TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

A FINAL YEAR PROJECT REPORT ON

ACTIVE CELL BALANCING APPROACH FOR EFFICIENT BATTERY MANAGEMENT SYSTEM

(As partial fulfillment of Bachelor's degree in Electrical Engineering)

(EE755)

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ABSTRACT

This project proposes a novel approach for improving the efficiency of battery management systems through active cell balancing using the Kalman filter algorithm and build a hardware prototype model for testing and validation of the results. The goal of this project is to develop a system that can extend the lifespan of batteries by ensuring that each cell is charged and discharged evenly.

The proposed system includes an active balancing circuit that uses the Kalman filter algorithm to estimate the state of each battery cell and determine the optimal charging and discharging currents. This approach is designed to reduce the energy loss associated with passive balancing circuits, which can be a significant source of inefficiency in battery management systems.

The project includes simulation studies using MATLAB and Simulink and experimental results to demonstrate the effectiveness of the proposed system. The simulation studies will be conducted to optimize the design of active balancing circuit and Kalman filter. The experimental results confirm the effectiveness of the Kalman filter algorithm in estimating the state of each battery cell and optimizing the charging and discharging currents. The experimental studies will involve testing hardware prototype model using actual battery cells and the developed active balancing system. The experimental setup will involve measuring the voltages, current of each battery cell and analyzing the result to assess the effectiveness of proposed system.

The scope of the project also includes identifying the limitations and challenges associated with the proposed system and developing the strategies to address them. The project will investigate potential applications of the developed system in various battery management scnenarios such as electric vehicles, renewable energy system and portable electronic devices

Overall, the scope of the project is to develop an innovative active cell balancing system, build a hardware prototype model for testing and validation, and evaluate its performance through simulation and experimental studies.

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LIST OF SYMBOLS AND ABBREVIATIONS

ADC	Analog to Digital Converter
BMS	Battery Management System
C	Capacitance
D	Duty Cycle
EKF	Extended Kalman Filter
ICE	Individual Cell Equalizer
L	Inductance
OCV	Open Circuit Voltage
PWM	Pulse Width Modulation
SOC	State of Charge
SOH	State of Health
T	Time Period
V_{OC}	Open circuit voltage
V_T	Terminal Voltage

CHAPTER ONE
INTRODUCTION

1.1 Background

With the concern of whole world being shifted towards environmental pollution due to exhaust emissions from automobiles and rising price of fuels the necessity of deployment of Electric Vehicles have been pronounced. One of the most important aspect that has enabled EVs to stand as a strong candidate of future of transportation is the revolution in its battery management system that has recently been experienced. But still there are lots of areas in battery management system itself which can be worked upon to improve its efficiency and reliability [1].

For the reliable and efficient operation of a battery management system, the importance of accurate estimation of State of Charge (SOC) and State of Health (SOH) of battery cannot be underemphasized. SOC is a measure of available capacity of a battery relative to its fully charged state while SOH is the indicative of aging level of battery. It quantifies the energy that battery can store now in a fully charged state compared to when it was manufactured.

Designing a battery pack that is both safe and capable of providing adequate energy is an extremely challenging task. Typically, a battery pack needs to supply direct current (DC) voltage in the range of hundreds of volts and deliver power in the range of hundreds of kilowatts to the vehicle's drivetrain. To meet these voltage and power requirements, a considerable number of battery cells are interconnected both in parallel and in series. Although these cells are considered identical however the cells in a battery pack exhibit mismatches in parameters due to manufacturing defects and aging [2]. These fluctuations result in a decrease in the effective capacity of the battery pack. As a result, it is almost always necessary to have a battery management system (BMS) with an external balancing circuit in order to fully utilize the energy capacity of all the individual cells. Additional circuits used for battery balancing are generally divided into two categories: passive balancing and active balancing. [3]. Passive balancing is characterized as a dissipative procedure, whereas active balancing is acknowledged as a non-dissipative procedure. In passive balancing circuits, a shunt resistor is employed to convert the energy of a cell into heat energy, thereby safeguarding the cells against overcharging. On the other hand, active balancing involves the direct transfer of energy to or from the cell by utilizing DC/DC converters or other methods of power transportation.

Hence by implementing proposed active balancing circuit the safety, durability , proper charge and discharge of battery packs, optimum utilization of available energy can be enhanced.

1.2 Problem Statement

The performance and life of Li-ion batteries are influenced by several factors such as overvoltage, undervoltage, overcharge, deep discharge, thermal runaway and cell voltage imbalance. If the battery parameters are not maintained optimally in all conditions, catastrophic casualties can occur e.g. toxic smoke or fire. Though the battery pack consists of cells of identical capacities, due to self-discharging rate of individual cells and uneven leakage from cells there exists variation in SOC of each cell. This causes cell imbalance resulting in variation of each cell voltage in the battery pack over time and hence decreases battery capacity rapidly [2]. The technique of cell balancing ensures the optimum performance of the battery pack by not allowing any cells to overcharge or over-discharge and hence increasing its life and usable capacity.

The two main techniques of cell balancing mentioned here are passive cell balancing and active cell balancing. Passive cell balancing is a dissipative process in which excess energy is dissipated in a resistor until all the individual cells are equally charged. This method has several drawbacks. The capacity of battery pack is limited by the weakest cell with the least SOC. The energy from the cell is wasted in the form of heat. Due to heat production, additional coolant technique is required. On the other hand, active cell balancing is a non-dissipative process in which energy is transferred from one cell to another with the help of capacitor or inductor or dc-dc converter. So energy is not wasted unlike in passive balancing. The SOC of pack is equal to average of all individual cells. Thus, the method of active cell balancing is preferred in our project.

1.3 Objectives

- To estimate SOC of lithium ion cells using Kalman filter algorithm
- To design an active balancing circuit to achieve balancing in lithium-ion battery packs.
- To model and simulate the circuit for unbalanced batteries.
- To develop a hardware prototype for verification of simulation results.

1.4 Scope of project

- Improve the properties of batteries to operate in all sort of circumstances.

- Investigate potential applications of the developed system in various battery management scenarios, such as electric vehicles, renewable energy system and portable electronic devices
- Develop an innovative active cell balancing system that can improve the efficiency and lifespan of battery management system
- Evaluate the performance of batteries through simulation and experimental results

1.5 Limitations

- The cost of active balancing circuit is higher than passive balancing circuit which could limit its practicality for application in some systems.
- The proposed system may not be easily scalable for larger battery arrays as implementation of active balancing circuit for each application may be impractical.
- The implementation of active balancing circuit requires additional safety considerations as circuit need to operate at higher current and voltages than passive balancing circuit.

1.6 Report organization

- This project constitutes five chapters including the current chapter. This chapter explains about the growing use of electric vehicles and revolution in its battery management system. Also, it covers the statement of the problem, objective of this project, scopes and its limitations.
- Chapter two provides a literature review on theoretical and articles or publications from IEEE conferences or transactions as well as books from major publishers. It is to find available information and previous results from other researchers.
- Chapter three explains the methodology of work for implementation of extended Kalman filter algorithm for SOC estimation of lithium ion cells .It also constitutes the proposed system for active balancing of cell and its working principle
- Chapter four presents the simulation results and discussion of the Kalman filter and proposed active balancing circuit in various cases considered.
- Chapter five conclude the result and further work to do.

CHAPTER TWO

LITERATURE REVIEW

2.1 Review of papers

While several recent studies have focused on eliminating the imbalance of energy stored in series-connected battery cells, very little attention has been given to balancing the energy stored in parallel-connected battery cells [4]. Looking back at the history several passive balancing method have been dominantly used for the purpose balancing of cells. Passive balancing is a dissipative approach where removing excess energy by increased cell body temperature and dissipative shunting through resistors were most popular method [3]. However passive balancing method being a method which involves wastage of excess energy in form of heat which creates an issue in thermal management in battery pack and related circuitry has failed to become a reliable method in balancing of cells. Under active balancing of cells too there are several methods [5], [4]. Switched capacitor charge shuttling method uses only one capacitor which reduces the cost but has greater equalization time. Multi winding transformer based balancing is also not that suitable as it has complex circuitry and is costly as it requires involvement of transformer. DC-DC Cuk converter based balancer is another popular method of balancing the cells which is also known as Individual Cell Equalizer (ICE). It is able to transform energy between adjacent cells only due to which circuit have longer equalization time. All above-mentioned shortcomings are well addressed by the application of buck-boost converter based battery balancer (Inductive Charge Shuttling) [6]. In this method either end of each cells is connected to each end of single inductor via two unidirectional paths .The inductor shuttles charge between any two batteries Because of high balancing currents this has small equalization time [2].

After briefly reviewing few methods of balancing of cells considering power loss, thermal management issues ,balancing speed, reliability, cost ,size, efficiency and application buck boost converter based battery balancer seems to have best balancing of cells [6].

2.2 Related Theory

The SOC exhibits the following relations with the open circuit voltage (OCV):

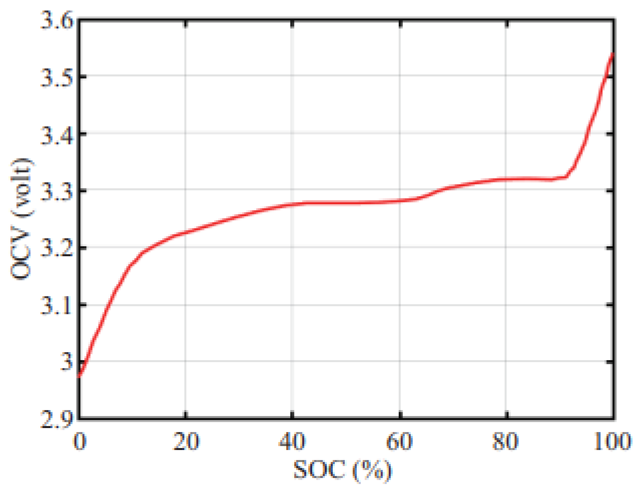

FIGURE 2. 1 OCV VS SOC [7]

From figure 2.1 we see that the voltage is nearly constant for a given range of SOC. So we anticipate that the voltage will not change even if there is charge deficit in a given battery. So to transfer energy from one cell to another we use an inductor type balancing system where the inductor stores the energy in its magnetic field and can cause voltage drop across it according to varying the current. To incorporate this method we can use various types of converters. The features of different type of converters used in active balancing is given in the table below which is based on practical review.

