Dynamic Electrical Model of Sealed Lead-Acid Battery for EV Simulation

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Declaration

We hereby declare that this thesis paper is an outcome of our own work and effort and any information from other sources have been acknowledged in the reference section.

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Abstract:

In recent times, Bangladesh is advancing towards Electric Vehicle system; popularly known as the EV system and one of its most prominent application we see these days are the motor operated rickshaws. Although the motors in these rickshaws run in rechargeable batteries it would be feasible to run them on solar power at some time and so in this paper we aim to develop a battery model for battery for a photovoltaic system that can be used in EV systems. In stand-alone photovoltaic power systems, the electrical energy produced by the photovoltaic panels cannot always be used directly. As the demand from the load does not always equal the solar panel capacity, battery banks are generally used. This work aims to study the charging and discharging mechanism of batteries used in photovoltaic systems and develop an electrical model of the battery that will take account of various factors such as charging and discharging current, state of charge, temperature etc.

Chapter 1

Introduction

1.1 Background:

Each year modern society uses approximately 500 exajoules (EJ) of the total primary energy which has been increasing at roughly 2% per year for the past two hundred years. Modern society has been shaped by the use of the fossil fuels as over 80% of the energy used by the mankind comes from fossil fuels [1].World population is increasing and so is the demand for fuel but fossil fuels being non-renewable energy source is slowly depleting in supply. Using fossil fuel may have taken us far in terms of technology but it has also slowed us down in terms of environment. Mankind is facing major environmental issues due to extensive use of fossil fuel; one of them being global warming since burning fossil fuel produces carbon dioxide which causes global warming. Lots of nations are now being aware of this environmental impact due to excessive use of fossil fuel and now in order to preserve the fossil fuel they are looking for option of using renewable energy.

Renewable energy sources mainly include wind power, hydroelectric power, solar power, geothermal energy etc. Many countries are now turning towards these aforementioned energy sources and the production of electricity using these sources has increased greatly.

In Bangladesh the conditions are not suitable to produce electricity using wind energy as it requires high wind speed. Also being a delta, Bangladesh still has only one hydro powered station in Kaptai, Chittagong and so the only feasible option is to produce electricity using solar power.

1.1.1 Energy storage system:

So choosing an energy source is not a big problem but the problem lies is extracting and storing the energy so that it can be used later. One of the major problem with natural energy resources is that they depend on weather and the generation time is uncertain with them. They might not be economically feasible and sometimes the power quality might not be up to the par. That is why energy storage system is introduced which will store the energy for later use. Some of the commonly used energy storage systems are:

- Super capacitor
- Flywheel
- Superconducting magnetic energy storage (SMES)
- Flow battery
- Rechargeable battery

Storage systems should be chosen based on the system that will use the energy such as for an Electric Vehicle running on solar power, a rechargeable battery is a suitable choice. Factors that should be taken into account for choosing a energy system are reliability, cost, efficiency, durability, portability etc.

1.1.2 Stand-alone PV-system:

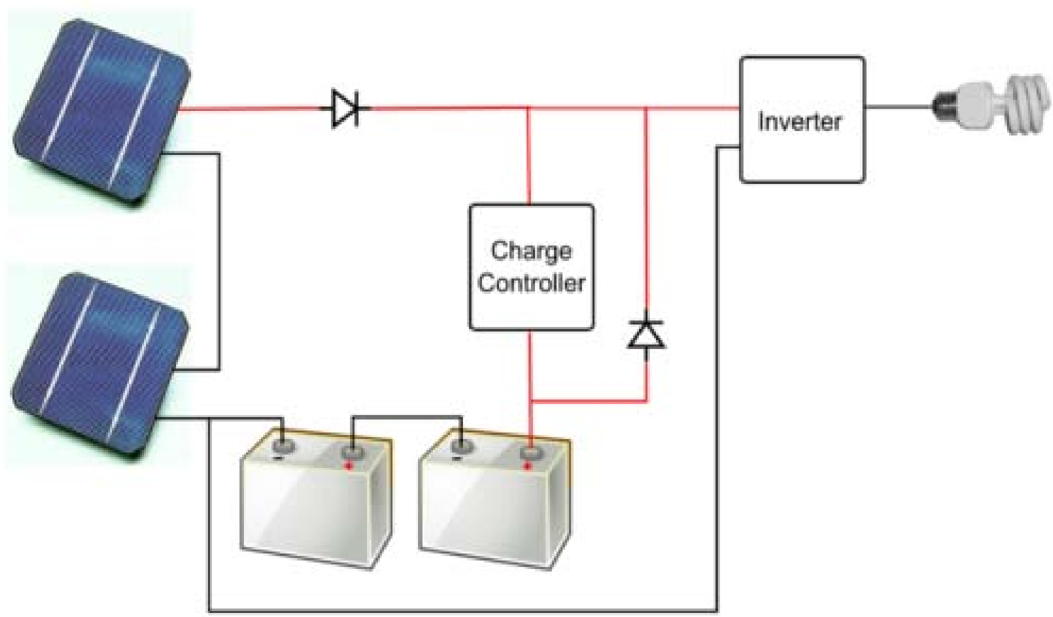


Fig 1: The stand-alone photovoltaic power system

Stand-alone photovoltaic power systems are electrical power systems energized by photovoltaic panels which are independent of the utility grid. These types of systems may use solar panels only or may be used in conjunction with a diesel generator or a wind turbine.

In stand-alone photovoltaic power systems, the electrical energy produced by the photovoltaic panels cannot always be used directly. As the demand from the load does not always equal the solar panel capacity, battery banks are generally used.

The primary functions of a storage battery in a stand-alone PV system are:

- Energy Storage Capacity and Autonomy: To store energy when there is an excess is available and to provide it when required.
- Voltage and Current Stabilization: To provide stable current and voltage by eradicating transients.
- Supply Surge Currents: to provide surge currents to loads like motors when required.[2]

1.1.3 Types of batteries:

In general, electrical storage batteries can be divided into two major categories, *primary* and *secondary* batteries.

Primary Batteries

Primary batteries can store and deliver electrical energy, but *can not be recharged*. Typical carbon-zinc and lithium batteries commonly used in consumer electronic devices are primary batteries. Primary batteries are not used in PV systems because they can not be recharged.

Secondary Batteries

A secondary battery can store and deliver electrical energy, and *can also be recharged* by passing a current through it in an opposite direction to the discharge current. Common *lead-acid* batteries used in automobiles and PV systems are secondary batteries. Table 1 lists common secondary battery types and their characteristics which are of importance to PV system designers. A detailed discussion of some of battery type follows.

- **Lead-acid:** It is the oldest form of rechargeable battery technology and contains liquid electrolyte in an unsealed container, requiring that the battery be kept upright and the area be well ventilated to ensure safe dispersal of the hydrogen gas it produces during overcharging. The lead–acid battery is also relatively heavy for the amount of electrical energy it can supply. Its low manufacturing cost and its high surge current levels make it common where its capacity (over approximately 10 Ah) is more important than weight and handling issues. A common application is the modern car battery, which can, in general, deliver a peak current of 450 amperes [3].

- **Nickel-Cadmium:** A Ni-Cd battery is a type of rechargeable battery using nickel oxide hydroxide and metallic cadmium as electrodes. Ni-Cd batteries are made in a wide range of sizes and capacities, from portable sealed types interchangeable with carbon-zinc dry cells, to large ventilated cells used for standby power and motive power [3].

- **Li-ion:** Widely used in cellphones and laptops, Li-ion batteries have become one of the most used rechargeable battery for portable electronics. In Li-ion batteries the ions move from anode to cathode during discharge and vice versa. Disadvantage of this battery is mainly the flammable electrolyte unlike most rechargeable batteries [3].

- There are other types of rechargeable batteries such as Ni-Fe, Ni-H, Na-S and many more.

1.2 Objective of the thesis:

The main objective of this thesis is to develop a model for the battery. The model will predict and reproduce the behavior of the battery parameters such as depth of discharge, state of charge, terminal voltage, cell temperature etc. The output from the model can then be used to design charge controllers that will increase efficiency of battery and prolong its life span.
The methodology followed to develop this model is to determine the battery parameters and then incorporate those parameters in the model. At first several existing battery models are studied in text and then the model is chosen according to the battery requirement. Experiment are then carried out on the battery and based on the data found unknown parameters are determined and then battery model is developed using MATLAB/Simulink. This project acknowledges the application of batteries and charge control in stand-alone systems and vows to use the information to improvise the current model to provide a better solution for the issues that are encountered in the PV system. Some of the issues are:

- Premature failure and lifetime prediction of batteries are major concerns within the PV industry [3].

- Batteries experience a wide range of operational conditions in PV applications, including varying rates of charge and discharge, frequency and depth of discharges, temperature fluctuations, and the methods and limits of charge regulation. These variables make it very difficult to accurately predict battery performance and lifetime in PV systems [3].

- Battery performance in PV systems can be attributed to both battery design and PV system operational factors. A battery which is not designed and constructed for the operational conditions experienced in a PV system will almost certainly fail prematurely. Just the same, abusive operational conditions and lack of proper maintenance will result in failure of even the more durable and robust deep-cycle batteries [3].

- Battery manufacturers’ specifications often do not provide sufficient information for PV applications. The performance data presented by battery manufacturers is typically based on tests conducted at specified, constant conditions and is often not representative of battery operation in actual PV systems [3].

- Wide variations exist in charge controller designs and operational characteristics. Currently no standards, guidelines, or sizing practices exist for battery and charge controller interfacing.[3]

1.3 Limitations:

The key limitation of this model is that it can determine the SOC of a battery but it can not predict the health of the battery. The health of battery depends on factors such as continuous charging and discharging of batteries. Due to time limitations and other constraints experiments that could include health of battery in the model was not studied and was finally excluded from the model.

Chapter 2

Lead Acid Battery

2.1 General Overview

2.1.1 Background

Lead acid was the first rechargeable battery for commercial use. It was invented by the French physician Gaston Planté in 1859. His model consisted of two lead sheets separated by rubber strips and rolled into a spiral. These batteries were first used to power the lights in train carriages while the train stopped at a station. In 1881, Camille Alphonse Faure invented an improved version that consisted of a lead grid lattice forming a plate into which a lead oxide paste was pressed. This design was easier to mass-produce. During the mid-1970's, researches developed a maintenance-free lead acid battery that could operate in any position. The liquid electrolyte was transformed into moistened separators and the enclosure was sealed. Safety valves were added to allow venting of gas during charge and discharge [4].

2.2 Lead Acid Battery Structure:

2.2.1 Physical Structure and cell composition:

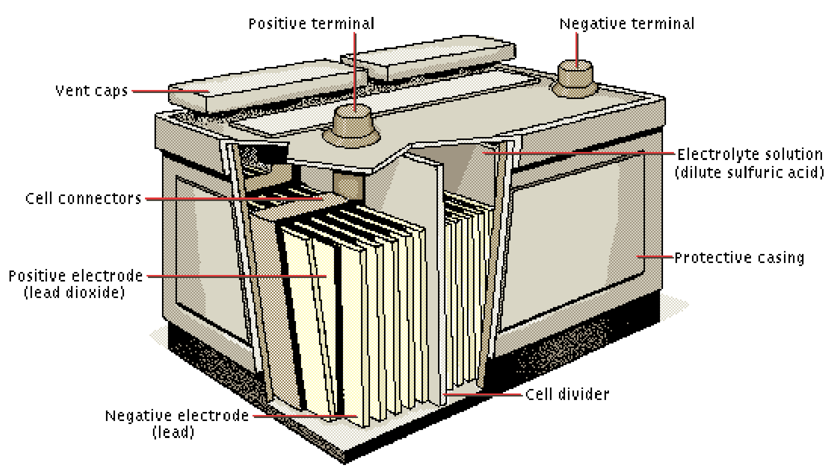


Fig 2: Physical structure of a lead acid Battery.

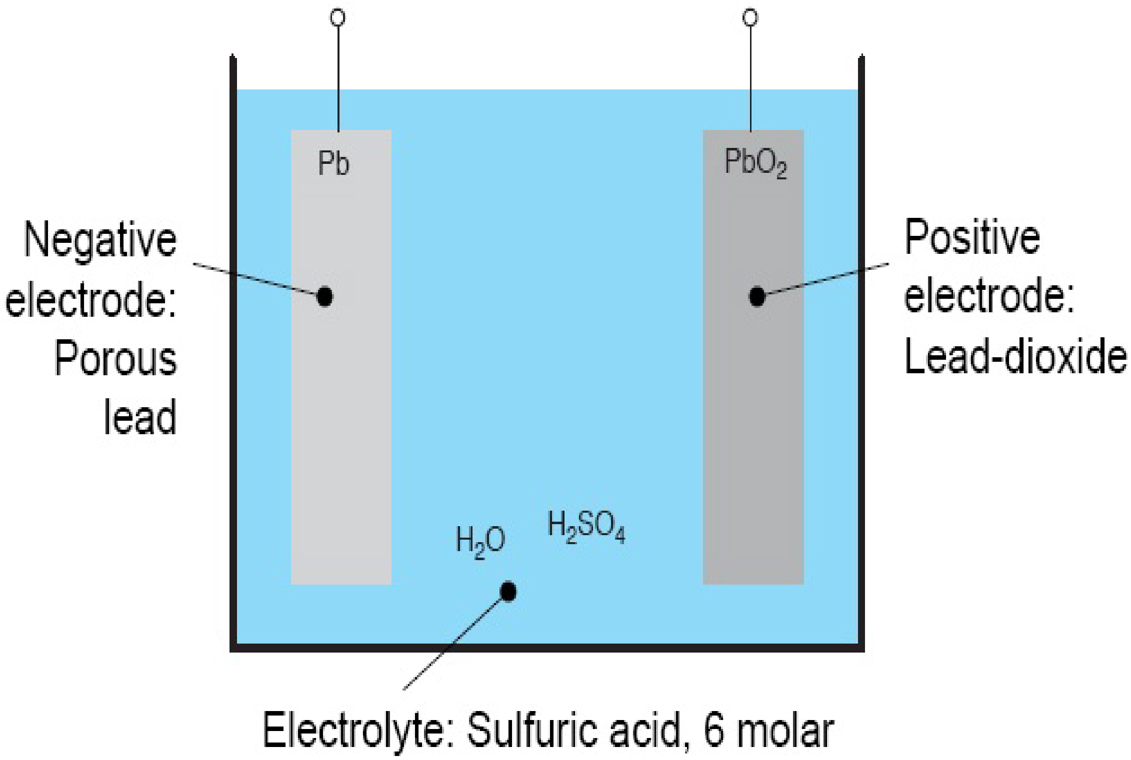


Fig 3: Cell composition of battery

Lead and lead-dioxide are good electrical conductors. The conduction mechanism is via electrons jumping between atoms. The electrolyte contains aqueous ions (H^+ and $SO4^{-2}$). The conduction mechanism within the electrolyte is via migration of ions via diffusion or drift.[5]

The following equations show the electrochemical reactions for the lead-acid cell. During battery discharge, the directions of the reactions listed goes from left to right. During battery charging, the direction of the reactions are reversed, and the reactions go from right to left. Note that the elements as well as charge are balanced on both sides of each equation.[5]

At the positive plate or electrode:

$PbO_2 + 4H^+ + 2e^- \Leftrightarrow Pb^{2+} + 2H_2O$

$Pb^{2+} + SO_4^- \Leftrightarrow PbSO_4$

At the negative plate or electrode:

$Pb \Leftrightarrow Pb^{2+} + 2e^-$

$Pb^{2+} + SO_4^- \Leftrightarrow PbSO_4$

Overall lead-acid cell reaction:’

$$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O$$

2.2.2 Types of lead acid battery:

Flooded battery

Flooded batteries have a conventional liquid electrolyte and have removable caps so that the electrolyte can be diluted. These batteries are used for large capacity backup power, computer centers, off grid system etc. Flooded lead acid batteries are less sensitive to the charging and should be kept upright [5].

