Active Cell Balancing Implementation to Lithium Polymer Battery based on Pulse Width Modulation (PWM) Output Control

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Abdul Jalil

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PREFACE

I would like to thank to Allah Subhanahu wa Ta'ala Who has given to the author His Mercy and Blessing to complete this thesis with the title "*Active Cell Balancing Implementation on Lithium Polymer Battery based on Pulse Width Modulation (PWM) Output Control*." This thesis completed to fulfill one of the requirements to get Master of Engineering (M.Eng.) degree on Post Graduate Program at Electrical Engineering, Engineering Faculty Universitas Gadjah Mada.

During the research and arrangement of the thesis report, the author has a lot of supports and helps from a lot of parties. Therefore, the author said thanks a lot for:

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The author realizes that this thesis is still far from perfection. Therefore, every recommendation and constructive feedback is desirable. In the end, hopefully this thesis gives an additional insight for the readers and especially for the author.

Yogyakarta, 5th April 2017

Abdul Jalil

SYMBOLS AND ABBREVIATIONS LIST

4s	= *4 Cells in Series-Connected.*
ADC	= *Analog to Digital Converter.*
Ah	= *Ampere hour.*
ANOVA	= *Analysis of Variance.*
BG	= *Between Groups.*
BMS	= *Battery Management System.*
C	= Capacitor.
CC	= *Constant Current.*
Cn	= *Capacity of the Battery*
COPD	= *Chronic Obstructive Pulmonary Disease.*
CV	= *Constant Voltage.*
D	= *Duty Cycle.*
DC	= *Direct Current.*
$\frac{dv}{dt}$	= *The Instantaneous Range of Voltage Change Over Time.*
EV	= *Electrical Vehicle.*
FLC	= *Fuzzy Logic Controller.*
I2C	= *Intra-Board Communication.*
L	= *Inductor.*
LiPo	= *Lithium Polymer.*
OCV	= *Open Circuit Voltage.*
PWM	= *Pulse Width Modulation.*
R	= *Resistance.*
SOC	= *State of Charge.*
SOH	= *State of Health.*

Toff = *Duty Cycle at Low State.*

Ton = *Duty Cycle at High State.*

.Tsw = *Switching frequency.*

VR = *Resistance Voltage*.

VC = *Capacitor Voltage.*

VT = *Terminal Voltage of the Cells.*

VG = *Gate Voltage.*

WG = *Within Groups.*

ABSTRACT

Battery as an energy storage has a number of unique characteristics in its operation. For more extensive applications, the battery needs to be configured in a series-connected to fulfill the power requirements. In the operations, some factors could lead it to operate in lower efficiency and capacity, shorter lifetime and high risk of catching fire during charging and discharging process. Battery Management System (BMS) collects and handles all of these issues using cell balancing technique to keep it safe, higher performance in the operations, easier to maintain and longer lifetime in usage.

In this paper, Pulse Width Modulation (PWM) Controlled Converter using Fuzzy Logic Controller to balance the cell capacity was proposed. The aim to use this method is to transfer energy among the cells and to reduce the loss of power during the balancing operation. By using five membership functions on the design of fuzzy logic input and output, it could make the computation quite fast.

By using absolute error of State of Charge (SOC) between two adjacent cells is 0.05% SoC, the charging process can be reached the target SoC charging at 85% and 95% SoC in balancing state.

Keywords— BMS; Cell Balancing; PWM; Fuzzy Logic; SOC

INTISARI

Batterai sebagai sumber energi dan penyimpanan energi memiliki karakteristik-karekteristik yang unik. Hal ini menjadikan baterai membutuhkan perlakuan yang khusus dalam pengoperasiannya. Dalam aplikasi yang luas, koneksi baterai secara seri dalam *baterai pack* diperlukan untuk memenuhi daya yang dibutuhkan oleh beban baterai. *Baterai Manajemen Sistem (BMS)* menghimpun permasalahan yang timbul pada pengoperasian baterai *pack* dan memberikan solusi sehingga dapat digunakan secara aman, dapat diobservasi, meningkatkan performa, mudah untuk perawatan dan dapat digunakan dalam jangka waktu yang lama.

Dalam tesis ini, *Pulse Width Modulation (PWM) Controlled Converter* dengan menggunakan algoritma *fuzzy logic* sebagai pengontrol untuk menyeimbangkan kapasitas antar sel baterai digunakan dalam penyelesaian permasalahan yang ada. Tujuan menggunakan metode ini adalah untuk mentransfer kapasitas yang berlebih dari satu sel baterai ke sel yang lainnya untuk mengurangi kerugian daya selama proses penyeimbangan kapasitas antar sel. Dengan menggunakan lima fungsi keanggotaan pada perancangan *Fuzzy Logic Controller,* waktu komputasi yang dibutuhkan untuk mendapatkan PWM keluaran cukup cepat.

Dengan menggunakan eror *State of Charge(SoC)* absolut antara dua cell yang berdekatan sebesar 0.05% SoC, proses pengecasan baterai dapat mencapai target pengecasan pada 85% SoC dan 95% SoC dalam keadaan seimbang.

Kata Kunci— BMS; PWM Controlled Converter; Fuzzy Logic, SoC

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CHAPTER I

1 INTRODUCTION

1.1 Motivations

Energy is very important for our lives. Without the energy, the people would have difficulty continuing their lives. Today, global consumption of energy focused on fossil fuels. Kind of fossil fuels used today by people in almost every country are oil, coal, and natural oil. By consuming it every day will make those things decreases. These conditions invite the researchers to study about renewable energy to find the solution of the problems[1].

Now a day, the battery is a widely technology used to store electrical energy and became an answer to the problems. It because the battery as one of renewable energy technology is very easy to convert to another kind of energy such as kinetic, heat, light, and etc. And because of those roles, the battery is applied to wide range of energy applications.

One of the battery applications is electric vehicles (EV's). The energy stored in the rechargeable battery to supply the power to the EV. In this case the motor controller of EV's is exactly replaced the role of internal combustion engine. It means can be a solution of fossil fuel energy crisis and the impact.

Lithium-Polymer battery with high lithium content and less weight made it one of the candidates to the EV's application[2]. By serial connection of several cell, Lithium-Ion battery would be produced the power which suitable for the applications. Otherwise, portable equipment such EV necessary a number battery cell in serial connection to fulfill its power consumption. Example of this case, figure 1 shows a series battery connection with 4 cells battery (4s), to supply 16-volt power to the load,

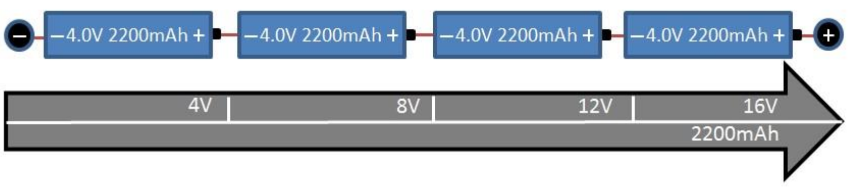


Figure 1.1. Battery in series connection to fulfill the load power.

Otherwise, unbalance battery cells is a challenge when it is connected to the loads. When each cell in a battery pack during charging and discharging process, the capacity of every cell become different one each other. Figure 2 shows a series battery connection 4s, in unbalanced state.

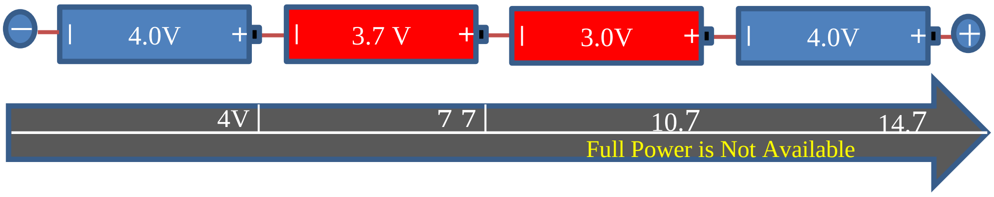


Figure 1.2. Unbalanced cell capacities in battery pack

In the condition, the cell of weakest capacity is a weak point. The cells can be easily overcharged and over-discharged. The higher capacity can be easily overcharged in charging process and the small capacity can be easily over-discharged when discharging process. It because the batteries including Lithium-Polymer battery has State of Charge (SOC) range value to keep it safe in charging and discharging process. Therefore, the battery characteristic has been written in every datasheet of the battery products.

The challenge can be solved by battery balancing technology. Balancer technology should protect the weakest cell and greatest cell capacity. The cell must be rise up equal when charging and must be down together in an equal state when discharging. The advantages using this technique are: safety, long lasting, easy to maintenance, the capacity can be observed and controlled. All of these activities collected in Battery Management System (BMS).

BMS has several important units to observed, they are current, voltage, SOC and SOH. SOC is the present capacity of the battery compared to the ideal state [3][4]. SOH drew as the condition of the present battery compared to the ideal condition[5]. Cell balancing is the condition of each cell which in series connected in a battery pack and has an equal capacity state when charging and discharging [5].

There are three the most used method has been existed in balancing battery capacity. They are battery selection, passive cell balancing and active cell balancing[6]. In this thesis, an Active Cell Balancing method has been provided. The main difference on passive cell balancing and active cell balancing lies on the balancing technique. When charging process, passive cell balancing heating the external resistor to release several its capacity when the capacity higher than the average SOC[7]. The process causes the overcapacity decreases to the average SOC and the smaller capacity from the average capacity continues to fill by the current and the capacity rise until equal to the average SOC in the battery pack. Active Cell Balancing equalizing of each cell by *transferring* the capacity from the higher cell to the lower cell until equal. Therefore, equalization the capacity of each cell in a pack by active cell balancing method will make the optimization in the application.

A lot of methods is existed in active cell balancing [6], but in this thesis more specific focused on a cell to cell Pulse Width Modulation (PWM) controlled converter as the method. Buck-Boost converter basic principal is used to do the equalization of the battery in a pack.

1.2 Problem Statement

Active cell balancing will be used to equalize of each cell. PWM controlled converter used to control the magnitude of the current that will release to the weakest. So the work of the system can be more efficient. But during the balancing process, the MOSFET will get heat, and several components must be ensured in good and safe performance.

1.3 Contribution

Before, in research group “Battery Management System” under Instrumentation and Control Laboratory Universitas Gadjah Mada has been done a research using passive balancing method by Erika Loniza[7]. We will use the result as a comparison using active cell balancing method. Boby Rian Dewangga has been provided the *Rint* model for battery modeling. Bhisma Adjie P. also used the same battery modeling to estimate SoH in his research[8]. We will use the model battery to estimate the Open Circuit Voltage (OCV) and SoC during balancing process[9].

The active cell balancing method refers to the journal that written by Javier Gallardo-Lozano entitled “*Battery equalization active methods*[6]*”* In the journal, there are many active balancing methods but especially to PWM controlled Converter, the writer said, “This method is good for high power application, but its control complexity.” The optimized topology overview of a cell to cell active cell balancing has been done by Tanh Hai Phung, Alexandre Collet and Jean Christope Crebier. The topology circuits produced nice graphics result, but the circuit is getting more complex[10]. However, the development technology in the embedded system by the time, help us to do improvement of the control algorithms. So, we will try to realize the method using Raspberry Pi3 model B+ to generate the PWM signal in KHZ level frequency and design the balancing circuit using 4s Lithium-Polymer battery using Fuzzy Logic Controller (FLC) to see the performance.

PWM control method also has been applied by K. Nishijima on his research. The result is the system can be equalized the battery in third minutes either discharging or charging process[11]. While in this study, using more simple circuit than K. Nishijima’s circuit, we use Raspberry Pi3 as the controller board.

Table 2.1 shows PWM controlled Converter which was featured by Javier Galardo-Lazano and K.Nijishima. In this study is using balancing technique and the fuzzy logic controller as the controller method.

1.4 Purpose of Study

The purpose of the research is to develop active balancing system using cell to cell pwm controlled converter in the best performance of the system development.

1.5 Benefits

We expect that the research can be produced some advantages, some of them are:

a) active cell balancing can be establish in charging process, reduce the charging term, and saving some energy in balancing term,

b) increase life time of battery pack,

c) increase performance of the battery, and

d) provide 4 cells active cell balancing prototype.

1.6 Thesis Organisation

The contents of the thesis are the result of the experiments and analysis according to the active balancing method using PWM controlled converter. To provide a good overview of the research report, the writing sections divided into certain sections:

1) **Chapter I: Introduction.**

This chapter explains about background research, the formulation of the research problems, the originality of the research, the purpose, and the advantages of the research.

2) **Chapter 2: The Literature Review and Theoretical Basis.**

The Literature Review explained about some studies related to active cell balancing research, the basics theory of battery modeling, buck-boost converter, and PWM controlled converter. Also some studies about fuzzy logic.

3) **Chapter 3: Methodology.**

In this chapter has been written the flow of the research, design of the system according to the active balancing method. Then we explain the analytical steps according to the results of the experiments.

4) **Chapter 4: Result and Analysis.**

Chapter 4 is the summary of all the results of the experiments

5) **Chapter 5: Conclusion and Recommendation.**

The conclusions of the experiments are written on this chapter. For the next studies several recommendations have been delivered for the better studies result.

CHAPTER II

2 Literature Review and Theoretical Framework

2.1 Literature Review

Renewable energy topics are coming in response to the researchers. The renewable energy topics are well known today because it is one of the fuel energy impact solutions. The pollution which comes from the combustion engine, power plan and a lot of industries always increases every day. The impact of pollution is occurring in public healthy and took the lives of many people. Impact on health, where the data of WHO in 2014 said that every year air pollution has relation to the death of 7 million people in the entire world[12]. In 2007, from the events that occur shows that relation between the increase of the air pollution with the deaths from a heart attack is 12% - 14% per 10 microg/m3[13]. In lung disease, air pollution causes *Chronic Obstructive Pulmonary Disease (COPD)* included *chronic bronchitis* and *emphysema*[14]. Not to mention another effect such as cancer[15] and the disease that occur in children[16]. The impact of air pollution also occurs in farming[17] and economic[18][19]. Therefore, the development technology in renewable energy and green living is needed in this era.

Electric Vehicles (EV’s) comes forward to face the detrimental effect of air pollution. Because one of the biggest contributions of air pollution is motor vehicle[20][21]. EV’s that using electric power to drive the vehicles can be reduced air pollution and at the same time also can be reduced the cost compared to combustion engine as much 20%[22].

In the EV’s development, the battery is an important part. In another hand, a battery has a unique characteristic. Therefore, in the battery study seems a lot of topics to be researched. One of the important topics is *Cell Balancing.* In the cell balancing also consists of several methods such as Battery Selection, Passive Balancing, and Active Balancing. Based on the flow of the energy, active cell balancing parted to five methods: *Cell Bypass, Cell to Cell, Cell to Pack, Pack to Cell, and Cell to Pack to Cell.* In Cell bypass, current on every cell will bypass when the capacity of the cell reach to the top of the limit. Cell to cell method is transferring energy from higher capacity to the lower capacity in one pack. Cell to pack method is transferring energy from higher cell capacity in a pack to the other battery pack. Pack to cell method is active cell balancing that can transfer energy from pack to the determine cell in other pack. The last method is cell to pack to cell, in this method transferring energy comes from cell battery to another pack, and the pack will transfer the energy to the its cell which has a small capacity.

This thesis using Cell to Cell method, where the capacity of each battery cells would be equalized by PWM controlled converter method. Figure 2 below, shows about active cell balancing methods,

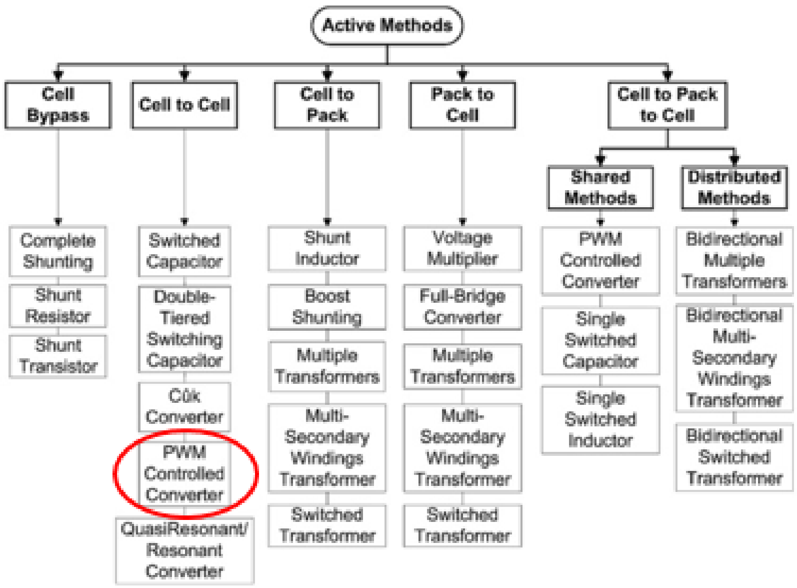


Figure 2.1. Active cell balancing methods.

As the main foundation to do this research, some of the literature were reviewed before continued the research. Literature review was explained in point 1.3 above, are the strength support to finished this study and the summary of explanations are in Table 2.1 below,

Table 2.1. Summary of literatures review.

No	Title	Explanation	Result
1	*Battery equalization active methods*	• Explain all of the active balancing methods	• The battery equalization methods are available and the

		• Using six MOSFET for 4s battery • Provide the power lost formula during the equalization	best method is depends on its application.
2	*An Optimized Topology for Next-to-Next Balancing of Series-Connected Lithium-ion Cells*	• Presented two systems balancing of eight cells in series	• Succeed to equalized eight cell battery in nice result.
3	*A PWM Control Simple and High Performance Battery Balancing System*	• Explain the principle of PWM control battery balancing system. • Provide the circuit schematic	• Equalization is succeed to performed either charge or discharge process
4	*Passive Balancing pada Baterai Lithium Polymer Dengan Shunt Resistor Secara Online*	• Using average SOC method to equalize each cell • For the battery modeling, using simple *Rint* model to estimate the OCV and SOC	• Succeed to equalize the 3s Lithium Polymer Battery and reach the maximum SOC in 2 hours and 14 minutes.
5	*Estimasi Arus pada Battery Management System Brbasis Sensorless Current Menggunakan Model Batrai Sederhana*	• Using Simple *Rint* method to estimate the OCV and piecewise approximation method to estimate the SoC • Using Coulomb Counting to estimate the SoC	• SoC estimation succeed and the accurate approximation is depends on the internal resistance approximation.
6	*Estimasi State of Health (SoH) pada Baterai Lithium Polymer*	• Using Simple *Rint* method to estimate the OCV and polynomial approximation method	• SoH estimation using coulomb counting method better than open circuit voltage with the small error

		to estimate the SoC • Using Coulomb Counting to estimate the SoH	values are, MAE 0.5990, MSE 0.7146, MAPE 0.6098%

2.2 Theoretical Framework

2.2.1 Battery

2.2.1.1 Lithium Polymer Battery Characteristics

A Lithium Polymer is an evolved of a lithium ion polymer battery development When the battery state in over charge or overheat, the battery might be vent with a flame[23].