Table 2.1 Comparison of active cell balancing topologies

Type	Balancing speed	Reliability	Control Strategy	Cost	Size	Charge & discharge	Efficiency	Application
Single switched capacitor	Low	Medium	Hard	High	Bulk	Both	High	++/+++
Multiple capacitors	Very low	Medium	Moderate	Medium	Moderate	Both	High	++/+++
Single/Multiple inductors	Medium	Medium	Hard	Medium	Moderate	Both	Medium	++/+++
Single Transformers	Low	Low	Hard	Low	Moderate	Charge alone	Low	++
Multiple Transformers	Low	Low	Moderate	Low	Compact	Charge alone	Low	++
Forward converters	Medium	Medium	Hard	Medium	Moderate	Both	Medium	++
Flyback convertors	Low	Low	Moderate	Medium	Moderate	Both	Medium,	++
Full bridge converters	High	Medium	Hard	Low	Compact	Both	High	++
Cuk converters	Medium	Medium	Hard	Medium	Moderate	Both	Medium	++/+++
Buck or boost converter	High	High	Hard	Medium	Moderate	Both	High	++/+++
Quasi-resonant converter	Low	Very low	Hard	Low	Moderate	Both	Medium	++/+++
Ramp converter	Low	Very low	Hard	Low	Moderate	Both	Low	++

+ - Low power, ++ - Medium power, +++ - High power

Several methods of active cell balancing have been compared on the basis of their balancing speed, reliability, cost, efficiency and so on as shown in table 2.1. Among these methods the buck boost converter method seems to have very good overall performance so in our project we proposed the active cell balancing using the buck boost converter.

Principle of Operation of Buck Boost Converter

Buck boost converter is a type of DC-DC converter whose output voltage is either less or greater than input voltage. When the output voltage is less than input, it performs as buck converter and if the output is greater than input, it performs as boost converter. The major elements of this circuit are:

1. Solid state device (switch or MOSFET)
2. Inductor

3. Diode (act as switch)
4. Capacitor
5. DC voltage source

In the given figure 2.2, the input voltage source is linked to a solid state device ‘S’ which can be a MOSFET switch. The diode is used as second switch. The diode is connected to a capacitor and the load in reverse to the direction of power flow from source, and the two are connected in parallel as shown in the figure 2.2.

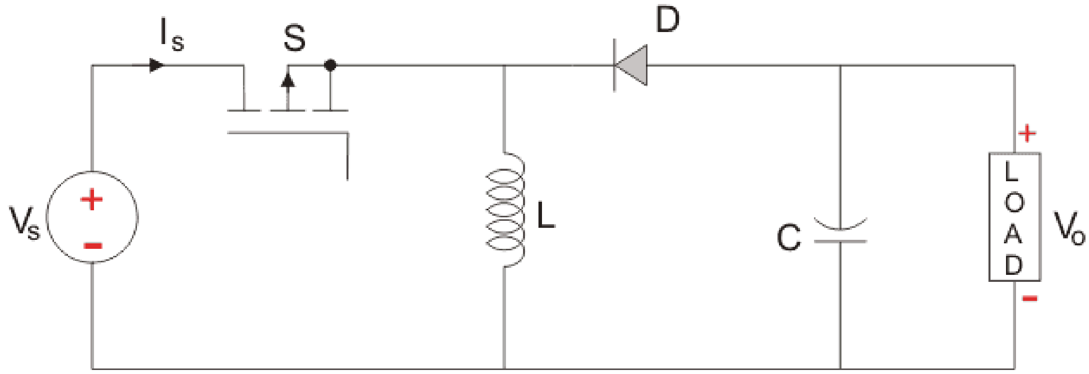

FIGURE 2. 2 BUCK BOOST CONVERTER [8]

Pulse Width Modulation (PWM) is employed to control the operation of the switch 'S' in this setup, allowing it to be turned on and off. PWM can be implemented using either time-based or frequency-based techniques. However, frequency-based modulation suffers from the limitation of requiring a wide range of frequencies to achieve precise switch control and attain the desired output voltage. In contrast, time-based modulation is commonly utilized in DC-to-DC converters due to its simplicity in construction and usage. Time-based PWM maintains a constant frequency throughout its operation. The Buck Boost converter operates in two distinct modes, with the first mode occurring when the switch is turned on.

Case I: Switch is ON, Diode is OFF

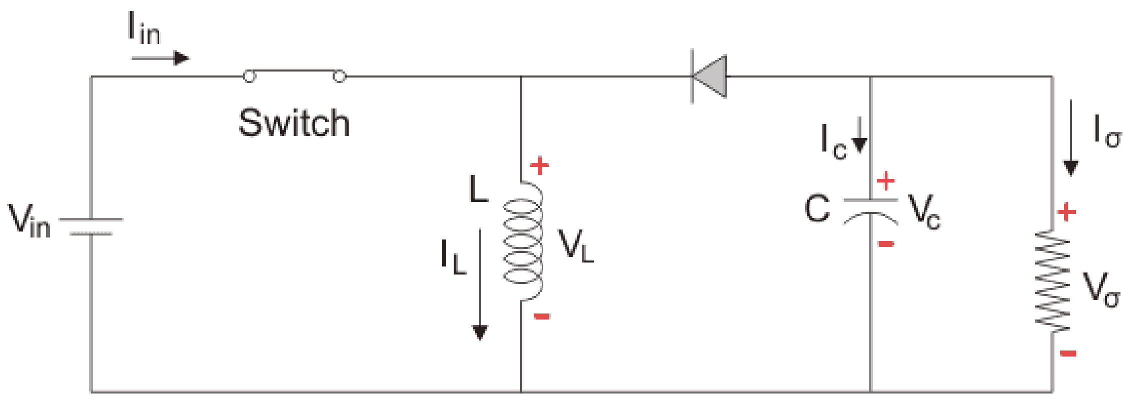

FIGURE 2. 3 OPERATION OF BUCK BOOST CONVERTER WHEN SWITCH IS ON [8]

When the switch is closed, the circuit presents negligible resistance to the flow of current, enabling the inductor to commence the process of charging. As a result, the inductor charges up to its maximum level.

While the switch is in the ON state, the inductor stores the charge and when the switch goes into its off state, charge across inductor reverses and flows through the load and back to the inductor thereby forward biasing the diode. Consequently, the direction of current flowing through the inductor remains unchanged.

Let us assume that the switch is on for a time T_{ON} and is off for a time T_{OFF}. The time period T is defined as $T = T_{ON} + T_{OFF}$ (2.1)

Similarly, the expression for switching frequency is given by;

$$F_{SWITCHING} = \frac{1}{T} \tag{2.2}$$

Duty Cycle is calculated as, $D = \frac{T_{ON}}{T}$ (2.3)

$T_{ON} = DT$, we can say that $\Delta t = DT$

$$(\Delta i_L)_{closed} = \left(\frac{V_{in}}{L}\right) DT \tag{2.4}$$

Duty cycle (D) ranges from 0 to 1. D > 0.5 results in higher output voltage, D < 0.5 leads to lower output voltage, and D = 0.5 yields equal input and output voltage.

While proceeding the analysis of the Buck-Boost converter we have to make sure that

1. By selecting a suitable value of L, it is possible to maintain a continuous current through the inductor.
2. During the ON state, the inductor current steadily increases from its initial value with a positive slope, reaches its maximum value, and then decreases back to its initial value with a negative slope in a steady-state. Consequently, the inductor current has a net change of zero over any complete cycle.

Case II: Switch is OFF, Diode is ON

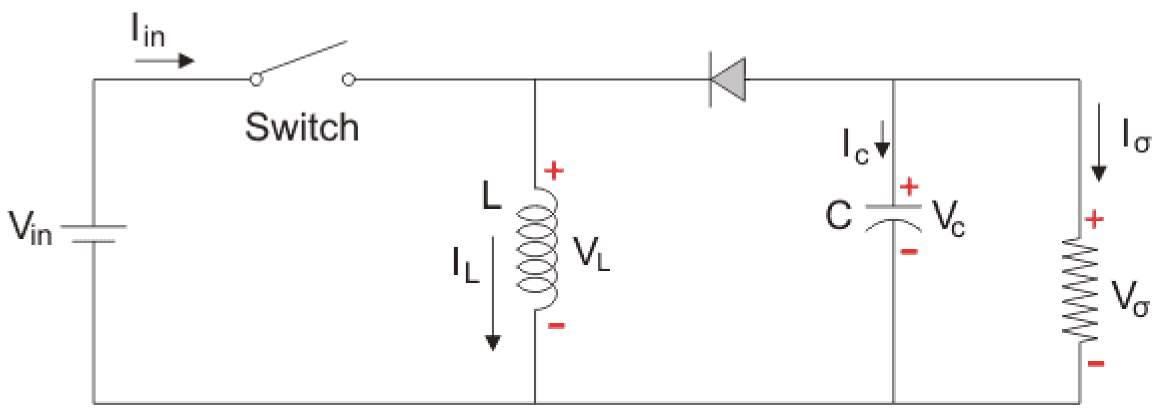

FIGURE 2. 4 OPERATION OF BUCK BOOST CONVERTER WHEN SWITCH IS OFF [8]

In this operating mode, when the MOSFET switch is open, the polarity of inductor current reverses causing it to discharge. The energy is then dissipated in the load resistance, which helps to keep the current flowing in the same direction through the load. Furthermore, the inductor now acts as a source in addition to the input source, resulting in an increase in the output voltage.

By applying KVL in this case II we will achieve the following results,

$$\therefore V_L = V_0 \tag{2.5}$$

$$\therefore V_L = L\frac{di_L}{dt} = V_0 \tag{2.6}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_0}{L} \tag{2.7}$$

Since the switch is open for a time $T_{OFF} = T - T_{ON} = T - DT = (1 - D)T$ we can say that $\Delta t = (1 - D)T$

As we already know that the net change of the inductor current over a complete cycle is zero. So,

$$\therefore (\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0 \tag{2.8}$$

$$\left(\frac{V_0}{L}\right)(1 - D)T + \left(\frac{V_{in}}{L}\right) DT = 0 \tag{2.9}$$

$$\frac{V_0}{V_{in}} = \frac{-D}{1-D} \tag{2.10}$$

The duty cycle (D) ranges from 0 to 1, representing the proportion of time during which the output voltage is higher than the input voltage. When D exceeds 0.5, the output voltage surpasses the input voltage, while a duty cycle below 0.5 results in the output voltage being lower than the input voltage. At a duty cycle of exactly 0.5, the output voltage matches the input voltage.

Therefore, it can be concluded from the above analysis that by varying the duty cycle of the switch, the power of output voltage can be lowered or boosted.

