University of Southern Queensland

Faculty of Health, Engineering and Sciences

Mathematical modelling of the Nickel Iron Battery

A dissertation submitted by

Jacob Febryadi Nithanel Dethan

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ENG8411/ENG8412 Masters Dissertation Project

(This is a 3 unit research project in a 16 unit Master of Engineering Science program)

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CERTIFICATION

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I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Student Name : Jacob Febryadi Nithanel Dethan

Student Number: 0061065369

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ABSTRACT

The main issue facing the renewable energy power plants nowadays is the availability of a durable energy storage system. The commonly used battery around the world for energy storage system is the lead acid battery which has life time typically ranging from 3 years to 5 years. On the other hand, the nickel iron battery has potentially a longer cycle life compared to any rechargeable battery made currently. However, the nickel iron battery can be damaged by overcharging and over discharging. Thus, it will be very beneficial if the performance of nickel iron battery can be optimised by a smart charger system that will start charging when the battery voltage drops below the set values and stop charging when the voltage reaches the set maximum level. This research aims to create a mathematical model specifically for nickel iron battery. This model will be used to simulate and predict the state of charge (SOC) of the battery. The outputs of this model will be used as inputs to design a smart charger for the nickel iron battery that can help overcome the drawbacks of the battery.

Keywords: Nickel iron, state of charge, overcharge, over discharge, mathematical model, energy storage, cycle life and smart charger.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

Overview

This section introduces the background of the proposed research and explains its aim and objectives.

1.1 BACKGROUND OF THE RESEARCH

This research will assist in providing a solution to overcome the lack of continuity of electricity service for people who live in rural places with dependence on renewable energy based power plants such as photovoltaic arrays. One of the places that could receive benefit of this research outcome is the Toianas sub-district East Nusa Tenggara Province Indonesia. Department of Mining and Energy - East Nusa Tenggara Province (2011) states that there are only 32 sub-districts were electrified from 291 sub-districts in East Nusa Tenggara Province, while the other 259 are still not electrified. Toianas sub-district is one of the sub-districts not electrified. The local government has tried to help the community in Toianas by providing 53 solar panels for the local people in 2008 (Department of Mining and Energy - East Nusa Tenggara Province 2011). Nevertheless, poor energy storage systems have been a problem.

All of the solar panel system in Toianas used lead acid battery to store the energy and because of the high cost of maintenance and short lifetime, the majority of the batteries cannot last for more than two to three years of operation. This is a huge disadvantage for the people because the majority of them are low income villagers who work as farmers. To live without electricity service is exacerbating not only to the economic condition but also to social development.

Even though the cost of nickel iron battery is more than lead acid battery, the investment in this type of battery will be paid back because of this battery's high durability. Ravikumar, Balasubramanian & Shukla (1995) claim that due to their long cycle life which is typically 3000 cycles, nickel iron batteries are categorised as attractive systems.

On the other hand, nickel iron battery can be damaged by overcharging and over discharging. This is because during overcharge each Ah overcharge will separate 0.366 ml of water and the electrolysis of 1 ml water produces 2000 ml of gas which consists of hydrogen and oxygen (Sichuan Changhong Battery Co Ltd, n.d.). In a short time, this condition will decrease the electrolyte of the battery and distilled water would have to be added continuously. Over a longer period, this could lead to an explosion of the battery due to the excessive amount of hydrogen. In addition, over discharging the battery reduces the capacity of the battery. By considering the negative effects mentioned above, it is important to design a smart charger that could be used to prevent the occurrence of negative effects mentioned above.

In order to create a smart charger, a mathematical model that can predict the state of charge of this battery is required. Currently, there is no comprehensive mathematical model specifically designed for nickel iron battery. Therefore, this model will be developed to predict the state of charge of this battery and to provide inputs to a programmable charger for the nickel iron battery.

1.2 AIM AND OBJECTIVES

The project aims to determine the state of charge of nickel iron battery using a comprehensive mathematical model.

The objectives are:

a) To conduct a general review of the nickel iron battery with a focus on its relative advantages and disadvantages compared to the two most widely used battery types.

b) To carry out a general review of existing battery mathematical models and their capabilities.

c) To analyse the applicability of the existing modelling methods to the nickel iron battery.

d) To design a MATLAB$^{®}$ model to predict the state of charge of the nickel iron battery.

e) To demonstrate how the model can be used to help with the design of smart chargers for the nickel iron battery.

f) To carry out tests on nickel iron batteries to validate model predictions.

From the above objectives, the following research questions arise:

- What are the advantages and disadvantages of currently available battery models?

- Are those generally available battery models suitable to simulate the performance of nickel iron battery?

- What are the advantages and disadvantages of nickel iron battery?

- Is the nickel iron battery a better battery compared to the two most widely used battery types?

- Is it possible to predict the state of charge of nickel iron battery using a MATLAB$^{®}$ based mathematical model?

- How is the Programmable Logic Controller (PLC) used in conjunction with a programmable charger employed to find out the Open Circuit Voltage (OCV) values during the charging of the nickel iron battery?

- How is the programmable DC load used in conjunction with the PV8500 software to find out the OCV values of nickel iron battery during discharging?

- How is the mathematical model for the nickel iron battery used to help design a smart charger for this battery?

1.3 SIGNIFICANCE OF THIS RESEARCH

This research will produce the first mathematical model specifically for nickel iron battery. This model will save time and cost which are required to predict the state of charge of this battery using laboratory measurements. This model will enable the prediction of state of charge of this battery and it is needed for a smart charger. The smart charger can be used to improve the performance of this battery that will lead to a longer cycle life and higher efficiency. This battery then can be used to replace the lead acid battery which is widely used for energy storage within photovoltaic systems. It will be very useful in rural areas such as Toianas village East Nusa Tenggara Province Indonesia. It is expected that this battery will provide a more durable energy storage system that can help the local community at the village to obtain a sustainable electricity supply.

1.4 THESIS OUTLINE

This thesis consists of the following 5 chapters:

- Chapter 1 is the introduction which covers background of this research, aim and objectives and significance of this research.

- Chapter 2 is the background and literature review covering a review of different available battery models and a review of the nickel iron battery compared to two most widely used battery types.

- Chapter 3 is the methodology which consist of Shepherd's equation based mathematical model, Peukert's equation based mathematical model, Impedance track mathematical model, hardware and software requirements and laboratory measurement system design.

- Chapter 4 is the results which covers Shepherd's based model, Peukert's based model and Impedance track model.

- Chapter 5 is the conclusions in which all results are summed up and recommendations are made.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

Overview

Section 2.1 provides a brief literature review on existing battery mathematical models. Section 2.2 describes the review of nickel iron battery compared to the two most widely used batteries.

2.1 A REVIEW OF EXISTING BATTERY MATHEMATICAL MODELS

In general, a battery model can be constructed by either mathematical modelling or circuit oriented modelling. Li and Ke (2011.) states that circuit oriented model utilises a mix of voltage and current sources, resistors, and capacitors to simulate battery performance. This approach can be divided into three categories. The first category is based on Thevenin's theorem (Salameh, Cassaca & Lynch, cited in Li & Ke 2011, p.7), the next one is impedance-based model (Buller et al., cited in Li & Ke 2011, p.7) and runtime-based model (Chen & Rincon-Mora, cited in Li & Ke 2011, p.7). On the other hand, mathematical modelling can be explained as the process of developing and using an equation or a compilation of equations to simulate the performance of the battery (Santhanagopalan & White 2011). This approach is based on the measured parameters of the battery and a mechanistic model that can be developed by relating the characteristic of the battery to the physical features of the component materials. There are two well-known equations used to build empirical models which simulate the performance of batteries namely Shepherd's and Peukert's equations. Currently, there are various types of empirical models based on Sheperd's and Peukert's equations which are created for general types of batteries. Some models are designed specifically for particular batteries such as the lead acid battery. Various authors have developed mathematical models to simulate the

discharge curve that can be used to predict the state of charge of the battery. However, this approach has limitations in that it depends on the history of charge and discharge. In addition, the flat section of the discharge curve makes it very difficult to predict state of charge accurately. Those mentioned types of models above are the major type of mathematical models. However, Jongerden and Haverkort (2008) claim that battery models can also be divided into various categories such as analytical models, kinetic models and stochastic models. Subsequently, after conducting the literature study, it was found that there is currently no comprehensive mathematical model precisely designed for the nickel iron battery. On the other hand, there is one promising method developed for lithium ion battery by Texas Instrument Inc called impedance track model. This method combines the advantages of ampere hour counting during loaded condition with open circuit voltage method during equilibrium state. It was decided to adopt that method to the nickel iron battery.

2.2 A REVIEW OF NICKEL IRON BATTERY COMPARED TO THE TWO MOST WIDELY USED BATTERY TYPES.

Sichuan Changhong Battery Co Ltd (n.d.) states that lead acid battery are progressively substituted by nickel iron battery in an extensive area of applications due to its long service life, smaller cost, high reliability and other desirable characteristic. Iron Edison (2013) claims for energy storage purposes, this battery easily outlasts the 7-year life cycle of lead acid battery as this battery can last to twenty-five years or more. Iron Core Power (n.d.) asserts that nickel iron battery has the longest life cycle of any rechargeable battery currently manufactured, is exceptionally robust, does not contains sulphate, does not freeze, and one cell can be replaced if it is damaged instead of replacing the whole battery.

Since there is no sulphate or lead in this battery, it is a very eco-friendly battery. On the other hand, the lead acid battery can be damaging to the environment (Brauer 2013). However, Dürr et al. (2006) claim that lead acid battery is still the cheapest storage battery that can be used for various purposes. This assumption is correct as the price of nickel iron battery is higher due to the price of its electrode material namely iron and nickel. However, this is just the purchase price. If the life cycle of the battery is also considered, then the nickel iron is more cost effective as it can potentially last for a longer period of time. Another widely used battery is the lithium ion battery. Lu et al. (2013) state that this battery has a high energy and power densities, extensive life cycle and is eco-friendly. Yet, this is an expensive battery and it must operate in a safe and reliable operational area with temperature and voltage limitations. On the other hand, the nickel iron battery is a robust battery and very safe to operate under various conditions. Tsai and Chan (2013) assert that iron electrodes of the nickel iron battery are both mechanically and electrically robust. Nonetheless, one of the problems of nickel iron battery is its discharge capacity depends not only on its discharge rate but also on the running temperature which restrict the operation of this battery for high discharge at low temperature (Shukla, Venugopalan & Hariprakash 2001). They also mention that water should be added continuously due to the losses caused by overcharge.

CHAPTER 3: METHODOLOGY

Overview

The section 3.1 provides explanation about Shepherd's equation based battery model, section 3.2 describes the Peukert's equation based model and section 3.3 provides information about the comprehensive model that will be developed for nickel iron battery.

3.1 SHEPERD'S EQUATION BASED MATHEMATICAL MODEL

A mathematical model which is based on Sheperd's equation will be developed to determine the discharge curve of nickel iron battery. This discharge curve can be used to predict the state of charge of this battery. Tremblay, Dessaint and Dekkiche (2007) created the adopted model below.
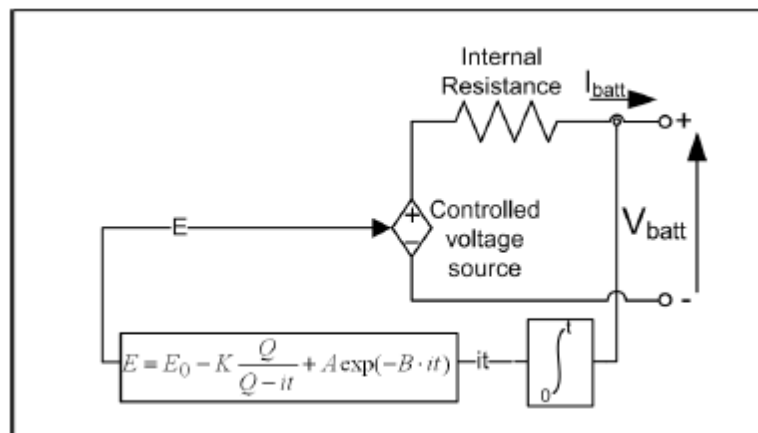
Figure 1: Non-linear battery model (Tremblay, Dessaint, & Dekkiche 2007)

Based on the equation given in figure 1 with:

E = no load voltage (V).

E_0 = battery constant voltage (V).

K = Polarization voltage (V).

Q = Battery capacity (Ah).

A = Exponential zone amplitude (V).

B = Exponential zone inverse time constant $(Ah)^{-1}$

V_{batt} = Battery voltage (V).

R = Internal resistance (Ω).

i = Battery current (A).

$\int idt$ = Actual battery charge (Ah).

The unknowns of the above model can be extracted from a typical discharge curve of any type of battery. Below is shown the typical discharge curve of battery that can be used for data extraction:
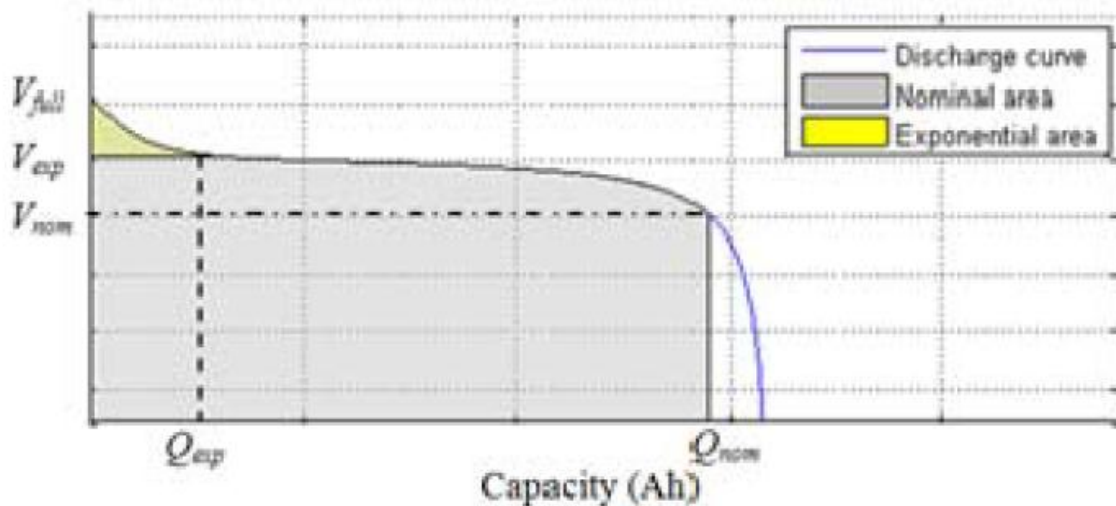
Figure 2: Typical battery discharge curve (Bao 2012)

The three determined points above are used to extract the values required to calculate the unknowns of the equation on figure 1 above. The efficiency of this battery is assumed to be 99.5% in order to get the most precise simulation result. The unknowns can be calculated using the following equations (Tremblay, Dessaint, & Dekkiche 2007):

- R: Internal resistance (Ω)

$$R = V_{Nom} \times \frac{1-\eta}{0.167 x QNom} \qquad [3.1]$$

$\eta = 99.5\%$

This method is an initiation to define the internal resistance when no other data is accessible.