The cell should cut off on 3.0 Volt. Operating temperature for discharging are -10°C -60°C [24]. Optimum performance either charging-discharging is at temperature 20°C. Figure 2.2 below shows the available capacity depend on temperature,

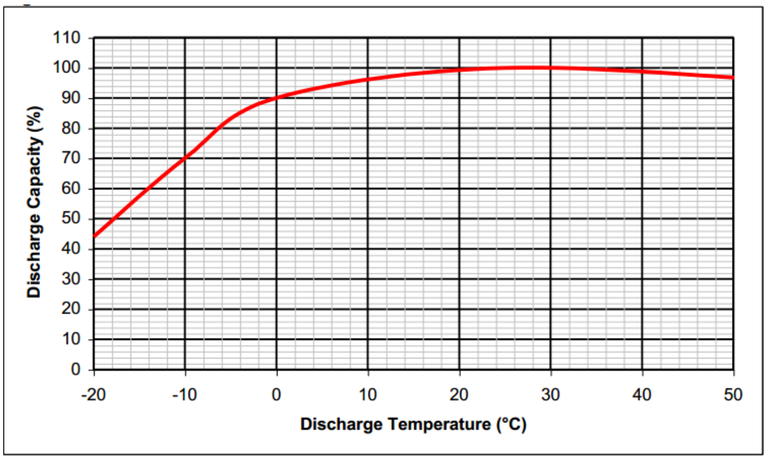


Figure 2.2 Temprature significant factor on available capacity[24].

In the charging process, the Lithium Polymer Battery cannot be charged more than 4.2 volts. The operating temprature of charging is at 0°C to 45°C. Figure 2.3 below shows the characteristics on charging process of Lithium Polymer Battery,

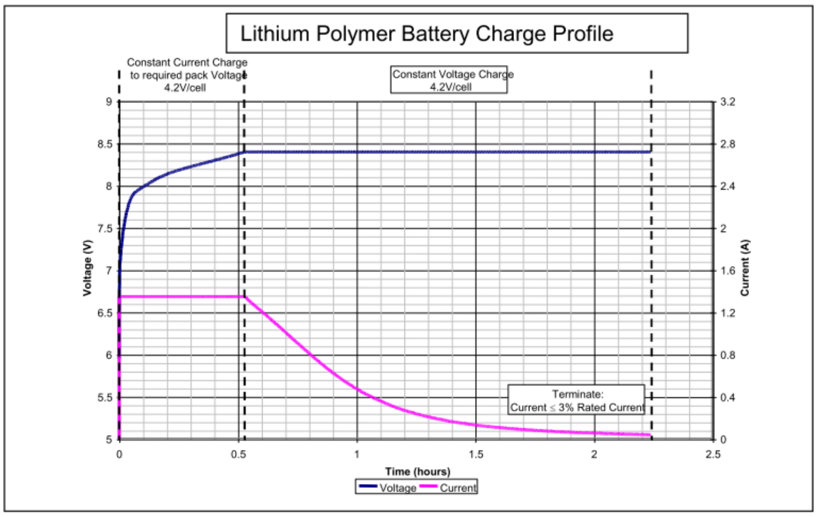


Figure 2.3 Charge Profile of Lithium Polymer Battery[24].

Figure 2.4 below from Sanyo lithium-polymer battery datasheet that contains a lot of information about its Li-Po battery product, including charge-discharge characteristics and the state of health characteristics[25].

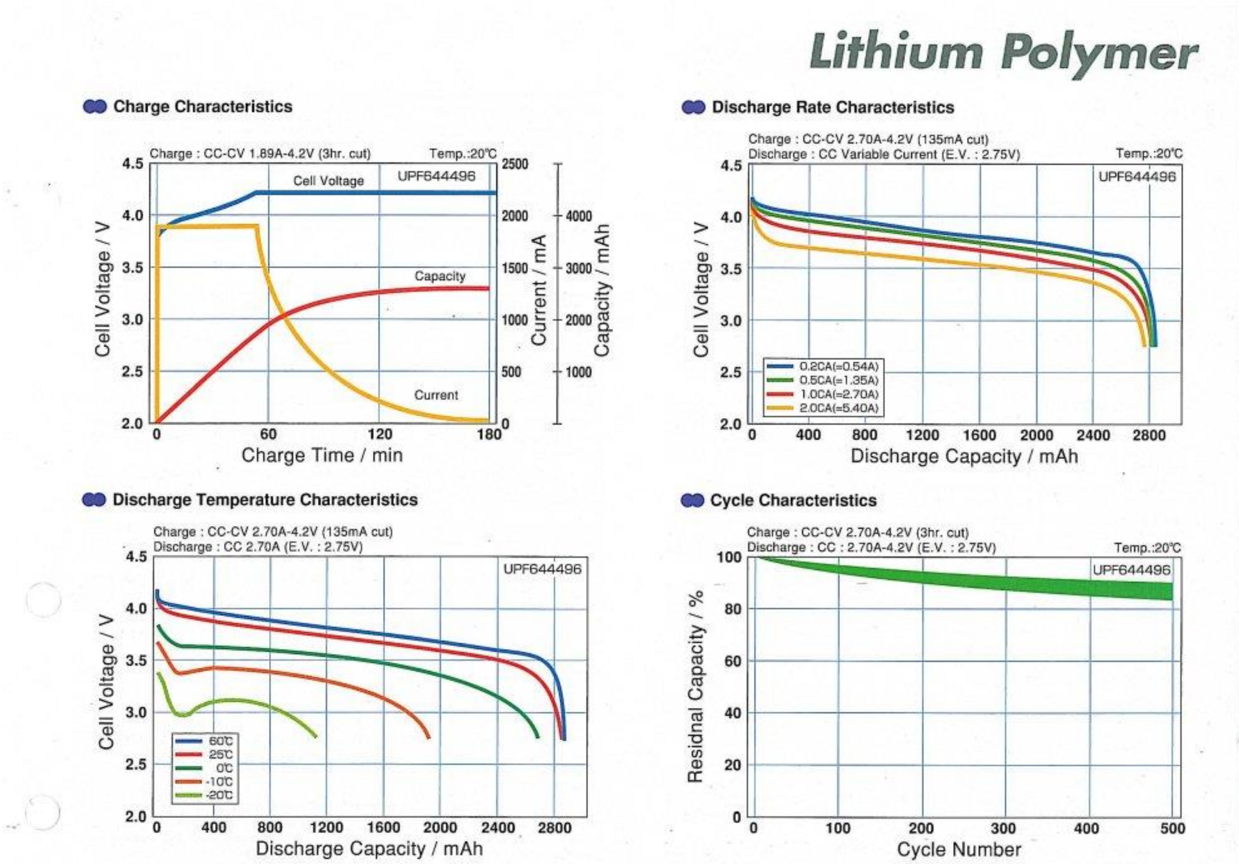


Figure 2.4 Lithium Polymer Characteristics[25].

2.2.1.2 Battery Modeling

The battery model is the approach modeling of the battery which has the aim to predict a non-linear power delivery dynamic given charge or discharge[9]. Many methods was proposed to the battery model. The model can be represented either *electrochemical model* which refers to the chemical reaction in the battery or equivalent circuit model which refers to electronics circuit model.

In the equivalent circuit model so far can be shared in simple model and Thevenin model. Other than the models, impedance model comes up as the development of Thevenin model. Figure 2.5 below shows the variation of the battery equivalent circuit model.

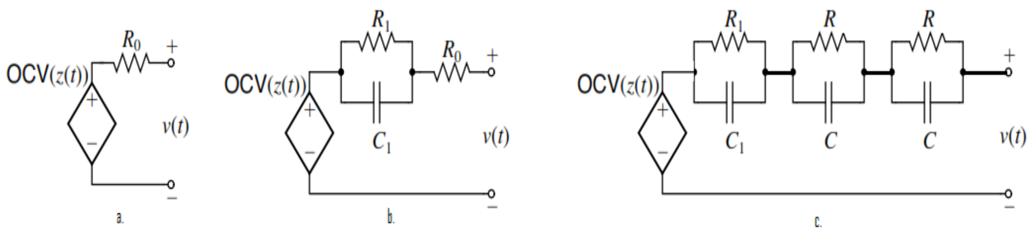


Figure 2.5. a. Simple Model, b. Thevenin model, and c. Impedance model

In this study, we will use simple *Rint* model was used by Boby Rian Dewangga[9], Bhisma Adjie P[8], and Erika Loniza[7], where they are the predecessor researcher at our BMS research group. More explanation according to the model will be enlightened further in Chapter 3.

2.2.2 Battery Management System

Battery management system is the system that taking the role to monitor and control the battery, the power and the energy system on battery storage. The basics task of the Battery Management System is to ensure that optimum used which made of the energy inside the battery powering the portable product and that the risk of damage inflicted upon the battery is minimized. This is achieved by monitoring and controlling the battery's charging and discharging[26].

The main purpose of the battery management system is to protect either the battery itself from an unsafe operation and environment or the portable device which its power source from the battery storage. In the real battery which installed in series-connected, there are often found unbalanced capacity. The condition also indicates that BMS needs to handle the problem. In this study, we found in battery pack cells have a difference voltage or capacity among the cells. In cell1, we found 3.83 Volt, in cell2 3.895 Volt, in cell3 3.91 Volt, and in cell4 3.85 Volt. Figure 2.6 shows the graph that represented this condition,

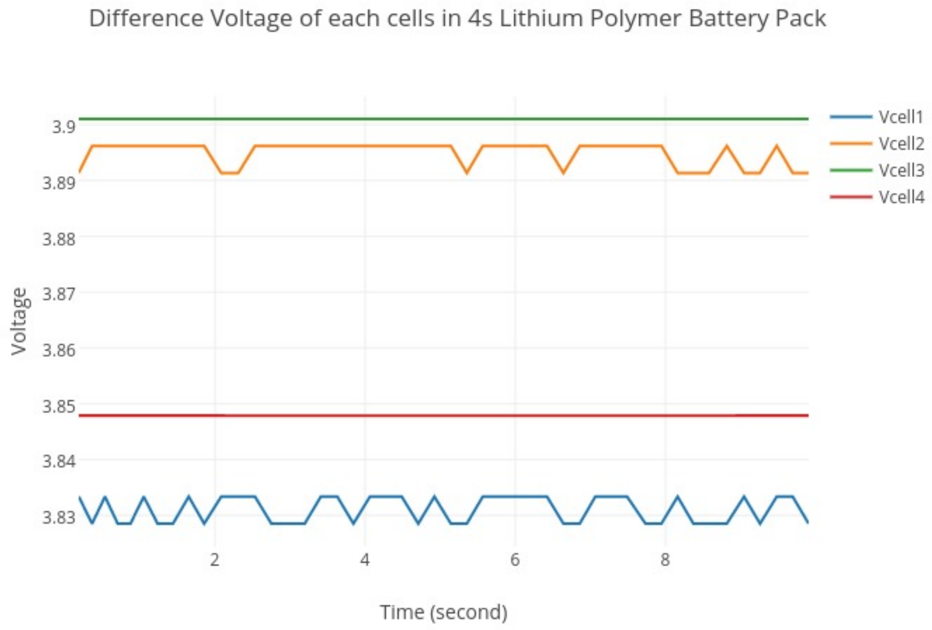


Figure 2.6. Differences voltage in 4s lithium polymer battery pack.

One of BMS occupations is handling this condition using battery balancing technique. The general representation of the BMS as shown in figure 2.7 below,

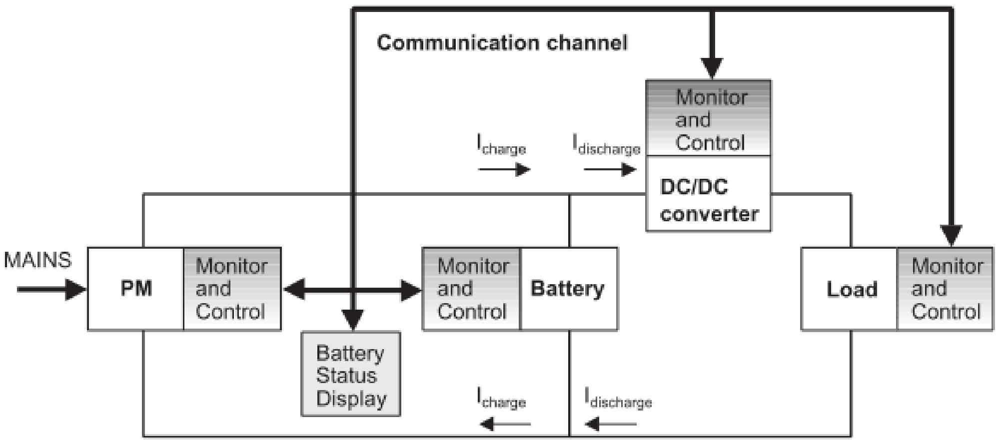


Figure 2.7. A general battery management system[26].

PM is the power module as the module which has a function to charge the battery and provide energy supply to another device. Battery statuses display taking a role to be displayed all of the battery status such as voltage, current, temperature, and SoC measurements. DC/DC converter actually is a buck or boost converter to keep the load work in its ambient power needs. The balancing technology has a role in handling balancing process and will be explained more in Chapter 3.

2.2.3 Buck-Boost Converter

Buck-Boost Converter produced DC voltage higher or lower than the input voltage dependent upon PWM output. Figure 2.8 shows the buck-boost converter circuit,

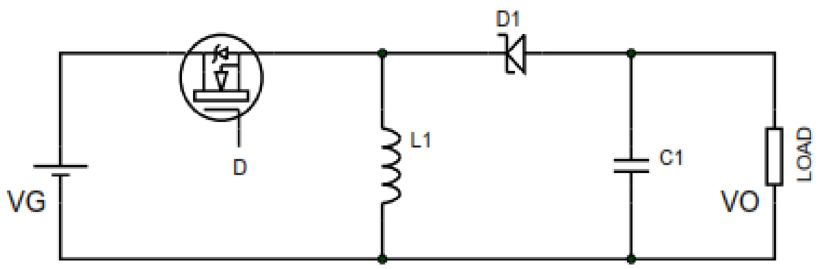


Figure 2.8. Buck-Boost Converter Circuit

When MOSFET Q1 is in the state of ON, current from input voltage VG will go to the inductor and imply diode D1 to the OFF state. The MOSFET will turn OFF the current i_L to build up through VO. Figure 2.9 below represents a steady state of current on the inductance and the PWM signal t in the MOSFET,

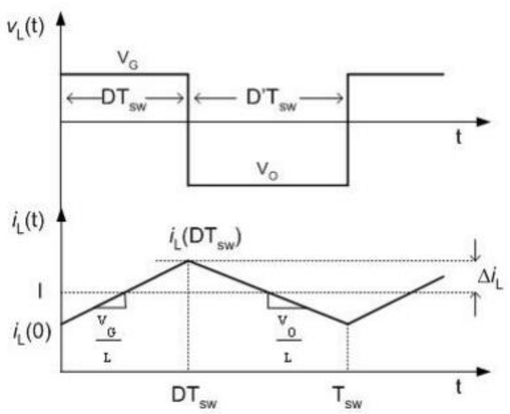


Figure 2.9. Voltage and current steady state on inductor of buck-boost converter circuit.

The result of the steady state signal using the balance voltage inductance principle is represented in equation (2.1) and (2.3) below,

$$Vg.Ton + Vo.Toff = 0 \qquad (2.1),$$

$$\frac{V0}{VG} = \frac{Tsw}{Toff} = -\frac{D}{1-D} \qquad (2.2).$$

where T_{sw} is switching frequency, T_{off} is D is duty cycle[23]. The output voltage can be lower or higher than the input voltage dependent upon the switching frequency.

2.2.4 Cell to Cell PWM Controlled Converter

In this research buck-boost converter is a basis for creating a circuit which used to transfer energy from one cell to another. The nominal of energy transferred from one cell to another is dependent upon the value of *duty cycles* generated by PWM, the generator, the generated of the *duty cycles* depends on the range of SOC values that have been measured between one cell to another. The large differences of SOC between two cells will make the controller to generate PWM in a high *duty cycle*. In contrast, the small differences of SOC will make a small *duty cycle* until both cells are balanced.

Figure 6 shows Cell to Cell PWM Controlled converter configuration. By using this configuration, the excess capacity of one cell can be transferred to another cell which has a less capacity. SOC became the parameter that measured to be equalized the cells. Where the State of Charge (SOC) values are depends on charging and discharging term of the battery itself.

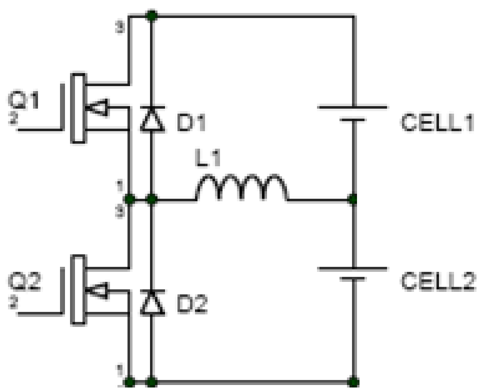


Figure 2.10. Two cells balancing PWM controlled converter.

When battery cells are already known their SOC value, the cells which decided to transfer its energy will be decided. For example, when CELL 1 is greater than CELL 2 and we want to transfer the energy from CELL 1 to CELL 2, then Q1 is ON and Q2 is OFF, after at the first time. After the capacity of inductor L1 is full the condition will be changed, the Q1 is OFF and diode D2 will ON. This condition will be transfer the *emf* (electromagnetic force) from the inductor to the CELL 2. The process will occur continuously until all capacities of the cells are balanced, and vice versa if the capacity of CELL 2 is greater than CELL 1.

Four series-connected cell batteries as shown in figure 2.11 is the development topology of two Cell to Cell PWM Controlled Converter Circuit that used in this experiment. Each of components in the module has a function to balance every voltage or SOC cells which connected between two different cells in series connected. The higher cell capacity will transfer its excess energy to the lower one,

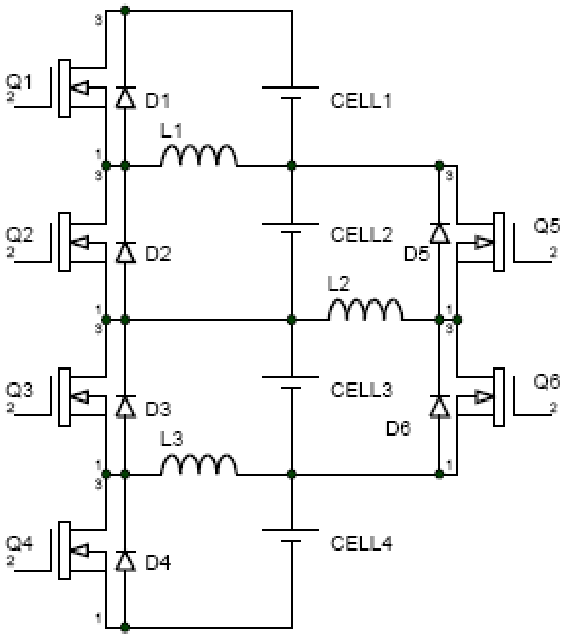


Figure 2.11. Four cells balancing PWM controlled converter circuit

2.2.5 Fuzzy Logic Controller

In this study, we used Mamdani fuzzy logic as the fuzzy logic controller (FLC). Unlike Boolean logic which has only two values in its operation and that is false and true, fuzzy logic has fuzzy or similarity value between false and true. In the fuzzy logic, a value of the variable can be false and true at the same time, depends on the weights of the memberships[27]. In the fuzzy controller, controlling rules is determines by a simple linguistic rule. A simple block diagram of fuzzy controller is shown in figure 2.12 below,

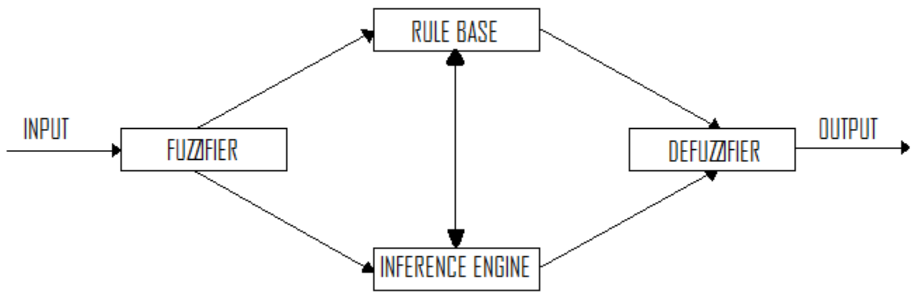


Figure.2.12. Block diagram of fuzzy controller.

