SYSTEM AND METHOD FOR PASSIVE CELL BALANCING WITH MULTICELL LI-ION BATTERY VOLTAGE MONITORING

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Abstract : The Battery Management System (BMS) has a crucial role to play in making battery use safe, reliable and cost-effective. The Battery Management System (BMS) has to integrate something called cell balancing which is the most crucial feature in dealing with cell unbalance. This paper explains, method for calculating the individual cell voltage of a Li-ion battery pack and performing cell balancing which usually involves bypassing certain cells during charging (and often during discharging) by attaching external discharge resistors parallel to the cells by regulating the corresponding FETs. The standard current for by-pass varies from a few milliamps to amperes which is depending upon the selection of discharge resistor.

***IndexTerms* – Battery Management System(BMS), Cell Balancing, Bleed resistor, Op-Amp, Arduino, State of Charge(SOC), Bootstrap circuit.**

I. INTRODUCTION

Because of its excellent performance, lithium-ion battery is widely used in large-scale energy storage and electric vehicles and other fields. A nominal lithium cell is only rated at around 4.2V, but in applications such as EV, portable electronics, laptops, power banks etc., we require much higher voltage than its nominal voltage. This is why designers combine more than one cell in series to form a higher-voltage battery pack. When combining different cells to form a battery pack, ensuring they are of the same chemistry and voltage value is always made sure. However, the parameters including the initial battery state, aging rate, connection mode and environmental are inconsistent among single cells when using battery connection in series and parallel, which can result in inconsistency of internal resistance and State of Charge (SOC) between batteries. Furthermore, the parameters inconsistency among cells becomes more remarkable after several cycles, which can result in poor performance and shorter cycle life of the battery. This change in voltage levels causes cell unbalance, resulting in problems such as Thermal Runaway, Cell Deterioration, Inadequate Pack charging, Inadequate use of Pack Energy and other important safety issues, such as explosion. The design of the balancing scheme is therefore important for the improvement of the energy efficiency, life cycle and protection of the battery pack. Cell balancing is a technique through which voltage levels of each individual cell connected in series to form a battery pack are maintained to be equal to achieving the optimum battery pack output. Now we know when a battery pack is created by putting the cells in series so all the cells are in the same voltage ranges. So there'll always be a fresh battery pack with balanced cells. But because of SOC imbalance, internal resistance variation, temperature, etc., the cells become unbalanced as the pack is put into use. Cell balancing is a process by which weaker cells are compensated by equalizing the charge on all cells in the chain to increase the overall battery life. For multi-cell battery chains minor variations between the cells tend to be magnified with each charge-discharge period due to manufacturing tolerances or operating conditions. Weak cells can be overburdened during charging and become even weaker until they finally fail, causing premature failure of the battery.

The BMS has to incorporate something called cell balancing which is its most important function to deal with this issue. A Battery Management System (BMS) has a key role to play in making battery usage as safe, efficient, and cost-effective. There are several types of cell balancing methods, but the ones widely used are cell balancing of the active and passive kind. Active balancing can transfer energy by employing inductors, capacitors, transformers, external power and other modes to eliminate the inconsistencies between the batteries. While the circuit is complex and the cost is higher, this kind of equalization method can achieve higher energy utilization. Although a dummy load like a resistor is used in passive balancing to discharge and equalize the excess voltage with other cells. Such resistors are known as bypass or bleeding resistors. Passive method of balancing cells is the easiest of all methods. It can be used where costs and size are great constraints. Each cell connected in series in a pack will

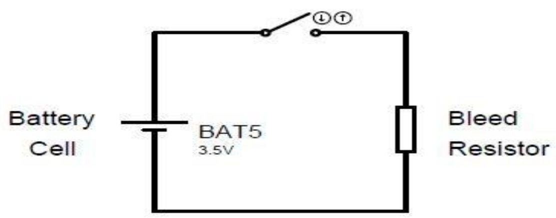

Figure 1.1. bleed resistor through switch

have its own bypass resistor connected through a switch as shown in figure 1.1. The high SOC cell is bled off (power is dissipated in the resistor) so charging can proceed until all cells are charged to maximum. Passive balancing requires all batteries to have the same SOC but it does not boost a battery powered system's runtime. It offers a fairly low cost method to balance the cells, but because of the discharge resistor, it wastes energy in the process.

