Design of ARM Controlled Cell Balancing Network-based Battery Management System for Electrical Vehicle

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Abstract

One of the important key factors used in Electrical vehicles is Battery management System. The main part of the Electrical Vehicle (EV) that is strongly associated with vehicle safety and its range estimation using an optimizing cell balancing unit. This research work objective is to build a BMS that can be used in EV and provide better information to a user for monitoring the data. The paper illustrates the use of the ARM Cortex -R4 processor and BQ76942 battery monitor with their high-end features providing SoC, SoH, battery current, voltage, and thermal protection with the increasing range of EV using the cell balancing technique. The passive balancing using Coulomb Counting and EKF methods to estimate SoC for a battery pack give precise results for vehicle range extension The MATLAB simulation is done and proposed the cell balancing algorithm to improve the battery management system. Lithium-ion batteries are used due to their low weight and high charge density. The cells in the battery pack are monitored individually for their efficient operation and safety concerns. Also, for monitoring charging-discharging cycles, overcurrent undercurrent protection, and under-voltage overvoltage protection. For this purpose, the main microcontroller unit which is based on Advanced RISC Machine architecture is used. To observe and sense various battery management system parameters another BMS IC a highly integrated and high-accuracy battery protector and monitor connects with the main microcontroller to observe the battery pack determines various parameters and sends them to the main microcontroller. Some key simulation results to gain well cell balancing also ensures that the battery pack is neither over-discharged nor over-charged.

Keywords
Battery Management System, State of Charge, State of Health, Lithium-ion Battery, and Electric Vehicle.

1. Introduction
In recent upcoming years, electrical battery technology is improving day by day and it provides solutions for extending the range of Electric Vehicles. A cell has energy in the electrochemical form, which is then released to do work. The Battery Management System (BMS) monitors parameters like current, voltage, and thermal values and also it provides over-current, over-charge, short circuit protection, over-discharge, and functionalities. It gives data regarding vehicle range estimation, data recording, and communications through various communication protocols like SPI, I2C, and CAN. BMS decides how much charge remains in the battery pack that is State-of-Charge (SOC), monitors the health of the battery pack is nothing but State-of-Health (SOH) so that provide prolonged state-of -Life (SOL) to the cells and battery pack. Due to the continuous charge-discharge operations voltages among the serially connected battery cell get imbalanced nothing but SOC imbalance. BMS contains the algorithm for the precise estimation of SOH & SOC. Also cares for no cell inside the battery pack going out of the limit of the given operated Safe-Operating-Area (SOA). Li-ion batteries are used widely because of their low weight, high charge density and high-performance characteristics. A typical Li-ion battery has the lowest voltage of 2.7V, an operating voltage of 3.7V and a voltage high of 4.2V. Battery cells lead to unstable conditions if they charge to their extreme limits

means the cell is undercharged below 2.7V or overcharged above 4.2V. In such unstable conditions, BMS keeps all cells within their safe operating limits by controlling current, voltage and temperature values and communicating with the main microcontroller unit for taking the necessary steps to bring each cell to its Safe Operating Area.

This paper presents how BMS works for a communication system, data acquisition system, safety management, electrical management, and thermal management besides providing protection and prevention of the system from damage. So, we develop a cell balancing algorithm and apply it by using an ARM-controlled main microcontroller to get good, expected battery optimization results. Passive cell technique used to balance the cells pack and for SOC calculation Coulomb Counting method has been discussed. The following sections give information about BMS and corresponding work simulations in MATLAB. Implement various cell balancing techniques. Analyze and evaluate the performance of cell balancing circuits in BMS. To simulate and test the parameters and decide the control strategy.

