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Rechargeable Battery Capacity Level Indicator

Helsinki Metropolia University of Applied Sciences

Bachelor Degree

Information Technology

Thesis

8 May 2015

Abstract

Author Title	Jared Ongere Rechargeable Battery Capacity Level Indicator
Number of Pages Date	56 pages + 4 appendices 8 May 2015
Degree	Bachelor of Engineering
Degree Programme	Information Technology
Specialisation option	Embedded Engineering, Measurement System
Instructor	Anssi Ikonen, Principal Lecturer

Technology on rechargeable batteries has advanced over the years as a result of the need to power portable devices that have risen in numbers in the last decade. Just like primary cells, rechargeable batteries work in the same way, only their chemical reactions are reversible.

This project aimed at building a system that would indicate the capacity level of a Nickel Metal Hydride battery upon charging and discharging. The Nickel Metal Hydride battery was selected in this project due to its preference among consumers. However, since the principle behind the rechargeable battery technology is similar, the system can be used to test other types of batteries.

System implementation involved designing and building a battery charger circuit and a discharge circuit. Software design then followed, after which testing was performed.

The project goal was achieved and results were presented through numeric figures, charts and indicators. The system is expected to help in planning with batteries to avoid halt of devices during operation. The results gathered during testing point to a possible reduced battery wastage. A better way to handle batteries to conserve capacity has also been highlighted.

Keywords	battery, NiMH, capacity

Contents

Appendices

Appendix 1. Charging and Discharging Circuit Design Layouts
Appendix 2. Charge Monitoring and Control Program
Appendix 3. Discharge Monitoring and Control Program
Appendix 4. Capacity Derivation Part of the Program

Abbreviations

ADC	Analog to Digital Conversion
CMOS	Complementary Metal-Oxide Semi-Conductor
DAQ	Data Acquisition Instrument
DMM	Digital Multimeter
DoD	Depth of Discharge
EMF/ e.m.f	Electro-Motive Force
KOH	Potassium hydroxide
LabVIEW	Laboratory Virtual Instrumentation Engineering Workbench
LED	Light Emitting Diode
mAh	milli-Ampere hours
NDV	Negative Delta Voltage
NI	National Instrument
NiCad	Nickel Cadmium
NiMH	Nickel Metal Hydride

1 Introduction

The goal of the project was to design and build a system that would indicate the capacity level of a rechargeable portable battery upon discharging a fully charged battery. Besides building the system, a highlight of the study on NiMH battery which is core component of the subject, is reviewed. The review is vital not only for system implementation but also for relating results with the other types of batteries.

Rechargeable portable batteries are used to power mobile devices that have been on the rise in recent years with products ranging from cameras, mobile phones and robots, just to mention but a few. The industries have therefore invested heavily, both financially and technologically, to come up with high-capacity, light and small rechargeable batteries. Sophisticated chargers that, in addition to indicating when the battery is full, and protect the batteries from overcharging by changing to trickle charging or switching off, are also available at low cost. The chargers however cannot indicate the level of capacity the battery holds after a number of charging and discharging cycles. A case where several batteries are used highlights a situation where, despite batteries being fully charged, not all of them will power the device for the same duration of time. This is the case that explains the capacity drop and knowing the level of a battery capacity helps to estimate how long the battery can supply power to the device. This project aims at addressing this scenario.

The project focuses on one particular type of rechargeable battery, NiMH, following its immense preference by the consumers. This is as a result of its higher energy density achievement and being environmentally friendly. These are among the attributes that have made NiMH outstanding among other types of batteries. The technology among rechargeable batteries is however similar. This expands the scope of the project to explore ways in which the system could apply to other types of rechargeable batteries.

2 Theoretical Background

2.1 NiMH Battery History

The history of the rechargeable battery technology dates back to 1859 when the early commercial example of using a controlled chemical reaction to produce electricity was first witnessed. Gaston Plante became the first in history to invent the first battery that could be recharged by passing a reverse current through it. The battery marking the beginning of rechargeable batteries is lead-acid [1, 823].

Over the years, several developments took place leading to introduction of some other types of rechargeable batteries that were portable, smaller and came in different sizes. It is however until 1990s that NiMH found its way into the market with consumer applications. Though similar to Nickel cadmium rechargeable battery in design and close in performance, NiMH’s ability to achieve higher energy density and being environmentally friendly earned it a recognition hence a reason to stay in the market [2].

Further improvements on NiMH with time enabled it to eliminate a number of weaknesses it previously had. The established product series had better charge retention, performance and more suitable to high-drain applications outperformed NiCad batteries in several areas. [2] Today, NiMH has won preference as performing, reliable and valuable battery among consumers.

2.2 NiMH Electrochemistry

Electrochemistry is a study that describes interchange of chemical and electrical energy. This is one way through which our daily life relates to chemistry. Ranging from igniting cars to the portable devices that are used today powered through batteries operate under this principle [3, 791].

2.2.1 Overview

Rechargeable batteries operate under the principle that electrochemical reactions at each of the electrodes are reversible. NiMH just like the other rechargeable batteries operates on their ability to absorb, release and move hydrogen between electrodes within the cell. The most basic components of a cell are Electrodes (anode and cathode), electrolyte, separator and packaging cover. Electrolyte plays an important role in the exchange of electrons between the two electrodes depending on whether charging or discharging is taking place. For this reason, conductivity of electrolyte matters for high power applications.

The reactions between the two electrodes are physically separated by separator to prevent shorting and reactions between the two electrodes. [5] The packaging cover ensures that the design of the cell is held together to achieve the desired performance. Energy is stored during charging and released upon discharging and the two processes responsible for this phenomenon are oxidation and reduction reactions. A general term that describes the overall reaction by the two processes is redox reaction. Redox is necessary for the purposes of balancing the overall chemical equations.

One of the common set up that has been used over the years to demonstrate electrochemical reaction is a galvanic cell. This is a device in which chemical energy is changed to electrical energy. The name galvanic cell honours Luigi Galvani (1737-1798), an Italian scientist generally credited with the discovery of electricity. [1, 828]

During redox reaction of a particular cell, the driving force which can as well be pull of electrons is called cell potential (e.m.f) and its unit is volt (V). Volt can basically be defined as 1 joule of work per coulomb of charge transferred. From this definition it is clear how electricity is generated from power sources operating under the same principle.

2.2.2 Positive Electrode Reaction

The development NiMH electrodes, their composition and design encompass the breakthrough in improved battery performance. Positive electrode of NiMH battery is Nickel hydroxide. It is well developed and since its composition is similar to that of NiCad, its design has been done with considerations to the experiences from NiCad batteries. Among the features improved over the years which has enhanced capacity and high current densities on nickel based alkaline batteries is the fabrication of electrodes with very large surface area making them more attractive. Other features include the fact that the electrodes' active material does not dissolve in the electrolyte (normally KOH) meaning that the abuse tolerance is improved leading to longer life. [5]

During charging, positive electrode reacts by releasing hydrogen into the electrolyte which is then absorbed and stored by the negative electrode. This reaction on the positive electrode is based on oxidation of nickel hydroxide in the presence of electrical potential. $Ni(OH)_2$ combines with the hydroxide in the electrolyte to produce Nickel oxyhydroxide (NiOOH), water (H_2O) into the electrolyte and one free electron (e^-).

Discharging the cell reverses the reactions that occur during charging. The hydrogen absorbed and stored by the negative electrode is released and combines with a hydroxyl ion to form water. The positive electrode is reduced to its lower valence state [6]. Water formed in the electrolyte releases a hydrogen ion that combines with Nickel oxyhydroxide (NiOOH) to form nickel hydroxide ($Ni(OH)_2$).

Figure 1 illustrates the simplified positive electrode chemical reaction during charging and upon discharging.

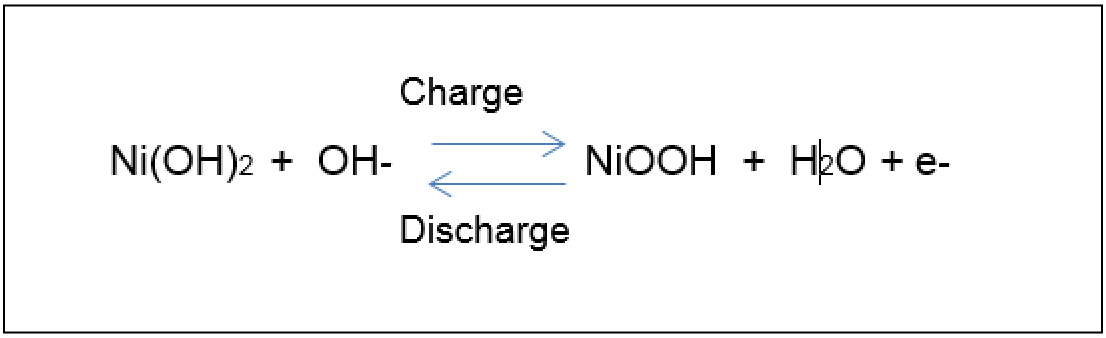


Figure 1: Chemical reaction on the positive electrode during charging and discharging. Copied from [2]

Figure 1 shows a chemical half reaction at the positive electrode. This equation demonstrated the reversible behaviour upon charging and discharging.

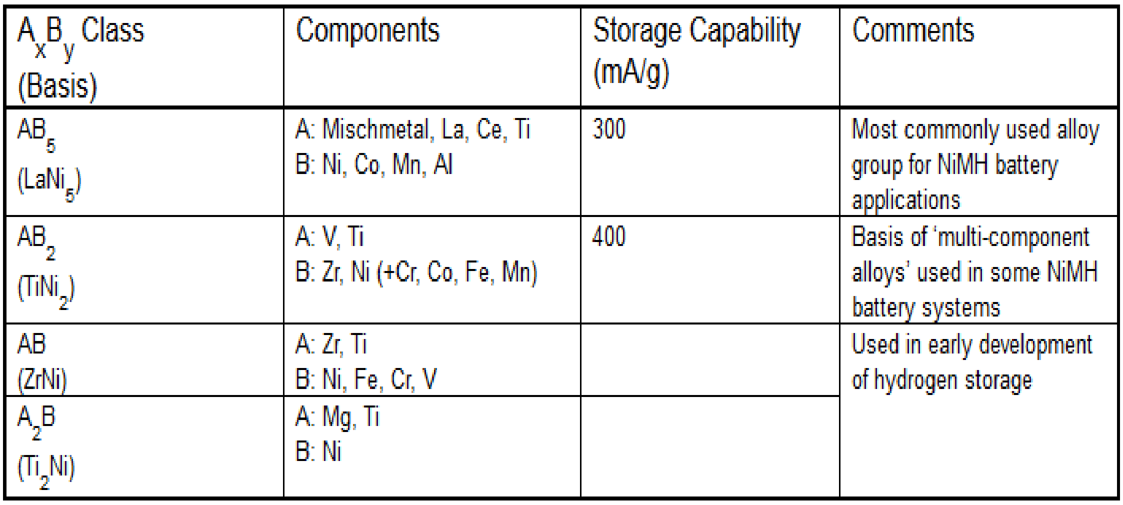
2.2.3 Negative Electrode Reaction

Negative electrode of NiMH battery is metal alloy though the active material is hydrogen. The concept of the negative electrode in NiMH was derived from years of research on how hydrogen can be stored for use as an alternative source of energy. Metal alloy was observed to be a better way to store hydrogen.

Metal hydride forming the negative electrode of NiMH hydride was then formed through combination of strong and weak hydride forming materials, careful selection of alloy particles and proportions by balancing the thermodynamics to allow absorption and release of hydrogen at room temperature. This breakthrough saw the alloy absorbing and releasing hydrogen in volumes of up to a thousand times its volume [5].

The metal alloys currently exist in classes and based on their composition and crystal structure they form groups classified by A_xB_y where A and B can each comprise of other different elements in varying range of stoichiometry. This permits improvement in design towards the desired characteristics like equilibrium pressure, corrosion resistance, reversibility, mechanical stability just to mention but a few. Table 1 highlights a few classes of metal hydrides and the constituent components.

Table 1: Commonly used classes of metal hydrides and their constituents. Copied from [5].



A_xB_y Class (Basis)	Components	Storage Capability (mA/g)	Comments
AB_5 ($LaNi_5$)	A: Mischmetal, La, Ce, Ti B: Ni, Co, Mn, Al	300	Most commonly used alloy group for NiMH battery applications
AB_2 ($TiNi_2$)	A: V, Ti B: Zr, Ni (+Cr, Co, Fe, Mn)	400	Basis of 'multi-component alloys' used in some NiMH battery systems
AB (ZrNi)	A: Zr, Ti B: Ni, Fe, Cr, V		Used in early development of hydrogen storage
A_2B (Ti_2Ni)	A: Mg, Ti B: Ni		

A number of common classes of metal hydride that are used currently and the components that forms them. AB_5 group is the most commonly used alloy in most batteries currently.

To better understand how the features mentioned influences the cell capacity, it is important to demonstrate how the metal alloy react when charged and discharged. During charging, water produced from the positive electrode into the electrolyte is decomposed to form hydrogen atoms. Hydrogen atoms then react with the metal alloy and an electron (e^-) to form metal hydride (MH) in the negative electrode and hydroxide in the electrolyte.

Figure 2 contains an equation that entails the chemical reaction.

$$M + H_2O + e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} MH + OH^-$$

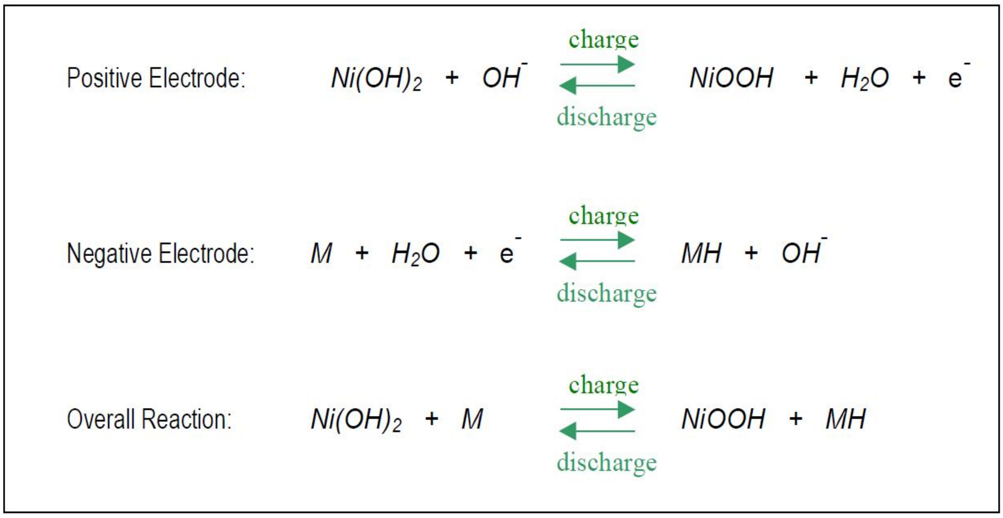
Figure 2: Chemical reaction on the negative electrode during charging and discharging. Copied from [2]

Figure 2 shows how the negative electrode reacts while charging the cell and the behaviour of the reaction on discharge. The reaction is reversed upon discharging the cell. Hydrogen is released and combines with a hydroxyl ion in the electrolyte to form water and an electron is produced in the process. Water once in the electrolyte reacts with the positive electrode and the reaction continues as shown in figure 1.

2.2.4 Overall Reaction

Overall reaction can as well be described as redox reaction since it involves combining two half-cell reactions to a single equation. Using the term redox entails interchangeable use of the terms oxidation and reduction which takes place concurrently. These terms shifts between the two electrodes depending on the one loosing electron or gaining electron.

Based on the equations presented in figure 1 and figure 2, the positive electrode is oxidized while negative is reduced during charging. Upon discharging, the processes shift, the negative electrode undergoes oxidation by losing an electron while the positive electrode experiences reduction by gaining the electron. The two processes are accompanied by energy exchange. Figure 3 combines the electrode reactions to present the overall chemical cell reaction.



