Active Cell Balancing with DC/DC Converter for Electric Vehicle

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2022 10th International Conference on Smart Grid and Clean Energy Technologies (ICSGCE) | 978-1-6654-8753-5/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICSGCE55997.2022.9953732

***Abstract*—Greenhouse gases and global warming are severe issues for the living on earth and the main factor of these issues is the emission of harmful gases from fossil fuel or petroleum-used vehicles. Thus, the electric vehicle is proposed and commercialized to cut down the use of fossil fuel vehicles. However, the problem of battery cell imbalance of the electric vehicle leads to unsatisfactory and critical bad impacts on the battery lifespan and operating duration, in turn, reducing the public interest in electric vehicles. This paper discussed and proposed the solution to the cell unbalanced issue by utilizing the active cell balancing methods based on the Buck-Boost DC/DC Converter topologies with the integration of several closed-loop control systems and algorithms on the serially connected Lithium-Ion (Li-ion) battery cells in this work. The proposed cell balancing system is tested under a constant load test. Eventually, the proposed model managed to bring all the cells to a balanced state with a nearly similar State of Charge (SOC) for all the cells. MATLAB/Simulink is used for the development of this simulation model.**

Keywords*—*active cell balancing, lithium-ion battery, DC/DC buck-boost converter, battery management system

I. Introduction

In this new era, greenhouse gases emission and global warming issues are raising intensely. These situations are majority caused by petroleum-used vehicles. Hence, many organizations and companies in the transportation sector are evolving vehicles into a form that is sound to the environment with producing less harmful effects to the surrounding by replacing the use of fossil fuels in the vehicle with portable energy storage or battery pack that can drive the vehicle instead of combustion of fossil fuels. A vehicle with a battery pack is known as Electric Vehicle (EV). Generally, rechargeable batteries are utilized in a battery pack.

From the current state, many types of rechargeable batteries as energy storage have been tested and investigated on various electric or electronic appliances, automobiles, and transportations as well such as lithium-ion batteries (Li-ion), nickel-metal hydride batteries (NiMH), lead-acid batteries, nickel-cadmium batteries (NiCd) and ultracapacitors (EDLC). However, according to the current trend, lithium-ion is widely used in many aspects and industries due to its outstanding performance and properties that have met most of the sectors' requirements [1]-[2].

Besides that, the frequency of battery maintenance for the lithium-ion battery is rarely happening along with the operating duration and its lifecycle and there is unnecessary to have scheduled cycling for the lithium-ion battery compared to other battery types [3]-[4].

However, to have higher capacity and energy usage, many industries combine the lithium-ion batteries into a pack to form a large serial-parallel connected battery pack which result in safety, thermal, and many more issues that could contribute to cell imbalance situation. Cell imbalance occurrence due to the combination of many battery cells could accelerate the cell degradation problem because of the imprecision of SOC estimation. This happens due to the difference in chemical properties and manufacturing characteristics of each cell even if they are from the same manufacturing industry as errors can result in cell voltage and capacity discrepancies [5]. Overcharging may happen and lead to distortion, leakage, a rise in pressure on the battery cells and even worse it might get exploded [6]. Over-discharge also leads to degeneration in the lifecycle of a battery cell. Hence, the cell balancing features in equalizing cells is a must in the Battery Management System (BMS).

Cell balancing is a feature or process that is carried out by a switching circuitry of balancing the SOC and voltages among all the full-charged cells in a battery pack. A good design of cell balancing or charge equalizing system could inflict the battery pack to have a longer lifespan and higher efficiency performance, indirectly protecting the battery energy storage from damage. Cell balancing can be classified into two major categories which are Passive and Active Cell Balancing. Passive balancing is also known as the 'resistor of bleeding' cell balancing technique [7] where this method is a simple, inexpensive, straightforward type of balancing and size-limited applications. It is mainly utilizing a resistor that acts as a bypass shunt resistor to remove the excessive energy from the highest voltage cell so that the charging process will not be terminated and until a point that all cells have the same voltage levels. Active cell balancing is preferable than passive cell balancing as it does not waste excessive energy in form of heat like the passive method which is inefficient. The active cell balancing is also known as the 'non-dissipative charge equalization' alternative that balances by transferring and converting the excessive charge from one cell to another cell that is low in charge level with the utilization of active components such as capacitors and inductors as the storing elements that can store charge for a while and further transfer to the weaker cells for equalizing purposes [8]-[9]. The previously proposed active cell balancing works could refer to [8], [10]-[13].

