A Practical Approach of Active Cell Balancing in a Battery Management System

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***Abstract*—Battery is the heart of electric vehicle and a way of improving the battery life is to equalize the energy of its cells. This can be done by either dissipating excess energy in the form of heat (passive cell balancing) or charging the low voltage cells through high voltage cells (active cell balancing). This paper presents a practical approach of active cell balancing along with a brief comparative study of passive and active cell balancing techniques. To improve the inconsistency present in the series-parallel connected lithium ion (Li-Ion) cells, a cell balancing scheme based on switch-matrix and forward converter with active clamp driver topology is presented. This cell balancing scheme is based on transferring the energy from the over-charged cell to auxiliary battery and from auxiliary battery to less charged cell. The balancing takes place for one cell at a time and the balancing current can be continuously monitored. The energy transfer efficiency of 90% for charging and 72% for discharging is achieved. The proposed battery management system can be used for communicating the faults generated in the battery pack to the master controller and corrective actions can be taken to avoid the damage to the battery.**

***Index Terms*—Active cell balancing, auxiliary battery, battery management system (BMS), bi-directional forward converter, electric vehicle (EV), lithium ion (Li-Ion) battery, switch matrix.**

I. INTRODUCTION

Electric vehicles play an important role in sustainable mobility because of its efficient energy utilization and zero emission. Zero emission is possible in EVs because they are powered by the batteries and electric motors. The battery being the only energy storage device, it has a great impact on the performance of EVs [1]. There are different types of battery cell chemistries used in EVs such as Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Li-Ion, etc [2]. However, the nominal voltage of single cell of these chemistries is very low ($\approx$ 3.6V). So, a set of series connected cells are required for driving high voltage, high current electric motor in EVs. This series connection of cells is also called as a battery string or a battery pack. Presently, Li-Ion battery chemistry is considered as one of the most capable energy storage device for EV, due to its high energy density and low self-discharge rate compared to other battery chemistries [3]. Li-Ion chemistry is very sensitive to overcharge and deep-discharge, and if these cells are operated outside their safe operating area, they can damage the battery, shortening its lifetime, and even causing hazardous problems. Thus development of BMS is necessary to check and control the status of the battery and to take corrective actions.

Due to manufacturing inconsistency, there are slight differences in the cell voltages or state of charge, cell internal resistance, self-discharge capacity [4], [5]. As the cells are connected in series to form a battery pack these slight differences causes imbalance in the battery, and they are magnified with each charge and discharge cycle [6], [7]. This imbalance causes cell degradation, shortening of battery lifetime and safety hazards due to over-charge or deep-discharge [6], [8]. In order to resolve these problems, energy in the battery needs to be distributed uniformly. This can be done by dissipating extra energy from the overcharged cell as heat through bleeding resistor or transferring the energy from the cell having higher cell-voltage to the cell having less cell-voltage [9]–[11].

Passive cell balancing is applied only when the battery pack is charging [12]. When a single cell reaches its charging voltage, the charging is stopped, then this cell energy is dissipated in bleeding resistor in the form of heat. This process is continued until the individual cell attains its full charge. This process is time consuming and inefficient as the energy of most charged cell is wasted in the form of heat [13], [14].

For enhancing the efficiency and performance of the battery pack, active cell balancing is the preferred method. In this method, the excess charge on the individual cell is transferred to the cell which has less charge comparatively [15]. This charge redistribution is done in two ways and they are named according to the direction of the energy flow [16]. First, the balancing in the battery pack can be achieved by making the flow of energy from overcharged cell to auxiliary battery and from auxiliary battery to less charged cell. Second, the flow of energy can be done driectly from overcharged cell to less charged cell [16]. The first method is called as cell-auxiliary battery balancing and the second method is called as cell-to-cell balancing [16]. But when using cell-to-cell balancing method, extra external and dedicated circuitry is needed [17].

