Defence Science Journal, Vol. 69, No. 3, May 2019, pp. 266-273, DOI : 10.14429/dsj.69.14418

Modelling of Multi Inductor-based Balancing of Battery Pack for Electrical Mobility

Rigvendra Kumar Vardhan, T. Selvathai*, Rajaseeli Reginald, and P. Sivakumar

DRDO-Combat Vehicles Research and Development Establishment, Chennai - 600 054, India

E-mail: selvathai.t@cvrde.drdo.in

ABSTRACT

The pre requisite for success of electrical mobility is driven by development of battery technologies. Reliable performance of electrical mobility necessitates for high energy density battery packs. The advent of Li ion cell chemistry revolutionised the electric and hybrid vehicle advancement due to its high energy density, lighter weight and wide range of temperature performance. Higher operating voltages of the battery are achieved by configuration of the cells in series and parallel combinations. The performance of these battery packs are affected by operating temperature and imperfections in manufacturability which causes mismatches in cell impedance, cell potential and state of charge (SOC) imbalance. These performance issues are overcome by cell and battery balancing techniques. In this paper, a dynamic battery pack balancing circuit by using multi inductor with SOC based logic controller for both cell and battery balancing are presented. The battery pack balancing performances during static, charging, discharging conditions are analysed.

Keywords: Battery module; Power MOSFET switch; PI controller; SOC-based switch logic controller

1. INTRODUCTION

Li ion cells are connected in series composition to form a battery module. Since, the individual cells in a battery hold different capacities and may be at different levels of SOC, the energy that can be charged and discharged from the battery pack is limited to the cell with the least capacity and it can be easily overcharged or over-discharged while cells with higher capacity may undergo only partial cycles. For the higher capacity cells to undergo full charge/discharge cycles without overcharging or over discharging any other cell in the battery pack, battery balancing is required[1].

2. EQUALISATION TECHNIQUES

Battery balancing is done by transferring energy between individual cells, until the SOC of the cell with the lowest capacity is equal to the battery's SOC. The cells imbalance occurs due to mismatch in internal impedance, manufacturability, different self-discharge rate and thermal difference[2]. These parameter variations are overcome using balancing techniques. There are two type of balancing techniques (a) passive balancing and (b) active balancing. In the passive balancing techniques, the excess energy of the highest charged cell are dissipated into passive element i.e. resistor so called dissipative balancing. The active balancing techniques uses active element i.e. inductor, capacitor, and transformer etc. to transfer energy from the higher energy cell to the other lower energy cell hence known as non-dissipative balancing[3]. There are several balancing techniques proposed and reviewed in literature. Passive balancing is easy, reliable and cheapest method but due to heat dissipation in passive element it shortens the battery backup time and increase the thermal issue[4-6]. Active equalisations are further divided into three categories based on the type of active element. Capacitive based balancing is compact, light weight and cheaper but balancing time is more[7-8]. Inductor based balancing circuits have fast balancing time and good efficiency but requires array of switches and precise control algorithms[9-11]. Transformer based balancing circuit have fast balancing speed and are suitable for HEV and EV application but it is expensive, bulkier, require complex control and also suffer from leakage flux & saturation problem[12-15].

3. PROPOSED BATTERY BALANCING

Modelling of single inductor based dynamic battery balancing is presented by Rigvendra[1], *et al.* to further improve the equalisation time dynamic equaliser circuit using multi inductor based balancing with state of charge (SOC) based switch controller and balancing current controller is proposed in this paper.

3.1 Multi Inductor based Battery Balancing

The schematic diagram of multi inductor based balancing is as shown in Fig. 1. Here, the battery consists of a string of 4 cells C_1, C_2, C_3 and C_4 where each cell is connected with MOSFET switches for controlling the charge storage in the inductor based on the SOC. When the MOSFET switch is in OFF state, the stored energy of the inductor is transferred through the diode to the other cells for balancing. For n-cell battery balancing n-MOSFET switches, n-diodes and n-inductors are required.

Received : 31 August 2018, Revised : 05 March 2019
Accepted : 14 March 2019, Online published : 30 April 2019

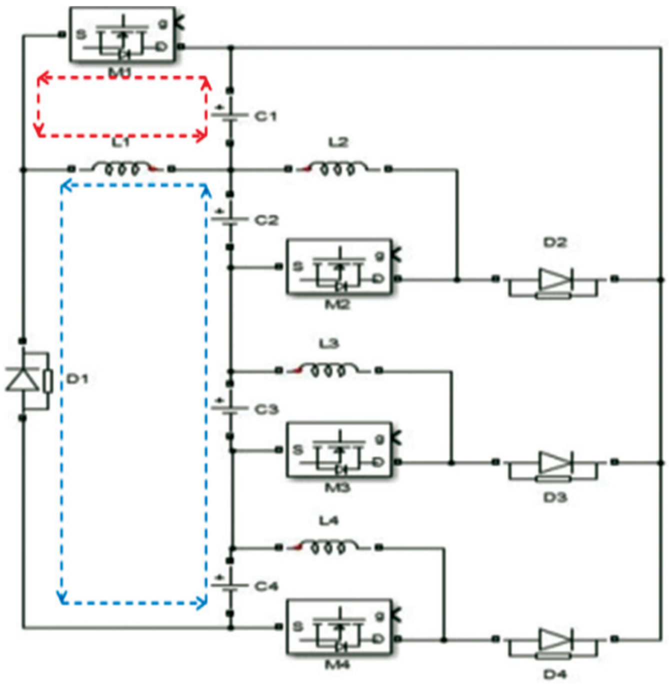

Figure 1. Schematic diagram of multi inductor based balancing circuit.