This paper demonstrates the proposed active cell balancing topology on lithium-ion batteries with a Buck-Boost converter that is based on SOC-based balancing, integrating with several control algorithms.

II. Proposed Model Circuitries & Designs

There are a total of four batteries utilized in this project. Fig. 1 shows the subsystem blocks connection. The line connections from the four batteries to the converter are illustrated where three lines are connected to the buck signal input while another three to the boost signal input. The battery pack is connected to the discharge and charge DC/DC converter interconnected with the common ground line from the converter to the negative pole of the battery pack. Then both DC/DC converters are connected to the load/charger for charging and discharging purposes.

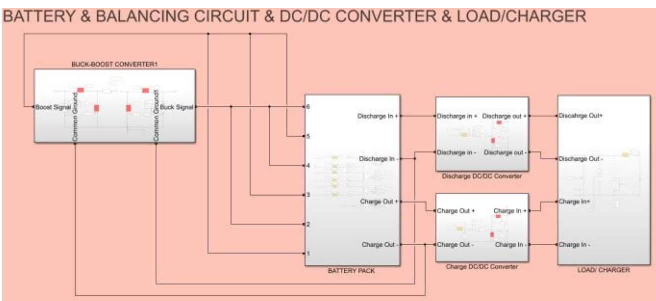

Fig. 1. Battery Pack, balancing, charging & discharging converter and load/charger.

A. Battery Pack

Fig. 2 shows four batteries are connected in a series. The two batteries in the middle which are B2 and B3 have two branches of ideal switches connected above them. For B2, swB1 acts as the switch in allowing the cell to operate in buck mode while swA2, is the switch in triggering the boost mode. The switches' names with the 'B' letter are mainly activated in buck mode while switches' names with the 'A' letter are for boost mode conduction.

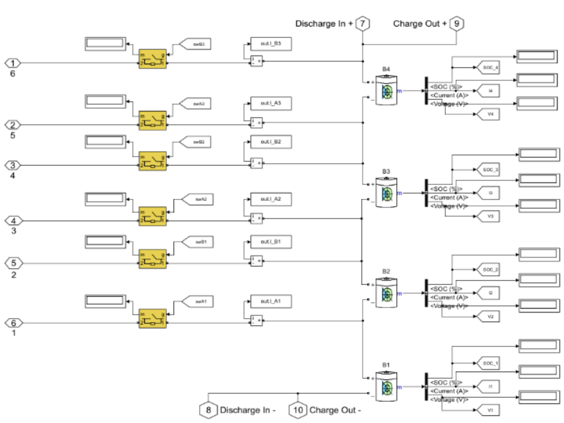

Fig. 2. Battery pack circuit connection.

B. Discharge/Charge DC/DC Converter

Fig. 3 shows the converter configuration as like a Buck converter with two MOSFETs switches in controlling the current flows instead of using a diode that results in high power losses in the practical world. The 'Switch_Mode' is used in closing or opening the DC/DC circuit connection. For the charge DC/DC converter, the circuit configuration is about identical to the discharge DC/DC as shown in Fig. 4, however with an additional capacitor connected in parallel with the inductor at the Charging Out. These circuitries are controlled by the charging/ discharging control algorithms by referring to [14]-[15].

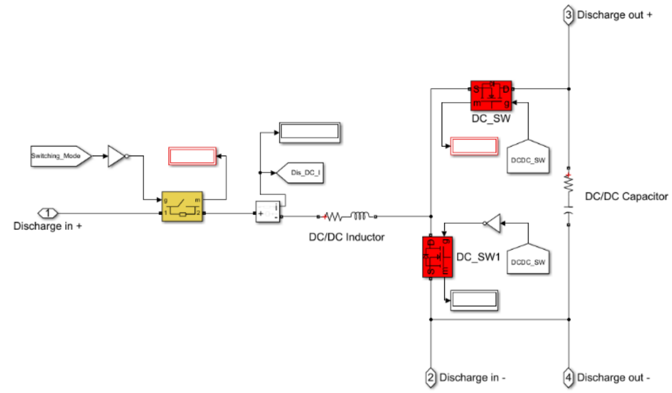

Fig. 3. Discharge DC/DC converter circuit connection.