Four commonly blocks in fuzzy control system are fuzzifier, rule base inference engine and defuzifier. Below the explanation of each block:

a) fuzzifier: in this block the input of the variable will be classified into suitable linguistic value in a set fuzzy input,

b) rule base: in this block, fuzzy rule will be written in IF-THEN statements,

c) inference engine: in this block, decision making or the fuzzy logic controller decision logic has determined,

d) defuzzifier: is the process of producing a quantifiable result in the crisp logic, given fuzzy sets and corresponding membership degrees. It is the process that maps a fuzzy set to a crisp set.[28].

The output of inference is still fuzzy value. This fuzzy output must convert to crisp value in order to be used in system[27]. The rule base comprises the knowledge of the application domain and the attendant control goals. It consists of “data base” and a “linguistics (fuzzy) control rule base”:

a) the data base provide a necessary definition which are used to define linguistic control and fuzzy data manipulation in FLC,

b) the rule base characterizes the control policy of the domain experts by means of a set of linguistic control rule.

In other hand, the fuzzy inference engine is the kernel of the FLC. It has a capability of a human decision-making based of fuzzy concept and inferring fuzzy control actions employing fuzzy implication and the inference of fuzzy logic.

The defuzzification interface performs the following function:

a) a scale mapping, which converts the range of values of output variables into corresponding universes of discourse

b) defuzzification, which yields a non-fuzzy control action from an inferred fuzzy control.

A fuzzification operator has the effect of transforming crisp data into fuzzy set. In this study we used trapezoidal as the commonly crisp fuzzy output set[29]. For the defuzzification method using centroid method which described in equation 2.3 below,

$$z^* = \frac{\int \mu C(z)\ .\ zdz}{\int \mu C(z)dz} \tag{2.3}$$

Where, z* is the defuzzified value,

μC is the average of the crisp member,

z is the of the boundaries of z value,

dz is the differences of maximum and minimum of the boundaries value.

The result example of the defuzzification of the fuzzy logic configuration can be seen in Chapter III figure 3.16.

CHAPTER III

3 METODOLOGY

3.1 Tools and Materials

3.1.1 Tools

a) Matlab,
b) Raspberry Pi 3 Model B+,
c) python 2.7,
d) multimeter,
e) analog to digital converter (ADC) IC MCP 3008,
f) dummy Load,
g) active cell balancing circuit,
h) personal computer (PC),
i) battery charger, and
j) sensor circuit.

3.1.2 Materials

a) Journals papers, conference papers, and article according to the BMS and balancer battery technology,
b) BMS reference books,
c) electronics datasheets, and
d) 4s Lithium Polymer Battery.

3.2 Research Flows

Figure 3.1 shows the research flows and the detail explanation as follows:

1. Literature Review

   Collecting and study about BMS literatures, battery modeling, SoC estimation, balancing methods, fuzzy logic, buck-boost converter and a lot of about python programming language. Determine the aim of the study and how to make it happen.

2. General Simulation

   The circuit and the algorithm are modeled in Simulink to observe the characteristics of the system, also as a principle to develop the hardware and the algorithm in hardware.

3. Hardware and Programming Development

   Designing and making hardware based on simulation. Create program in python language based on simulation algorithm and battery modeling that have discussed and analyzed before.

4. Testing and Data Collection

   The battery is tested by pulse tests to get the internal resistance. The algorithm is tested to justify the OCV and the SoC result. After every parameters work properly, the balancing test will be done and every data will be collected for analyzed.

5. Analysis

   Data that have been collected will be analyzed to determine the accuracy of the system in balancing operation. The analysis results will be written in the thesis report.

6. Report

   All matters relating to the research starting from introduction until conclusion will be written in the thesis report.

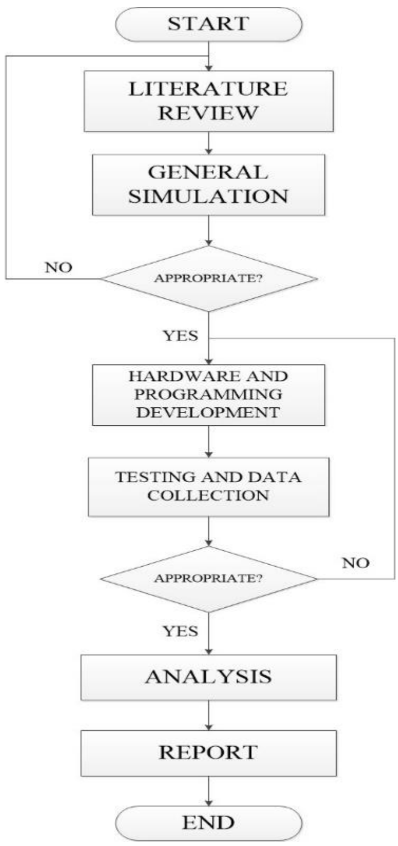


Figure 3.1. Research flows.

3.3 Simulation

In the simulation, the result has shown to us the balancing result in the idle state. Based on the simulation we will be developed the hardware and the program.

In the simulation design, the inductor value is one of the most important things to be considered. Inductors have two commonly parameters which are often used, there are the inductance value and the current capacity. In the simulation design, we want the inductor is fully charged on 0.01 second. The current capacity of the inductors determined is 3 Ampere. So based on the electromotive force (*emf*) equation (3.1)[30] of inductance where,

$$v(t) = L\frac{di}{dt} \qquad (3.1).$$

Since v(t) is equal to determine maximum battery voltage, *di* is the maximum current capacity of the inductor and we want 100 Hz frequency, we can calculate the L value using equation (3.2) below,

$$L = v(t)\frac{dt}{di} \qquad (3.2).$$

The error of the SOC in steady state is handled by squared error where the value is 0.005% which means 0.07% for the error tolerance. The error tolerance can be adjusted by replacing *compare to constant* block value on the simulation block parameters for more accuracy. Figure 3.2 below shows the overview of the simulation block diagram,

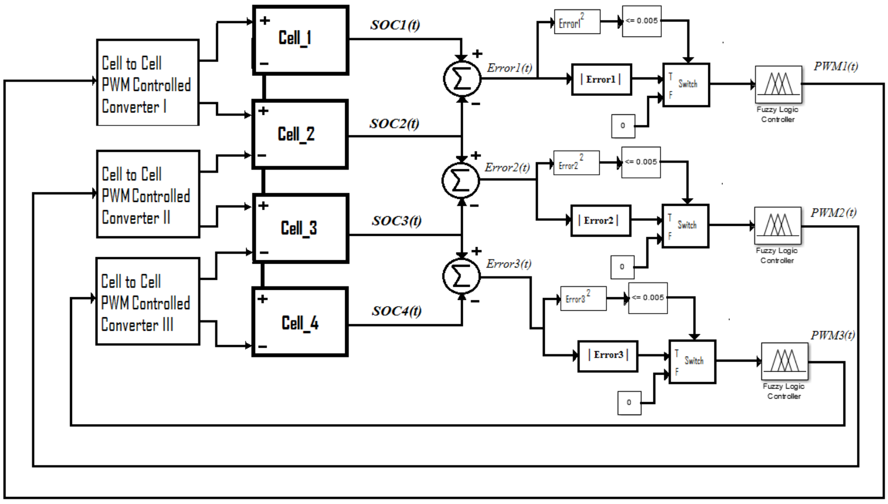


Figure 3.2. Simulation block diagram.

Balancing system uses the same fuzzy logic controller configurations for PWM1, PWM2, and PWM3. The output of PWM1, PWM2 and PWM3 became feedback input signal for the Cell to Cell PWM Converter I, Cell to Cell PWM Converter II and Cell to Cell PWM Converter III to be balanced among adjacent cells until every cell are equalized.

The whole process consisted four step. First step was the initialization battery's parameters with the same parameters for each battery cells that we used. The second was regarding the determination of nominal SOC with some different values for each cell. This condition will give us the representation of the real condition in battery pack that consisted of difference cells capacity. The third and fourth were determine frequency we used for the PWM generator and for active balancing using fuzzy logic to balance the battery capacity of each cell respectively. The flowchart of experiments is shown in figure 3.3,

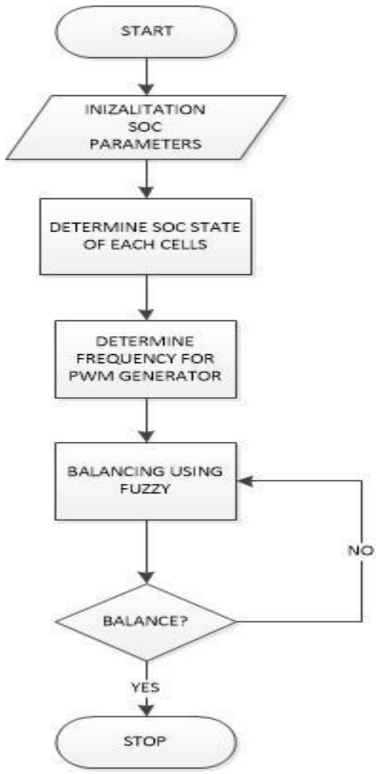


Figure 3.3. FL-PWM Controlled Converter flowchart

Figure 3.4 below shows the result in idle state (nor either charging or discharging) with determine SOC for CELL 1 is 90%, CELL 2 is 70%, CELL 3 is 75%, CELL 4 is 85%,

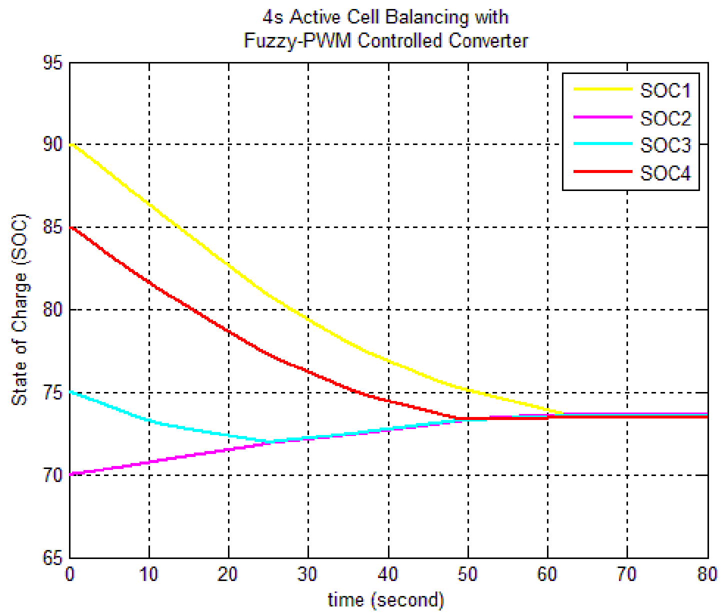


Figure 3.4. SOC during 80 seconds simulation.

3.4 Hardware and Programming Development

3.4.1 Hardware Development

There are several things which have to be concerned with designing the hardware setup. One of them is the voltage sensor. Battery lithium polymer installed in series-connected in a battery pack cannot be directed to measure the voltages and connected to the controller's analog digital converter (ADC). It is because the ground reference in adc is joint into the ground controller. Meanwhile, the cell voltage ground reference connected independently into their negative porous itself. The condition requires us to develop electronic hardware to measure the cells voltage inappropriate measurement. Therefore, the differential amplifier circuit is required to measure the voltage cells one by one.

Differential amplifier sometimes called analog *subtractor* circuit. The principle of this configuration is two adjacent voltage cells will be subtracted to get the real voltage measurement of the cell. Figure 3.5 below shows the voltage sensor which constructed by differential amplifier configuration

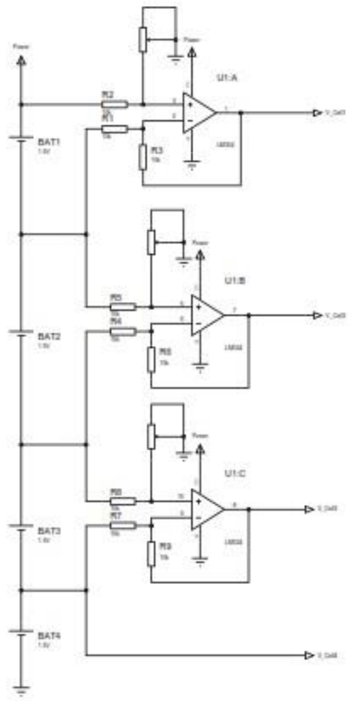


Figure 3.5. Voltage sensor circuit.

The controller uses Raspberry Pi3 Model B+ that will produce pulse width modulation (PWM) signals. The controller also will be taken monitoring of the cells capacity and send the data to the computer display. Raspberry Pi 3 do not has analog to digital converter in its board. Therefore, IC MCP 3008 which has the I2C connection will be read the analog voltage from voltage sensor circuit then convert it to a digital value and transfer the data to the Raspberry. Figure 3.6 below show the configuration,

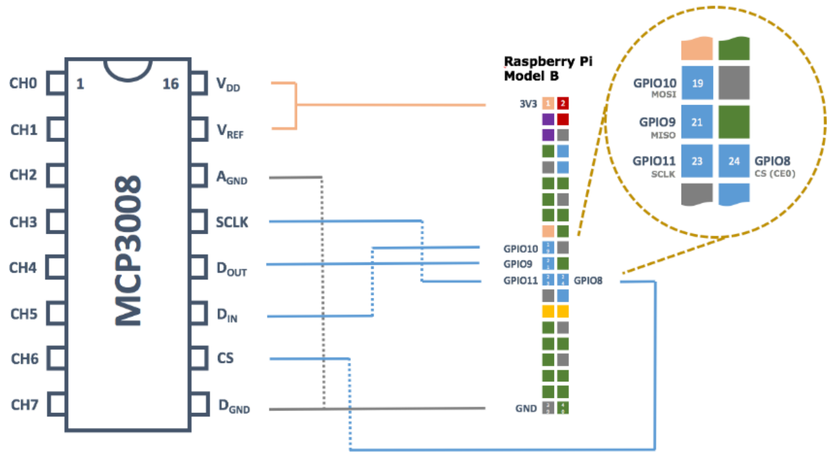


Figure 3.6. Raspberry configuration to MCP3008[31]

The hardware configuration setup begin from voltage sensor circuit, MCP 3008 and Raspberry are displayed on figure 3.7. Where, the balancing circuit configuration and description refers to point 2.2.4,

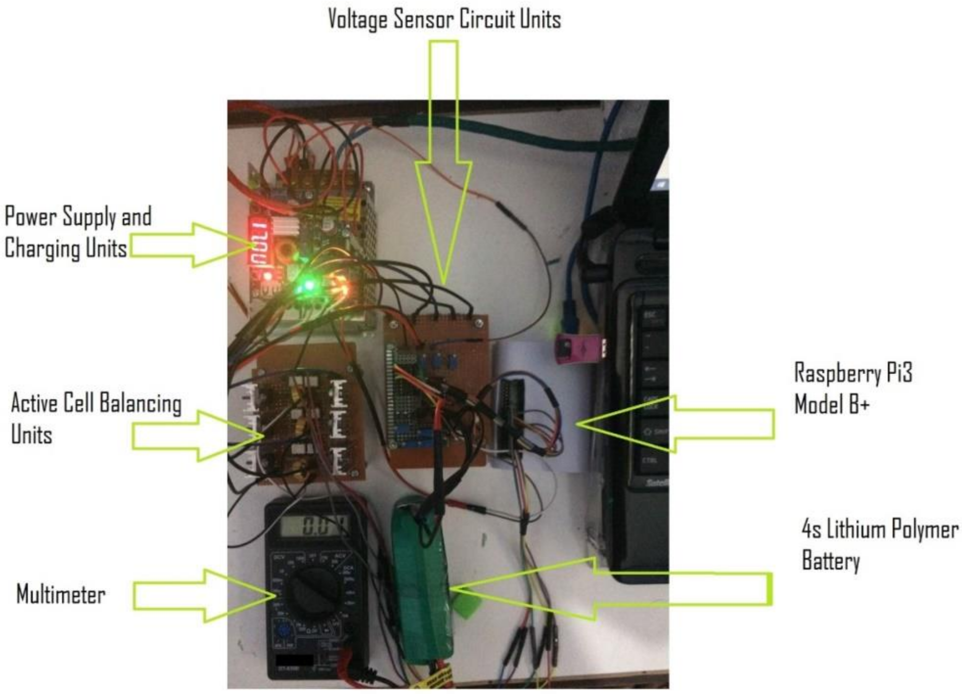


Figure 3.7. Hardware setup.

Figure 3.8 below represented the implementation of the system in block diagram,

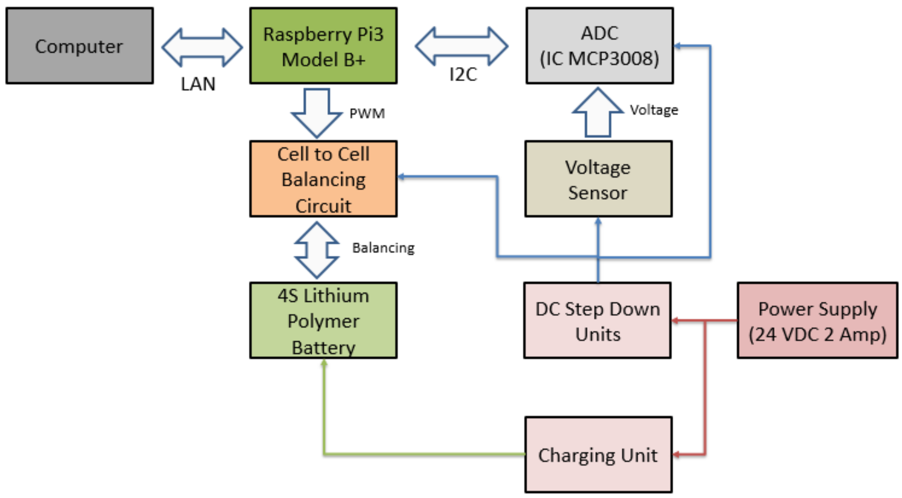


Figure 3.8. System implementation.