Positive Electrode: $Ni(OH)_2 + OH^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} NiOOH + H_2O + e^-$

Negative Electrode: $M + H_2O + e^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} MH + OH^-$

Overall Reaction: $Ni(OH)_2 + M \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} NiOOH + MH$

Figure 3: Redox reaction summary of both electrode reactions. Copied from [6, 11].

Overall chemical reaction in figure 3 combines two half-cell reactions to give a general reaction that show what happens on both positive and negative electrodes. An electron lost from the positive electrode combines with the metal alloy to form metal hydride on the negative electrode. Reversing the equation explains what happens during discharging.

The exchange of hydrogen during charging and discharging in the overall reaction can be further demonstrated by a cell circuit indicating the flow of charge and similarly the flow of current. Figure 4 illustrates the overall equation represented in figure 3 and the role played by the electrolyte to complete the circuit.

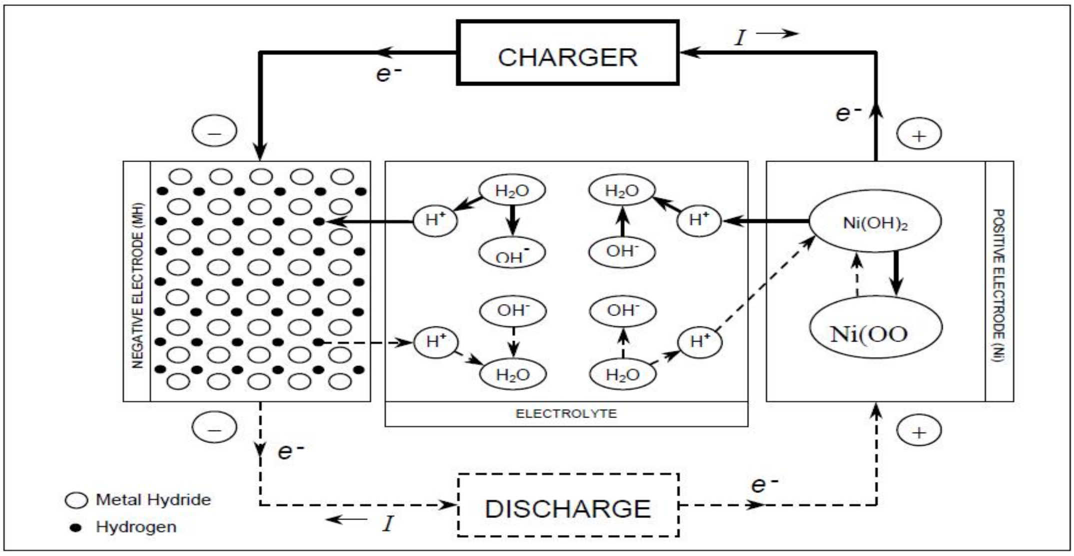


Figure 4: Representation of the overall reaction in the figure 3 in a circuit. Copied from [6]

Figure 4 represents the overall process of charging and discharging the NiMH battery. The same process applies to all rechargeable batteries with the difference only in the chemical reaction depending on the type of the battery. Not only the reactions of the positive and negative electrode shown in figure 4 but also the direction of the flow of the current during charging and upon discharging.

3 Battery Capacity

Capacity of the rechargeable batteries and its variation is the main idea explored in this project. It is therefore necessary to highlight the meaning of battery capacity without confusing battery capacity with the percentage of terminal voltage to charge voltage.

3.1 Capacity Definition

Battery capacity is a measure of the maximum amount of charge stored by the battery expressed in ampere-hours (Ah). It is a representation of the mass of active material stored by the battery. Sections 2.2.3 and 2.2.4 highlight how the electrolyte volume and the surface area of the plates relate to capacity. [4]

Each battery has a rating known as rated capacity describing a battery's ability to deliver current under certain specified conditions. Battery capacity therefore varies with discharge rate.

3.2 Units of Battery Capacity

Batteries are not all equal even if they have the same chemical reactions. Battery development trade-off is between energy and power. A C-rate is the measure at which a battery is discharged relative to its maximum capacity. An E-rate on the other hand describes a discharge power. The energy stored in a battery is measured in Watt-hours (Wh) or ampere-hours (Ah) [4].

Ampere is the measurement of electrical current and its basic definition is a coulomb of charge passing through an electrical conductor per second. An easy representation mostly used is milli-Ampere-hours (mA). This is because most circuits drain the currents in milliamps. It is important to briefly clarify how the battery voltage relates to capacity especially after mentioning circuits in the previous statement.

Battery voltage which is also referred to as nominal voltage is the amount of voltage that a battery outputs across its terminals when fully charged. Besides the mAh rating, each battery has a nominal voltage specified in the spec. For instance, a 9-volt battery provides 9 volts across its terminals when connected in a circuit. The voltage decreases during operation and usage hence become less and less. The AA batteries usually have a voltage range of 1.2 - 1.5 volts. It is important however to check the specification as some types of batteries have totally different nominal voltage.

3.3 Examples of Battery Rating

Batteries come in standard cells which describe the size and shapes. They are denoted by letters such as AAA, AA, C, or D. AA for instance references a specific shape, size and style of the cell. The rating on each battery, describes its capability to supply power at the stated rate.

Suppose a battery rating states 2000mAh, means that it can supply 2000 milli-ampere of current during its lifetime. The lifetime of a battery refers to how long the battery remains in operation before reaching the end of discharge voltage. The same rating can also refer to the following:

200mA for 10 hours,
20mA for 100 hours,
2A for 1 hour and 2mA for 1000 hours.

The bigger the mAh rating, the longer a battery can take to power a device before the next recharge. A D-type battery usually has bigger mAh than AA-type battery cells and this explains why they are bigger in size.

4 Charging Battery

4.1 Charging Overview

Charging of a secondary cell restores back the cell's used charge. This is achieved by applying an external electrical energy causing the reaction that occurred during discharge to be reversed. In other words the battery to be charged is connected through a constant voltage source or constant current source forcing the current through the battery. The circuitry used in this process to control the rate of charge and supply external energy is called a charger.

Charging is a major factor in capacity maintenance and it is a delicate process in some types of batteries. It is categorized into three functions; charging the battery, optimising charging rate and charge termination. Proper regulation of these three functions which determines how good the charging process is, constitute charging algorithm. [6]

There are numerous types of chargers available in the market today. Among them are simple chargers, fast chargers, intelligent (smart) chargers, inductive chargers, solar charges among others. These types of chargers operate on some common charging modes. The charging modes depend on the size and type of battery being charged. This is the reason why some type of batteries can only use a special type of charger while others can be charged by more than two different type of chargers.

A charger can take care of all the charging stages depending on its level of sophistication. Some chargers for instance, cannot take care of the third function of charging which is charge termination. Some simple chargers can terminate charge after duration of time specified on the timer; otherwise they are like dumb chargers. Intelligent chargers on the other hand can handle a charging cycle without human monitoring. These chargers can switch from fast charging to trickle charging mode when the battery is full to avoid overcharging. This is because smart chargers are capable of modifying their charging actions based on the condition of the battery being charged.

Due to advanced innovation and technology in the field of energy, more so in the battery industry, manufacturers have also produced “smart” batteries.

Smart batteries and smart chargers should not be confused as the terms can be used closely. A smart battery contains a chip which can communicate with a smart charger while being charged about its charging conditions and behaviour. This therefore means that smart batteries cannot be charged by simple chargers. Smart chargers however can charge both smart and any other type of battery as long as power rating conditions are met.

4.2 Charging Methods

Section 4.1 highlighted how charging cycle is considered successful based on the proper regulation of charging functions which can as well be handled by smart chargers. This section not only focusses on the methods of charging but also points the possible charger type that can be used for a particular mode.

Charging methods vary with the rate of charging which determines how much power is supplied to the battery per unit of time and the charge termination process. Numerous methods of charging can be derived from different charging rates. The following discussed charging modes are the proposed key methods.

4.2.1 Constant Current

This form of charging employs single low level current set at fixed rate to the discharged battery. Chargers used for this form of charging vary the voltage applied to the battery for constant current maintaining. The common types of batteries that are charged with this method include NiCad, NiMH and lithium-ion. When the voltage reaches the level of full charge, the current is switched off. Higher rates of current level would charge the battery in a short time and in this case, appropriate charge termination method would be applied to avoid overcharge. [8]

Figure 5 illustrates the characteristics of the constant current charging.

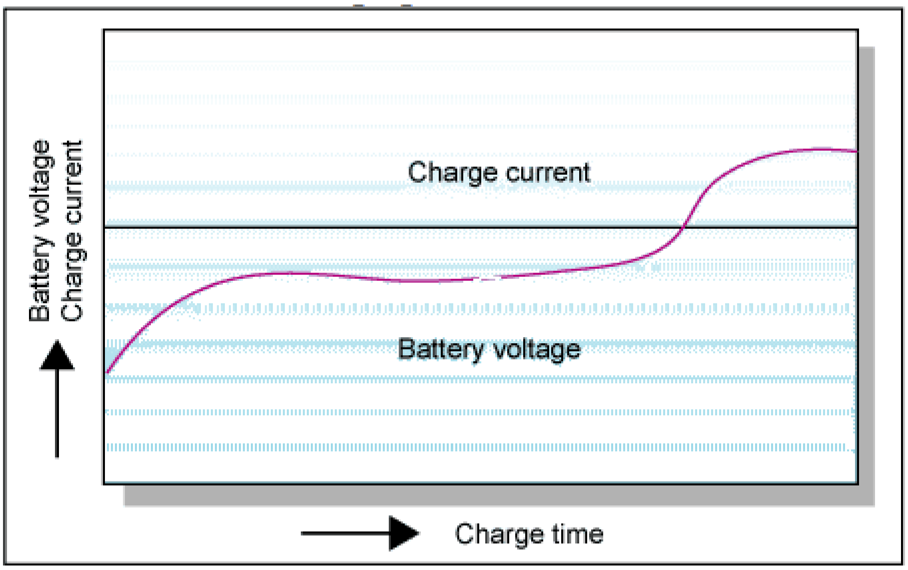


Figure 5: An illustration of constant current charging curve. Copied from [9]

The constant current curve in figure 5 shows that this method keeps the current constant irrespective of the voltage level during charging.

4.2.2 Constant Voltage

Constant voltage charging involves application of constant voltage between the battery terminals. This allows maximum current to flow into the battery until the voltage reaches the set limit when it starts to drop to a minimum value.

4.2.3 Constant Voltage Constant Current

Constant voltage constant current charging method describes a combination of two charging methods aimed at limiting the maximum charge current until the cell voltage reaches the set limit. When the cell voltage gets to the limit, the voltage control takes over and gives way for current to gradually drop to a minimum value as the battery voltage nears full charge.

An advantage of this method is the fact that fast charging rate can be applied without the release of extreme amount of gases causing pressure and overheating. Common types of batteries that this method of charging suits are NiCad and sealed lead acid.

Figure 6 indicates the charging characteristics of this method. Most smart chargers have this method applied.

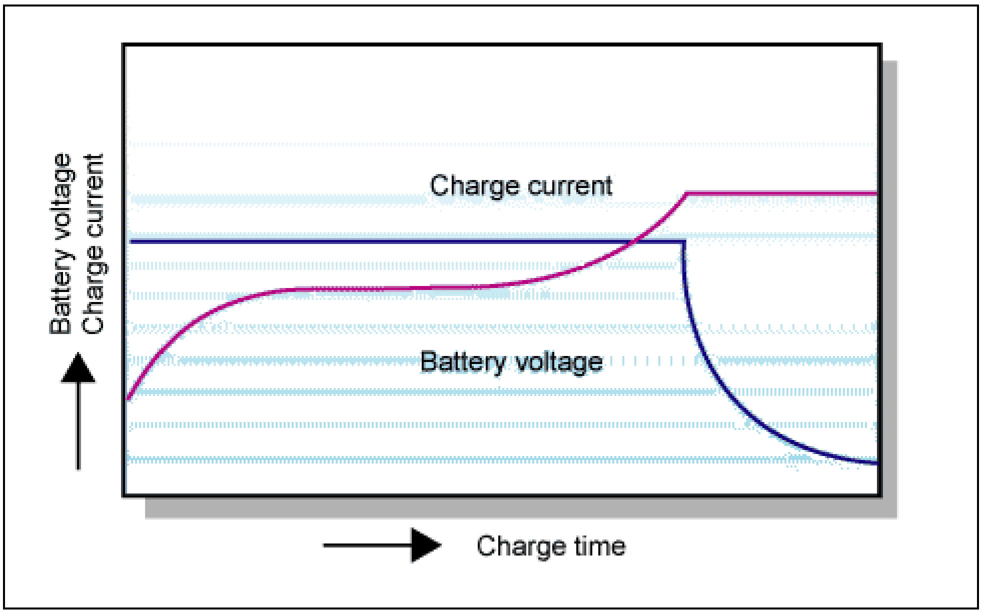


Figure 6: Constant-voltage constant-current charging curves. Copied from [9]

Figure 6 is a representation of constant voltage constant current form of charging. When a cell's full voltage is reached, voltage curve coloured red in the figure stays completely constant. The current on the other hand steeply drops as shown by the blue curve. Both current and voltage curves show the point at which the end of charge is reached.

4.2.4 Two step Constant Voltage

Under this method of charging, two steps of constant voltage charging methods are employed. At the initial stage of charging, the first constant voltage charging is applied to pass a high set up voltage to the cell and current monitored. When the current has dropped to the pre-set value, the second step begins where a constant low rate set-up voltage is applied.

Figure 7 shows the difference in behaviours between this charging method and the other methods.

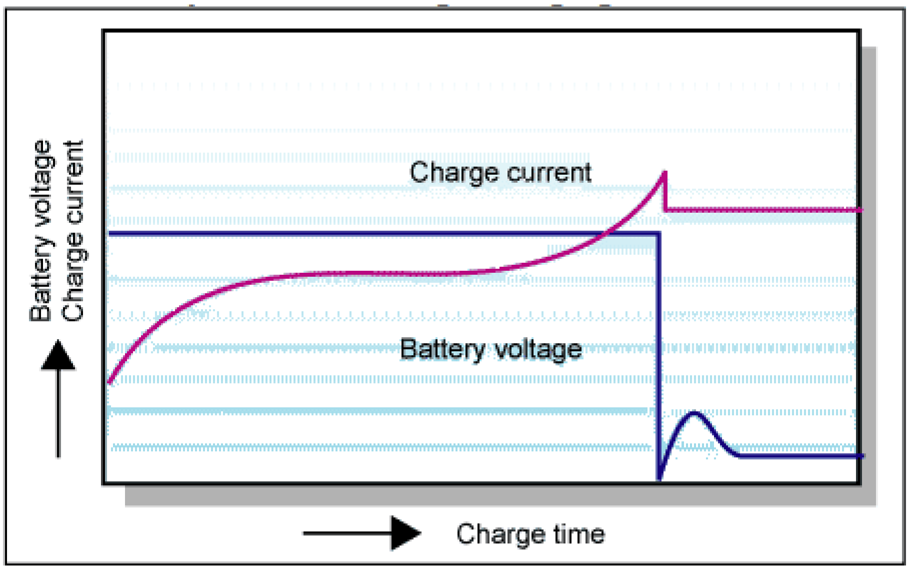


Figure 7: illustration of two-step constant voltage charging method. Copied from [9]

Figure 7 indicates the clarification between a two-step voltage charging method and the closely constant voltage constant current charging method. When the end of charge is realised from the current drop, the voltage curve is seen to drop instead of staying constant as in figure 6. This is because the voltage is dropped to a pre-set low-rate value.

4.3 Charging Rates

Charging rate is determined by the amount of charge passed into the battery in a unit of time. Higher rates of charging fall under the fast charging rate category. Charging rate and charging method are used interchangeably in many materials but the difference is that while any charging method can be used to fast charge a battery, it is only through those that can charge a battery safely on a fast mode that would be on the fast charging category.

