacitor. Energy is lost in the equivalent series resistance between the cells and the capacitor

Table 1: Comparative analysis of two different cell balancing topologies for two different cell voltages

Cell Voltage	Cells	Initial SoC	Passive Cell Balancing using Switched Shunt Resistor			Active Cell Balancing using Single Switched Capacitor		
			Final SoC	Equalization Time (sec)	Energy Loss(mWh)	Final SoC	Equalization Time (sec)	Energy Loss(mWh)
3.3 V	Cell 1	100%	60%	2200	7.1	94%	-	0.5 (in 12 hrs)
	Cell 2	90%	55%			90%		
	Cell 3	60%	60%			66%		
7.1 V	Cell 1	100%	65%	950	11.5	85%	40000	0.5
	Cell 2	90%	65%			85%		
	Cell 3	60%	60%			80%		

during cell balancing. Energy lost during the balancing process is 0.5 mWh.

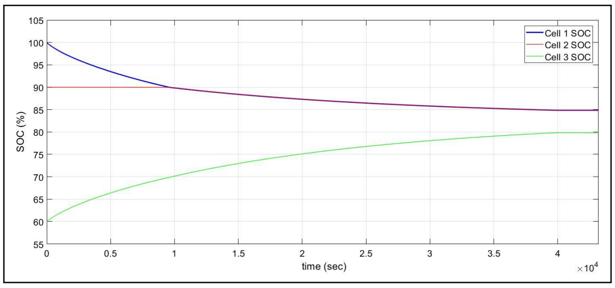

Figure 18: SoC of Cells in Active Balancing for 7.1V

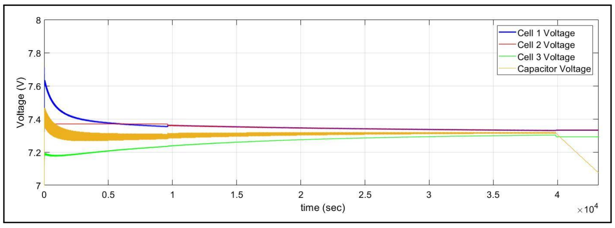

Figure 19: Voltages in Active Balancing for 7.1V

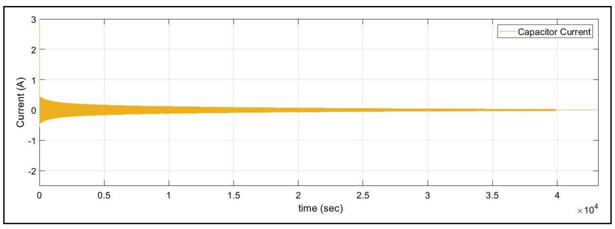

Figure 20: Capacitor Current in Active Balancing for 7.1V

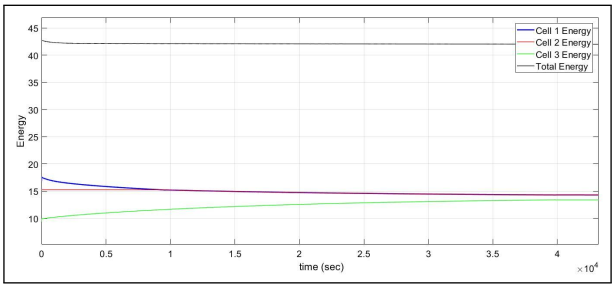

Figure 21: Energy Content of Cells in Active Balancing for 7.1V

In switched shunt resistance passive balancing, the current flows through the resistors until cells are balanced. During this period, the cell voltages drops steadily as long as the switch remains closed and return to nominal voltage when the switch opens. In SSC active balancing, the voltage difference across the capacitor steadily drops to zero as the cells get closer to being balanced. It is observed that in modules with higher cell voltage equalization time for cells is faster i.e. cell balancing occurs faster. This is because higher voltages facilitate faster loss of energy through resistors in passive cell balancing and faster exchange of charges through capacitor in active cell balancing.

4. Conclusion

Increasing the battery pack lifetime by using the cell balancing methods, one major task of Battery Management System is fulfilled. Cell balancing optimizes the battery capacity and increases safety of the battery system. Two topologies viz. Switched Resistance method for Passive Cell Balancing and Single Switched Capacitor method for Active Cell Balancing were studied and simulated with the help of MATLAB/Simulink. The result of the simulation has been tabulated in the Table 1.

Three battery cells of 2.3 Ah capacity and 3.3 nominal voltage each were balanced using fixed resistor and single-switched capacitor methods.The initial SoC for the cells were 100%, 90% and 60% respectively. The simulated results were 60%, 55% and 60% SoC, achieved in 2200 seconds with 7.1 mWh energy loss, for passive balancing. The final SoC for single switched capacitor balancing after 43200 seconds were 94%, 90% and 66% with 0.5 mWh energy loss. The increased efficiency of active balancing comes at the cost of higher balancing time. The simulation result validates both algorithms for cell balancing.

Similarly, three battery cells of 2.3 Ah capacity and 7.1 nominal voltage each were balanced using fixed resistor and single-switched capacitor methods.The initial SoC for the cells were 100%, 90% and 60% respectively. The simulated results were 65%, 65% and 60% SoC, achieved in 950 seconds with 11.5 mWh energy loss, for passive balancing and 85%, 85% and 80% SoC, achieved in 40000 seconds with 0.5 mWh energy loss, for single switched capacitor balancing. Here too, the increased efficiency of active balancing comes at the cost of higher balancing time.

5. Future Works

In continuation to the simulation performed in this paper, further works could involve the testing of these algorithms during the charging and discharging state of the batteries.

Furthermore, it has been observed in this work that the voltage across the capacitor has significant effect on equalization time. Hence, any future work may also involve the usage of converters to increase the voltage across the capacitor and analyze its effect in the performance of the Cell Balancing Topology.

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