Design and Simulation of The Multistage Constant-Current Charging System with Passive Balancing BMS for Lithium-Ion Batteries

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***Abstract*—Energy storage systems have been widely used in the electric vehicle and renewable energy systems. Lithium-Ion batteries are one type of widely used energy storage system. Lithium-Ion batteries are sensitive to over current, temperature, and voltage. An appropriate method in charging Lithium-Ion batteries is needed to ensure optimal battery performance and long battery life. The Multistage Constant-Current Charging System with Passive Balance BMS for Lithium-Ion batteries is expected to be a solution for charging Lithium-Ion batteries fast but still under the characteristics of Lithium-Ion batteries. Multi Stage Constant Current Charging with Passive Balance BMS for Lithium-Ion batteries utilizes a boost converter circuit in the charging process and maintains current values as needed. Besides, it also uses the Switching Shunt Resistor method in the BMS passive balance process.**

Keywords—Battery, Charging, Passive Balance, MSCC, Switching Shunt Resistor, Boost Converter

I. INTRODUCTION

Energy storage systems are starting to be widely used in electric vehicles and renewable energy systems. The potential use of energy storage systems is getting bigger with the plan to increase the use of renewable energy systems in Indonesia. In the Business Plan for the Provision of Electricity (RUPTL) 2021-2030, the portion of NRE power plants is increased to 51.6%, larger than fossil generators at 48.4% [1]. In addition, the electric vehicle sector is also experiencing rapid development. Based on the General National Energy Plan (RUEN), in 2025, the government will support the development of 2,200 units of four-wheeled electric vehicles and 2.1 million units of two-wheeled vehicles, and develop 1000 units of public electric charging station systems (SPLU) constructions [2]. The development of energy storage systems in Indonesia will be more advanced with these opportunities and potentials. The existing energy storage system must adapt to the needs of each of these sectors. The energy storage system must assist and improve the performance of electric vehicles and renewable energy systems, one of which is by having an efficient ability to store and redistribute the stored energy as needed.

The Lithium-Ion batteries are energy storage systems widely used in electric vehicle and renewable energy systems, especially solar power plants on a small scale. Lithium-Ion batteries have several advantages, including Lithium-Ion batteries having lower self-discharge rates, higher cell operating voltages, higher energy and power density, longer life/charge-discharge cycles, and are suitable for fast charging [3].

The Lithium-Ion batteries are sensitive to the presence of excessive voltage, current, and temperature. These factors can cause a decrease in battery performance and battery life. On the other hand, the electric vehicle sector and renewable energy systems work quickly and efficiently, thus requiring an efficient charging system. The current fast charging method is not compatible with the characteristics of Lithium-Ion batteries because it utilizes high currents to speed up the charging process.

Research on the charging and balancing system of Lithium-ion batteries has been carried out by several researchers. Muhammad Adam Alkhadir [4], in his research "Design of a Battery Management System From Solar Panel Sources Using the 4-Stage Charging Method" obtained simulation results that the charging system with the 4-stage charging method is faster in terms of charging time with a battery capacity of 97 ,58% while the conventional method only reaches a capacity of 93.94% with the same charging time. Furthermore, there is a study conducted by Khan Abdul Basit [5] entitled "Optimal Charge Pattern for the High Performance Multi-Stage Constant Current Charge Method for the Li-Ion Batteries" showing that the CC-CV method is widely used in the process charging lithium ion batteries is not suitable for the fast charging process. In this study, researchers used the MSCCC method and succeeded in increasing the value of Charging Efficiency (CE) and reducing Charging Time (CT). However, both studies only focused on the charging process without paying attention to the balancing and protection process for lithium ion batteries.

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Based on these problems, it needs a charging method that can accommodate the electric vehicle sector and renewable energy systems but still under the characteristics of Lithium-Ion batteries so that the battery can still work with optimal performance and long battery life. Therefore, a charging system was designed using the Multi-Stage Constant Current method combined with a BMS passive balance system.