3.2 Working Principle

Assuming that SOC of cell C_1 is highest in the string then switch M_1 is turned ON and current flows from C_1 to L_1 via switch M_1 i.e. excess charge transferred from cell C_1 to inductor as shown in dotted red line. When switch M_1 is turned off then current flows from inductor L_1 to Cell 2, 3, 4 via Diode D_1 as shown by dotted blue lines in the circuit. Table 1 summarise the switching action and balancing current path of the multi inductor based balancing.

Table 1. Balancing path of the multi inductor equaliser

Highest cell SOC	Switch	Balancing current path	
		Switch ON period	Switch OFF period
$Cell_1$	M_1	C_1-M_1-L_1	L_1-D_1-C_4-C_3-C_2
$Cell_2$	M_2	C_2-M_2-L_2	L_2-C_1-D_2
$Cell_3$	M_3	C_3-M_3-L_3	L_3- C_2-C_1- D_3
$Cell_4$	M_4	C_4-M_4-L_4	L_4-C_3-C_2-C_1-D_4

3.3 SOC based Switch Logic Controller

SOC based switch logic controller is implemented in MATLAB. SOC of all the cells are taken as input to generate the switching signal to turn ON/OFF the corresponding MOSFET switch. The switching action is automatically controlled based on cell SOC comparisons and the switching action is stopped when the SOC difference between all cells is within 50 micron The SOC based switch logic controller algorithm flow chart is as shown in Fig. 2.

3.4 Balancing Current in Continuous Current Mode

To maintain the balancing current between upper threshold and lower threshold values (10 % ripple of balancing current) continuous current mode (CCM) of operation is performed.

The waveform of CCM is as shown in Fig. 3. In this mode, the inductor current toggle between I_{max} and I_{min} during the period of switching signal.

In the Fig. 3, T_{on} denotes the ON period of switching signal that stores energy into the respective inductor from Cell which have higher SOC up to I_{max} current. T_{on} to T denotes the OFF period of switching signal that release the energy from inductor to other cell up to I_{min} current.

T denotes total time period of switching signal.

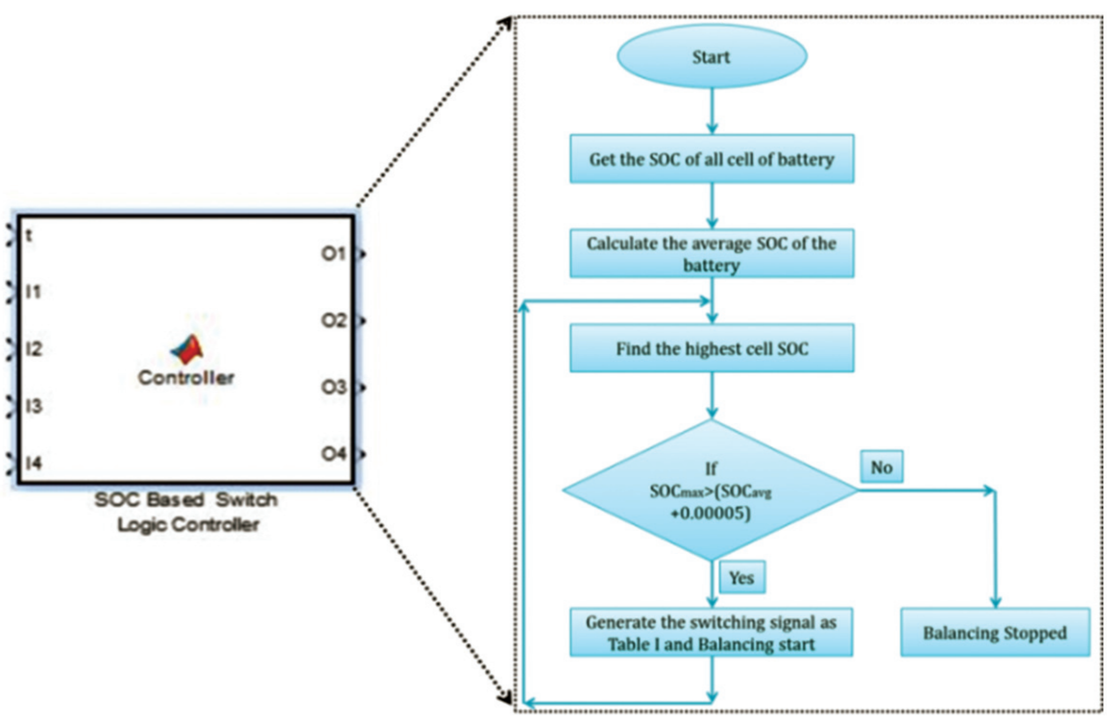

Figure 2. Flow chart of SOC based switch logic controller algorithm.