- A: Voltage drop during exponential zone (V)

$$A = V_{Full} - V_{Exp} \qquad [3.2]$$

- 3/B: Charge at the end of exponential zone (Ah)

$$B = \frac{3}{QExp} \qquad [3.3]$$

The polarisation voltage K can be obtained from the third point (End of nominal zone: Q_{Nom} and V_{Nom}) and the fully charged voltage (V_{Full}):

- Polarisation voltage K (V)

$$K = \frac{(VFull - VNom + A(\exp(-BxQNom)-1)) x (Q-QNom)}{QNom} \qquad [3.4]$$

Then the fully charged voltage is used to calculate the voltage constant E_0

- Voltage constant E_0 (V)

$$E_0 = V_{Full} + K + R - A \qquad [3.5]$$

After obtaining all the parameter values, the model is implemented using MATLAB®.

3.2 PEUKERT'S EQUATION BASED MATHEMATICAL MODEL

The next model that will be developed is based on Peukert's equation. Peukert is a German scientist who defined the relationship between capacity and discharge rate of a battery with the following equation (Peukert, cited in Doerffel & Shark 2005):

$$I^{pc}t = C \qquad\qquad [3.6]$$

Where,

I $\quad$ = Discharge current.

C $\quad$ = Battery capacity.

t $\quad$ = Maximum discharge time.

pc $\quad$ = Peukert's coefficient which is unique for each type of battery and its value is usually between 1 and 2.

The above equation can be used to calculate the discharge time and capacity discharged from the battery.

This next model will be developed with the use of above equation which will enable the state of charge prediction of nickel iron battery. Farre, Closas and Casals (2013) state that the SOC can be simulated using the equation as follows:

$$SOC = 100\frac{C_o - C_t}{C_m} = 100\,\frac{C_o - I^n t}{C_m} \qquad\qquad [3.7]$$

Where:

C_m $\quad$ = The maximum available capacity of the battery.

C_o $\quad$ = The capacity before the discharge starts.

t $\quad$ = Discharge time.

I $\quad$ = Discharge current.

n   = Peukert's coefficient.

3.3 IMPEDANCE TRACK MATHEMATICAL MODEL FOR NICKEL IRON BATTERY

Due to the limitations of Shepherd's model and Peukert's model, another comprehensive model will be implemented. This model is adopted from Texas Instruments Incorporated. This global semiconductor design and manufacturing company developed this model for lithium ion battery. This model will be applied to predict the SOC of nickel iron battery since it can tackle drawbacks of both previous methods and combine their advantages to produce the most accurate and reliable SOC predictions.

Impedance track operates with the following (*Single cell gauging 101 Part 3: Impedance Track Benefits* 2013):

- A fixed table of open circuit voltage as a function of SOC and temperature should be obtained.

- By applying ohm's law, the equation below can be applied to determine the resistance of the battery:

$$R_{BAT} = \frac{OCV - V_{BAT}}{I}$$
[3.8]

R_{BAT} = Resistance of the battery.

OCV = Open circuit voltage (f(soc,T) that will be obtained by direct measurement and will be stored as a lookup table.

V_{BAT} = Voltage of the battery.

I = Battery discharge current.

- The battery voltage equation will be as follows:

$$V_{BAT} = OCV\ (T, SOC) - I \times R_{BAT}\ (T, SOC, Aging) \qquad [3.9]$$

Application of impedance track method to the lithium ion battery can be seen in the figure

3:
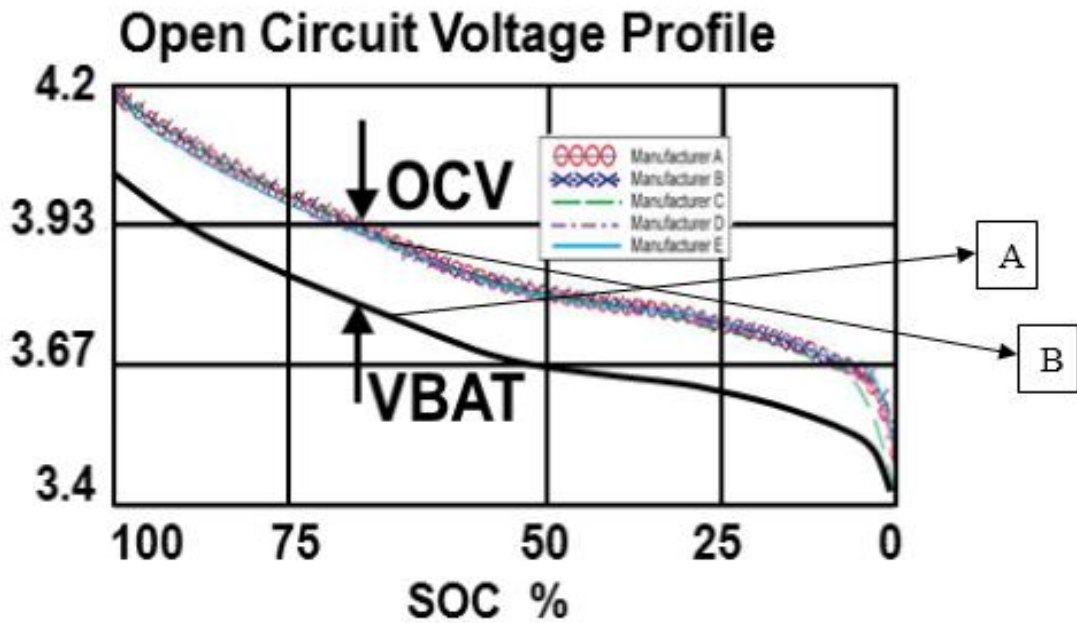
Figure 3: Open circuit voltage profile of lithium ion battery from different manufacturers vs. VBAT (Texas Instruments 2013)

It is assumed that the SOC of battery is 100% when the voltage of the battery is 4.2 V. Subsequently, the battery should be discharged by certain current rate and we can start applying the ampere hour counting method as used by Shepherd. The V_{BAT} can be directly measured at point A as voltage under load. Then the value can be compared to point B to know the OCV value at that point. As a result, the R_{BAT} can be calculated using equation [3.8]. The R_{BAT} values then stored as at a lookup table with resistance as function of SOC and temperature. All R_{BAT} values for different SOC can be used to simulate and to correct the V_{BAT}. This algorithm can be applied precisely since the V_{BAT} can be simulated and calculated using equation [3.9] above. By knowing the R_{BAT} and V_{BAT}, important factors

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such as battery ages and variations of temperature can be accounted accurately. Furthermore, self-discharge can be accounted effortlessly as the OCV is known and can be compared to the measured V_{BAT} to find out the initial SOC after the battery has been stored for a period of time.

The Qmax value of the battery can be updated and learned by the following process:
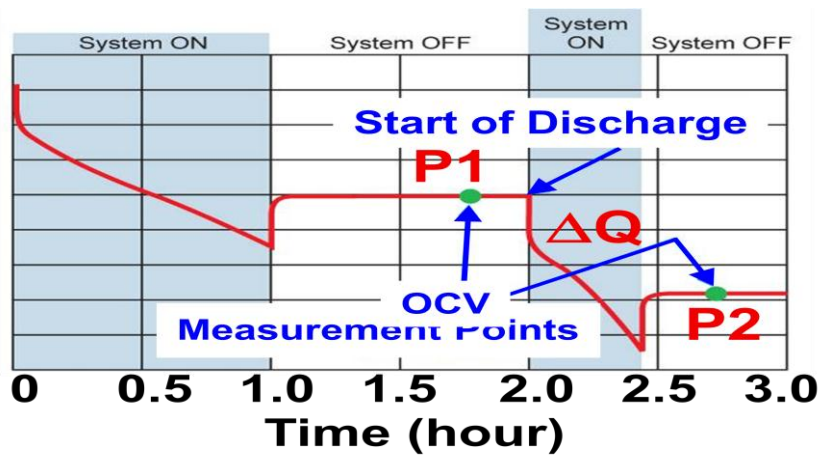
Figure 4: Qmax calculation method during discharge (Texas Instruments 2013)
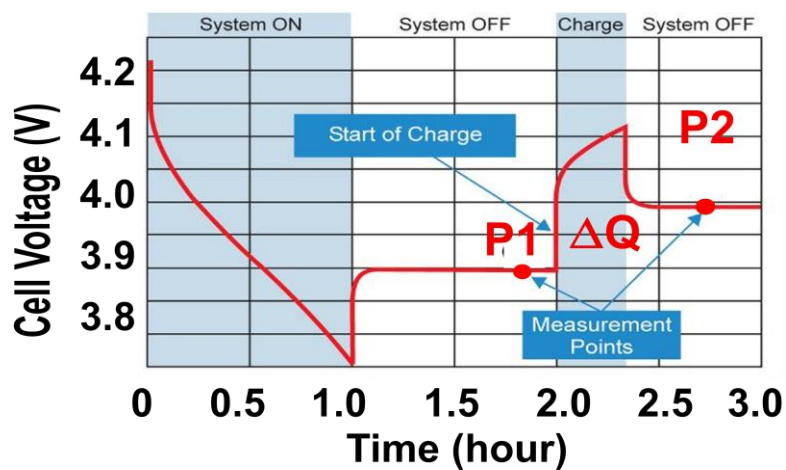
Figure 5: Qmax calculation method during charge (Texas Instruments 2013)

As seen in the figures above, the Qmax can be calculated by measuring two points during system off period (no load). The charge passed is calculated with ampere hour counting method. SOC1 and SOC2 are determined by their OCV values and the Qmax will be determined by the following equation:

$$\text{Qmax} = \frac{\Delta Q}{SOC1 - SOC2} \qquad [3.10]$$

Where:

Qmax: Maximum capacity of the battery.

ΔQ: Charge passed measured by ampere hour counting between two measurement points.

SOC1: State of charge of point 1 measured by OCV method.

SOC2: State of charge of point 2 measured by OCV method.

3.4 HARDWARE AND SOFTWARE REQUIREMENTS.

3.4.1 Hardware components.

This research requires the following hardware components:

- 1 10Ah Nickel Iron Battery.

  1 unit of 10Ah battery is chosen since this is the smallest capacity of battery available at USQ energy laboratory. In addition, all required parameters for this project can be obtained by measuring the characteristics of this battery and the size of battery capacity does not affect the behaviour of the battery.

- 1 unit of multi meter.

  Multi meter is required to validate the magnitude of current and voltage generated by PLC and programmable charger. It will be known whether the magnitude of current and voltage which were set by the click programming software are identical or not. Further adjustment can be done to fix any variations of the current and voltage magnitudes.

- 1 unit of programmable charger.

  Programmable charger is required since it is expected that charger can communicate with PLC to determine the required magnitude of voltage and current used to charge the battery. The programmable charger can also be set to stop charging at certain voltage limit.

- 1 unit of PLC.

  PLC is used to control the programmable charger. PLC is chosen since this equipment can generate logical outputs and it can read back the voltage and current magnitudes from the programmable charger.

- 1 unit of programmable load.

  Programmable load is used to discharge the nickel iron battery with the desired parameters. For this project, it was set to discharge the battery with C/5 rate. The OCV values during discharge can be monitor by this programmable load.

3.4.2 Software components.

This research requires the following software:

- MATLAB®.

  MATLAB® is used to programme the Shepherd's equation based model, Peukert's equation based model and Impedance track model. This software is chosen since it can run complex mathematical models and calculations easily.

- Click programming software.

  Click programming software is used to construct the logic of controlling the PLC. All parameters used for charging the nickel iron battery are set with this software. It also offers a user-friendly interface for the user.

- PV8500 software.

  PV8500 software is provided by BK precision which is the programmable load manufacturer. It is used to determine the parameters required to discharge the battery. It can also monitor the discharge data during the battery discharge process.

3.5 LABORATORY MEASUREMENT SYSTEM DESIGN.

3.5.1 The battery charging system.

The battery charging system of this research is the designed to measure the OCV of nickel iron battery with the following system:
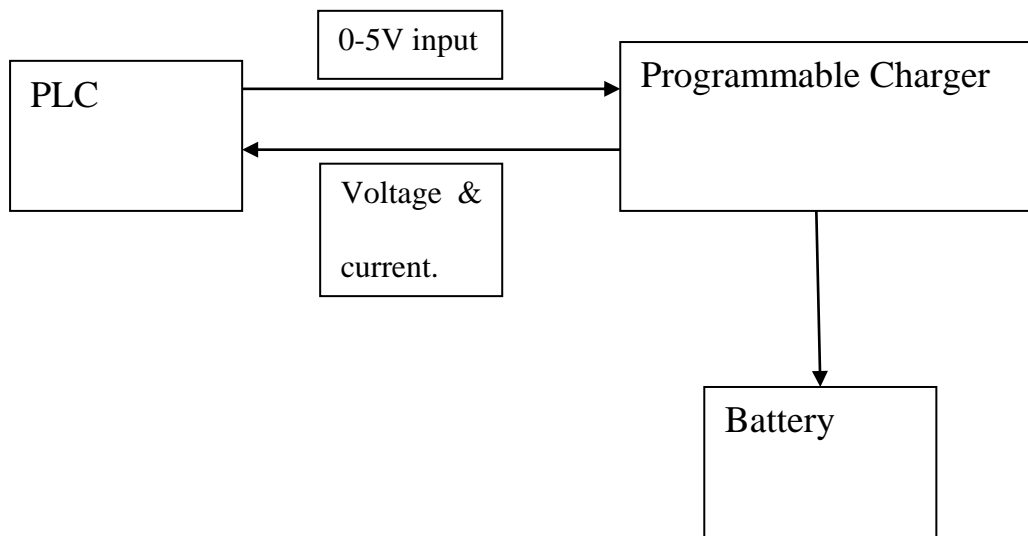
Figure 6: Block diagram for battery charging system

The click programming software has been programmed to control the PLC with the following parameters:

Input parameters:
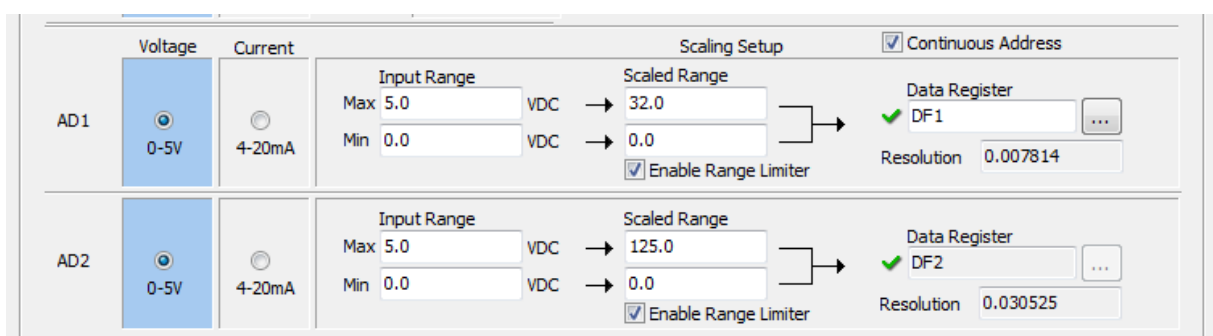
Figure 7: Click programming software input parameters for charging system

Analogue to digital 1 (AD1) is used to receive the voltage signal back from the programmable charger with 0-5VDC to 0-32 VDC signal scaling setup. This data is stored in data register DF1.