The charging methods that only work best when a low-rate charge is supplied to the battery form the slow charging rate. Quick and fast charging rate can be easily confused as well but the difference lies in the duration of recharge.

4.3.1 Slow Charging Rate

Slow charging rate is also referred to as continuous low rate charging. The rate involves supplying a low rate charge to the battery. The common rate most chargers use for this mode is 0.1 C which usually takes 12 hours or more. Time estimation is in respect to the AA size rechargeable battery. Despite the low charge rate, some types of battery can still be damaged if not managed properly since this mode of charging is common with simple chargers.

Batteries like NiMH and Lithium ion can still suffer from overcharge if left to charge for longer time under this method. Lead acid and NiCad can however tolerate overcharge at low charge rate without serious damage. This is so because of their internal chemistry. For instance while NiCad's recombination process pertain to keep the voltage down to a safe level, NiMH's overcharge produces gases which lead to increased temperature. For this reason, NiMH cells have a range of between 0.4 C to 0.1 C slow charging rates. This rate of charging is not only safe for charging certain types of batteries but also less expensive as the chargers used are simple or dumb. The charging time is however long and batteries like NiMH are not protected from a possible overcharge.

4.3.2 Standard Charging

Under this charging rate, the chargers used are timer based. Timer controlled chargers unlike dumb ones terminate charge after a predetermined time. The user does not have to monitor the charging battery for fear of overcharge. Some of these types of chargers switch to trickle charge to top up the battery capacity instead of stopping the charge process. In some cases where low rate charge is applied, the batteries are left to charge overnight without damage.

Despite having a timer controlled charger, this method is not always safe for batteries. Since the state of charge cannot be monitored through this method of charging, there is a possibility of overcharging a battery or undercharging. Repetition of either of the two possibilities can cause severe effect on the battery capacity.

Another case that can lead to overcharging is an incident of timer reset in case of power loss. This means that the timer will start counting from the beginning leading to overcharging.

4.3.3 Quick Charging Rate

Quick rate of charging takes less time compared to slow charging rate to complete a recharge. The recharge duration is normally 3 to 6 hours at charging rate of 0.3 C and an ambient temperature range of 10°C to 45°C. The recommended charge termination method for this rate of charging is -∆V which can be backed by a timer control set to 120% of charge input and a temperature cut-off of 60°C (140°F).

Even though this rate of charging is sometimes regarded as the fast charging rate, it is important to mention that a C/3 rate of charging should not apply dT/dt charge termination method. This is because the rate of temperature increase might not be sufficient enough to terminate the charge. [10]

4.3.4 Fast Charging Rate

Fast charging rate takes 1 hour or less to complete a recharge. This takes less time than the quick charging rate. At the rate of C/2 or 1.0 C, battery being charged under this rate can easily be overcharged or undercharged. Not all types of batteries can be charged under this rate as each cell has different cell chemistry. In most cases, each battery type charged under this rate has its own charger. This is important because with different cell chemistries, some batteries will require totally different charge termination method which is determined by the charger being used.

A timer control method of charge termination is discouraged under this rate. The best recommended method is by sensing the rate of temperature increase (dT/dt) which should be 1°C per minute with a backup temperature cut-off of 60°C. Since the termination of charge under this rate should be applied early into overcharge, it should be followed by trickle charge to ensure full charge of the battery. There is a possibility of terminating charge by monitoring the decrease in voltage (-∆V) and increase in temperature (∆T) as well [11]

4.3.5 Trickle Charging

Trickle charging is aimed at compensating for the self-discharge of the battery. Most smart chargers switch to this form of charging when battery is fully charged or almost full. Trickle charging can cause overcharge to some types of batteries like NiMH and Lithium even though the charge rate is quite small. The recommended rate is C/300 at a temperature range of between 10°C to 35°C.

4.4 Charge Termination Methods

A number of charging methods discussed in the previous sections especially those operating on fast charging modes must have a way to tell when the full charge of a particular cell is reached. Many innovative charge termination methods have been developed to boost the performance of rechargeable batteries and prolong their cycle life. Smart chargers use two or more of these charge termination methods to stop charging or change from fast charge to trickle charging which is a more safe way to top up charge without the battery being overcharged.

Besides terminating charge based on timer, most of the primary used methods are based on temperature and voltage sensing. An explanation for this being, during fast charging, the rate of voltage change will vary with cell’s state of charge. It is therefore possible to tell when full charge is reached. The temperature is similarly a major factor during charging. Considering the cell’s chemistry, which can be endothermic or exothermic, temperature sensing can still apply to detect the end of charging point. NiMH cell reaction is exothermic and in this regard, heat dissipated increases the cell’s temperature during charging. The rate of a temperature rise sharply increases when the battery’s full charge is reached. NiCad cell on the other hand undergoes an endothermic reaction which explains the insignificant increase in temperature. Towards the full charge however, there is decrease in the amount of energy used in the endothermic reaction and instead, the amount dissipated in heat increases, thereby making the cell hot. [12].

The common behaviour possessed by both NiMH and NiCad is of the cell temperature rise of about 10°C above ambient temperature when the cell is charged to full.

This makes it possible to design a circuit for both the batteries that can cut off the high current charge at the 10°C rise point. An example of temperature-based charge termination method.

Various key methods of both temperature-based and voltage-based charge termination methods have been highlighted and briefly explained. Figure 8 show a number of key features on charge termination.

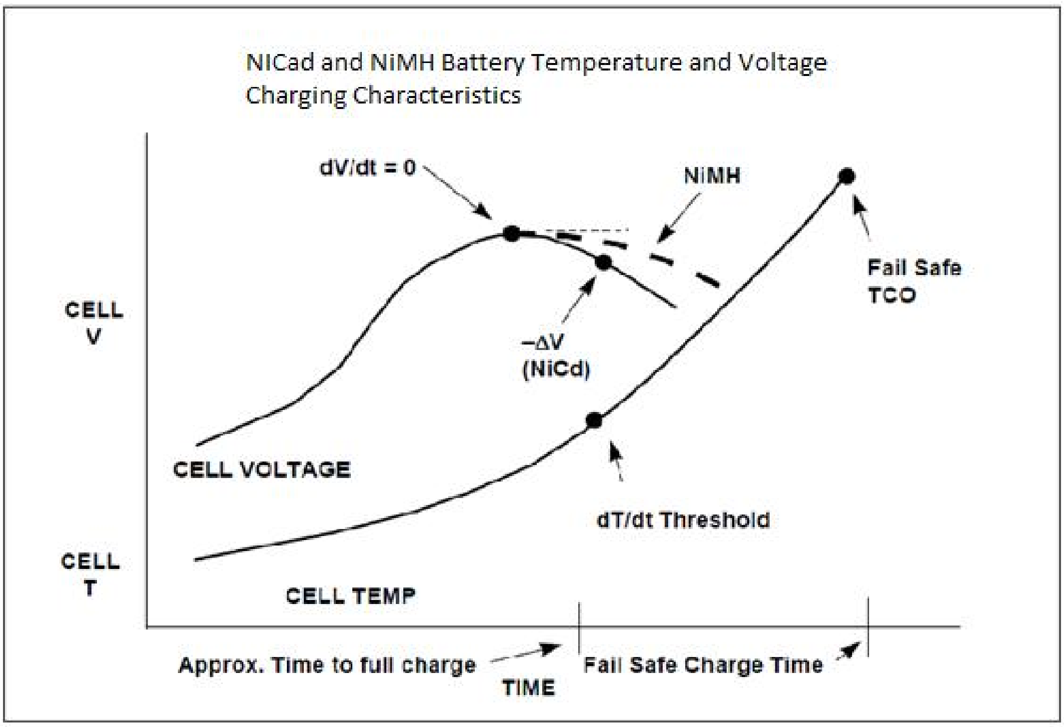


Figure 8: Various characteristics of charge termination methods. Copied from [10]

Figure 8 represents the features of a charging curve to show the various points where each feature is detected. The slight difference on the voltage curve between NiMH and NiCad is indicated as well.

4.4.1 Maximum Temperature Cut-off (MTC)

Under this technique, temperature is monitored during charging and upon reaching the beginning of overcharge level, termination of charge is applied.

Relying on this method alone to terminate charge may not be enough since there is a possibility of overcharging a cold battery before reaching the cut-off temperature or similarly a battery may be undercharged.

It is therefore recommended that a combination of this method and another technique should be applied to improve charging process. When used to terminate charge before other control methods, a recommended 60°C at 1C rate should be the cut-off temperature. [12]

4.4.2 Delta Temperature Cut-off (∆TC)

By measuring the battery temperature rise above the starting temperature, this technique compares the temperature difference to the predetermined value. When the predetermined value is exceeded, charge is terminated. There are different results when this charge termination method is applied to different types of batteries. The cut-off value is likely to be greater in NiMH than in NiCad. The recommended value is 15°C at the charge rate of 1C and a backup charge control.

4.4.3 Rate of Temperature Increase (dT/dt)

This method of charge termination monitors the rate of increase of the cell's temperature per unit time. When the predetermined value is reached, the charge is terminated or switched to trickle charge. This method is preferred for NiMH as it avoids overcharge and boosts long cycle life.

Detecting dT/dt is an expensive technique but preferred to NDV method of charge termination as it senses the start of overcharge early. The battery is therefore exposed to less overcharge and overheating which results to in less loss of cycle life. A recommended charge rate is 1C and rate of temperature increase of 1°C per minute with a backup temperature cut-off of 60°C. The top up charge should be of C/10 for half an hour. [12]

4.4.4 Voltage Plateau

A charge termination method, also referred to as “peak voltage-detect” where a battery cell experiences a drop in voltage peak and slope upon reaching full charge. This is a behaviour explored by voltage based charge termination methods. Through this approach, charge is terminated when voltage peak and slope is detected to be zero.

Quite close to the NDV method of charge termination but with an exception of detecting when the voltage peak begins to flatten. This makes it the best choice for the type of batteries with minimal voltage drop upon reaching full charge. There can be a possibility of a premature cut-off in cases where top-up charging is not applied.

4.4.5 Negative Delta Voltage (-∆V / NDV)

Negative Delta Voltage method is similar to the voltage plateau method of charge termination but with a development of monitoring the difference of a voltage drop. The difference measured value is constantly compared to predetermined value. Upon exceeding the value, charge is terminated.

The types of batteries with significant voltage drop on reaching full charge adopt this method of charge termination. Otherwise, the batteries can be exposed to longer period of overcharge.

5 Discharging Battery

In respect to rechargeable batteries, discharging a battery is seen as the reverse process of charging. It can simply be described as the function of removing the current from a battery. However, for better understanding and demonstration of the weight that this section has in the project, a need to restate the purpose of a battery cannot be avoided.

A battery is meant to store energy and release it at an appropriate time and in a controlled manner to satisfy the power specifications for the portable electronics. The technology that highlights the process of storing energy, as discussed in chapter 2, and the process of passing energy into the cell, as described in chapter 4, is one part. The second part is the satisfaction of the load demands, which is partly demonstrated in chapter 3. The other part that this chapter addresses is the delivery of the stored energy without over discharging or without leaving usable energy behind when the process is terminated. [13]

Various discharge characteristics for different types of batteries will be highlighted and compared besides introducing new terms that better describe some discharging elements.

5.1 Discharge Voltage

The discharge voltage of a rechargeable battery is the closed-circuit voltage during discharge [13]. It is affected by the current and ambient temperature. Both NiMH and NiCad have a 1.25v nominal voltage (this is the battery voltage) compared to 3.6 v of Li-ion cell. The advantage that NiMH and NiCad have over Li-ion is seen on their discharge curves. Figure 9 indicates a steeper curve for Li-ion which means that while NiCad and NiMH are suited for use with linear regulators, Li-ion require a switching converter.

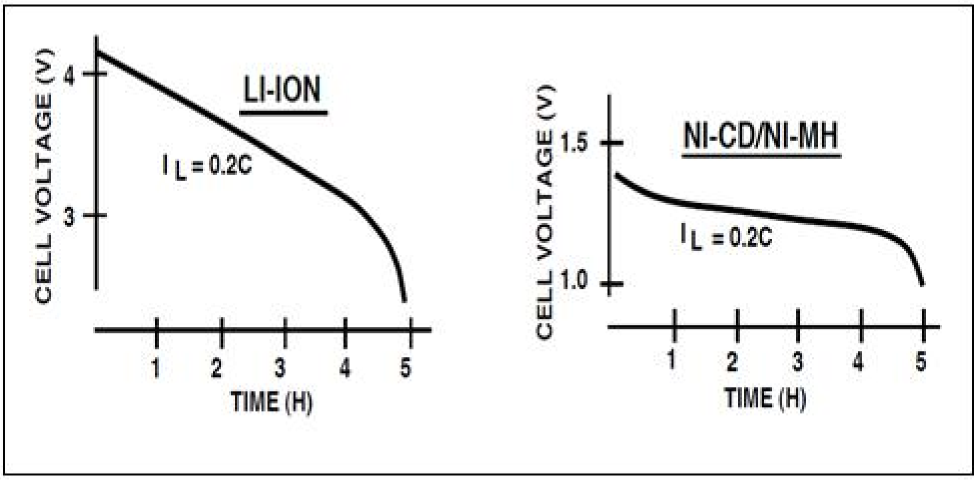


Figure 9: Discharge curves comparison. Copied from [8, 4]

Figure 9 shows the comparison of nominal voltage based on discharge curves for different types of rechargeable batteries.

5.2 Discharge Capacity

The capacity during discharge is majorly affected by temperature and the rate of discharge. Repetitive uncontrolled charging, discharging or poor storage form a poor history on the battery’s capacity which affects the performance after a period of time.

A battery being discharged at a high rate has a negative effect on the rated capacity. Being that high rates of discharge involve extracting large amount of energy at a faster rate, the necessary constituents involved in electrochemical reaction will not have enough time to move to the right areas. This leads to battery capacity drop and successive high rates discharge forms bad reaction history.

The battery performance increases with temperature. This means that increasing temperature has a positive effect on the discharge capacity as long as extreme temperature level is not reached. Just like the effects of temperature during charging, extreme high temperatures will reduce the battery capacity hence less energy delivery. This factor is true on most types of batteries except for the case of Li-ion which is not affected much with an extreme high temperature.

Similarly, extreme lower temperatures affect the discharge capacity, especially on batteries with aqueous electrolyte. The possibility of electrolyte freezing may affect the range of the operating temperature.

The general recommended range of discharge temperature for NiMH and NiCad is between 0 – 50°C with the gap narrowing from 10 - 40°C for the case of a high rate of discharge. The Li-ion cell has a discharge temperature range specified as -20 to 60°C. [9]

5.3 Internal Impedance

Internal Impedance or internal resistance as commonly referred to, determines the maximum current a battery deliver. Since the current flowing out of the battery is affected by the internal resistance, there is power dissipation within the battery. Low internal resistance allow high rates of performance and higher internal resistance produces the opposite.

NiMH and NiCad have low internal resistance making them produce peak discharge current. Even though Li-ion has higher internal impedance compared to the other two battery types, the effect is not pronounced.

5.4 Self-Discharge

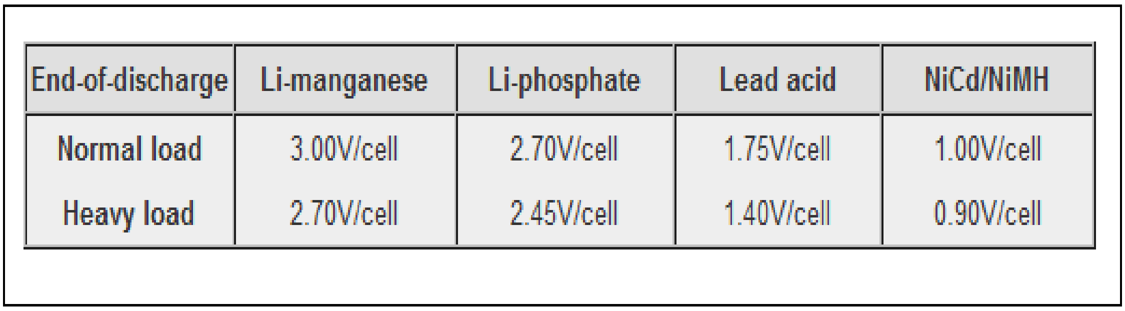
Self-Discharge is another characteristic of battery discharge which describes how a battery cell loses its stored charge without being connected to a load or on a circuit. The rate of self-discharge depends majorly on the ambient temperature and the cell chemistry. Among the commonly used rechargeable batteries, Li-ion suffers the least with 2 – 3 % discharge a month. Lead acid experiences 4 – 6 % discharge a month while both NiCad and NiMH suffer the most.