2. Literature Review

Samaddar et al. (2020) developed Li-ion batteries for automotive applications. The Li-ion cells are used widely of having high performance but at the same time, they are very fragile so sophisticated electronics are to handle them in Safe Operating Area (SOA). Passive components like resistors and capacitors are used for cell balancing. Bleeding resister dissipates extra energy of cell which has the highest state of charge in the battery pack. For ease of control and simplicity passive cell balancing method is implemented rather than active balancing. Li-ion batteries are charged operated Constant-Current-Constant-Voltage (CCCV) concept. This supplies a regular current to the cell and constant voltage maintained to 4.2V across cells. Design specifications of cells like cell type, capacity, voltage, current of a cell, and balancing techniques are explained. Simulation results of SOC, Voltage graphs with the logic of four cells balancing in series showed in Simulink. Kivrak et al. (2019) developed BMS with a Passive control method using MOSFET as load. Here the implement MOSFET as the passive load has been discussed. A STM32f103C8 controller is implemented as Master and PIC18f4520 controller as Slave. MOSFET switch used as load. Voltage signal using buck converter and DAC circuit is given to the Gate of MOSFET. Stone Resister is utilized for extra energy dissipation in a slave control module. The slave microcontroller is connected to the computer system via the main master controller. Data received from the slave controller to the main IC decides the cell which is to be balanced. Algorithms for both controllers are utilized for balancing the battery pack. LiFePo4 battery cells in this setup are utilized. Di Rienzo et al. (2020) Passive balancing algorithm for charge equalization. Algorithms used in balancing for charge estimation of batteries that are connected in series impact the whole BMS system. The iterative algorithms manage to reduce a most charged cell to its balancing condition by activating a resister called Bleeding Resister. These algorithms are tested o the 10 Cells of a Li-ion battery and successfully demonstrated their functionality. Here is the use of LG DBHE21865 Nickle Manganese Cobalt (NMC) battery cells to validate the system implemented mechanism. Cells are of the capacity of 2.5Ah and an operating voltage of 3.6V. BMS system is composed of two boards one is the Master and another is a Slave. According to the master main board command, MOS switch is driven to operate the proper balancing command. The Master board is based on NXP Cortex-M3 CPU architecture and the slave board for BMS cell monitoring is based on Texas Instruments BQ76PL455A. So overall how BMS balances with proper algorithm implementation are shown here. Petri and Petreuș (2021) developed Balancing and SOC estimation in BMS for EV. Besides the charge equalization, one of the important factors is balancing the State of Charge (SoC) of the batteries and its proper estimation in the BMS for EV. In this paper, the implementation of active and passive balancing methods using MATLAB Simulation. The use of the extended Kalman's filter and Coulomb Counting for SoC estimation in the passive balancing method and observed that extended Kalman's Filter results are more accurate than Coulomb Counting. Also, for active balancing, they implement Switched Capacitor technique that provides cell-to-cell charge transfer to balance the cells which give higher efficiency and efficient results compared to passive technique. Various parameters data received from BMS system to main MCU unit, system process the data, generate the commands as per received information and send back to the system to balance cell charge, provides safety and prevent damage of batteries. Abronzini et al. (2019) developed optimization of passive BMS for automotive applications. One of the crucial parameters is the thermal administration of the BMS system. For the optimization of temperature-related issues, an adaptive cell balancing algorithm has been proposed that minimizes balancing time under various thermal constraints in the BMS. The various numerical analysis confirms that the implemented system intensively minimizes the cell equalization time. Dalavi and Thale (2020) developed a design of DSP-controlled passive cell balancing for EV. A Digital Signal Processor (DSP) with a passive balancing technique put a huge impact on the system of BMS. For balancing the State of Charge of batteries along with the battery pack health issue has been resolved using the implemented mechanism. The Voltage, current and temperature parameter monitoring is carried out and sent this data to the main DSP processor for balancing SoC of batteries. Li-ion Phosphate batteries are used along with TI TMS320F28379D DSP processor controller. Simulation prototyping of cell equalization circuit is brought for charging, steady-state system and discharging. DSP provides high-end features at a reasonable cost so as the BMS balancing goes very cost-effective and made available more features for the functioning of the system. Guran et al. (2021) developed 4-cell BMS for automotive applications. Parameters like cell voltages, pack temperatures, and current are transmitted through Electronic Control Unit (ECU) using communication protocols like CAN for EVs. Balancing of 12V battery pack the parameters of the whole battery system needs some algorithm that estimates the State-of-Charge, State-of-Health and offers protection for charging-discharging and steady-state operations. Some communications protocols like CAN, SPI, I2C, and UART make it easier for system communication. Process communication circuitry and PCB layout of logic board explains in this paper easily and shows cell balancing simulation circuit.

3. Battery Management Network Design

Battery Management Network is an electronic control system that regulates and monitors cycles of charging and discharging along with providing protection and preventing a system from damage. Also, BMS provides many functions like current protection, voltage protection, electrical management, communication, data acquisition, safety and thermal management. The various methods are used in the Battery Management System to decide the State of Charge, Current, Voltage, State of Health and Temperature. Here the main part is to obtain a good cell balancing network using the ARM controller and using the BMS controller which connects with the main master microcontroller system. And this prototype was implemented in the MATLAB simulation to obtain possible nearer results like a prototype system with some graphical results. There are two ways to balance the cell of the battery pack using Active balancing and another is the passive balancing of cell. A passive cell equalization design has been considered here to gain the proper battery management data from the system.

3.1 Circuit for Passive Balancing

Samaddar et al. (2020) developed Li-ion batteries for automotive applications. Li-ion cells are utilized widely in the Battery of the EV because of their high-performance, high-energy and specified energy. They are very specific to their Fragile property so that required to be handled by an electronics circuit to make they should be operated in a given specific Safe Operation Area (SOA). Generally, a typical cell has an operating voltage of 3.7V, the lowest voltage is 2.7V and the highest voltage is 4.2V. If the battery limits of maximum and minimum voltages are crossed due to somehow reason the cells of the battery pack get imbalanced and which may cause fire hazards incidents. For charging and discharging operations of Li-ion cells there are passive components like Capacitors and resister-based switches are used. Dalvi and Thale (2020) developed a design of DSP-controlled passive Balancing. Passive battery balancing transfers the excessive charge from the battery into the external connecting shunt register either by switching shunting or fixed shunting resister. Whenever there is a charge unbalanced created in the battery cell we as BMS designers have to create an algorithm to balance the cells and that algorithm is operated by using a microcontroller via switches like MOSFET. The passive cell balancing technique is used in most battery applications due to its simplicity and reliability (Figure 1).