In addition, analogue to digital 2 (AD2) is used to receive the current signal back from the programmable charger with 0-5VDC to 0-125VDC signal scaling setup. This data is stored in data register DF2.

The complete click programming software codes for charging system are as follows:
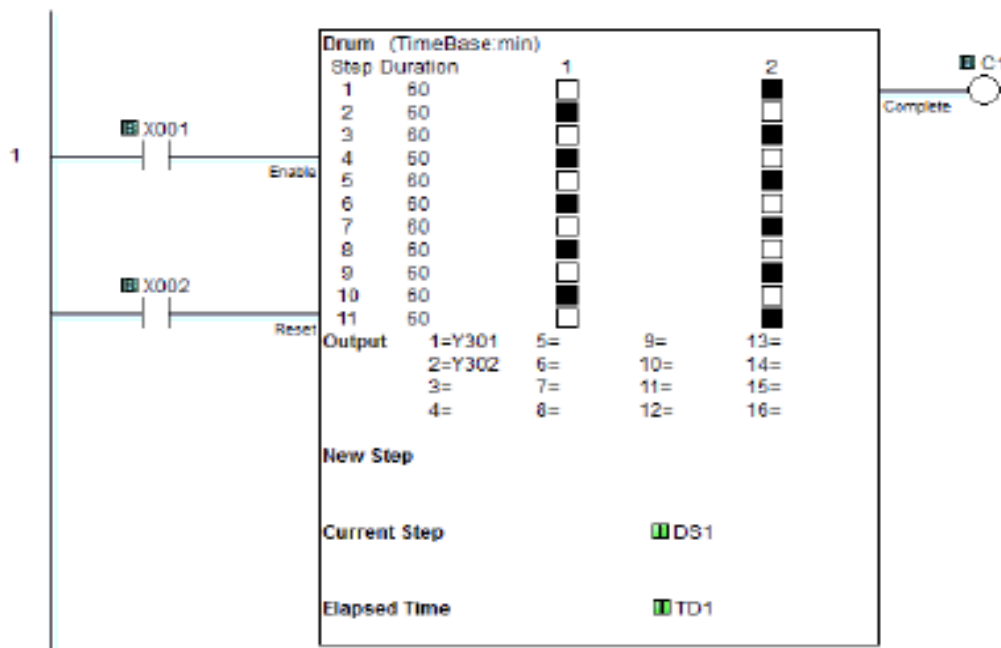
Figure 8: First rung of PLC codes for charging system.

The first rung determines the duration and sequence of the charging process. The first step was to charge the battery for 60 minutes followed by the resting the battery for 60 minutes at the second step. This process continues to 5 hours of charging period and 5 hours of resting period.
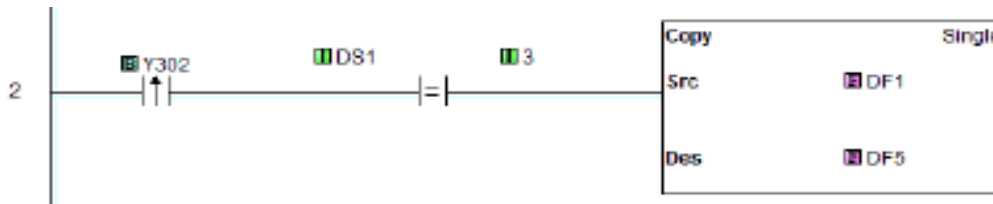
Figure 9: Second rung of PLC codes for charging system.

The second rung stores the OCV of the nickel iron battery provided by DF1 to memory address DF5 after the first rest period.
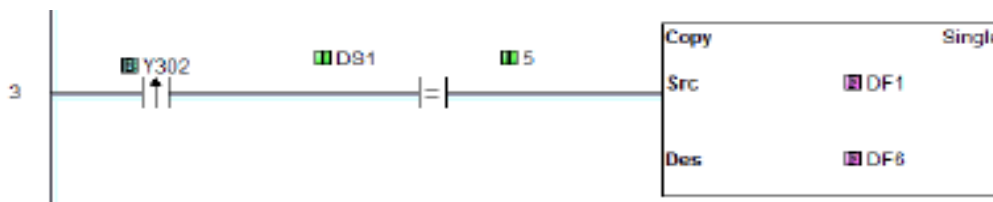
Figure 10: Third rung of PLC codes for charging system.

The third rung stores the OCV of the nickel iron battery provided by DF1 to memory address DF6 after the second rest period.
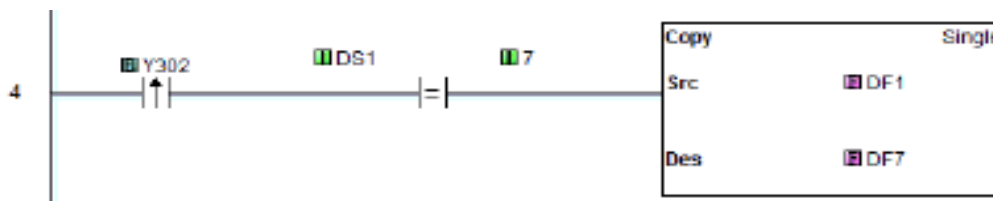
Figure 11: Fourth rung of PLC codes for charging system.

The fourth rung stores the OCV of the nickel iron battery provided by DF1 to memory address DF7 after the third rest period.
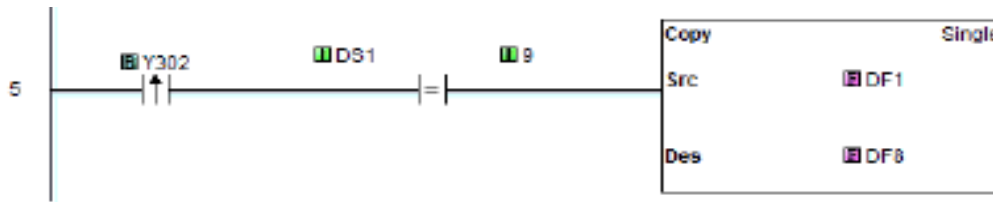
Figure 12: Fifth rung of PLC codes for charging system.

The fifth rung stores the OCV of the nickel iron battery provided by DF1 to memory address DF8 after the fourth rest period.
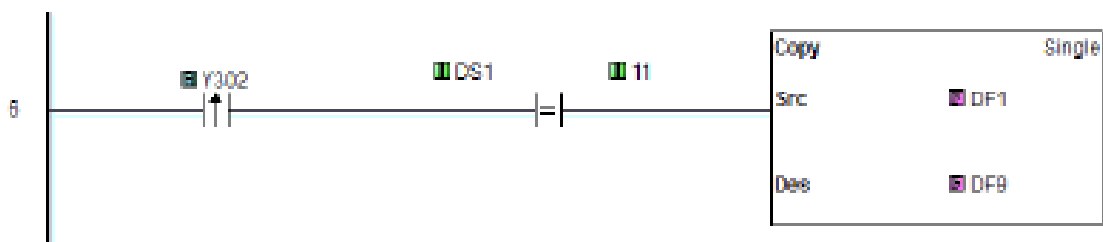
Figure 13: Sixth rung of PLC codes for charging system.

The sixth rung stores the OCV of the nickel iron battery provided by DF1 to memory address DF9 after the fifth rest period.
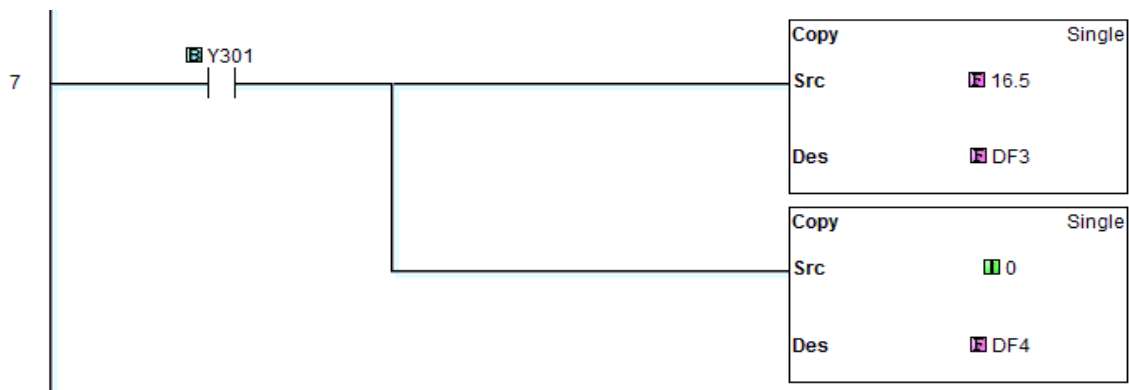
Figure 14: Seventh rung of PLC codes for charging system.

The seventh rung determines the magnitude of output voltage as 16.5V and output current as 0A. These parameters are used during the rest periods.

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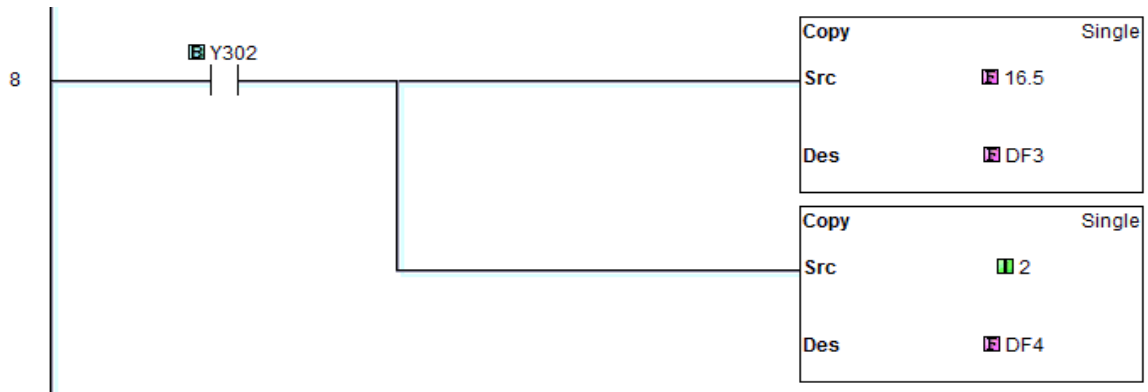
Figure 15: Eighth rung of PLC codes for charging system.

The eighth rung determines the magnitude of output voltage as 16.5V and output current as 2A. These parameters are used during the charging periods.
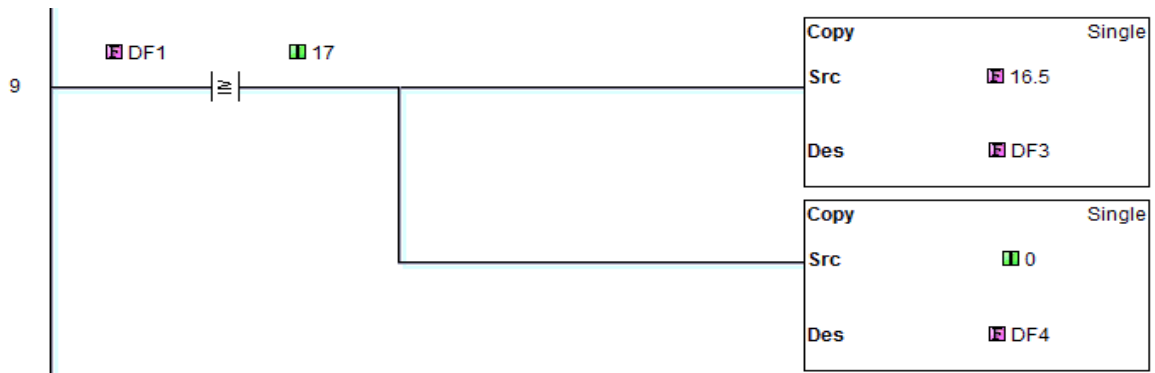
Figure 16: Ninth rung of PLC codes for charging system.

The ninth rung acts as a safety rung. This rung determines that if the input voltage DF1 larger than 17 volts, charge the battery with 0A.

Figure 17: Tenth rung of PLC codes for charging system.

The tenth rung ends the ladder diagram.

It can be seen from figure 8 to figure 17 above that these codes are developed to charge the 10Ah nickel iron battery with 16.5V and 2A for 1 hour and then the battery is rested for 1 hour. At the end of that 1 hour rest period, the OCV is measured and stored at address DF5. This cycle continues up to 5 hours charging since the rate which is used to charge this battery is C/5 rate. There is a safety system in which if the battery voltage is equal or larger then 17V, the programmable charger will be set to charge the battery with 0A.