Raspberry Pi3 communicate to the computer trough Local Area Network (LAN) connection. Raspberry Pi3 connect with the ADC MCP 3008 using I2C connection and RaspberryPi3 control the balancing circuit by fabricated PWM signals from fuzzy logic function inside the program algorithm. Then for the power side, consist of 24 Volt and 2 Ampere Power Supply that connected to the DC Step Down units and Charging unit to Supply the sub-circuit such as Cell to Cell Circuit, Voltage Sensor and MCP 3008 configuration.

3.4.2 Programming Development

Programming development is the way to proof the concept of this study. Is that the concept can be implemented or not. All of the concepts were explained in Chapter II will be tested in this part. Is it can be realized or not.

Python 2.7 is the interface programming language which used to translate all of the mathematic formulas and logical languages into the real implementation. Why python? Because the author before has already accustomed to C or C++ programming language and Python still new to the author. The question of course tried to ask at the beginning then the author has tried to implement using C++ but failed. The answer is because of the Raspberry Pi very suitable to this programming language. Since the python also free to use, and also friendly to the programmers.

Back to our topic, the programming language will be covered all of the implementation of the algorithm. Figure 3.9 below shows the programming flowchart,

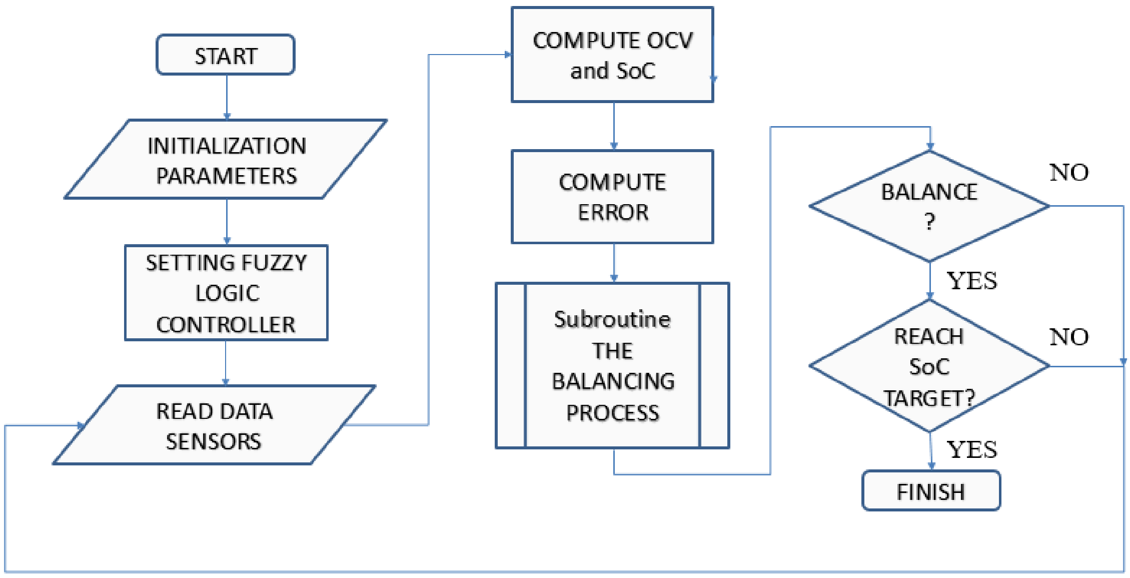


Figure 3.9. Programming Flowchart.

The algorithm begin from initialization the parameters. Then the fuzzy logic configuration will be set to determine the number of duty cycle of the MOSFET's. Then voltage of each cells will be read. After that, OCV and SoC calculated by the battery modeling formulation which the explanations will be enlighten further. Then the error will be computed. Then the minimum of cell capacity in battery pack will be computed. After that, the balancing process will be established until reach the SoC target which was set previously.

The breakdown of *Balancing Process* block diagram contain sub-block diagram. Figure 3.10 below shows the block,

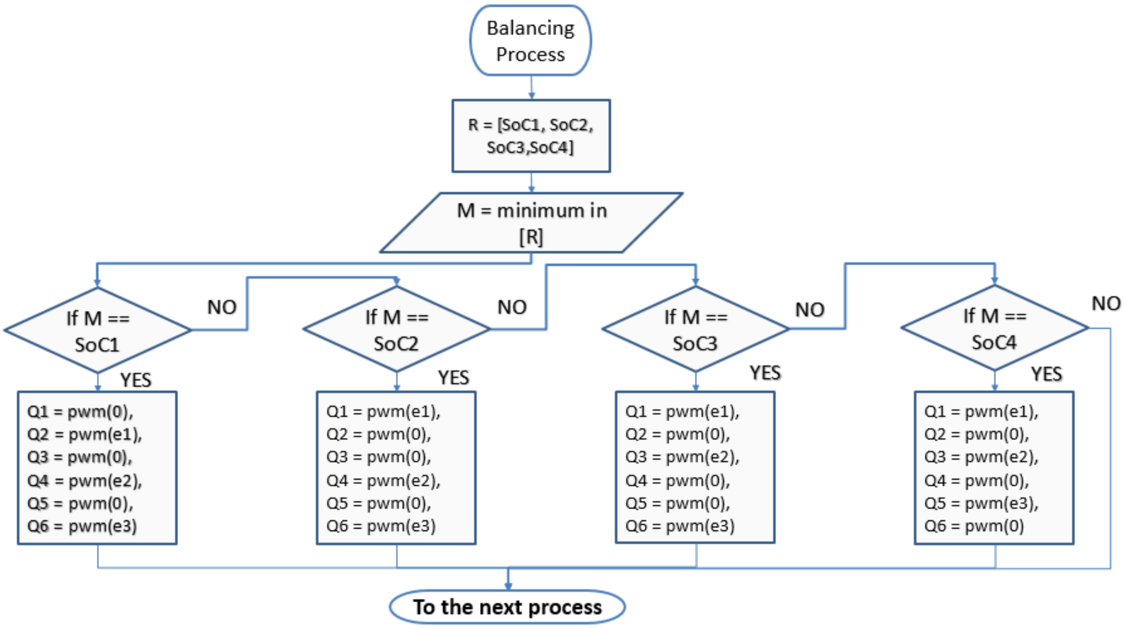


Figure 3.10. Balancing process.

The process to determine the minimum SoC value among the cells and the firing steps of the MOSFET's were presented in this sub-block diagram. Where the collection of SoC value was entered in an array "R." Then array "M" will determine the minimum value of array "R." After this step, the minimum cell capacity will be detected. If the SoC1 is the lowest capacity, then the flow of the energy transfer will be directed to the SoC1. Similar process will be established to another process if the lowest SoC capacity in pack is the cells. Then the process will be continued until the cells are balanced and reach the previous SoC target set up. The *pseudecode* of the programming logic is available at the appendix section.

3.5 Analysis Method

3.5.1 Battery Modeling

Just like the previous research[7], this thesis also uses the simple *Rint* (Internal Resistance) method[7][32]. The model consists of a resistance *R* and the capacitor *C* as a charged storage has a capacity in V_c. Figure 3.11 shows the configuration of the model,

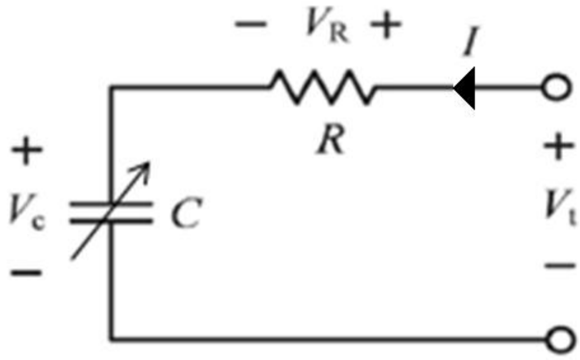


Figure 3.11. Rint Battery Model.

The relation between the terminal voltage V_t , the capacitance of C in V_c and the voltage drop on V_R have been modeled by *Kirchoff Law*[33]. The relationship can be described as the equation (3.3) – (3.5) below,

$$Vt - VR - Vc \qquad = 0 \tag{3.3}$$,

$$Vt - iR - Vc \qquad = 0 \tag{3.4}$$,

$$Vt - C\frac{dVc}{dt}R - Vc \qquad = 0 \tag{3.5}$$.

Based on the equations above, the *Laplace* transform will establish to the equation (2-3) and the equation will become,

$$Vt(s) - RCsVc(s) - Vc(s) \qquad = 0 \tag{3.6}$$,

$$Vt(s) = sRCsVc(s) - Vc(s) \qquad = 0 \tag{3.7}$$,

$$\frac{Vc}{Vt} = \frac{1}{sRC+1} \quad (3.8)$$

The equation above necessary to be discretized from frequency domain to discrete domain, where:

$$Vc(s) \quad = Vc[k] \quad (3.9),$$

$$Vt(s) \quad = Vt[k] \quad (3.10),$$

$$sVc(s) \quad = \quad \frac{Vc[k]-Vc[k-1]}{Ts} \quad (3.11).$$

By substituting the equation 3.9 and 3.10 above into the equation 3.7, the equation will become,

$$Vt[k]-RC\frac{Vc[k]-Vc[k-1]}{Ts}-Vc[k] \quad = 0 \quad (3.12),$$

$$Vt[k]+\frac{RC}{Ts}Vc[k-1] \quad = \quad (\frac{RC}{Ts}+1)\ Vc[k] \quad (3.13),$$

$$(RC+Ts)Vc[k] \quad = \quad RC\,Vc[k-1]+Vt[k]Ts \quad (3.14),$$

$$Vc[k] \quad = \quad \frac{RC}{RC+Ts}Vc[k-1]+\frac{Ts}{RC+Ts}Vt[k] \quad (3.15).$$

Since,

Vc[k] is the voltage of Capacitor and it is depends on Vt[k],

Vt[k] is the terminal voltage,

Ts is time sampling,

R is internal resistance, and

C is the variable capacitance of Capacitor.

Since,

$$\alpha \quad = \quad \frac{RC}{RC+Ts} \quad (3.16).$$

$$\alpha - 1 = \frac{TS}{RC + Ts} \qquad (3.17).$$

So we can reconstruct the equation (3.15) above become equation (3.18) below,

$$\text{Vc[k]} = Vc[k-1](\alpha) + Vt[k](\alpha - 1) \qquad (3.18).$$

SoC value calculated by coulomb counting method[26], [28], [29], [9]. Coulomb counting method is the commonly method that used to calculated the SoC because it is simple. To calculate SoC using coulomb counting, we can use the equation (3.19)[7]–[9] below,

$$S(t) = S_0 - \frac{1}{Cn}\int_0^t IdT \qquad (3.19).$$

The internal resistance is taken from the difference of terminal voltage of the cell in pulse tests. The equation is represented in the equation (3.20) below,

$$R = \frac{Vt\,\frac{dvt}{dt}}{IL} \qquad (3.20)$$

where,
IL is the load current.

The variable capacitance value is taken from differential of battery capacitance and the equation can be followed as equation (3.21) below,

$$C = \left[Cn\,.\frac{dSOC}{dVc}\right] \qquad (3.21).$$

The relation between SoC and OCV can be described into graph as shown in figure 3.12 below, where SoC value is produced by equation 3.19 above and the data paired with OCV data in lookup table data. The result plotted as shown in figure 3.12,

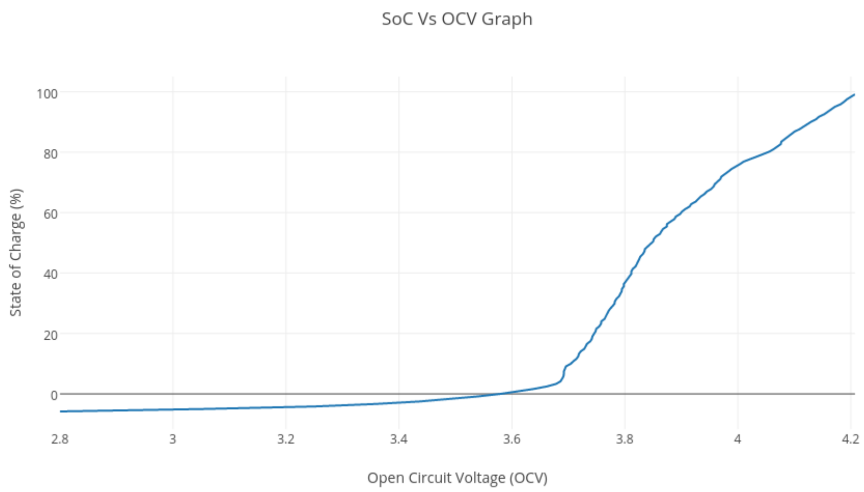


Figure 3.12. Correlation between SoC and OCV.

3.5.2 Fuzzy Logic Configuration

In this research, fuzzy logic was used to control the output of PWM through MOSFET. Equation 4, 5, 6, 7 and 8 are the representation of each area of the membership function of fuzzy input. The membership function of fuzzy input consists of Z (Zero), PS (Positive Small), PM (Positive Medium), PL (Positive Large) and PVL (Positive Very Large). The SOC in balance state represented with *Zero*. The small difference SOC among the cells represented by *Positive Small* which has range between two cells are about 2 - 3 SOC. The medium scale difference SOC represented by *Positive Medium* which has range between 2 - 6 SOC. The large scale difference SOC represented by *Positive Large* which has range between 5 - 10 SOC. The last is the very large scale difference SOC represented by *Positive Very Large* which has range greater than 8 SOC difference. Figure 3.13, shows the membership function plots of the fuzzy input,

$$\mu[x]Z = \{0\} \tag{3.22}$$

$$\mu[x]PS = \begin{cases} \frac{x-0}{0.5}; \leftarrow 0 < x < 0.5, \\ 1; \leftarrow 0.5 < x < 2, \\ 3-x; \leftarrow 2 < x < 3, \\ 0; \leftarrow otherwise, \end{cases} \tag{3.23}$$

$$\mu[\mathrm{x}]PM = \begin{cases} x-2; \leftarrow 2 < x < 3, \\ 1; \leftarrow 3 < x < 4.5, \\ \dfrac{6-x}{1.5}; \leftarrow 6 < x < 4.5, \\ 0; \leftarrow otherwise, \end{cases} \tag{3.24}$$

$$\mu[\mathrm{x}]PL = \begin{cases} x-5; \leftarrow 5 < x < 6, \\ 1; \leftarrow 6 < x < 8.5, \\ \dfrac{10-x}{1.5}; \leftarrow 8.5 < x < 10, \\ 0; \leftarrow otherwise, \end{cases} \tag{3.25}$$

$$\mu[\mathrm{x}]PVL = \begin{cases} x-8; \leftarrow 8 < x < 9, \\ 1; \leftarrow 9 < x < 100, \\ 0; \leftarrow otherwise, \end{cases} \tag{3.26}$$

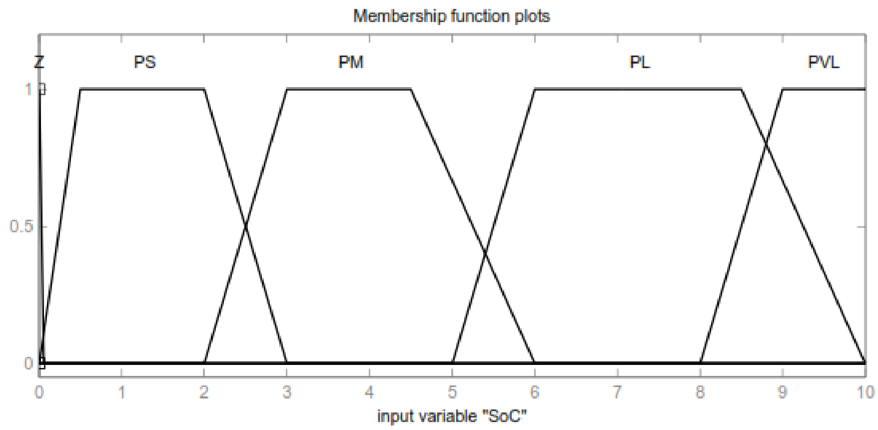


Figure 3.13. A set of fuzzy for input.

For the fuzzy output, equation 9, 10, 11 and 12 represent membership function to determine the membership function area of the *fuzzy single tone* output that consists of Z for *ZERO* PWM output, PS for *Positive Small* PWM output, PM for *Positive Medium* PWM output, PL for *Positive Large* for PWM Output, and PVL for *Positive Very Large* PWM output. Figure 3.14 shows the fuzzy logic output membership function plot,

$$\mu[\mathrm{x}]Z = \{0\} \tag{3.27}$$

$$\mu[\mathrm{x}]PS = \{55\}, \tag{3.28}$$

$$\mu[\mathrm{x}]PM = \{65\} \tag{3.29}$$

$$\mu[\mathrm{x}]PL = \{75\} \tag{3.30}$$

$$\mu[\mathrm{x}]PVL = \{85\} \tag{3.31}$$

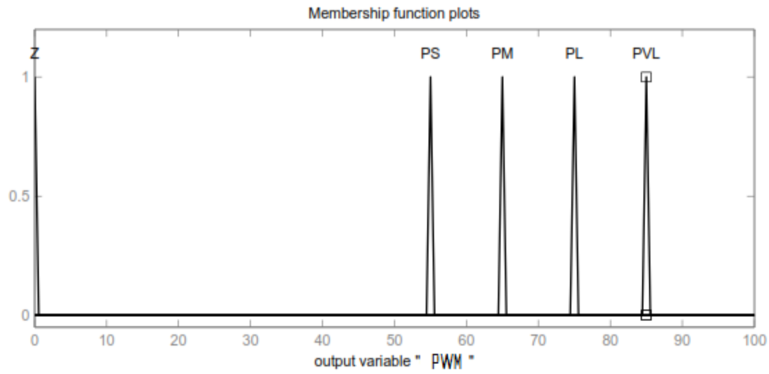


Figure 3.14. A set of fuzzy for output.