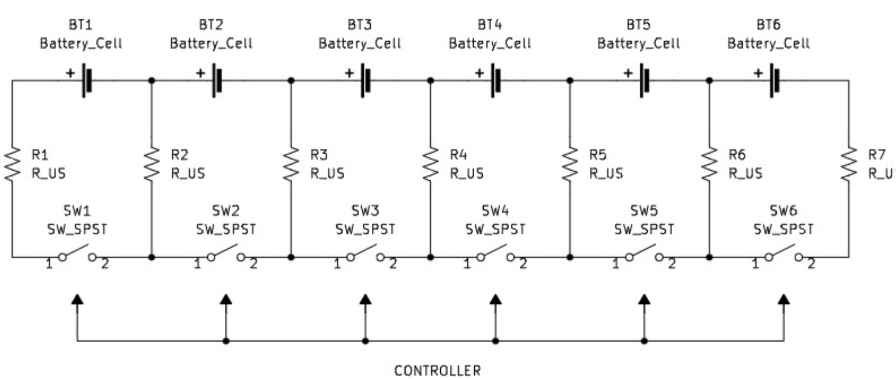

Figure 1. Switching Shunting resistor circuit of cell balancing

In the above topology, there are the six MOSFET switches (SW1, SW2, …, SW6) that are connected across battery cells (BT1, BT2, …, BT6) for switching shunting operation. These switches are operated as per the instruction coming from the main microcontroller. When the unbalancing is detected between the cells the microcontroller determines the switching operation of the MOSFET switches for cell balancing. Cell balancing means balancing the voltages of the individual cell and making the charge of each cell equal. When the Gate signal is High, the MOSFET switch is closed, and circuit gets completed and the charge from the excess cell gets dissipated through the bleeding resistor. And if the Gate signal is getting at low, then the switch gets open and the cell got balanced.

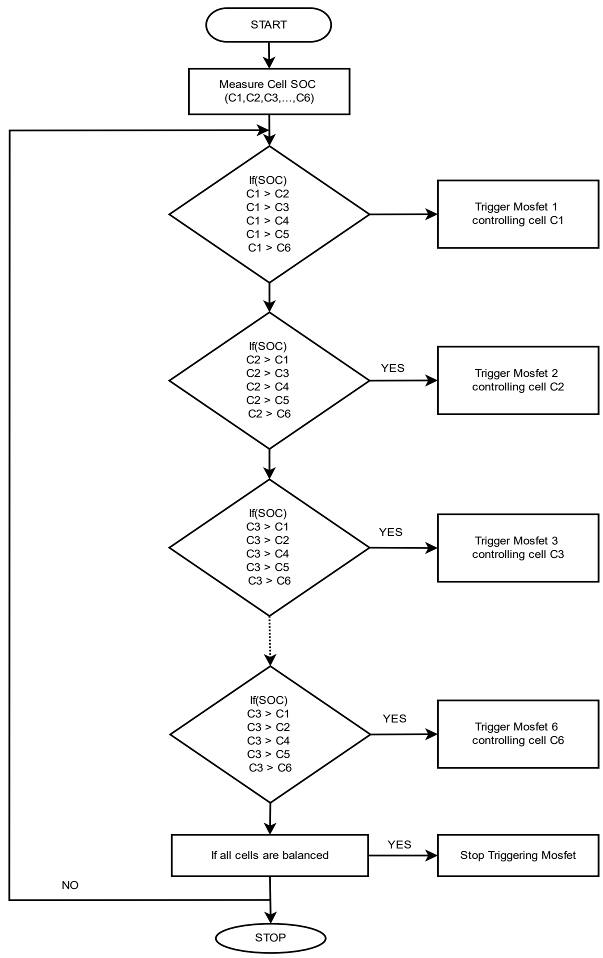

Figure 2. Balancing algorithm for Cells SOC estimation

The cell balancing algorithm shown in above shows how the six cells can be operated by using MOSFET switches and a bleeding resistor (Figure 2). Initially, the system measures the SOC of the battery and decides which cell is to be balanced using switches. All such decision-making algorithms are applied behind the system to get the work expected.

3.2 Estimation of State of Charge (SoC)

State of Charge is the available volume of the battery concerning with the rated range of the battery. To measure the SoC of the battery one should know the parameters like cell current, temperature levels of each cell, and terminal voltage. For SoC of the battery pack, there are many traditional approaches like OCV and Current Integration measurements, but these are accurate reasonably in some cases. In modern battery chemistries for estimating the SOC that has flat OCV-State of Charge discharge requires a different kind of approach. The results of Extended Kalman filtering (EKF) for a reasonable computational effort provide almost accurate results.