3.5.2 The battery discharging system.

The battery discharging system of this research use PV8500 software and programmable load instead of Click programming software and PLC. Therefore, the discharge system is designed to measure the OCV of nickel iron battery with the following system:
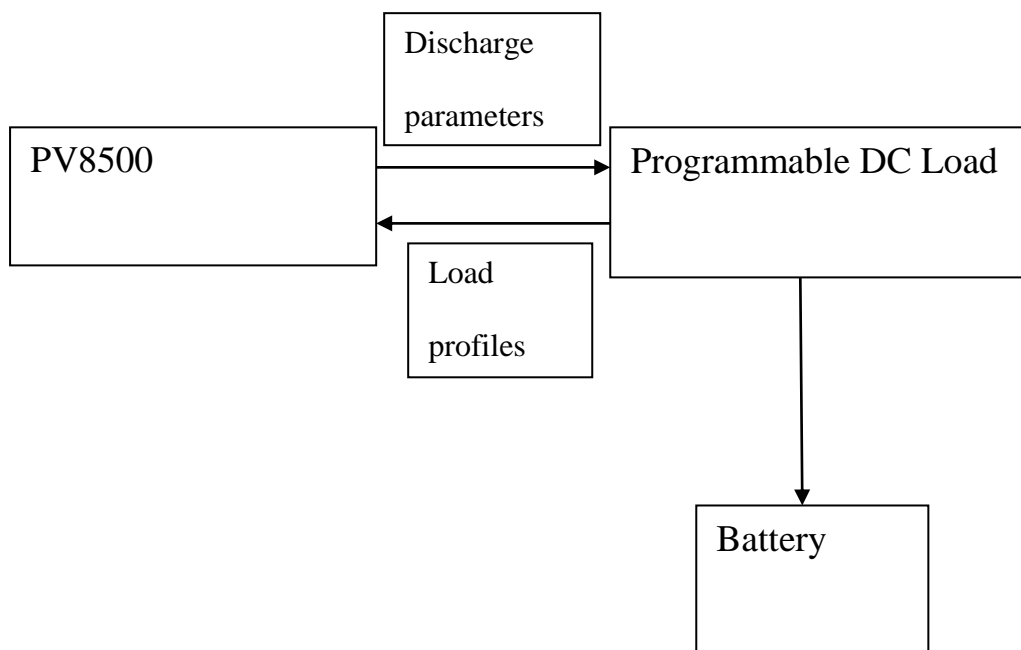
Figure 18: Block diagram of discharging system

The PV8500 software is programmed with the following parameters:
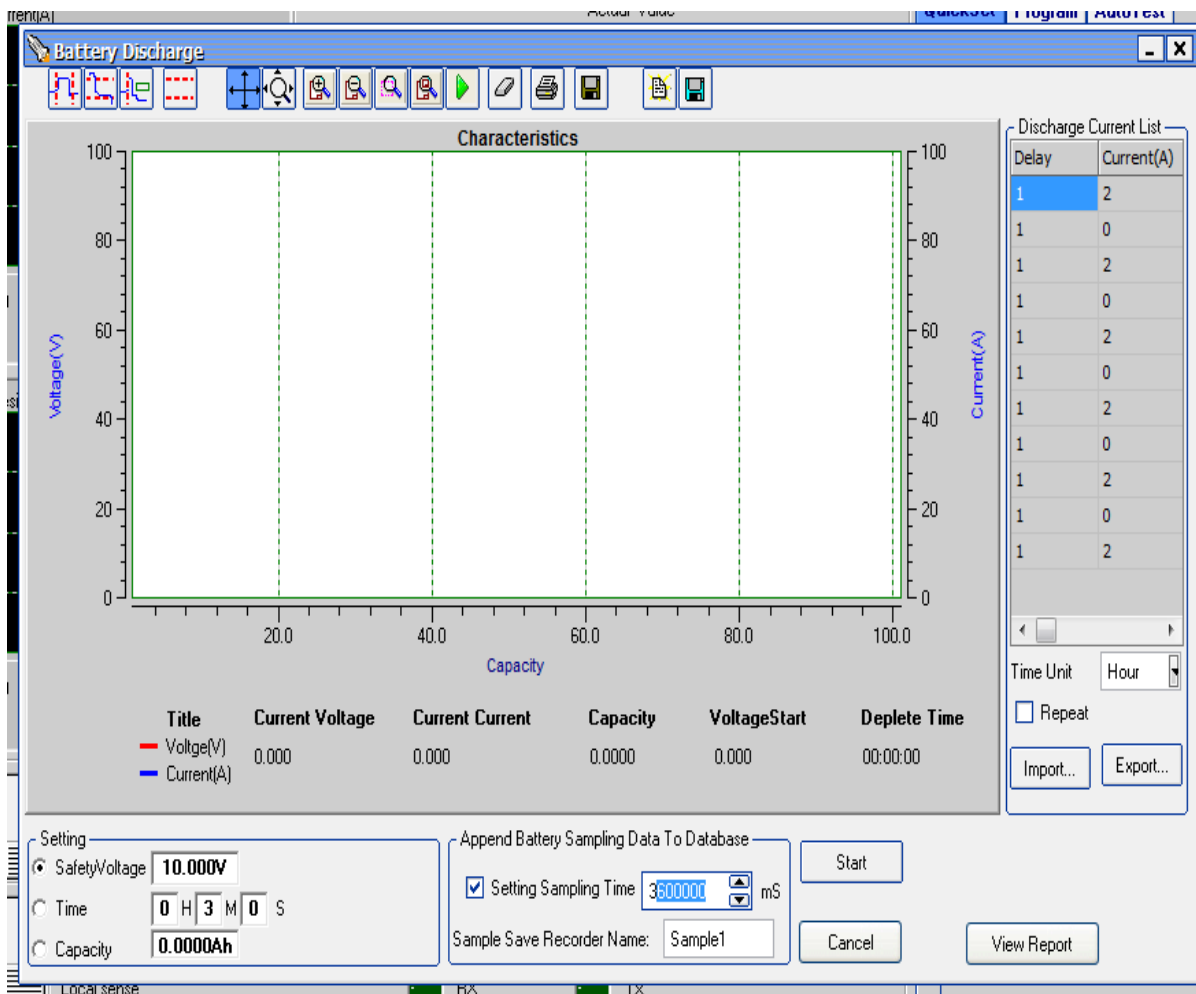
Figure 19: PV8500 programming parameters

The PV8500 software is programmed to discharge the nickel iron battery with C/5 rate. The programmable DC load will discharge the battery with 2A for 1 hour and then the battery will be rested for 1 hour (can be seen at Discharge Current List section of figure 19). The sampling time is done with 1-hour interval and the OCV data will be recorded in the sample1 file (can be seen at Append Battery Sampling Data to Database section of figure 19). The battery will stop discharging when the battery voltage reaches 10V (can be seen at Setting section of figure 19).

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The complete connections of equipment for the charging and discharging systems can be seen at the figure 20:
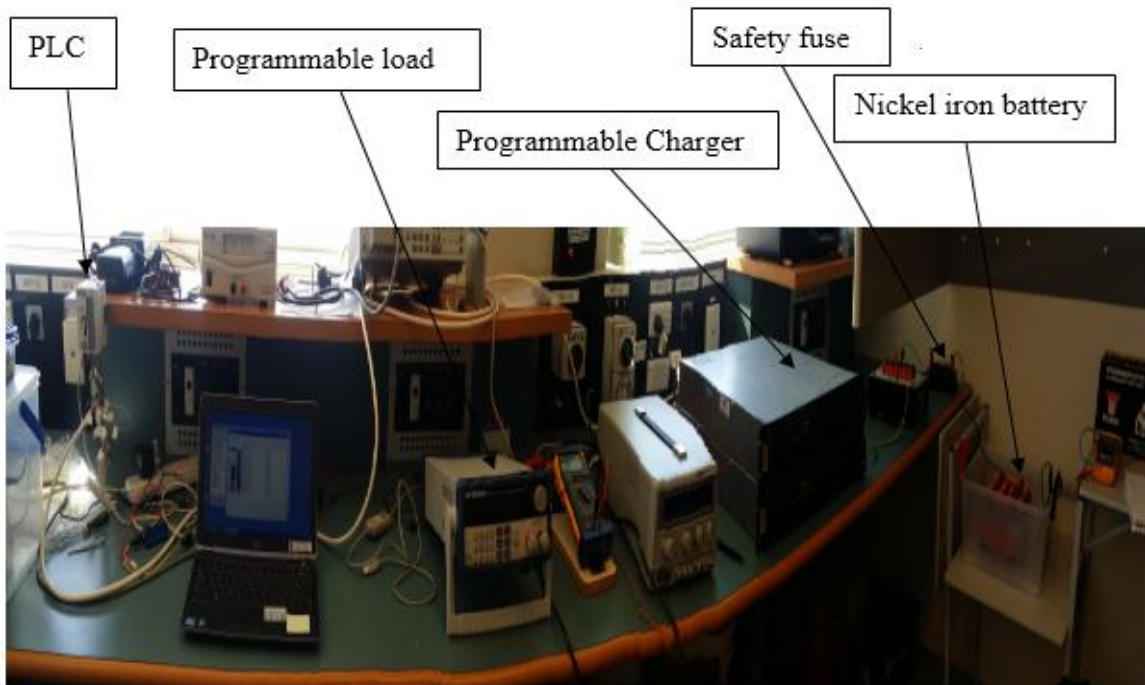
Figure 20: Connection of charging and discharging equipment

The programmable load is connected to the PLC, laptop, safety fuse and nickel iron battery whereas the programmable load is connected to the laptop and nickel iron battery. The nickel iron battery is placed in a safety enclosure. An exhaust fan is also used on the top of the battery to make sure that no excessive hydrogen generated from the battery. All the activities in this laboratory session have been assessed by risk management plan that can be seen in section appendix E.

CHAPTER 4: RESULTS

4.1 SHEPERD'S BASED MODEL

A mathematical model which is based on Sheperd's equation has been evaluated and tested to simulate the discharge of nickel iron battery. This discharge curve can be used to predict the state of charge of this cell. A typical discharge curve of nickel iron cell shown below is used for the parameters extraction process:
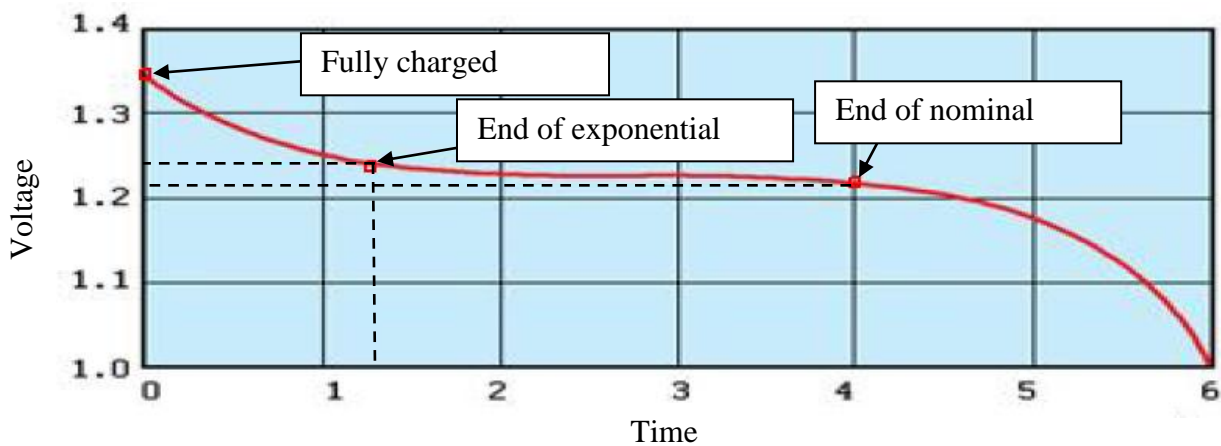
Figure 21: Typical discharge curve of nickel iron cell 0.167C (Iron Core Batteries n.d.)

4.1.1 Parameter extraction

The three determined points above are used to extract the values required to calculate the unknowns of the equation on figure 12 above. The efficiency of this cell is assumed to be 99.5% in order to get the most precise simulation result. The unknowns can be calculated as follows:

- R: Internal resistance (Ω) using equation [3.1]:

$$R = V_{Nom} \text{ x } \frac{1-\eta}{0.167xQNom} = 1.2 \text{ x } \frac{1-0.995}{0.167x10} = 0.0036\Omega$$

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- A: Voltage drop during exponential zone (V) using equation [3.2]:

  $A = V_{Full} - V_{Exp} = 1.35 - 1.24 = 0.11$ V

- 3/B: Charge at the end of exponential zone (Ah) using equation [3.3]:

  $B = \dfrac{3}{QExp} = \dfrac{3}{1.67 \text{x} 1.27} = 1.4145$ Ah^{-1}

- Polarisation voltage K (V) using equation [3.4]:

  $K = \dfrac{(VFull - VNom + A(\exp(-BxQNom)-1))x(Q-QNom)}{QNom}$

  $K = \dfrac{(1.35 - 1.2 + 0.11(\exp(-1.4145x6.68)-1))x(10-6.68)}{6.68}$

  $K = 0.0199$

- Voltage constant E$_0$ (V) using equation [3.5]:

  $E_0 = V_{Full} + K + R - A = 1.35 + 0.0199 + 0.0036 - 0.11 = 1.2659$ V

4.1.2 Simulation results

The discharge curve of the nickel iron cell can be plotted as follows (MATLAB$^{®}$ codes can be seen in Appendix B):
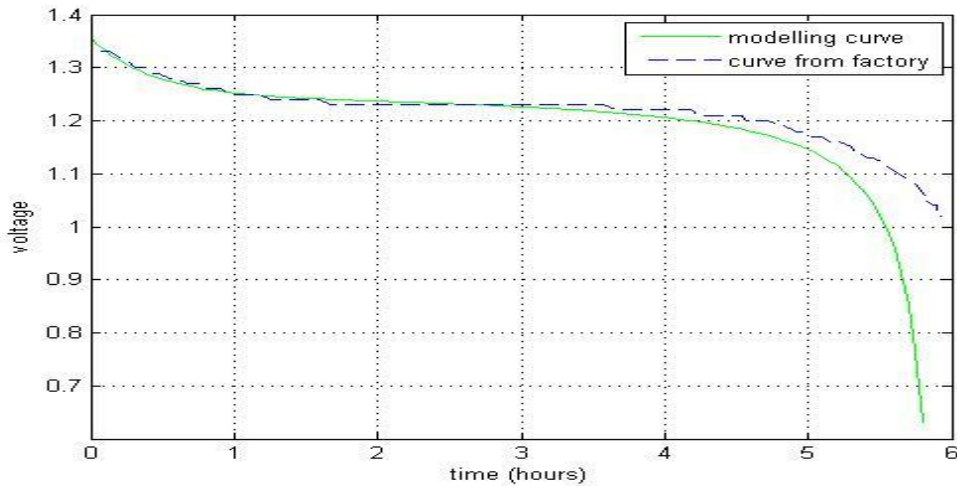
Figure 22: Discharge curve of nickel iron cell 1.67A (0.167C) 1.2V 10Ah factory curve in figure 12 versus modelling curve

This graph shows that Shepherd's equation can be used to predict the discharge curve of the nickel iron cell. However, the dependence of discharge history which consist of flat areas between one hour and 4 hours makes it difficult to predict the state of charge of this battery within that period of time. Furthermore, the efficiency of the battery should be assumed very high which is not the case in reality. Generally, nickel iron battery has efficiency less than 85%. This generates inaccuracy of SOC prediction with Shepherd's equation. Therefore, it is assumed that this approach is impractical to predict the state of charge.