5.5 Depth of Discharge (DoD)

DoD describes the amount of battery capacity removed from the cell during discharge and normally expressed as percentage.

Depth of discharge is closely similar in meaning to state of charge (SoC) but with slight disparity in reference. Different types of batteries have different end-of-discharge voltages which describe when to disconnect the load. This protects batteries from over-discharging.

Figure 10 illustrates various end-of-discharge voltages for different types of batteries.



End-of-discharge	Li-manganese	Li-phosphate	Lead acid	NiCd/NiMH
Normal load	3.00V/cell	2.70V/cell	1.75V/cell	1.00V/cell
Heavy load	2.70V/cell	2.45V/cell	1.40V/cell	0.90V/cell

Figure 10: Various recommended end-of-discharge voltages for different battery types. Copied from [7]

Figure 10 not only highlights the comparison of end-of-discharge voltages but also give the range when under a heavy load.

6 System Implementation

The information gathered on the previous chapters provides theoretical background and parameter definition upon which the operation of the system is based on. This chapter describes the implementation of the system aimed at determining the level of a battery capacity which is not to be confused with the battery's state of charge. Understanding the behaviour of different types of batteries and the capacity variation is important to the construction of the various specifications for the system.

6.1 System Overview

The system is made up of different parts with each playing a different role to constitute the overall functioning of the application. The different parts can be categorized into hardware and software. The hardware part consist of the charging circuit, discharging circuit, battery holders, switches and the DAQ equipment that connects the external hardware to the software running in the computer. The software part of the system is based on LabVIEW programming environment.

The description is summarized through a block diagram in figure 11.

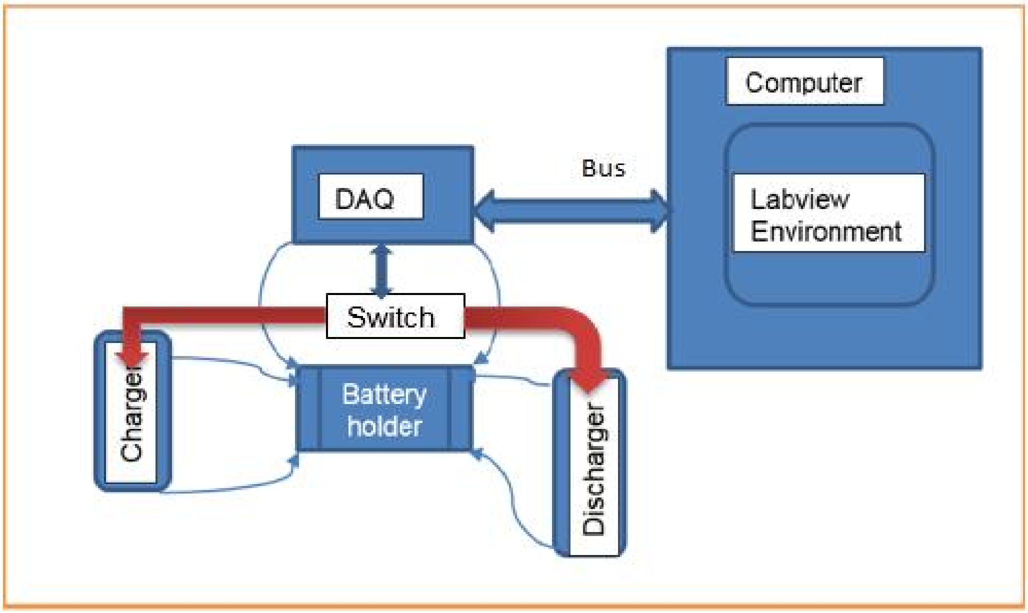


Figure 11: A block diagram showing different parts of the system.

Figure 11 shows a block diagram of the system and its major parts. Communication between the external hardware and the computer is through the Data Acquisition device. This is connected to LabVIEW, a program installed on the computer.

The primary method of charge termination applied in the system is zero slope voltage termination method. This is because among the voltage based charge termination methods, the likely efficient one which is negative delta voltage method, do not apply to some types of batteries especially those that experience a very small drop in voltage upon reaching end of charge. Temperature based methods of charge termination are employed in cases where the temperature within the cell can be measured accurately. The type of batteries used in this project makes it difficult to read the cell’s temperature without destroying the case. This fact disqualifies temperature based charge termination methods alongside the negative delta voltage method employment in this system.

The primary method of charge termination is supported by a secondary one that checks the maximum voltage as the battery approaches full charge. This method is accurate only on highly individualized basis. It does not mean that the application only relies on the mentioned two methods of charge termination. Timer can be added as a third parameter just in case the two methods fail to work but either way, time has to be recorded for capacity calculation purposes. In case a different type of battery is under test, the timer can be set conforming to the battery’s specifications.

The system applies constant current charging method. Basing the calculations on the type of battery used, the rate of charging that the system uses is quick. It can also apply slow charging with a change of resistor value in the circuit. The circuits operations are discussed in the succeeding sub-chapters. Fast charging rate does not fit this system because it would require the use of temperature based charge termination methods which would be unattainable with the type and size of batteries used in the project.

Discharging circuit on the other hand is important in that the data gathered during discharge are used in capacity level determination. The rate of battery discharge is slow but appropriate to ensure proper monitoring of the battery during discharging. The time taken during discharge will depend on the amount of energy the battery can give out at a specified rate. This forms the battery capacity.

Quick charging rates take between 4 hours to 7 hours as compared to fast charging which takes 2 hours or less. This rate is favorable for voltage monitoring and the charger circuitry falls under the quick chargers category.

6.2 Hardware Components

The system is comprised of a number of hardware parts besides the computer which runs the LabVIEW program. Among the key hardware parts are; charging circuit, discharging circuit, switch, battery holder and the DAQ device. Some of these parts were designed to fit the recommended requirements needed for some parameters. Other hardware parts like the battery holder only play the role of holding the battery, which is not much but still important. A highlight of some vital functions played by the key hardware components are stated in sections 6.2.1.

6.2.1 DAQ Device and SPST Switch

The computers acquire physical phenomenon signals and interpret them through a device that converts the signals from Analog to digital. DAQ hardware manufactured by National Instruments Company is an example of such devices. It acts as an interface that digitizes the incoming Analog signals and passes them to the computer through a computer bus. [14]

DAQ device is made up of three components that form the measurement and data transfer process namely; Signal conditioning circuitry, Analog-to-digital converter (ADC) and computer bus. Signal conditioning serves as signal manipulator into a form that is suitable to pass into ADC. ADC on the other hand is a digital representation of Analog signals at an instant of time. The computer buses for instance USB, PCI, PCI Express, Ethernet and wireless connects the DAQ devices to the computer through a port or a slot and transfer the measured data and instructions to the software running in the computer that offers the environment to manipulate the data before displaying the results. [14]

The project through the DAQ device monitors the battery charging and discharging processes. LabVIEW software development environment provided a platform to deduce conclusions from the data.

Since the DAQ devices vary in their function and design, figure 12 is an image of the DAQ instrument used in the project showing the Analog and digital pins.

Figure 12: The DAQ device used during the project.

Figure 12 is an image of the NI USB DAQ device with Analog and digital input output ports. The number of digital ports is 12 while the Analog has 10 besides the power ports. The power ports includes the ground and the 5V power source.

SPST Switch is a monolithic CMOS with single input and only one output. These switches are designed using advanced process that ensures high switching speed, minimal leakage current and low on resistance. [15] The SPST switch is used to switch charging or discharging circuits on or off once the end of charge or discharge is detected from the software. Other switches could replace the SPST switch but given the properties mentioned in the previous statements, it is among the outstanding switches.

6.2.2 Charging Circuit

Charging as described in Chapter 4 is the restoration of energy in the rechargeable battery. The charging circuit designed for this project is a simple one that passes a constant current of around 500mA across the battery under charge.

However, having studied the need of smart chargers and to be able to fulfill the objective of the project, the circuit is extended to the software running on the computer. It is therefore possible to monitor the charging, detect end of charge, analyze and deduce the battery capacity before presenting the results. Upon reaching end of charge, the power source is shut down automatically through the SPST switch connected to the DAQ device.

The circuit is comprised of various circuit components that make sure the required constant current is achieved. Before demonstrating the operation of the circuit, figure 13 shows the circuit schematic.

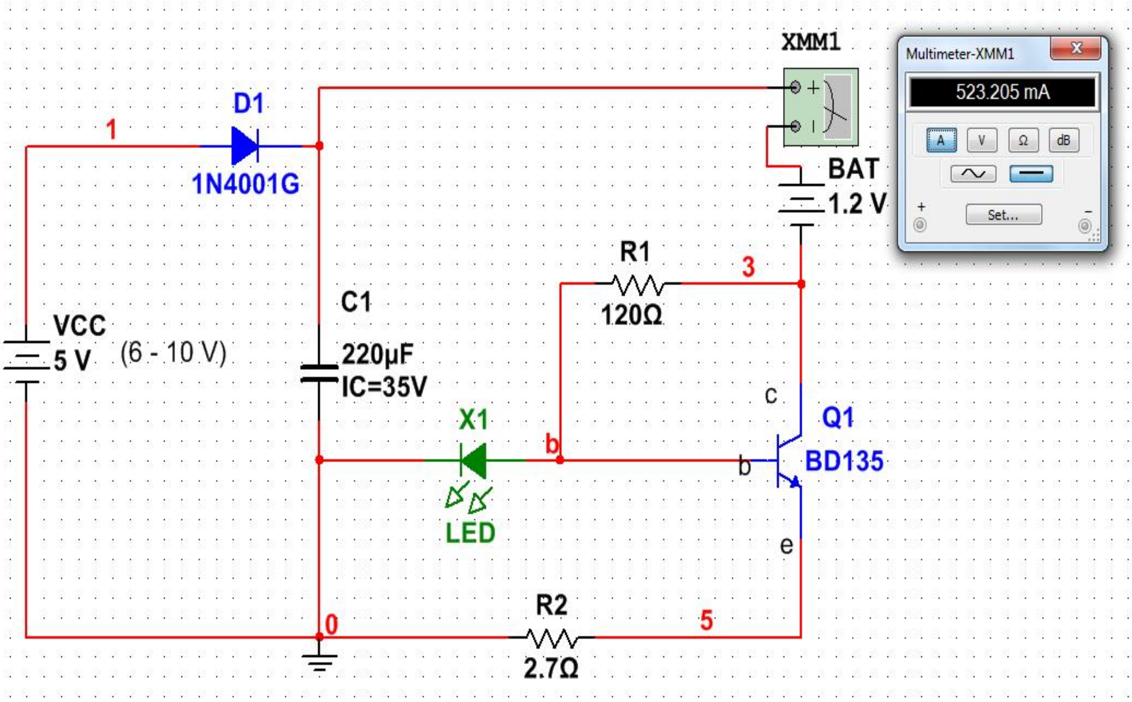


Figure 13: The charger circuit schematic connected to 1.2V battery. Redesigned from [16]

Figure 13 shows the connection arrangement of the charging circuit. Each component play an important role to ensure safe charging by moderating the current and voltage across the battery under charge. The voltage source ranges between 6 - 10 volts. The resistor (R2) connected to the emitter of the transistor regulates the amount of current that flows through the connector pin which constitute a huge percentage of constant current flowing through the battery.

The operation of the circuit can be verified through calculations based on the properties of each component. An example of calculation based on the components value shown in figure 13 to derive the current through the battery is described in the following statements. First, BD135 is a NPN transistor with a DC current gain of 40-240 according to datasheet. One can begin the calculations from various points but if the analysis is from the source voltage, then a voltage drop of around 0.8v and 1.2v is expected across the diode and the battery under charge.

It means that the junction along net 3 is 8v if one takes the source voltage to be 10v. Current across R1 (I_{R1}) is therefore:

$$I_{R1} = V_3 / R_{1,}$$

$$8v / 120\Omega = 66.67mA.$$

Without calculations the LED (X1) needs around 2v to operate for the yellow or orange LED. That makes the junction ‘b’ 2.0v hence voltage along the emitter (Ve) is 1.3v as voltage drop from the base to the emitter (Vbe) in semiconductor transistors is always around 0.7v. The current across R2 (I_{R2}) which is also the emitter current (Ie) is;

$$Ie\ (I_{R2}) = Ve / R2,$$

$$1.3v / 2.7\Omega = 481.48mA.$$

Based on the principles of NPN transistor operations, current gain which is also described as beta (β) is the ratio between the output current (Ic) and the input current (Ib). The ratio between the output current (Ic) and the emitter current (Ie) is called alpha (α) and it is close to unity. Standard low power transistors like the one used in the charger circuit, have alpha ranging between 0.95 - 0.99.

Playing around with the equations leads to finding the base current and collector current even without knowing the current gain at the given source voltage. The known current gain makes the calculations simple, however.

$\beta = Ic / Ib$,
$\alpha = Ic / Ie$, meaning,

$$Ic = Ie*\alpha \text{ and } Ib = Ie - \alpha*Ie.$$

Taking the value of alpha to be 0.99 gives the output current (Ic) value of 476.67mA. Further manipulation of the equations gives a more elaborate explanation of the flow of the current and voltage across the transistor. The current through the battery is therefore equal to the output current plus the current across R1. It is important at this point to mention that the current flow is in the opposite direction to that of voltage.

$I_{BAT} = I_{R1} + Ic$,
$I_{BAT} = 66.67mA + 476.67mA$,
$I_{BAT} = 543.34\ mA$.

Different values of the current through the battery can be regulated by replacing the resistor R2 with one of a different value or the voltage source variation. Charging a battery rated 2300mAh using the charger circuit in figure 13, will take approximately 4.5 hours if charged from empty state.

6.2.3 Discharging Circuit

A discharge circuit is similar to a battery connected to a load. A device powered by battery draws current from the battery at certain rate depending on its power requirement. Rechargeable batteries generate power by losing electrons from negative electrodes to positive electrode and when connected to a load a complete circuit is formed inducing current to flow in the opposite direction. Figure 3 highlights the summary.

Though discharge circuit can be constructed by simply powering an LED or bulb, to be able to regulate the discharge rates and make adjustments without much effort besides close study on the objective of the project, simple yet flexible circuit shown on figure 14 was constructed to discharge a battery under test.