$$SOC(t) = SOC(t_0) + \frac{\int_{t_0}^{t} i(t)\,dt}{Q_{nominal}}$$

From the above formula for Coulomb counting SOC(t)-state of charge at time T, SOC(T_0)-initial charge, Int of i(t) dt is the total amount of charge transferred during charging and discharging conditions and Q $_{nominal}$ is showing rated capacity of the battery. This method has a significant number of inaccuracies but required less computation power. Dalvi and Thale (2020) developed the design of DSP-controlled passive cell balancing. A direct method for SOC estimation is current integration (Ampere Hour) which estimates the SOC value by performing the amount of current flowing through from the battery for few times and integrating it. While integrating we should know the initial charge of the battery and high accuracy of current is required. As change in temperature in batteries the efficiency of charging and discharging changes so which affects the Coulomb counting accuracy. Khalil et al. (2018) developed SOC of Li-ion battery using EKF. Extended Kalman Filter is widely utilized for SOC estimation of non-linear energetic systems. This filter made available an efficient computational way for state estimation through a linearization procedure. EKF uses a dual-stage predictor-corrector algorithm. Petri and Petreuș (2021) developed Balancing and SOC estimation in BMS for EV. For the implementation of EKF, some parameters are taken into consideration like initial SOC value, battery model, battery capacity, previous SOC estimated by the filter, and actual measurement way to predict the SOC. Additional parameters are used for high-efficiency estimation. Bhovi et al. (2021) developed Modelling and simulation of BMS for the electrical vehicle. Coulomb Counting (CC), Unscented Kalman Filter (UKF) and Extended Kalman Filter (EKF) results and algorithms are analyzed in their article. Cell balancing is performed over a 6-Cell battery pack. The BMS cell Voltage, Cell Current, Cell equalization with SOC measure were carried out using MATLAB and compared with the algorithms. It is observed that UKF recovers from errors more than EKF but at the same time, EKF estimates more accurately and gives finer SoC estimation than Coulomb Counting.

4. Hardware and Software Implementation of the System

4.1 Software Execution

Software execution using MATLAB Simulation of the BMS system using simulation model prototyping has been carried out. Many cases related to battery charging, discharging and SOC estimating have been demonstrated. MATLAB model of the six-cell battery pack is shown, and specifications sets as per Li-ion cell battery capacity. For SOC balancing using semiconductor switches like MOSFET and Resister are put in parallel with every cell so that cell-to-cell discharge has been done as per our implemented control algorithm. Depending on the conditions, if SOC of one cell is more than the other battery cell's SOC then, condition depending upon the occurred situation MOSFET switches is triggered simultaneously and all cells inside the battery pack are balanced and triggering is stopped corresponding to the MOSFET switching operation. Above model six Li-ion cells are used and each cell has one separate resistor connected. Passive balancing has been carried out through this resister by making SOC of each cell equal and dissipating extra energy through the resister. Six MOSFET switches are connected and operated through switching control of the logic subsystem.

The elementary SoC of each cell is given and can be balanced by MOSFET through a switching mechanism. There are the six MOSFET switches (SW1, SW2, …, SW6) that are connected across battery cells (Cell 01, Cell 02, …, Cell 06) for switching shunting operation. Cell balancing means balancing the voltages of the individual cell and making the charge of each cell equal. When the Gate signal is High, the MOSFET switch is closed and circuit gets completed and the charge from the excess cell gets dissipated into the bleeding resistor. And if Gate signal is getting at low, then the switch gets open and cell got balanced. Initial SOC of cell 01, cell 02, cell 03, cell 04, cell 05, and cell 06 is 46%, 23%, 61%, 37%, 25% and 66% respectively. The six Scopes and displays are shown in the Figure 3 that shows the parameters and SOC values of BMS system. SOC values are shown on display and in scope, you can see SOC current and voltage waveform. Before running the above model we can set the stop time to zero showing the initial SOC values of the battery pack on the display and then run it, the SOC of each cell come to equality and which is almost 23.96%. As soon as the SOC of each cell will become equal the simulation stops automatically.