Among various active cell balancing techniques, one cell balancing circuit uses decentralised controller for each cell [18]. But the complexity, volume and cost of complete BMS

978-1-5386-9316-2/18/$31.00 ©2018 IEEE

is very high. The energy from overcharged cell is transferred to less charged cell in three modes of operation, which is time consuming and less efficient as energy leakage increases during these modes. The circuits of [7] and [18] uses external and dedicated circuitry for cell balancing. Also the balancing current in these circuits is not programmable.

This paper presents the implementation of cell-auxiliary battery balancing method for a string of 16 series connected cells, in which the charge from the overcharged cell is efficiently transferred to auxiliary battery and then to undercharged cell. The balancing current is programmable and can be varied from 2A to 4A. As cell-auxiliary battery balancing is used, the complexity of the circuit is highly reduced.

The paper is organized as: Section II gives the system description of the BMS. This section includes detailed description of the complete BMS with explanation of important blocks. Section III explains the system configuration and the experimental setup. Section IV gives experimental results of the designed BMS. Conclusions are explained in section V.

II. System Description

The proposed design presents the BMS that is based on master-slave architecture in which one master and several slave modules are used depending on the number of cells forming the battery pack. The proposed design is explained in the following section.

A. Master-Slave Architecture

The complete BMS is divided into two discrete physical units; monitoring and control, alternatively slave and master respectively . A single master printed circuit board can control many slave boards. In this work one master controller and one slave module is used. Fig. 1 shows one master and one slave module used for the BMS.

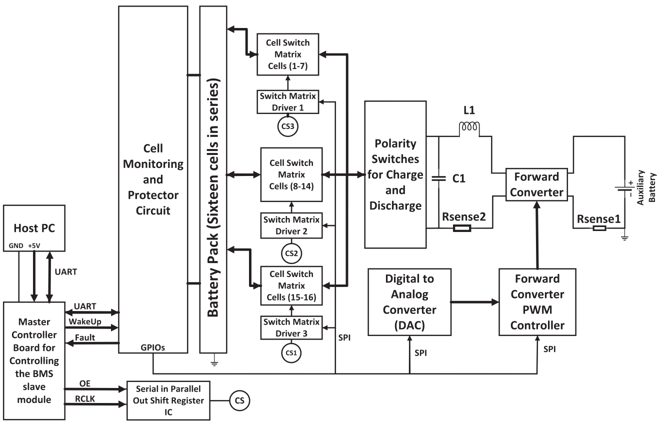

Fig. 1. BMS Slave Module

The slave module is an evaluation board of the active balance chipset for use in large format Li-Ion batteries that provides monitoring, balancing, and communications. With precise and robust active balancing, the BMS is capable of bidirectional power transfer at each cell. This module is able to manage 6 to 16 cells (70-V max) for Li-Ion battery applications. The system provides fast cell balancing, diagnostics, and slave to master controller communication. Independent protection circuitry is also provided in the slave module which is explained in coming section.

As shown in Fig. 1 the BMS slave module monitors and protects 16 cells connected in series with the help of cell monitoring and protector circuit. Cell switch matrix is used to select switches that are used for balancing of the selected cell. To operate this switch matrix, a switch matrix driver IC is used. As this switch matrix driver IC can balance only seven cells, three such driver ICs are used. As only seven cells are controlled by the switch matrix driver IC, the battery pack of 16 series connected cells is divided into top-stack, mid-stack and bottom-stack. Top-stack contains first seven cells from cell 1-7, mid-stack contains cells from 8-14 and bottom-stack contains cells 15 and 16. The forward converter continuously senses inductor (L1) current so that its magnitude is regulated around a user-defined magnitude. The serial in parallel out shift register is used to select a cell switch matrix driver that is going to be used during balancing. The digital to analog converter (DAC) is used to set the balancing current. The output of DAC is given to forward converter pulse width modulation (PWM) controller, which controls the switching of the forward converter to set the balancing current. Each block is explained in detail as follows:

B. Cell Monitoring and Protector Circuit

The cell monitoring and protection circuit is designed for automotive applications. One circuit can monitor and protect 6 to 16 cells connected in series. This circuits monitors cell voltages and temperatures with high accuracy through 14-bit successive approximation register based analog to digital (ADC) converter. The voltage sensing unit is shown in Fig. 2.