II. LITERATURE REVIEW

A. Proteus Software

Proteus software is software for designing the electronic circuits [6]. Proteus software is equipped with features that can assist users in simulating and measuring experimental results, such as voltmeter, ammeter, oscilloscope, and other virtual features.

Proteus software is software produced by Labcenter Electronics that provides various types of components and microcontrollers for simulation [7].

B. Multi-Stage Constant Current Charging

The Multi-Stage Constant Current (MSCC) charging method is a charging the battery method by decreasing the current gradually when it reaches the cut-off voltage or limit voltage [8]. In the Multi-Step Constant Current charging method, the use of high current is carried out in a short time until it reaches the cut-off voltage or limit voltage so as not to damage the battery so that battery performance remains optimal and battery life is long.

The number of charging steps, the current value of each step, and the length of time for charging each step, affect the optimization of the performance of the Multi-Stage Constant Current (MSCC) method. The Multi-Stage Constant Current (MSCC) filling method is easy to apply and has a better charging speed performance than the CC-CV method [9].

The selection of the number of charging steps or the number of current levels affects the charging time and charging efficiency. In Multi-Stage Constant Current, the number of charging steps or the current level of more than 5 steps or level has a very small and even negligible effect on the value of charging time and charging efficiency [10].

Determination of the maximum current value at each step can be done by determining the current value of the first step and the last current value first. Determination of the maximum current level of the first and last stages based on the maximum current value allowed in the battery specifications and the expected battery charging capacity. Furthermore, the current value at the next level can be done through the following equation [5]:

$$I_3 = \sqrt{I_1 I_5} \tag{1}$$

$$I_2 = \sqrt{I_1 I_3} \tag{2}$$

$$I_4 = \sqrt{I_3 I_5} \tag{3}$$

Where:

I_1 = Current value in first step

I_2 = Current value in second step

I_3 = Current value in third step

I_4 = Current value in fourth step

I_5 = Current value in fifth step

C. Boost Converter

Boost Converter is one form of application of DC to DC converter which serves to increase the voltage [11].

In designing a boost converter, there are several influential variables, namely input voltage, desired output voltage, switching frequency, capacitor value, inductor value, and output current value. The equation used in determining the variables in the boost converter is:

$$V_{out} = V_{in} \frac{D}{1-D} \tag{4}$$

$$\mathrm{L} = \frac{(1-D)^2 R}{2f} \tag{5}$$

$$C_{min(boost)} = \frac{DV_0}{V_r R f} \tag{6}$$

D. Battery Management System

Battery Management System (BMS) has a key role to play in making battery usage safe, reliable, and cost-effective. The most important feature of BMS is cell balancing, which distributes energy evenly between battery cells [12].

In addition to functioning in cell balancing, the battery management system also plays a role in estimating the State of Charge (SoC), Depth of Discharge (DoD), State of Health (SoH), battery protection, and monitoring battery condition [13].

Cell balancing system affects battery performance life. Without a cell balancing system, the condition of the cells in the battery pack becomes unbalanced, this will affect the performance of the battery pack, such as a rapid reduction in battery capacity when discharging, the charging process cannot reach its maximum capacity, and shorten the working life of the battery [14].

E. Passive Balance

In general, there are two cell balancing methods that are widely used in battery management systems, namely passive and active balance.

The passive balance method is a balancing battery cells method by transferring excessive energy to the cells that have the most SOC using passive electronic components. The passive balance method works by utilizing an energy dissipation system [15].

In the passive balance method, there are two balancing techniques that are widely used, namely Fixed Shunt Resistors and Switching Shunt Resistors. Fixed Shunt Resistor technique is a cell balancing technique by installing resistors in parallel by adjusting the required balancing current value, while the Shunt Resistor Switching technique is a cell balancing technique by utilizing a semiconductor switch connected to a controller which functions to perform switching if there is an unbalanced cell [16].

III. METHODOLOGY

The Multistage Constant-Current Charging system with Passive Balance BMS is divided into two main parts, namely the charging system using the MSCC method with a boost converter circuit and the BMS passive balance system using a shunt resistor switching technique.

