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Active Cell Balancing Approach for Efficient Battery Management System

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***Abstract*—With the increasing concern for EV and its battery management system, the effective life and performance of li-ion battery is of utmost importance. The battery cells should be frequently equalized in order to increase the lifetime of battery pack. The conventional method of cell balancing is passive cell balancing where excess energy from cell is dissipated in the form of heat until all the cells are equally charged, causing thermal issues and efficiency in the battery pack. This paper proposes a novel approach for improving the efficiency of battery management systems through active cell balancing using the Kalman filter algorithm thereby overcoming the drawbacks of passive cell balancing. The goal of this paper 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.**

***Keywords*— State of charge, Lithium-ion battery, Kalman filter, Cell balancing, Battery management system.**

Introduction

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 aspects 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 drive train. 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.

Proposed Scheme

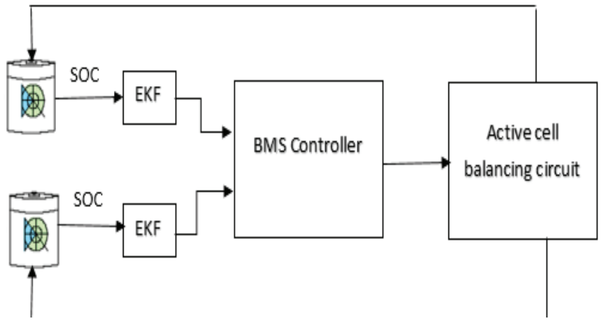

Fig 1. Proposed Block Diagram

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Figure 1 shows the block diagram of the proposed scheme. The state of charge (SOC) of each cell is determined using extended kalman filter algorithm. The controller senses the SOC of each cell and sends signal to the active cell balancing circuit to operate accordingly there by transferring the charge from cell with higher SOC to lower SOC and eventually equalizing the charge in each cell of a battery pack.

A. SOC estimation using extended Kalman filter algorithm:

While SOC can be estimated using various techniques, the extended Kalman filter is used 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. It is started by figuring out the various property of a battery and their dependencies. Figure 2 shows the equivalent circuit model of a battery which is designed using a lumped parameter model.

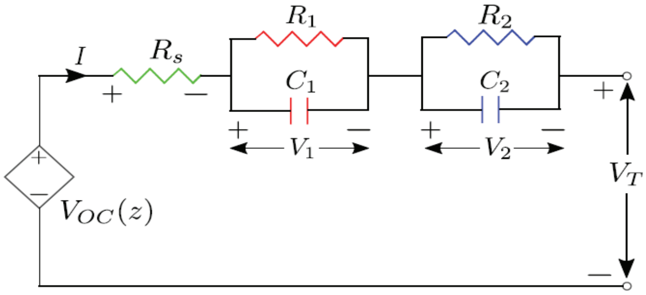

Fig 2 Dual Polarity Model

By utilizing Kirchhoff's Voltage Law (KVL) to analyse 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.

$$V_T = V_{OC}(soc) - R_s I - V_1 - V_2 \qquad (1)$$

By applying KCL to both RC branches, the following equations are derived:

$$\frac{dV_1}{dt} = \left(\frac{1}{C_1}\right) I - \left(\frac{1}{R_1 C_1}\right) V_1 \qquad (2)$$

$$\frac{dV_2}{dt} = \left(\frac{1}{C_2}\right) I - \left(\frac{1}{R_2 C_2}\right) V_2 \qquad (3)$$

The SOC of the battery has its relationship with the current of the circuit by the following equation (4).

$$\frac{dSOC}{dt} = -\left(\frac{1}{C_{bat}}\right) I \qquad (4)$$

By using the above equations, the state space model is developed as shown in equation (5):

$$\begin{bmatrix} \frac{dSOC}{dt} \\ \frac{dV_1}{dt} \\ \frac{dV_2}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{-1}{R_1 C_1} & 0 \\ 0 & 0 & \frac{-1}{R_2 C_2} \end{bmatrix} \begin{bmatrix} SOC \\ V_1 \\ V_2 \end{bmatrix} + \begin{bmatrix} \left(\frac{-1}{C_{bat}}\right) \\ \left(\frac{1}{C_1}\right) \\ \left(\frac{1}{C_2}\right) \end{bmatrix} I \qquad (5)$$