4.2 PEUKERT'S BASED MODEL

To overcome the problems which have occurred during the use of Sheperd's equation before, Peukert's equation is used in this step.

4.2.1 Peukert's coefficient calculation

In order to use Peukert's equation, Peukert's coefficient of nickel iron battery should be calculated firstly.

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The factory test results of the nickel iron battery are as follows (Helwig & Ahfock 2011):

Table 1: 10Ah and 80 Ah rated nickel iron battery discharge characteristics

From IronCore batteries - 19 Feb 2011: from manufacturers' factory type test data.
1.32 V / Cell Initial voltage to end of discharge at 1.0 V / Cel   =   average for 10 cell battery   11.6 V

Discharge Characteristic		10 A-hr rated nickel iron battery			80 A-hr rated nickel iron battery		
Discharge time	time Units	Amps	Amp-hr capacity	W-hr	Amps	Amp-hr capacity	kW-hr
10	hour	1.1	11.000	127.600	8.4	84.000	0.974
8	hour	1.3	10.400	120.640	10.5	84.000	0.974
5	hour	2	10.000	116.000	16.3	81.500	0.945
3	hour	3	9.000	104.400	23.9	71.700	0.832
2	hour	4	8.000	92.800	29.8	59.600	0.691
1.5	hour	4.7	7.050	81.780	35	52.500	0.609
1	hour	5.5	5.500	63.800	44.2	44.200	0.513
45	minute	6	4.500	52.200	48	36.000	0.418
30	minute	6.9	3.450	40.020	54.8	27.400	0.318
20	minute	7.6	2.533	29.387	60.5	20.167	0.234
15	minute	8.1	2.025	23.490	64.8	16.200	0.188
10	minute	8.5	1.417	16.433	67.6	11.267	0.131
5	minute	9.3	0.775	8.990	74.5	6.208	0.072
1	minute	10.8	0.180	2.088	87.2	1.453	0.017
30	second	11.5	0.096	1.112	94.5	0.788	0.009
5	second	13.8	0.019	0.222	109	0.151	0.002
1	second	14.3	0.004	0.046	114	0.032	0.000

Lee, Kim and Cha (n.d.) state that Peukert's coefficient can be calculated using the formula below:

$$k = \frac{logT2 - logT1}{logI1 - logI2} \qquad\qquad [4.1]$$

Thus, Peukert's coefficient for nickel iron battery can be calculated by considering the nickel iron factory test data presented on the table above.

Take $T_1 = 10$ hour

   $T_2 = 2$ hour

   $I_1 = 1.1$ A

$I_2 = 4$ A

$$k = pc = \frac{logT2 - logT1}{logI1 - logI2} = \frac{log2 - log10}{log1.1 - log4} = 1.25$$

4.2.2 Simulation results

Using the following equation [3.6]:

$$I^{pc}t = C$$

With

I = 1.67 A

C = 10 Ah

PC = 1.25

The discharge capacity versus discharge time of the nickel iron battery can be calculated and simulated as follows (MATLAB® codes for Peukert's equation simulation can be seen in appendix C):
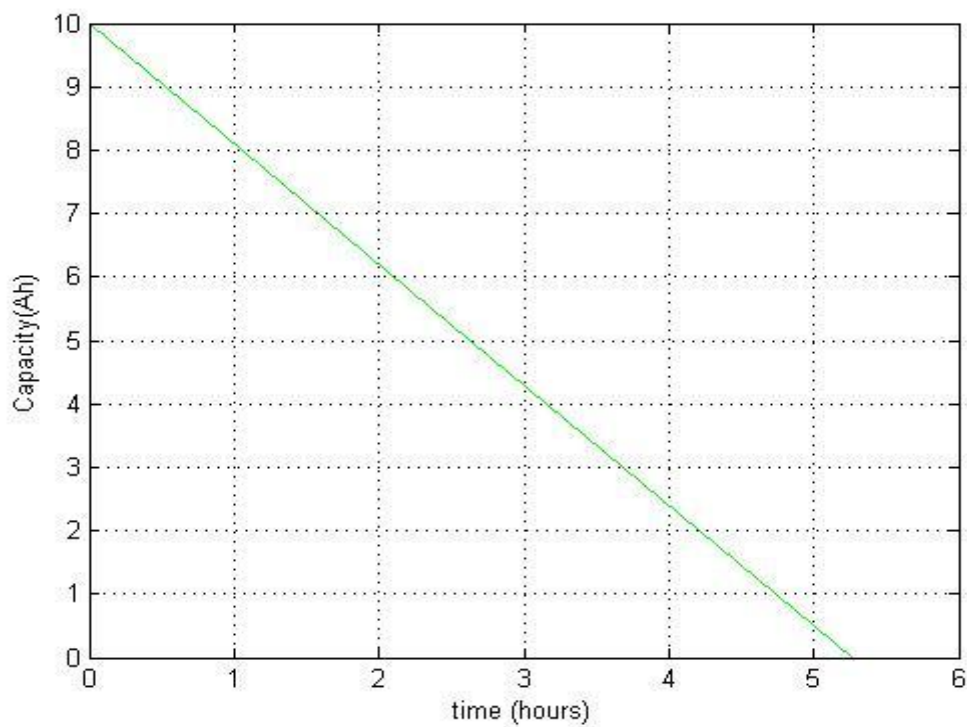
Figure 23: Discharge capacity vs. discharge time using Peukert's equation

It can be seen from the figure above that the 10 Ah nickel iron battery will be fully discharged at around 5.2 hours of discharge time.

This simple equation has been verified by applying the SOC calculation using equation [3.7] below:

$$SOC = 100\frac{C_o - C_t}{C_m} = 100\,\frac{C_o - I^n t}{C_m}$$

The input values are as follows:

I = 1.67 A

C_o = 10 Ah

C_m = 10 Ah

n = 1.25

t = 0 to 6 hours

The result of SOC calculation and simulation of the nickel iron battery can be seen below:
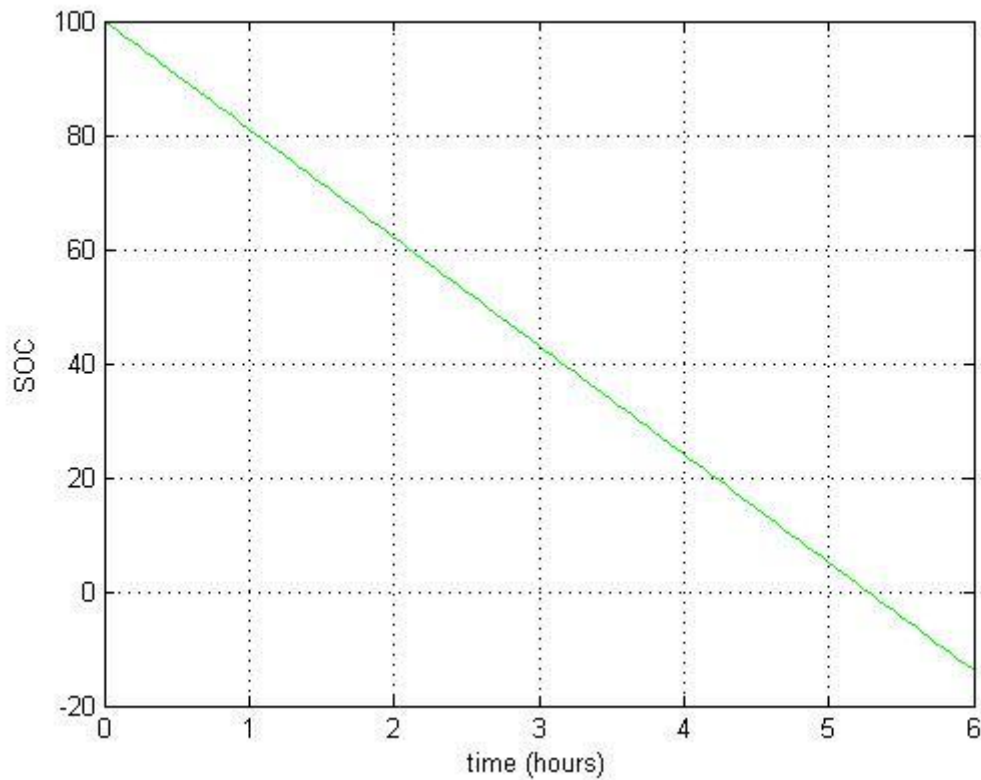
Figure 24: State of charge simulation result using Peukert's equation

The result of this SOC simulation is identical with the result generated by the calculation using the simple Peukert's equation. It is anticipated that the 10Ah nickel iron battery will reach the 0% SOC at 5.2 hours. However, Peukert's coefficient changes due to various factors such as temperature changes and battery aging. Therefore, this model is also impracticable for nickel iron battery.

4.3 THE IMPEDANCE TRACK MODEL

The impedance track model requires OCV lookup table of nickel iron battery. In order to construct this table, laboratory tests are conducted. One 10Ah nickel iron battery is charged and discharged with C/5 rate. Each process has been described in section 3.5.1 and 3.5.2.

Before running the battery tests, the maximum and minimum OCV values of nickel iron battery should be worked out to determine the open circuit fully charged and discharged voltage of nickel iron battery.

The fully charged OCV can be found using the standard reduction-oxidation (redox) potential (Shukla, Venugopalan & Hariprakash 2001):

$$2NiOOH + Fe + 2H_2O \underset{Charge}{\overset{Discharge}{\rightleftharpoons}} 2Ni(OH)_2 + Fe(OH)_2 \quad (E_{cell} = 1.37 \text{ V}) \qquad [4.2]$$
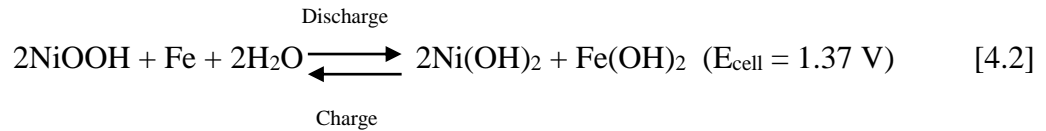
Thus the fully charged OCV value of 1 cell of nickel iron battery is 1.37 V.

This can be verified with Nernst equation and the Nernst equation for the positive electrode of nickel iron battery can be formed below:

$$E_{Ni} = E_0^{Ni} + \frac{RT}{1F} \ln \frac{a_{NiOOH} \; x \; a_{H_2O}}{a_{Ni(OH)_2} \; x \; a_{OH^-}} \qquad [4.3]$$

In which:

E_0^{Ni} = Standard electrochemical cell potential = 0.49 V (Watanabe & Kumagai, cited in Tsai & Chan 2013, p. 313)

R = Ideal gas constant = 8.314 J K^{-1} mol^{-1}

F = Faraday constant = 96,485 C mol^{-1}

T = Temperature

a = activity

If the product of all activity is assumed to be 1, E_{Ni} can be obtained as:

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$E_{Ni} = 0.49$ V

Turning to the negative electrode of nickel iron battery, the Nernst equation can be formed below:

$$E_{Fe} = E_0^{F+} + \frac{RT}{2F} \ln \frac{a_{Fe(OH)_2}}{a_{Fe} \ x \ a_{2OH^-}}$$ [4.4]

In which:

E_0^{F+} = Standard electrochemical cell potential = -0.88 V (Sathyanarayana, cited in Shukla, Venugopalan & Hariprakash 2001, p.128)

If the product of all activity is assumed to be 1, E_{Fe} can be obtained as:

E_{Fe} = -0.88 V.

E_{Fe} value is converted to positive for E total calculation,

Therefore, the total value of E using Nernst equation can be calculated as:

E total = E_{Ni} + E_{Fe} = 0.49 + 0.88 = 1.37 V [4.5]

This value of E total confirms the OCV value using the standard redox potential.

On the other hand, the fully discharged OCV value of each cell of nickel iron battery can be determined as 1.05 V using the following equation (Shukla, Venugopalan & Hariprakash 2001):

$$NiOOH + Fe(OH)_2 \xrightleftharpoons[\text{Charge}]{\text{Discharge}} Ni(OH)_2 + FeOOH \ (E_{cell} = 1.05 \text{ V})$$ [4.6]
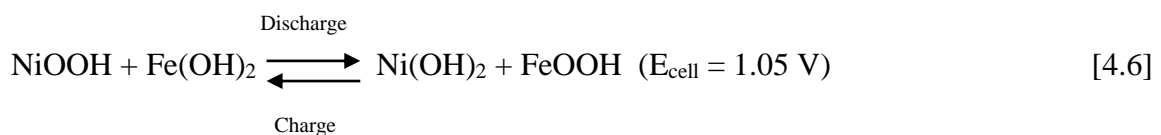
4.3.1 Simulation results