Gelled electrolyte

The electrolyte in the battery as the name suggested is gelled so will not leak. However, these electrolyte cannot be diluted so that overcharging must be avoided. These batteries only last for 1 to 2 years but they are environmentally friendly and easy to work technically [5].

Valve Regulated Lead Avid Battery (VRLA)

The electrolyte in VRLA batteries are sealed in the container. The plates, size and weight of these kinds of batteries are different from other kind of batteries as they are totally dependent on the container type. They can be mobilized and mounted in any position. There is very low gassing due to the internal gas recombination and used in vehicles [5].

Absorbed Glass Mat (AGM) Batteries

The electrolyte in these kinds of batteries is held between the plates absorbed into the mat in such a way that the electrolyte is immobilized. Unlike gelled batteries they can withstand overcharging but the electrolyte is not leaked as in gelled batteries. However these batteries are much more expensive [5].

The table below states the advantage and disadvantages of different types of batteries:

Battery Type	**Advantages**	**Disadvantages**
Flooded Lead-Acid		
Lead-Antimony	Low cost, wide availability, good deep cycle and high temperature performance, can replenish electrolyte	High water loss and maintenance

Lead-Calcium Open Vent	Low cost, wide availability, low Water loss, can replenish Electrolyte	Poor deep cycle performance, intolerant to high temperatures and overcharge
Lead-Calcium Sealed Vent	Low cost, wide availability, low water loss	Poor deep cycle performance, intolerant to high temperatures and overcharge, cannot replenish electrolyte
Lead Antimony/Calcium Hybrid	Medium cost, low water loss	Limited availability, potential for stratification
Captive Electrolyte Lead-Acid		
Gelled	Medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	Fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Absorbed Glass Mat	Medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	Fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Nickel-Cadmium		

Sealed Sintered-Plate	Wide availability, excellent low and high temperature performance, maintenance free	Only available in low capacities, high cost, suffer from ‘memory’ effect
Flooded Pocket-Plate	excellent deep cycle and low and High temperature performance, tolerance to overcharge	Limited availability, high Cost, water additions required

Table 1: Battery Characteristics

Chapter 3

Battery Parameters

3.1 Battery parameters:

3.1.1 Open Circuit Voltage

When the battery is in rest or steady state the output is called open circuit voltage. The open circuit voltage depends on the battery design, specific gravity and temperature.

3.1.2 Depth of Discharge (DOD)

The depth of discharge (DOD) of a battery is defined as the percentage of capacity that has been withdrawn from a battery compared to the total fully charged capacity.

3.1.3 State of charge (SOC)

The state of charge (SOC) is defined as the percentage of the energy stored in a fully charged battery. State of charge increases when the battery is charged and decreases as the battery is discharged.

3.1.4 Internal Resistance

The internal resistance (Ri) of the battery depends upon SOC. It remains nearly constant up to 90% of SOC after that it increases exponentially. It is an important parameter because as this parameter will be higher, during charging or discharging process, the ohmic drop will increase or decrease. The value of this resistance differs depending on whether the battery is charging or discharging [15]. The charging and discharging behavior of the battery is not same because the internal resistance of the chemical substances is not same.[16]

There are 3 classes of internal resistance

• Self-discharge Resistance: its which takes account of resistances in (a) electrolysis of water at high voltage and (b) slow leakage across the battery terminal at low voltage. This resistance is more temperature sensitive and inversely proportional to the temperature change [17].

• Resistances for Charge and Discharge (*Rc*/*Rd*): These are the resistances associated with electrolyte resistance, plates resistance and fluid resistance, however all these resistances can be different in charging and discharging.

• Overcharge and Over-discharge Resistance: When the battery is overcharged or over-discharged, the internal resistance will be increased significantly due to the electrolyte diffusion. These resistances are attributed largely to the electrolyte diffusion during over charging and over discharging.[18]

3.1.5 Diffusion Capacitance

The diffusion process can be defined as the movement of chemical species (ions or molecules) under the influence of concentration difference. In the case of the battery, the electrolyte solution can be divided into three distinct parts: the bulk solution and the two diffusion layers at the surface of the electrodes. The concentration of the bulk solution can be assumed as uniform. The species transport in this layer occurs only through convection, while the mass transport in the diffusion layer is possible only through diffusion. The two diffusion layers carry opposite charges (negative and positive). The bulk electrolyte behaves like as dielectric. It means the combination of three layers produce capacitance effect that is known as diffusion capacitance. The time constant of the RC circuit due to the diffusion capacitance is much larger as compare to the double layer capacitance. It is in the range of hours. It depends on SOC, temperature.[16]

3.1.6 Double Layer Capacitance

Electrical double-layer capacitors are based on the operating principle of the electric double-layer that is formed at the interface between activated metallic surface (electrode) and an electrolyte. The electrodes are used in the solid form, and the electrolyte is the liquid form. When these materials come in contact with each other, the positive and negative poles are distributed relative to each other over an extremely short distance. Such a phenomenon is known as an electrical double-layer. When an external electric field is applied, the electrical double-layer is formed in the vicinity of the electrolyte surface and the electrolyte fluid surface. The physical behavior of double layer capacitance can be more precisely cascaded RC network. A single capacitance and resistance model of an electrochemical capacitor can be used in many applications like battery modeling. The time constant of RC circuit depends upon the surface area of the electrode, type of electrode, electrolyte etc. The voltage across this capacitor also contributes on the terminal voltage of the battery.[16]

3.1.7 Gassing Effect

During energy conversion process in the battery, not only main reaction takes place but side reactions also. If the battery is charged faster than its nominal charge rate, the battery is heated more in consequences hydrogen and oxygen gasses are produced in the positive and negative plates respectively [19], [20]. The cause of the gassing is that when the battery is charged faster, the energy conversion process can not be faster than its capacity so side reactions take place. The gassing phenomenon occurs even though the battery is charged by nominal rate. When the terminal voltage of the battery crossed the onset voltage (also known as gassing voltage), the gassing process starts. In electrical term, gassing phenomenon can be represented by the current known as the gassing current. As shown in fig. 2 when the battery charged, internal voltage increases correspondingly and terminal voltage too. The onset voltage can be compared to the forward bias voltage of a diode. As voltage across the diode crosses this value, gas current flows. With respect to the time, gas resistance decreases exponentially and the gas current increases exponentially. It means the main reaction current (Imr), which converts electrical energy to chemical energy, decreases correspondingly. Finally complete charging current becomes the gassing current. In this stage, further increment in the internal voltage is not possible.[16]

3.1.8 Voltage Recovery

After a battery has been subjected to a current, it takes some time for the voltage to return to the open-circuit value, due to the capacitance effects occurring between the plates of the battery.

For this battery model, the capacitance effects were approximated during discharge of the batteries as a constant voltage suppression. When the batteries were at rest, the capacitance effects are modeled using the solution to (4) and (6) for the case,

where the battery current *i(t)* is 0:

$$V_{co}(\text{Resting}) = V_{\text{initial}}\, e^{(-t/\tau)}$$

where τ (s) is equal to R_oC_o

3.2 Charging and discharging the battery:

3.2.1 Overview:

The quantity C is defined as the current that discharges the battery in 1 hour,so that the battery capacity can be said to be C Ampere-hours (units confusion)If we discharge the battery more slowly, say at a current of C/10, then we might expect that the battery would run longer (10 hours) before becoming discharged. In practice, the relationship between battery capacity and discharge current is not linear, and less energy is recovered at faster discharge rates.

Capacity, $C = I \times T$

Charging rate=$\frac{C}{t}$

3.3 Charging:

There are three stages of charging:

Bulk or Normal Charge: it is the first phase of the charging cycle, can be done at any charge rate. Bulk charging generally occurs up to between 80 and 90% state of charge.[3]

Float or Finishing Charge: after bulk or normal charge the battery is around 80% charged, most of the active material in the battery has been converted to its original form. Finish charging is usually conducted at low to medium charge rates.[3]

Equalizing Charge: in equalizing charge, after batteries are fully charged they are allowed to settle and the voltage is expected to become stable within that time . For batteries less severely discharged, equalizing may only be required every one or two months. An equalizing charge is typically maintained until the cell voltages and specific gravities remain consistent for a few hours.[3]

3.3.1 Charging circuit:

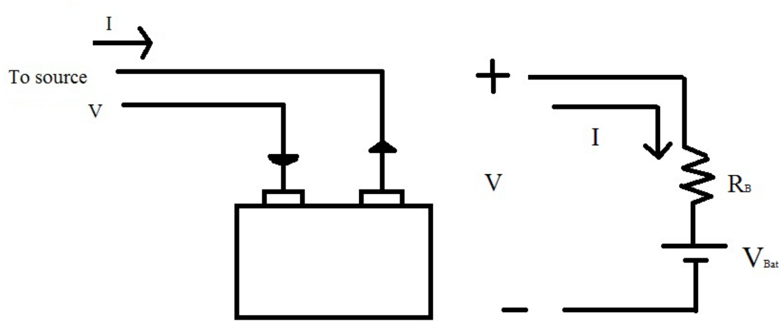


Fig 4: The charge flow path of the battery in charging mode.

$$V = V_{Bat} + IR_B$$

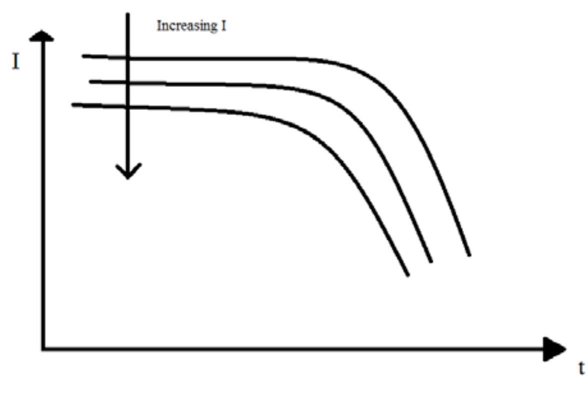


Fig 5: the I vs t charging graph

3.3.2 Experiment of battery charging:

Constant-voltage (often called constant-potential) chargers maintain nearly the same voltage input to the battery throughout the charging process, regardless of the battery's state of charge.

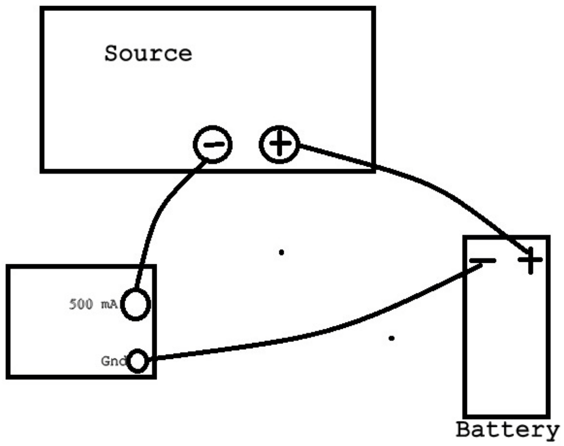


Fig 6: The simple circuit setup for battery charging without using a commercial recharger.

According to the setup of the diagram as shown in previous page, the open circuit voltage has to be measured in every 15 minutes interval by keeping a voltage constant on the power supply. The current maybe increased in the power supply from time to time to maintain constant voltage. Repeat until the open circuit voltage is almost 80% of the rated voltage. This part of the charging cycle was the bulk charging.

Repeat experiment but charge the battery at a constant current. Since the battery is bulk charged and approximately 80% charge is accumulated in the battery so after 15 minutes interval, take the open circuit voltage reading. Meanwhile, the voltage may have to be increased a little bit to keep the current constant. This part of the charging cycle was the float or finishing charging.

After that we kept the battery to settle down for 1 hour. This is the equalizing charge of the charging cycle where we simply wait for the battery to settle at a constant voltage.