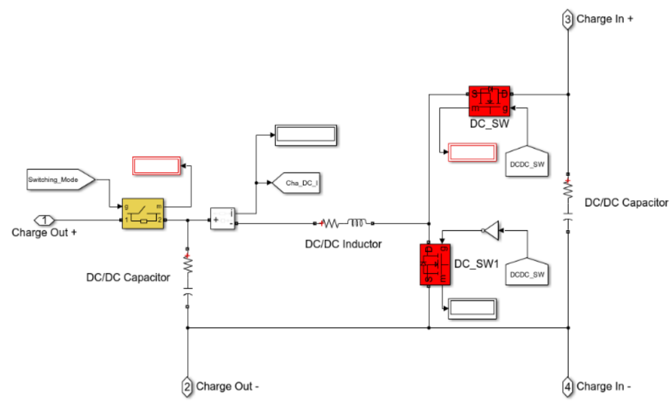

Fig. 4. Charge DC/DC converter circuit connection.

Table I listed the inputted values of the DC/DC inductor and capacitor for both Charge and Discharge DC/DC converters that are according to one of the published work in [15].

TABLE I. Input Values of DC/DC Converter

Components	Charging DC/DC Converter	Discharging DC/DC Converter
Inductor, *H*	5.76×10^{-2}	5.76×10^{-2}
Inductor Series Resistance	0.05 Ω	0.05 Ω
Capacitor, *F*	5600×10^{-6}	1000×10^{-6}
Capacitor 1, *F*	1000×10^{-6}	-
Capacitor Series Resistance, Ω	0.001	0.001

C. *Load/Charger*

In the Load/Charger subsystem in Fig. 5, the switching mode From Tag is responsible for selecting the circuit to be charged or discharged with the ideal switch. The constant load is set as 5 Ω while the DC voltage source could be set around 25.6 V or 26 V about double the total nominal voltage of the battery pack.

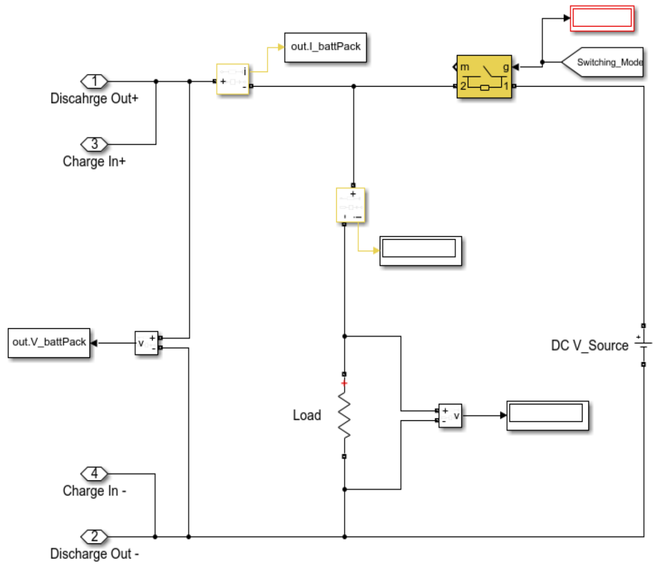

Fig. 5. Load/Charger circuit connection.

D. *Buck-Boost Balancing Converter*

In terms of designing the parameter of the converter, the calculation for both the buck and boost modes are considered to suit the requirements based on [15]-[16]. The calculated values shown in Table II are with a switching frequency of 200 kHz and an output current of 2.75 A.