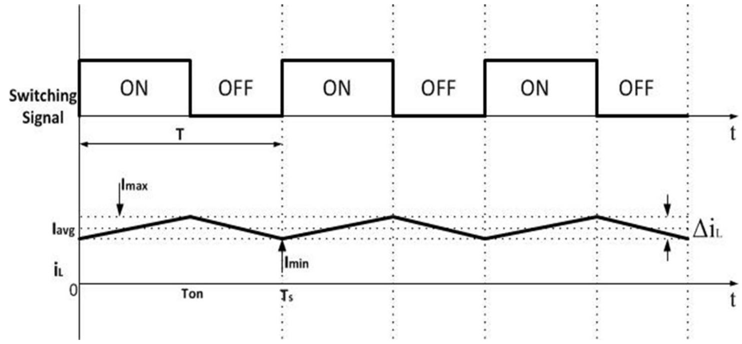

Figure 3. Waveform of CCM.

$$T = \frac{1}{f} \quad (1)$$

where f is switching frequency.

I_{avg} = Average inductor current

I_{max} = Maximum inductor current

I_{min} = Minimum inductor current

So, the ripple current, Δi_L is

$$\Delta i_L = I_{max} - I_{min} \quad (2)$$

where

$$I_{max} = \frac{V_n}{L_n} T_{on} = \frac{V_n}{L_n} \alpha T \quad (3)$$

where V_n is voltage of highest SOC cell in the string

$$I_{min} = \frac{V_o}{L_n} T_{off} = \frac{V_o}{L_n} (1-\alpha) T \quad (4)$$

where V_o is the sum of all the lower cell voltages connected with respective inductor when n=1.

Otherwise, V_o is the sum of all the upper cell voltages connected with respective inductor when n = 2, 3, 4. Here, n is shows the cell and inductor sequence.

Here, the duty ratio, α is

$$\alpha = \frac{ON\ Time}{Total\ Time} = \frac{T_{on}}{T} \quad (5)$$

Therefore, the parameters, T and L can be determined by using above equation with the selection of average inductor current. Therefore, the parameter can be deduced from above Eqns. (1), (2) and (3) as T = 100 µs and L = 330 uH for the average inductor current, I_{avg} = 8A.

To achieve the equalisation in CCM, the current sensed from the inductor is controlled using PI controller to generate the duty ratio for PWM to control the corresponding MOSFET switch. The block diagram of the balancing current under continuous current mode is as shown in Fig. 4.

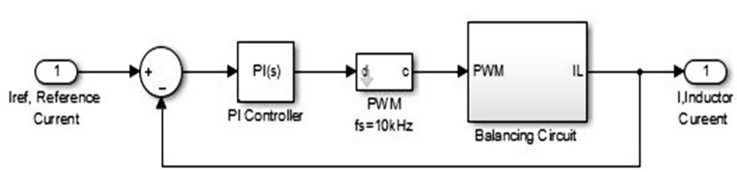

Figure 4. Continuous current mode.

4. SIMULATION RESULT

4.1 Multi Inductor-based Balancing Circuit for Battery

The battery consists of four Li–ion cells. Matlab-simulink generic cell model with 3.7 V nominal voltage and 75 Ah capacity is considered for simulation. Table 2 shows the initial SOC of the cells. 8 A balancing current is considered for the balancing circuit simulation.

Table 2. Initial SOC of cells in battery

Cell no.	Assumed initial SOC
Cell1	60.001
Cell2	60.003
Cell3	60.002
Cell4	60.004

The multi inductor balancing circuit is simulated in three different modes: a) static mode, b) charging mode, and c) discharging mode.

(a) *Static Mode*

In this mode, the battery is neither connected to the charging source nor the load. Whenever SOC imbalance occurs due to temperature or manufacturing mismatch then balancing circuit will be activated. It can be inferred from Fig. 5 that balancing is achieved within 1.48 s for assumed initial SOC as shown in Table 2.

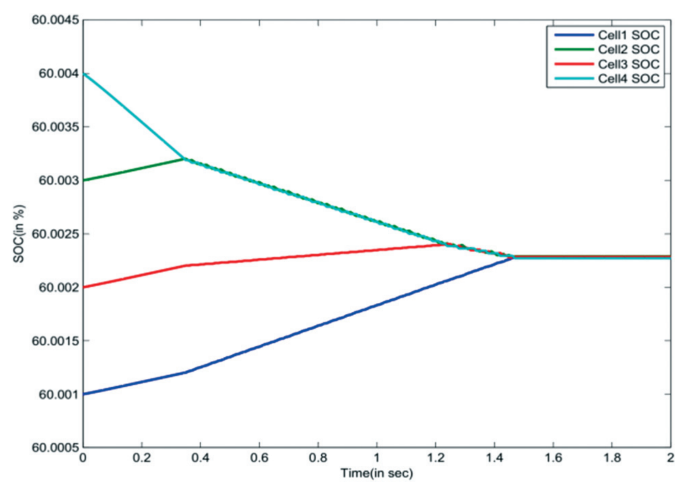

Figure 5. Cell equalisation during static modes.