3.4 Discharging:

Discharging is a very crucial step in this thesis because at the beginning of the experimenting the SOC is unknown and so caution has to be maintained so that one does not just over-discharge the battery and hinder the battery lifespan. Listed below are the few factors that must be taken into account when discharging the battery:

- **Depth of Discharge (DOD):** The depth of discharge (DOD) of a battery is defined as the percentage of capacity that has been withdrawn from a battery compared to the total fully charged capacity. By definition,the depth of discharge and state of charge of a battery add to 100 percent.[3]

- **State of Charge (SOC):** The state of charge (SOC) is defined as the amount of energy in a battery, expressed as a percentage of the energy stored in a fully charged battery. Discharging a battery results in a decrease in state of charge, while charging results in an increase in state of charge. A battery that has had three quarters of its capacity removed, or been discharged 75 percent, is said to be at 25 percent state of charge.[3]

- **Autonomy:** Generally expressed as the days of storage in a stand-alone PV system, autonomy refers to the time a fully charged battery can supply energy to the systems loads when there is no energy supplied by the PV array.[3]

- **Self-Discharge Rate:** In open-circuit mode without any charge or discharge current, a battery undergoes a reduction in state of charge, due to internal mechanisms and losses within the battery. Different battery types have different self-discharge rates, the most significant factor being the active materials and grid alloying elements used in the design [3].

3.4.1 Discharging Circuit

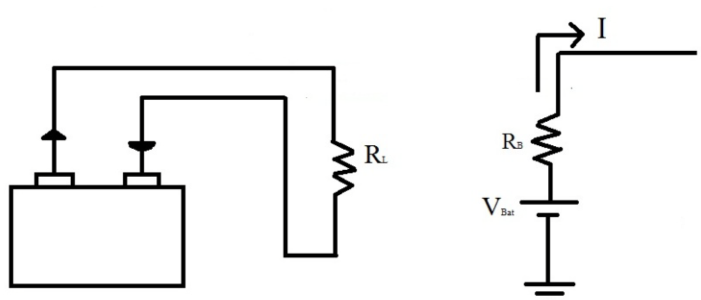


Fig 7: The charge flow path of the battery in discharging mode.

$$V = V_{Bat} - IR_B$$

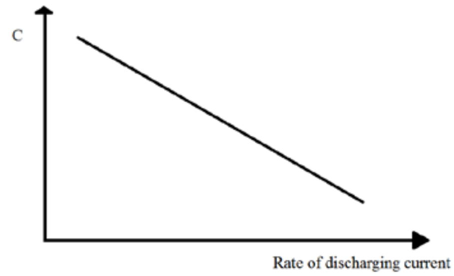


Fig 8: the I vs t discharging graph

3.4.2 Experiment of battery discharging:

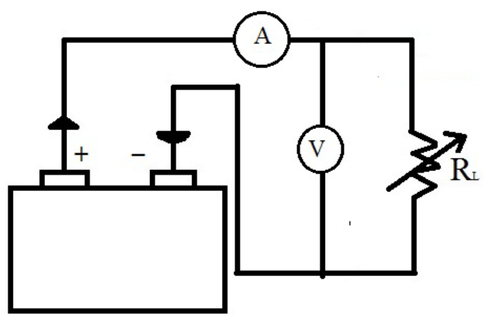


Fig 9: The simple circuit setup for battery discharging with a variable load.

According to the setup of the diagram, the fully charged battery is now assumed to have an SOC of 100% and is discharged by varying the current. To vary the current the load is changed and in every 1~2 minutes interval the terminal voltage is measured. After a suitable set of data is taken the battery is then discharged for a while at constant current and so that the SOC decreases exactly by 10%. The experiment is then repeated by decreasing SOC by 10% each time until the SOC is 30%.

Chapter 4

Types of Battery Models and Model Selection

4.1 Different types of battery model:

4.1.1 Simple Battery Model

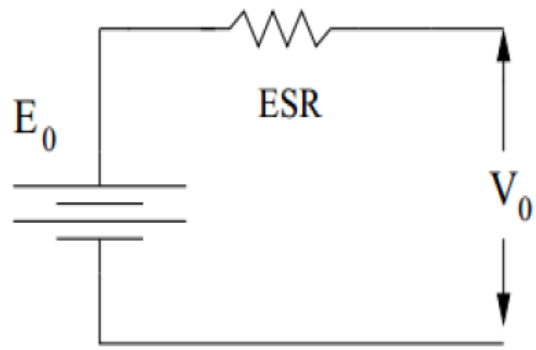


Fig 10: Equivalent circuit model of simple model

If battery was linear then it acts as an electric bipole. A simple ideal model consists of E0 as the electromotive force of the battery and a constant equivalent resistor ESR connected in series as an internal resistance.V0 is the terminal voltage of the battery [6]. V0 can be obtained by measuring the open circuit voltage and ESR can be obtained from both open circuit measurement and with load connected when the battery is fully charged.

4.1.2 Thevenin Battery Model

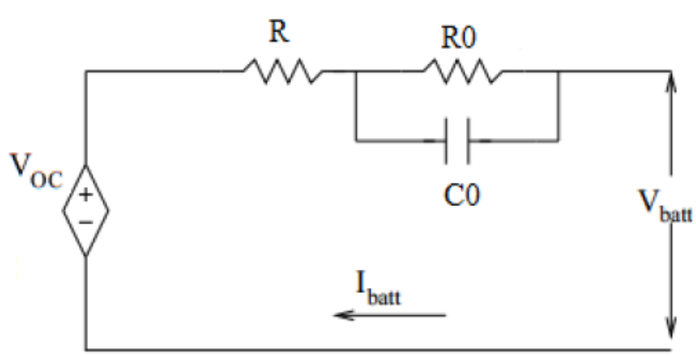


Fig 11: Equivalent circuit of Thevenin model [9]

Thevenin battery model is one of the most commonly used battery model. The model consists of ideal no-load battery voltage Voc, internal resistance (R), Capacitance (Co) and over voltage resistance (R0). Capacitance between electrolyte and electrodes is given by (C0) whereas R0 represents the battery overvoltage due to the contact resistance of plate to electrolyte [9].

$$V_{batt} = V_{oc} - (I_{batt}R + V_0)$$

$$V_0 = \left(\frac{1}{R_0} + \frac{1}{C_0}\right) I_{batt}$$

4.1.3 Dynamic Battery Model

This model is the modified Thevenin battery model. Similar to modified simple battery model it takes account the non linear characteristics of the open circuit voltage and the internal resistance [10].

The internal resistance is given by $\frac{k}{soc}$.

$$V_b = V_{oc} - \left(R_b + \frac{k}{soc}\right) I$$

Where, Vb is the terminal battery voltage, Voc is the open circuit voltage and Ri is the battery terminal resistor.

4.1.4 Copetti Model:

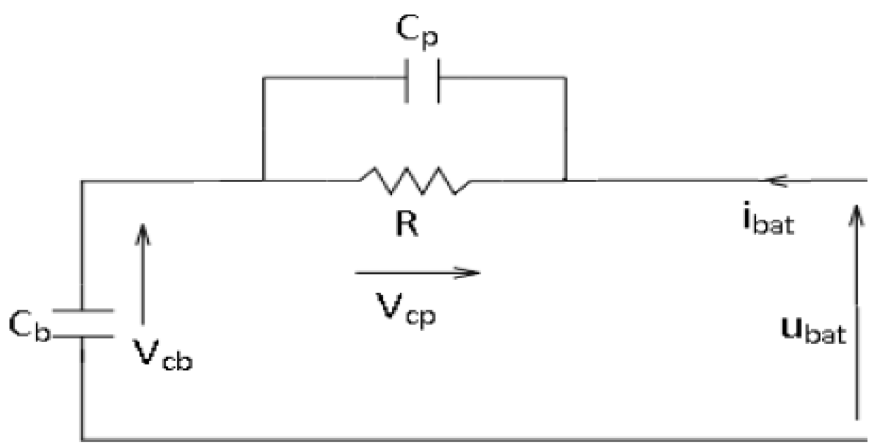


Fig 12: Equivalent circuit of Copetti model [11]

The model is a generic battery model with constant parameters that is valid for any size of the battery. This model is simple, because the experimental identification of empirical parameters is not required. The model is described by the following equation:

If $u_{bat} < n\,V_g$

$$u_{bat} = n\left(V_{cb}(t) + V_{cp}(t)\right)$$

$$\frac{dV_{cb}}{dt} = \frac{i_{bat}(t)}{C_b(t)}$$

$$\frac{dV_{cp}}{dt} = -\frac{1}{R(t)C_p}V_{cp} + \frac{i_{bat}(t)}{C_p}$$

If $u_{bat} > n\,V_g$

$$u_{bat}(t) = n\left(V_{cb}(t) + R(t)i_{bat}(t)\right)$$

$$SOC(t) = 1$$

$$V_{cb}(t) = 2.16\,V$$

With

$$R(t) = \frac{1}{C_{10}}\left(\frac{6}{1 + i_{bat}^{0.6}(t)} + \frac{0.48}{\left(1 - \left(\frac{V_{cb}(t) - 2}{0.16}\right)\right)^{1.2}}\right)$$

$$C_b(t) = \frac{1.67\,C_{10}}{1 + 0.67\left(\frac{i_{bat}(t)}{I_{10}}\right)^{0.9}}\frac{1}{n0.16}$$

$$I_{10} = \frac{C_{10}}{10}$$

Here, ibat is the battery current, ubat is the battery voltage, n is the number of the cells, Vg = 2.35V is the gassing voltage, Vcp is the polarization voltage, Vcb is the electromotive force, R is the internal resistance, Cp is the polarization capacitor,C10 is the nominal capacity and I10 is the charge current corresponding to C10.

4.1.5 Randle's Battery Model

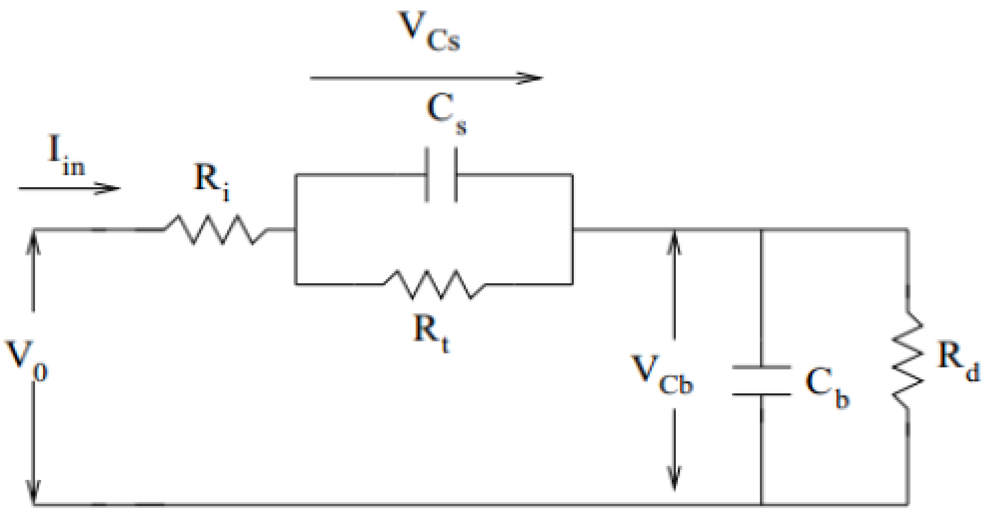


Fig 13: Equivalent circuit of Randle's model [12]

The fig 6 represents the Randle's model circuit where Ri is the resistance of the battery's terminals and inter-cell connections. Similarly, Rt and Cs describe transient effects due to shifting ion concentrations and plate current densities. While Rd represents the self-discharging resistance, Cb is considered the main charge store, and the voltage across it is the suitable indicator of SOC, whilst SOH can be inferred by any decrease in the value of Cb [12].

$$\dot{V_{cb}} = \frac{I_{in} R_d - V_{cb}}{C_b R_d}$$

$$\dot{V_{cs}} = \frac{I_{in} R_t - V_{cs}}{C_s R_t}$$

A large time constants is involved with typical combinations of Cb and Rd, the accurate estimation of the exact values of these large components might hindrance the transient parameter variation. Thus, a structured subspace estimation model is used in which the time constant associated with the product CbRd is assumed to be large, hence neglected. Likewise, Rd is assumed to be sufficiently large so that a negligible current is drawn by the discharge resistance. The modified Randles model is then given by [10]:

$$\dot{V_{cb}} = \frac{I_{in}}{C_b}$$

$$\dot{V_{cs}} = -\frac{V_{cs}}{C_s R_t} + \frac{I_{in}}{C_s}$$

$$V_0 = V_{cs} + V_{cb} + I_{in} R_i$$

Where Cs, Rt ,Cb and Ri are the parameters to be estimated.

4.2 Electrochemical models:

The electrochemical models are based on the chemical processes that take place in thebattery. The models describe these battery processes in great detail. This makes thesemodels the most accurate battery models. However, the highly detailed description makesthe models complex and difficult to configure [13].

4.3 Electrical-circuit models:

The first electrical-circuit models were proposed by S.C. Hageman. He used simple PSpice circuits to simulate nickel-cadmium, lead-acid and alkaline batteries. The core of the models for the different types of batteries is the same:

- a capacitor represents the capacity of the battery,
- a discharge-rate normalizer determines the lost capacity at high discharge currents,
- a circuit to discharge the capacity of the battery,
- a voltage versus state-of-charge lookup table,
- a resistor representing the battery's resistance [13].

4.4 Analytical models:

Analytical models describe the battery at a higher level of abstraction than the electro-chemical and electrical circuit models. The major properties of the battery are modeled using only a few equations. This makes this type of model much easier to use than the electrochemical and electrical circuit models [13]. Below given are the two analytical battery models:

Peukert's law:

The simplest model for predicting battery lifetimes that takes into account part of the non-linear properties of the battery is Peukert's law. It captures the non-linear relationship between the lifetime of the battery and the rate of discharge, but without modeling the recovery effect. According to Peukert's law, the battery lifetime (L) can be approximated by:

$$C_p = I^k t$$

where:

C_p is the capacity at a one-ampere discharge rate, which must be expressed in A·h.

I is the actual discharge current relative to 1 ampere, which is then dimensionless.

t is the actual time to discharge the battery, which must be expressed in h.