TABLE II. SPECIFICATION OF BUCK-BOOST CONVERTER

Parameters	Buck	Boost
V_{in}, V	6.4 – 12.8	3.2 – 9.6
V_{out}, V	3.2 – 9.6	6.4 – 12.8
Duty Ratio	0.25	0.75
Capacitors, µF	135	412.5
Inductor, µ*H*	26.2	

III. CONTROL ALGORITHM & SWITCHING SELECTION

Fig. 6 contains the balancing control unit and selection of converter mode in switching the switches accordingly. The balancing algorithm block and the cell states blocks in the middle are chiefs in determining and controlling which mode and switches to be activated and deactivated. While both converter switching and normal switching blocks are responsible for arranging and sending the control signals to every switch.

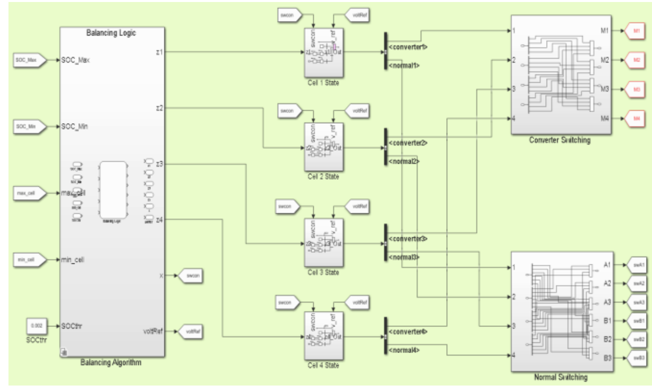

Fig. 6. Balancing algorithm & switching selection block connections.

A. *Balancing Algorithm*

The Stateflow chart of the balancing algorithm is shown in Fig. 7. The output ports from ‘z1’ to ‘z4’ indicate the state of cells in terms of balancing where the 0 represents the cell state is not in balancing mode. The variable ‘x’ is used to select which switch combination to be activated and ‘voltRef’ is for determining the voltage value that the balancing system requires to refer. The ‘Stt1’to ‘Stt4’, ‘SwCon’ and ‘v’ are acting as local data while ‘z1’ to ‘z4’, ‘x’ and ‘voltRef’ are output data in the chart. The ‘SOCthr’ is 0.002.

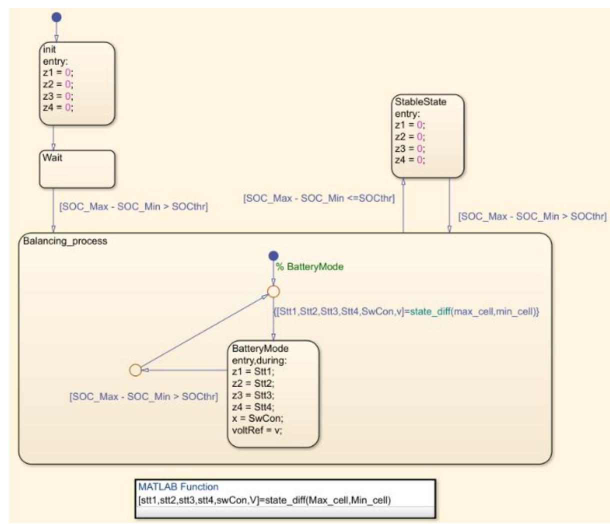

Fig. 7. Stateflow chart of balancing algorithm.

The usage of the ‘state-diff’ function is articulated in Fig. 8. Before defining the state selection of the cells, it is mandatory to set all the output variables equal to zero.