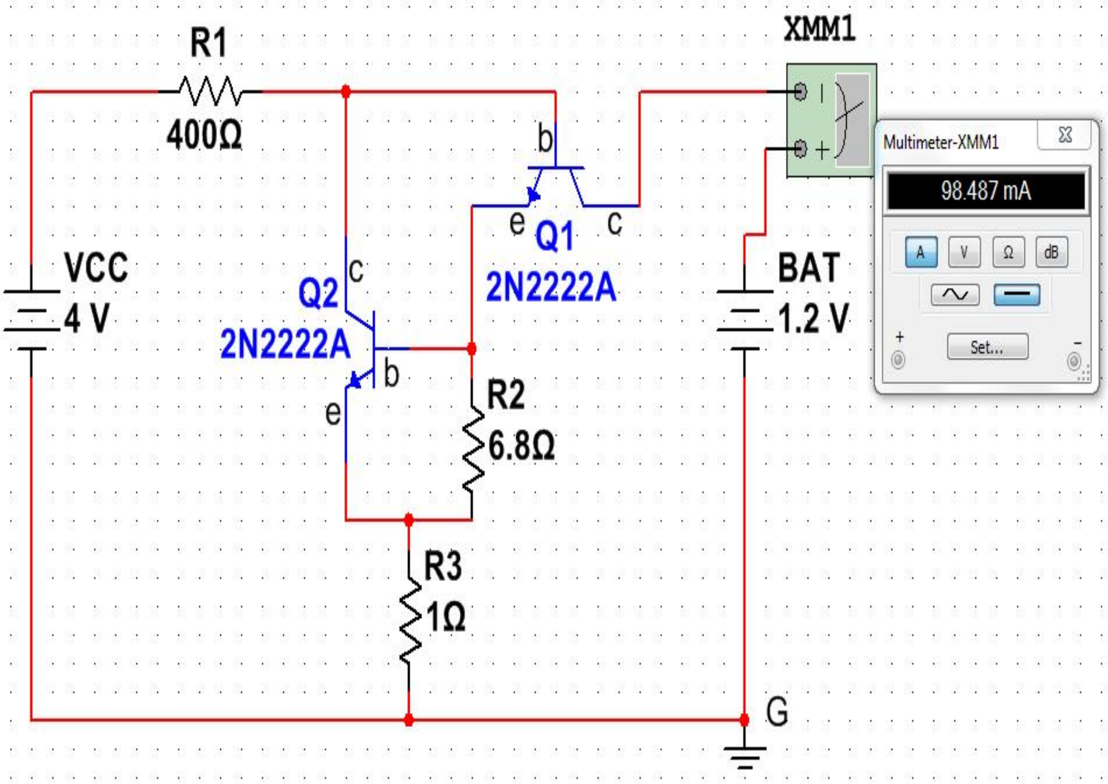


Figure 14: Discharging circuit on multism simulator. Redesigned from [17]

Figure 14 shows a simple circuit that draws a constant current from the battery. The current drawn can be varied by changing resistor values R2 and R3.

The voltage source VCC hardly affects the current through the battery but it is needed for the operation of the transistors. The voltage on terminal c of Q1 and b of Q2 are the same. The voltage at terminal c of Q1 however is 1.2V and current equal to the reading on the multimeter. The voltage at point G however is 0V.

Similar approach and formulas as the illustration in section 6.2.2 charger circuit analysis is applied to analyse the circuit. Since in this case the battery is giving out power, it means that the circuit has two power sources making Thevenin’s theorem preferable tool for operation analysis. Figure 14 shows the reading on a multimeter connected on a connection to the battery giving the value of the constant current.

6.3 Software Environment

Monitoring charging and discharging processes of a rechargeable battery needs a software environment that besides the communication with the external devices has some form of indication functionalities. LabVIEW is among the programs with numerous functions that suits most of the requirements demanded by the project. Its suitability is due to the comprehensive tools for building measurement and control applications in less time. In addition to the graphical development environment that is intuitive with the capability of majority hardware integration and software, offers extensive data analysis and signal processing. [18]

In the software environment, user interface (front panel) is built with controls and indicators. While controls are input mechanisms like push buttons, knobs, etc. indicators are output displays like graphs, LEDs etc. Once the front panel is created, the code is added on the block diagram to perform the operation given and control the objects on the front panel. Since LabVIEW programs imitate the physical instruments like multimeters or oscilloscopes, they are called virtual instruments (vi) [18, 9]. Additional advantages for the software environment include: storage and sharing of data, deployment of code to the right hardware and performance benefits provided by multicore processors.

6.3.1 Software Algorithm

The operation of the software that monitors the charging and discharging processes then deduce a battery’s capacity, is based on the parameters, mainly voltage, time, battery type and current. The significance of these factors was broadly covered in sections 4.1, 4.4, and Chapter 5.

Based on the broad study conducted, the capacity of a battery can be best determined when a battery is discharged. The project therefore focused on designing software that would first charge the battery to full and then begin discharging the battery at favourable rate to ensure the energy extracted from the battery corresponds to its current capacity.

The program then implements the calculation of battery's capacity from the data taken and compares it to the ideal capacity (rated capacity) to deduce the current battery's capacity level. According to the plan, the program should contain both the charging and discharging algorithms. Figure 15 shows the general operation of the software.

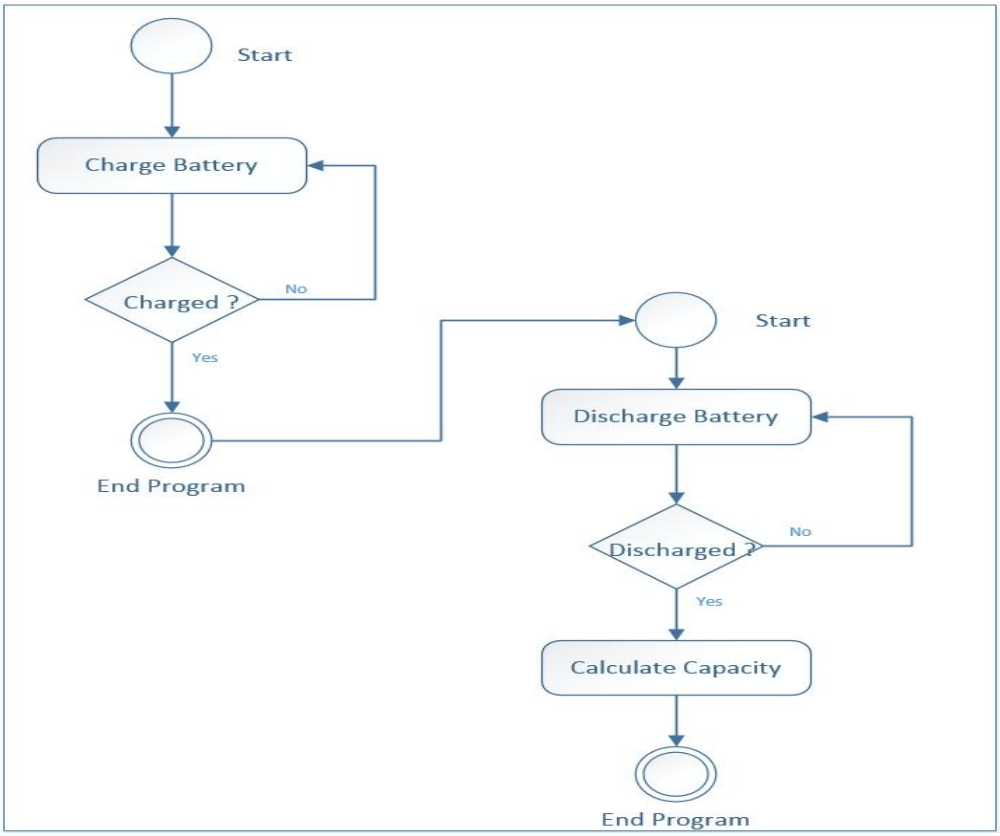


Figure 15: The activity diagram capturing the project's software operation

The summary highlighted in figure 15 is the software algorithm that controls the charging and discharging processes before presenting the deduced capacity level of the rechargeable battery under test. The activity diagram does not give the details of what goes on in an individual activity instance because that is its purpose, to only give the summarized action.

Clarity on the sequence of each activity is however bold with charging process first before the battery is discharged and capacity calculated. Implementation of the activities in figure 15 takes more steps numerous of which are concentrated on the condition instances.

The condition in figure 15 is not a single logic. For instance, checking whether the battery is charged or not implements three different methods of charge termination. The primary method is voltage plateau detection and it is supported by charge voltage detection as the secondary method. Timer method is the last parameter implemented in case the first two methods fail. The same applies to the conditions on discharging with two different implementations detecting the end of discharge. The details in figure 15 are shown in the flow charts in Figure 16 and figure 17.

6.3.2 Software Operation

A close look at the individual activities shown in figure 15 illuminates the operation(s) performed on the instance. The details of the two processes with elaborate demonstration of how the program was implemented is given in section Figure 16 and figure 17.

Chronologically, the program begins by charging the battery till the end of charge before discharge begins. The implementation therefore begins with the charging process as a single program illustrated by the flow chart in figure 16.

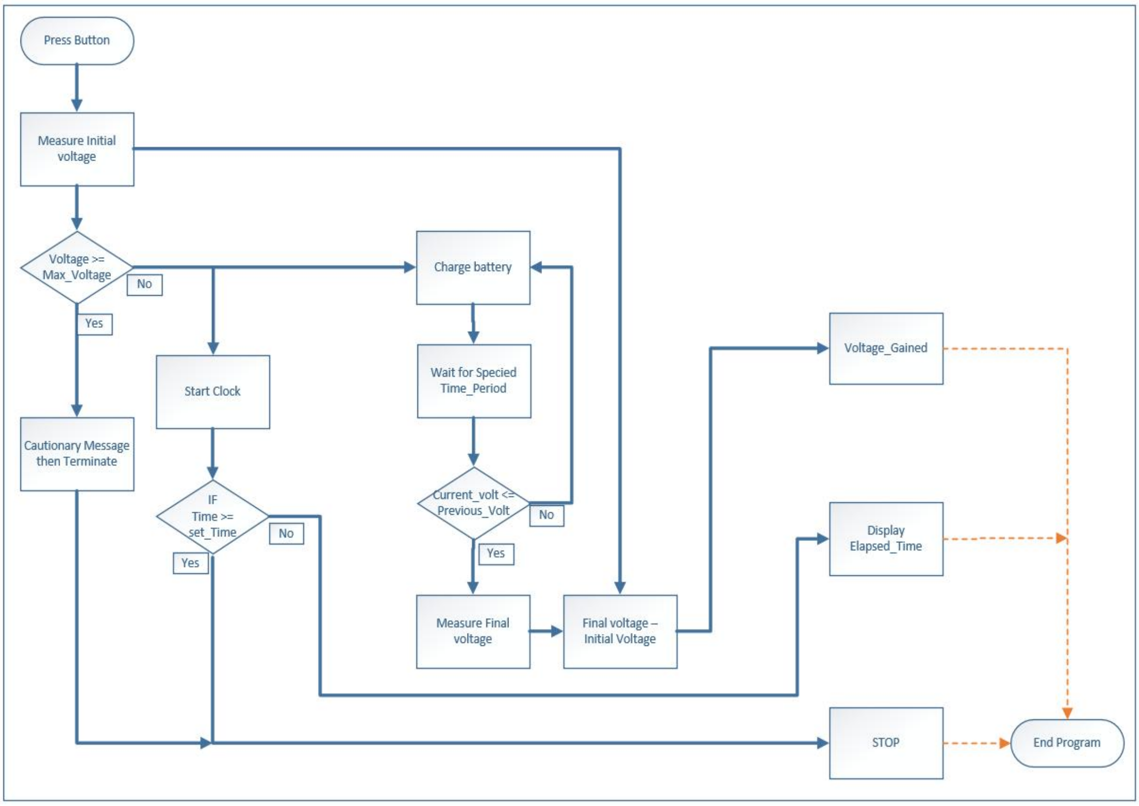


Figure 16: A flow chart illustrating the system’s charging flow chart.

The details of charging process highlighted in figure 16 gives an expanded view of the activity diagram. The program starts with a button press by the user and begins to execute the code. The charge voltage is checked first though it is a secondary charge termination method. This is to make sure that a battery that is full is not overcharged. The program then applies charge if the condition is not true.

The flow chart also indicates actions that are performed in parallel. For instance applying charge and starting the clock begins at the same time. The primary charge termination method is then applied by checking if there is voltage level or drop after a specified time is detected. This is performed by comparing the average sample of voltage data collected to a delayed voltage reading with the delay time being a constant based on the expected voltage increase.

The third charge termination method implemented is the timer. Upon reading the estimated time that charging process is expected to take, the program terminates with a message to show that termination is induced by the third method. If charge is terminated by the first two methods, the clock gives a display of the total time duration the process took. The information on initial and final voltage reading would be important if program was broadened to give a comparison upon the end of discharge which is not the case.

One advantage of designing a program first before coding like the case presented in figure 15 and 16 simultaneously is the freedom to implement the program from any coding development environment. The graphical code implemented on LabVIEW for the flow chart in figure 16 is shown in appendix 2.

Discharging algorithm, though simple, looks complex with the inclusion of the capacity calculation. Since discharging process begins after charging the battery, chances are that the battery voltage level is high. This is therefore a great point to insert the primary end of discharge check. This will ensure that when the lowest battery voltage limit is reached, the program will terminate immediately to avoid over-discharging the battery and to ensure that the data collected for capacity calculation are indeed proper.

The secondary method of checking the end of discharge is through timer method. A constant value is given based on the calculation of the expected duration of discharge; the battery should take at the rate specified by the discharge circuit. The input constant inserted as timer parameter, differs with different types of batteries or with same type of batteries but of different manufacturers. User is therefore prompted to give the needed information like; rated capacity, minimum voltage and maximum voltage about the battery to be tested.

The details of the battery discharge of and capacity level determination are highlighted through the flow chart in figure 17.

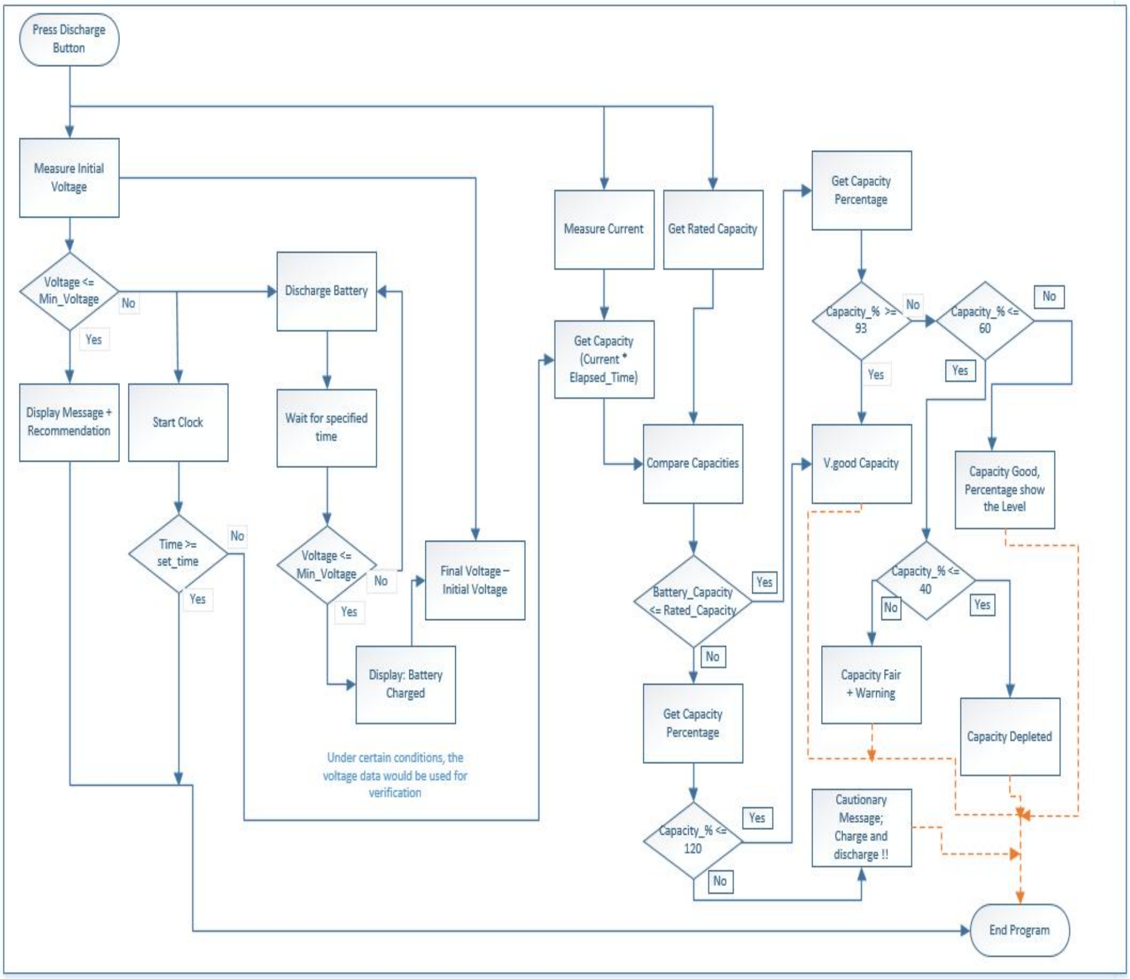


Figure 17: Battery discharge and capacity level determination.