II. SYSTEM DESIGN

Because of its limited voltage and capacity, the single Lithium-ion battery cannot meet the demand for electric vehicles or large-scale energy storage. Therefore, system voltage and current levels need to be increased by series and parallel battery link strategy. To increase the voltage number of cells in the system are connected in series. Similarly to increase the current capacity parallel connection is used. Cells connected in parallel are self-balanced, the only difficulty being that the cells are in series. So there's a large number of cells connected together in series, measuring the individual cell voltage of a battery pack is a bit challenging. But it is only when we know the individual cell voltage that we can perform cell balancing and provide protection for cells. So our primary requirement is the measurement of a battery pack's individual cell voltages. The implemented system is designed for a pack of four Lithium-ion cells connected in series (4S1P battery pack), with a pack nominal voltage of 14.8 V, which can replace the traditional Lead-Acid battery in a vehicle or 12 V applications. The cells have following specifications: nominal voltage 3.7 V, nominal current capacity 2400 Ah, operating voltage 2.7 – 4.2 V, discharging minimum cut-off voltage is 2.7 V, charging maximum cut-off voltage is 4.2 V.

2.1 Individual cell voltage measurement in a Series Battery Stack

In a series of connected battery pack, the issue with measuring individual cell voltage is that the reference point stays the same. The picture below illustrates exactly the same.

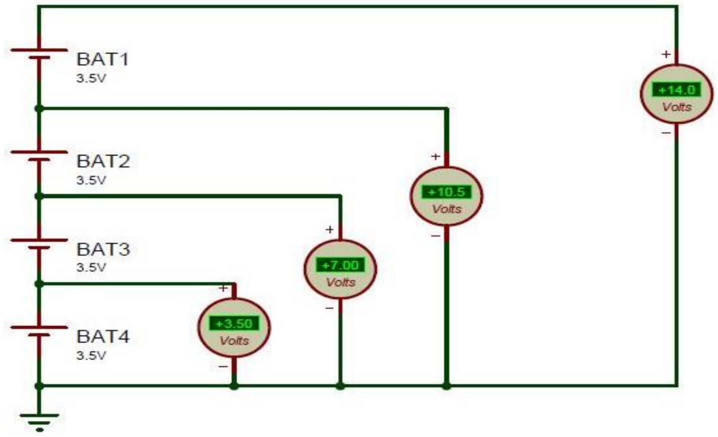

figure 2.1.individual cell voltages with same reference point

For simplicity let us assume that as shown above all four cells are at a voltage level of 3.5V. Now if we use a microcontroller like Arduino to calculate the voltage of the cell, we would have no problem in measuring the voltage of the 1st cell because it is attached to the ground at the other end. But we need to calculate the voltage of that cell together with the previous cells for the other cells, for example when we calculate the voltage of the 4th cell we must measure the voltage of all four cells together. That is because it's difficult to shift the reference point from ground. So we need to implement some additional circuit here that could help us calculate the individual voltages. A potential divider is used crudely to map the voltage levels and then calculate them, but this approach would limit the read value resolution to more than 0.1V. Therefore, to measure the difference between each cell terminal, we will use the Op-Amp Differential Circuit to measure individual voltages. When operating as a differential amplifier, we already know an Op-Amp gives the difference between the two voltage values it offers for its inverting and non-inverting plate. Thus we need three differential op-amps as shown for our purpose of measuring 4 cell voltages which is shown below figure 2.2.