(b) *Charging mode*

In this mode, the battery is connected to 0.5 C rate constant current source to charge the battery with balancing. It can be inferred from Fig. 6 that the SOC of individual cells are balanced within 1.48 s.

(c) *Discharging mode*

In this mode, the battery is connected to 0.5 C rate constant current source to charge the battery with balancing. It can be inferred from Fig. 7 that the SOC of individual cells are balanced within 1.48 s and all cells of discharge at approximately the same rate.

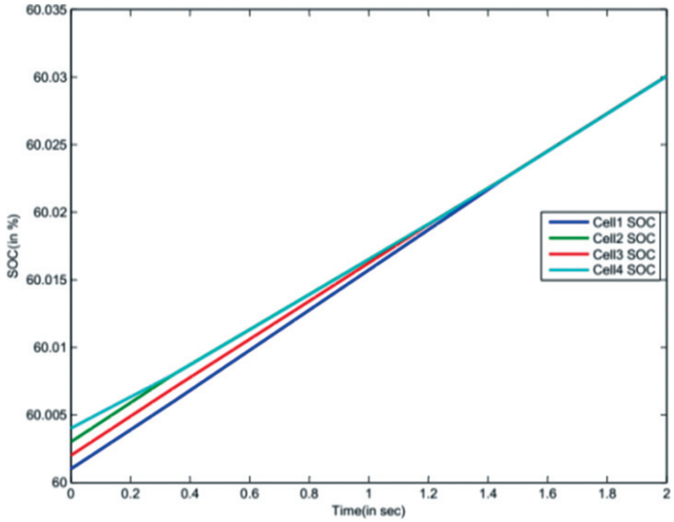

Figure 6. Cell equalisation during charging modes.

As per above simulation result of Multi inductor based equaliser, it is also found that the equalisation time also depends on SOC distribution as summarised in Table 3 in static condition. The minimum equaliasation time of 1.48 s is achieved for cell arrangement No. 3 and maximum equalisation time of 4.5 s is achieved for cell arrangement no.10.

Table 3. Initial SOC of cells in battery

Arrangement no.	Cell 1	Cell 2	Cell 3	Cell 4	Balance time	SOC after balancing
1	60.001	60.002	60.003	60.004	1.61	60.0022
2	60.001	60.002	60.004	60.003	1.55	60.0022
3	60.001	60.003	60.002	60.004	1.48	60.0022
4	60.001	60.003	60.004	60.002	2.2	60.0022
5	60.001	60.004	60.002	60.003	1.6	60.0022
6	60.001	60.004	60.003	60.002	2.1	60.0022
7	60.002	60.001	60.003	60.004	1.85	60.0022
8	60.002	60.001	60.004	60.003	1.78	60.0023
9	60.002	60.003	60.001	60.004	2.9	60.002
10	60.002	60.003	60.004	60.001	4.5	60.0018
11	60.002	60.004	60.001	60.003	3.4	60.002
12	60.002	60.004	60.003	60.001	4.4	60.0018
13	60.003	60.001	60.002	60.004	1.95	60.0022
14	60.003	60.001	60.004	60.002	1.76	60.0022
15	60.003	60.002	60.001	60.004	2.45	60.0022
16	60.003	60.002	60.004	60.001	4.1	60.0018
17	60.003	60.004	60.001	60.002	3.45	60.002
18	60.003	60.004	60.002	60.001	3.9	60.0019
19	60.004	60.001	60.002	60.003	1.95	60.0022
20	60.004	60.001	60.003	60.002	1.85	60.0022
21	60.004	60.002	60.001	60.003	2.46	60.0021
22	60.004	60.002	60.003	60.001	3.5	60.002
23	60.004	60.003	60.001	60.002	2.9	60.002
24	60.004	60.003	60.002	60.001	3.44	60.002

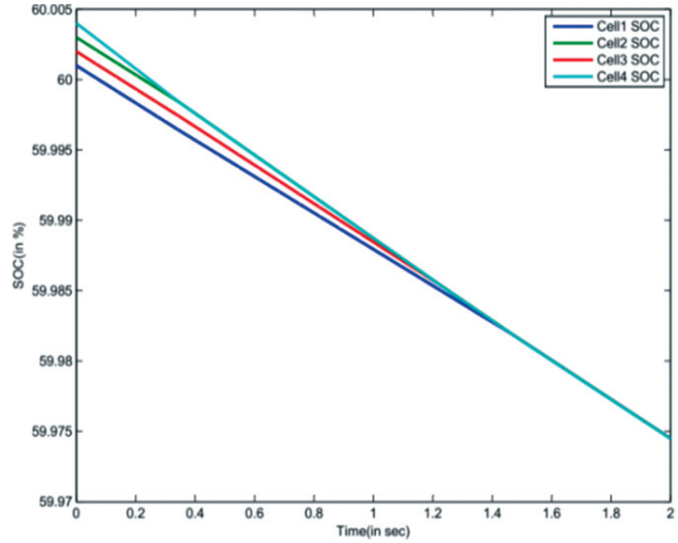

Figure 7. Cell equalisation during discharging modes.