The rules of fuzzy logic using Mamdani Rule[29][36] determine as follows :

1. If (SOC is ZERO) then (PWM is ZERO)
2. If (SOC is PS) then (PWM is PS)
3. If (SOC is PM) then (PWM is PM)
4. If (SOC is PL) then (PWM is PL)
5. If (SOC is PVL) then (PWM is PVL)

All of input membership function drawn using trapezoidal membership function except ZERO membership function which using the sinlgle tone membership function. It's because we want the output pwm is Zero when the input SOC is Zero. In this case, the correlation output and input membership function from every rule, as drawn in a surface graph is represented in Figure 3.15 below,

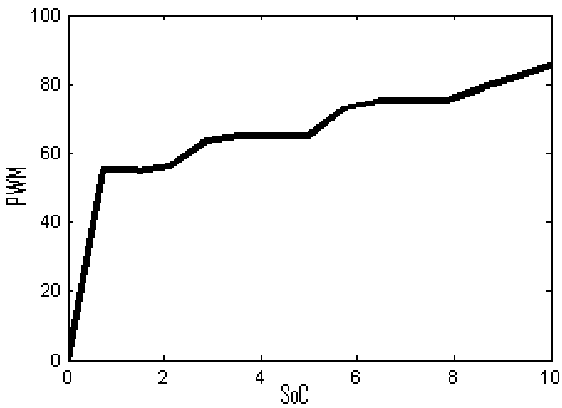
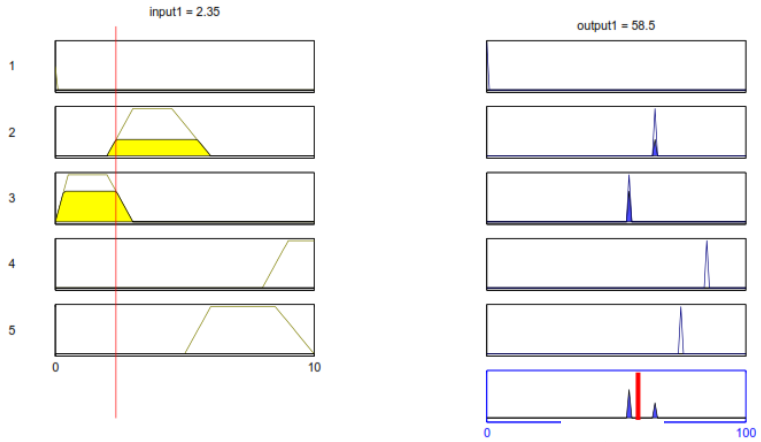


Figure 3.15 Surface output and input

For the example of the fuzzification of the input, output and rule base above described of the figure 3.16 below,



a, b,

Figure 3.16. a. Fuzzification example result of input and b. Defuzzification of the output of the fuzzy configuration.

3.5.3 Charging Method

Our goal is charging four cells lithium polymer battery to 95% in balancing state. It's because the battery safety charging at 95% SoC maximum[37]. In this study 4s lithium polymer battery in series connected will be charged together to reach the maximum safety limit. For the first charging, we was tried to increase the charging limit to 85 % SOC for 0.05% SoC tolerance. Finally we increase the limit of the charging target to the maximum safety limit at 95% SoC balancing state.

After the best result obtained, then the algorithm will be implemented to another charging process in the later experiments.

3.5.4 Error

Error, in this case is the deviation between two SoC at adjacent cell in of each cell value. In cell balancing application, the difference SoC values of each cell are the problems. The error appeared when the dynamic capacity of a cell starts moving towards a point. During the balancing term, the error will be changed convergence along with the balancing process. The equations below are the error between two cells of each cell in 4s lithium polymer batteries in series-connected,

$$error1 = SoC1[k] - SoC2[k] \tag{3.32),}$$

$$error2 = SoC2[k] - SoC3[k] \tag{3.33),}$$

$$error3 = SoC3[k] - SoC4[k] \tag{3.34),}$$

$$where,\ k = a\ sequence\ in\ discrete\ domain.$$

3.5.5 Analysis of Variance (Anova)

Analysis of variance (ANOVA) is the statistic method used to test differences between two or more means on the populations[38]. ANOVA is also used to test general rather than specific differences among the means.

In this case, we will be calculated and tested on the means in the data populations of cell1, cell2, cell3 and cell3.ANOVA tests the non-specific null hypothesis that four population means are equal that is

$$\mu 1 = \mu 2 = \mu 3 = \mu 4 = ... = \mu k \tag{3.35).}$$

Where, Ho is the null hypothesis and k is the number of conditions. In the study, k = 4 and the null hypothesis is

$$H0: \mu Cell1 = \mu Cell2 = \mu Cell3 = \mu Cell4 \tag{3.36).}$$

If the null hypothesis is rejected, then it can be concluded that at least one of the population means is different from at least one other population mean[38]. The test is based on two estimates the population variance. In other word, if the null hypothesis is rejected it means that the means of each cell populations data is not equal or can be concluded that not in steady state or the cells are not balanced.

Further analysis can be done with *Sum of Squares (SS)* calculation. The equation (3.37) below is Sum of Squares (SS) formula,

$$SS = \sum (value - mean)^2 \tag{3.37}$$

In order to understand something about how ANOVA works, the understanding about Between Groups (BG) and Within Groups (WG) ANOVA's partition the SS differently and how F value are constructed by each.

Variance partitioning of the BG design is how to get *SS BG* which represented to the equation (3.38) below,

$$SS\ BG = \sum_i n_i(\bar{Y}_i - \bar{\bar{Y}}) \qquad (3.38),$$

where, i is number of data in population and n is the data.

Mean square needs to calculate to get SS mean by dividing it with the degree of freedom (df_{Effect}) of population where equation (3.9) is how to get df_{Effect},

$$df\ Effect = j - 1 \qquad (3.39),$$

where, j is number of population.

Since df_{Effect} is already known, the mean square calculated with equation (3.40) below,

$$BG\ MS = \frac{SS\ BG}{df\ Effect} \qquad (3.40).$$

Variance portioning of the Within Groups (WG) design is how to get *SS WG* which represented in equation (3.41) below

$$SS\ WG = \sum_i \sum_j (Y_{ij} - \bar{Y}_i)^2 \qquad (3.41)$$

Mean square of WG needs to calculate to get SS mean by dividing it with the degree of freedom entire data in populations ($df_{subj.}$) where equation (3.42) is how to get $df_{subj.}$,

$$df\ subj. = (i.j) - j \qquad (3.41),$$

Where, n is sum of data in entire population.

Since $df_{subj.}$ is already known, then the WG mean square calculated with equation (3.42) below,

$$WG\ MS = \frac{SS\ WG}{df\ Subj.} \qquad (3.42).$$

Finally, F ratio will be calculated using equation (3.43) below,

$$F\ ratio = \frac{BG\ MS}{WG\ MS} \qquad (3.43)$$

Now, to test Hypothesis Null (H0) is accepted or rejected by compared F ratio and F critical. If F ratio is greater than F critical, then we will be rejected H0. In other hand, if F ratio smaller than F critical, then we will be accepted H0. Back to the relation to the study, if H0 is rejected, it means cell1, cell2, cell3, and cell4 are not *Balance.* If H0 is accepted, it means cell1, cell2, cell3, and cel4 are *Balance.*

We will use the Anova to analyze the balancing state of the result of the study in Chapter IV.

CHAPTER IV

4 RESULT AND ANALYSIS

4.1 Pulse Test

The pulse tests were established for the four cells lithium polymer in series connected (reverse to Figure 2.9). It is completed separately one by one of each cell. By taking each terminal voltage in 105 seconds, we established the pulse test every 30 seconds until the end of term. A dummy load is used to pull up the current of 1.1 Ampere. The first 30 second, the dummy load in rest position. In this state, the dummy load does not pull the current from the battery. The cell is just in the rest position.

After the first 30 second the current will be taken from the battery of 1.1 Ampere for 5 seconds. After that, the dummy load back to the rest state. This process will be repeated for three times. Figure 4.1 below is represented the pulse tests result of the cell1. The data begin from 3.80 Volt in first thirty minutes then dropped to 3.63 volts in t > 30 seconds < 35 seconds. The process will be looped for three times,

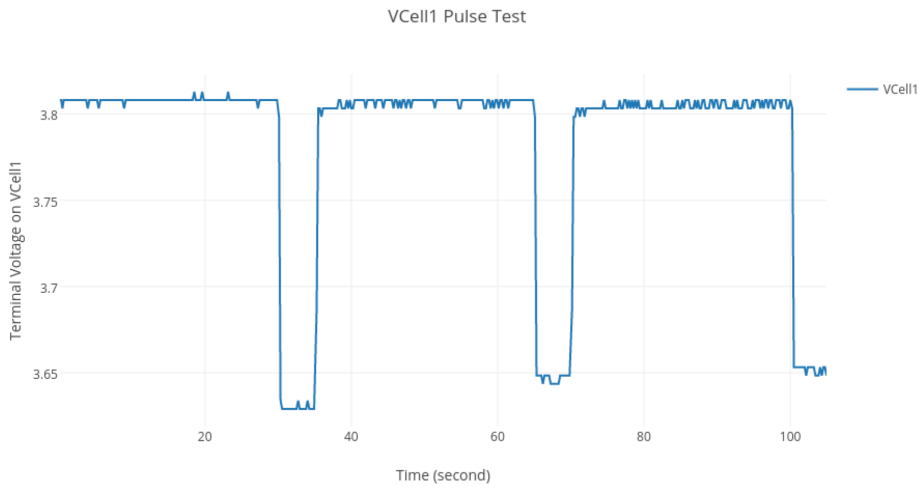


Figure 4.1. Terminal voltage of Cell 1.

Figure 4.2 below is represented the pulse tests result of the cell2. The data begin from 3.81 Volt in first thirty minutes then drop to 3.67 volts at t > 30 seconds < 35 seconds. The process will be looped for three times,

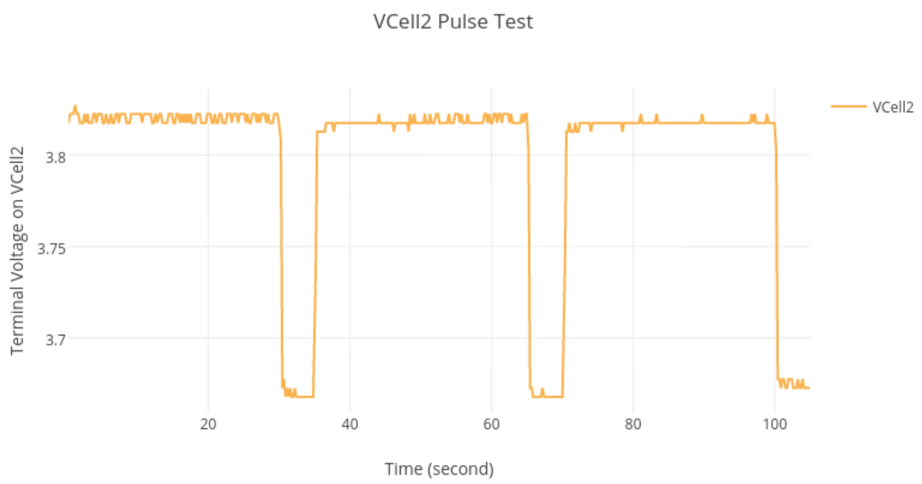


Figure 4.2. Terminal voltage of Cell 2.

Figure 4.3 below is represented the pulse tests result of the cell3. The data begin from 3.86 Volt in first thirty minutes then drop to 3.75 volts at t > 30 seconds < 35seconds. The process will be looped for three times,

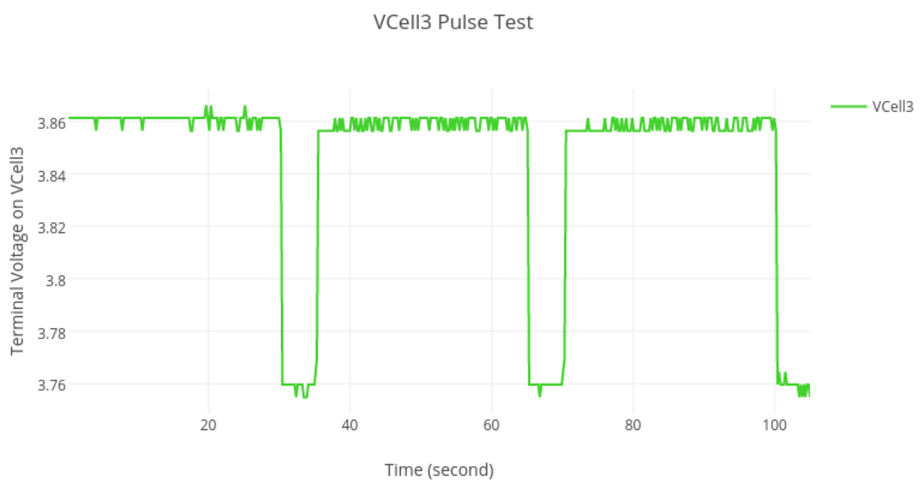


Figure 4.3. Terminal voltage of Cell 3

Figure 4.1 below is represented the pulse tests result of the cell4. The data begin from 3.85 Volt in first thirty minutes then drop to 3.03 volts at t > 30 seconds < 35seconds. The process will be looped for three times,

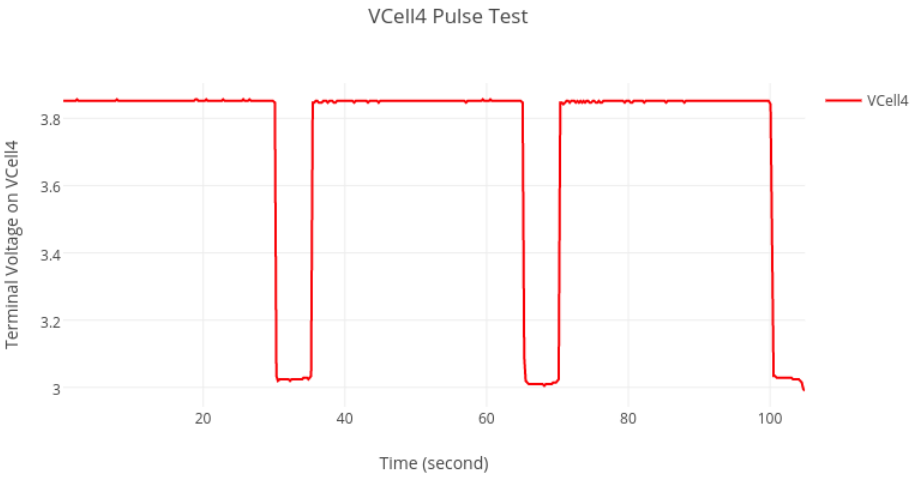


Figure 4.4. Terminal voltage of Cell 4

4.2 Internal Resistance of Each Cell Measured in Load Current at 1.1 Ampere

After taking the pulse test data of each cell of 4s lithium polymer battery in series connected, now it is the time to measured internal resistance for each one. By establishing the equation 3.11 above, we will be developed the value of each internal resistance of each cell in the battery pack.

In the specific method, all of the terminal voltage in 30-second rest (*i(t) = 0*) and all of the terminal voltage in 5 seconds where *i(t)* > 0 terms will be calculated as an average of each cell at each state. The equation (4.1) below is how to calculate the internal resistance during the experiment,

$$R = \frac{\sum_{i=0}^{3}(\mu Vti(i(t=0)) - \mu Vti(i(t>0)))}{IL} \quad (4.1),$$

$where,$

$\mu Vt = the \ \ average \ \ of \ \ Vt, and$

$IL = the \ load \ current$

Table 4.1 below shows the average of each cell in, after collected the data in three times pulse tests.

Table 4.1. R internal of each cell in 4s lithium polymer batery pack.

The Cells	µVt where *i(t)* =0	µVt where *i(t)* > 0	R internal
Cell 1	3.807995392	3.629692082	0.240695908
	3.806712524	3.646847507	
	3.804757484	3.651906158	
Cell 2	3.820481499	3.669124424	0.21785736
	3.818398618	3.66840176	
	3.817635199	3.674560117	
Cell 3	3.860904628	3.758797654	0.147609838
	3.859247312	3.759457478	
	3.858464799	3.759237537	
Cell 4	3.851897533	3.024853372	1.212753895
	3.851257116	3.014516129	
	3.850835884	3.040603086	

4.3 OCV and SOC Estimation

After the internal resistance data is taken then calculations to Open Circuit Voltage (OCV) and the State of Charge can be established. By establish equation (3.18), we can approximate the OCV value. The result is shown in figure 4.5 is OCV estimation of cell1, where the estimation value start at 3.808 at the first second to 3.807 at the end of data,

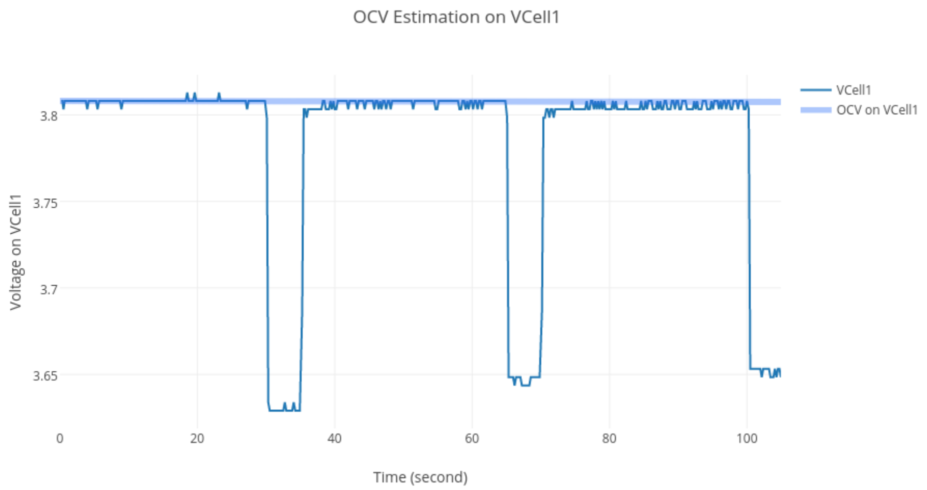


Figure 4.5. OCV Estimation of Cell 1

The result of OCV2 estimation is shown in figure 4.6, where the estimation value begin at 3.877 Volt at the first second to 3.807 volts at the end of data,

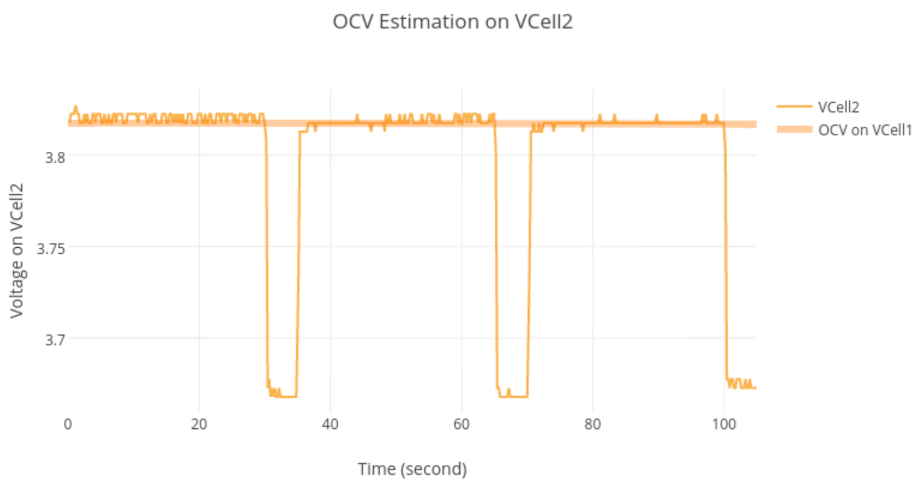


Figure 4.6. OCV estimation of Cell 3.