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:

$$A_d = e^{A_c T} \; B_d = \int_0^T B_c e^{A_c \tau} d\tau \qquad (6)$$

$$\begin{bmatrix} SOC_{k+1} \\ V_{1,k+1} \\ V_{2,k+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{\left(\frac{-T}{R_1 C_1}\right)} & 0 \\ 0 & 0 & e^{\left(\frac{-T}{R_2 C_2}\right)} \end{bmatrix} \begin{bmatrix} SOC_k \\ V_{1,k} \\ V_{2,k} \end{bmatrix} + \begin{bmatrix} \left(\frac{-T}{C_{bat}}\right) \\ R_1\left(1 - e^{\left(\frac{-T}{C_1 R_1}\right)}\right) \\ R_2\left(1 - e^{\left(\frac{-T}{C_2 R_2}\right)}\right) \end{bmatrix} I \qquad (7)$$

Now it is ready to apply the Kalman filter algorithm with the developed state space models.

State space model

$$x_{k+1} = f(x_k, u_k) + w_k \qquad (8)$$

$$y_k = g(x_k, u_k) + v_k \qquad (9)$$

Where, w_k and v_k are independent, zero mean Gaussian noise processes of covariance matrices Σw and Σv respectively.

Definitions: $A_k = \frac{\partial f(xk,uk)}{\partial x} x_k = \hat{x}_k^{+}$, $C_k = \frac{\partial g(xk,uk)}{\partial x} x_k = \hat{x}_k^{-}$

Initialization: for k=0, set $\hat{x}_0^{+} = E[x_0]$, $\Sigma^{+}_{\tilde{x},0} = E[(x_0 - E[x_0])(x_0 - E[x_0])^T]$ (10)

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

Time Update:

$$\hat{x}_k^{-} = f(\hat{x}_{k-1}^{+}, u_{k-1}) \qquad (11)$$

$$P^{-}_{\tilde{x},k} = A_{k-1} P^{+}_{\tilde{x},k} (A_{k-1})^T + P_w \qquad (12)$$

Measurement Update:

$$L_k = P^{-}_{\tilde{x},k} C_k^T [C_k P^{-}_{\tilde{x},k} C_k^T + \Sigma_v]^{-1} \qquad (13)$$

$$\hat{x}_k^{+} = \hat{x}_k^{-} + L_k [y_k - g(\hat{x}_k^{-}, u_k)] \qquad (14)$$

$$P^{+}_{\tilde{x},k} = (I - L_k C_k) P^{-}_{\tilde{x},k} \qquad (15)$$

B. Principle of Operation of Buck Boost Converter

Figure 3 shows the circuit diagram of Buck boost converter It 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.

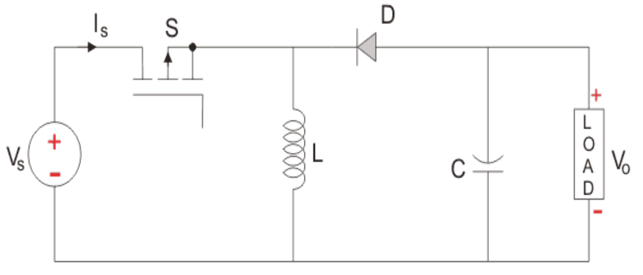

Fig 3. Buck Boost Converter

Case I: Switch is ON, Diode is OFF

While the switch is in the ON state, the inductor stores the

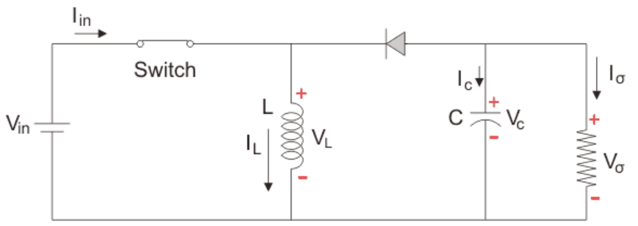

Fig 5. Switch is ON, Diode is OFF

Case II: Switch is OFF, Diode is ON

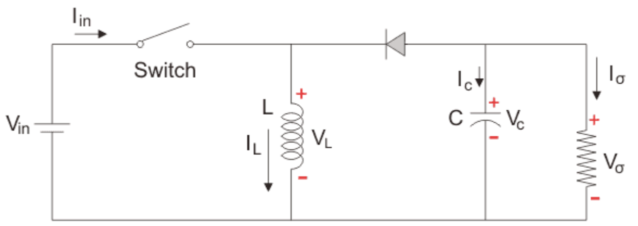

Fig 6 Switch is OFF, Diode is ON

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.