The MSCC charging system with a boost converter consists of a current sensor, a voltage sensor, and a boost converter circuit with an Arduino Uno microcontroller, while the BMS passive balance system consists of a current sensor, a voltage sensor, and a passive balance circuit, with an Arduino Nano Microcontroller.

A. *Research Block Diagram*

The block diagram of the Multi-Stage Constant Current system with Passive Balance BMS is as follows:

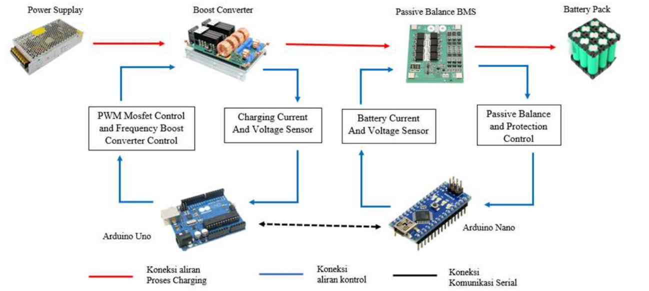

Fig. 1. Research Blok Diagram

In the block diagram above, the flow of the charging system starts from the power supply which then goes to the boost converter circuit. The boost converter circuit is regulated by the Arduino Uno based on the current and voltage sensor indicators for the charging circuit and the battery voltage from the passive balance circuit. Furthermore, the output of the MSCC process will go through a passive balance process on the BMS so that the battery pack charging process becomes more balanced and there is no imbalance between cells. The passive balancing process is regulated by the Arduino nano microcontroller by considering the current sensor readings and battery voltage. Furthermore, there is serial communication between Arduino Uno and Arduino Nano to send data from the battery voltage sensor readings as an indicator in the Multi-Stage Constant Current Charging process.

B. *Flowchart of Multi-Stage Constant Current Charging*

The flow chart of the Multistage Constant-Current Charging system with a boost converter circuit is as follows:

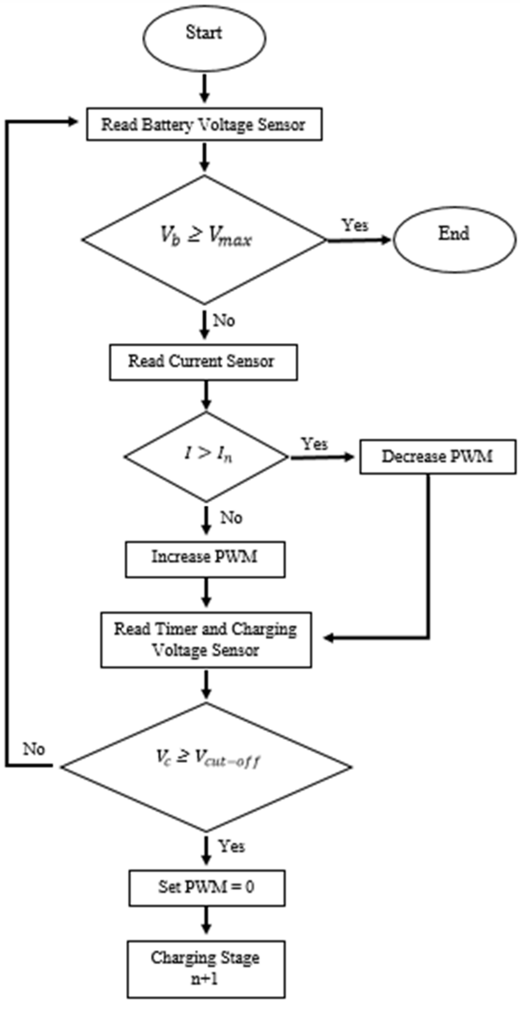

Fig. 2. MSCC Flowchart

The Multi-Stage Constant Current system begins by reading the battery capacity voltage condition. If the battery capacity is not full or reaches the maximum voltage limit, the charging process begins by reading the current. The current value is maintained at the current limit in the n step by adjusting the PWM pulse width on the switching MOSFET. If the current value is too large, the PWM pulse width is reduced and vice versa. Furthermore, the voltage sensor readings are carried out periodically based on the set timer, and when it reaches the cut-off voltage, the charging process is stopped. When the first step in the MSCC process has reached the cut-off voltage and the battery capacity is not full, the charging process will continue to the second step, and so on until it reaches the fifth step or the battery capacity is full.