2.2.1 SOC estimation using Extended Kalman Filter

While SOC can be estimated using various techniques we used the extended kalman filter to estimate the SOC. This is a repetitive process where the SOC is estimated accounting for the various noise and errors encountered with the instruments and estimations. We start by figuring out the various property of a battery and their dependencies. We refer to the equivalent circuit model of a battery which is designed using a lumped parameter model which is shown in figure 2.5.

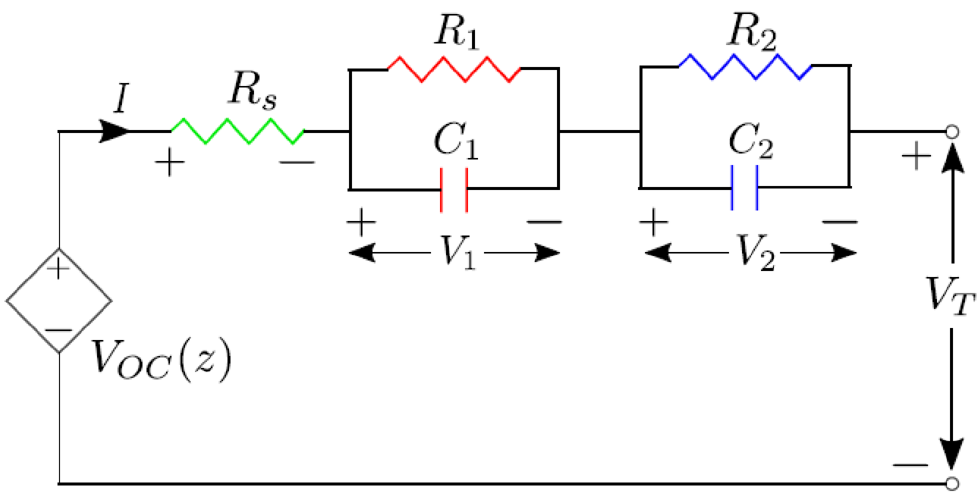

FIGURE 2. 5 DUAL POLARITY MODEL [9]

By utilizing Kirchhoff's Voltage Law (KVL) to analyze the entire circuit loop, we derive the subsequent equation representing the terminal voltage of the circuit. This equation is dependent on the internal components of the circuit.

$$V_T = V_{OC}(soc) - R_s I - V_1 - V_2 \tag{2.11}$$

By applying **KCL** to both RC branches we derive the following equations

$$\frac{dV_1}{dt} = \left(\frac{1}{C_1}\right) I - \left(\frac{1}{R_1 C_1}\right) V_1 \tag{2.12}$$

$$\frac{dV_2}{dt} = \left(\frac{1}{C_2}\right) I - \left(\frac{1}{R_2 C_2}\right) V_2 \tag{2.13}$$

The SOC of the battery has its relationship with the current of the circuit by the following equation

$$\frac{dSOC}{dt} = -\left(\frac{1}{C_{bat}}\right) I \tag{2.14}$$

By using the equations mentioned above we develop a state space model.

$$\begin{bmatrix} \frac{dSOC}{dt} \\ \frac{dV_1}{dt} \\ \frac{dV_2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \left(\frac{-1}{R_1 C_1}\right) & 0 \\ 0 & 0 & \left(\frac{-1}{R_2 C_2}\right) \end{bmatrix} \begin{bmatrix} SOC \\ V_1 \\ V_2 \end{bmatrix} + \begin{bmatrix} \left(\frac{-1}{C_{bat}}\right) \\ \left(\frac{1}{C_1}\right) \\ \left(\frac{1}{C_2}\right) \end{bmatrix} I \tag{2.15}$$

$$V_T = V_{OC}(soc) - R_s I - V_1 - V_2 \tag{2.16}$$

Although the continuous time model is a crucial step in system estimation, it is much simpler to utilize discrete time models on modern computers that inherently work with limited numerical representation and discrete processes.

The process of converting the continuous time model to a discrete time state space involved utilizing closed form discretization formulas on the relevant matrices and vectors from the continuous time model. This resulted in the creation of the discrete state and output equations which are as follows:

$$A_d \;=\; e^{A_c T} B_d = \int_0^T B_C e^{A_c \tau} d\tau \qquad (2.17)$$

$$\begin{bmatrix} SOC_{k+1} \\ V_{1,k+1} \\ V_{2,k+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{\left(\frac{-T}{R_1 C_1}\right)} & 0 \\ 0 & 0 & e^{\left(\frac{-T}{R_2 C_2}\right)} \end{bmatrix} \begin{bmatrix} SOC_k \\ V_{1,k} \\ V_{2,k} \end{bmatrix} + \begin{bmatrix} \left(\frac{-T}{C_{bat}}\right) \\ R_1\left(1 - e^{\left(\frac{-T}{C_1 R_1}\right)}\right) \\ R_2\left(1 - e^{\left(\frac{-T}{C_2 R_2}\right)}\right) \end{bmatrix} I \qquad (2.18)$$

We now are ready to apply the kalman filter algorithm to our problem with the developed state space models.

State space model

$x_{k+1} = f(x_k, u_k) + w_k$ (2.19)

$y_k = g(x_k, u_k) + v_k$ (2.20)

where w_k and v_k are independent ,zero mean ,Gaussian noise processes of covariance matrices Σ_w and Σ_v respectively.

Definitions: $A_k = \left.\frac{\partial\, f(xk, uk)}{\partial x}\right|_{x_k=\hat{x}_k^+}$ $\quad C_k = \left.\frac{\partial g(xk,uk)}{\partial x}\right|_{x_k=\hat{x}_k^-}$ (2.21)

Initialization: for k=0 , set $\hat{x}_0^+ = E[x_0]$, $\Sigma^+_{\tilde{x},0} = E[(x_0 - E[x_0])(x_0 - E[x_0])^T]$ (2.22)

Computation: For k= 1, 2, 3…….. compute

Time Update:

$\hat{x}_k^- = f(\hat{x}_{k-1}^+, u_{k-1})$ (2.23)

$P^-_{\tilde{x},k} = A_{k-1} P^+_{\tilde{x},k} (A_{k-1})^T + P_w$ (2.24)

Measurement Update:

$$L_k = P^{-}_{\tilde{x},k} C_k^T [C_k P^{-}_{\tilde{x},k} C_k^T + \Sigma_v]^{-1} \tag{2.25}$$

$$\hat{x}_k^+ = \hat{x}_k^- + L_k[y_k - g(\hat{x}_k^-, u_k)] \tag{2.26}$$

$$P^{+}_{\tilde{x},k} = (I - L_k C_k) P^{-}_{\tilde{x},k} \tag{2.27}$$

CHAPTER THREE

DESIGN AND METHODOLOGY

3.1 Overview

The goal of this project is to account the SOC variation among li-ion cells and design the balancing circuit to ensure efficient battery management system. For the active balancing of li-ion cells, first it is required to estimate the state of charge (SOC) of the cells then balancing is done using buck boost converter circuit. The overall methodologies of the project are mentioned below:

Step 1: Estimation of SOC using Extended Kalman filter algorithm

Step 2: Design active balancing circuit in matlab Simulink

Step 3: Simulate the balancing circuit for li-ion cells with different values of SOC

Step 4: Implement the extended kalman filter source code in raspberry pi for hardware I implementation

Step 5: Develop the hardware prototype of the balancing circuit using respective hardware components

Step 6: Verify the simulation results using hardware prototype

3.2 Software Used

We have done simulation in simulink for the circuit of active balancing of cell and for SOC estimation using kalman filter we have written code in MATLAB. Also we implemented kalman filter algorithm in python code for the loading of kalman filter code in microcontroller IDE for actual estimation of SOC.

Software used:

i. MATLAB
ii. Simulink
iii. Pycharm for python programming
iv. Proteus

3.3 Hardware required for project

i. Batteries
ii. Inductor, capacitor, diodes
iii. MOSFET
iv. Pulse generator
v. DC voltage source
vi. AND gates
vii. Voltage sensor and current sensor

3.4 Circuit diagram of proposed system (for active balancing of cell):

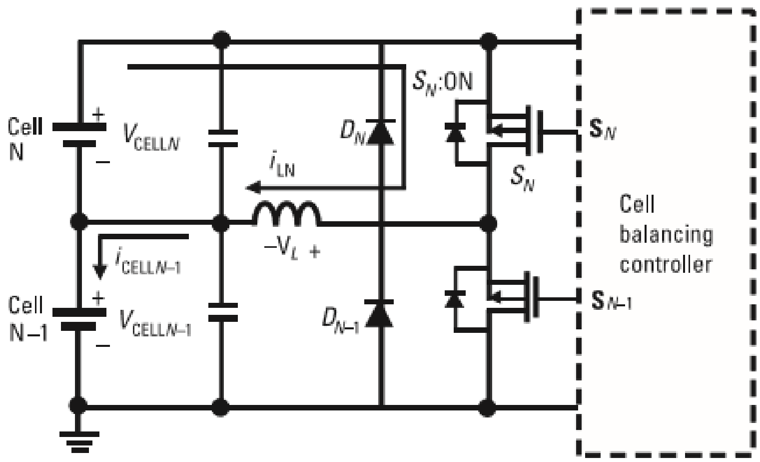

FIGURE3. 1 BALANCING CIRCUIT DIAGRAM [10]

3.4.1 Description of working principle

1. The controller senses the SOC imbalance between cells and distinguishes the cell from where the charge transfer should take place.
2. The controller sends the output signal to turn on the switch of the cells. In the above figure 3.1 if the controller senses that top cell N needs to transfer its energy to bottom cell N-1. It sends signal to switch S_N.
3. The signal sent will be a PWM of certain frequency and duty cycle.
4. The inductor starts to store energy and after the energy stored in the inductor reaches a maximum value the signal sent to the switch S_N is turned off.
5. After the switch is turned off the inductor voltage reverses in the direction and diode D_{N-1} becomes forward biased.

6. The inductor starts to transfer the energy to the Cell N-1 through the path of diode D_{N-1}.
7. In similar manner the energy is transferred from the bottom cell to the top cell if the controller detects that bottom cell has to transfer its energy from bottom cell to top through switch S_{N-1} .