5. BATTERY PACK BALANCING FOR MILD HYBRID ELECTRIC VEHICLE-48V

Considering the latest innovation on components, standardisation, protection strategies, design and architectures related to 48 V power supply systems for mild hybrid electric vehicles, battery balancing for the same is modeled. The proposed battery pack consists of 4 batteries and each battery comprises of 4 cells. The total rated voltage of the battery module is approximately 57 V and rated capacity is 75 Ah. The battery module equaliser uses modular topology for balancing both individual cells and the batteries. The balancing current is controlled using current sensor feedback and PI controller based PWM techniques. The switching action in balancing circuit is controlled by sensing the SOC of cell or battery of respective SOC based controller.

The automatic battery pack equalizer consists of the following subsystems as shown in Fig. 9.

1. Battery pack with balancing circuit comprising of
   - Batteries-[$Battery_1$, $Battery_2$, $Battery_3$, $Battery_4$],
   - Switches-[M_a, M_b, M_c, M_d],
   - Inductors-[L_a, L_b, L_c, L_d]
   - Diodes –[D_a, D_b, D_c, D_d]
2. Battery balancing current controller
3. Cell balancing current controller
4. SOC based switch controller

The individual battery subsystem [$Battery_1$, $Battery_2$, $Battery_3$, and $Battery_4$] consists of the following as shown in Fig. 10.

1. Cells with balancing circuit comprising of :
   - Cell-[C_1,C_2,C_3,C4],
   - Switches-[M_1,M_2,M_3,M_4],
   - Inductors-[L_1,L_2,L_3,L_4]
   - Diodes –[D_1,D_2,D_3,D_4]
2. SOC based switch controller

Battery pack is an array of batteries connected in series or parallel to increase the nominal voltage and capacity. Each battery has 4-cell which is connected with

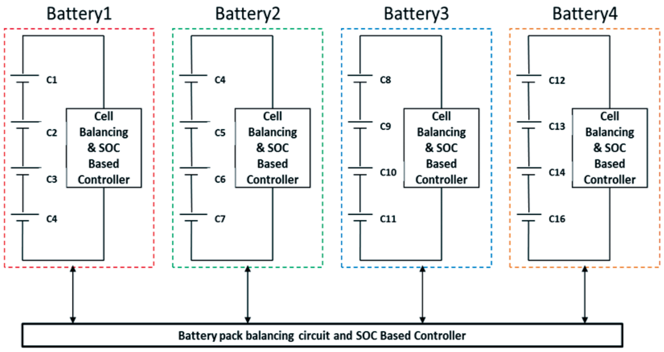

Figure 8. Schematic diagram battery pack.

multi inductor based balancing circuit and its controller to achieve the balancing between cells. The internal diagram of battery model is as shown in Fig. 10

6. SIMULATION RESULT

6.1 Multi Inductor-based Balancing Circuit for Battery Pack

The battery pack modelled in matlab-simulink is as shown Fig. 9, 14 V nominal voltage and 75 Ah capacity of each Li-ion battery is to be considered for simulation. Table 4 shows the change in initial SOC of battery cell and battery. 8 A balancing current is considered for the balancing circuit simulation.

The multi inductor balancing circuit for battery pack is simulated in three different modes: a) static mode, b) charging mode, and c) discharging mode.

(a) *Static Mode*

Within the battery pack when the battery converges 500 µ SOC difference then battery balancing is stopped by its controller and when the cell within the battery converges to 50 µ SOC difference then cell balancing is stopped by its controller.

Table 4. Initial SOC of cells and battery

Battery No.	SOC	Cell No.	SOC
		Cell1	60.001
Battery1	60.0025	Cell2	60.003
		Cell3	60.002
		Cell4	60.004
Battery2	60.0105	Cell5	60.009
		Cell6	60.011
		Cell7	60.010
		Cell8	60.012
Battery3	60.0065	Cell9	60.005
		Cell10	60.007
		Cell11	60.006
		Cell12	60.008
Battery4	60.145	Cell13	60.013
		Cell14	60.015
		Cell15	60.014
		Cell16	60.016

(b) *Charging Mode*

From Fig. 12, it is inferred that, the battery SOC converges to the 500 µ SOC difference within 5 s and cell SOC converges to the 50 µ SOC difference within 2 s for the assumed initial SOC during the charging mode.

(c) *Discharging Mode*

From Fig. 13, it is inferred that, the battery pack SOC converges within 5 s and individual cell SOC converges within 2 s for the assumed initial SOC during the discharging mode.