The result of OCV3 estimation is shown in figure 4.7, where the estimation value begin at 3.861 Volt at the first second to 3.860 volts at the end of data,

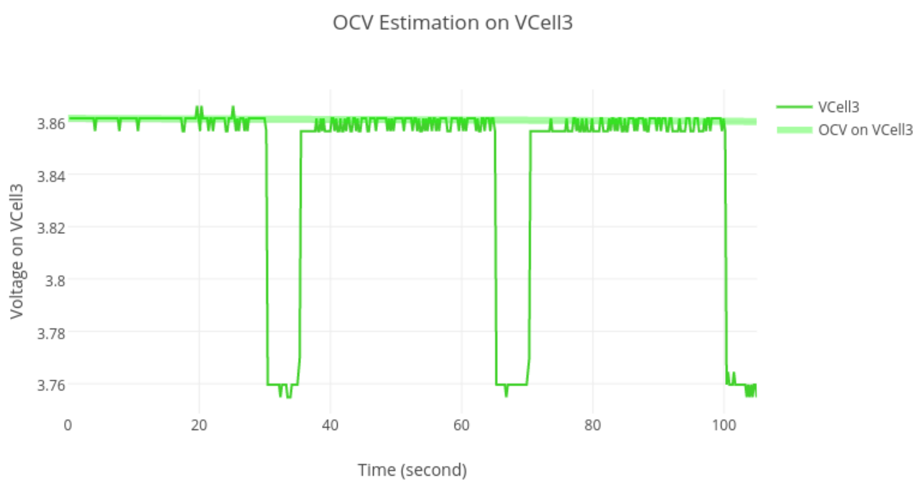


Figure 4.7. OCV estimation of Cell 3.

The result of OCV3 estimation is shown in figure 4.8, where the estimation value begin at 3.8516 Volt at the first second to 3.8510 volts at the end of data,

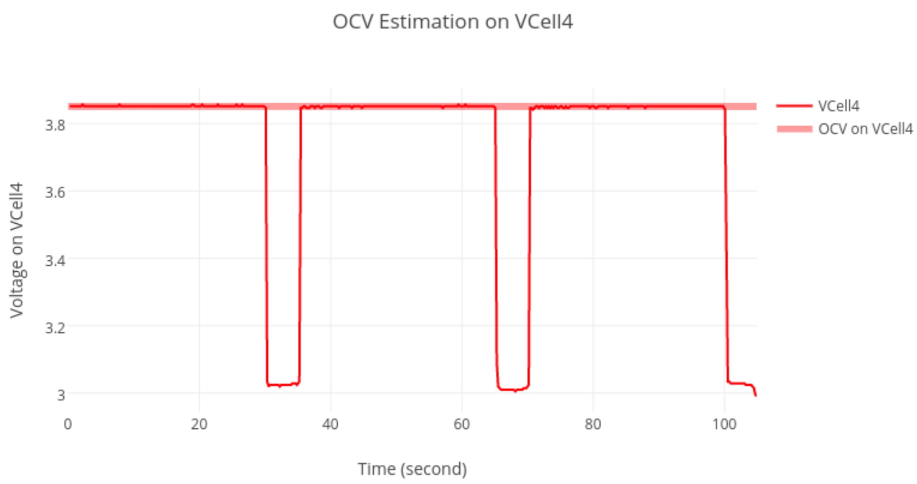


Figure 4.8. OCV estimation of Cell 4.

After estimating the OCV value, then SoC Value can be estimated excessively. Figure 4.9 below shows the result of SoC estimation on cell1. The graphic shows that the trending is continued decrease along with the data collection term. The SoC state at begin on 38.97% SoC to 38.83% at the end of data collection,

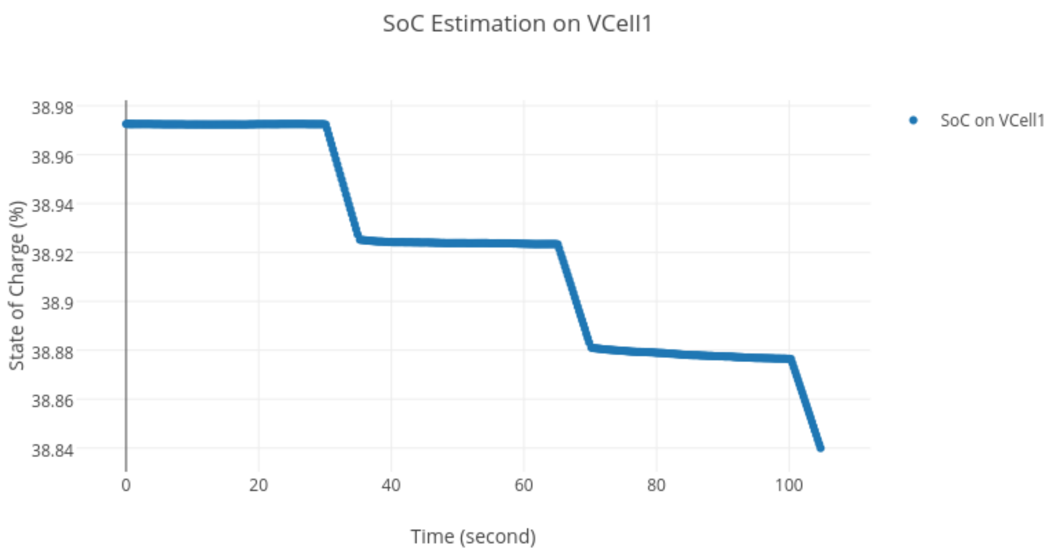


Figure 4.9. SoC estimaton of Cell 1.

Figure 4.10 below shows the result of SoC estimation on cell2. The graphic shows that the trending is continued decrease along with the data collection term. The SoC state at begin on 41.99% SoC to 41.88% at the end of data collection,

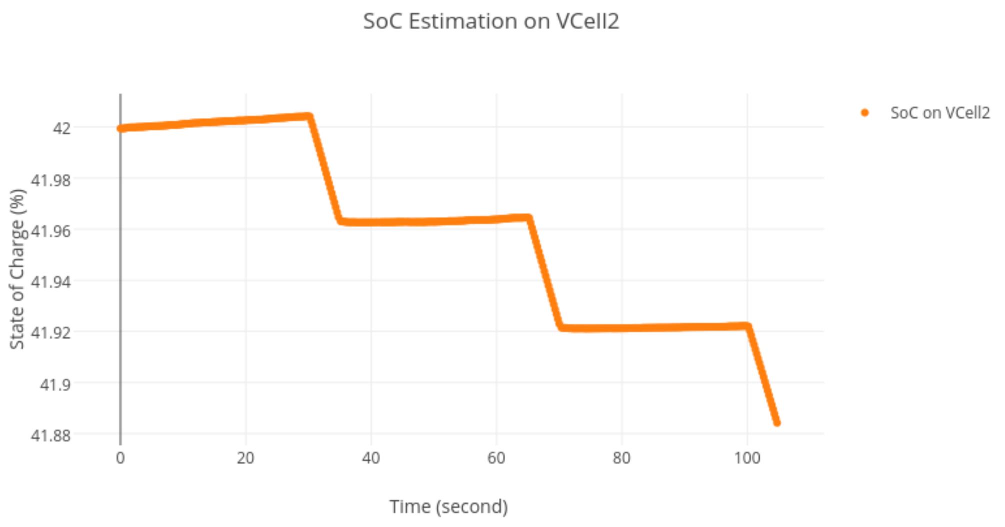


Figure 4.10. SoC estioamtion of Cell 2.

Figure 4.11 below shows the result of SoC estimation on cell3. The graphic shows that the trending is continued decrease along with the data collection term. The SoC state at begin on 52.84% SoC to 52.71% at the end of data collection,

Figure 4.11. SoC estimation of Cell 3.

Figure 4.12 below shows the result of SoC estimation on cell1. The graphic shows that the trending is continued decrease along with the data collection term. The SoC state at begin on 51.37% SoC to 51.24% at the end of data collection,

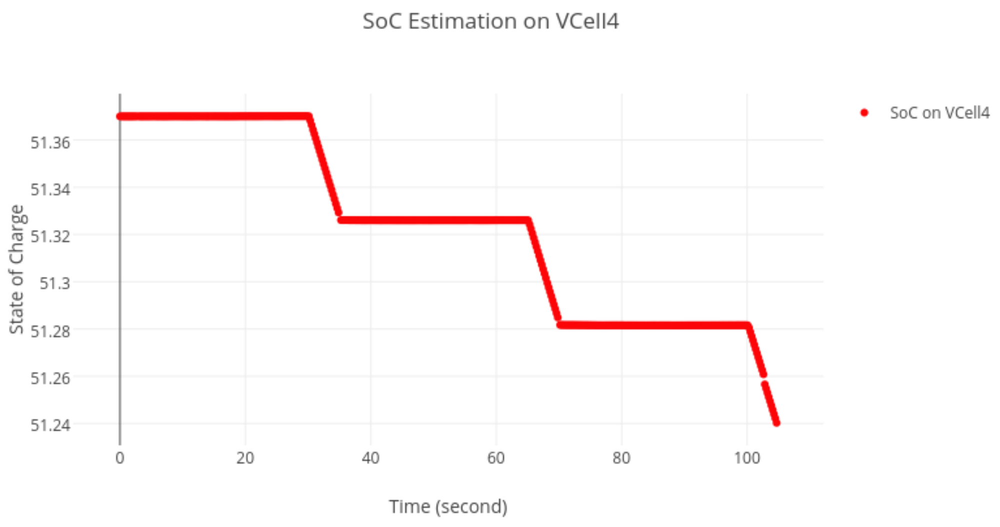


Figure 4.12. SoC estimation of Cell 4.

4.4 First Experiment of Balancing 4s Li-Po Battery in Charging State using 16.32 Constant Voltage and 1.1 Ampere Constant Current to 0.05% Error Tolerance of Each SoC's Steady State

The first charging experiment which has displayed in figure 4.13 is 4s lithium polymer battery's SoC in pack. The graphic contents have differences SoC of each cell at the beginning. SoC1 for cell1 is 70.46% SoC, SoC2 for cell2 is 59.40%, SoC3 for cell3 is 54.53, and SoC4 for cell4 is 56.54%,

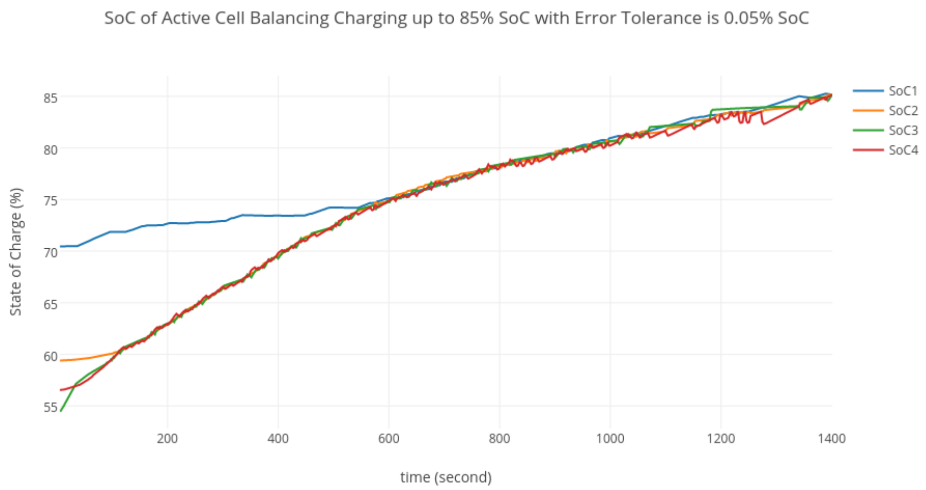


Figure 4.13. SoC of active cell balancing charging up to 85% at first experiment.

By established cell to cell active balancing algorithm in the charging process, the SoC of the cells get increased and leading to be balanced. The first three cells which reach the balancing state at the beginning at 142 secondss are cell2, cell3 and cell 4. The charging process continued until cell1 reach to the balancing state at 550 second. In this state, all of cells reached SoC at 74%, then the charging process continued until every cell reach SoC at 85% in 1400 seconds.

Table 4.2 presents data average and variance of 675 data along with data collection. Table 4.3 Shows the analysis variance of Table 42 that measured at alpha 0.05. The main table contents are F value and F critical. Based on calculation in section 3.5.5 , the result shows that the Hypothesis 0 is rejected which said that the means of cell1, cell2, cell3, and cell4 have an equal means. It is because F value is larger than F. This is also make sense since the state of all cells difference until 550 seconds.

Table 4.4 and table 4.5 are similar with table 4.2 and 4.3. The difference lies on the large of data test. In these table, the rest of 320 data in figure 4.13 has used. The decision to do this analysis was to proof that the algorithm able to hold its balanced position to the target charging state. The result of table 4.5 shows that the Hypothesis 0 is accepted by means the averages of cell1, cell2, cell3 and cell4 is equal. This conclusion approved since F value is less than F critical.

Table 4.2. Average and Variance of 675 data of figure 4.13,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Cell1	675	51449.87	76.22203	27.32466
Cell2	675	48968.17	72.54544	75.30376
Cell3	675	48832.87	72.34499	82.21665
Cell4	675	48757.47	72.23329	79.24148

Table 4.3 ANOVA of 674 data of figure 4.13,

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	7527.726	3	2509.242	38.00636	2.608204
Within Groups	177994.3	2696	66.02164		
Total	185522.1	2699			

Table 4.4. Average and Variance of the rest 320 data of figure 4.13,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	320	25679.24	80.24762	8.758271
Column 2	320	25643.28	80.13526	7.507867
Column 3	320	25657.28	80.17899	8.348923
Column 4	320	25573.01	79.91567	7.450145

Table 4.5. ANOVA of the rest 320 data of figure 4.13,

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	19.75964	3	6.586546	0.821644	2.611877
Within Groups	10228.8	1276	8.016302		
Total	10248.56	1279			

Figure 4.14 shows the OCV of figure 4.13 above. In this section, the ANOVA test also will be established to the figure's data. The graphic contents have differences OCV similar with the SoC if figure 4.13 of each cell at the beginning. OCV1 for cell1 is 3.96 Volt, OCV2 for cell2 is 3.89 Volt, OCV3 for cell3 is 3.86 Volt, and SoC4 for cell4 is 3.97 Volt.

During established cell to cell active balancing algorithm in charging process, the OCV of the cells got increased and leading to be balanced. Same of the SoC result, the first three cells which reach the balancing state at the beginning at 142 seconds are cell2, cell3 and cell 4. The charging process continued until cell1 reach to the balancing state at 550 seconds. In this state, all of cells reached OCV balancing state at 3.99 Volt, then the charging process continued until every cell reach final OCV balancing state at 4.09 Volt for the four cells in 1400 seconds. The graphic below is figure 4.14 that displayed the result,

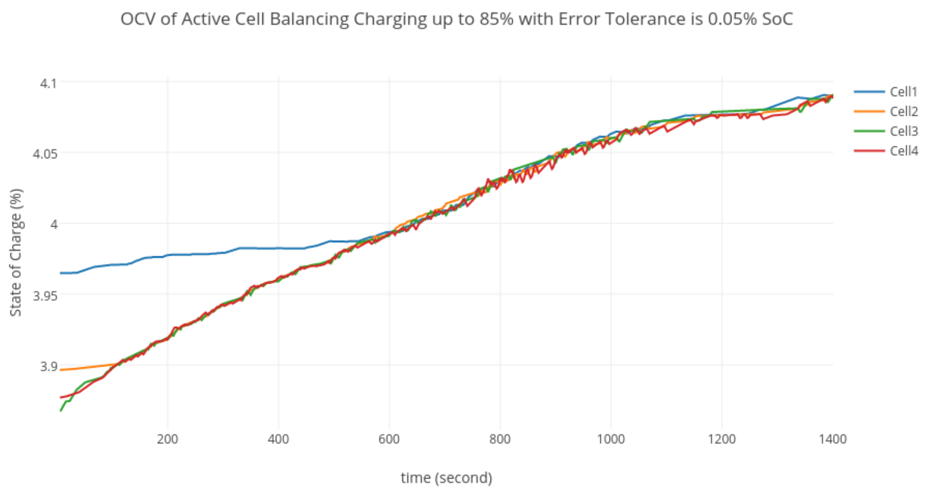


Figure 4.14. OCV of Active Cell Balancing Charging up to 85% at first experiment

Table 4.6 presents data average and variance of 675 data along with data collection. Table 4.7 Shows the analysis variance of Table 42 that measured at alpha 0.05. The main table contents are F value and F critical. Based on calculation in section 3.5.5 , the result shows that the Hypothesis 0 is rejected which said that the means of cell1, cell2, cell3, and cell4 have an equal means and Hypothesis 1 is accepted that said the average of the cells are notewual. It is because F value is larger than F. critical. This is also make sense since the OCV state of all cells are different until 550 seconds,

Table 4.6. Average and Variance of 675 data of figure 4.14,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	675	2708.025	4.011888	0.0017
Column 2	675	2693.224	3.989961	0.003973
Column 3	675	2692.351	3.988668	0.004293
Column 4	675	2691.747	3.987774	0.004157

Table 4.7. ANOVA of 674 data of figure 4.14,

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	0.271479476	3	0.090493	25.63026	2.608204
Within Groups	9.518810695	2696	0.003531		
Total	9.790290171	2699			

Table 4.8 and table 4.9 are similar with table 4.6 and 4.7. The difference lies on the large of data test. In these table, the rest of 320 data in figure 4.13 has used. The decision to do this analysis was to proof that the algorithm able to hold its balanced position to the target charging state. The result of table 4.9 shows that the Hypothesis 0 is accepted by means the averages of cell1, cell2, cell3 and cell4 is equal. This conclusion approved since F value is less than F critical value. In this condition give a clue that Hypothesis 1 is rejected which said that the averages of OCV due to cell1, cell2, cell3, and cell4 are unequal,

Table 4.8. Average and Variance of 320 data of figure 4.14,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	320	1295.759	4.049247	0.000872
Column 2	320	1295.541	4.048565	0.00077
Column 3	320	1295.612	4.048788	0.000838
Column 4	320	1294.988	4.046838	0.000806

Table 4.9. ANOVA of 320 data of figure 4.14,

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	0.001065575	3	0.000355	0.432476	2.611877
Within Groups	1.04797517	1276	0.000821		
Total	1.049040745	1279			

4.5 Second Experiment of Balancing 4s Li-Po Battery in Charging State using 16.82 Constant Voltage, 1.1 Ampere Constant Current to 0.05% Error Tolerance of Each SoC's Steady State, and Charge up to 95% SoC

The second charging experiment which has displayed in figure 4.15 is 4s lithium polymer battery's SoC in pack charging to 95%. The graphic contents have differences SoC of each cell at the beginning. SoC1 for cell1 is 70.46% SoC, SoC2 for cell2 is 50.3%, SoC3 for cell3 is 50.33, and SoC4 for cell4 is 48.34%,

By established cell to cell active balancing algorithm in charging process, the SoC of the cells get increased and leading to be balanced. The first three cells which reach the balancing state at the beginning at 45 seconds are cell2, cell3 and cell 4. The charging process continued until cell1 reach to the balancing state at 535 seconds. In this state, all of cells reached SoC at 70%, then the charging process continued until every cell reach SoC at 95% in 2115 seconds,

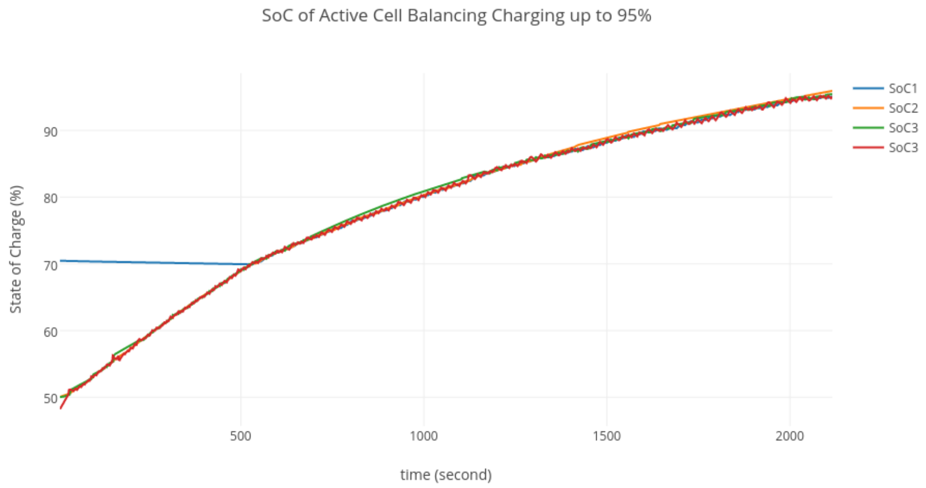


Figure 4.15. SoC of active cell balancing Charging up to 95% at second experiment

Table 4.10 presents data average and variance of 912 data along with charging process in figure 4.15. Table 4.11 Shows the analysis variance of Table 4.10 that measured at alpha 0.05. The main table contents are F value and F critical. Based on calculation in section 3.5.5 , the result shows that the Hypothesis 0 is rejected which said that the means of cell1, cell2, cell3, and cell4 have an equal means. It is because F value is larger than F. This is also make sense since the state of all cells difference until 535 seconds.