Rakhmatov and Vrudhula:

Next to the extended Peukert's law, Rakhmatov and Vrudhula give a new analytical battery model in [14]. The model describes the diffusion process of the active material in the battery. The diffusion is considered to be one-dimensional in a region of length w. C(x, t) is the concentration of the active material at time t and distance x ϵ [0,w] from the electrode. To determine the battery lifetime one has to compute the time at which the concentration at the electrode surface, C(0, t), drops below the cutoff level C_{cutoff} [13].

4.5 Battery Model selection:

4.5.1 Model Selection

Modeling and simulation are important for electrical system capacity determination and optimum component selection. The battery model is an important part of electrical system simulation so the battery model needs to have high fidelity to achieve meaningful simulation results. So, a model based approach is used in the project to estimate the status of the battery. Hence a suitable mathematical model was to be introduced that can characterize the battery.

First of all, from the experiment various discharge tests were performed in the battery and the data's were recorded to examine the characteristic of the battery. Then, these data's recorded were used to find the approximate model of the system. Secondly, from the literature various models were researched and analyzed. Then the models were simulated with the parameters given in the research papers. Then a comparative study was done between the graph obtained from the experimental data and from the models. Finally, an appropriate model was chosen based on the comparative study. Our final model must give the approximate output as the experimental data and the key output such as terminal voltage, cell temperature and state of charge of the battery.[21]

4.5.2. Simple Battery model

The simple battery model is an ideal battery model where the resistance is considered constant. The model fails to account the varying characteristics of the internal resistance of the battery with the state of charge, sulphate formation and electrolyte concentration. This type of model can be used only where the state of charge of battery is little important and battery plays very less role and energy drawn out the battery is assumed to be unlimited.[21]

4.5.3. Thevenin Battery Model

In Thevenin battery model all the elements are assumed to be constant. Therefore this model is limited due to its dynamic accuracy as this model does not take account into the state of charge.[21] This model can be used which do not consider the dynamic state of charge. Hence, it is not suitable for our project.

4.5.4. Simplified Battery model with constant voltage drop

Taking the simple battery model and the Thevenin model as a starting point, the resistance and capacitance is incorporated into the model and dynamic response is taken into consideration and a better simplified battery model is proposed which takes the internal voltage drop due to the capacitance effect into account. Thus for this model when the battery is discharged, the voltage recovery is observed and the equivalent transient equation for this voltage recovery is calculated which is discussed in the analysis part. This model suits our needs because we wanted to use a model that has the simplicity of the simple battery model but also takes the constant internal voltage drop due to the capacitance effect of the battery into account so we will be using this model.

The basic model uses a voltage source and resistor in series, with both values varying with respect to the state of charge (SOC) of the battery. The model starts with a requested power value P(W), which is related to voltage and current as:

$$P = V_t * I \quad (1)$$

Where, V_t (V) is the voltage measured at the terminals and I(A) is the battery current. The measured voltage is the open-circuit voltage V_{OC} (V) minus the voltage decrease caused by the effective internal resistance R (Ω) of the battery pack:

$$V_t = V_{OC} - IR \quad (2)$$

Where, V_{OC} is determined by the SOC of the battery, which in turn can be tracked by counting the ampere-hour extracted from the battery. Equations (1) and (2) can be solved to find the current:

$$I = \frac{\mathrm{VOC} - \sqrt{\mathrm{VOC}^2 - 4RP}}{2R} \quad (3)$$

Once the current is known, the measured terminal voltage of the batteries can be determined using (2).

The previous battery model doesn't take the constant voltage drop and the dynamic response of the battery which is influenced by the capacitive effects of the battery plates and by the charge-transfer resistance into the account. In the model that we are developing there is a constant internal voltage drop. From (2) we get,

$V_t = V_{OC} - V_d - IR$ (4)

And from this V_t we get

$$I = \frac{VOC - Vd - \sqrt{(VOC - Vd)^2 - 4RP}}{2R} \quad (5)$$

Due to the variable resistance, described as R in the Thevenin model, the overall internal resistance of the batteries varies substantially with current magnitude.

The resistances also vary depending on whether the battery is charging or discharging, and there is an additional self-discharge resistance in parallel with the voltage source.

From (4) we can say that

$V_{OC} - V_t = V_d + IR$ (6)

Using this equation we can find our V_d and R by discharging the battery.

The above part was the battery model with constant voltage drop but if we recall the Thevenin model we are also taking the dynamic response into the account.

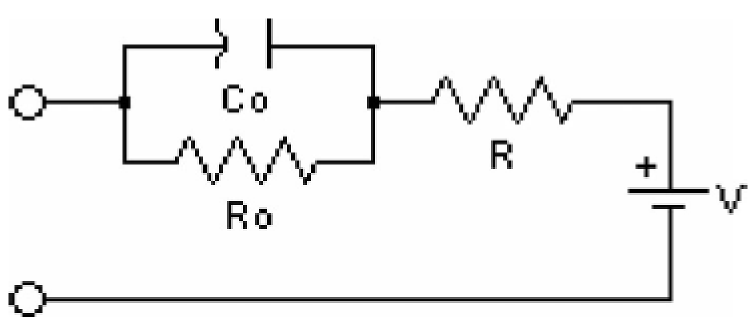


Fig 14: equivalent circuit model of simple model with constant voltage drop

The parallel RC-branch, comprising Ro and Co, is used to model this capacitive behavior. The voltage across the parallel resistor and capacitor is

$V_{Ro} = i_{Ro} Ro = V_{Co} = \int i_{Co}\, dt + V_{initial}$ (7)

where V_{Ro} and V_{Co} (V) are the respective voltages across the two elements; i_{Ro} and i_{Co} (A) are the respective currents; $V_{initial}$ (V) is the voltage across the capacitor Co at the start of whatever time period is under consideration; and t (s) is time. Ro (Ω) and Co (F) are the defining quantities for the resistor and capacitor shown in Fig. 1. As the elements are in parallel, they must have equal voltages; therefore, taking the derivative of both sides of (4) gives

$$i_{Co} = R_o C_o \frac{di_{Ro}}{dt} \qquad (8)$$

The sum of the currents i_{Ro} and i_{Co} must be equal to the battery current i(t); therefore

$$R_o C_o \frac{di_{Ro}}{dt} + i_{Ro} = i(t) \qquad (9)$$

Complicating this equation is the fact that Ro varies substantially based on the magnitude of the discharge current. This is due to the charge-transfer resistance of the electrochemical reaction; the rate at which electrons take part in the reaction (the charge transfer) is proportional to the current and this appears as a higher resistance at lower currents [11].

4.6 Experiments and Analysis of the Result:

4.6.1 Overview:

For this thesis, two Diamec 12V, 40 A-h batteries were used and some of the characteristics of the battery were found from the test. Experiments were carried out to and the data collected from the test were used to determine different parameters and then incorporated into the model.

Experimental data was analyzed find different battery parameters such as :

- Internal Resistance
- Open circuit Voltage
- Internal Voltage Drop
- Time constant for voltage recovery
- Capacity of the battery

The first 3 parameters were found for both charging and discharging of batteries.

Chapter 5

Experiments, Results and Analysis

5.1 EXPERIMENTS FOR DISCHARGING:

Experiment 1: Discharging the battery by its entire capacity to find battery parameters: R, V_{OC} and $V_{d.}$

Apparatus:

- A DC source
- Diamec Battery (12V 40 A-hr)
- Multimeters
- Rheostat
- Connecting wires

Circuit diagram:

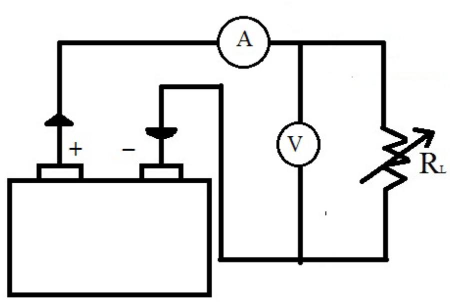


Fig :The simple circuit setup for battery discharging with a variable load.

Method:

The circuit was set up and the load was connected to discharge the battery. The experiment was carried out just as explained in the previous chapter and the battery was discharged for different current levels and Voc, Vt, I etc were recorded. For each set of data taken, 10% of the total capacity was discharged every time.

In this experiments, two Diamec batteries were used and both were discharged from a fixed SOC (presumably 100~90%) to 30% and the data was then fitted using the least square method using the following equations:

$$a = \frac{(\sum \mathrm{y})(\sum \mathrm{x}^2) - (\sum \mathrm{y})(\sum \mathrm{xy})}{n(\sum \mathrm{x}^2) - (\sum \mathrm{x})^2}$$

$$b = \frac{\mathrm{n}(\sum \mathrm{xy}) - (\sum \mathrm{x})(\sum \mathrm{y})}{n(\sum \mathrm{x}^2) - (\sum \mathrm{x})^2}$$

Where, a is the Resistance of the battery and

b is the internal voltage drop of the battey.

Results and Analysis:

The graphs below show how the terminal voltage varies with current and that the slope of this graph gives internal resistance R and the y-intercept gives the internal voltage drop.

The conditions for this experiments was that the SOC was decreased by 10% each time.

The graphs below illustrates the data taken from the battery.