In order to match the requirement of impedance track method, the graph produced by Shepherd's equation based model that can be seen in figure 13 should be converted to a single model curve that consists of voltage vs. SOC. This graph then can be plotted with the OCV values obtained from the laboratory measurement than can be seen at table 4. For simulation purposes, those OCV values at table 4 were converted to a single cell values which means that they were divided by 10 since this battery consist of 10 cells. The combination of the graphs can be seen below (MATLAB® codes can be seen in appendix D):
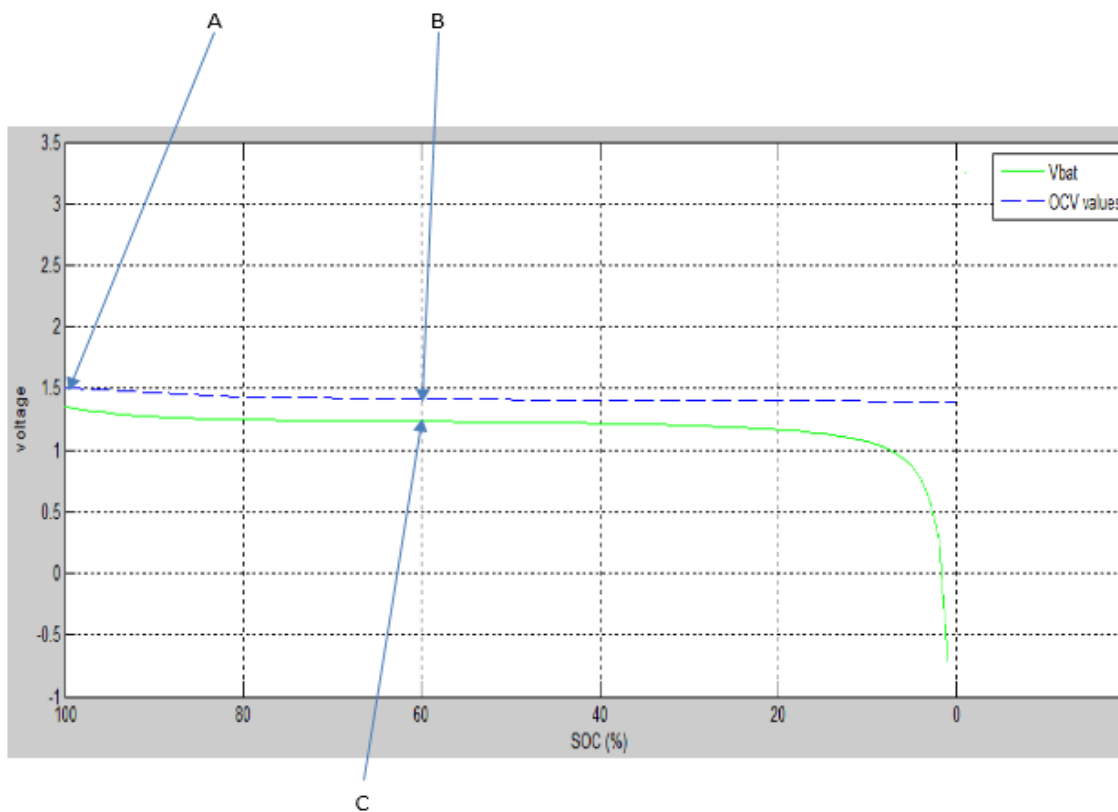
Figure 25: V$_{bat}$ vs. OCV of nickel iron battery using impedance track method

The open circuit voltage method is used to validate that nickel iron battery is in fully charged condition at point A. According to discharging measurement data at table 4, this

battery is considered as fully charged with OCV = 1.499 V for a single cell voltage. Once it is validated that this battery is fully charged, the ampere hour counting process begins to discharge the battery. In order to maintain the accuracy of the SOC prediction, another validation process is created at points B and C. At these points, V_{bat} value is used to calculate R_{BAT} using equation [3.8]. This R_{BAT} value then stored as a function of time, SOC and temperature. After the R_{BAT} value is calculated, the V_{bat} value is corrected using equation [3.9]. This will ensure that the SOC prediction accounts the changes of battery chemical reactions caused by factors such as temperature changes and aging factor.

Furthermore, impedance track method enables Q_{max} to be determined without having to fully discharge the battery. This is very useful since the maximum capacity of the battery can be calculated in a very short period. The changes of the battery maximum capacity due to aging factor and temperature effect can accurately be accounted since the OCV method can represent an accurate SOC in an equilibrium state and the ampere hour counting method works very well under loaded condition.

The Q_{max} calculation is determined as follows (MATLAB® codes can be seen in appendix D):
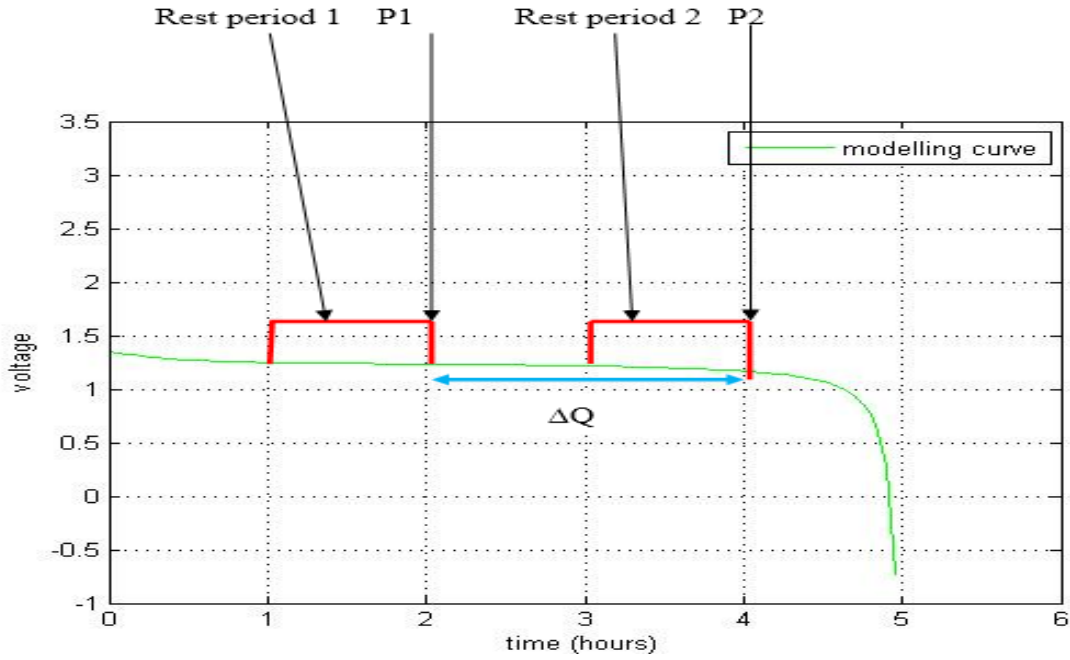
Figure 26: Q_{max} calculation using impedance track method

When the battery is rested during rest period 1, the battery voltage increases approximately as the red coloured area and P1 is measured with OCV method to find out the SOC of that position. Subsequently, ΔQ is measured with ampere hour counting to find out the amount of charge passed from point 1 to point 2. Finally, when the battery is rested during rest period 2, the battery voltage rises roughly as the red coloured area and P2 is measured with OCV method to obtain the SOC at this position.

The above figure is a discharge model for a 10Ah battery which is discharged with 0.2C rate. We can prove the Q_{max} calculation method can figure out that the Q_{max} value should be 10Ah without having to fully discharge the battery. According to figure 16, SOC1 at P1 = 0.6 whereas SOC2 at P2 = 0.2. Moreover, since the capacity of the battery is 10Ah, ΔQ = 4Ah. Using equation [3.10]:

$$Q_{max} = \frac{\Delta Q}{SOC1 - SOC2}$$

$$Q_{max} = \frac{4Ah}{0.6 - 0.2} = 10Ah$$

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It is proven that without fully discharging the battery, the maximum capacity of the battery can be calculated effectively.

4.3.2 Laboratory measurement results

The temperature during the laboratory processes is considered as an average room temperature 23 °C. The OCV data obtained during charging process can be seen at table 2:

Table 2: OCV data obtained during charging process

Before charging the battery, it was discharged to 0% SOC at 10V. It can be seen from table 2 above that the 10Ah nickel iron battery then was charged with 2A (DF4) and 16.5V (DF3). The last fully charged voltage of the battery is 16.37117V (DF1). The OCV values are displayed by address DF5 to DF9 and these values can be converted to OCV vs. SOC table under charging process:

Table 3: OCV vs. SOC under charging process 1st measurement.

OCV (V)	SOC (%)
13.6	0
15.36311	20
15.37874	40
15.37874	60
15.37874	80
15.37874	100

It can be seen from table 3 above that the OCV was 13.6 V at 0% SOC (obtained by direct measurement using multi meter). Then the OCV significantly rose to 15.36311 V at 20% SOC. Subsequently, the OCV value hit a plateau from 40% to 100% SOC. Since this battery used at this project is not a new battery and by looking at those identical OCV values from 20% SOC to 100% SOC, the battery capacity should be verified. This verification is required to find out whether the battery capacity is 10Ah as the original capacity or it has decreased due various factors such as aging.

After the battery is fully charged for the measurement above, the battery is rested for 24 hours and the first discharging process was conducted and the results are:

Battery capacity   = 0.5025 Ah

Voltage start   = 13.670 V

Deplete time   = 00:14:53

Current   = 1.999 A

The voltage vs. capacity curve can be seen in figure 27:
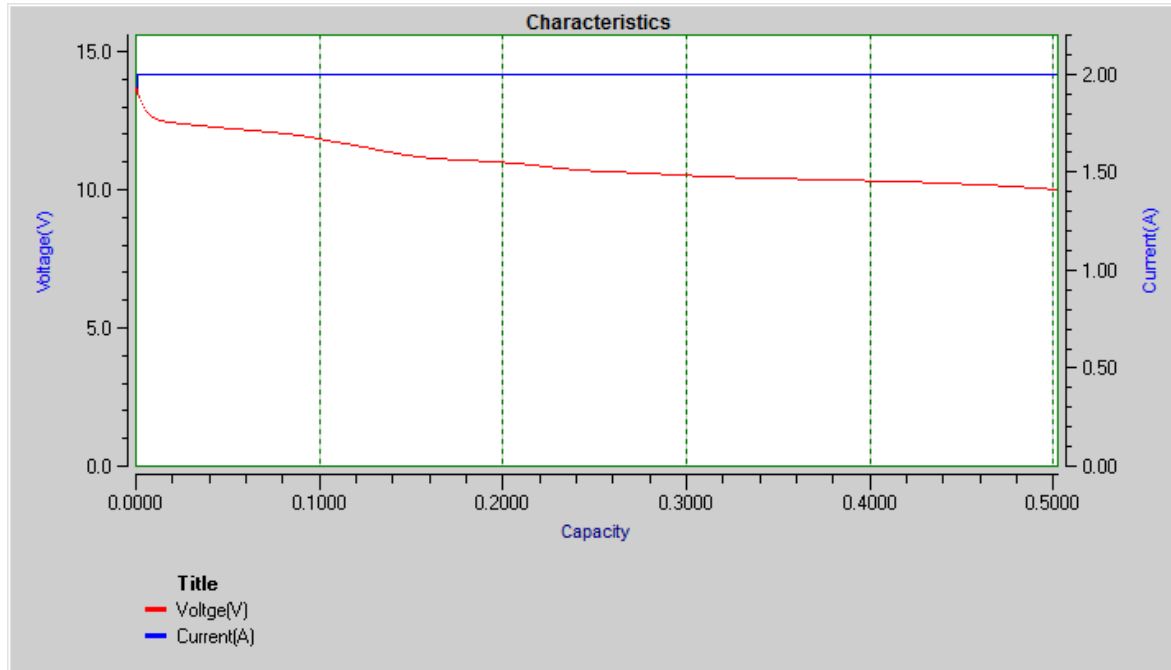
Figure 27: 1ˢᵗ Discharge voltage vs. capacity.

The obtained data above shows that the battery capacity is very small which was only

0.5025 Ah. Therefore, the battery is then charged for 5 hours without rest period with 2 A

and 16.5 V. The battery is then discharged for the with C/5 rate to find out the most

accurate battery capacity and the results are as follows:

Battery capacity   = 1.2521 Ah

Voltage start   = 14.760 V

Deplete time   = 00:37:05

Current   = 1.999 A

The voltage vs. capacity curve can be seen in figure 28:
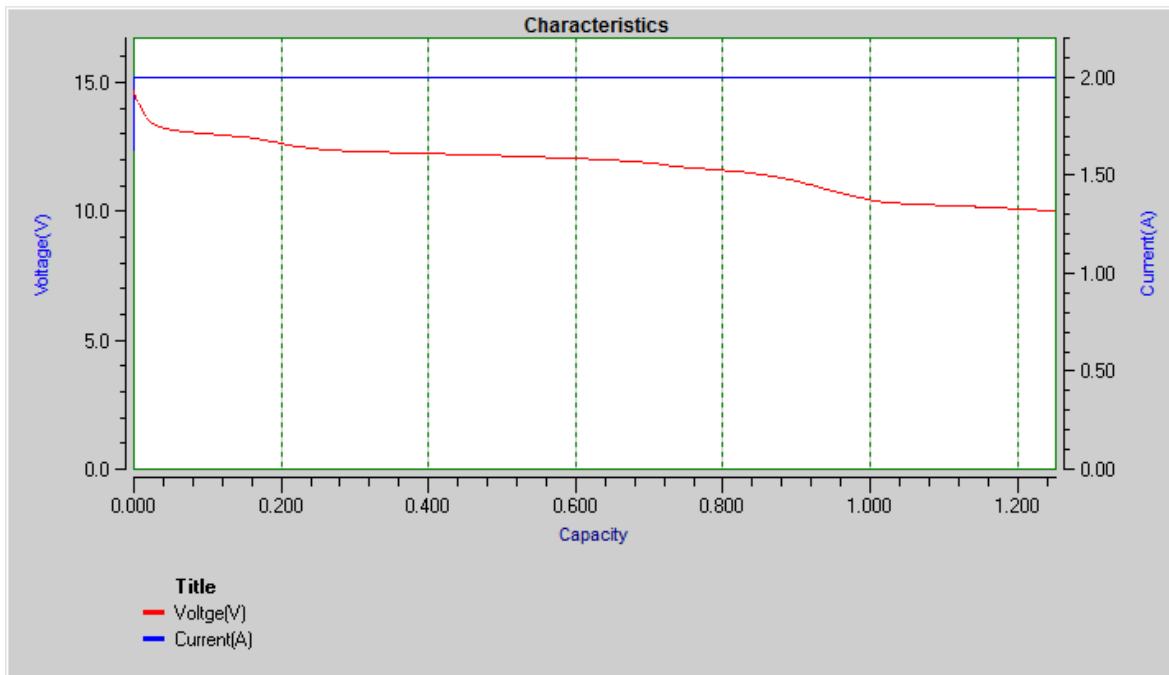
Figure 28: 2nd Discharge voltage vs. capacity.

The result shown in figure 28 above is the most accurate indicator for the battery capacity. Therefore, it can be concluded that the battery capacity used in this project is 1.25 AH instead of 10Ah. As a consequence, parameters set for discharging and charging processes should be adjusted. The C/5 rate should be 1.2521 Ah/5 = 0.25A. By using the new defined C/5 rate, the OCV data for the battery during discharge can be seen at table 4:

Table 4: OCV values under discharging process.