3.4.2 Description of controller logic:

The controller will send signal to the respective switch for it to act when the controller senses some change in the SOC. If **(S_i)** be the SOC of i[th] cell.($\bar{S}$) Be the average SOC of parallel connected cell. **(S_{thr})** be the allowable difference in the SOC then the controller should carry out the action on basis of the following equations:

$S_i - \bar{S} > S_{thr}$ (Discharging)

$S_i - \bar{S} < S_{thr}$ (Charging)

Others (Islanding)

The flowchart for the Controller can be illustrated as follows:

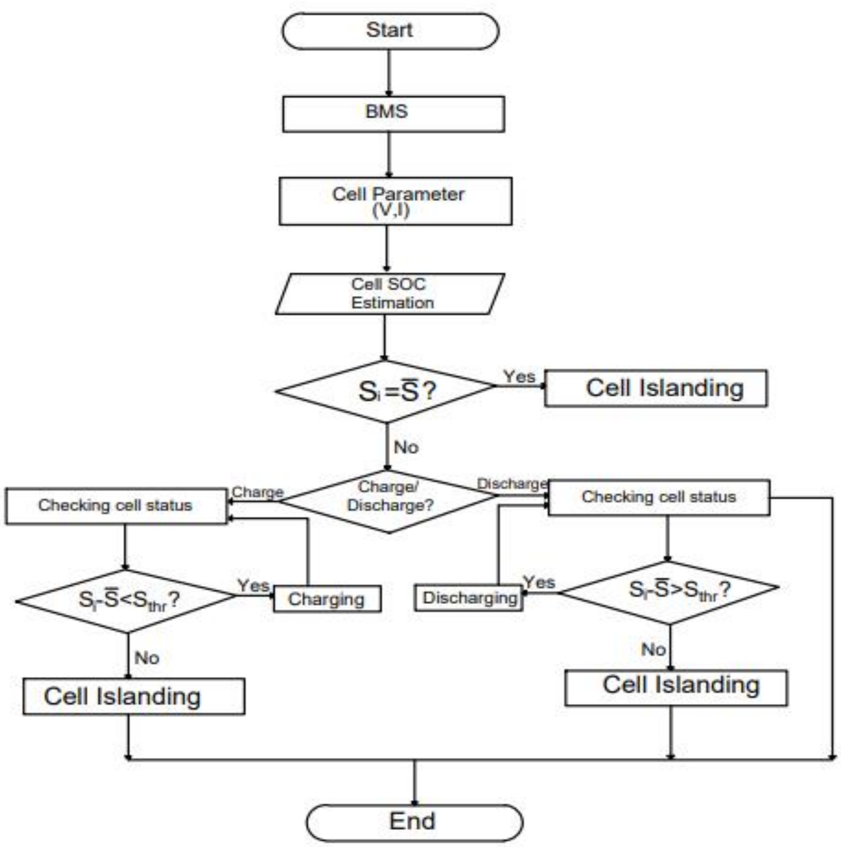

FIGURE3. 2 FLOWCHART FOR CONTROLLER OPERATION

3.5 Hardware Works Performed:

- Serial communication between Arduino and Raspberry pi was established where Arduino acts as slave and Pi as master. Arduino is used as ADC because Pi does not have inbuilt ADC.
- Used voltage and current sensor to measure voltage and current of li-ion cell respectively
- Successfully estimated the SOC of lithium ion battery using sensor measurements in EKF source code
- Displayed the SOC in LCD module.
- Designed a MOSFET driving circuit to enable the switching operation of MOSFET switch
- Designed a voltage regulator circuit to maintain constant gate threshold voltage
- Designed a boost converter circuit

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 SOC estimation using extended kalman filter

To elaborate the algorithm let us take the following example:

Given battery parameters:

C1=1000, C2=2500, R1=0.015, R2=0.0015, R0=0.02402

The noise in the instrument of measurement V= 1 $*10^{-4}$

The disturbance in the prediction W= $2.5*10^{-7}$

The discrete matrices formed by the battery parameters is given by:

$$f(x) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.99335 & 0 \\ 0 & 0 & 0.9736 \end{bmatrix} \tag{4.1}$$

$$B = \begin{bmatrix} -5.55 * 10^\wedge - 6 \\ 9.66 * 10^\wedge - 5 \\ 3.94 * 10^\wedge - 5 \end{bmatrix} \tag{4.2}$$

If we set the initial values of SOC as 0.98 the value of both voltages across the capacitor to 0, the process covariance=0 and the current I=5A initially. And now we iterate the extended kalman filter process for the 1st time

I.e. for the first iteration

$\hat{X}$ = SOC = $\hat{X}(0)-5.55*10^{-6}*5$ (4.3)

= $0.98-5.55*10^{-6}*5$

= 0.9799

$V1(1) = 9.66*10^{-5}*5$ (4.4)

= $4.83*10^{-4}$

$V2(2)= 1.97*10^{-4}$ (4.5)

To find out the Jacobian matrix C(1) we interpolate the value of voltage at $\hat{X}(1)$ using the following graph of $\frac{dVoc}{dSOC}\ vs\ SOC$ using matlab. We get the value of C(1)= 0.9856.

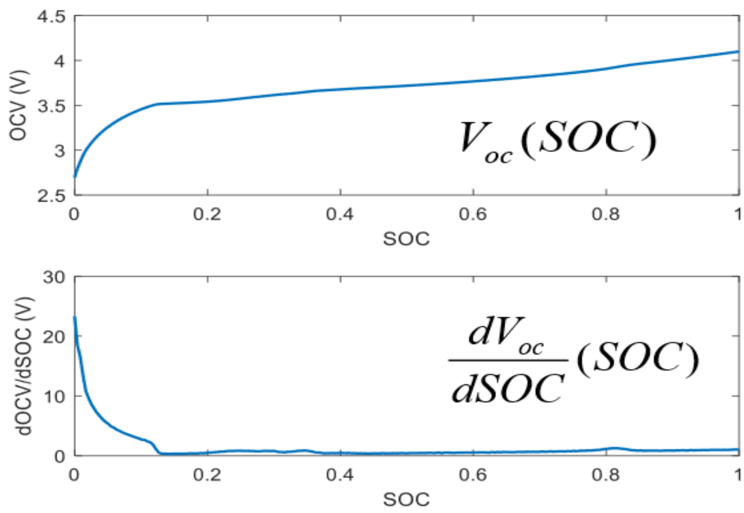

FIGURE 4. 1 **OCV VS V_{OC} AND $\frac{dOCV}{dSOC}$ VS SOC**

Figure 4.1 includes two plots first one OCV vs SOC and second one $\frac{dOCV}{dSOC}$ vs SOC. First graph shows the variation of open circuit voltage (OCV) of li-ion cell with state of charge (SOC). For higher state of charge of cell open circuit voltage is more and OCV remains almost constant for lower value of SOC. Similarly second plot shows the variation of SOC with slope of SOC vs OCV curve.

The next step is to calculate the process covariance matrix

$P = P(0)+W = 2.5*10^{-7}$ (4.6)

Calculating $L = P*C^T*inv(C*P*C^T+V)$ (4.7)

$= 2.5*10^{-7}*0.9856*inv(0.9856*2.5*10^{-7}*0.9856+1*10^{-4})$

= 2.464*10^-3

$\hat{X}(1)=\hat{X}(0)+L(Y(1)-G(1))$ (4.8)

The value of G(1) is found out by interpolation of the graph of Vocv vs SOC in the above figure and was found to be 3.95912 and the value of Y(1) is an experimental measurement data of voltage of the battery which was 3.9692.

The value of $\hat{X}(1)$ is thus = 0.98.

The process covariance is also updated by

$P(1) = P-L*C(1)*P$ (4.9)

$=2.5*10^{-7}-2.464*10^{-3}*0.9856*2.5*10^{-7}$

$=2.493*10^{-7}$

We also formulated a code in Matlab and plotted a graph for the results from the algorithm as shown below in figure 4.2 and 4.3.