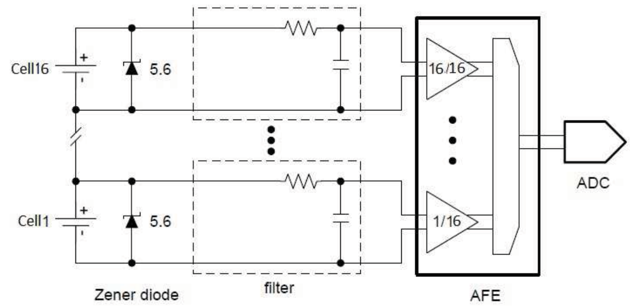

Fig. 2. Cell Voltage Sensing Unit

The cell terminal voltage is first sent into the low pass RC filter to remove the unwanted noise from the signal. The filtered cell voltage signal is sent to the analog front end (AFE) where it is buffered and level translated to AFE ground. Then this signal is transferred to ADC to convert it into 14 bit digital word. The digital word is transferred to the master controller through serial communication interface (SCI). Zener diodes are placed across each cell to provide protection to the AFE in case of over-voltage fault occurring in the cell.

The cell monitoring and protection circuit monitors and detects different fault conditions namely, over-voltage, under-voltage, over-temperature, and communication faults. It also provides upto six general-purpose, programmable, digital I/O ports, as well as eight auxiliary ADC inputs, typically used to monitor external temperature sensors. The device is powered from the stack of cells to which it is connected.

C. Switch Matrix

To select a target cell for balancing, a cell switch matrix is used. Fig. 3 shows the switch matrix. This matrix helps in connecting the target cell to the auxiliary battery for sinking or sourcing the energy from it.

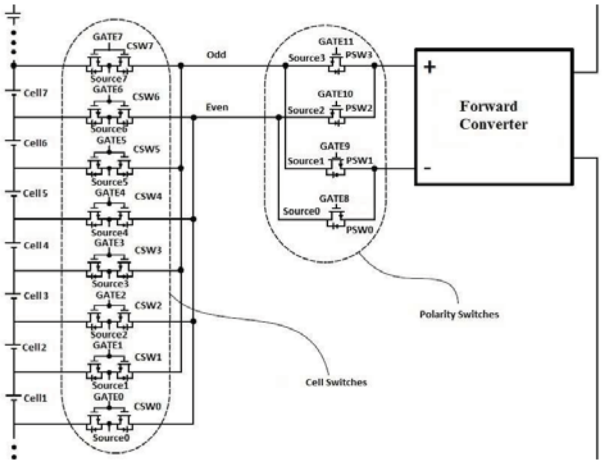

Fig. 3. Switch Matrix

The switches that are directly connected to the cells are termed as "cell switches". Each cell switch comprising two 40-V N-FETs is connected in a common source and common gate manner across each positive and negative terminal of the cell. The switch assembly is capable of allowing flow of current in both directions. From the 7 cells controlled by the switch matrix driver, assume the bottom cell is Cell 1, the one above it is Cell 2, and so on. Cell 1 is connected to two cell switches, i.e cell switch 0 and cell switch 1 (CSW0 and CSW1). Cell 2 is connected to CSW1 and CSW2. Same pattern repeats for all cells. Each cell switch has one drain connected to the either even rail (if the switch is even numbered) or odd rail (if the switch is odd numbered).

The switches directly connected to forward converter are called "polarity switches(PSW)". Each polarity switch is 100-V N-FET which has the capability of allowing the flow of current in one direction only. The polarity switches are designated as PSW. Each PSW has a drain or source either connected to the positive or negative end of forward converter and a source or drain connected to the even or odd rail.