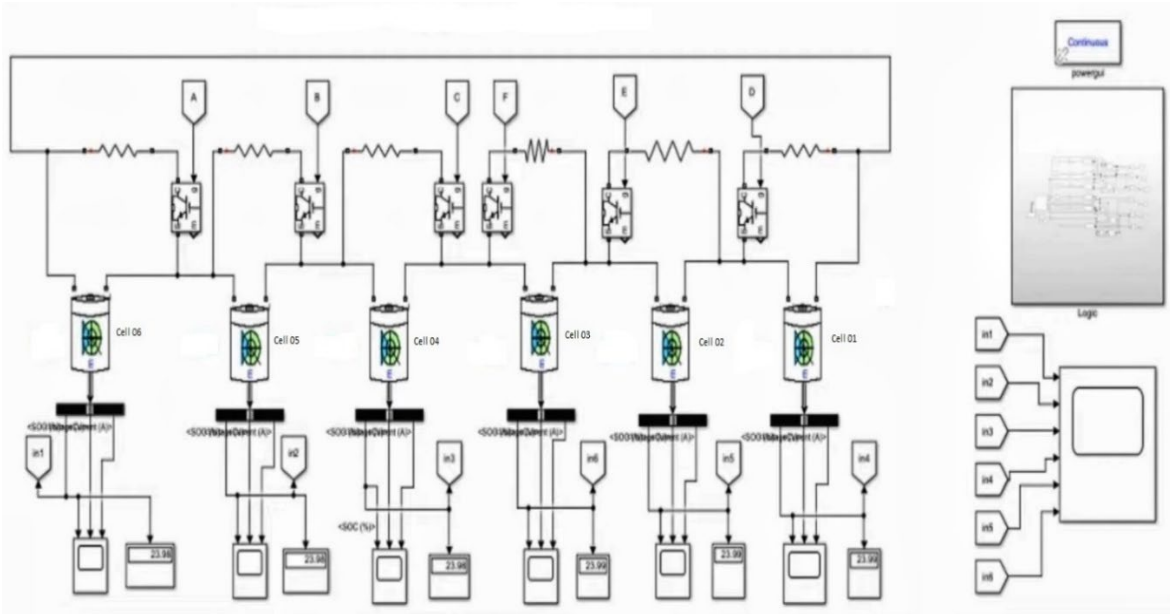

Figure 3. MATLAB Simulation model for passive balancing

4.2 Hardware Implementation

The hardware prototype for BMS includes an Advanced RISC Machine-based main microcontroller and BMS battery monitor that together connects with the computer system to verify the parameters like voltage, current, and temperature system of the BMS. In this system, use of the Texas Instruments microcontroller and high-accuracy battery monitoring system. The master controller used of Texas Instruments' high-performance TMS570LS0432 series microcontroller based on the ARM Cortex -R4 CPU architecture. This controller comes with the Hercules TMS570LS04 Launchpad Development Kit which is designed to help the users to evaluate and start development. This board receives the data from the battery monitor and takes the decisions to balance the state of charge (SoC), and voltages of battery cells. The developed algorithm has been implemented by using Code Composer Studio (CCS) software IDE to the controller and this module for works for the system according to data receives from the battery cell monitor.

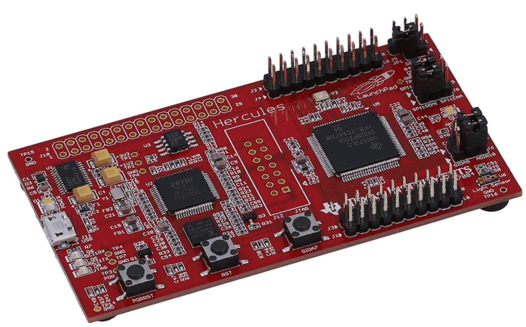

Figure 4. TMS570LS04 Launchpad Development Kit

Besides the main master microcontroller, the high-accuracy battery monitor is added extra advantage and safety to the system (Figure 4). The Texas Instruments BQ76942 battery monitor utilizes in the system for improving data accuracy obtained from the battery system. It contains an arrangeable protection sub-system and backing for autonomous or host-controlled balancing. Here a host-controlled communication is used and peripheral supporting I2C, SPI communication protocol. It provides features like protection including temperature, current, voltage, and internal diagnostics. The Evaluation Module (EVM) which is used for simple monitor function includes one integrated circuit (IC), thermistors, power FETs, sense resistor, and all onboard necessary components to safeguard the cells from short circuits, over-temperature and under-temperature, overcurrent discharge, overcharge, over-discharge. This circuit module directly connects across the cells in a battery. Communication is available with available on the 4-pin connector or included USB interface adapter (Figure 5).

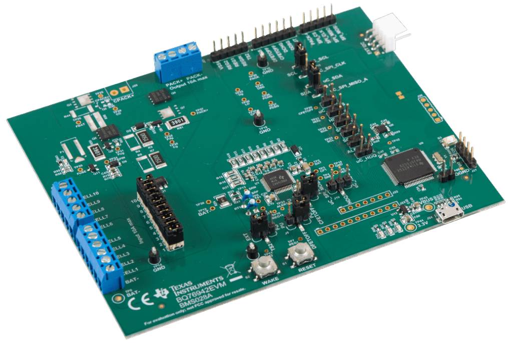

Figure 5. BQ76942 Slave Battery Monitor with an evaluation module

BQStudio (Battery Management Studio) software is used for the evaluation of the BQ76942 monitor and is compatible with Windows 7 and onwards. Battery Management Studio assist with the process of evaluating, configuring, testing and providing access to registers and data memory. It also includes support for graphing, logging and real-time watching (Figure 6).