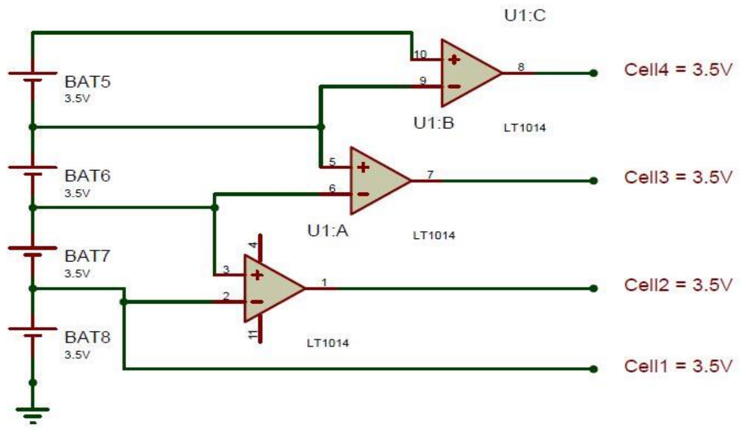

figure 2.2. differential op-amps circuit

The first op-amp U1:A calculates the 2nd cell voltage by measuring the difference between the 2nd cell terminal and the 1st cell terminal (7-3.5) which is 3.5. The Op-amp U1:B and U1:C similarly calculate the voltage of the 3rd and 4th cells respectively. We didn't use an op-amp for the 1st cell since it could be directly assessed. Differential Circuit for calculating individual Cell voltage is shown below in figure 2.3. The circuit was developed using Proteus and we will also be using the same to make our PCB.

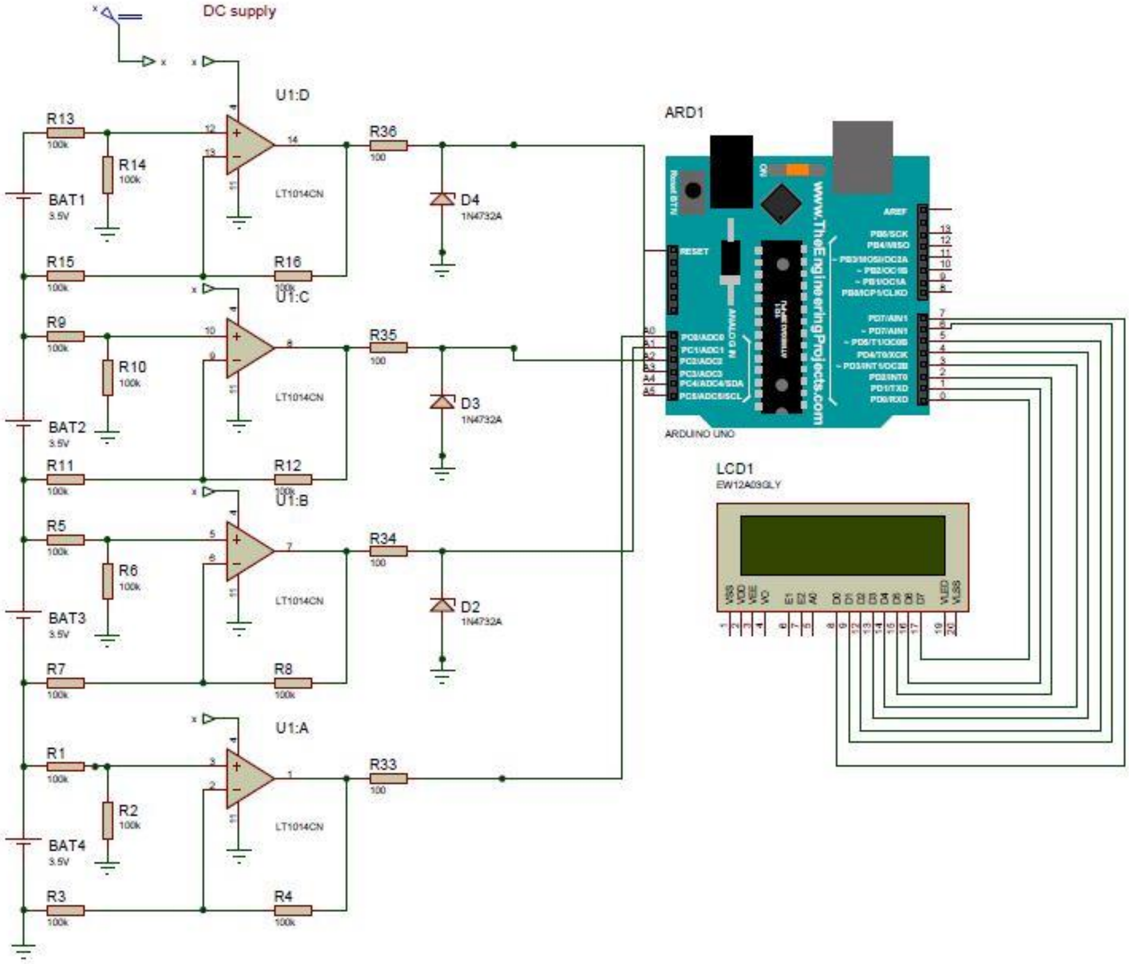

figure 2.3. schematic of individual voltage monitoring system with controller

The above circuit requires the use of precision op-amp like LT1013/LT1014 which will provide very good precision. The Op-Amp IC operates at the maximum (4.2 * 4) 16.8V pack voltage, which is why the Op-amp should be able to handle high voltages. The output of op-amp is connected to the microcontroller's analog input. Since each cell's voltage is less than 5 V, the amplification factor can be unitary, so that all resistors have the same value (100 k). At the analog input of the controller 5V zeners are used for overvoltage protection purposes.