D. Switch Matrix Driver

The switch-matrix gate driver works in conjunction with the forward converter PWM controller to support active cell balancing scheme. The switch-matrix gate driver provides 12 floating gate drivers necessary to turn on the cell switches and polarity switches to balance upto seven cells connected in series. As each driver can balance upto seven cells, three such drivers are used in the slave module. This driver makes interfacing with forward converter PWM controller to control and enable charging and discharging modes. The switch-matrix gate driver uses an serial peripheral interface (SPI) bus to accept commands from cell monitoring and protection circuit. This command contains the cell number which requires charging or discharging and responds any faults back to the cell monitoring and protection circuit.

E. Forward Converter PWM Controller

The forward converter PWM Controller provides PWM gate signals to the forward converter which in result, regulates the balancing current around a user defined magnitude. In balancing application, the Forward Converter PWM Controller exchanges energy between a single cell and the auxiliary battery that is connected to slave module externally. The forward converter has the inductor side (also called "secondary side") connected to the switch matrix and the other side (also called "primary side") to the auxiliary battery. With such an arrangement, cell balancing action is an exchange of energy between the cell and the auxiliary battery.

F. Other Important Components of BMS Slave Module

The other important components of BMS slave modules include DAC, which sets the balancing current around a user-defined magnitude. A particular switch matrix driver and DAC chip are selected via serial in parallel out shift register.

III. System Configuration and Experimental Setup

Before starting the cell monitoring and balancing process, the BMS needs to be configured by setting the address to the slave board, setting baud rate for master-slave communication, configuring AFE, etc.

A. System Configuration

For the development of these algorithms, a software code is written in Texas Instruments based code composer studio integrated development environment. Modular functions are developed for cell voltage monitoring, selection of the cell for balancing, serial communication between master-slave. The designed system is configured as follows:

1) Setting baud rate: The baud rate is the rate at which information is transferred in a communication channel. For this master slave architecture baud rate of 250 kbps is set. This is the default baud rate for the communication.
2) Set identity to the slave board: The designed system incorporates one master board and one slave module. The slave module in the designed BMS is given an address "0". This address becomes the device identity of the slave board for cell voltage monitoring and balancing.

3) Configuring AFE: Analog front end is a set of analog signal conditioning circuitry which conditions the signals received from the sensor and performs the analog to digital conversion. In this AFE, the sampling time for the analog to digital conversion is programmable depending upon the accuracy required for measurement of cell voltage. The number of cell voltage channels to be sampled can be selected through AFE. The minimum and maximum sampling periods recommended for this system is 12.6μsec and 1000μsec respectively. The slave module can measure cell voltage from cell 1 upto cell 16 which can be configured through this AFE.
4) Converting the cell data received to voltage: The cell voltage data received from the slave module after sampling is hexadecimal in nature. The length of data received from the slave module is 35 bytes. The response data are always in the following order: voltage of cell 16 to cell 1, data from AUX 7 to AUX 0(auxiliary pins for temperature measurement), internal digital die temperature, internal analog die temperature. This data is bifurcated as shown in Table I.

TABLE I
FORMAT OF CELL DATA RECEIVED FROM SLAVE MODULE (FOR SIXTEEN CELLS)

Packet Header (1 byte)	Data (32 bytes)	Cyclic redundancy check (CRC) (2 bytes)

The first byte (packet header) represents the length of the cell data received from the slave module. The last 2 bytes represents the CRC (CRC is a technique used to detect errors in the digital data) byte, which is used to check the authenticity of the data. And the remaining 32 bytes represents the cell data. From these 32 bytes, every 2 bytes represents cell voltage of one cell. Also, only one byte is sent from slave module to master at a time, the master concatenates this byte to make it 2 bytes, and then calculates the cell voltage using the following formula:

$$\textit{Cell Voltage} = (ReceivedData[2bytes]) * \frac{5}{2^{16}} \qquad (1)$$

5) Channel identification bearing maximum and minimum cell voltage: After the cell data is converted into voltage, the channels bearing maximum and minimum cell voltage is found out. The difference between maximum cell voltage and nominal voltage is also calculated. The flowchart depicting this logic is shown in Fig. 4.
6) Selecting the cell for balancing: After identifying the channels having maximum and minimum cell voltage, difference; the cell showing maximum deviation from the nominal voltage is chosen for balancing. The balancing process can be charging or discharging. The decision for charging or discharging operation is taken based on the flowchart shown Fig. 5.