Table 4.10. Average and Variance of 912 data of figure 4.15,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	912	71913.9	78.85296	84.29265
Column 2	912	68784.63	75.42174	189.0801
Column 3	912	68826.97	75.46817	184.7962
Column 4	912	68636.99	75.25986	185.0893

Table 4.11. ANOVA of 912 data of figure 4.15,

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*

Between Groups	8256.4	3	2752.133	17.11371	2.607346
Within Groups	586008.3	3644	160.8146		
Total	594264.7	3647			

Table 4.12 and table 4.13 are similar with table 4.10 and 4.11. The difference lies on the large of data test. In these table, the rest of 598 data in figure 4.13 has used. The decision to do this analysis was to proof that the algorithm able to hold its balanced position to the target charging state. The result of table 4.13 shows that the Hypothesis 0 is accepted by means the averages of cell1, cell2, cell3 and cell4 is equal. This conclusion approved since F value is less than F critical.

Table 4.12. Average and Variance of the rest 598 data of figure 4.15,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	598	49954.14	83.53536	56.60587
Column 2	598	50112.46	83.8001	60.0221
Column 3	598	50120.72	83.81392	55.46647
Column 4	598	49979.16	83.57719	56.42886

Table 4.13. ANOVA of the rest 598 data of figure 4.15,

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	38.17523	3	12.72508	0.222736	2.608629
Within Groups	136428.4	2388	57.13083		
Total	136466.6	2391			
Total	10248.56	1279			

Figure 4.16 shows the OCV of figure 4.15 above. In this section, the ANOVA test also will be established to the figure's data. The graphic contents have differences OCV similar with the SoC if figure 4.15 of each cell at the beginning. OCV1 for cell1 is 3.96 Volt, OCV2 for cell2 is 3.84 Volt, OCV3 for cell3 is 3.84 Volt, and SoC4 for cell4 is 3.87 Volt.

During established cell to cell active balancing algorithm in charging process, the OCV of the cells got increased and leading to be balanced. Same of the SoC result, the first three cells which reach the balancing state at the beginning at 43 seconds are cell2, cell3 and cell 4. The charging process continued until cell1 reach to the balancing state at 535 seconds. In this state, all of cells reached OCV balancing state at 3.96 Volt, then the charging process continued until every cell reach final OCV balancing state at 4.17 Volt for the four cells in 2115 seconds. The graphic below is figure 4.14 that displayed the result,

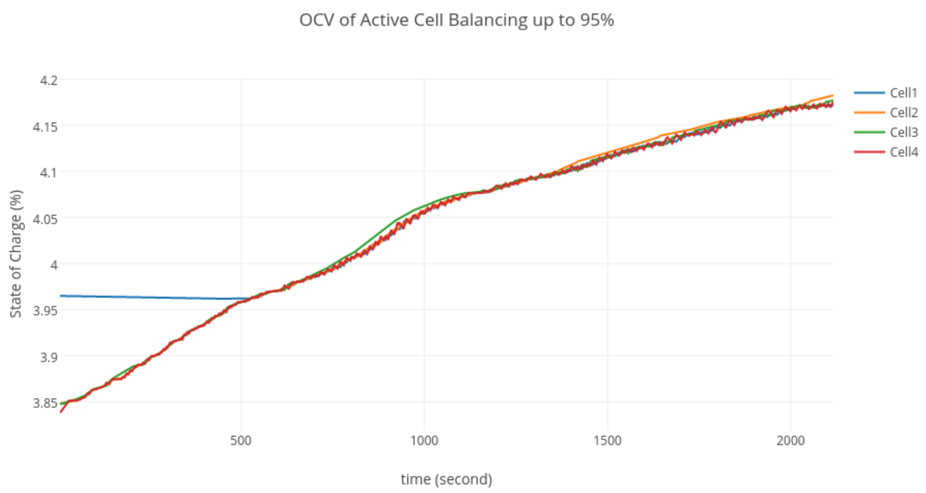


Figure 4.16 OCV of active cel balancing charging up to 95% SoC at second experiment.

Table 4.14 presents data average and variance of 912 data along with data collection. Table 4.15 shows the analysis variance of Table 4.14 that measured at alpha 0.05. The main table contents are F value and F critical. Based on calculation in section 3.5.5 , the result shows that the Hypothesis 0 is rejected which said that the means of cell1, cell2, cell3, and cell4 have an equal means and Hypothesis 1 is accepted that said the average of the cells are notewual. It is because F value is larger than F. critical. This is also make sense since the OCV state of all cells are different until 523 seconds,

Table 4.14. Average and Variance of 912 data of figure 4.16,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	912	3681.202	4.036405	0.005618
Column 2	912	3662.909	4.016347	0.010499
Column 3	912	3663.192	4.016658	0.010221
Column 4	912	3661.54	4.014847	0.010191

Table 4.15. ANOVA test of 912 data of figure 4.16.

ANOVA

Source of Variation	SS	df	MS	F	F crit
Between Groups	0.287895184	3	0.095965	10.50841	2.607346
Within Groups	33.27779026	3644	0.009132		
Total	33.56568544	3647			

Table 4.16 and table 4.17 are similar with table 4.6 and 4.7. The difference lies on the large of data test. In these table, the rest of 598 data in figure 4.15 has used. The decision to do this analysis was to proof that the algorithm able to hold its balanced position to the target charging state. The result of table 4.9 shows that the Hypothesis 0 is accepted by means the averages of cell1, cell2, cell3 and cell4 is equal. This conclusion approved since F value is less than F critical value. In this condition give a clue that Hypothesis 1 is rejected which said that the averages of OCV due to cell1, cell2, cell3, and cell4 are unequal,

Table 4.16. Average and Variance of the rest 598 data of figure 4.16,

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	598	2436.808	4.074929	0.004254
Column 2	598	2438.262	4.077362	0.004519
Column 3	598	2438.365	4.077533	0.004157
Column 4	598	2436.999	4.075249	0.00425

Table 4.17. ANOVA of the rest 598 data of figure 4.16,

ANOVA

Source of Variation	SS	df	MS	F	F crit
Between Groups	0.00336451	3	0.001122	0.261126	2.608629
Within Groups	10.25614206	2388	0.004295		
Total	10.25950657	2391			

4.6 Third Experiment of Balancing 4s Li-Po Battery in Charging State using 17.32 Constant Voltage, 1.1 Ampere Constant Current to 0.05% Error Tolerance of Each SoC's Steady State, and Charge up to 95% SoC

The third charging experiment which has displayed in figure 4.17 is 4s lithium polymer battery's SoC in pack charging to 95%. The graphic contents have differences SoC of each cell at the beginning. SoC1 for cell1 is 70.46% SoC, SoC2 for cell2 is 65.50%, SoC3 for cell3 is 67.00, and SoC4 for cell4 is 57.77%,

By established cell to cell active balancing algorithm in charging process, the SoC of the cells get increased and leading to be balanced. The first three cells which reach the balancing state at the beginning at 118 seconds are cell1, cell2 and cell 4. The charging process continued until cell1 reach to the balancing state at 289 seconds. In this state, all of cells reached SoC at 73,44%, then the charging process continued until every cell reach SoC at 95% in 1565 seconds,

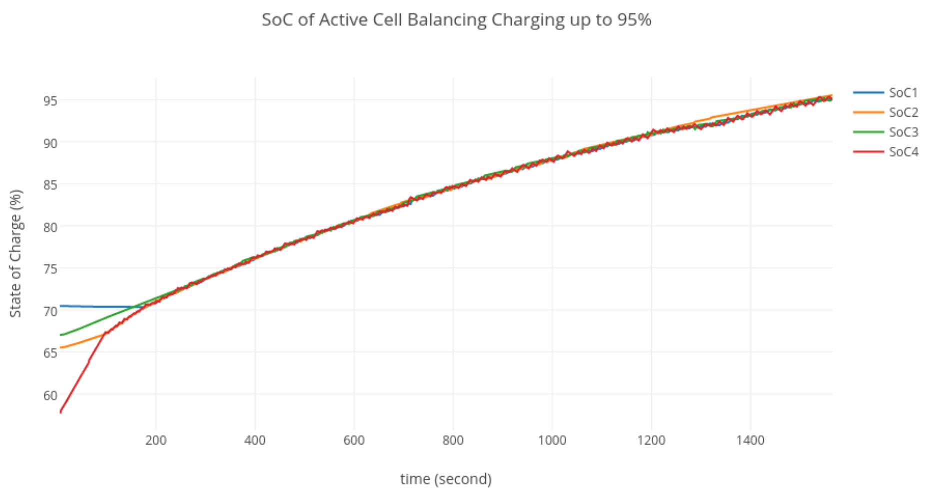


Figure 4.17. SoC of active cell balancing charging up to 95% SoC at the third experiment

Table 4.18 presents data average and variance of 777 data along with charging process in figure 4.17. Table 4.19 Shows the analysis variance of Table 4.18 that measured at alpha 0.05. The main table contents are F value and F critical. Based on calculation in section 3.5.5 , the result shows that the Hypothesis 0 is rejected which said that the means of cell1, cell2, cell3, and cell4 have an equal means. It is because F value is larger than F. This is also make sense since the state of all cells difference until 289 seconds.

Table 4.18. Average and Variance of 912 data of figure 4.17,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	777	63019.19	81.10578	74.27481
Column 2	777	62768.67	80.78336	88.58101
Column 3	777	62931.23	80.99257	80.28988
Column 4	777	62426.07	80.34243	97.76101

Table 4.19 ANOVA of 777 data of figure 4.17,

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	264.2436	3	88.0812	1.033493	2.607771
Within Groups	264543.6	3104	85.22668		
Total	264807.9	3107			

Table 4.20 and table 4.22 are similar with table 4.18 and 4.19. The difference lies on the large of data test. In these table, the rest of 637 data in figure 4.17 has used. The decision to do this analysis was to proof that the algorithm able to hold its balanced position to the target charging state. The result of table 4.21 shows that the Hypothesis 0 is accepted by means the averages of SoC at cell1, cell2, cell3 and cell4 are equal. This conclusion approved since F value is less than F critical,

Table 4.20. Average and Variance of the rest 637 data of figure 4.17,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	637	53234.02	83.56989	49.1328
Column 2	637	53349.07	83.7505	51.28815
Column 3	637	53325.89	83.71412	48.92659
Column 4	637	53269.49	83.62558	48.93896

Table 4.21. ANOVA test of the rest of 637 data of figure 4.17,

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	12.94599	3	4.315331	0.087052	2.608401
Within Groups	126110.2	2544	49.57162		
Total	126123.2	2547			

Figure 4.18 shows the OCV of figure 4.17 above. In this section, the ANOVA test also will be established to the figure's data. The graphic contents have differences OCV similar with the SoC if figure 4.17 of each cell at the beginning. OCV1 for cell1 is 3.96 Volt, OCV2 for cell2 is 3.93 Volt, OCV3 for cell3 is 3.94 Volt, and SoC4 for cell4 is 3.88 Volt.

During established cell to cell active balancing algorithm in charging process, the OCV of the cells got increased and leading to be balanced. Same of the SoC result, the first three cells which reach the balancing state at the beginning at 43 seconds are cell1, cell2 and cell 4. The charging process continued until cell1 reach to the balancing state at 289 seconds. In this state, all of cells reached OCV balancing state at 3.98 Volt, then the charging process continued until every cell reach final OCV balancing state at 4.17 Volt for the four cells in 1565 seconds. The graphic below is figure 4.18 that displayed the result,

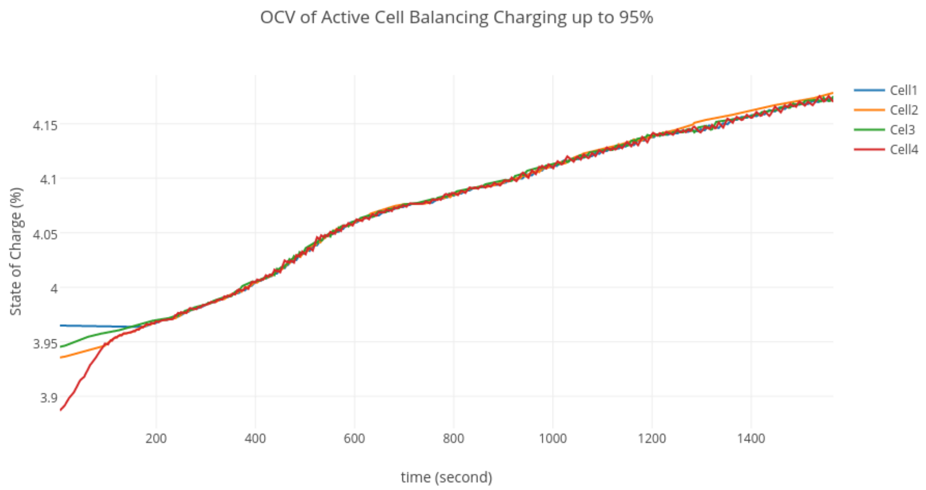


Figure 4.18. OCV of active cell balancing charging up to 95% SoC at the fourth experiment

Table 4.22 presents data average and variance of 777 data along with data collection. Table 4.23 shows the analysis variance of Table 4.14 that measured at alpha 0.05. The main table contents are F value and F critical. Based on calculation in section 3.5.5 , the result shows that the Hypothesis 0 is acceppted which said that the means of cell1, cell2, cell3, and cell4 have an equal with seignificant level at 0.05.Then the Hypothesis 1 is rejected that said the average of the cells are not equal. It is because F value is less than F. critical. In this case, the H0 is accepted even the entire populations of each cell was calculated. The reason is because at the begin of the charging process, all of the cells are almost balanced. The accepted of H0 in this case also make sense since the OCV state of all cells are balanced in earlier seconds,

Table 4.22. Average and Variance of 777 data of figure 4.18,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	777	3150.849	4.055146	0.004893
Column 2	777	3149.827	4.053832	0.005605
Column 3	777	3150.743	4.055011	0.005153
Column 4	777	3147.45	4.050772	0.005998

Table 4.23. ANOVA test of 777 data of figure 4.18.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	0.009632	3	0.003211	0.593233	2.607771
Within Groups	16.79959	3104	0.005412		
Total	16.80922	3107			

Table 4.24 and table 4.25 are similar with table 4.22 and 4.23. The difference lies on the large of data test. In these table, the rest of 637 data in figure 4.17 was used. The decision to do this analysis was to proof that the algorithm able to hold its balanced position to the target charging state. The result of table 4.25 shows that the Hypothesis 0 is accepted by means the averages of OCV at cell1, cell2, cell3 and cell4 are equal. This conclusion approved since F value is less than F critical. Even in the ANOVA test of entire populations at table 4.23 calculation accepted H0, but in this calculation the F value of table 4.25 still less than the F value of 4.23,

Table 4.24. Average and Variance of the rest 637 data of figure 4.18,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	637	2595.826	4.075079	0.003762
Column 2	637	2596.813	4.07663	0.003926
Column 3	637	2596.607	4.076307	0.003754
Column 4	637	2596.158	4.075602	0.003743

Table 4.25. ANOVA test of the rest 637 data of figure 4.18.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	0.00093	3	0.00031	0.081691	2.608401
Within Groups	9.657551	2544	0.003796		
Total	9.658481	2547			

4.7 Fourth Experiment of Balancing 4s Li-Po Battery in Charging State using 17.32 Constant Voltage, 1.1 Ampere Constant Current to 0.05% Error Tolerance of Each SoC's Steady State, and Charge up to 95% SoC

The fourth charging experiment which has displayed in figure 4.19 is 4s lithium polymer battery's SoC in pack charging to 95%. The graphic contents have differences SoC of each cell at the beginning. SoC1 for cell1 is 68.29% SoC, SoC2 for cell2 is 69.59%, SoC3 for cell3 is 67.55, and SoC4 for cell4 is 58.85%,

By established cell to cell active balancing algorithm in charging process, the SoC of the cells get increased and leading to be balanced. The first two cells which reach the balancing state at the beginning at 118 seconds are cell1 and cell 4. The charging process continued until cell1 reach to the balancing state at 426 seconds. In this state, all of cells reached SoC at 68%, then the charging process continued until every cell reach SoC at 95% in 1756 seconds,

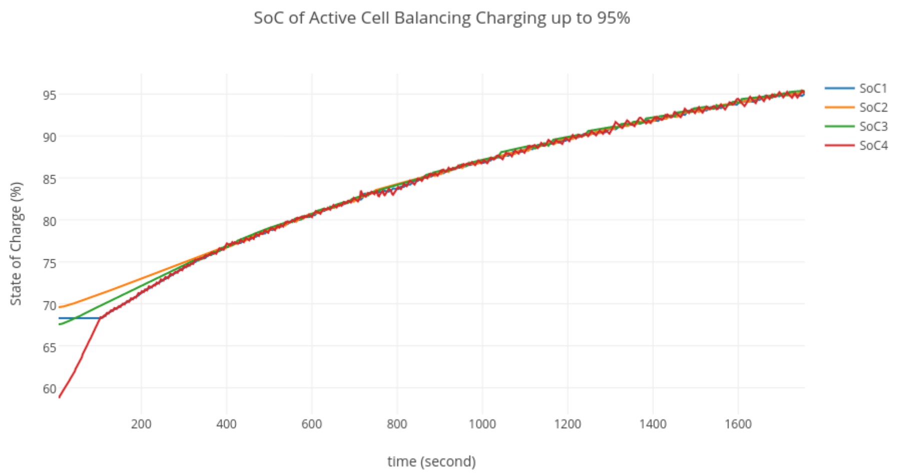


Figure 4.19. SoC of charging to 95% SoC at the fourth experiment.