	Cells			
Max SOC \ Min SOC	1	2	3	4
1		Stt1 = 2 Stt2 = 0 Stt3 = 0 Stt4 = 0 SwCon = 1 V = 1	Stt1 = 2 Stt2 = 0 Stt3 = 0 Stt4 = 0 SwCon = 2 V = 2	Stt1 = 2 Stt2 = 0 Stt3 = 0 Stt4 = 0 SwCon = 3 V = 3
2	Stt1 = 0 Stt2 = 1 Stt3 = 0 Stt4 = 0 SwCon = 1 V = 1		Stt1 = 0 Stt2 = 2 Stt3 = 0 Stt4 = 0 SwCon = 4 V = 2	Stt1 = 0 Stt2 = 2 Stt3 = 0 Stt4 = 0 SwCon = 5 V = 3
3	Stt1 = 0 Stt2 = 0 Stt3 = 1 Stt4 = 0 SwCon = 2 V = 1	Stt1 = 0 Stt2 = 0 Stt3 = 1 Stt4 = 0 SwCon = 4 V = 2		Stt1 = 0 Stt2 = 0 Stt3 = 2 Stt4 = 0 SwCon = 6 V = 3
4	Stt1 = 0 Stt2 = 0 Stt3 = 0 Stt4 = 1 SwCon = 3 V = 1	Stt1 = 0 Stt2 = 0 Stt3 = 0 Stt4 = 1 SwCon = 5 V = 2	Stt1 = 0 Stt2 = 0 Stt3 = 0 Stt4 = 1 SwCon = 6 V = 3	
		Colour:	BUCK	BOOST

Fig. 8. MATLAB function state selection algorithm.

Table III indicates whether the Maximum cell will operate in Buck or Boost mode. For instance, taking the example of Maximum cell is 2 and minimum cell is 3, ‘Stt2’ represents the state of cell 2 will be equal to the input of ‘2’ which means cell 2 will be operated in form of Boost mode. If the ‘Stt2’ is equal to the input of ‘1’ meaning cell 2 will be operated in Buck mode.

TABLE III. THE INPUT OF STATE OF THE MAXIMUM CELLS

The input of ‘Sttx’	**Mode of the cell selected**
0	No/Normal Mode
1	Buck Mode
2	Boost Mode

‘SwCon’ variable is for numbering the table boxes in Fig. 8. From Table IV, there have 6 columns for Buck mode and another 6 for Boost mode, however, the 6 columns for Buck mode are typically having the same groups of ideal switch combinations as Boost mode.

TABLE IV. DETERMINATION OF SWITCH COMBINATION BY ‘SWCON’

The input of ‘SwCon’	***Buck/Boost***					
	1	**2**	**3**	**4**	**5**	**6**
Group of switch combinations to be activated *(Applicable for Buck & Boost)*	1	2	3	4	5	6

The ‘V’ variable in Fig. 8 acts as a variable in selecting the voltage reference for the cell balancer to refer to. Table V articulates the usage of this variable according to its input that reflects the output of this feature. To illustrate an example, if ‘V’ equals 1 in Buck mode, then the cell balancer will balance by referring to the reference voltage of 3.2 V.

TABLE V. REFERENCE VOLTAGE SELECTED BY ‘V’

The input of ‘V’		***Buck/Boost***	
		Buck reference voltage, V	***Boost reference voltage, V***
Buck/Boost	**1**	3.2	6.4
	2	6.4	9.6
	3	9.6	12.8

B. Cell state

Cell 1, 2, 3 and 4 state subsystems are identical to each other, the block connections refer to Fig. 9. This subsystem contains 3 input ports and 1 output signal “z1_Out”. The multiport switch with 4 inputs of data ports, the first input is the control port while the rest are data ports. The control port will select which data ports to be chosen according to the similarity of the input value with the data ports’ number by referring to Table III.

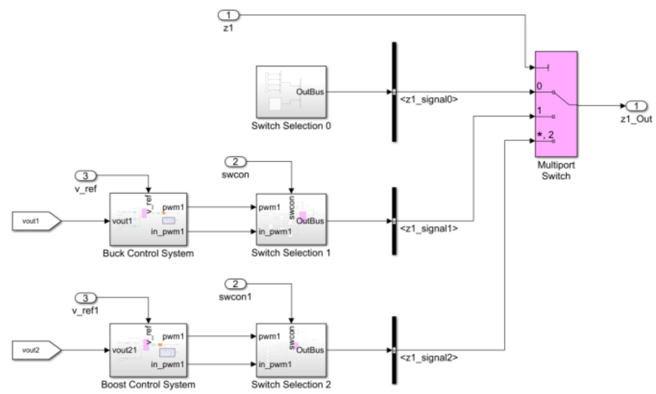

Fig. 9. Cell 1 state subsystem connection.