V_{OC}-V_t Vs Battery Current

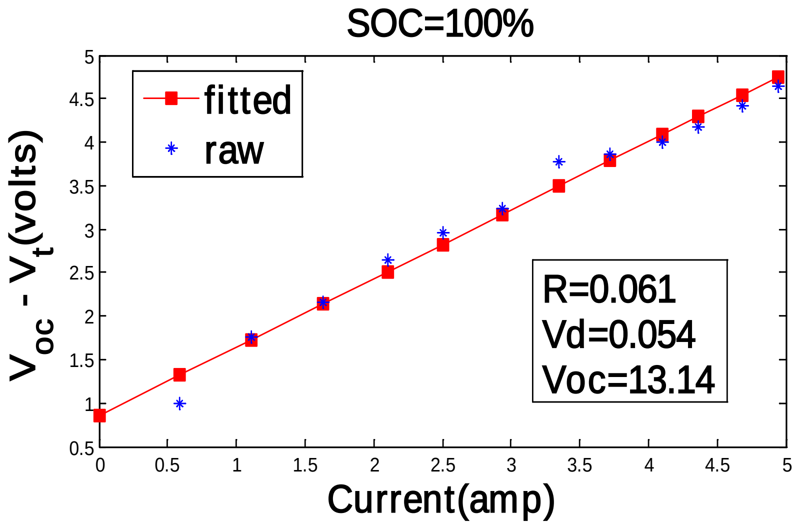


Fig 15: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 100% SOC and r.t.p

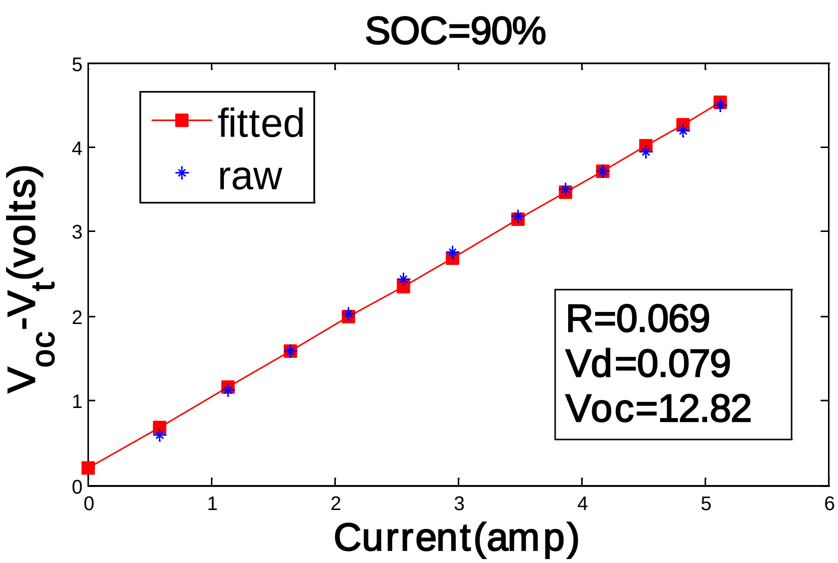


Fig 16: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 90% SOC and r.t.p

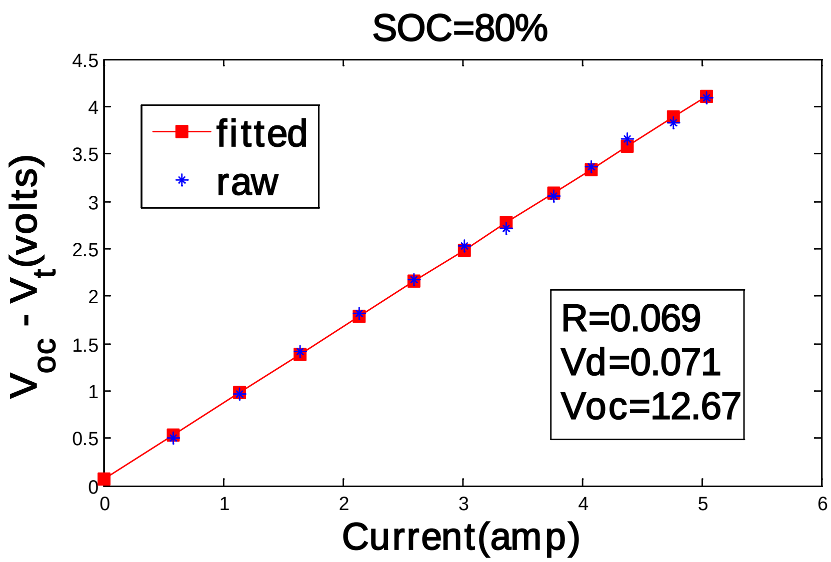


Fig 17: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 80% SOC and r.t.p

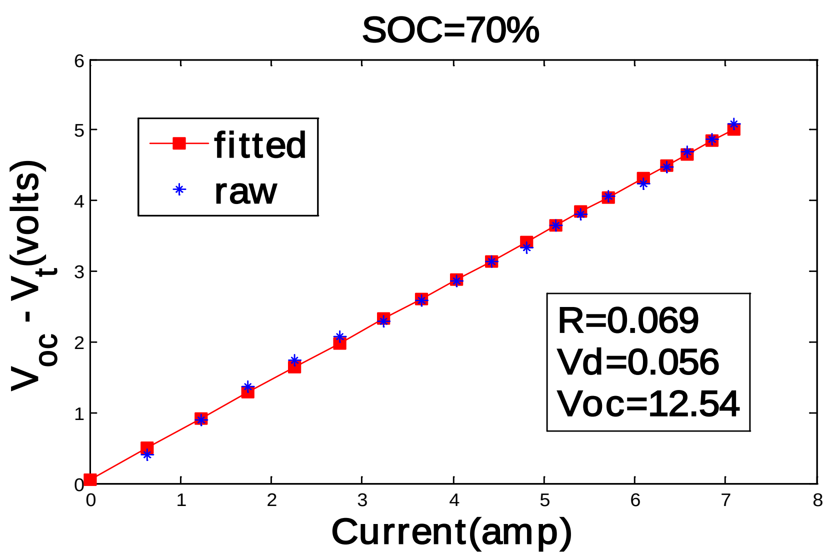


Fig 18: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 70% SOC and r.t.p

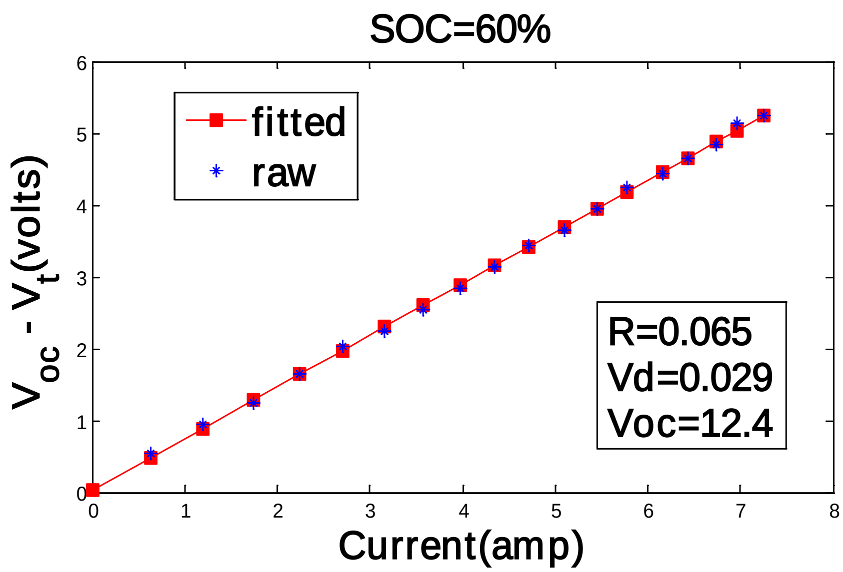


Fig 19: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 60% SOC and r.t.p

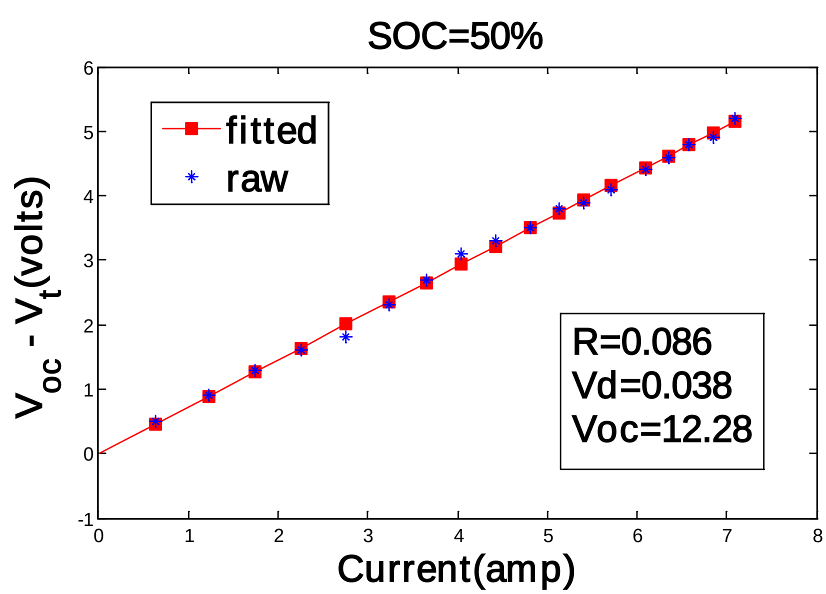


Fig 20: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 50% SOC and r.t.p

Experiment 2: Discharging the battery by its entire capacity to find battery parameters: τ

Apparatus:

- A DC source
- Diamec Battery (12V 40 A-hr)
- Multimeters
- Rheostat
- Connecting wires

Circuit diagram:

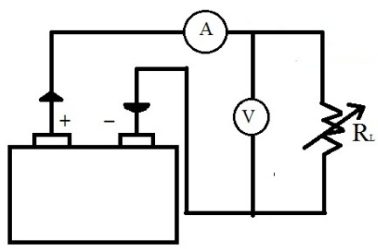


Fig : The simple circuit setup for battery discharging with a variable load.

Method:

The circuit was set up and the load was connected to discharge the battery. The experiment was carried out just as explained in the previous chapter and the battery was discharged for different current levels. After a while the load was disconnected and the battery was given time to return to its open circuit voltage. This way data of the terminal voltage and the time was recorded. For each set of data taken, 10% of the total capacity was discharged every time.

In this experiment, two Diamec batteries were used and both were discharged from a fixed SOC (presumably 100~90%) to 30% and the data was then fitted using the exponential method using the following equations:

$$a = \frac{(\sum y)(\sum x^2) - (\sum y)(\sum xy)}{n(\sum x^2) - (\sum x)^2}$$

$$b = \frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2}$$

Where, a is the internal voltage drop of the battery and

b is the time constant τ of the battery

Results and Analysis:

The graphs below show how the terminal voltage varies with time and from the exponential fitting we can find the internal voltage drop and the time taken for the

The conditions for this experiments was that the SOC was decreased by 10% each time.

The graphs below illustrates the data taken from the battery.

V_{OC}-V_t Vs Time

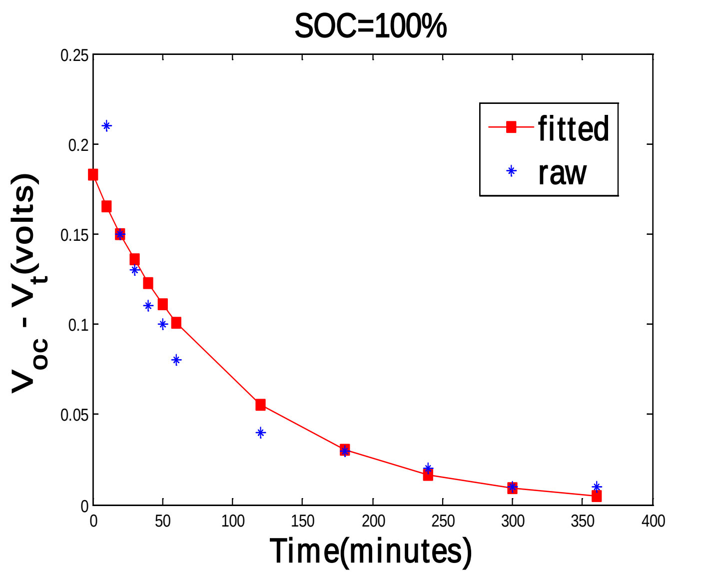


Fig 21: graph of difference between open circuit voltage and terminal voltage that is varying with time at 100% SOC and r.t.p

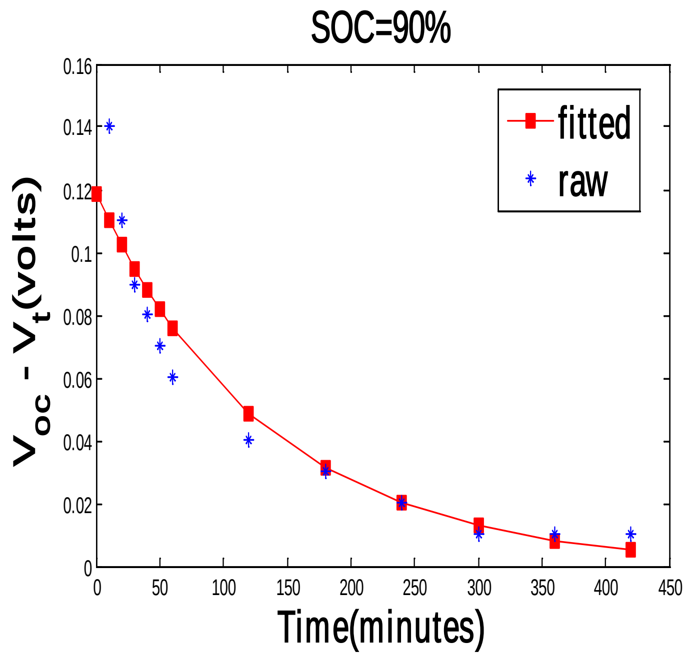


Fig 22: graph of difference between open circuit voltage and terminal voltage that is varying with time at 90% SOC and r.t.p

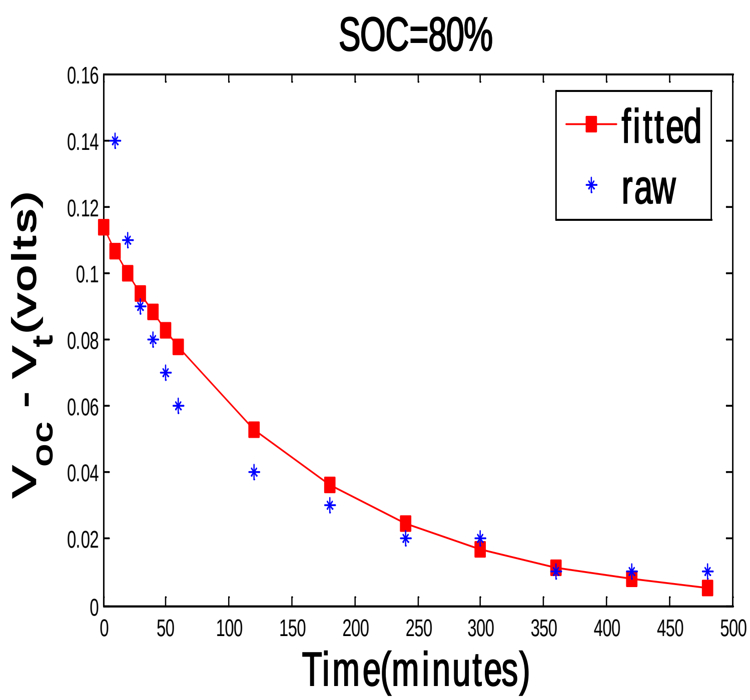


Fig 23: graph of difference between open circuit voltage and terminal voltage that is varying with time at 80% SOC and r.t.p

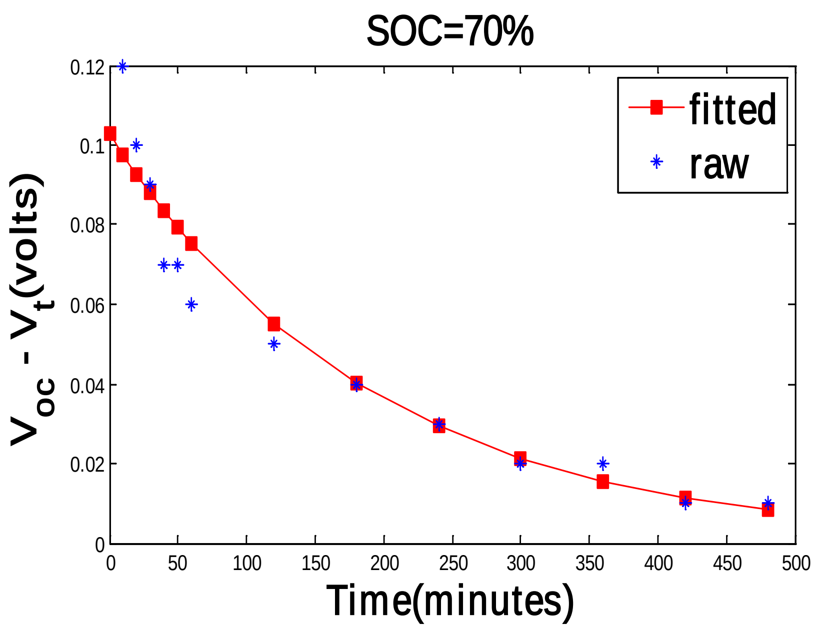


Fig 24: graph of difference between open circuit voltage and terminal voltage that is varying with time at 70% SOC and r.t.p

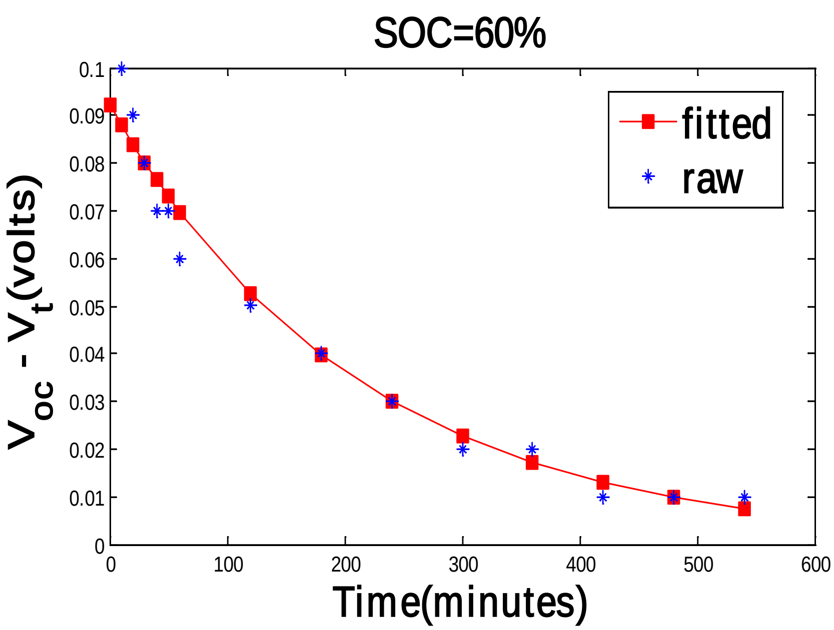


Fig 25: graph of difference between open circuit voltage and terminal voltage that is varying with time at 60% SOC and r.t.p