Table 4.26 presents data average and variance of 828 data along with charging process in figure 4.19. Table 4.27 shows the analysis of variance of Table 4.26 that measured at alpha 0.05. The main table contents are F value and F critical. Based on calculation in section 3.5.5 , the result shows that the Hypothesis 0 is accepted which means that cell1, cell2, cell3, and cell4 have an equal means. This case is same with the third experiment at OCV calculation section. The H0 is accepted even the entire SoC populations of each cell was calculated. The reason is because at the begin of the charging process, all of the cells are almost balanced. The accepted of H0 in this case also make sense since the SoC state of all cells are balanced in earlier seconds,

Table 4.26. Average and variance of 828 data of figure 4.19,

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	828	67532.46	81.56095	78.97036
Column 2	828	67957.71	82.07453	68.98808
Column 3	828	67792.21	81.87466	76.34532
Column 4	828	67217.76	81.18088	92.57647

Table 4.27. ANOVA test of 828 data of figure 4.19.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*F crit*
Between Groups	378.0912	3	126.0304	1.59089	2.607594
Within Groups	262060	3308	79.22006		
Total	262438	3311			

Table 4.28 and table 4.29 are similar with table 4.26 and 4.27. In the tables we used the rest of 548 data in figure 4.19 has used. The decision to do this analysis was to proof that the algorithm able to hold its balanced position to the target charging state. The result of table 4.29 shows that the Hypothesis 0 is accepted by means the averages of SoC at cell1, cell2, cell3 and cell4 are equal till the end of charging process. This conclusion approved since F value is less than F critical. Even in the ANOVA test of entire populations at table 4.27 calculation accepted H0, but in this calculation the F value of table 4.29 still less than the F value of table 4.27,

Table 4.28 Average and variance of the rest 548 data of figure 4.19,

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	548	47497.64	86.67453	27.62794
Column 2	548	47531.56	86.73642	27.46113
Column 3	548	47605.48	86.87132	27.549
Column 4	548	47512.18	86.70106	27.71531

Table 4.29. ANOVA test of the rest 548 data of figure 4.19.

ANOVA

Source of Variation	SS	df	MS	F	F crit
Between Groups	12.56234	3	4.187447	0.151783	2.60897
Within Groups	60363.3	2188	27.58835		
Total	60375.86	2191			

Figure 4.20 shows the OCV of figure 4.19 above. In this section, the ANOVA test also will be established to the figure's data. The graphic contents have differences OCV similar with the SoC if figure 4.19 of each cell at the beginning. OCV1 for cell1 is 3.9550 Volt, OCV2 for cell2 is 3.9599 Volt, OCV3 for cell3 is 3.9501 Volt, and SoC4 for cell4 is 3.8916 Volt.

During established cell to cell active balancing algorithm in charging process, the OCV of the cells got increased and leading to be balanced. Same of the SoC result, the first two cells which reach the balancing state at the beginning at 188 seconds are cell1, cell2 and cell 4. The charging process continued until cell1 reach to the balancing state at 426 seconds. In this state, all of cells reached OCV balancing state at 4.01 Volt, then the charging process continued until every cell reach final OCV balancing state at 4.17 Volt for the four cells in 1756 seconds. The graphic below is figure 4.18 that displayed the result,

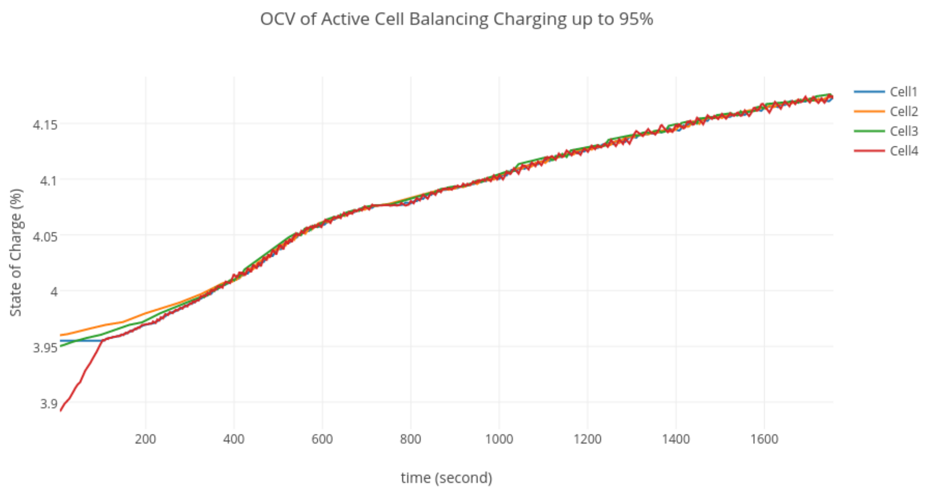


Figure 4.20. OCV of active cell balancing charging up to 95% SoC in the fourth experiment.

Table 4.30 presents data average and variance of 826 data along with data collection. Table 4.23 shows the analysis variance of Table 4.30 that measured at alpha 0.05. The main table contents are F value and F critical. Based on calculation in section 3.5.5 , the result shows that the Hypothesis 0 is acceppted which sid that the means of cell1, cell2, cell3, and cell4 are equal with seignificant level at 0.05.Then the Hypothesis 1 is rejected that said the average of the cells are not equal. It is because F value is less than F. critical. In this case, the H0 is accepted even the entire populations of each cell was calculated. The reason is because at the begin of the charging process, all of the cells are almost balanced. The accepted of H0 in this case also make sense since the OCV state of all cells are balanced in earlier seconds (at 426 seconds),

Table 4.30. Average and Variance of 828 data of figure 4.20.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	828	3361.754	4.06009	0.005041
Column 2	828	3364.126	4.062954	0.004604
Column 3	828	3363.566	4.062278	0.004954
Column 4	828	3359.709	4.05762	0.005745

Table 4.31. ANOVA test of 828 data of figure 4.20.

ANOVA

Source of Variation	SS	df	MS	F	F crit
Between Groups	0.014428	3	0.004809	0.945595	2.607594
Within Groups	16.82437	3308	0.005086		
Total	16.8388	3311			

Table 4.32 and table 4.33 are similar with table 4.30 and 4.32. The difference liess on the large of data test. In these tables, the rest of 548 data in figure 4.32 was used. The decision to do this analysis was to proof that the algorithm able to hold its balanced position to the target charging state. The result of table 4.25 shows that the Hypothesis 0 is accepted by means the averages of OCV at cell1, cell2, cell3 and cell4 are equal. This conclusion approved since F value is less than F critical. Even in the ANOVA test of entire populations at table 4.2\31 calculation accepted H0, but in this calculation the F value of table 4.33 still less than the F value of 4.31.The test proved that the averages of populations in table 4.33 is closed to equal rather than table 4.31,

Table 4.32. Average and Variance of 828 data of figure 4.20.

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	548	2248.75	4.103559	0.00183
Column 2	548	2249.043	4.104093	0.001814
Column 3	548	2249.757	4.105396	0.001799
Column 4	548	2248.901	4.103834	0.001831

Table 4.33 ANOVA test of the rest 548 data of figure 4.20.

ANOVA

Source of Variation	SS	df	MS	F	F crit
Between Groups	0.001088	3	0.000363	0.199496	2.60897
Within Groups	3.978573	2188	0.001818		
Total	3.979662	2191			

4.8 Research Contributions

At the beginning of data collecting, pulse tests to get the internal resistances of each cell is already done. After getting the data, then estimating OCV and SoC of each cell has established. Then the charging experiments have been done also using Cell to Cell Active Balancing Method. To control the MOSFET's using Fuzzy Logic Controller based on error input between two adjacent cells. The result in these experiments was succeeded to be balanced the cells and the analysis to justify our hypothesis of balancing statement using Analysis of Variance. All of the Anova tests accepted the statements that all of the means of populations of each cell in battery pack are equal. The hardware setup also succeeded to deliver the algorithm to reach the goals.

The review from the previous study which was delivered by Erika Loniza in 2016, she used the average from Open Circuit Voltage of each cell to do the balancing technique. Bobby and Bhisma in 2014 provide the battery modeling and this thesis follow the method From Javier Gallardo study result in 2014 provide the topology circuit of the cell to cell PWM controlled converter.

The systematic study of the research in active balancing method find fuzzy logic controller to determine the PWM output of the MOSFET and the error between adjacent cells to do the balancing process is explained and already established in the algorithm. Every literature which have explained in literature review section at point 2.1 above are construct the balancing topology circuit, the balancing algorithm and the battery modeling. But the balancing algorithm in detail is produce by doing the research. The statement also strengthen the contribution of the result of this thesis. Table 4.34 below presents the summary of all of the experiments result using the proposed method,

Table 4.34. Summary of the experiments result.

No. Experiments	Charging Target to	The Cells	Initial SoC (%)	End of SoC After Charging (%)	Duration (minute)	Data Count	Average	Variance	F Value	F Critical Value	The Accepted Hypothesis
I	85% SoC	Cell1	70.4642	85.1635	29.2678	320	80.2476	8.7583	0.8216	2.6119	H0
		Cell2	59.4052	85.1795		320	80.1353	7.5079			
		Cell3	54.5333	85.1883		320	80.1790	8.3489			
		Cell4	56.5496	85.1407		320	79.9157	7.4501			
II	95% SoC	Cell1	70.4642	95.0594	35.2606	598	83.5354	56.6059	0.2227	2.6086	H0
		Cell2	50.0330	95.9236		598	83.8001	60.0221			
		Cell3	50.0330	95.4373		598	83.8139	55.4665			
		Cell4	48.3449	95.0811		598	83.5772	56.4289			
III	95% SoC	Cell1	70.4642	95.1510	26.0920	637	83.5699	49.1328	0.0871	2.6084	H0
		Cell2	65.5054	95.5465		637	83.7505	51.2881			
		Cell3	67.0059	95.0938		637	83.7141	48.9266			
		Cell4	57.7747	95.0569		637	83.6256	48.9390			
IV	95% SoC	Cell1	68.2852	95.0539	29.2678	548	86.6745	27.6279	0.1518	2.6090	H0
		Cell2	69.5992	95.2324		548	86.7364	27.4611			
		Cell3	67.5509	95.2149		548	86.8713	27.5490			
		Cell4	58.8562	95.2645		548	86.7011	27.7153			
V	95% SoC	Cell1	60.4009	95.3084	47.4349	831	85.5934	36.3657	0.0683	2.6076	H0
		Cell2	69.5992	95.1917		831	85.5299	36.2236			
		Cell3	60.4009	95.1188		831	85.5592	35.3528			
		Cell4	75.1720	95.3355		831	85.4656	35.2534			
VI	95% SoC	Cell1	86.3282	95.0799	32.2075	323	90.9066	7.2243	0.2405	2.6118	H0
		Cell2	60.4009	95.4065		323	91.0291	7.4721			
		Cell3	50.0330	95.2929		323	91.0017	7.2693			
		Cell4	25.0870	95.0495		323	90.8759	7.1547			
VII	95% SoC	Cell1	75.1720	95.1699	60.0697	858	86.9130	36.3042	0.1259	2.6075	H0
		Cell2	36.5803	95.2227		858	87.0295	36.8355			
		Cell3	67.0059	95.0350		858	86.9576	36.2829			
		Cell4	22.4227	95.0442		858	86.8566	36.1168			
VIII	95% SoC	Cell1	86.9265	95.0764	58.3344	500	90.7926	8.3598	0.8192	2.6094	H0
		Cell2	25.0870	95.4787		500	90.8636	8.7215			
		Cell3	62.4449	95.4357		500	90.8194	8.6639			
		Cell4	17.8580	95.0667		500	90.5958	8.4658			

CHAPTER V

5 Conclusion and Recommendation

5.1 Conclusion

Based on the results of the experiments, the conclusions can be drawn as follows,

1. Pulse tests that have been established succeeded to estimate the internal resistance of each cell.
2. Simple *Rint* battery model is succeeded to estimate the OCV and SoC values of each cell.
3. The error calculation between two adjacent cells for input of Fuzzy Logic Controller (FLC) succeed to determine the PWM output to drive the MOSFET's of Cell to Cell Controlled Converter arrangement.
4. The fuzzy logic configuration is succeeded to determine from input to output of controlling system.
5. The Analysis proved that the method can hold the balancing state until reach the SoC target.

5.2 Recommendation

For the further research, some improvement can be tried to get more satisfying results:

1. In the proposed method, the transfer capacity just can be done to adjacent cells. To improve the weakness, the *flyback converter* can be added to balancing circuits in order to do direct energy transfer from the larger cell capacity to the lowest one.
2. The others battery modeling algorithm also can be tried to estimate the OCV and SoC of the cells to get more comparison and improvement to the estimation.
3. For the controlling method, other methods also can be tried to get the improvement results.
4. In cell to cell active balancing method, can be tried another method such as *Switched Capacitors* method. The method is look like simple and the cost to build the circuit probably less than the proposed method.
5. The number of the cells in battery pack can be increased for the further study.

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APPENDIX

Appendix .1. **Pseudecode**

```
Initialize Ch0, Ch1, Ch3, and Ch4 as Input Cells Voltage

Initialize Q1, Q2, Q3, Q4, Q5, and Q6 as Output PWM

Initialize SoC1, SoC2, SoC3, and SoC4 as State of Charge of Each Cell

InitializeOCV1, OCV2, OCV3, and OCV4 as Open Circuit Voltage of Each Cell

Initialize R1, R2, R3, and R4 as Internal Resistance of Each cell

Initialize Cn as The Cells Capacity

Initialize second[], OCV1[], OCV2[], OCV3[], OCV4[], SoC1[], SoC2[], SoC3[], SoC4[], Vt1[], Vt2[],
Vt3[], Vt4[] as Array

Initialize k, i as index

READ SoC_OCV.csv as f

OCV = coulomb1 (open circuit voltage)

SoC = coulomb2 (state of charge)

f = coloumb3 (gradien)

SETTING FUZZY LOGIC CONTROLLER as pwm(value)

OCV1, OCV2, OCV3, OCV4 = 0

SoC1, SoC2, SoC3, SOC4 = 0

R1, R2, R3, R4 = internal resistance of cell1, cell2, cell3, cell4

Cn = 2200, Second= 0

e1, e2, e3, e4 = 0

k = 0, i = 0

While True:

        Vt1[] = Ch0

        Vt2[] = Ch1

        Vt3[] = Ch3

        Vt4[] = Ch4

        Second [ ]← present

        FOR i in Range length of (f):

                IF OCV1[k-1]<=[i] and OCV1[k-1] >= OCV[i+1]:

                        Grad1 = f[i+1] soc1  = SOC[i+1]+grad1*100*(OCV1[k-1]-OCV[i+1])
```

```
                    SoC1[] =  SoC[i+1]+Grad1*100*(OCV1[k-1]-OCV[1+1])
FOR i in Range length of (f):
        IF OCV2[k-1]<=[i] and OCV2[k-1] >= OCV[i+1]:
                    Grad2 = f[i+1]
                    SoC2[] =  SoC[i+1]+Grad2*100*(OCV2[k-1]-OCV[1+1])
FOR i in Range length of (f):
        IF OCV3[k-1]<=[i] and OCV3[k-1] >= OCV[i+1]:
                    Grad3 = f[i+1]
                    SoC3[] =  SoC[i+1]+Grad3*100*(OCV3[k-1]-OCV[1+1])
FOR i in Range length of (f):
        IF OCV4[k-1]<=[i] and OCV4[k-1] >= OCV[i+1]:
                    Grad4 = f[i+1]
                    SoC4[] =  SoC[i+1]+Grad4*100*(OCV4[k-1]-OCV[1+1])
C1 = Cn*Grad1*3.6
C2 = Cn*Grad2*3.6
C3 = Cn*Grad3*3.6
C4 = Cn*Grad4*3.6
Dt = second[k]-second[k-1]
Alfa1 = Dt/(Dt+(R1*C1))
Alfa2 = Dt/(Dt+(R2*C2))
Alfa3 = Dt/(Dt+(R3*C3))
Alfa4 = Dt/(Dt+(R4*C4))
OCV1[] = OCV[k-1]*(1-Alfa)+Vt1[k]*Alfa
OCV2[] = OCV[k-1]*(1-Alfa)+V21[k]*Alfa
OCV3[] = OCV[k-1]*(1-Alfa)+Vt3[k]*Alfa
OCV4[] = OCV[k-1]*(1-Alfa)+Vt4[k]*Alfa
Average[] = (SoC1[k]+SoC2[k]+SoC3[k]+SoC4[k])/4
IF SoC1[k] >= 96 or SoC2[k] >= 96 or SoC3[k] >= 96 or SoC4[k] >= 96:
        Q1, Q2,Q3,Q4, Q5, Q6 = pwm.Stop()
        Stop_Charging()
        PRINT “One of Cells is greater than 95% SoC”
```

```
            PRINT "PLEASE CHECK THE BATTERY VOLTAGE"

            Break

        ELSE IF (e1 and e2 and e3 ) >=0.05 and (SoC1[k] and SoC2[k] and SoC3[k] and SoC4[k])
>=95:

            Q1, Q2,Q3,Q4, Q5, Q6 = pwm.Stop()

            Stop_Charging()

            PRINT "THE CELLS ARE BALANCED"

            Break

        IF (absolute(SoC1[k]-Average[k])<=0.05 and absolute(SoC2[k]-Average[k])<=0.05 and
        absolute(SoC3[k]-Average[k]) <=0.05 and absolute(SoC4[k]-Average[k]<=0.05)):

            Q1,Q2,Q3,Q4 = 0

        ELSE IF (abs(SoC1[k]-Average[k])>0.05 and abs(SoC2[k]-Average[k])>0.05 and abs(SoC[k]-
        Average[k]) >0.05 and abs (SoC4[k]-Average[k]>0.05)):

            R = [All of the SoC Cells Values]

            r = the smallest SoC in (R) array

            e1 = absolute(SoC1[k]-SoC2[k])

            e2 = absolute(SoC2[k]-SoC3[k])

            e3 = absolute(SoC3[k]-SoC4[k])

            e1 = Compute.Fuzzy(e1)

            e2 = Compute.Fuzzy(e2)

            e3 = Compute.Fuzzy(e3)

            IF r == SoC1[k]:

                Q1 = pwm(0), Q2 = pwm(e1), Q3 = pwm(0), Q4 = pwm(e2), Q5=0, Q6=pwm(e3)

            ELSE IF r == SoC2[k]:

                Q1 = pwm(e1), Q2 = pwm(0), Q3 = pwm(0), Q4 = pwm(e2), Q5 = pwm(0), Q6 =
                pwm(e3)

            ELSE IF r == SoC3[k]:

                Q1 = pwm(e1), Q2 = pwm(0), Q3 = pwm(e2), Q4 = pwm(0), Q5 = pwm(0), Q6 =
                pwm(e3)

            ELSE IF r == SoC4[k]:

                Q1 = pwm(e1), Q2 = pwm(0), Q3 = pwm(e2), Q4 = pwm(0), Q5 = pwm(e3), Q6 =
                pwm(0)

        Start.Charging()

        k += 1
```

Appendix.2. **Supplementary Graphics**