2.2 DESIGN OF PASSIVE BALANCING CIRCUIT

Battery pack passive balancing technology is widely used in many areas because of its simple circuit, low cost and other advantages. Each individual cell is connected by a separate passive balancing control circuit which is shown in BMS Architecture in figure 2.4.

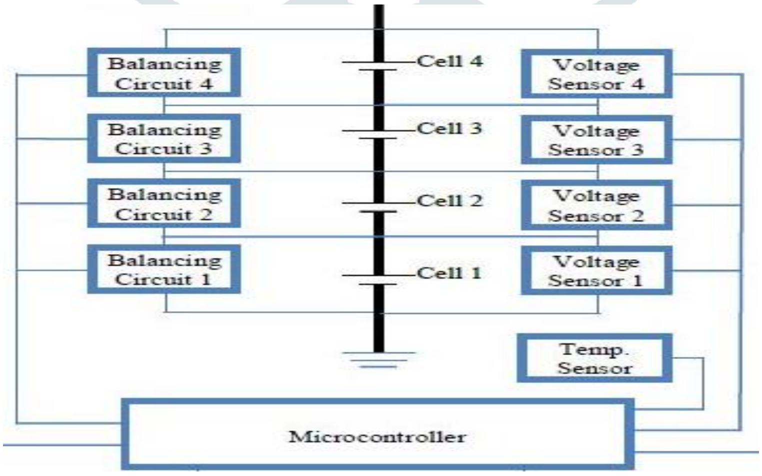

figure 2.4 bms architecture

2.2.1 CIRCUIT DESIGN

Fast switching operation gives precise balancing of cells so MOSFET is better choice for switching. The high-sided MOSFET cannot be controlled simply by applying the gate voltage (VGS) between 10V and 20V as suggested, but a suitable approach must be assigned to bring the MOSFET into operating mode. We used Bootstrap circuit here for MOSFET switching. The microcontroller controls the balance circuits of the four cells and the protection circuit, based on the proposed balancing algorithm. The balancing circuit for each cell is composed of MOSFET and discharge resistor is shown below in figure 2.5.

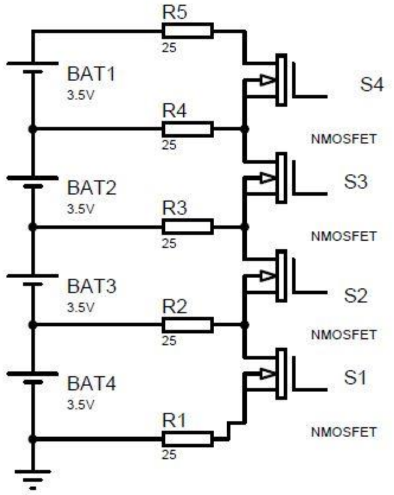

figure 2.5. mosfet with discharge resistor

A high side MOSFET driver circuit was designed and assembled to drive S1(M1) as shown in Figure 2.6. Similarly, driving S2-, S3, and S4 can duplicate the same circuit.