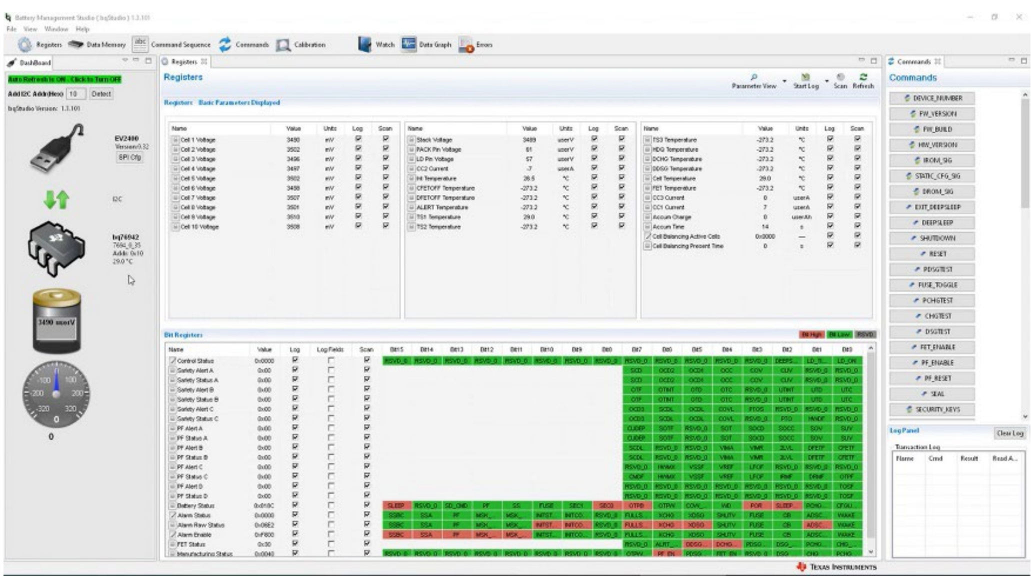

Figure 6. BQStudio Software Interface

The implementation of BMS system is shown in Figure 7. With a hardware system of a six-cell battery system is shown below figure which connects the master microcontroller and slave battery monitor. The six-cell Lithium-ion batteries with SOC approximation of algorithm is on Texas Instruments ARM TMS570LS04 microcontroller. The battery balancing was designed for a switching shunting passive resister method to give quick and competent balancing. The Constant Current Constant Voltage (CCCV) modes are used for programmable DC power supply for battery pack chargers. Electrical DC load is connected

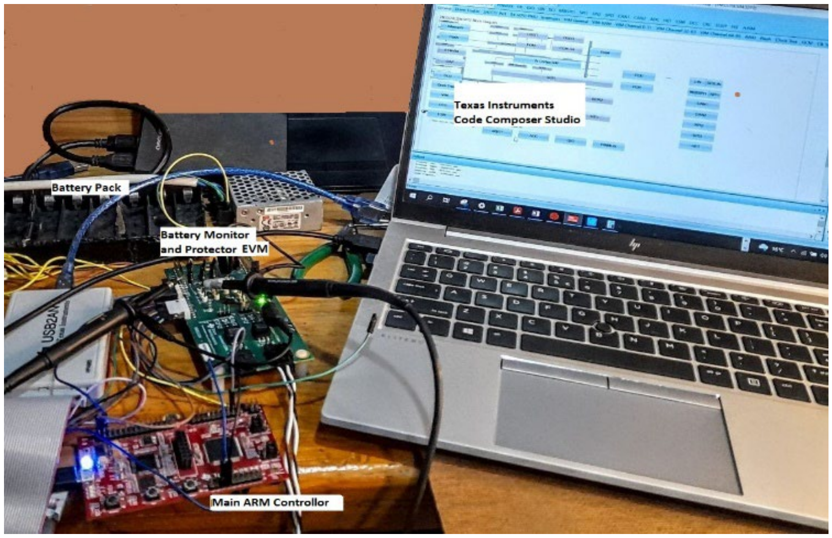

Figure 7. Hardware Prototype of six-cell battery management system

The BMS master and slave algorithms are shown in below Figure 8 and Figure 9. The master controller takes data from the battery monitoring module and takes a required action based on the situation that occurs in the system. The Various parameters data like SOH, SOC, Current, Voltage, and Temperature are collected by the slave controller and send it to the main controller for cell balancing.