Figure 17 is an illustration of a section of the software that forms the core objective of the project.

As in figure 16, there are actions performed parallel and those that depend on the state of a condition. Besides giving the derivation steps on capacity, figure 17 highlights ending of the program after displaying capacity through the dotted lines.

The constant current at which the circuit draws energy from the battery is measured automatically through the functions on LabVIEW’s block diagram and the information used in calculation of capacity upon detecting the end of discharge. There is an option prompting the user to give that information from the front panel (user interface). The end of battery discharge process is marked by the instance displaying a message that the battery is discharged. The instances that proceed perform capacity calculations and representation. The graphical code implementing the flow chart is attached on appendix 3 and appendix 4.

6.3.3 Capacity Derivation and Representation

The section of figure 17 that highlights capacity calculation and capacity level determination begins when the discharge ends successfully. Battery capacity is then calculated by getting the product of elapsed time and the constant discharge current.

The calculated-capacity is then compared to the rated capacity which the user gives when prompted or the value is pre-set in the program. The comparison condition as highlighted in figure 17 is “less than or equal to” (≤) returning either true or false as an output. The true case means that the calculated-capacity is less than or equal to the rated capacity which is the likely case. This is because batteries have life cycles and once in use, capacity degradation begins to take place with the rate depending on battery handling and maintenance. The false case outcome is not expected but highly possible. The reason being, a battery that is still in good capacity state can give slightly more energy than the specified rate if handled properly. Other possible causes of this case can be as a result of errors during measurements.

To begin with a true case, the calculated-capacity percentage is with reference to the rated capacity. The result shows the degree of disparity from the ideal capacity which in this case is 100%. This is however not enough given the objective of the project. The next task is to provide additional information on the significance of calculated-percentage.

For the percentages more than 93, a message stating that the battery is still in very good capacity state is displayed. Batteries with percentage capacity within the range of 60 - 92 are considered good. However, there is a huge difference in capacity between a battery with 80% and that with 65% capacity.

Part of the implementation of the code not included in the flow chart but visible in appendix 3, takes the constant discharge current and calculates the number of hours the percentage disparity translates to. For example, if a battery is rated 2300mAh and upon testing at a discharge constant current rate of 100 mA results in 70% capacity, then here is how the disparity in hours is deduced;

$$(70\% \div 100\%) \times 2300 \text{ mAh} = 1610 \text{ mAh},$$

$$((2300 - 1610) \text{ mAh} \div 100 \text{ mA}) = 6 \text{ hours } 54 \text{ min.}$$

Disparity in hours is approximately 7 hours. If a different discharge rate is used in calculation, the disparity in hours will be different whereas capacity percentage remains constant.

Batteries with capacity percentages below 60 fall under fair capacity state category but with a warning stating serious drop in capacity. The user interface in LabVIEW will show a blinking LED for the percentages below 40% to incur the seriousness of the level of capacity degradation of the respective batteries.

The false case in capacity comparison is if the battery capacity is greater than rated capacity. The program then compares the percentage difference against two categories. The first category is for the capacities that are more than 100% but below 120%. They are grouped under very good capacity states. Those with more than 120% capacity receive an error message suggesting a retest. The allowed category in this case is allowed on condition of possible errors.

7 Project Outcome

The project undertaking can be described in phases following the importance each phase held to the succeeding one. The first step was to understand the behaviour of rechargeable batteries and focus on one type where NiMH was selected. This established the foundation for defining proper design for the charger and discharger. The success in the circuit design then gave way to use the achieved rates of charging and discharging to design the software for the system. The next stage was to implement the software design into a program able to execute the instructions and display progress.

7.1 Achieved Prototype

The achieved prototype was close to the setup in figure 11 but following a few challenges and emergence of new ideas, a few changes were made during implementation. The challenges included uncompleted milling of the charging circuit following the stall of the milling machine. Better ideas saw the replacement of the DAQ device with almost similar device called the DMM. The new device improved the data readings significantly from the external circuit.

The charger circuit components were soldered on a strip board which is as good as a printed circuit board. Figure 18 illustrates the set-up of the system prototype during testing.

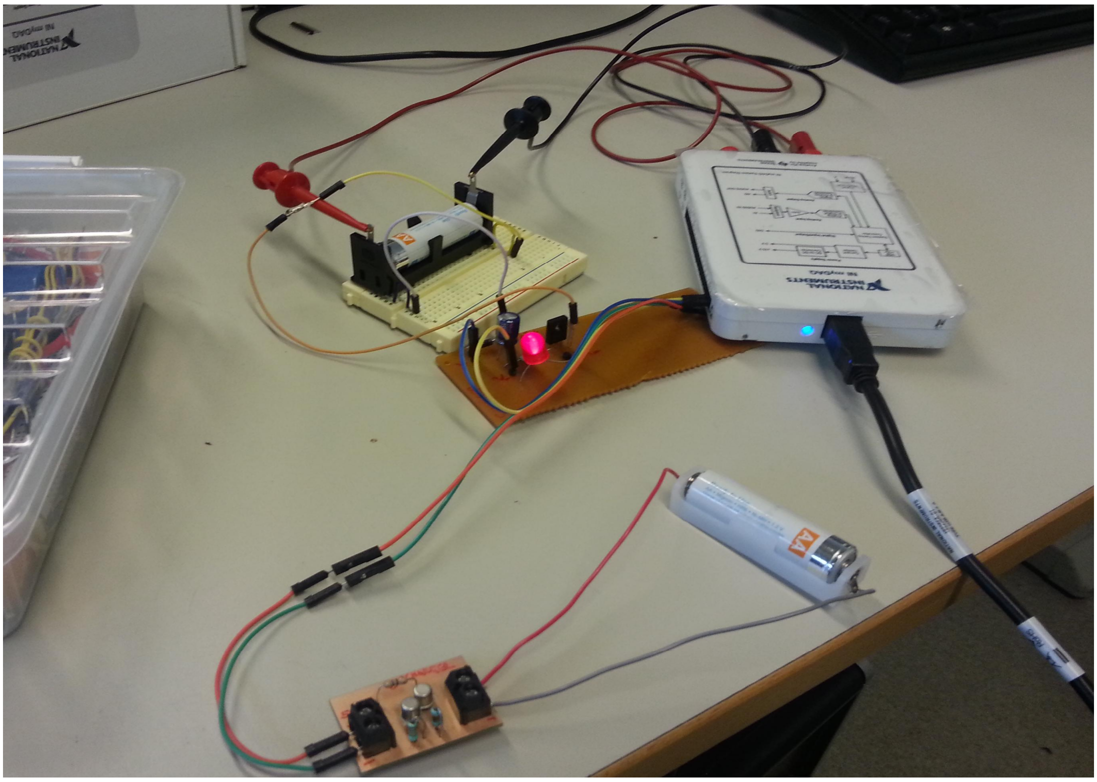


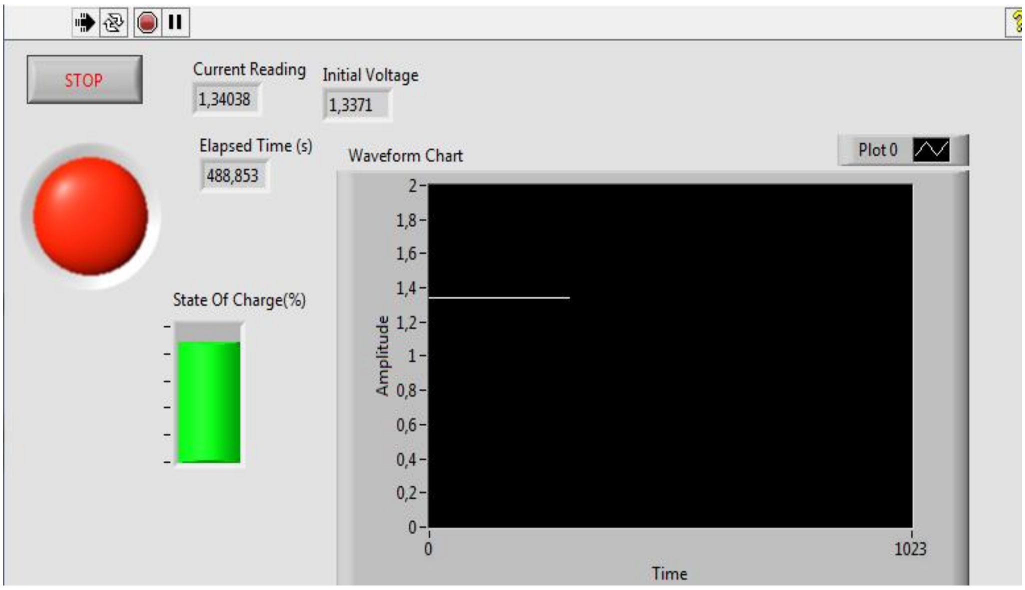
Figure 18: System prototype showing the charging circuit in operation.

The DMM is connected to the computer through a USB connector. The two circuits are powered by the device which offers a range of power source between 0 to 5 volts. A battery holder was placed on a bread board for better connection to the battery. The holder also provides a clip attached to the battery terminals making sure that measurements are based on the battery terminal voltage and not the circuit.

7.2 Charging Results

Charging begins by taking the initial voltage measurement in the first five seconds. The process is monitored while the important indicators are displayed on the front panel. Like the indicators in other mobile devices like phones or laptops, the state of charge indicator serves the same purpose.

Testing different conditions gave satisfactory results terming the charging part of the system a success. Figure 19 shows the front panel of the program during charging. The graphical code as mentioned in section 6.3.2 is attached to appendix 2.



Current Reading 1,34038

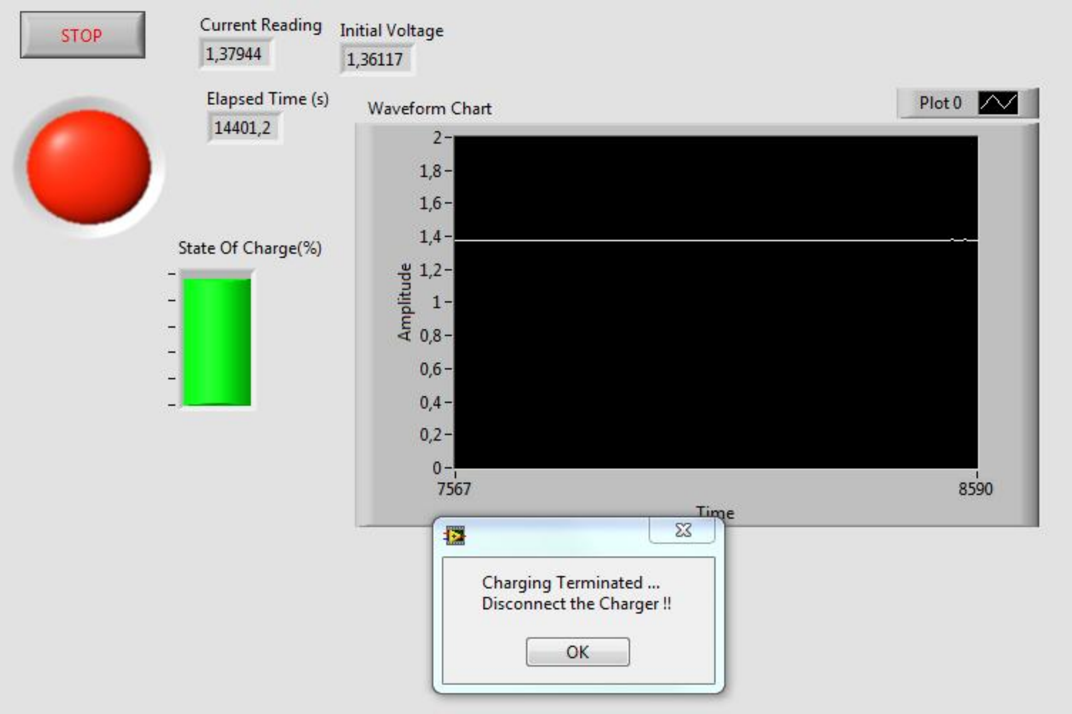
Initial Voltage 1,3371

Elapsed Time (s) 488,853

Figure 19: LabVIEW front panel showing the battery under a charging test

Figure 19 shows the user interface of a running program during charging. LED turns red during charging but changes to green upon reaching the end of charge. The chart shows the voltage pattern across the battery during charging. The elapsed time indicator displays the amount of time in seconds that charge has taken.

Important indicators besides the elapsed time in figure 19 are the initial voltage indicator and the current reading. The two indicators give a clear highlight of the progress of the charging process to the user. One can easily see if something is going wrong by looking at the readings on the indicators. The state of charge indicator holds the summary that most users will focus on.



Current Reading 1,37944

Initial Voltage 1,36117

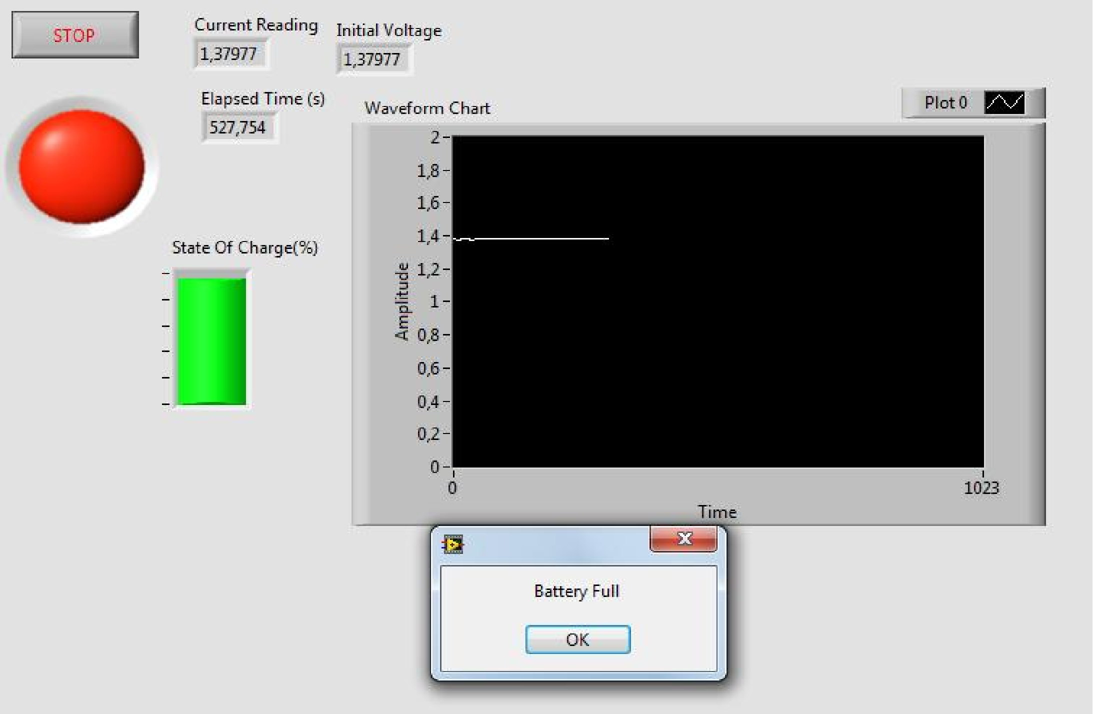
Elapsed Time (s) 14401,2

Charging Terminated ...
Disconnect the Charger !!

Figure 20: Charge termination through the third charge termination parameter.