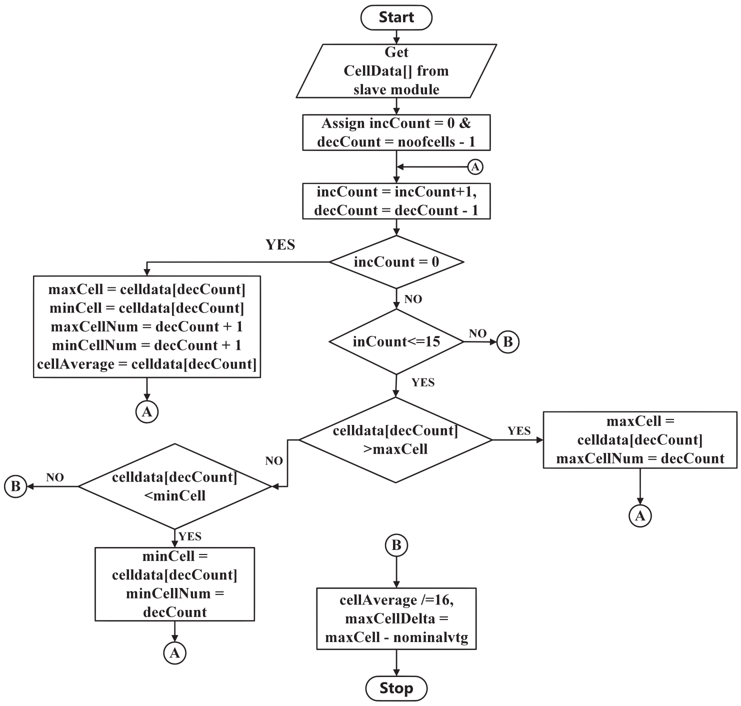

Fig. 4. Flowchart for channel selection having maximum and minimum cell voltage

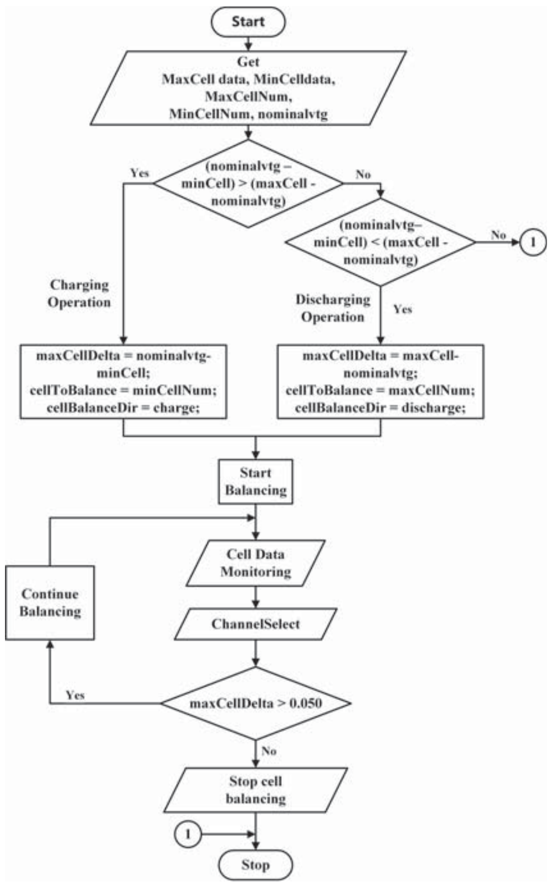

Fig. 5. Flowchart for selecting the cell to balance

B. Experimental Setup

To understand the practical scenario of active cell balancing, a battery pack consisting of 16 cells in series connection is made. Li-Ion cells are used for making the battery pack. In order to charge or discharge the target cell, auxiliary battery is used as source and sink. This auxiliary battery can be a lead acid battery which is usually used in automobiles. But for this experimental setup four Li-Ion cells in series connection are used making it an auxiliary battery. Fig. 6 shows the hardware setup of designed BMS. The nomenclature of the components are as follows: 1. Host PC, 2. Master Controller, 3. Slave Module, 4. Auxiliary Battery, 5. Battery Pack, 6. Digital Multimeter, 7. Wire harness for master-slave communication, 8. Wire harness for connection between each cell and the slave module, 9. Cell 1, 10. Cell 16.

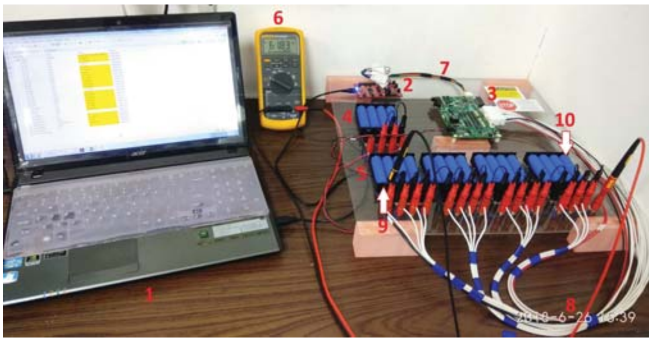

Fig. 6. Hardware setup

IV. Experimental Results

A. Cell Voltage Data Acquisition

Before implementing the cell balancing algorithm, the designed system is tested for the accuracy in cell voltage data acquisition. Table II gives the cell voltage data acquired in debugging window of code composer studio. The cell data acquired is compared with voltage observed in the digital multimeter.

TABLE II
Cell voltage of each cell in battery pack

Cell Number	Cell voltage observed in software (V)	Cell voltage observed on multimeter (V)	Difference (mV)
1	3.219	3.221	2
2	3.735	3.737	2
3	3.935	3.937	2
4	3.816	3.818	2
5	3.787	3.788	1
6	3.829	3.830	1
7	3.789	3.790	1
8	3.834	3.836	2
9	3.875	3.876	1
10	3.952	3.953	1
11	3.838	3.839	1
12	3.851	3.852	1
13	4.030	4.031	1
14	3.828	3.830	2
15	3.878	3.880	2
16	3.841	3.842	1