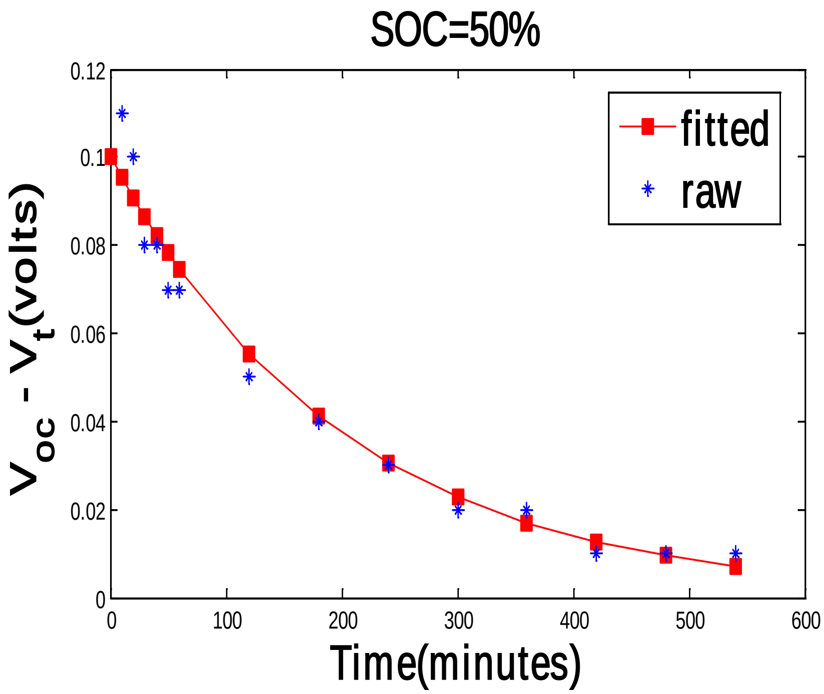


Fig 26: graph of difference between open circuit voltage and terminal voltage that is varying with time at 50% SOC and r.t.p

Summary of the experiment Results:

From the graphs the y intercept and x intercept was found and were plotted against SOC to find a relationship between V and SOC and R and SOC, τ and SOC etc.

To do so, data from the voltage vs battery current and voltage vs time graphs was extracted and then using least square fitting the following graphs were plotted.

Results and Analysis:

The graphs were as follows:

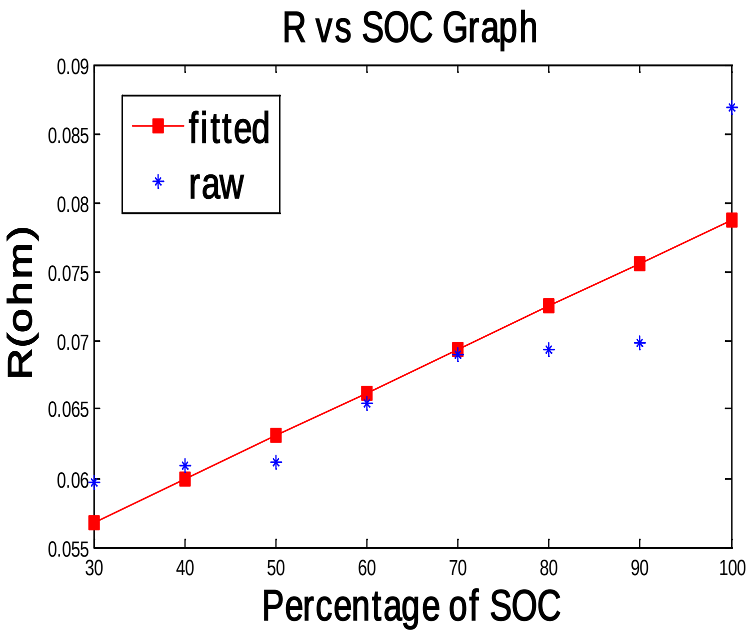


Fig 27: graph of R varying with SOC at r.t.p

The equation obtained from the least square fitting method that shows the relationship between R and SOC is as follows:

$$R(SOC) = 0.031 * SOC + 0.047$$

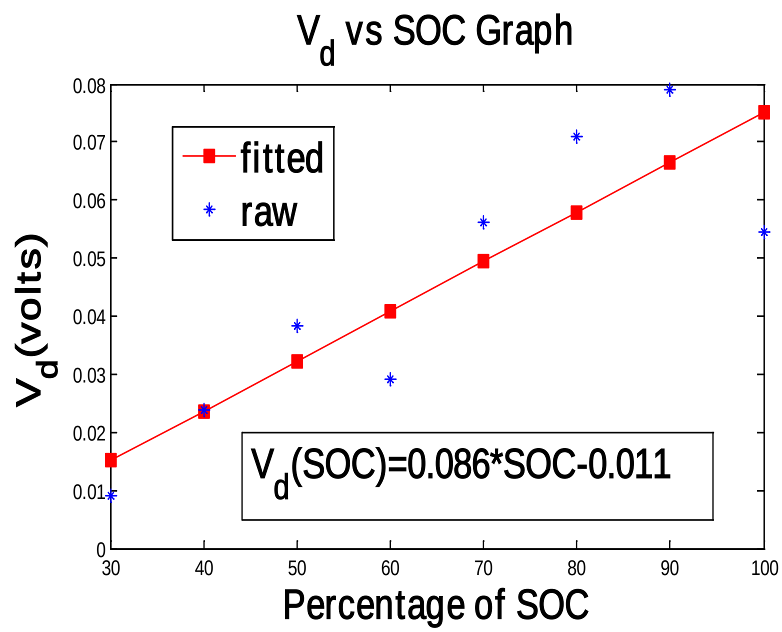


Fig 28: graph of V_d varying with SOC at r.t.p

The equation obtained from the least square fitting method that shows the relationship between V_d and SOC is as follows:

$V_{drop}(SOC) = 0.086 * SOC - 0.011$

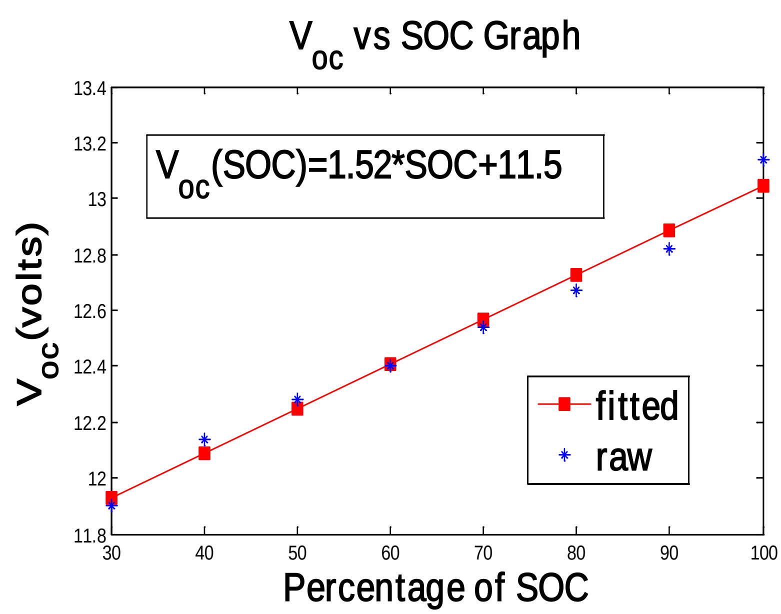


Fig 29: graph of V_{OC} varying with SOC at r.t.p

The equation obtained from the least square fitting method that shows the relationship between V_{OC} and SOC is as follows:

$$V_{oc}(SOC) = 1.52 * SOC + 11.5$$

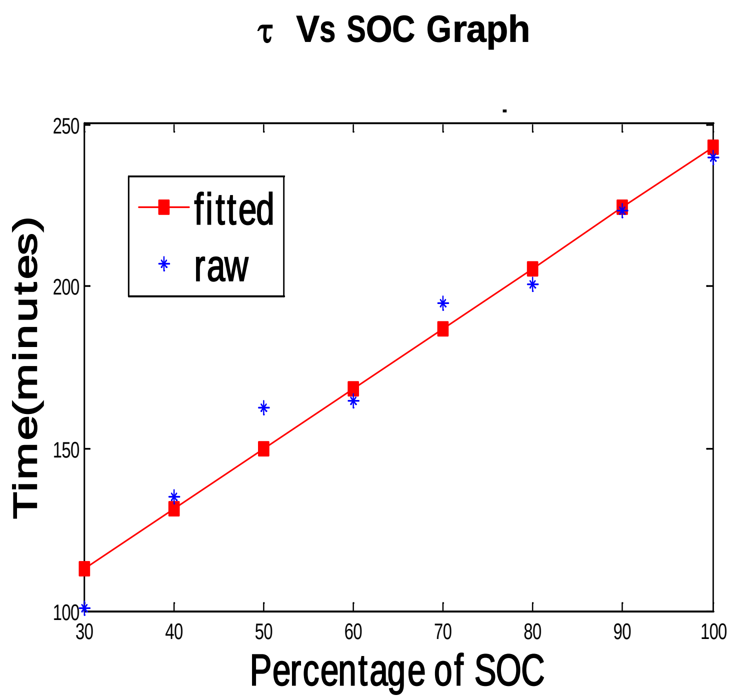


Fig 30: graph of τ varying with SOC at r.t.p

The equation obtained from the least square fitting method that shows the relationship between τ and SOC is as follows:

$$\tau(SOC) = 185 * SOC + 57.1$$

From all the above equations, an overall equation to find V_t is obtained:

$$V_t = V_{oc}(SOC) - V_{drop}(SOC) - I * R(SOC)$$

5.2 EXPERIMENT FOR CHARGING:

Experiment 1: Discharging the battery by its entire capacity to find battery parameters: R, V_{OC} and V_d.

Apparatus:

- A DC source
- Diamec Battery (12V 40 A-hr)
- Multimeters
- Rheostat
- Connecting wire

Circuit diagram:

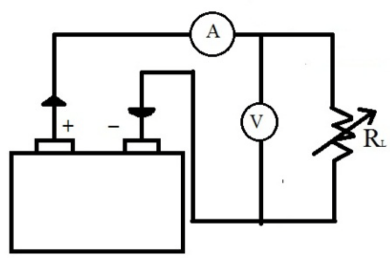


Fig : The simple circuit setup for battery discharging with a variable load.

Method:

The circuit was set up and the load was connected to discharge the battery. The experiment was carried out just as explained in the previous chapter and the battery was discharged for different current levels and Voc, Vt, I etc were recorded. For each set of data taken, 10% of the total capacity was discharged every time.

In this experiments, two Diamec batteries were used and both were discharged to 0% at the start of the experiment from a fixed SOC (presumably 100~90%) and then it charged back to its highest possible capacity and the data that was extracted was then fitted using the least square method using the following equations:

$$a = \frac{(\sum y)(\sum x^2) - (\sum y)(\sum xy)}{n(\sum x^2) - (\sum x)^2}$$

$$b = \frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2}$$

Where, a is the Resistance of the battery and

b is the internal voltage drop of the battery.

Results and Analysis:

The graphs below show how the terminal voltage varies with current and that the slope of this graph gives internal resistance R and the y-intercept gives the internal voltage drop.

The conditions for this experiment was that the SOC was increased by 10% each time.

The graphs below illustrates the data taken from the battery.

V_{OC}-V_t Vs Battery Current

For 2 Ampere:

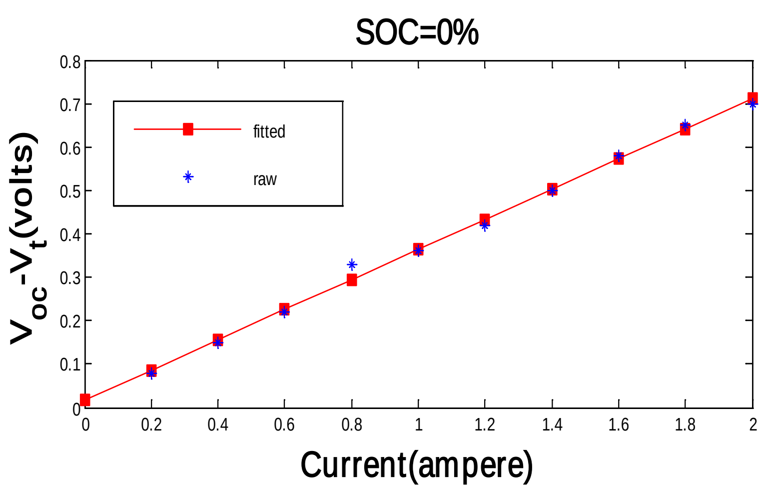


Fig 31: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 0% SOC and r.t.p

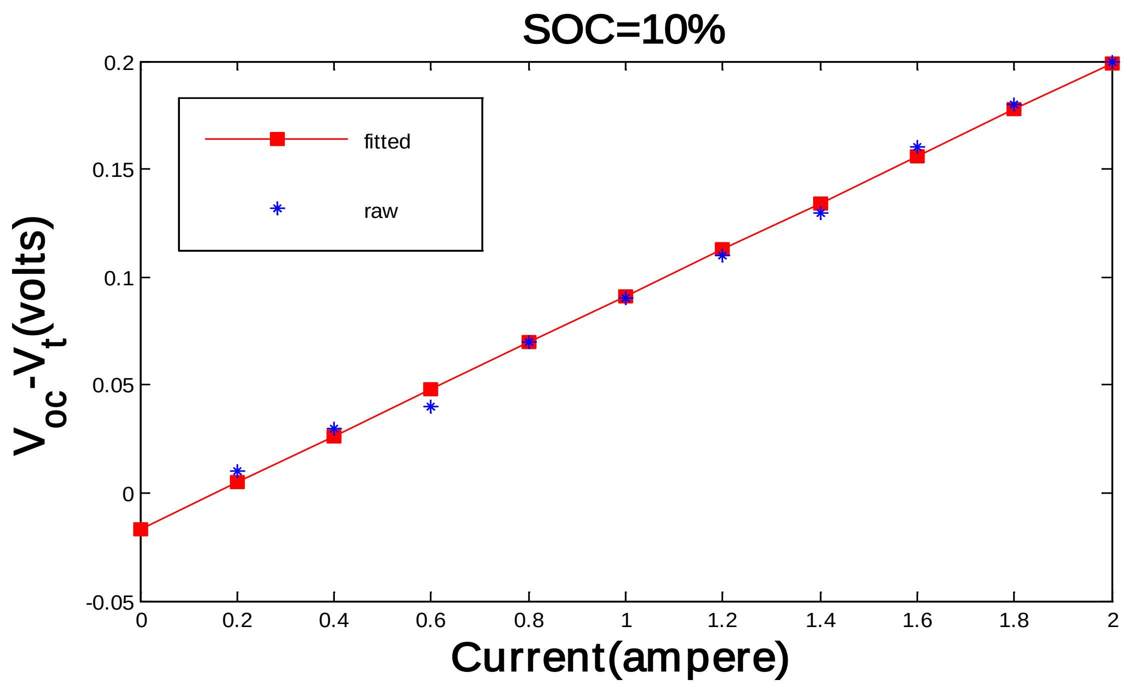


Fig 32: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 10% SOC and r.t.p

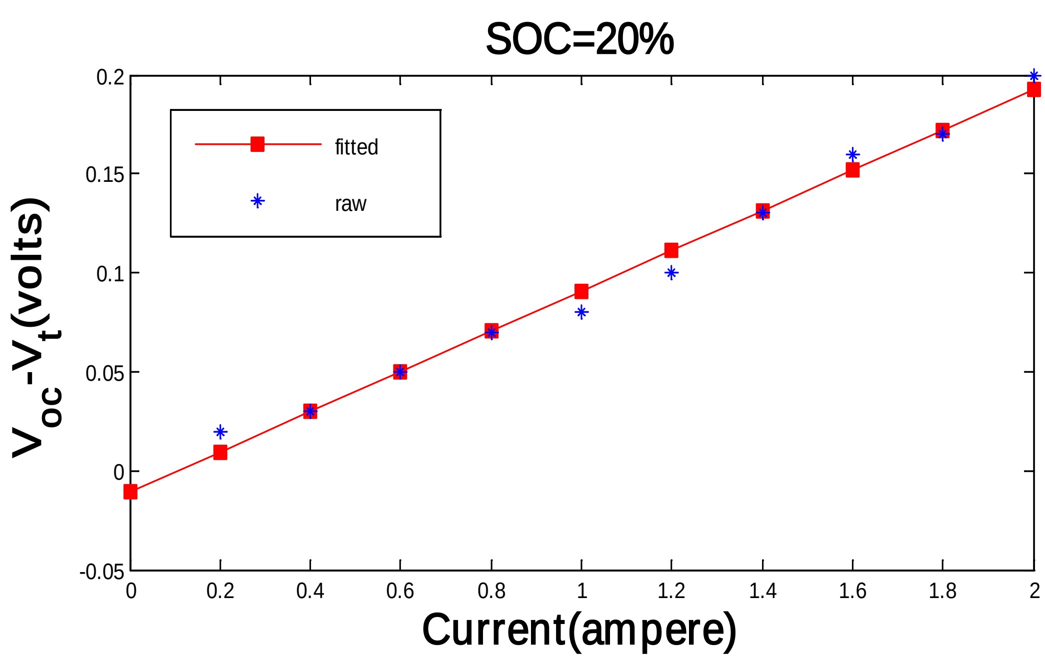


Fig 33: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 20% SOC and r.t.p

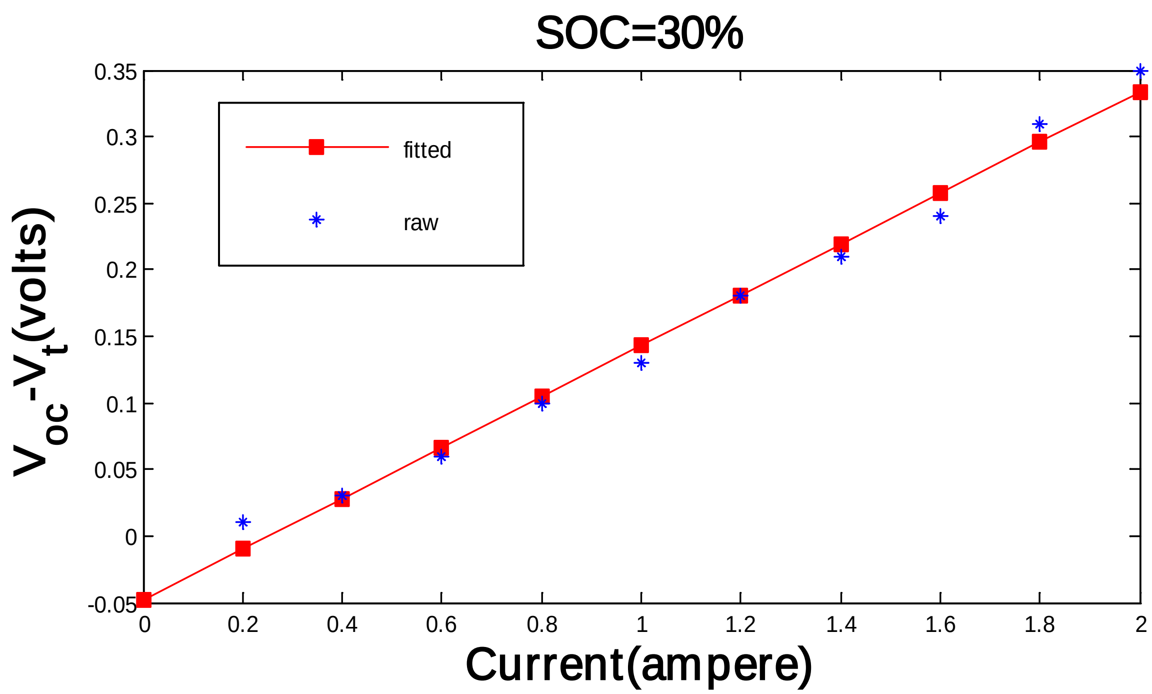


Fig 34: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 30% SOC and r.t.p

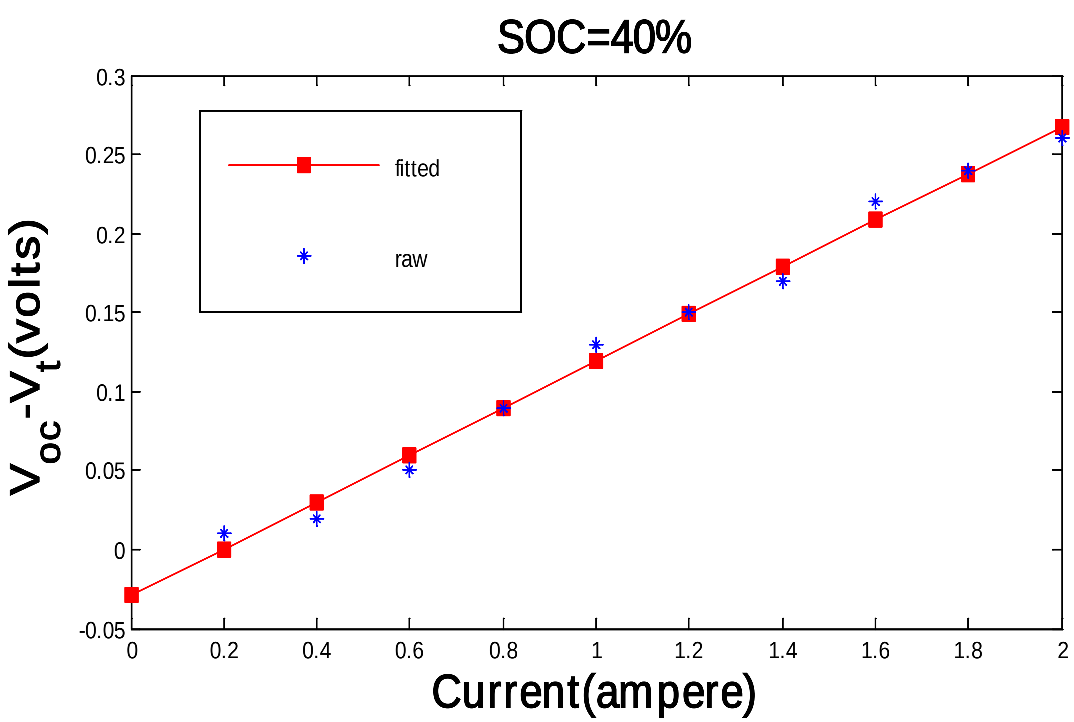


Fig 35: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 40% SOC and r.t.p

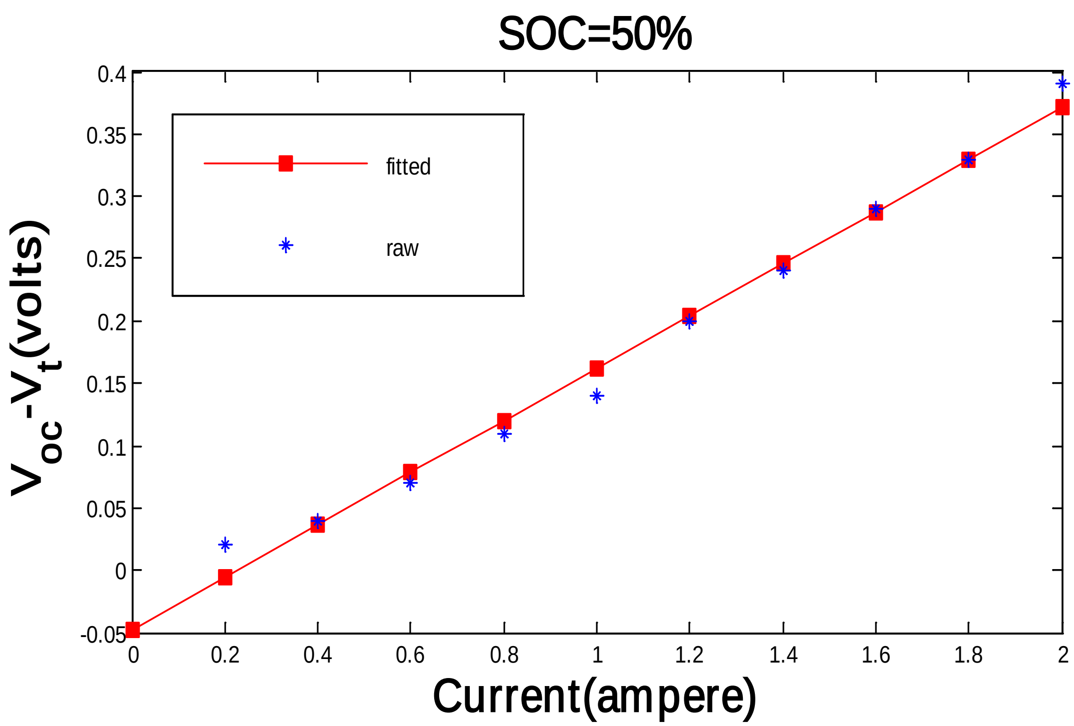


Fig 36: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 50% SOC and r.t.p

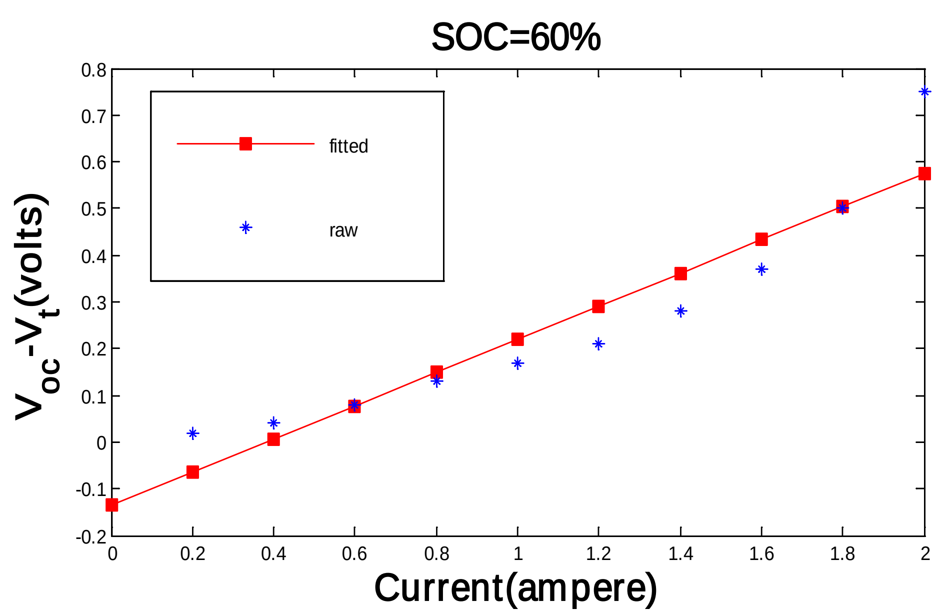


Fig 37: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 60% SOC and r.t.