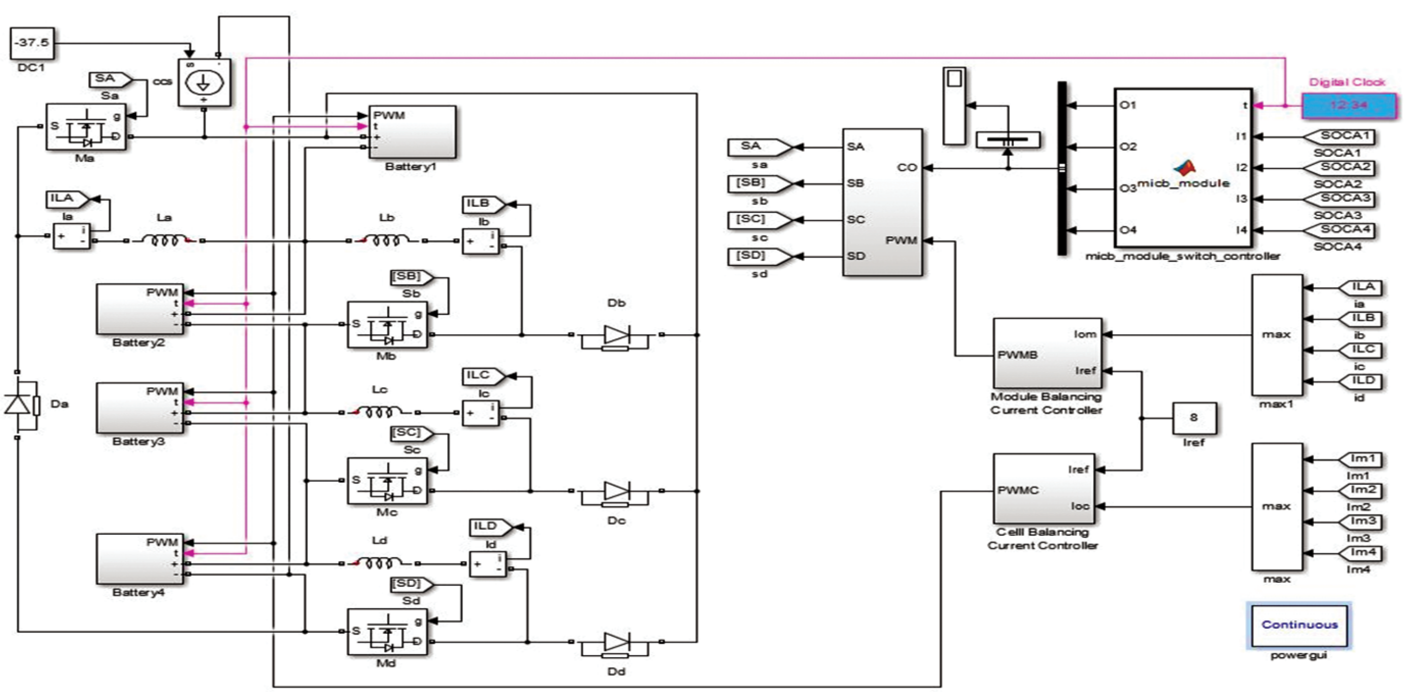

Figure 9 Dynamic battery pack balancing circuit model.