C. *Passive Balance Flowchart*

The flow chart of the Passive Balance BMS system with the Switching Shunt Resistor technique is as follows:

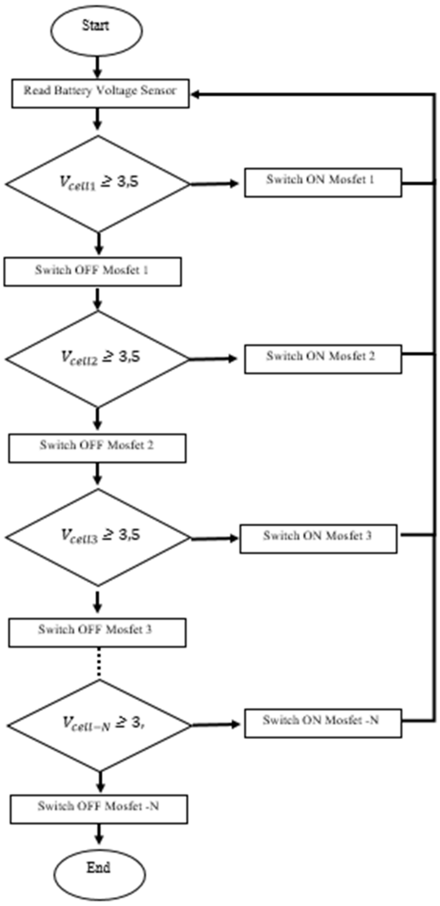

Fig. 3. Passive Balance Bms Flowchart

BMS passive balance system using the Shunt Resistor Switching technique is carried out sequentially from the first cell of the battery. If the voltage in the first cell of the battery exceeds the maximum voltage limit that has been determined, then the passive balance 1 MOSFET will be active, and the passive balance process will be carried out in cell 1. Next, the voltage reading is repeated periodically until the voltage in the first cell is under the voltage limit. If the first cell matches, it proceeds to the second cell and until the n cell.

D. Boost Converter Circuit

The boost converter circuit designed for the Multistage Constant Current system is as follows:

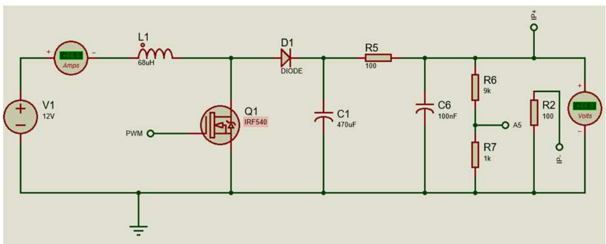

Fig. 4. Boost Converter Circuit

The boost converter circuit designed in Proteus software consists of a 12V power supply, 68 uH inductor, 470 uF capacitor, an R-C filter, Mosfet IRF540 and runs with a frequency of 62.5 kHz.

E. Mosfet Driver Circuit

The series of Mosfet drivers designed for the Multistage Constant Current system are as follows:

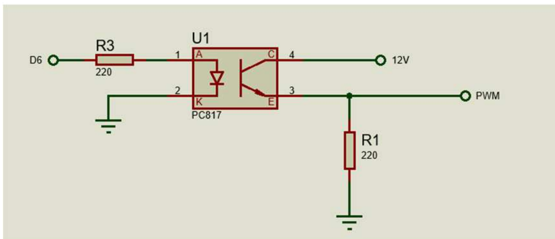

Fig. 5. Mosfet Driver Circuit

The series of Mosfet drivers designed in simulation with proteus software is to use optocoupler PC817. The PC817 optocoupler gets the anode input from the arduino uno digital pin and the cathode pin to ground. While on the collector side, it gets a 12V input voltage from the power supply which is then used as the IRF540 gate Mosfet input.