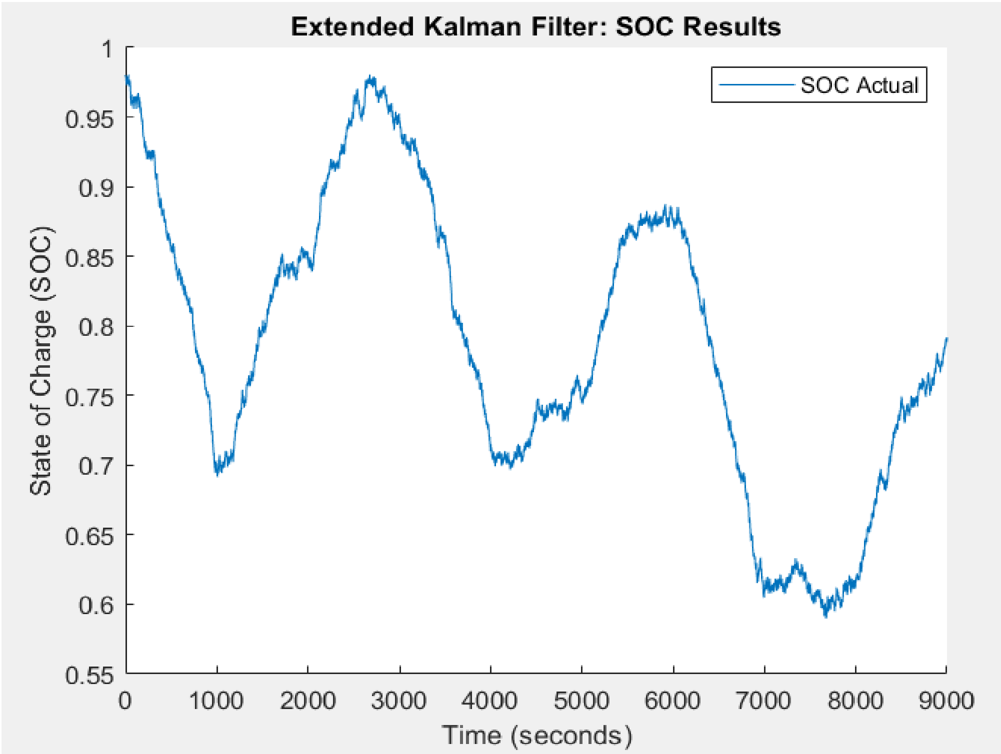

FIGURE 4. 2 ACTUAL SOC VS TIME

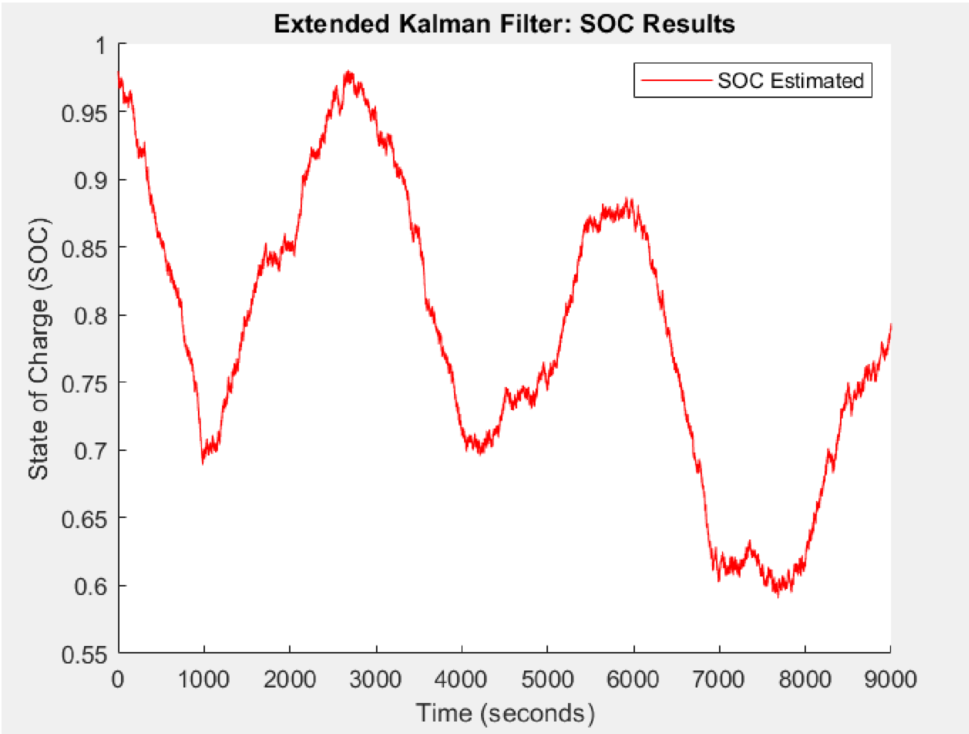

FIGURE 4. 3 ESTIMATED SOC VS TIME

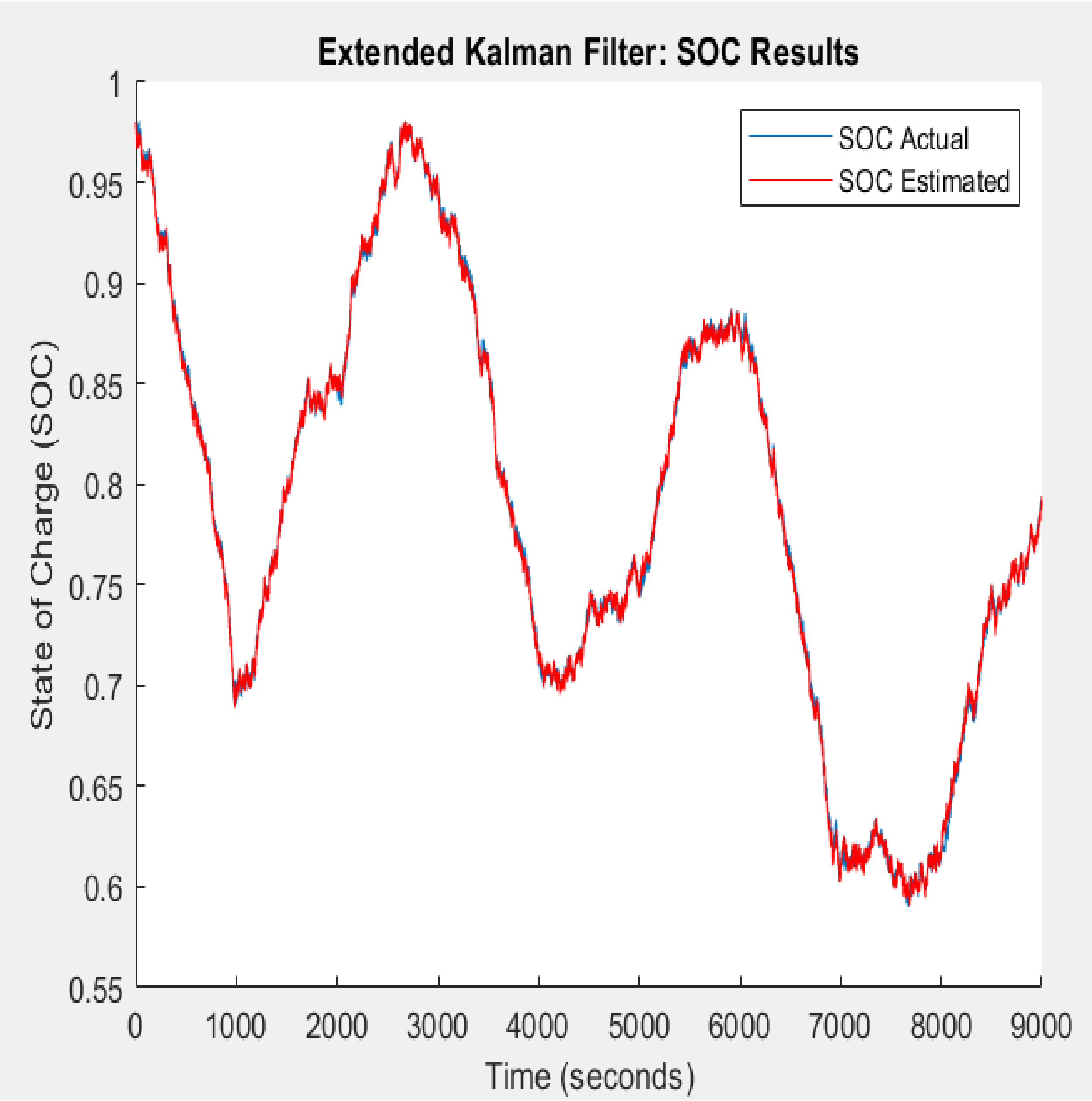

FIGURE 4. 4 ACTUAL SOC AND ESTIMATED SOC VS TIME

In the figure 4.4 both estimated SOC and actual SOC are plotted together. This figure shows that the plot of estimated SOC vs time is same as the plot of actual SOC vs time which indicates that extended kalman filter algorithm is successfully implemented in matlab to estimate the state of charge of the cell.

4.2 Active Cell Balancing Using Chopper

We were successful in simulating the active cell balancing using matlab. The Circuit diagram is presented below in figure 4.5.

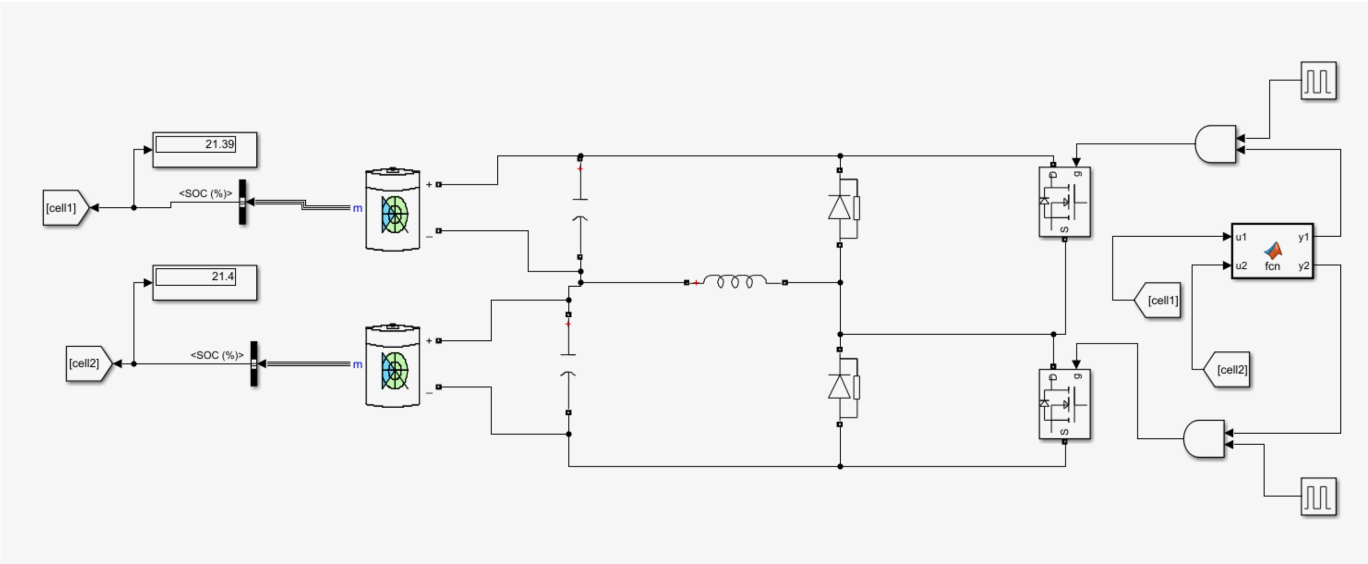

FIGURE 4. 5 SIMULATION OF ACTIVE CELL BALANCING CIRCUIT IN MATLAB

The circuit working can be explained as follows:

1. The controller will sense the SOC of both the cells in the circuit.
2. When there is a difference in the SOC the controller sends a signal to the corresponding gate.
3. The gate will make the switch operational, at first the switch corresponding to the battery having higher SOC will become operational.
4. By the given pulse at the AND gate the switch will be ON and OFF according to the pulse and given duty cycle.
5. According to the duty cycle the current flowing through the inductor from the switch will be fluctuating with time
6. The inductor will then oppose this changing current by establishing a voltage across it essentially it will begin to store energy in its magnetic field raising the voltage. $V_L = L\frac{di}{dt}$
7. The other switch will now become operational closing the switch which was operational before.

8. Now, due to the higher potential across the inductor due to storing of charges the charge flows towards the battery with lower SOC and hence increases the SOC of the battery

Hence active cell balancing is achieved in this way for two cells.

The following observations are made varying the parameters of different components used in this experiment

The upper battery was set to 23% SOC and the lower battery was set to 20% SOC.

Table 4.1: Varying the Value of L and keeping Period =1.5s and 50% duty cycle

L(inductance) in H	Time taken to balance in sec	Final SOC (%)
1	423	21.45
0.5	228	21.4
0.1	80	21.02
0.01	39	20.16
0.001	34	21.5

Table 4.2: Varying the value of Period keeping L=0.5H and duty cycle 50%

Period (s)	Time taken to balance in sec	Final SOC (%)
1	329	21.44
1.5	228	21.4
2	187	21.36
2.5	143	21.34

Table 4.3: Varying the duty cycle keeping period=1.5s and L=0.5H

Duty cycle (%)	Time taken to balance in sec	Final SOC (%)
30	594	21.45
40	340	21.43
50	228	21.4
60	72	21.2
70	51	20.93

Table 4.1 shows that final SOC deviates from average SOC (21.5%) of the cells on decreasing the value of inductance for constant period and duty cycle. On increasing period, time taken to balance decreases but final SOC deviates from the average value as indicated in table 4.2. Similarly, on increasing duty cycle keeping period and L constant, balancing time decreases but final SOC is deviated from the average value of SOC as shown in table 4.3. Hence the overall result shows that there is a trade-off between the time taken to balance and the final balanced SOC.