From Table II it can be observed that the difference between the acquired cell voltage data and voltages observed in multimeter is very small (upto 2mV) and within acceptable limits. Having observed the accuracy in cell data acquisition, the algorithm for cell balancing is tested.

B. Cell Balancing

To verify the robustness and reliability of algorithm of cell balancing three test cases are considered. Initially the balancing algorithm is tested on single cell (case 1A & 1B) for simplicity, then for sixteen cells (case 2). The maximum deviation of cell voltage below the nominal voltage rating is termed as maximum negative deviation. Similarly, the maximum deviation above nominal voltage is termed as maximum positive deviation.

1) Test Case 1A: Balancing (charging) at different balancing currents (for 1 cell): Once the cell voltage data acquisition is complete, the cell showing maximum deviation from nominal voltage setting is selected for balancing. From Table II, cell 1 shows maximum negative deviation from its nominal voltage rating. Hence cell 1 is selected for balancing (charging) operation. The voltage of all cells is monitored in the software at every five minutes to see noticeable change in the cell voltages. Fig. 7 gives a clear view of charging at different balancing current. It can be observed that when the balancing current is 4A, target cell reaches to its nominal voltage faster as compared to 2A and 3A balancing current.
2) Test Case 1B: Balancing (discharging) at different balancing current (for 1 cell): Similar to charging operation, the target cell is discharged at different balancing currents. Table II shows, cell 13 has maximum positive deviation from its nominal voltage rating. Therefore, cell 13 is selected by master controller for discharging. The voltage of all cells is monitored in software at an interval of five minutes. Fig. 8 gives clear view of discharging at different balancing current. From Fig. 8 it becomes clear that in the given time the cell discharged by 4A current reaches to the nominal voltage value earlier than that discharged by 2A and 3A currents.