F. Voltage Sensor Circuit Charging

The series of charging voltage sensors designed for the Multistage Constant Current system are as follows:

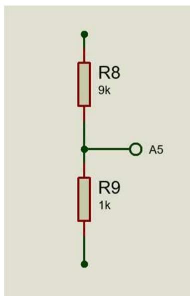

Fig. 6. Voltage Sensor Circuit

The voltage sensor circuit designed on the charging side uses a voltage divider circuit with a resistor value of 9 kΩ and 1 k. The voltage sensor with this voltage divider circuit can read a voltage of up to 50 V on the output side of the boost converter circuit.

G. Circuit of Charging Current Sensor and Battery

The series of charging current sensors and batteries designed for the Multistage Constant Current and Passive Balance BMS system are as follows:

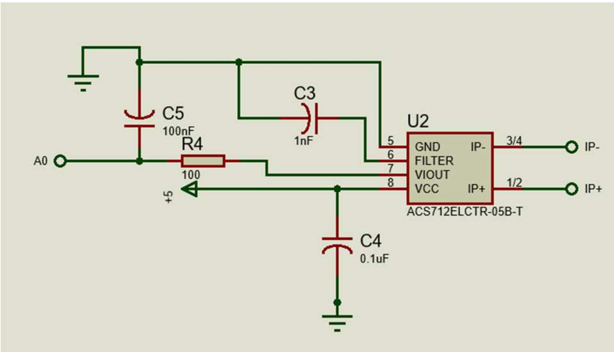

Fig. 7. Current Sensor Circuit

The current sensor circuit designed on the charging side or boost converter circuit and the passive balance side of the BMS is to use ACS712 05B-T which has the ability to read currents up to 5A. The current sensor is considered to be in accordance with the needs of the Multistage Constant-Current Charging system with Passive Balance BMS.

H. Battery Voltage Reading Circuit

The series of battery voltage sensors designed for the Passive Balance system are as follows:

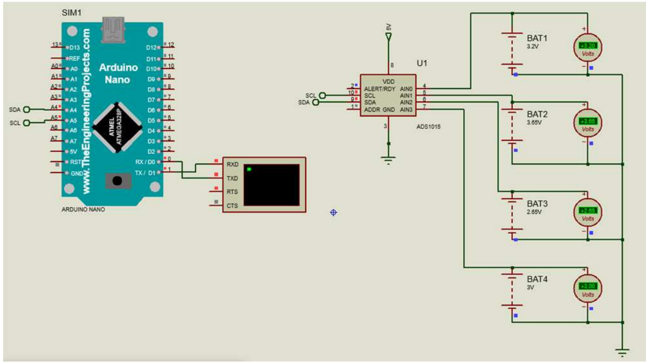

Fig. 8. Voltage Reader Circuit

The series of battery voltage readings on the passive balance BMS which is designed in a simulation using Proteus software is to use the ADS1015 IC. The simulation of voltage and current readings is carried out by referring to the method used by the battery monitoring IC using the ADC (Analog to Digital Converter) method.

I. Passive Balance Circuit

The BMS passive balance circuit designed is as follows:

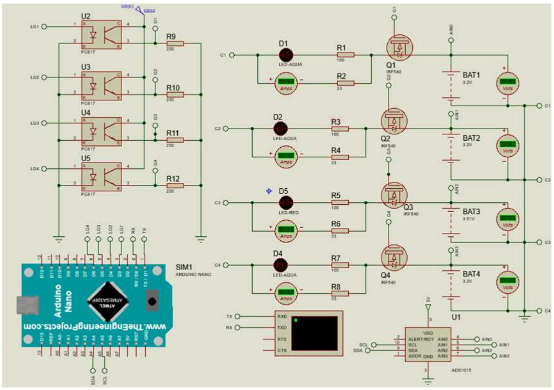

Fig. 9. Passive Balance Circuit

BMS passive balance circuit designed in simulation using Proteus software using the Switching Shunt Resistor method. In the simulated circuit there is an IRF540 mosfet as a semiconductor switch that functions to perform switching when there is one cell that has a voltage above the maximum limit, which is 3.5 V. When there is one battery cell that has a voltage above 3.5 V and it reads by the voltage sensor, the mosfet will get a trigger so that it becomes close and will channel excessive voltage from the battery cell to the resistor which is marked by the LED light.