Date	Time	OCV Voltage	SOC(%)
6/7/2016	4:19:45 PM	14.99	100
6/7/2016	6:19:45 PM	14.24	80
6/7/2016	8:19:45 PM	14.17	60
6/7/2016	10:19:46 PM	14.09	40
6/8/2016	12:19:46 AM	14.02	20
6/8/2016	2:19:46 AM	13.96	0

The voltage vs. capacity curve can be seen in figure 29:
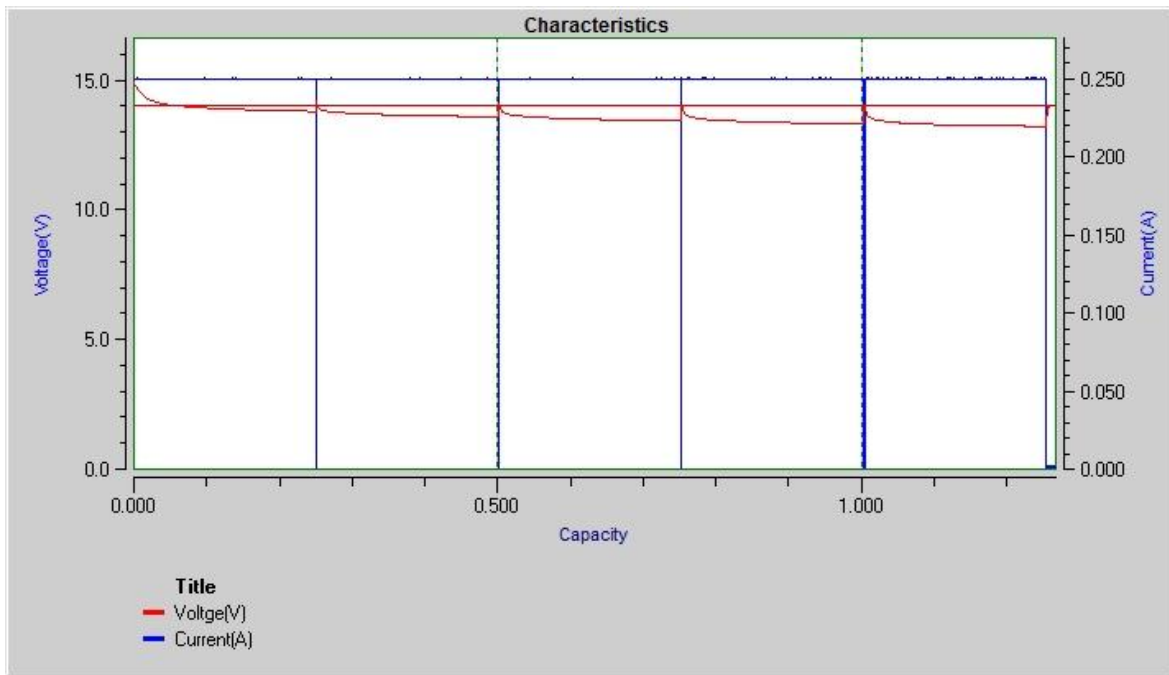
Figure 29: Under load voltage & OCV vs. capacity during discharging process.

It can be seen from figure 29 above that every there are peak values of voltage curve every 1-hour period. Those values are the OCV values after 1-hour rest period.

After obtaining accurate OCV values during discharging process, the 2nd measurement to obtain accurate OCV values during charging process was conducted and can be seen at table 5 and 6:

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Table 5: OCV data obtained during 2nd charging process

Data View -[DataView1]

No.	Address	Nickname	Current Value	Viewing Format
001	F DF1		15.23027	Real
002				
003	F DF4		0.25	Real
004	F DF3		16.5	Real
005	F DF5		15.07398	Real
006	F DF6		15.26152	Real
007	F DF7		15.34748	Real
008	F DF8		15.37874	Real
009	F DF9		15.37874	Real
010				

Before charging the battery, it was discharged to 0% SOC at 10V. It can be seen from table 5 above that the 10Ah nickel iron battery then was charged with 0.25A (DF4) and 16.5V (DF3). The last fully charged voltage of the battery is 15.23027V (DF1). The OCV values are displayed by address DF5 to DF9 and these values can be converted to OCV vs. SOC table under charging process:

Table 6: OCV vs. SOC under charging process 2st measurement.

OCV (V)	SOC (%)
13.8	0
15.07398	20
15.26152	40
15.37874	60

15.37874	80
15.37874	100

*OCV values at 0% SOC obtained by direct measurement using multimeter.

It can be seen from table 6 above that the identical OCV values from 40%-100% SOC at table 3 can be reduced at this 2nd measurement. However, the OCV still hit a plateau from 60% to 100%. This condition is commonly for the nickel iron battery. However, a further investigation in the future with different batteries is suggested to be conducted.

4.3.3 Step by step application of impedance track method to determine remaining battery capacity.

The gauging system of impedance track method can be explained with the following steps:

a) Assume that the lookup table for OCV as a function of SOC and temperature has been constructed.

b) When there is a battery that has been left unused for a period of time, the SOC of the battery should be not 100% due to various factors such as self-discharge. Impedance track method identifies the initial state of charge of the battery by measuring the battery voltage and compares it with the OCV lookup table. By doing so, the initial SOC of the battery will be obtained.

c) The obtained initial SOC determines the Q_{max} value. This Q_{max} value is then used to perform ampere hour counting. During loaded condition, ampere hour counting determine the remaining capacity of the battery.

d) To maintain the accuracy of gauging system, Q_{max} can be updated by measuring two points under rested periods. Equation [3.10] is used to calculate Q_{max}. Battery

aging can be accounted by this update. Additionally, temperature changes are also taken into account. For example, if the temperature of the battery decreases from 23°C to 10°C, the resistance of the battery will be increased. As a result, the battery voltage be decreased. Q_{max} update makes sure that the reported capacity is correct by comparing the battery voltage to the OCV lookup table. Instead of 60% SOC Q_{max} update could report that the SOC is only 30% because of the voltage drop during low temperature condition.

e) During ampere hour counting period, the R_{BAT} values will be calculated at each point of SOC. In order to calculate R_{BAT} values, V_{BAT} values under loaded condition are measured at each point of SOC. Then, equation [3.8] is used to calculate R_{BAT} values.

f) The calculated R_{BAT} values then stored as a lookup table. This lookup table is a function of SOC and temperature.

g) Once the first cycle of discharging is completed, a lookup table of R_{BAT} as a function SOC and temperature is fully created.

h) The lookup table of R_{BAT} is then used to calculate the V_{BAT} of the battery using equation [3.9] during the next discharging cycle. This enables SOC prediction without having to do ampere hour counting for the entire cycle. As an example, a 10Ah battery can be discharged for with C/5 rate and gauged with OCV method and ampere hour counting method for the first two-hour period. The SOC during the remaining three-hour period can be easily predicted by using R_{BAT} values to calculate $V_{BAT.}$

i) The learning cycle of R_{BAT} values should be done continuously to make sure that any changes to the battery capacity due to various aspects such as temperature changes can be accounted.

CHAPTER 5: CONCLUSIONS

5.1 SUMMARY OF PROJECT OUTCOME

The general review of nickel iron battery with a focus on its relative advantages and disadvantages compared to the two most widely used battery types has been conducted (referred to project objective 1.2a). The nickel iron battery is found more effective to be used as energy storage system for renewable energy applications. One reason is due to its long life cycle that can potentially reach up to more than 20 years. Another widely used battery has such as lead acid battery can only last between 5 to 7 years of operation.

In addition, the general review of existing battery mathematical model has been carried out (referred to project objective 1.2b). It is then found that there are various methods of mathematical model such as Thevenin's theorem based model and run-time based model. However, it is found that currently there is no mathematical model developed for the nickel iron battery. Furthermore, there is one promising method called Impedance track model that was chosen to be applied for nickel iron battery.

Moreover, three methods namely Shepherd's equation based model, Pekuert's equation based model and Impedance track model have been analysed (referred to project objective 1.2c). The Shepherd's equation based model has been tested and evaluated and the results show that this approach is impractical to predict the state of charge of nickel iron battery as this method depends on the history of discharge curve which also contains flat area under certain period of time and it requires a very high efficiency value of the battery.

As a result, the next model which is based on Peukert's equation has been tested to find a better solution. A simple Peukert's equation which relates the discharge capacity, discharge current, discharge time and Peukert's coefficient can be used to predict the time

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required for the nickel iron battery to reach the zero capacity. The result of the ampere hour counting method combined with Peukert's coefficient can represent the SOC of nickel iron battery better than pure ampere hour counting or Shepherd's equation since Peukert's coefficient represents the real operating condition of the nickel iron battery. Nevertheless, Peukert's model cannot be used at variety of discharge rate, the discharge rate should be assumed constant. Furthermore, Peukert's coefficient will be changed in the real life of battery operations due to battery aging and temperature changes.

Those problems mentioned above that cannot be tackled by Shepherd's equation and Peukert's equation can be solved by the impedance track method. The impedance track method can predict the SOC of nickel iron battery accurately since this method combines OCV method which is very accurate during equilibrium period of the battery with ampere hour counting which is reliable during loaded condition. Self-discharge, aging, and temperature change can be accounted by this model. It is also has been shown that this method which was developed for lithium ion battery is applicable to nickel iron battery if an accurate voltage meter is employed. An accurate voltage meter is required since the discharge curve of nickel iron battery is more flat if compared to lithium ion battery's discharge curve.

Those three models mentioned above have been created using Matlab$^{®}$ software (referred to project objective 1.2d). The state of charge predictions using Shepherd's equation based model and Peukert's equation based model can be simulated. However, state of charge prediction using impedance track model can only fully work when this system is created for smart gauging system which includes hardware components that can perform ampere hour counting, voltage measurement and integrated circuit (IC) that can store lookup tables for OCV and R_{BAT} values.

Therefore, if the required hardware components can be combined with the impedance track model, a smart gauge can be constructed (referred to project objective 1.2e). The smart gauge then enables the construction of a smart charger for the nickel iron battery.

The nickel iron battery has also been tested during charging and discharging processes (referred to project objective 1.2f). The tests provide OCV values that can be used as lookup tables for impedance track method.

5.2 SUGGESTION FOR FUTURE WORK

It is suggested that the impedance track method is used to build a smart gauge for the nickel iron battery. This smart gauge can be used to construct a smart charger for nickel iron battery. Furthermore, it can be seen that the OCV values during charging process are identical for 60% to 100% SOC by referring to table 6. This means that it will be hard to implement impedance track for SOC prediction during charging process of the nickel iron battery. This requires further investigation to find out the cause of this identical values.

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APPENDIX A
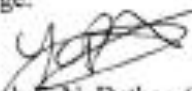
University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG8411/8412 Research Project

PROJECT SPECIFICATION

FOR: Jacob F. N. Dethan

TOPIC: Mathematical Modelling of Nickel Iron Battery

SUPERVISOR: A/Prof. Tony Ahfock

PROJECT AIM: The project aims to predict the State of Charge of Nickel Iron battery.

SPONSORSHIP: AusAID

PROGRAMME: **(Issue B, 07 May 2016)**

1. Research the general review of different available battery models and their capabilities.

2. Research the general review of Nickel Iron battery with a focus on its relative advantages and disadvantages comes to the two most widely used battery types.

3. Analyse the applicability of the modelling methods for different available battery models to the Nickel Iron battery.

4. Design and construct battery testing systems for measuring open circuit voltage during charging and discharging.

5. Design a MATLAB model to simulate the State of Charge of Nickel Iron battery.

6. Demonstrate how the model can be used to help with the design of smart chargers for the Nickel-Iron Battery.

7. Submit a dissertation on this research.
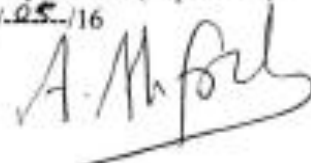
As time permits:

8. Simulate more performance features of Nickel Iron battery such as output voltage and self-discharge.

AGREED: Jacob F. N. Dethan (Student)   Assoc Prof. Tony Ahfock (Supervisor)
Date: 07/05/16   Date: 07/05/16

Examiner/Co-examiner: Dr. Andreas Nataadmadja

APPENDIX B

MATLAB® codes for Shepherd's equation:

R calculation:

```
Vnom = 1.2;
Qnom = 10;
n = 0.995;

R = Vnom * ((1-n)/(0.167*Qnom))
```

K calculation:

```
Vfull = 1.35;
Vnom = 1.2;
A =  0.11;
B = 1.4145;
Qnom = 6.68;
Q = 10;

K = ((Vfull-Vnom+A*(exp(-B*Qnom)-1))*(Q-Qnom))/Qnom
```

E0 calculation:

```
Vfull=1.35;
k=0.0199;
R=0.0036;
i=1.67;
A= 0.11;

E0=Vfull+k+(R*i)-A
```

Shepherd's mathematical model:

```matlab
% Generic Battery model (Oliver Tremblay; Louis Dessaint; Abdel-Illah
% Dekkiche)

close all;
clc, clear;

%%Importing the data

nife=xlsread('nife_discharge_data.xlsx');
x_axis=nife(:,1);
y_axis=nife(:,2);


E0 = 1.2659; % (V)
R= 0.0036; % ( ohm)
K=0.0199; % (V)
A= 0.11; % (V)
B = 1.4145; % 1/(Ah)
I = 1.67 ; % (A)
Q = 10 ; % (Ah)

tim = [ 0: 0.05 :5.8];
siztim= size(tim);
Vbat  = zeros( 1, siztim(1,2));
for ii=1:siztim(1,2)

    Vbat(ii) = E0 - K*(Q/(Q-I*tim(ii))) + A*exp(-B*I*tim(ii)) ;

end

plot(tim, Vbat,'g',x_axis,y_axis,'--')
legend('modelling curve','curve from factory')
xlabel('time (hours)')
ylabel('voltage')
grid on
```

Factory curve data extracted from nickel iron discharge curve produced by Iron Core Batteries:

Time (h)	Voltage	Time (h)	Voltage	Time (h)	Voltage
0.0439	1.34	2.06	1.23	4.31	1.21
0.0789	1.33	2.1	1.23	4.38	1.21
0.132	1.33	2.18	1.23	4.44	1.21
0.202	1.32	2.24	1.23	4.51	1.21
0.272	1.31	2.3	1.23	4.54	1.21
0.316	1.3	2.36	1.23	4.57	1.2
0.377	1.3	2.44	1.23	4.63	1.2
0.43	1.29	2.52	1.23	4.7	1.2
0.474	1.29	2.6	1.23	4.72	1.2
0.544	1.28	2.68	1.23	4.8	1.19
0.596	1.28	2.75	1.23	4.83	1.19
0.667	1.27	2.82	1.23	4.91	1.18
0.711	1.27	2.87	1.23	4.97	1.18
0.772	1.27	2.95	1.23	5.03	1.17
0.807	1.26	3.03	1.23	5.1	1.17
0.842	1.26	3.08	1.23	5.15	1.16
0.904	1.26	3.14	1.23	5.22	1.16
0.982	1.25	3.22	1.23	5.3	1.15
1.05	1.25	3.28	1.23	5.33	1.14
1.12	1.25	3.34	1.23	5.36	1.14
1.18	1.25	3.42	1.23	5.41	1.13
1.25	1.24	3.49	1.23	5.46	1.13
1.32	1.24	3.53	1.23	5.52	1.12
1.38	1.24	3.57	1.23	5.56	1.11
1.42	1.24	3.65	1.22	5.64	1.1
1.46	1.24	3.72	1.22	5.69	1.09
1.52	1.24	3.8	1.22	5.75	1.08
1.6	1.24	3.85	1.22	5.79	1.07
1.67	1.23	3.91	1.22	5.81	1.06
1.7	1.23	3.99	1.22	5.82	1.05
1.75	1.23	4.06	1.22	5.87	1.04
1.83	1.23	4.11	1.22	5.89	1.04
1.91	1.23	4.18	1.22	5.9	1.03
1.98	1.23	4.24	1.21	5.92	1.02