The dialog box in figure 20 recommends the user to disconnect the charger following failure of the first two charge termination methods. The picture was taken while testing the operation of the timer method to control the end of discharge. The elapsed time indicates 14401.2 seconds which is about 4 hours as set on the timer.

The first parameter of charge termination was to detect the point where the voltage increase levels off. The software implementation compares the current reading with values read earlier under a defined time period. Figure 21 is the result of the test performed on the condition.



Current Reading 1,37977

Initial Voltage 1,37977

Elapsed Time (s) 527,754

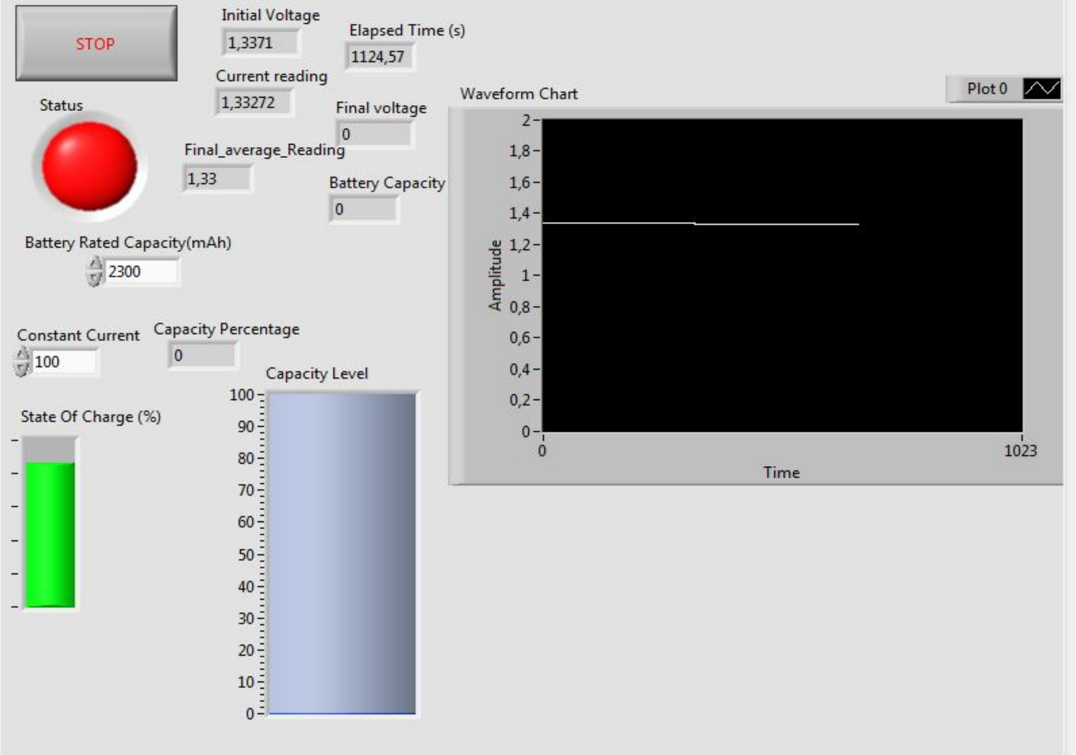
Battery Full

Figure 21: Testing the first method applied to detect end of charge.

The result in figure 21 was performed with a time difference of 500 seconds between the readings. This was however used for the testing purposes. The defined time difference for using the system is between 20 to 30 minutes.

7.3 Discharging Results

Unlike charging, the discharging program has additional indicators and controls on the user interface. The discharge program is initiated upon charging a battery to full and the circuit powered. Upon the end of discharge, data gathered is used to calculate the battery’s capacity. While appendix 3 contains the block diagram with the graphical code, figure 22 shows the program’s user interface during discharge.



Initial Voltage 1,3371

Elapsed Time (s) 1124,57

Current reading 1,33272

Final voltage 0

Final_average_Reading 1,33

Battery Capacity 0

Battery Rated Capacity(mAh) 2300

Constant Current 100

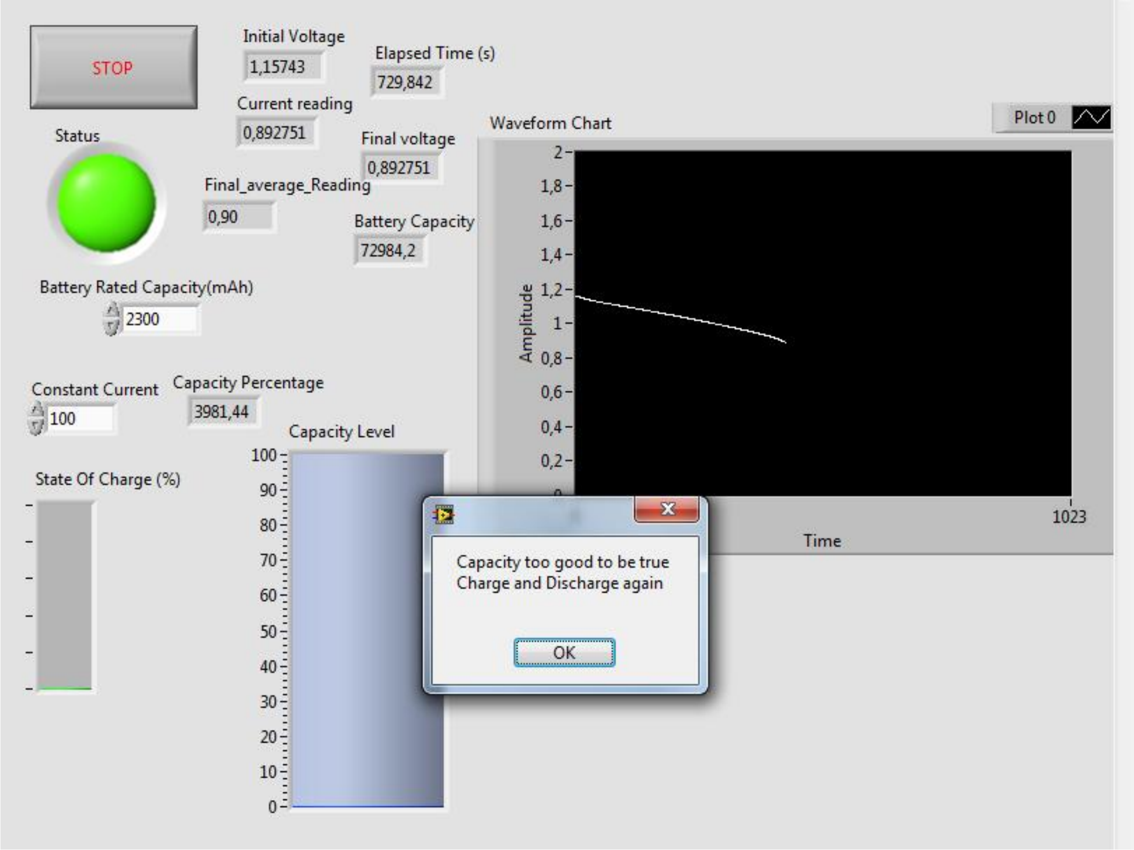
Capacity Percentage 0

Figure 22: Monitoring battery discharge.

Figure 22 shows various indicators representing different parameters during battery discharge. The tank shows the battery's capacity level when the discharge process ends successfully. The chart however shows the voltage reading in waveform format. LED works the same way as in charging, when the end of discharge is detected, it turns green. It also displays other properties on occurrence of certain events. For instance, when a battery capacity is below 40% it blinks.

Additional indicators include capacity percentage which shows the battery's level of capacity with reference to the ideal capacity. The ideal capacity has a control icon where the users fill the battery's rated capacity. This makes it possible to test any other type of rechargeable battery.

The capacity is only displayed upon reaching the end of discharge. Figure 23 shows the result on one terminated testing case.



Initial Voltage 1,15743

Elapsed Time (s) 729,842

Current reading 0,892751

Final voltage 0,892751

Final_average_Reading 0,90

Battery Capacity 72984,2

Battery Rated Capacity(mAh) 2300

Constant Current 100

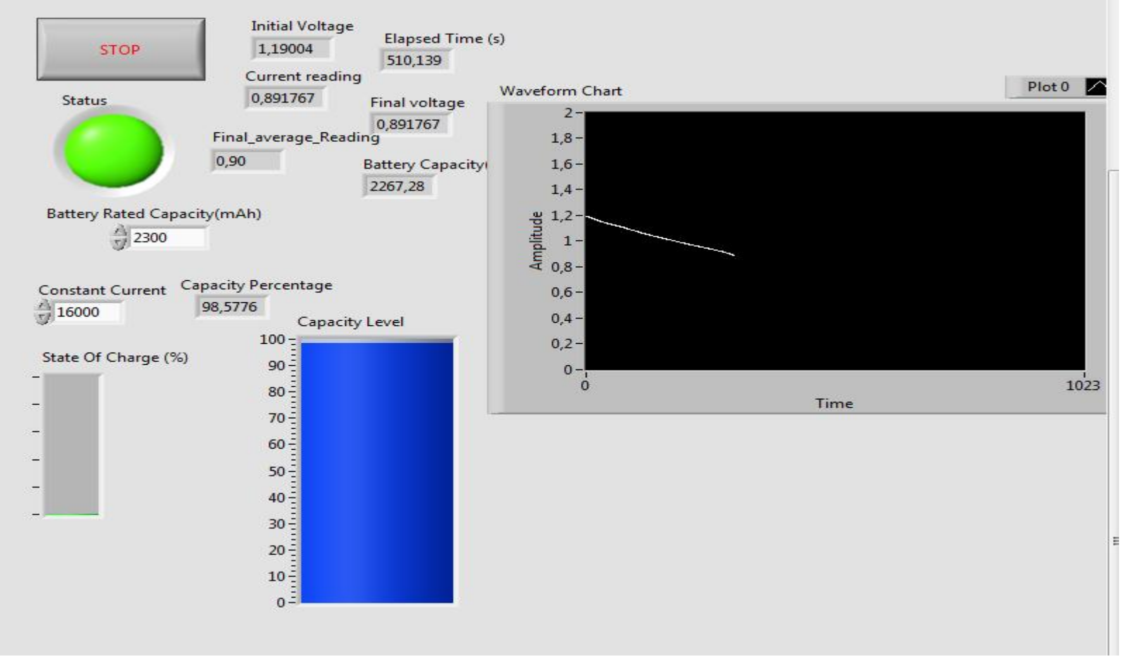
Capacity Percentage 3981,44

Capacity too good to be true
Charge and Discharge again

Figure 23: Termination falling under unexpected category.

The demonstration in figure 23 is one extreme case of boundary checking on capacity calculation. The result shows a huge amount of energy discharged at a very short time with over 3000% capacity which is unrealistic. This is one of the tests aimed at checking the program's control of the extreme cases.

A successful discharge process would take around 20 hours at the rate the discharge circuit is operating on. During testing the process would be interrupted more often. The few cases produced great results. For purposes of demonstrating how a battery with very good capacity level is represented, figure 24 shows one test result.



Initial Voltage 1,19004

Elapsed Time (s) 510,139

Current reading 0,891767

Final voltage 0,891767

Final_average_Reading 0,90

Battery Capacity(2267,28

Battery Rated Capacity(mAh) 2300

Constant Current 16000

Capacity Percentage 98,5776

Figure 24: A case of high rate discharge on a battery with very good capacity level.

Figure 24 shows a test aimed at checking the systems performance when high rate of discharge is applied. The battery was not charged to full before commencing the discharge process and constant discharge current increased to suit the test case. The result in figure 24 shows a successfully discharged battery with a very good capacity level.

8 Discussion

8.1 Overview

Following the results achieved and the testing done in different conditions, the general outcome of the project can be termed as successful. This however does not mean that the project achieved all the intended objectives. A simple conclusion of the system's performance from the observations made is given in figure 25.

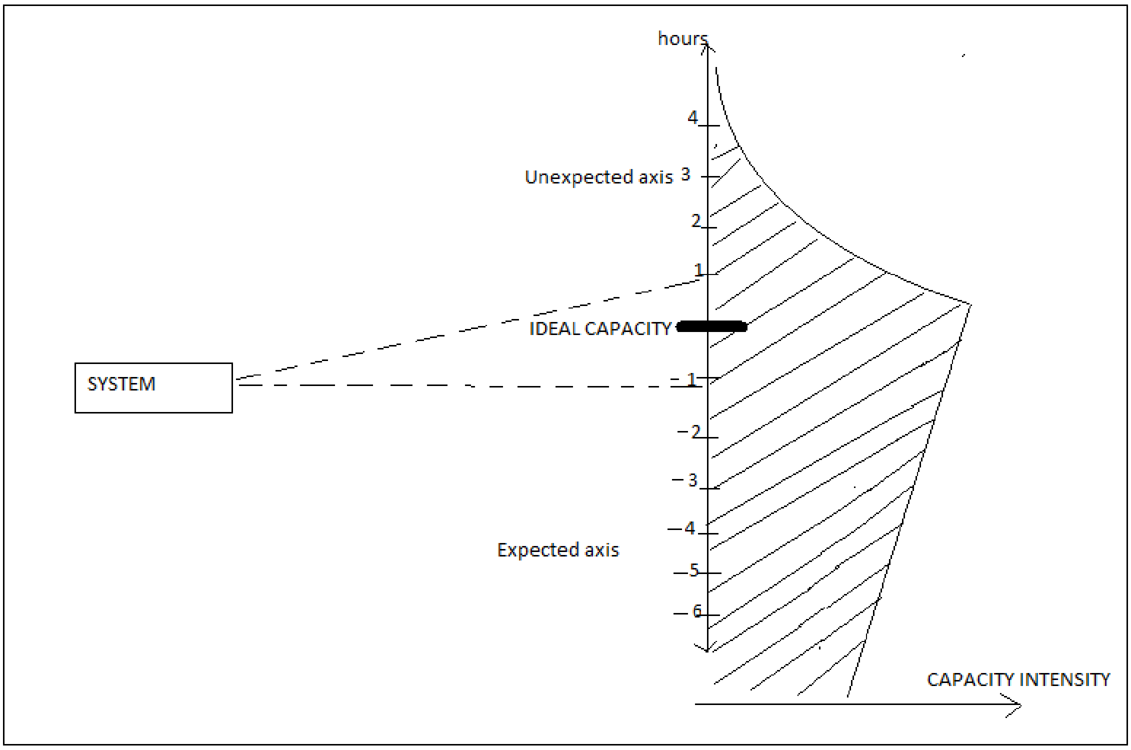


Figure 25: Representation of the system's interpretation of capacity.

A highlight of the systems representation of capacity level in figure 25 depicts the summary of capacity level determination and interpretation. The positive axis represents the unexpected cases explained in chapter 6.3.3 where a test with around two hours or less, more than the expected time is recognized as having very good capacity. Otherwise, the capacity level will seem unrealistic as the case in figure 23.

The expected case has a more linear decrease in capacity level from the deduced results. The disparity in hours can be translated into percentages as well. The results mean that the system meets all the requirements needed to test the batteries. A few improvements on the system would see a huge amount of energy saved and sorted chunks of batteries according to capacities in places they are used on a large scale.

8.2 Challenges

This project like many engineering projects came with a few challenges. Circuit design and making the calculations to fit the expected parameters to operate at certain rates, took time with moderation on every step of the project. The rate of charging and discharging was based on varying the value of some circuit components and power source. It therefore meant that a change would lead to another and before long the process has to be commenced from the beginning.

The challenge on parameter calculation was coupled closely by the limited experience of the important details to check before making electronic components online order. Learning of these challenges and getting guidance was not just helpful but helped to see the little mistakes and weaknesses.

One of the challenging phases of the project was working on the program software algorithm. The Software activity diagram hides numerous condition tests under the diagrams. Deriving the algorithm that forms the code and ensuring that the operation is in order, proved quite a process. Despite working on a graphical programming environment combining numerous operations to the working system software was at some point confusing.