IV. Result and Analysis

A. Boost Converter Circuit

The specifications for the boost converter circuit designed in the simulation using Proteus shown in the table 1.

TABLE I. Boost Conveter Specification

Input	12 V
Frecuency	62,5 kHz
Inductor	68 uH
Capacitor	470 uF

The simulation was done by varying the value of the PWM pulse width which affected the duty cycle value. By changing the value of the duty cycle, it would affect the output value of the boost converter circuit.

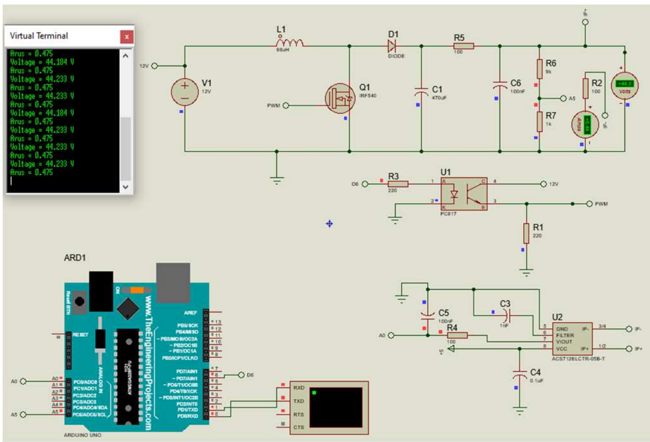

Fig. 10. Boost Converter Simulation

The simulation results of the boost converter circuit are as follows:

TABLE II. BOOST CONVERTER OUTPUT TEST RESULT

Input	PWM	Duty Cycle	Output
12 V	25	10 %	10, 1 V
	51	20 %	13,5 V
	77	30%	16,2 V
	102	40%	18,9 V
	128	50%	21,6 V
	153	60%	28,7 V
	158	62%	31,7 V
	166	65%	37,5 V
	173	68%	44,2 V
	179	70%	49,5 V
	205	80%	49,7 V
	230	90%	40,1 V
	255	100%	5,59 V

From the results above, it can be seen that the output voltage value of the boost converter circuit changes according to the change in the value of the duty cycle and the value of the PWM pulse width. Based on these results, the appropriate duty cycle value used for the Multi-Step Constant Current Charging circuit for 12 series cells and 1 parallel Lithium-Ion battery is 62% for the lower limit of the voltage and 68% for the upper limit of the battery charging voltage.

B. Voltage Sensor Circuit and Charging Current Sensor

Testing the voltage sensor and current sensor in the boost converter circuit was carried out by comparing the values read on the virtual ammeter and voltmeter in the Proteus software with the values displayed on the virtual monitor as a result of sensor calculations using the Arduino Uno microcontroller. The test was carried out simultaneously with testing the output voltage of the boost converter circuit. The results of testing the accuracy of the voltage sensor and current sensor are as follows:

TABLE III. CURRENT SENSOR AND VOLTAGE SENSOR TEST RESULTS

Voltage in Voltmeter	Sensor Read Voltage	Current in Probe	Sensor Read Current ACS712
44,2 V	44,233 V	0,4417 A	0,475 A
Voltage Error	0,033 V	Current Error	0,0333 A
Accuracy	92,5%	Accuracy	92,5%

From the results of the sensor accuracy test, it is known that there are error values for reading voltage and current. In the voltage reading, there is an error of 0.033 V, while in the current reading, there is an error of 0.033 A. The error value comes from the researchers' lack of accuracy when calibrating the voltage and current sensor.