Fig. 10 shows the Buck subsystem of cell 1 state with 2 inputs of data ‘v_ref’ and ‘vout1’ which is the output voltage of C1. Two PI controllers are utilized in tuning and regulating the voltage and current of the balancing circuit to maintain a steady-state condition. A PWM generator block in generating the PWM signal according to the regulated signal from the PI controller. The inverted PWM pulses are created in the purple border that is essential to be used in cell balancing. The output voltage of C1 will act as feedback from the Buck-Boost converter to this control system to deduct with the respective reference voltages (3.2/ 6.4/ 9.6 V) to produce the error signal so that the PI controllers could further adjust and reduce the error and bring the output signal back to the wanted responses. A similar configuration is applied to the Boost subsystem as shown in Fig. 11.

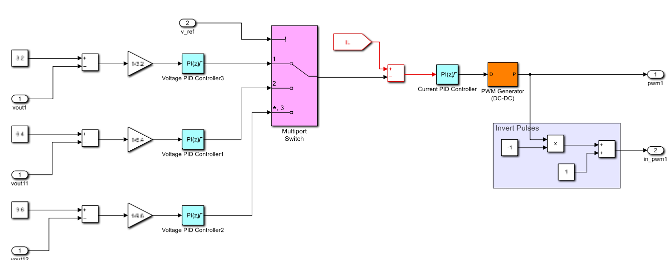

Fig. 10. Control system of Buck subsystem of cell 1 state.

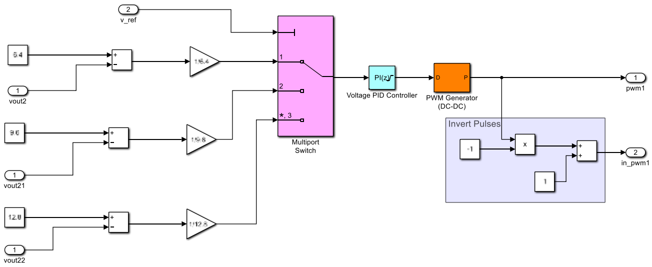

Fig. 11. Control system of Boost subsystem of cell 1 state.

IV. Simulation Results & Discussion

In this section, the investigation is based on the variation of the battery pack's outputs on a constant load. Two simulations with and without the proposed cell balancing system were carried out on the constant load over 2000 seconds of simulation time in the MATLAB/Simulink environment.

A. Parameters settings

Table VI shows the initial parameters settings for each SOC battery (SOC_B) of the simulations. Lithium Iron Phosphate (LiFePO4) is employed and the specification refers to [17].

TABLE VI. Initial Simulation Parameters Setting

Parameters	Values
SOC_{B1}, %	74
SOC_{B2}, %	75
SOC_{B3}, %	78
SOC_{B4}, %	72
Cell capacity, Ah	5500 m
Cell nominal voltage, V	3.2
Discharge current, A	2.75

B. Results

Fig. 12 illustrates the discharge SOC profile of the batteries on a constant load without balancing. Cell 3 contained the highest SOC value followed by Cell 2, 1 and 4. Each of the SOC values decreases linearly without balancing each other. The entire process stopped at 2000s. All the SOC values decreased from about 80% - 70% range to around 50% - 40% range and the highest SOC cell remained the highest same for the rest of the cells.

Fig. 13 is the simulation result with the proposed cell balancing system. Cell 3 was the highest SOC value while cell 4 was the lowest SOC value. In this case, the starting balancing mode was based on Boost mode operation in balancing the cell. The cell balancing circuit was activated, cell 4 was discharged at a slower rate while the rest of the cells were discharged at a faster rate. This is because cells 3, 2 and 1 were trying to balance cell 4 by discharging their charge to cell 4. This means that battery cells 3, 2 and 1 were demanded to output their charge to the constant load at the same time they were needed to transfer the energy to cell 4 as well. At 200 seconds, cell 1 was met with cell 4 and both would discharge at the same rate. Then the duty ratio that was controlled by the PI controller would be increased to speed up the balancing rate of the cells. Hence, the SOC profile values of cells 2 and 3 were sharpened in shape to catch up with the weaker cells. When cell 2 met with cells 1 and 4 at 1046.3 second, then cell 3 was the only 1 responsible for balancing the rest of the weaker cells, thereby, the control algorithm adjusted the duty ratio of the MOSFETs' switches of the Buck-Boost to supply higher current to achieve the equalize state at around 1071 seconds with 51.74%. Afterwards, when all cells were balanced, the balancing process stopped and continue to discharge at a steady rate.