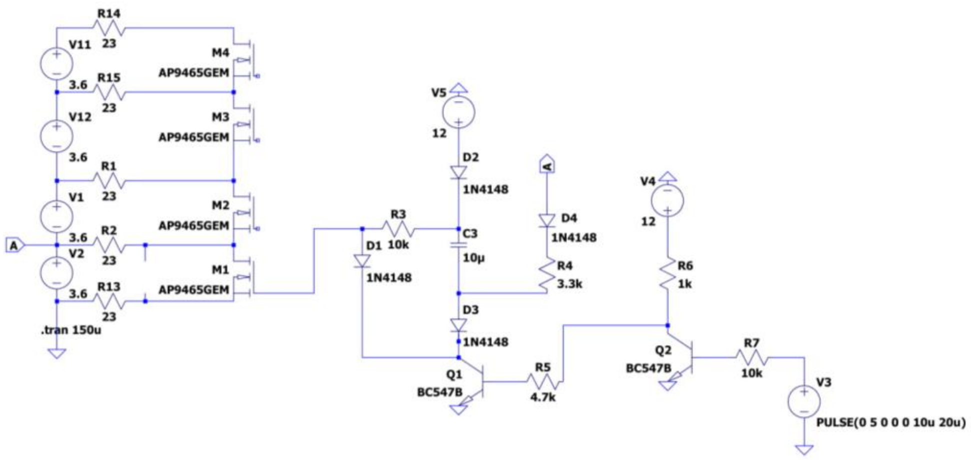

Figure 2.6. bootstrap circuit for high side mosfet driver

When the +5V input pulse is at low or zero volt, the transistor Q2 is turn-off, thereby turning on the transistor Q1. As Q1 is on, the +12V voltage will charge-up around the capacitor C3. On the other hand, the S1 gate terminal also connected directly to ground via Q1 and switched off S1(M1).Alternatively, because the input + 5V input pulse is high, Q2 is turned on, thus turning Q1 off. As Q1 is in off mode, a point A voltage supply appears at the Q1 collector through the D1 diode and add-up to the + 12V voltage previously stored across the capacitor C3. Therefore, the gate voltages with respect to ground would be greater than 12V, thus triggers S1(M1). As S1 activates resistor R2 and R13 beomes in series and linked across cell1 and discharge it. Again all cell voltages are tested, if any mismatch is found, i.e. the overloaded cell will discharge the cell's next lowest voltage in the battery pack before its voltage is equal to. This balancing process continues until all the voltages in the cells are at the same level.
The complete balancing circuit for all four cell is shown in below figure 2.7.

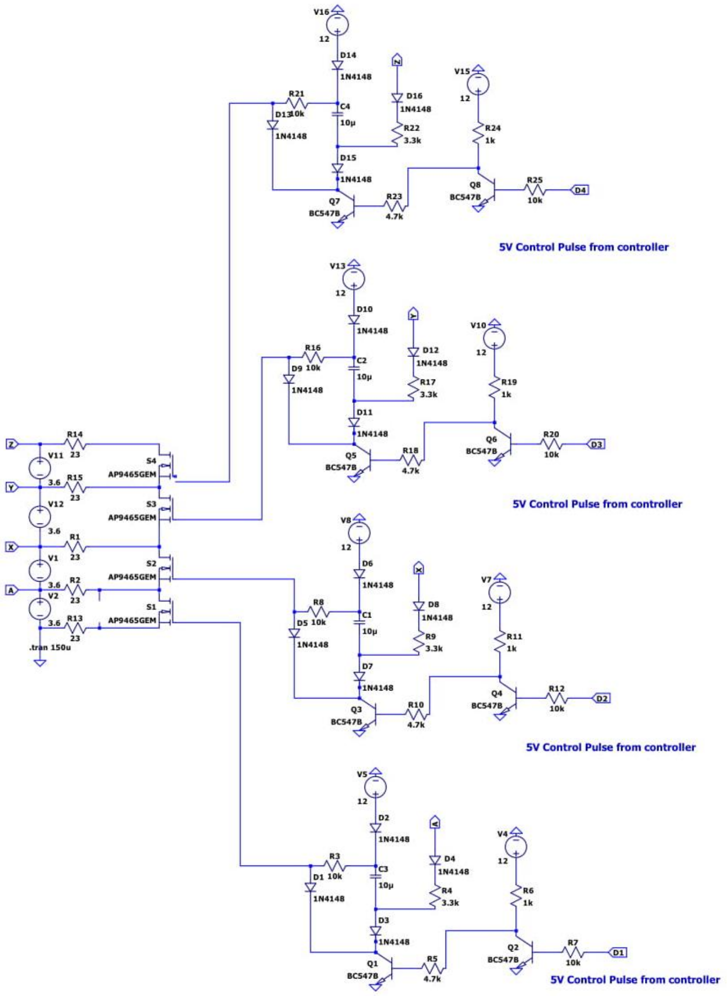

figure 2.7 schematic of cell balancing circuit

The above circuit shows four cells which are connected by a switch like MOSFET to two bypass resistors each. For the cell whose voltage is higher than the other cells, the Controllers tests the voltages of all four cells and switches on the mosfet. When you turn on the mosfet on that particular cell, it starts to discharge through the resistors. Because we know the resistor value we can predict how much charge the cell is dissipating. During switching, the capacitors can be connected in parallel with the cell to filter the voltage spikes.