The journey was however worthwhile as every single challenge brought with it numerous important lessons on understanding and confidence to face more challenges. The general lesson winds to good project planning.

8.3 Recommended Improvements

Despite the good project outcome, there is room for a number of improvements to make the system not just better but one that can test more than one battery at a time. A better system would be one that analyses the battery capacity level based on the two processes without human interaction. Testing more than one battery at a time will not only save time but will make it easy for those working with numerous batteries improve efficiency. This would mark a major improvement on the system.

A close improvement on the circuits would also see trickle charging performed when the end of charge is reached to ensure full charge and a good charging history. This ensures that the battery test performed is based on proper regulation of the two processes, thereby limiting errors that may result from improper charging and bad history of battery charging and the discharging.

The circuit with adjustable charging and discharging rates offers the option to choose the time duration to spend on testing a battery. This can be barked with options of selecting the type of battery to test.

The list for improvements can be endless but the few mentioned are among those that can be achieved without much change to the current system design and operation.

8.4 Battery Maintenance

Different types of rechargeable batteries vary in their chemical reactions leading to the difference in their properties. While some batteries have lower rates of self-discharge, some lose a huge percentage of charge on self-discharge. Battery maintenance is however important in prolonging the life of batteries and ensuring a better performance during use.

There are a few general ways of rechargeable battery maintenance that apply to all types of batteries but the key methods are battery type specific. Battery handling precautions however apply to all types of rechargeable batteries.

The rate of charging or discharging has significant effect on the battery capacity irrespective of type. High rates of charging need to be controlled by the use of smart chargers or close supervision of the process. Overheating caused by fast chargers tend to affect the electrochemistry of the battery. This has a negative effect on the battery capacity. Over-discharge on the other hand leads to battery capacity drop.

The other major maintenance methods are battery type related. NiCad for instance has good capacity and a reasonable shelf life but suffers from the “memory effect”. This effect can be reduced by making sure the battery is used until fully drained to minimize crystal build up. Performing deep discharge is another way to limit the memory effect but it should be done time after time and not every now and then. Every month is recommended for the batteries used more often.

NiMH has similar advantages to NiCad besides not suffering the memory effect. However, they experience high self-discharge rate while not in use or in storage. A recommended way to maintain the battery capacity is to keep it trickle charging while not in use. [19]

Li-ion besides having the advantages shared by both NiCad and NiMH has longer life. They neither suffer memory effect nor high self-discharge which makes them the outstanding for electronic devices like laptops. The only drawback they experience which cannot be avoided is in the chemical breakdown leading to a 10% drop in capacity each year. Maintaining these types of batteries is by reducing the number of discharge cycles so as to extent the battery life.

The battery type maintenance methods require the user to know the type of battery. The precautions of how to handle rechargeable batteries however, apply to all battery types. Among the common precautions are:

- Do not drop the batteries or impact them as it may lead to exposure of corrosive cell contents.
- Do not short-circuit the batteries. Likely to cause severe damage or a possible explosion.
- Do not store the batteries in a hot, wet and dirty place.
- Transport the batteries in the right packages.

- Consider recycling options before disposing the batteries and when disposed, ensure disposal is in the right place.[19]

There are more precautions and battery maintenance methods not mentioned but the highlighted few are key.

9 Conclusion

The goal of the project was to design and build a system that would indicate the rechargeable battery capacity level. The project stressed the understanding of batteries' behaviour to define the system's operational parameters.

Besides the study and design of circuits, important activities that are part of Embedded Engineering projects, like ordering components and performing tests before critical stages just to mention a few, were equally important in understanding the management aspect of engineering projects. Following the study on batteries, numerous recommendations surfaced, which are not only helpful to the users but to the manufacturers as well.

The outcome of the project, despite a few challenges, met the objective target but with room for improvement. The system is expected to help in planning with the batteries to avoid unnecessary malfunction of devices and avoid wastage by throwing away batteries which are still useful. Proper charging through the use of smart chargers and the understanding of how different rates of charging and discharging affect batteries covered in this report are as important as promoting the tips on energy saving.

The findings from the project encourages proper use of batteries, improved battery management and conservation of energy with the help of the system.

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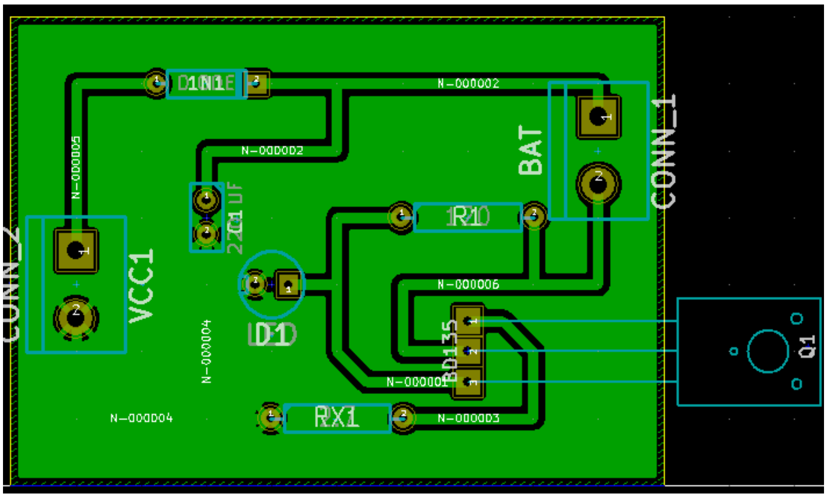
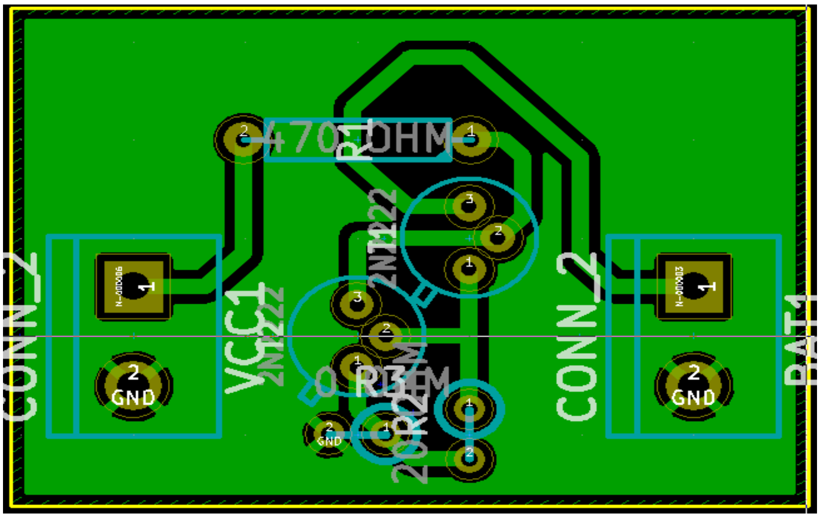
Charging and Discharging Circuits Design Layout

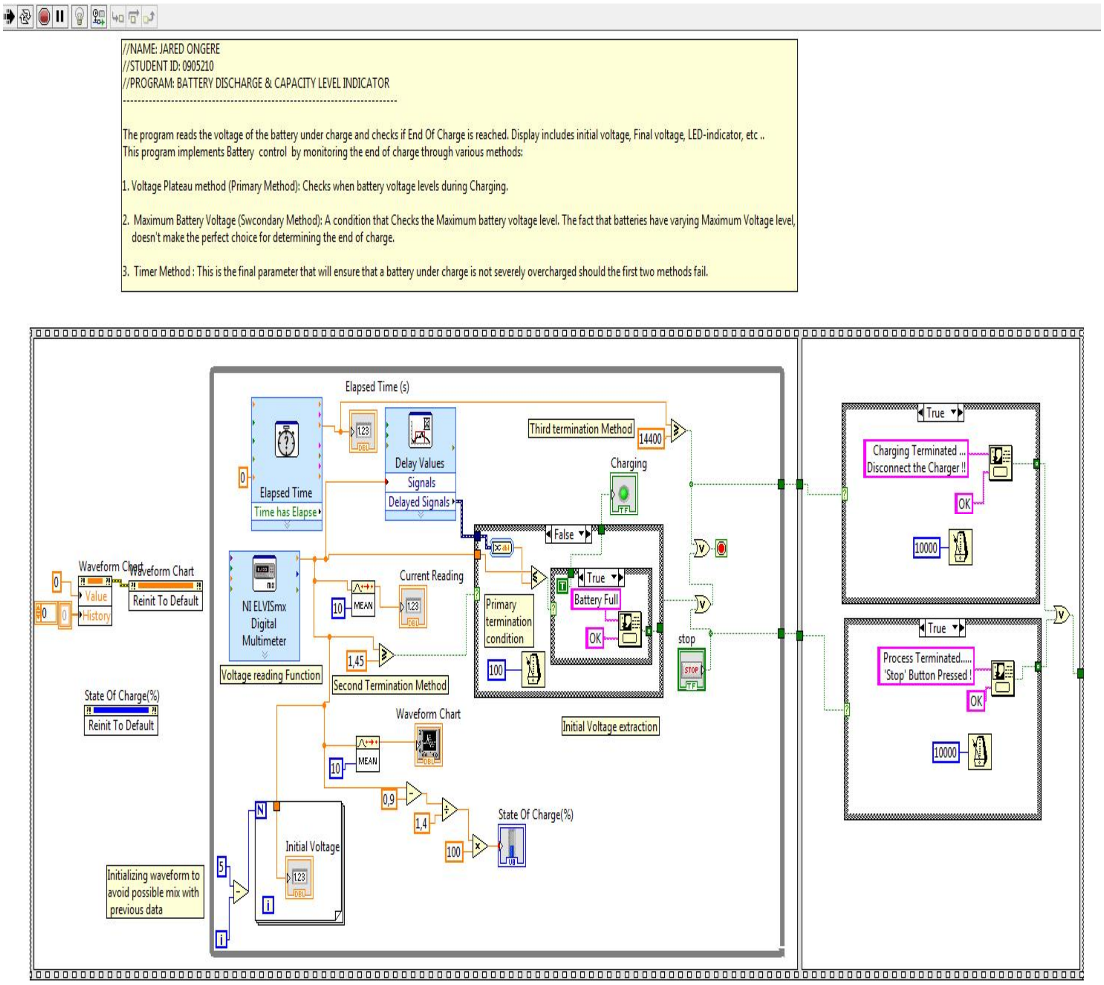


Charging Circuit layout designed on Ki CAD.



Discharge Circuit Layout Design

Charge Monitoring and Control Program



//NAME: JARED ONGERE
//STUDENT ID: 0905210
//PROGRAM: BATTERY DISCHARGE & CAPACITY LEVEL INDICATOR

The program reads the voltage of the battery under charge and checks if End Of Charge is reached. Display includes initial voltage, Final voltage, LED-indicator, etc ..
This program implements Battery control by monitoring the end of charge through various methods:

1. Voltage Plateau method (Primary Method): Checks when battery voltage levels during Charging.

2. Maximum Battery Voltage (Swcondary Method): A condition that Checks the Maximum battery voltage level. The fact that batteries have varying Maximum Voltage level, doesn't make the perfect choice for determining the end of charge.

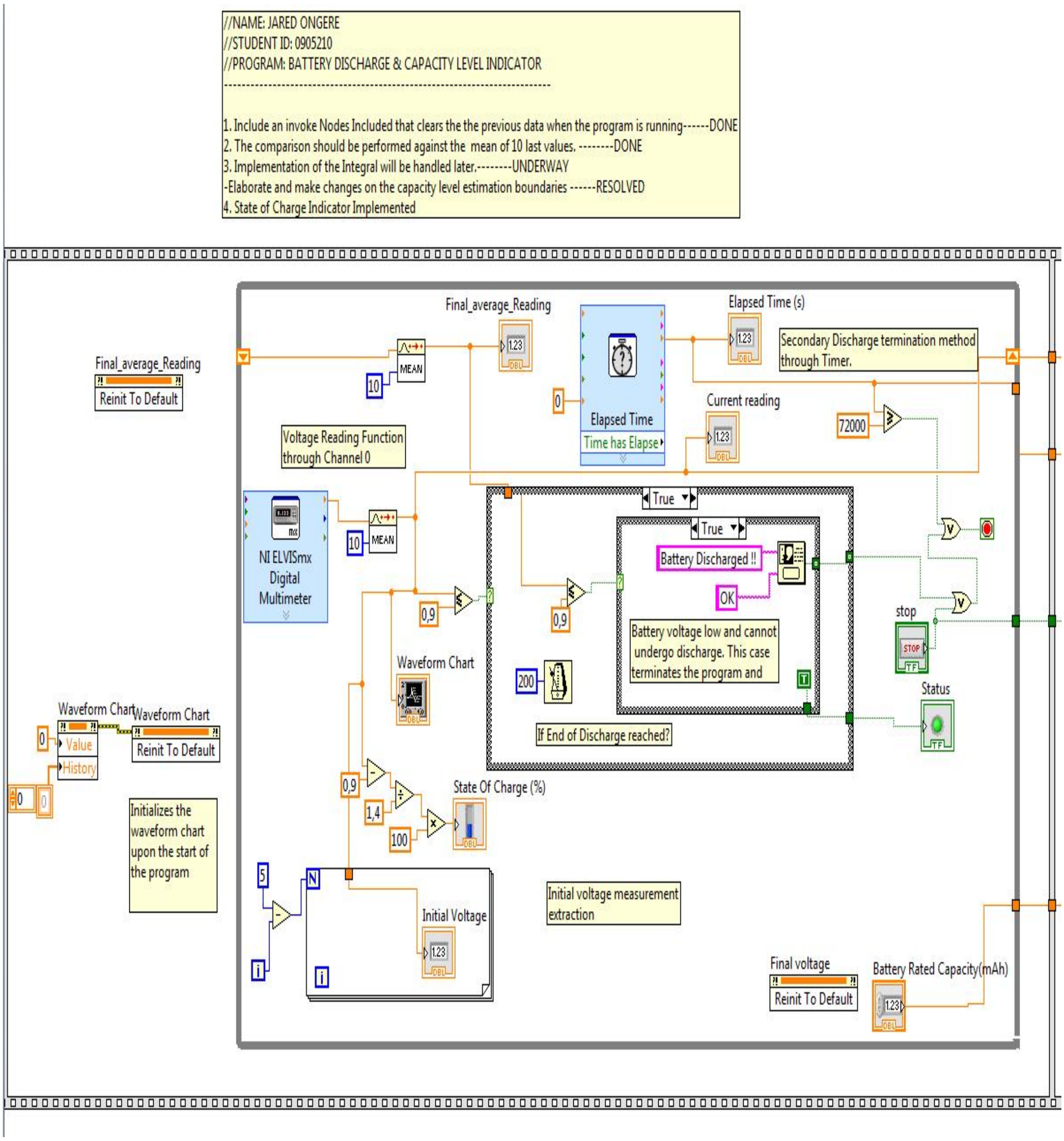
3. Timer Method : This is the final parameter that will ensure that a battery under charge is not severely overcharged should the first two methods fail.

Battery Full

Charging Terminated ... Disconnect the Charger !!

Process Terminated..... 'Stop' Button Pressed !

Discharge Monitoring and Control Program



//NAME: JARED ONGERE
//STUDENT ID: 0905210
//PROGRAM: BATTERY DISCHARGE & CAPACITY LEVEL INDICATOR
----

1. Include an invoke Nodes Included that clears the the previous data when the program is running------DONE
2. The comparison should be performed against the mean of 10 last values. --------DONE
3. Implementation of the Integral will be handled later.--------UNDERWAY
-Elaborate and make changes on the capacity level estimation boundaries ------RESOLVED
4. State of Charge Indicator Implemented

Secondary Discharge termination method through Timer.

Voltage Reading Function through Channel 0

Battery voltage low and cannot undergo discharge. This case terminates the program and

If End of Discharge reached?

Initializes the waveform chart upon the start of the program

Initial voltage measurement extraction

Capacity Derivation Part of the Program