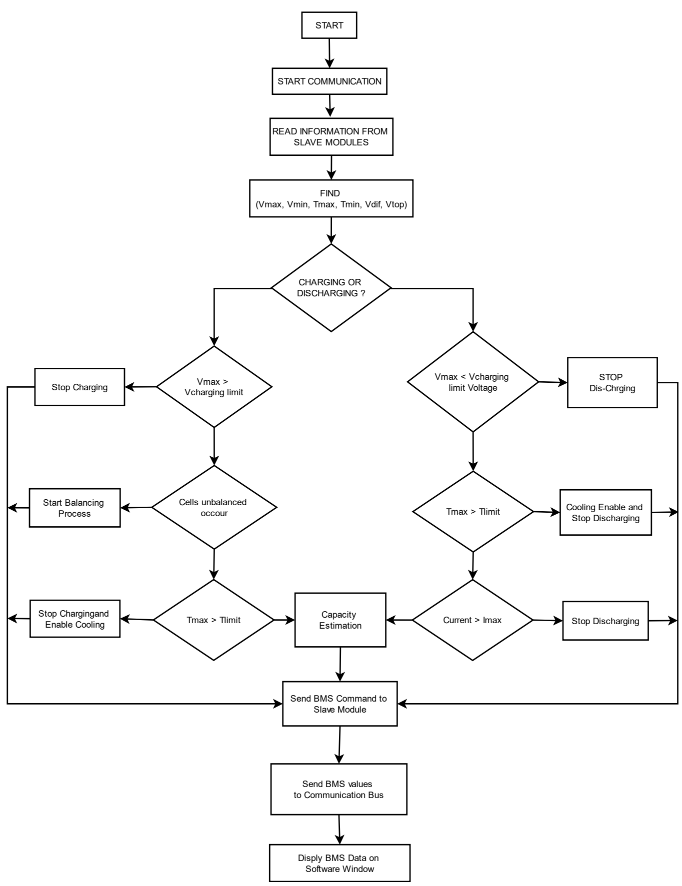

Figure 8. Main Microcontroller Algorithm

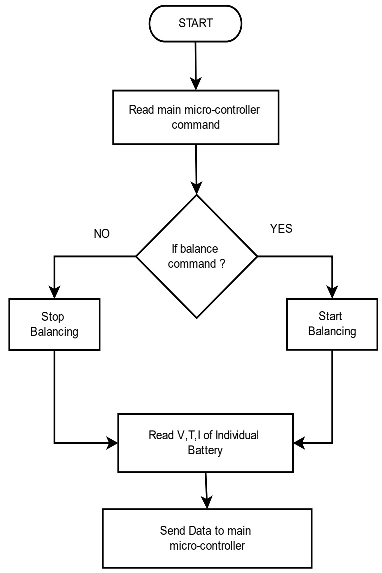

Figure 9. Slave Battey Monitor algorithm

5. Results and Discussion

MATLAB simulation results are shown here in graphical format. As soon as the cell imbalance is detected the proposed algorithm starts balancing of the cells and the SOC of the cells gets balanced via the algorithm implemented in the module. The SOC of the cells gets balanced to 23.99% after about 2800 seconds. Initial SOC of cell 01, cell 02, cell 03, cell 04, cell 05, cell 06 is 46%, 23%, 61%, 37%, 25%, 66% respectively. As soon as the SOC of each cell will become equal the simulation stops automatically. The cell that has less SOC gets balanced first and the cell has higher SOC takes some time to balanced (Figure 10).

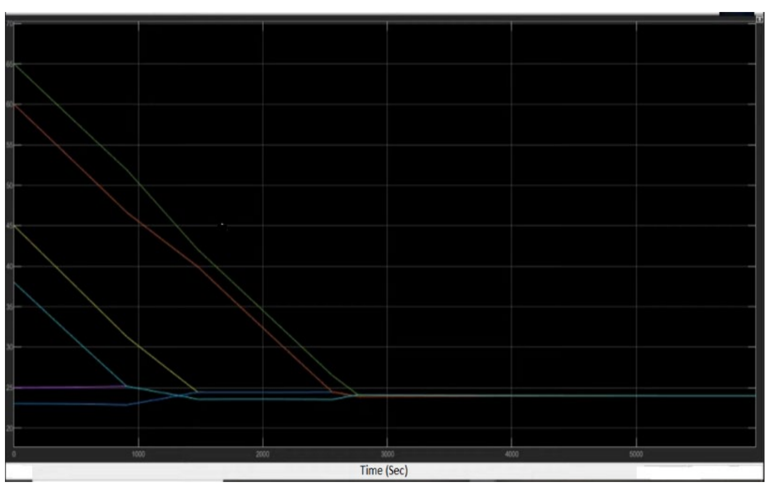

Figure 10. SOC cell balancing waveform

After Simulation, the BMS model gives the following graph of the battery cell parameters such as battery pack, cell voltages, and cell temperatures. The temperature generated in the battery pack while its charging and discharging is corelative to the current into and out of it. The chart of the hottest and the coolest cell Figure 11 shows the different cells temperature conditions based on BMS stages accordingly. Cell 1, 2 and 3 gets hotter compared to Cell 6. The BQ76942 battery monitor includes an on-chip temperature measurement system. The resistor values are and stored within the device for use during temperature calculation.