2.2.2 BALANCING CURRENT CALCULATION

The balance circuit is used to calculate the passive balancing current. The dissipation resistor is limited by the maximum voltage and current allowed, and its value is 23 ohms. The current for balance (Ib) is calculated as equation (1).

$$Ib = \frac{V}{Req} \text{ Amp}\ldots\ldots\ldots\ldots\ldots(1)$$

Where V denotes the voltage of the cell, R1=R2=R3=R4=R5 are dissipative resistors (in figure 2.5).When S1 ON Req=R1+R2, similarly when S2 ON Req=R2+R3 etc. Higher the dissipation resistor value lower the balancing current but increases the balancing time, which should be less for higher balancing current balancing time.

III. SOFTWARE IMPLEMENTATION

The software component consists of the code loaded onto the microcontroller. The key steps of the balancing algorithm are:

- The parameters of the battery pack are calculated and displayed on an LCD: voltages per cell, voltage of the pack, current of the pack and temperature of the pack. To improve the accuracy of the measurements, an average of over 100 samples is applied, the voltages shown are 1 mV accurate and the current is 10 mA accurate;
- Based on the current signal, the algorithm checks whether the battery pack is charging or discharging and activates the balancing cells or not.
- If the battery pack is charging and the difference between the cell voltages reaches a certain threshold, known as the balancing voltage which is set to 25 mV, the balancing circuits for the most charged cells are triggered. If the voltage of a cell is greater than 4.20 V or the pack temperature is greater than 47˚C, then the safety relay is triggered and the charging cycle is interrupted
- If the battery pack is discharging and the voltage of a cell is smaller than 2.70 V, then the protection relay is activated and the discharging process is interrupted.

IV. SIMULATION RESULTS

Figure 4.1 shows simulation result of voltage monitoring circuit. We can directly connect 1st cell to the controller because voltage range of it is below 5V,which can handle easily by the controller. Op-amp U1:B calculates the 2nd cell voltage by measuring the difference between the 2nd cell terminal and the 1st cell terminal (7.113-3.5333) which is 3.5805 shown at the output of op-amp U1:B (D2K).Similarly individual voltages are measured for op-amp U1:C and U1:D. Input terminal x at pin 4 represents input supply to the op-amp.

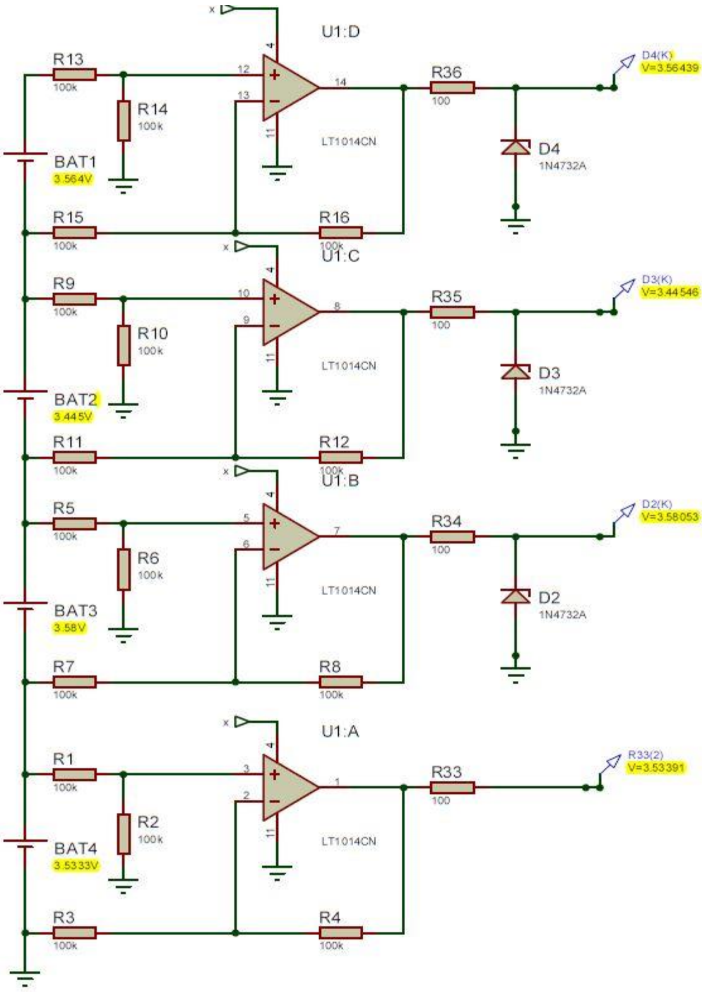

Figure 4.1. simulation of voltage monitoring circuit

Following figures shows simulation results of switching of individual MOSFET from the balancing circuit.