4.3 Implementation of Extended Kalman Filter Algorithm in Python:

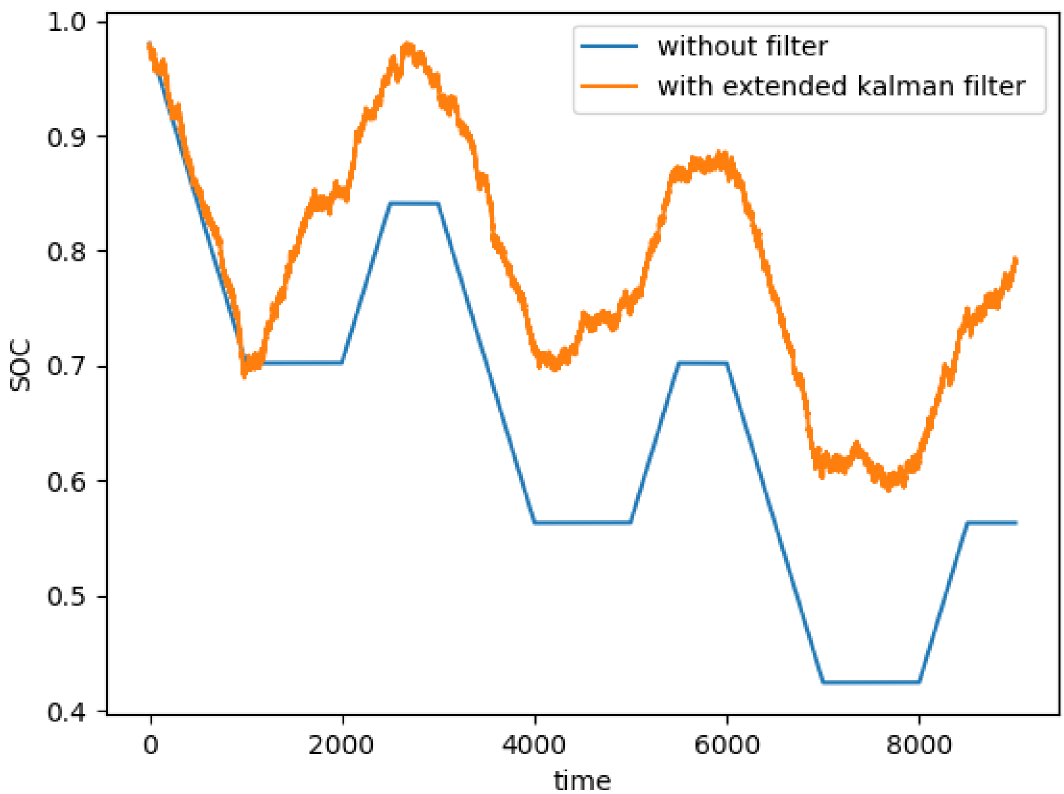

Figure 4. 6 SOC vs time with and without extended kalman filter

We successfully implemented the extended kalman filter algorithm in python programming language. We chose python code to implement kalman filter algorithm because python is one of the powerful programming language with extended libraries so it is very useful for estimation of variables for non-linear systems required for our project. Also it is supported in arduino using pyserial module which is required for the hardware implementation of our project in further stages. The python code loaded in arduino will help to read actual inputs from the battery itself and will estimate the SOC of the battery which is one of the objectives of our project.

Here, we used the same experimental values of battery parameters as used in matlab code to generate python code. Figure 4.6 shows the graph of SOC versus time obtained through python program and is similar to that obtained from matlab which verified the successful implementation of extended kalman filter algorithm in python.

4.4 Implementing the balancing circuit in Proteus

We simulated the balancing circuit in proteus in the hopes to figure out our components for the hardware and came to the following conclusions.

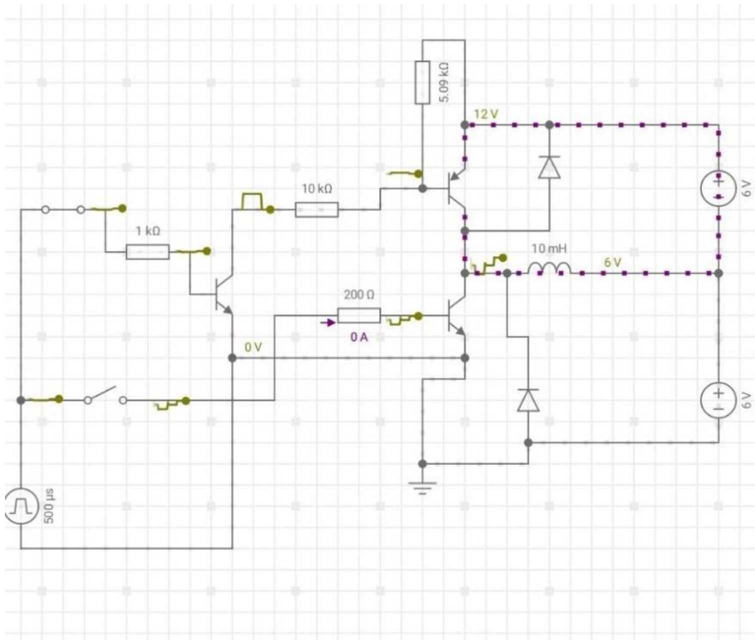

FIGURE 4. 7 BALANCING CIRCUIT DIAGRAM WHEN SOC OF UPPER CELL > THAN LOWER CELL

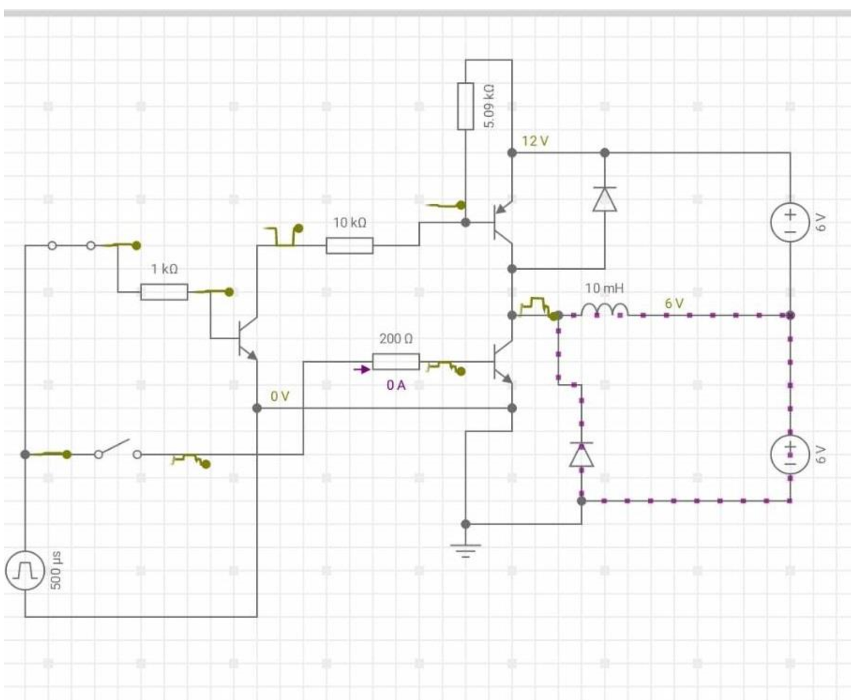

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FIGURE 4. 8 SOC TRANSFERRING TO LOWER CELL