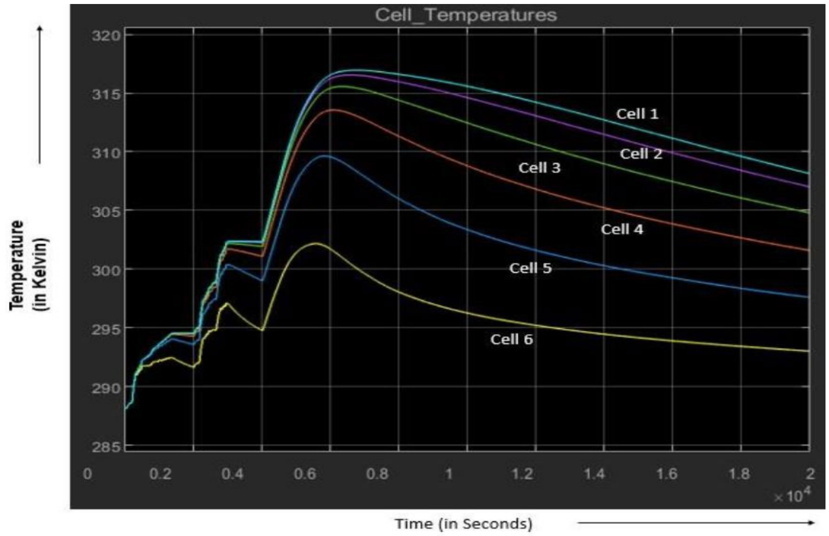

Figure 11. Cell Temperature Graph

The Slave Battery Monitor incorporates a voltage-based cell balancing algorithm which can be fully controlled by host microcontroller manually based on the implemented algorithm. When Mater device-controlled balancing is initiated, device starts timer and starts balancing until new balancing command is issued. Cell balancing is principal factor in Battery system. The Figure 12 shows the balancing role of BMS and charts of six cells are shown in diagram.

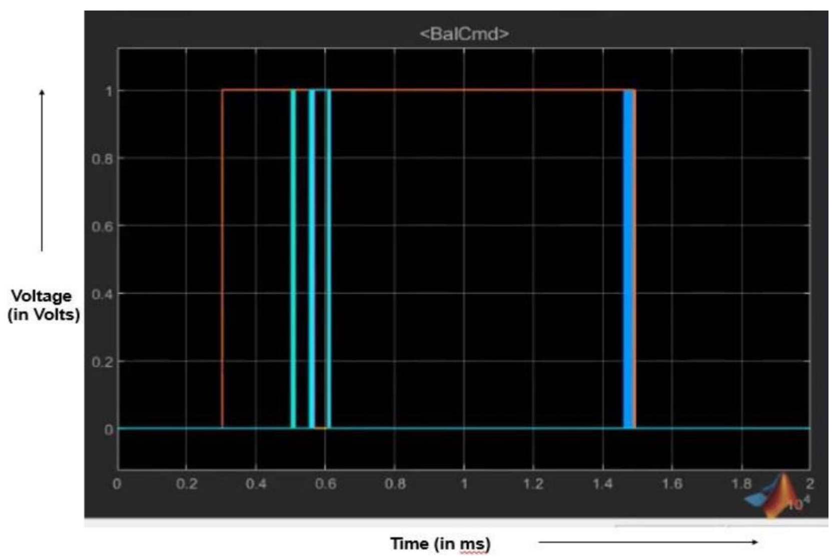

Figure 12. Cell Balancing Graph

The two main State of Charge estimating methods shown below the graph. The red colour graph track indicates the Extended Kalman Filer (EKF) method and the yellow trace shows the SoC evaluation of the Coulomb Counting method. Discharging phase at the starting, the SoC parameter of the cells vary for different method. The EKF method is more accurate and precise than the Coulomb Counting estimation of SOC. The Figure 13 shows a detail description of how EFK estimation performs better recovery from initial error.

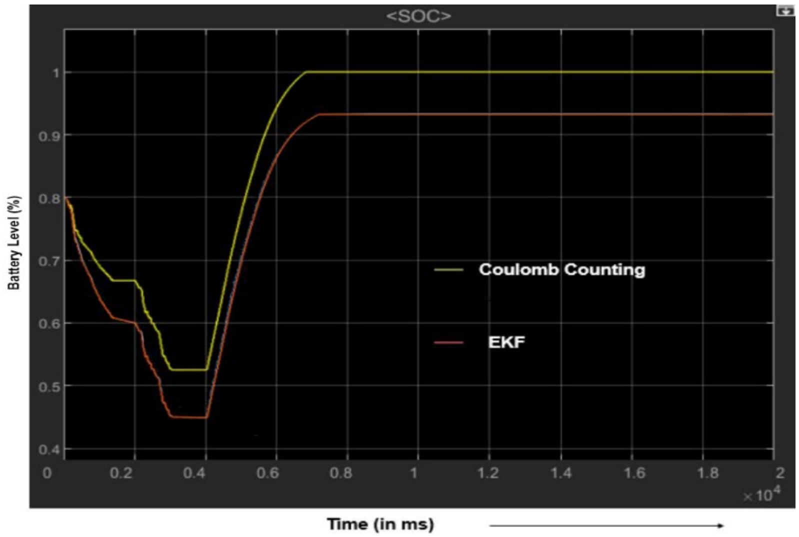

Figure 13. SoC comparison in EKF and CC

6. Conclusion

Work presented in this paper illustrate is to build a BMS that can be used in EV and come up with better information to a user for data monitoring. In this research work, the paper illustrates the use of the ARM Cortex -R4 processor and BQ76942 battery monitor with their high-end features providing SoC, SoH, battery current, voltage, and thermal protection with the increasing range of EV using the cell balancing technique. The passive balancing using Coulomb Counting and EKF methods to estimate SoC for a battery pack give precise results for vehicle range extension. The MATLAB simulation is done and proposed the cell balancing algorithm to improve the battery management system. Some key simulation results to gain well cell equity accompanied by the Coulomb Counting and EKF for SOC decide also ensures that the battery pack is neither over-discharged nor over-charged. The overall results show that the SOC estimation and cell balancing are effectively achieved using this topology.

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