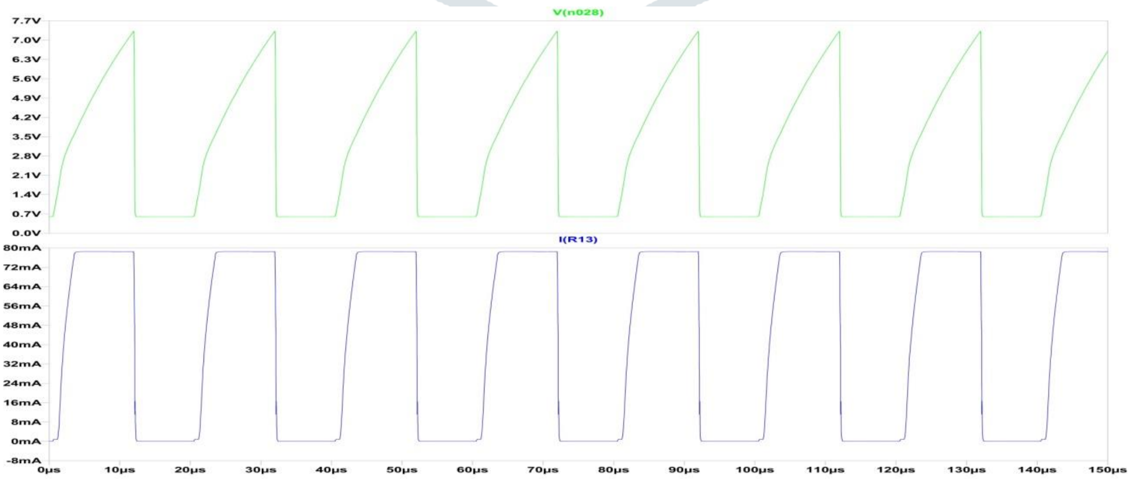

figure 4.2 waveform of mosfet(S1) switching

Once the system detects the overloaded cell in the battery pack , balancing circuit of that particular cell is triggered to match the voltage level at the lowest cell of the battery. When we turn on the mosfet on that particular cell, it starts to discharge through the resistors which is connected across the cell. Figure 4.2 shows the waveform of gate to source(Vgs) of mosfet S1 and Balancing current through R13 when balancing circuit of cell1 is triggered. When S1 is ON, resistor R13 and R2 become in series having value of 23ohm of each connected across the cell1(3.6V). Now the balancing current at the instant is calculated from equation(1) as,

$Ib = \frac{V}{Req}$ Amp

Here: V = 3.6 v;

Req = R2 + R13

= 23 + 23

=46 ohm

$Ib = \frac{3.6}{46}$ =0.078A

Hence the S1 is ON for the period of 10us, balancing current of 78mA is flowing through R13 which is shown in figure 4.2 for the period of 10us.