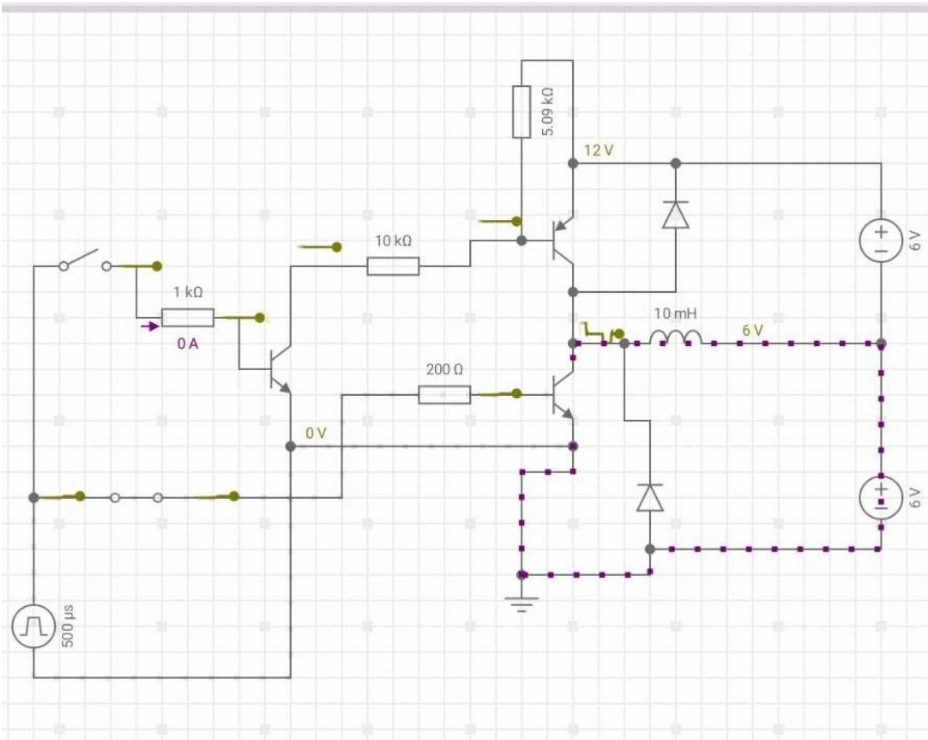

FIGURE 4. 9 BALANCING CIRCUIT DIAGRAM WHEN SOC OF LOWER CELL IS GREATER THAN LOWER CELL

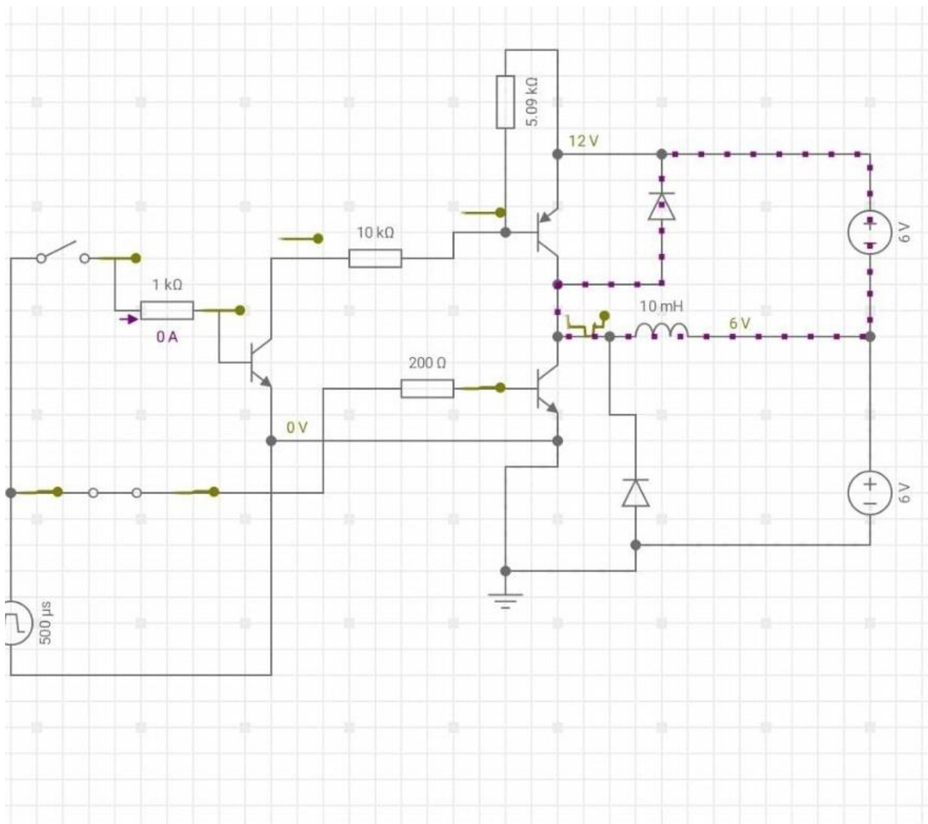

FIGURE 4. 10 SOC TRANSFERRING TO UPPER CELL

The figure 4.7 shows that the soc of upper cell is greater than that of lower cell. So, in order to equalize the charge in both the cells the soc of upper cell is transferred to lower cell as shown in figure 4.8. Similarly in figure 4.9 the soc of lower cell is greater than that of upper cell. The soc is transferred from lower cell to upper cell as shown in figure 4.10.

4.5 Hardware Implementation of Project

Following works have been done for the hardware implementation of our project:

4.5.1 Practical estimation of SOC using hardware components

The hardware components used for Kalman Filter code implementations are:

i) Raspberry Pi as master controller
ii) Arduino as slave
iii) Li-ion battery
iv) Current sensor
v) Voltage sensor
vi) LCD display module

Description:

In this hardware implementation of Kalman filter, we first established a serial communication between Arduino and Raspberry Pi. The neccesity of using these two controllers is that Pi doesn't have any Analog to Digital(ADC) converter as it is a microprocessor module but Arduino has inbuilt ADC of 10-bit. And we have implemented the kalman filter code using Python and only Raspberry Pi is capable of executing this code. So, we have used two controllers. We have used voltage sensor and current sensor to measure the voltage and current coming from the baterry and it is made to discharge through a load . The measurement values is then fed to the Arduino and it converts the analog values to digital number and gives it to the Raspberry Pi . The Pi uses this value and processes it in python program to give the value of SOC.

4.5.2 MOSFET Driving Circuit

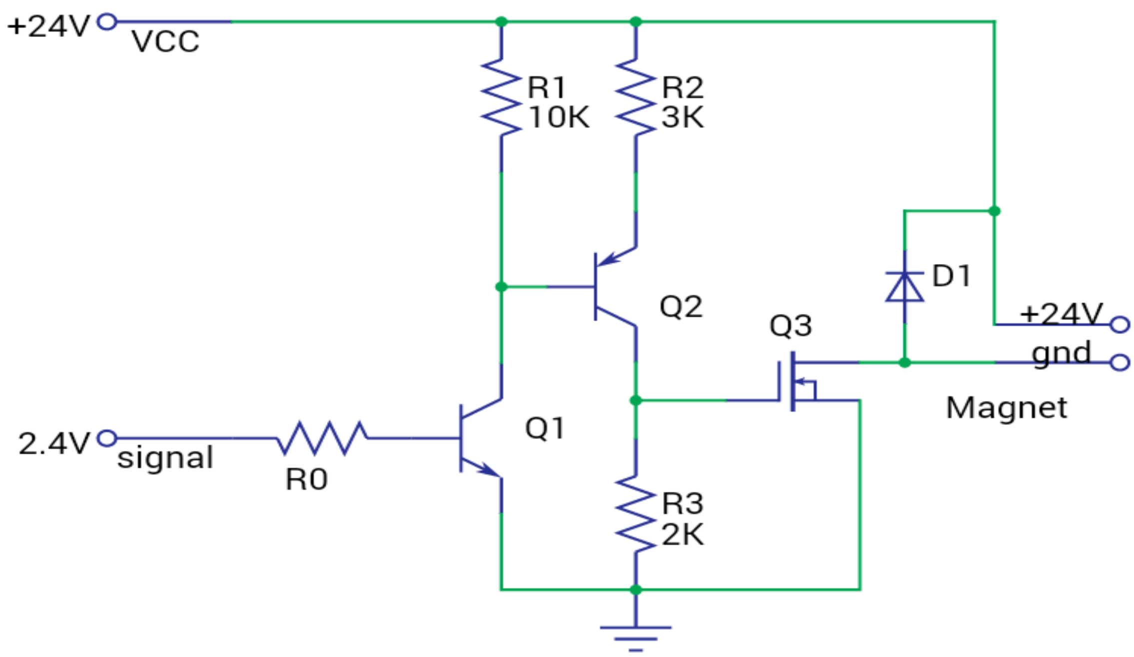

FIGURE 4. 11 MOSFET DRIVING CIRCUIT

The need for mosfet driving circuit is due to the fact that the IRF540N MOSFET has gate threshold voltage of 12V. The microcontroller cannot provide such output to make the gate ‘ON’. Hence, the gate should be provided with sufficient voltage such that it is able to perform its switching operations. Hence a gate driving circuit is connected so that the MOSFET runs smoothly. In this circuit shown in figure 4.14 the transistors are used to give the required voltage to the mosfet. The base of the transistor is connected with the microcontroller and collector is connected to the gate threshold voltage. When there is a signal that appears across the base of the transistor it becomes ‘ON’ and hence the mosfet gate receives the gate threshold voltage via the collector of the transistor and hence it turns ‘ON’.

4.5.3 Voltage Regulator Circuit:

This circuit is essential for the gate driver of the mosfet. In this circuit the required gate threshold voltage is maintained constant irrespective of the variation in source voltage. A voltage regulator IC is used to achieve this constant voltage.

4.5.4 Boost Converter Circuit

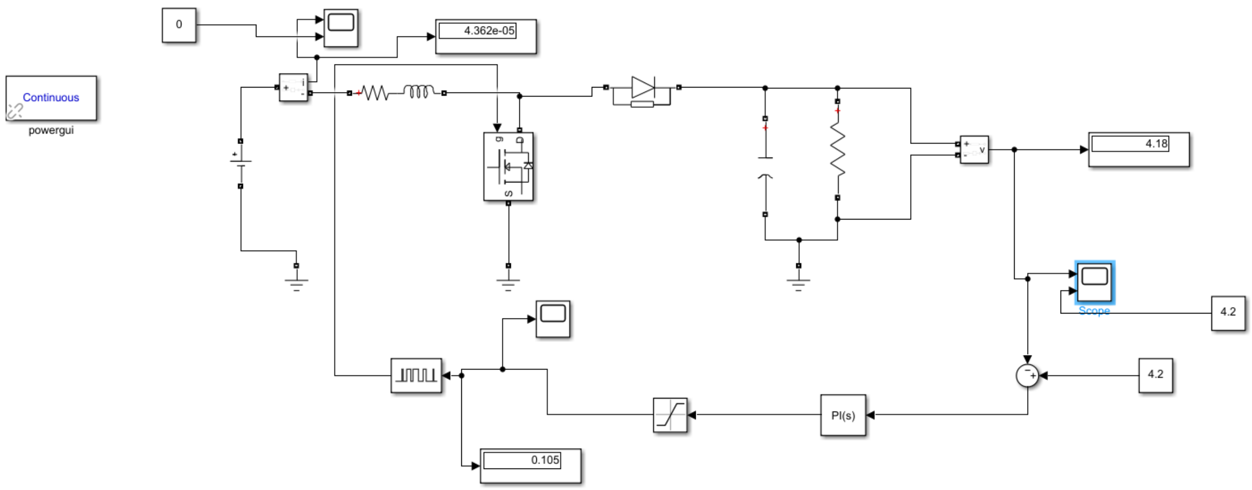

FIGURE 4. 12 BOOST CONVERTER CIRCUIT

In the circuit shown in figure 4.15 we have designed a boost converter such that the output of the converter circuit is equal to the constant charging voltage of the given Li-ion Battery. This circuit was tested in simulation and with the help of PID controller the gate of the mosfet was Switched and the required output was obtained. We also tested the battery to charge it and we found that the SOC of the battery increased. The voltage output of the circuit is described by the waveform below as shown in figure 4.16.

FIGURE 4. 13 OUTPUT VOLTAGE WAVEFORM OF BOOST CONVERTER CIRCUIT

We now tried to design this circuit in proteus and obtained the following simulations as shown in figure 4.17.