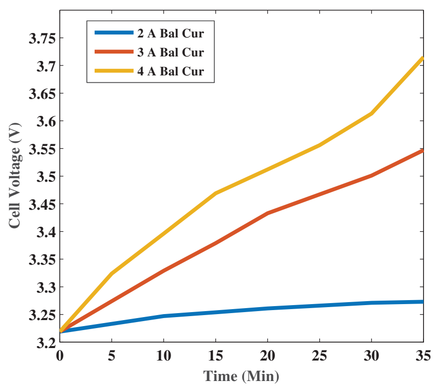

Fig. 7. Charging at different balancing current (for 1 cell)

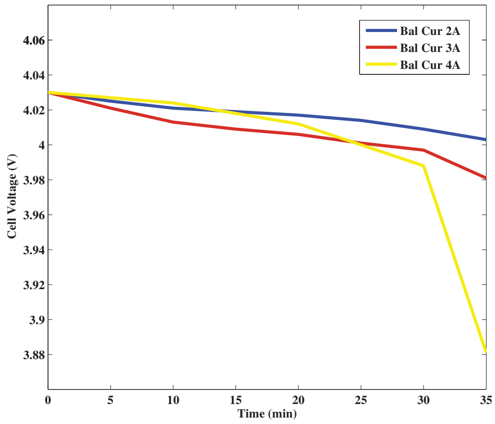

Fig. 8. Discharging at different balancing current (for 1 cell)

3) Test Case 2: Balancing of sixteen cells: From Fig. 7 & Fig. 8 the algorithm of balancing is verified for one cell. Now the balancing algorithm is tested for all sixteen cells. The threshold voltage at which the cells are said to be balanced is kept at 50 mV. Fig. 9 shows the balancing of sixteen cells.

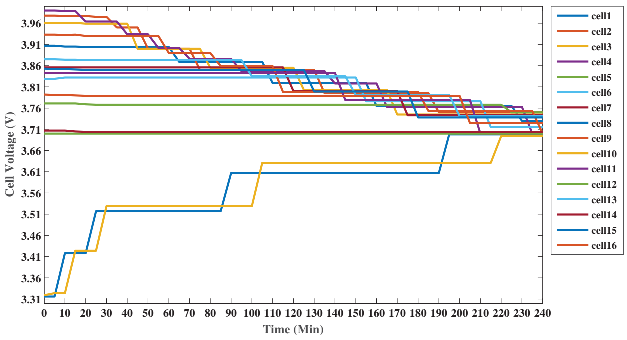

Fig. 9. Balancing of sixteen cells

From Fig. 9 it can be observed that at the end of 240 minutes, all cell voltages are within the threshold limits. Therefore, the cells in the battery pack are balanced.

V. CONCLUSION

A practical approach for active cell balancing is proposed using switch-matrix and a forward converter with active clamp driver topology. The overall system is able to monitor the voltage of all cells with high accuracy upto 2 mV and perform the process of active cell balancing. Initially the balancing algorithm is tested on only one cell at different balancing currents and it is concluded that at higher balancing current the cells are balanced quickly. After the balancing control algorithm is validated for one cell, balancing of sixteen cells is performed. To validate the algorithm for sixteen cells the balancing is performed at constant balancing current of 4 A. However, balancing current can also change according to cell voltage deviation. The balancing of one and sixteen cells is achieved and the BMS design and algorithm for active cell balancing is validated.

ACKNOWLEDGMENT

The first author would like to acknowledge TATA Motors, Pune and Department of Electrical Engineering, College of Engineering, Pune for their guidance and support.

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