C. Active Cell Balancing Circuit

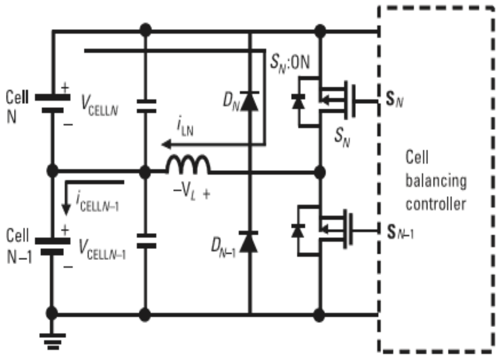

Fig 6. Active cell balancing circuit diagram using dc-dc converter

Figure 6 shows the circuit diagram of Active Cell Balancing system. Here, the controller senses the SOC imbalance between cells and distinguishes the cell from where the charge transfer should take place. The controller sends the output signal to turn on the switch of the cells. In the above diagram 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. The signal sent will be a PWM of certain frequency and duty cycle. 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. After the switch is turned off the inductor voltage reverses in the direction and diode D_{N-1} becomes forward biased. The inductor starts to transfer the energy to the Cell N-1 through the path of diode D_{N-1}. 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} .

Simulation Results

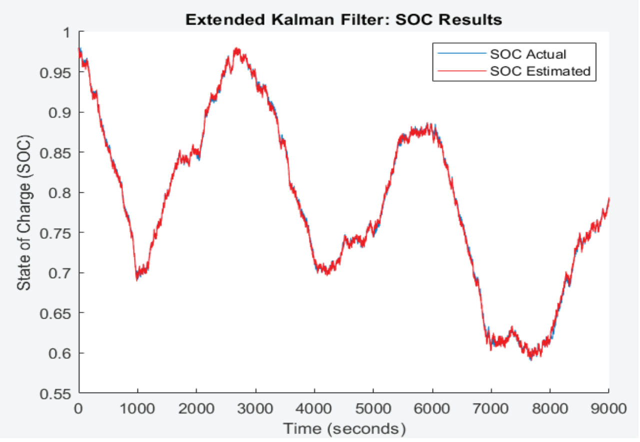

Fig 7. Plot of actual SOC and estimated SOC vs time

In the figure 7, 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.

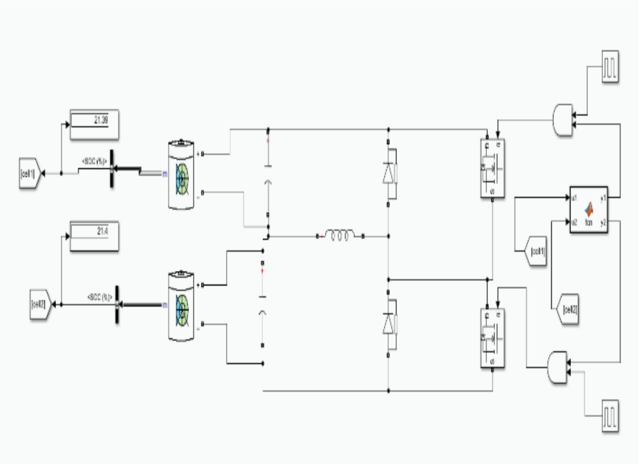

Fig 8. Simulation of active cell balancing circuit in matlab using buck boost converter

Figure 8 shows the Matlab simulation model of active cell balancing circuit with buck-boost converter. The upper battery was set to 23% SOC and the lower battery was set to 20% SOC. After simulation, the final balanced SOC was obtained as 21.39% in upper cell and 21.4% in lower cell which is almost equal to the average value of SOC contained initially in each cell. Hence, the equalization of charge in each cell has been successfully carried out using the active cell balancing circuit.

The following observations are made varying the parameters of different components:

TABLE 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 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 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

Hence the overall result shows that there is a trade-off between the time taken to balance and the final balanced SOC.

Conclusions

The paper 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. 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. 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.

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