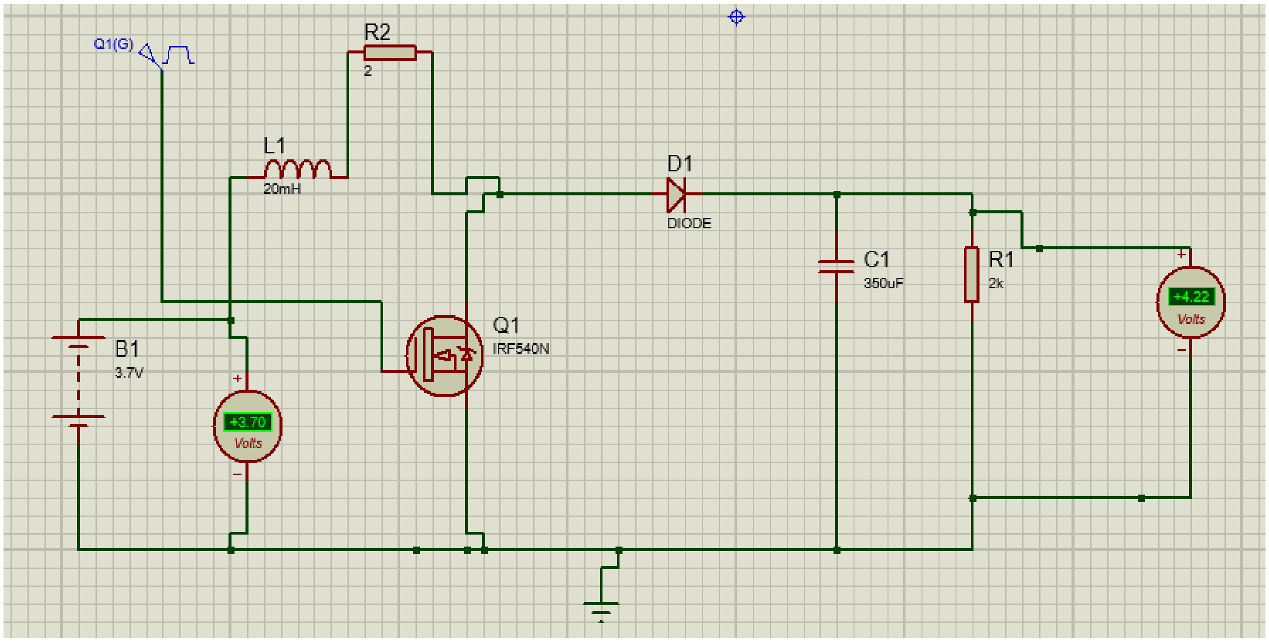

FIGURE 4. 14 BOOST CONVERTER CIRCUIT IN PROTEUS

4.6 Problems Faced During Hardware Works

- The accuracy of current sensor was quite low for lower values of currents. The sensitivity of current sensor is 185 mV/A, which is good for high value of current but we worked with low value of currents so there was problem while reading the value form current sensor.
- It was required to fill the parameters of the generic battery with a variety of accurate values in order to generate reliable data. However, several of these parameters were unavailable, and we were forced to compromise the data's reliability.
- Raspberry Pi setup was difficult and hectic.
- Our inductor in simulation was of 0.5H hence we faced problem in designing the inductor of this capacity.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The project was focused on the topic of active cell balancing which is a technique used to balance the charge levels of individual cells in a battery pack. Upon the completion of project, an active balancing circuit was designed and simulation of circuit was done to obtain the required result. In addition to this, a hardware prototype of balancing circuit was also designed to verify the simulation result. The aim of the project was to investigate the effectiveness of active cell balancing in improving battery performance, extending battery life, and reducing safety hazards. By the end of project, the objectives were satisfactorily met.

The project involved a thorough review of the literature on active cell balancing, including research studies, technical papers, conference papers, and so on. The review highlighted the importance of active cell balancing in battery systems, particularly in applications where battery packs are made up of multiple cells. A number of methods were studied for SOC estimation of individual cell, out of which extended kalman filter method was adopted because of its accuracy in estimating non-linear parameters. Further research was also done to explore the performance, efficiency and cost-effectiveness of different active cell balancing topologies.

Overall, the project was successful in demonstrating the effectiveness of active cell balancing in improving battery performance and reducing safety hazards. However it also highlighted the need for careful consideration of the specific requirements of battery systems and applications in order to determine the most appropriate active cell balancing system.

5.2 Future Recommendations

- Further research is required to explore the performance, efficiency and cost-effectiveness of different cell balancing techniques and systems so that most effective and efficient solutions for different applications can be identified.
- The project can be extended for large number of li-ion cells in order to improve the performance and usage life of overall battery pack.

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APPENDIX:A

Technical Specifications

Li –ion cell

- Samsung lithium-ion cell with the part number INR 21700
- Nominal Voltage: 3.7V
- Rated Capacity: 4.9Ah
- Cut off Voltage: 2.5V

FIGURE A. 1 LITHIUM ION CELL

.

Micro controller

- SoC: Broadcom BCM2837B0 quad-core A53 (ARMv8) 64-bit @ 1.4GHz
- GPU: Broadcom Videocore-IV
- RAM: 1GB LPDDR2 SDRAM
- Networking: Gigabit Ethernet (via USB channel), 2.4GHz and 5GHz 802.11b/g/n/ac Wi-Fi
- Bluetooth: Bluetooth 4.2, Bluetooth Low Energy (BLE)
- Storage: Micro-SD
- GPIO: 40-pin GPIO header, populated
- Ports: HDMI, 3.5mm analogue audio-video jack, 4x USB 2.0, Ethernet, Camera Serial Interface (CSI), Display Serial Interface (DSI)
- Dimensions: 82mm x 56mm x 19.5mm, 50g

FIGURE A. 2 RASPBERRY PI MODULE

Voltage Sensor

- Input Voltage: 0 to 25V
- Voltage Detection Range: 0.02445 to 25
- Analog Voltage Resolution: 0.00489V
- Needs no external components
- Easy to use with Microcontrollers
- Small, cheap and easily available
- Dimensions: 4 × 3 × 2 cm

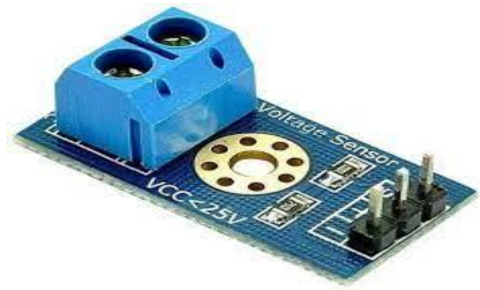

FIGURE A. 3 VOLTAGE SENSOR

Current Sensor

- 80kHz bandwith
- 66 to 185 mV/A output sensitivity
- Can measure upto 30Amperes
- Low-noise analog signal path
- Device bandwith is set via the new FILTER pin
- 1.2 mΩ internal conductor resistance
- Total output error of 1.5% at TA = 25°C
- Stable output offset voltage
- Near zero magnetic hysteresis

FIGURE A. 4 CURRENT SENSOR

LCD

- Operating Voltage is 4.7V to 5.3V
- Current consumption is 1mA without backlight
- Alphanumeric LCD display module, meaning can display alphabets and numbers
- Consists of two rows and each row can print 16 characters.
- Each character is build by a 5×8 pixel box
- Can work on both 8-bit and 4-bit mode
- It can also display any custom generated characters
- Available in Green and Blue Backlight

FIGURE A. 5 LCD DISPLAY MODULE

APPENDIX:B

<u>Source code for SOC estimation</u>

```
import numpy as np

import math

import pandas as pd

from matplotlib import pyplot as plt

from scipy.interpolate import interp1d

from pandas import DataFrame

# battery parameters

C1 = 1000

C2 = 2500

R1 = .015

R2 = .0015

R0 = .02402

alpha = .65

Cbat = 5*3600

Tau1 = C1*R1

Tau2 = C2*R2

dt = .1

# discrete time model

Ad=np.array([[1,0,0],[0,math.exp(-dt/Tau1),0],[0,0,math.exp(-dt/Tau2)]])

Bd=np.array([[-dt/Cbat],[R1*(1-math.exp(-dt/Tau1))],[R2*(1-math.exp(-dt/Tau2))]])

Cd=np.array([[alpha,-1,-1]])

Dd=np.array([[-R0]])
```

```
# kalman parameters

wk_mean = 0

Q = 2.5e-7

vk_mean = 0

R = 1e-4;

A_ek = 1

E_ek = 1

F_ek = 1

# importing all the files

soc_input_for_slope=pd.read_excel('slope_vs_SOC.xlsx',usecols="B")

OCV_slope=pd.read_excel('slope_vs_SOC.xlsx',usecols="A")

soc_intpts_OCV_slope=soc_input_for_slope['SOC input'].to_list()

OCV_slope_intpts=OCV_slope['OCV slope'].to_list()

soc_for_ocv=pd.read_excel('SOC_vs_OCV.xlsx',usecols="B")

ocv=pd.read_excel('SOC_vs_OCV.xlsx',usecols="A")

soc_intpts_OCV=soc_for_ocv['SOC'].to_list()

OCV_intpts=ocv['OCV'].to_list()

time=pd.read_excel('time.xlsx',usecols="A")

t=time['Time'].to_list()

current=pd.read_excel('current_input.xlsx',usecols="A")

I=current['current'].to_list()

voltage=pd.read_excel('Voltage_input.xlsx',usecols="A")

V=voltage['Voltage'].to_list()
```

```
# initial condition
p=[]
x1=[]
x2=[]
x3=[]
x1_hat=[]
V_hat=[]
p.append(0)
x1.append(0.98)
x2.append(0)
x3.append(0)
x1_hat.append(x1[0])
V_hat.append(0)
# using the kalman filter algorithm
for i in range(89999):
    k=i+1
    x = Ad[0, 0] * x1[k - 1] + Bd[0, 0] * I[k - 1]
    x1.append(x)
    y = Ad[1, 1] * x2[k - 1] + Bd[1, 0] * I[k - 1]
    x2.append(y)
    z = Ad[2, 2] * x3[k - 1] + Bd[2, 0] * I[k - 1]
    x3.append(z)
    x1_hat_prev = Ad[0, 0] * x1_hat[k - 1] + Bd[0, 0] * I[k - 1]
    if (x1_hat_prev > 1):
```

```
        x1_hat_prev = 1
    C_f = interp1d(soc_intpts_OCV_slope, OCV_slope_intpts, 'cubic')
    C_ek = C_f(x1_hat_prev)
    p_prev = p[k - 1] + Q
    v_f = interp1d(soc_intpts_OCV, OCV_intpts, 'cubic')
    v1 = v_f(x1_hat_prev) - I[k] * R0 - x2[k] - x3[k]
    V_hat.append(v1)
    j = C_ek * p_prev * C_ek + R
    L = p_prev * C_ek / j
    wp = V[k] - V_hat[k]
    x1_hat.append(x1_hat_prev + L * wp)
    p.append(p_prev - L * C_ek * p_prev)

plt.plot(t,x1,label="without filter")
plt.plot(t,x1_hat,label="with extended kalman filter ")
plt.xlabel("time")
plt.ylabel("SOC")
plt.legend()
plt.show()
```

ACTIVE CELL BALANCING APPROACH FOR EFFICIENT BATTERY MANAGEMENT SYSTEM

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