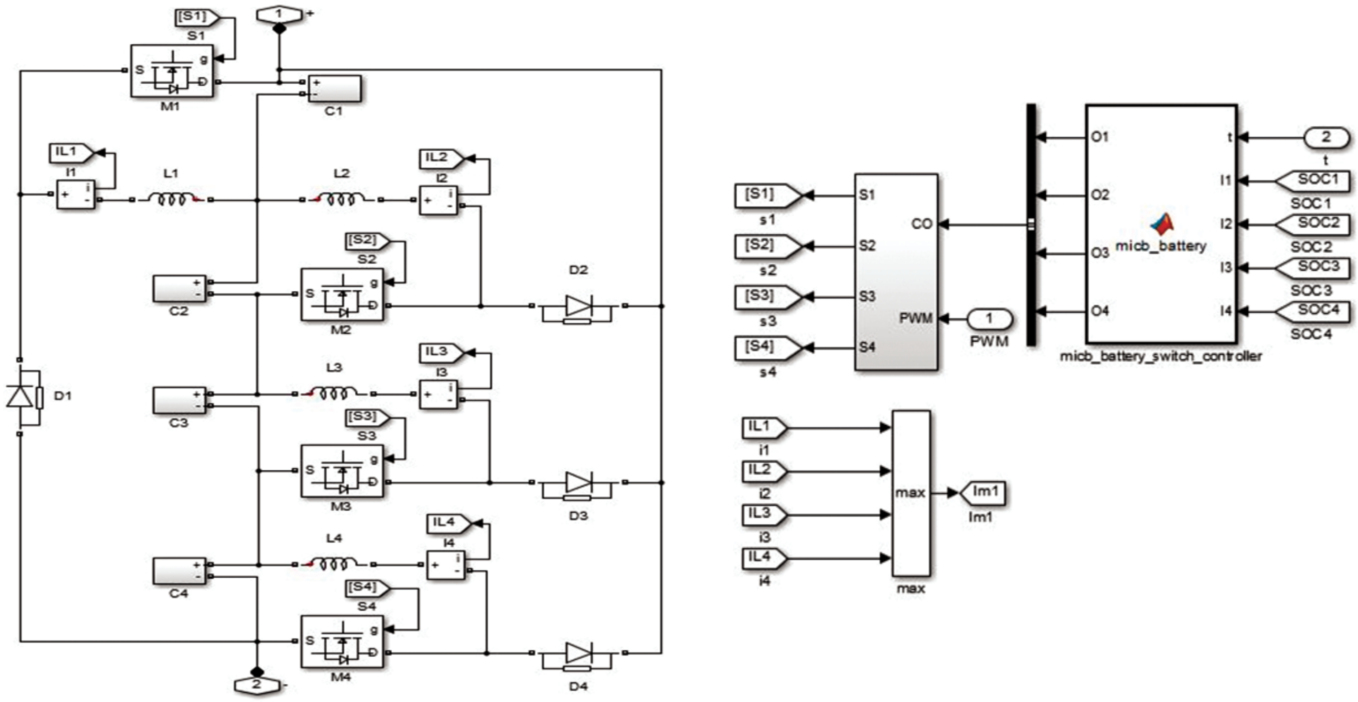

Figure 10. Internal diagram of battery model.

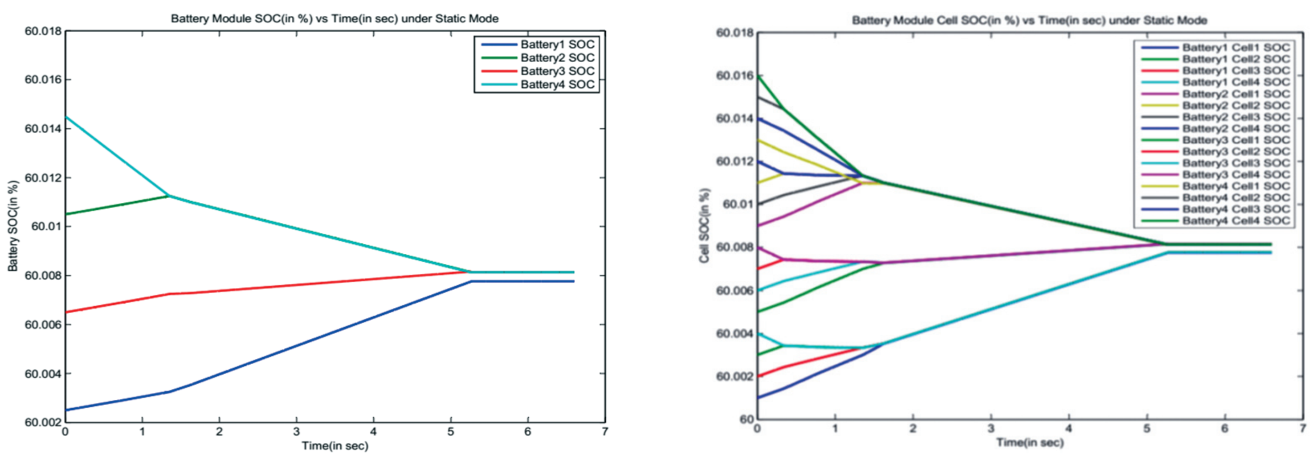

Figure 11. Battery pack balancing during static mode.

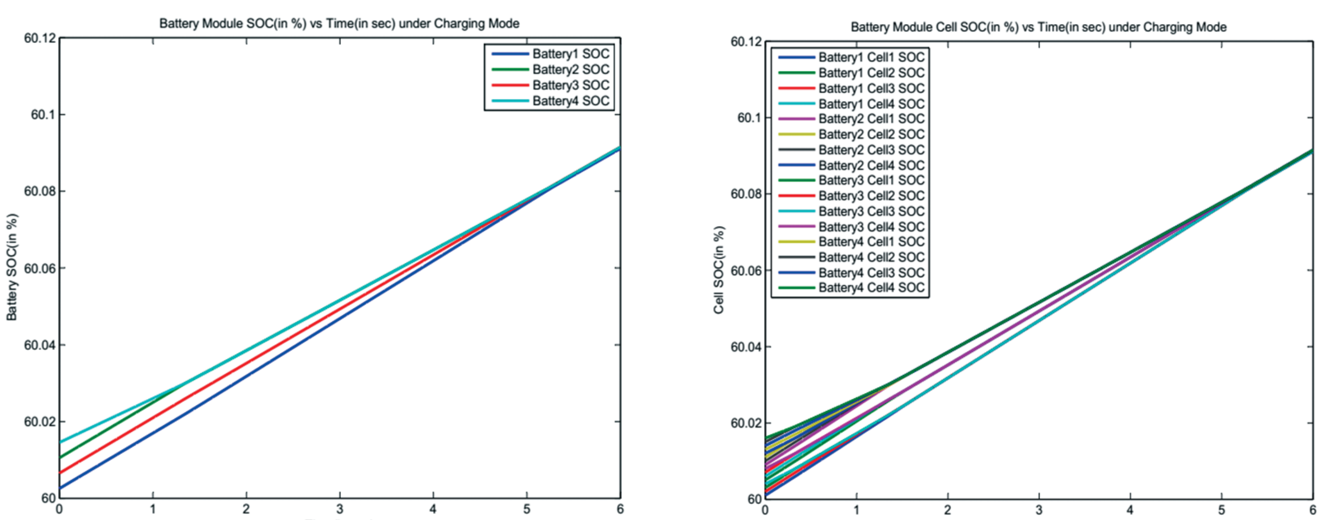

Figure 12. Battery pack balancing during charging mode.