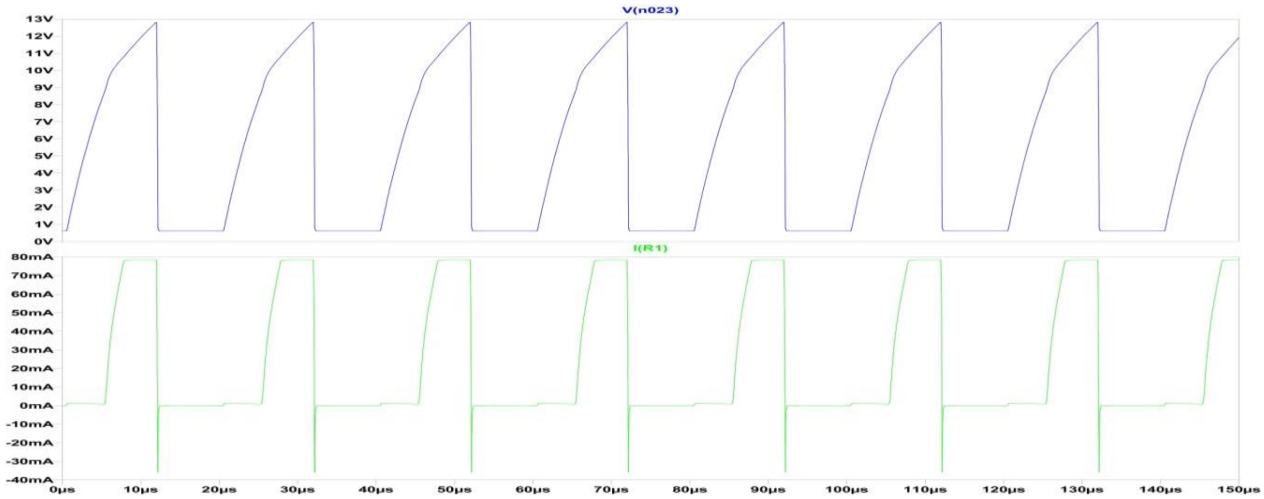

figure 4.3 waveform of mosfet(S3) switching

For simulation purpose we select the voltages of four cell is at same level(i.e 3.6V) and the value of Rdischarge is also same, so the balancing current should be equal in all four cases of switching i.e 78mA. Similarly figure 4.3, figure 4.4 and figure 4.5 shows the output result during S3 and S4 triggering respectively.

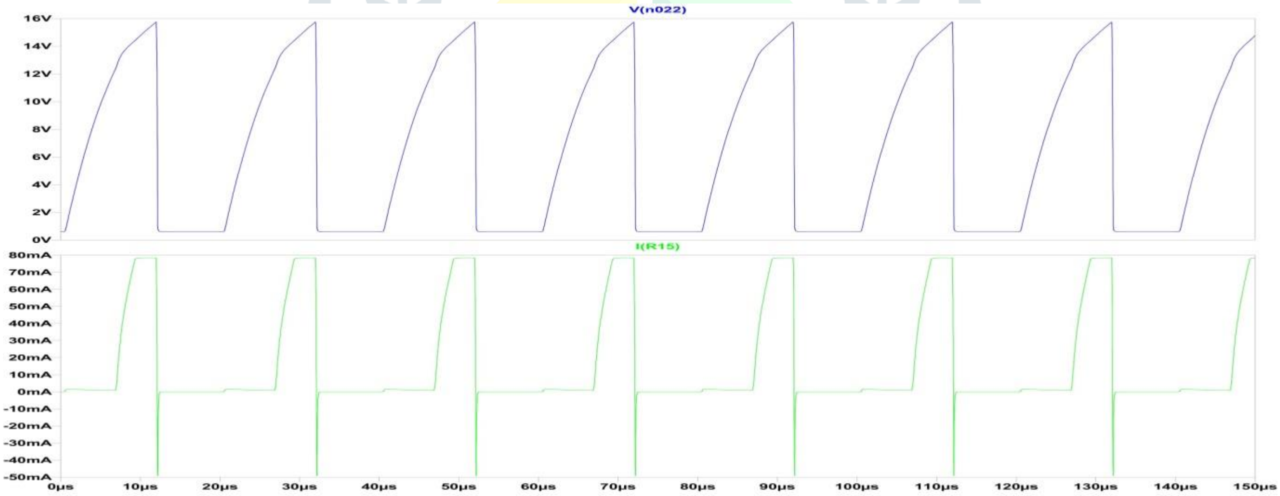

figure 4.4 waveform of mosfet(S4) switching

V. CONCLUSION

For a fast balancing of four Li-ion serially connected cells, the passive balancing system proposed in this paper contains discharge resistors and power MOSFET as the key components for dissipating the surplus energy. Also, the system was designed to implement and analyse the performances of different cells balancing algorithms and estimation techniques for SOC, SOH, RUL, etc. Although the passive balancing technique is not effective, this simplicity and low cost make it more widely used. We can also use few readily available IC's such as LTC6804 and BQ77PL900 from renowned manufacturers such as Linear and Texas instruments, instead of designing the hardware. These ICs can be cascaded to track multiple cells and save time and cost of growth.

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