APPENDIX C

MATLAB® codes for Peukert's equation:

Capacity vs. time code:

```matlab
clc,clear;
close all;

Idis = 1.67; % Discharge rate
C = 10; %Manufacturer's rated capacity in Ah
k =1.25; % Peukert's coefficient

Full_discharge_time = C / ((Idis)^k);%full discharge time in hours
eighty_percent_discharge_time=0.8*Full_discharge_time; %hours
seventy_five_percent_discharge_time=0.75*Full_discharge_time; %hours
fifty_percent_discharge_time=0.5*Full_discharge_time; %hours
twenty_percent_discharge_time=0.2*Full_discharge_time; %hours


Tdischarge1 = Full_discharge_time;
Idischarge1 = 1.67;

Cdischarge1 = Tdischarge1 * ((Idischarge1)^k);%amount of capacity
discharged Ah at full discharge time

Tdischarge2 = eighty_percent_discharge_time;
Idischarge2 = 1.67;

Cdischarge2 = Tdischarge2 * ((Idischarge2)^k);%amount of capacity
discharged Ah at 80% discharge time

Tdischarge3 = seventy_five_percent_discharge_time;
Idischarge3 = 1.67;

Cdischarge3 = Tdischarge3 * ((Idischarge3)^k);%amount of capacity
discharged Ah at 75% discharge time

Tdischarge4 = fifty_percent_discharge_time;
Idischarge4 = 1.67;

Cdischarge4 = Tdischarge4 * ((Idischarge4)^k);%amount of capacity
discharged Ah at 50% discharge time

Tdischarge5 = twenty_percent_discharge_time;
Idischarge5 = 1.67;

Cdischarge5 = Tdischarge5 * ((Idischarge5)^k);%amount of capacity
discharged Ah 20% discharge time
```

```
A=[0;twenty_percent_discharge_time;
fifty_percent_discharge_time;seventy_five_percent_discharge_time;eighty_p
ercent_discharge_time;Full_discharge_time];

B=[10,10-Cdischarge5,10-Cdischarge4,10-Cdischarge3,10-Cdischarge2,10-
Cdischarge1];
plot(A, B,'g')
xlabel('time (hours)')
ylabel('Capacity(Ah)')
grid on
```

State of charge calculation:

```
% State of charge calculation model
% using equation developed by Lluís Farré, Lluís Closas and Pau Casals

clc;
clear;
close all;

I = 1.67;
C0 = 10;
Cm = 10;
n = 1.25;
tim = [ 0: 0.05 :6];

siztim= size(tim);
soc  = zeros( 1, siztim(1,2));
for ii=1:siztim(1,2)

    soc(ii) = 100*((C0  - (I^n)*tim(ii))/(Cm));
end

plot(tim, soc,'g')
xlabel('time (hours)')
ylabel('SOC')
grid on
```

APPENDIX D

MATLAB® codes for Impedance Track method:

```matlab
% Generic Battery model (Oliver Tremblay; Louis Dessaint; Abdel-Illah
% Dekkiche)

close all;
clc, clear;

%%Importing the data

nife=xlsread('OCV _data_example.xlsx');
x_axis=nife(:,1);
y_axis=nife(:,2);


E0 = 1.2659; % (V)
R= 0.0036; % ( ohm)
K=0.0199; % (V)
A= 0.11; % (V)
B = 1.4145; % 1/(Ah)
I = 2 ; % (A)
Q = 10 ; % (Ah)

tim = [ 0: 0.05 :5.05];
siztim= size(tim);
Vbat  = zeros( 1, siztim(1,2));
for ii=1:siztim(1,2)

    Vbat(ii) = E0 - K*(Q/(Q-I*tim(ii))) + A*exp(-B*I*tim(ii)) ;

end

plot(tim, Vbat,'g',x_axis,y_axis,'--')
legend('Vbat','OCV values')
xlabel('SOC (%)')
ylabel('voltage')
grid on
```

Qmax calculation:

```matlab
% Generic Battery model (Oliver Tremblay; Louis Dessaint; Abdel-Illah
% Dekkiche)

close all;
clc, clear;




E0 = 1.2659; % (V)
R= 0.0036; % ( ohm)
K=0.0199; % (V)
A= 0.11; % (V)
B = 1.4145; % 1/(Ah)
I = 2 ; % (A)
Q = 10 ; % (Ah)

tim = [ 0: 0.05 :5.05];
siztim= size(tim);
Vbat  = zeros( 1, siztim(1,2));
for ii=1:siztim(1,2)

    Vbat(ii) = E0 - K*(Q/(Q-I*tim(ii))) + A*exp(-B*I*tim(ii)) ;

end

plot(tim, Vbat,'g')
legend('modelling curve')
xlabel('time (hours)')
ylabel('voltage')
grid on
```

APPENDIX E

Risk Assessment

The following risk assessment has been submitted online on USQ internal risk assessment portal. It is approved by Mr. Brett Richards, Senior Technical Officer, on the 15/03/2016. It is then signed by dissertation supervisor Assoc Prof. Tony Ahfock on 10/04/2016.

University of Southern Queensland

USQ Safety Risk Management System

| Save As New RMP... | Close |

Safety Risk Management Plan

Risk Management Plan ID:	Status:	Current User:	Author:	Supervisor:	Approver: i:0#.w|usq\richardj
RMP_2016_212	Approve	i:0#.w|usq\u1065369	i:0#.w|usq\u1065369	i:0#.w|usq\ahfock	

Assessment Title:	Risk management plan for laboratory activity at room Z205.	Assessment Date:	16/03/2016
Workplace (Division/Faculty/Section):	Faculty of Health Engineering and Sciences	Review Date:	16/03/2021 (5 years maximum)

Context

DESCRIPTION:

What is the task/event/purchase/project/procedure?	The charging and discharging of nickel iron battery.
Why is it being conducted?	For the collection of data that is useful for the master dissertation C research.
Where is it being conducted?	Z205.
Course code (if applicable)	ENG8412

Chemical Name (if applicable)	Potassium Hydroxide.

WHAT ARE THE NOMINAL CONDITIONS?

Personnel involved	1.
Equipment	- 1 DC programmable power supply, Type: Sorensen DLM 32-125E, USQ Asset tag: 014-4174, Manufacturer: Ametek, Inc. - 1 Fluke 289 True RMS multimeter. - 1 Fluke 87 III Ture RMS multimeter. - 1 Click Koyo PLC C002DD2D. - 1 Hp Presario CQ41 Laptop. - 1 Nickel iron 10 Ah 1.2V battery, Manufacturer: Iron Core Batteries. - 1 Programmable DC electronic load, Type: 8500 DC Load series, Manufacturer: BK Precision.
Environment	Energy Laboratory Z205
Other	-
Briefly explain the procedure/process	- The battery will be discharged to 1 V with C/5 current rate. - The battery will be charged to a fully charged open circuit voltage 1.34 V with C/5 current rate and 1.35V. - The open circuit voltage will be measured in 1 hour interval of the charging and discharging processes.

Assessment Team - who is conducting the assessment?

Assessor(s):	Brett Richards
Others consulted: (eg elected health and safety representative, other personnel exposed to risks)	-

Risk Matrix

Probability	Consequence				
	Insignificant ❓ No Injury 0-$5K	**Minor** ❓ First Aid $5K-$50K	**Moderate** ❓ Med Treatment $50K-$100K	**Major** ❓ Serious Injury $100K-$250K	**Catastrophic** ❓ Death More than $250K
Almost Certain ❓ 1 in 2	M	H	E	E	E
Likely ❓ 1 in 100	M	H	H	E	E
Possible ❓ 1 in 1,000	L	M	H	H	H
Unlikely ❓ 1 in 10,000	L	L	M	M	M
Rare ❓ 1 in 1,000,000	L	L	L	L	L

	Recommended Action Guide
Extreme:	E= Extreme Risk – Task **MUST NOT** proceed
High:	H = High Risk – Special Procedures Required (Contact USQSafe) Approval by VC only
Medium:	M= Medium Risk - A Risk Management Plan/Safe Work Method Statement is required
Low:	L= Low Risk - Manage by routine procedures.

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Risk Register and Analysis

	Step 1	Step 2	Step 2a	Step 3				Step 4				
	Hazards: From step 1 or more if identified	The Risk: What can happen if exposed to the hazard with existing controls in place?	Existing Controls: What are the existing controls that are already in place?	Risk Assessment: Consequence x Probability = Risk Level				Additional Controls: Enter additional controls if required to reduce the risk level	Risk assessment with additional controls: Has the consequence or probability changed?			
				Consequence	Probability	Risk Level	ALARP		Consequence	Probability	Risk Level	ALARP
	Example											
	Working in temperatures over 35° C	Heat stress/heat stroke/exhaustion leading to serious personal injury/death	Regular breaks, chilled water available, loose clothing, fatigue management policy.	catastrophic	possible	high	No	temporary shade shelters, essential tasks only, close supervision, buddy system	catastrophic	unlikely	mod	Yes
1	Excessive hydroge	Can lead to a batter	An appropriately sized safety f	Moder ▾	Unlik ▾	Mediu...	☐	-The exhaust fan will be used to pre - Suitable enclosure used to contair	Minor ▾	Unlik ▾	Low	☑
2	Short circuit of th	Can lead to power :	The power supply has been co	Minor ▾	Unlik ▾	Low	☑		▾	▾		☐
3	Short circuit of cc	Can lead to equipm	All the connecting cables have	Minor ▾	Unlik ▾	Low	☑		▾	▾		☐
4	Electric shock fro	The user could face	The user has been trained and	Minor ▾	Unlik ▾	Low	☑		▾	▾		☐
5	Skin damage caus	The skin of the use	The electrolyte will be filled by	Minor ▾	Unlik ▾	Low	☑		▾	▾		☐
6	Battery internal s	Can lead to a batter	- A safety fuse is used. - The physical condition of the - The separator and plates are	Moder ▾	Unlik ▾	Mediu...	☐	- The battery terminal voltage will l - The battery will be secured in a pr	Minor ▾	Unlik ▾	Low	☑

Step 5 – Action Plan (for controls not already in place)

	Additional Controls:	Exclude from Action Plan: (repeated control)	Resources:	Persons Responsible:	Proposed Implementation Date:
1	-The exhaust fan will be used to prevent hydroge - Suitable enclosure used to contain the battery.	☐	-The exhaust fan has been installed. -Suitable enclosure has been installed.	Jacob Dethan	16/03/2016
6	- The battery terminal voltage will be monitored - The battery will be secured in a proper position	☐	- PLC has been installed to monitor and test th - The battery has been properly secured in a p	Jacob Dethan	16/03/2016

Supporting Attachments

📎 Click here to attach a file

Step 6 – Request Approval

Drafters Name:	Jacob F. N. Dethan	Draft Date:	7/03/2016
Drafters Comments:			

Assessment Approval: **All risks are marked as ALARP**　　　　　　　　　　0

Maximum Residual Risk Level: **Low - Manager/Supervisor Approval Required**　　　　1

Approver:	Supervisor: (optional - for notification of Risk Assessment only)	Document Status:

Brett Richards:		Tony Ahfock:		Approve

Step 6 – Approval

Approvers Name:	Brett Richards		Approvers Position Title:	Senior Technical Officer
Approvers Comments:				

I am satisfied that the risks are as low as reasonably practicable and that the resources required will be provided.

Approval Decision: Approve	Approve / Reject Date: 15/03/2016	Document Status:	Approve

Supervisor Approval

Approvers Name:

Assoc Prof. Tony Ahfock.

Approvers comments:

Approvers signature: A. Ahfock   10/4/16.

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UNIVERSITY
OF SOUTHERN
QUEENSLAND

Faculty of Health Engineering and Science
University of Southern Queensland
WEST St. TOOWOOMBA 4350

Z205 Energy Research Laboratory Induction Checklist.
To be completed for any person other than Electrical Engineering Staff requiring access to Z205
Energy Research Laboratory.

Introduce Laboratory Accountable Staff (Professional and Academic)   ✓

- Explain:

Emergency Procedures for Z Building	2222	✓
	Exits	✓
	Assembly Point	✓
	Alarm System	✓

Appropriate Clothing – covered footwear, no dangling/conductive jewellery   ✓

- Show Location of:

Safety Data Sheet (SDS) location and procedures	✓
First Aid Kit	✓
Safety Notice Board	✓
Fire Extinguishers	✓
Evacuation Alarms	✓
Personal Protective Equipment (PPE)	✓
Wash Stations	✓
Toilets	✓
Telephones	✓

- Protocols for Laboratory:

PPE and specified by Risk Assessment, Risk Management Plan (RMP),
Safe Working Procedure (SWP) and/or SDS.   ✓
Supervisor to be notified when working in the laboratory   ✓
Follow all instructions given by staff   ✓
Intellectual property and confidentiality   ✓
Instructions provided for specific machine or tool or task   ✓
SWP read and understood for specific machine, tool or task   ✓
Risk assessment required?   ✓
Relevant Qualifications – ....B Eng Electrical............

- Special conditions

Competency assessed by supervisor before using equipment or undertaking task.   ✓
Work only to be performed during normal business hours (8am-6pm Mon-Fri)   ✓
NO electrical work (ie working with voltage greater than Extra Low Voltage)
shall be performed without appropriate staff member present and appropriate   ✓
RMP signed by Supervisor.

Student Supervisor (Print) Assoc Prof. Tony Ahfock
Sign................A. Ahfock................ Date...../...../......

Student Name (print) Jacob Oethan
Sign................ Date 15 / 02 / 2016

Staff(print) Brett Richards
Sign................ Date 15 /02/16