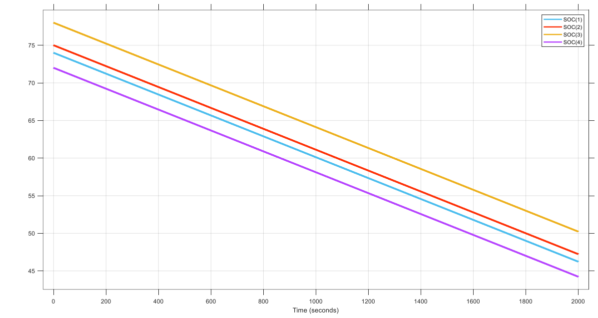

Fig. 12. Batteries SOC profile without the proposed cell balancing system.

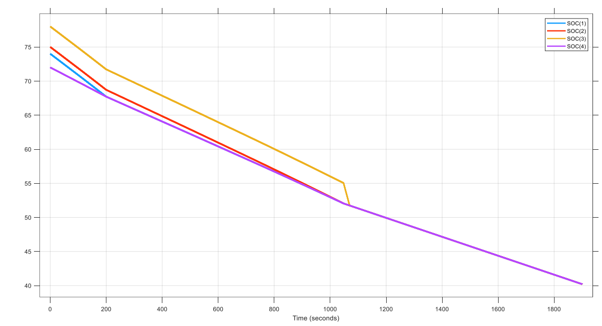

Fig. 13. Batteries SOC profile with the proposed cell balancing system.

Fig. 14 shows the current (upper graph) and voltage (bottom graph) profile of each battery. The current of each cell was discharging at a constant current rate as the right conner box displayed the Cell 1 current with the mean value of +2.75 A, which was the desired constant current discharge value that was set in the system. The positive value of current indicates the battery cells were discharging while the negative sign represents charging current. The voltage values were decreased gradually. This is due to the energy and the capacity of each battery were reducing to maintain to have a constant output power supplied to the load side with the constant current. Thus, the voltage profile curve reduced exponentially.

The result of the proposed cell balancing system is shown in Fig. 15. As seen from 0 to 200 seconds, the current and voltage values were around 0 A to 20 A and 3.25 V to 3.4 V which were considered quite low values as 3 cells were balancing the weakest cell. As cell 1 and cell 4 were balanced, the duty ratio was tuned to be higher as it seemed to have only 2 cells responsible for balancing the battery stack, the higher the duty cycle the higher the output voltage. This in turn led to the fluctuation of the voltage and indirectly influenced the current as well. When cell 2 met with cells 1 and 4, basically the battery pack seemed to only have 2 cells as cells 1, 2 and 4 contained the same amount of energy and capacity. Thus, the control system regulated the duty ratio again by letting cell 3 discharge a significant amount of energy to achieve the equalization state as soon as possible. Fig. 15 individually illustrates the current of cell 3 maintained for some time and dropped to the desired current value when the SOC values of all the battery cells were met.

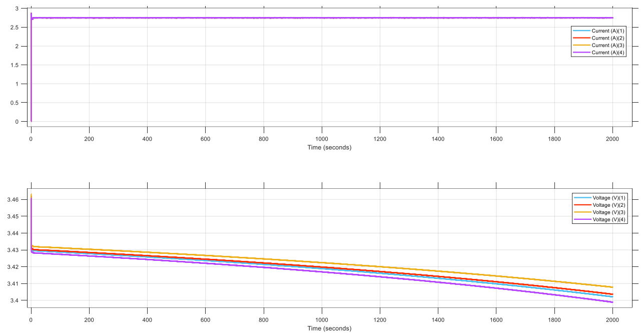

Fig. 14. Batteries current & voltage profile without the proposed cell balancing system.