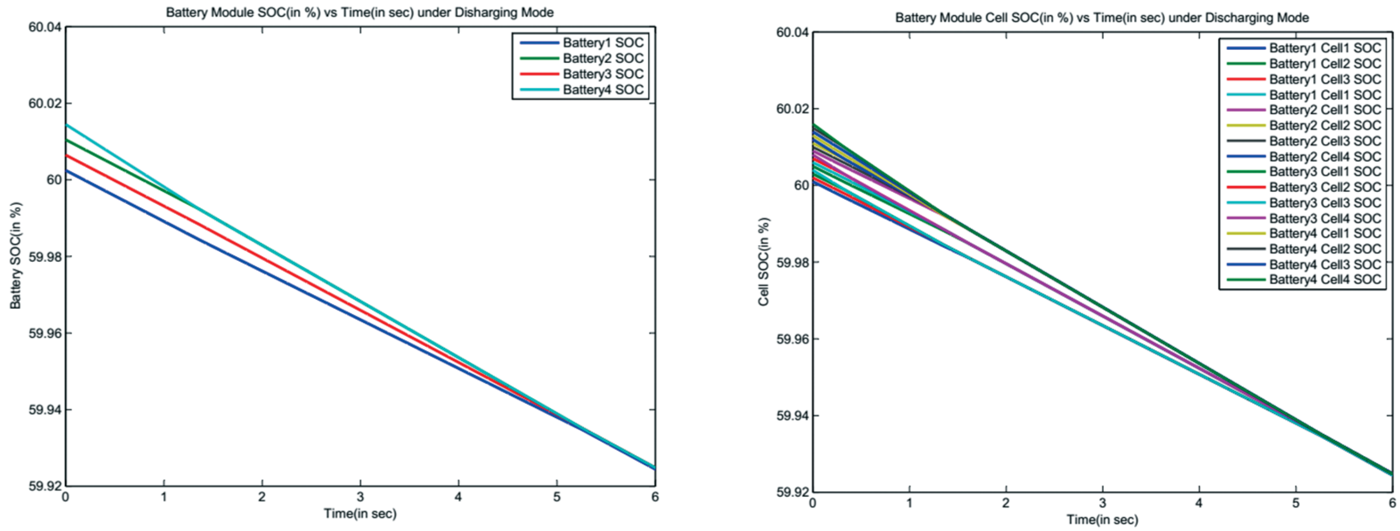

Figure 13. Battery module equalisation during discharging mode.

7. CONCLUSIONS

In this paper multi-inductor based automatic battery module balancing circuit with SOC based switch logic controller is modelled and analysed and results are simulated in MATLAB. It is observed that once the cells of battery pack is balanced then all cells and the battery pack will have same SOC during charging, discharging and steady state modes.

8. FUTURE WORK

The developed model is to be simulated in Hardware-in-loop Simulator to analyse the dynamic characteristics. Further, it is proposed to develop an Intelligent Battery Management system incorporating temperature monitoring and charging circuits. Also, the cooling system issue for battery pack is to be analysed using FEM tool.

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CONTRIBUTORS

Mr Rigvendra Kumar Vardhan has completed MTech (Electronics and Communication Engineering) from Government College of Engineering, Pondicherry. Presently working as a Research Associate atDRDO-Combat Vehicles Research & Development Establishment, Chennai. He was working in the study and MATLAB simulation of various cell balancing techniques for hybrid electric vehicles.
In this current study he had conceived the concept and implemented the MATLAB code.

Ms T. Selvathai has completed her BTech (Electronics and Communication Engineering) from MG University, Kerala. Presently she is working as Scientist E at DRDO-Combat Vehicles Research & Development Establishment, Chennai and her major contributions include: Development of autonomous ground tracked vehicles, algorithms for complimentary fusion of electro-optic and infrared videos for driver's enhanced vision. She is core member for hybrid power pack team and is responsible for the electrical subsystems.
In the current study, she has contributed towards the simulation studies

Ms Rajaseeli Reginald, received her BE(ECE) from Thiagarajar College of Engineering, Madurai and MTech (Communication systems) from IIT Madras. Currently working as a Scientist 'F', and team leader of Hybrid Powerpack at Combat Vehicles Research & Development Establishment, Chennai. She is specialised in Automatic transmission controller, in-vehicle networking and virtual instrumentation. Her areas of interest include : Hybrid electric vehicles, in-vehicle networking and real time embedded systems. She received *National Science Day Oration-2017* and *Laboratory Technology Group Award -2015*.

Dr P. Sivakumar has completed his PhD (Machine Design) from IIT, Madras, in 2011. He retired as Distinguished Scientist and Director, DRDO-Combat Vehicles Research & Development Establishment, Chennai. His research areas include design and development of AFV automatic transmission in the range of 150-1500 hp, combat aircraft transmission, conceptualisation of configuration for main battle tanks both present and future, infantry combat vehicles, armoured repair and recovery vehicles, self-propelled catapult vehicles, carrier command post and unmanned ground vehicles.
His contribution in the current study is overall guidance during the work and conclusion through results.