C. Battery Voltage Sensor Circuit

The series of battery voltage readings in the simulation using Proteus software used IC ADS1015. The simulation was done by varying the voltage value on four batteries which will be read by the IC ADS1015 as shown in the following figure:

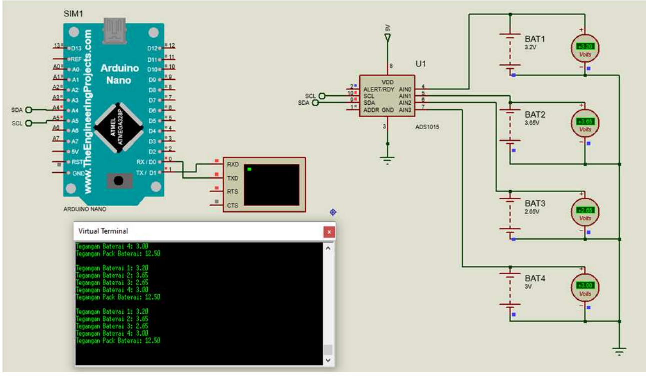

Fig. 11. Voltage Reading Simulation

The results of testing the battery voltage readings using the IC ADS1015 are:

TABLE IV. VOLTAGE READING TEST RESULT

Sequence	Voltmeter	ADS1015
Battery 1	3,2 V	3,2 V
Battery 2	3,65 V	3,65 V
Battery 3	2,65 V	2,65 V
Battery 4	3 V	3 V

The test results above show that the voltage reading using the IC ADS1015 which utilizes the ADC method is appropriate. All values read on the voltmeter on the 4 batteries are under the readings using the IC ADS1015.

D. Passive Balance Circuit

Testing the passive balance circuit in the simulation using Proteus software was done by changing the value of one of the battery voltages to be above the maximum voltage of 3.5V. It aimed to determine the accuracy of the voltage reading using the IC ADS1015 and the response of the IRF540 MOSFET and MOSFET drivers to excess voltage in one of the battery cells.

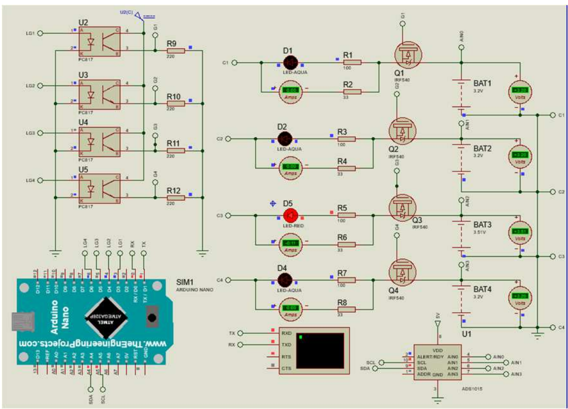

Fig. 12. Passive Balance Bms Simulation

The simulation was carried out by changing the third battery voltage value to 3.51 V. The results showed that the passive balance process was done well. The IRF540 MOSFET in cell 3 has reacted well so that it managed to channel excess energy in cell 3 battery to the marked resistor with the LED light on.

V. Conclusion

The Multi Step Constant Current Charging system with Passive Balance BMS for Lithium-Ion batteries consisted of 2 main parts, namely the charging system using the MSCC method with a boost converter circuit and the BMS passive balancing system using the Switch Shunt Resistor method. In the simulation that has been carried out using the Proteus software, it can be seen that the boost converter system has been designed properly. The output voltage value would change according to the value changes of the duty cycle and PWM pulse width. For reading the current and voltage values in the boost converter system, there was an error value of 0.33 V on the voltage reading and 0.333 A on the current reading. These happens because the researchers was not careful in calibrating the sensors used. The reading of the voltage value on the battery using the IC ADS1015 has succeeded in reading the battery voltage which was varied according to the value read by the voltmeter with 100% accuracy. The passive balance system using a Shunt Resistor Switch has been running well, which was indicated by the LED on the battery that is experiencing excessive voltage.

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