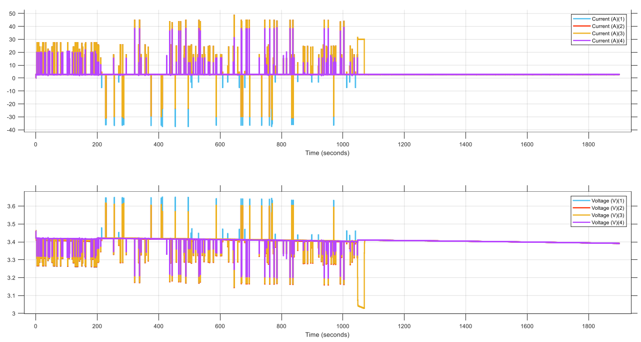

Fig. 15. Batteries current & voltage profile with the proposed cell balancing system.

In Table VII, the final values of batteries SOC for both simulations were collected at 1070 seconds right after the balanced point. Observing the Final SOC values on the simulation without cell balancing, all the SOC values are unidentical with large differences among them with a high standard deviation value of 2.1650. This could cause an issue in discharging the battery pack as the lowest SOC value will restrict the entire discharging process of the battery pack, thereby, resulting in the remaining energy in other cells will be wasted. With the cell balancing system simulation, all the SOC values are approximately the same as each other with low differences among the battery cells that have a relatively low standard deviation of 0.0009 compared to the simulation without balancing.

TABLE VII. DATA COLLECTION ON BOTH SIMULATIONS

	Cells				
	1	2	3	4	Parameters
Without cell balancing	59.1248	60.1247	63.1247	57.1250	Final SOC, %
	2.1650				SD Final SOC
With cell balancing	51.7236	51.7236	51.7256	51.7237	Final SOC, %
	0.0009				SD Final SOC

(SD = Standard Deviation)

V. CONCLUSION

All in all, this paper presented the significance of the existence of the cell balancing of the BMS for an electric vehicle and indicated the aims in solving the cell charge unbalanced situation. The series-connected cells are employed with the integration of the active cell balancing method and the Buck-Boost DC/DC converter-based topologies on both cell balancing and charging/ discharging aspects were proposed and tested by using MATLAB/Simulink software. In concluding the overall review of the simulation experiments, by using the cell balancing system under different testing conditions, the balancing system was managed to balance all the cells with a low standard deviation of 0.0009 and differences among all the SOC of each cell.

VI. FUTURE IMPROVEMENT

There are several ways to make improvements to this current proposed model as listed in the following.

A. *Parameters of Buck-Boost Cell Balancing Converter Improvement*

Looking into the energy conversion of the cell balancing converter in both Buck and Boost mode and further making adjustments to the parameters input to the cell balancing converter. Besides, the closed-loop control system for Buck and Boost mode should be further investigated as well. These mentioned parts would contribute to the high voltage and current fluctuations in the capacitors and inductors of the Buck-Boost cell balancing converter. The high voltage and current fluctuation would influence the balancing current to be drawn with a higher or lower value. Hence, this will result in higher energy used in balancing the cells.

B. *Number of Buck-Boost Cell Balancing Converter*

Only one converter in balancing all the cells will require a long balancing time to achieve the balanced state for all the cells. Generally, the number of cells being employed in the model will equal the number of Buck-Boost converters in balancing. For example, there are 4 cells employed in this thesis work, then an improvement would be the addition of another 3 Buck-Boost converters for balancing. Hence, overall, there will have 4 Buck-Boost converters in total. However, this improvement will increase the complexity and difficulty of the control algorithm part.

C. *Battery Modelling*

By modelling a battery cell could relatively acquire a more precise and accurate reading of the effective capacity and SOC energy of each cell. The battery modelling could imitate the dynamic responses of an actual battery cell in real life under various environmental and limiting factors such as the ambient temperature, temperature of the cell itself and ageing effect of the cell. All of these elements could intensely affect the properties of a cell such as the effective capacity value, life-span of the cell and the allowable current to be drawn as well.Consequently, battery modelling could provide advantages in getting precise and accurate parameters of the cells and it seems similar to an actual real-life battery in providing the more convincing parameters to be used.

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