And their corresponding R, V_d and V_{OC} graphs:

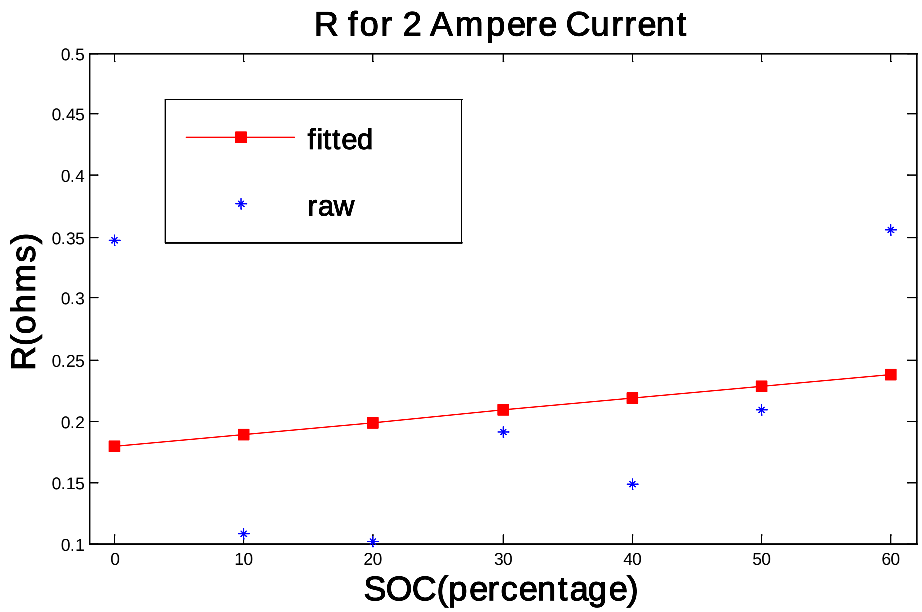


Fig 38: graph of R varying with SOC at r.t.p

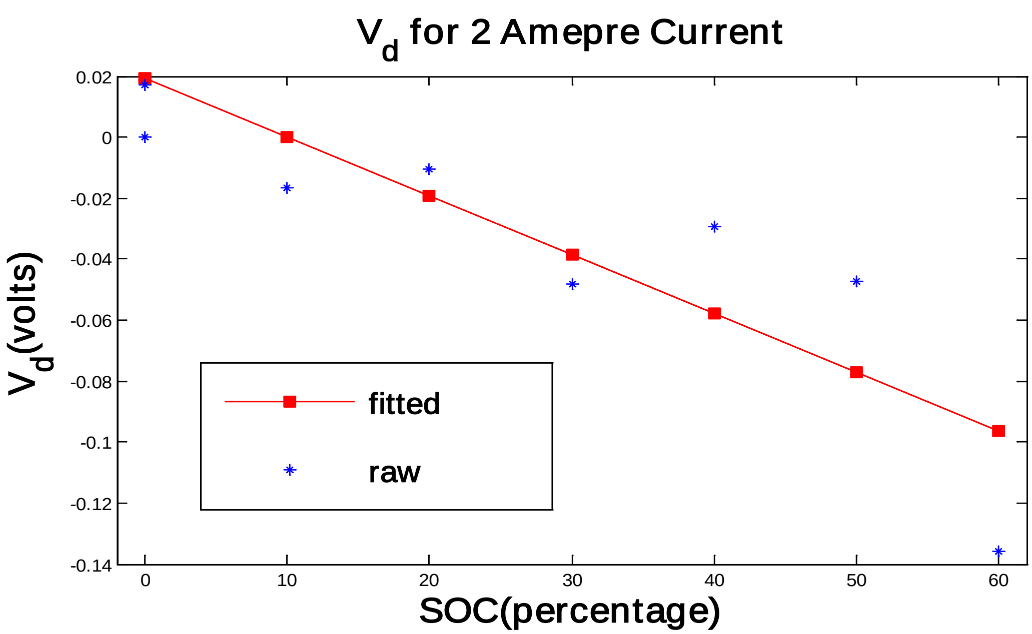


Fig 39: graph of V_d varying with SOC at r.t.p

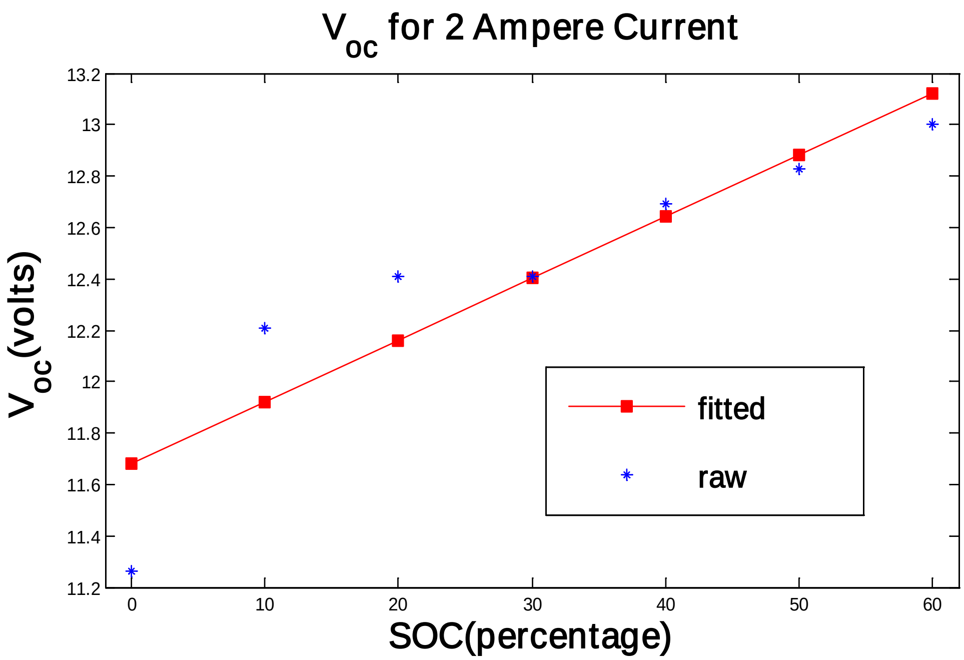


Fig 40: graph of V_{OC} varying with SOC at r.t.p

The Equations that were found using l;east square fitting from the graphs are:

For 2 Ampere

$$R(SOC) = \ 0.00098 * SOC + 0.179$$

$$Vd(SOC) = \ -0.00193 * SOC + 0.019$$

$$Voc(SOC) = \ 0.024 * SOC + 11.67$$

For 4 Ampere:

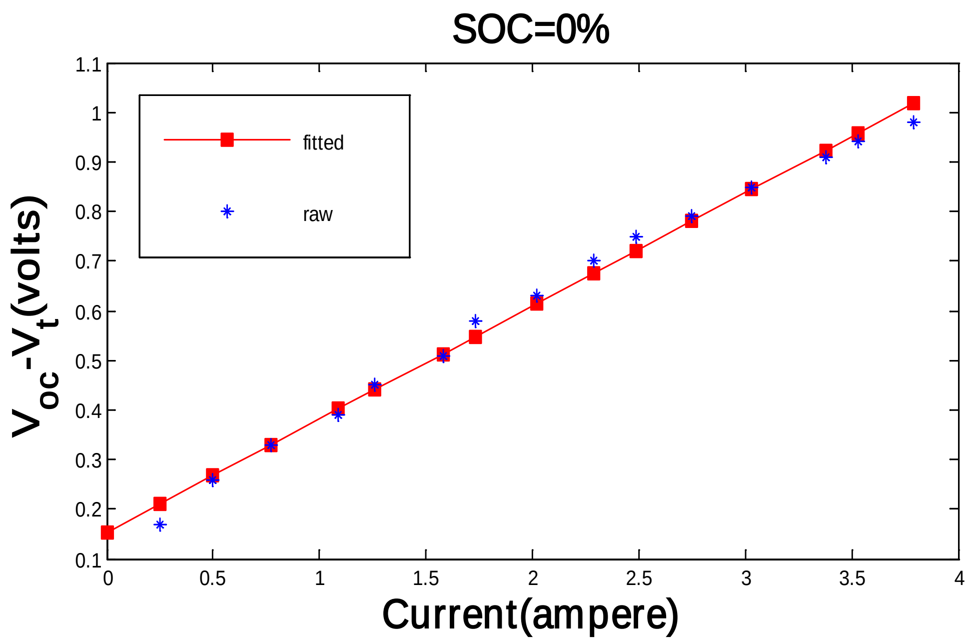


Fig 41: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 0% SOC and r.t.p

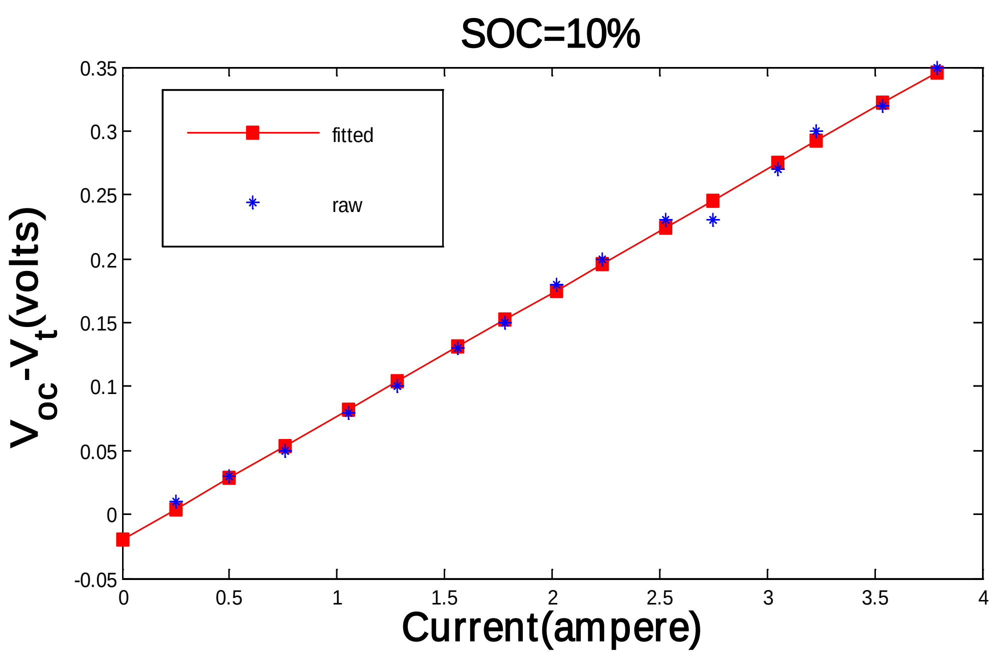


Fig 42: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 10% SOC and r.t.p

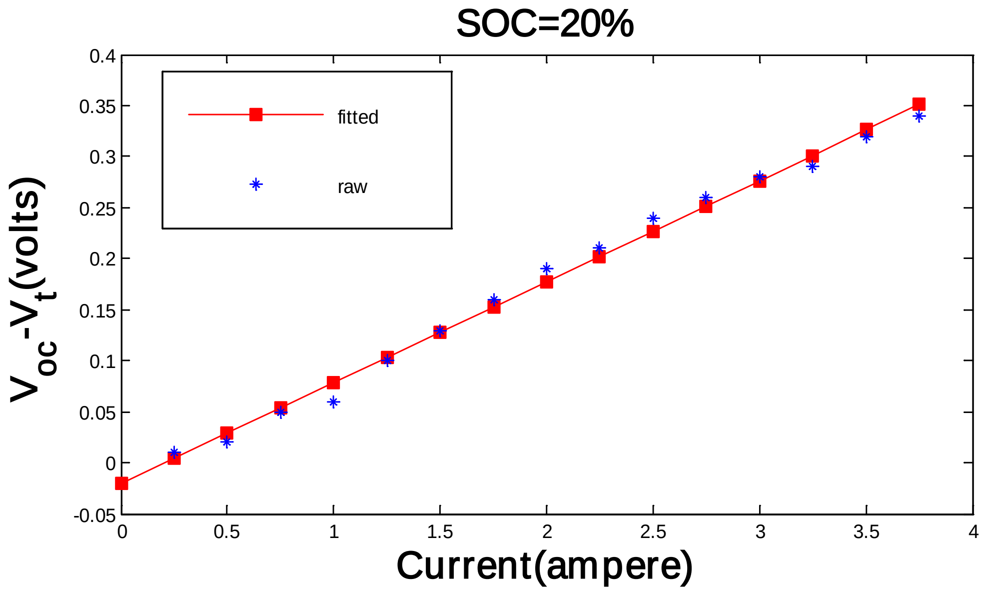


Fig 43: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 20% SOC and r.t.p

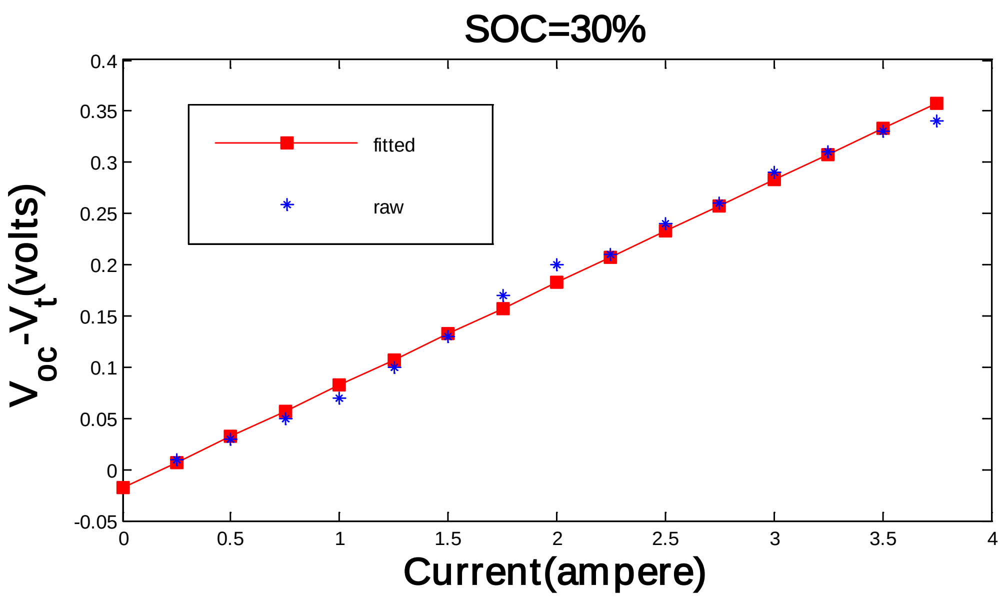


Fig 44: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 30% SOC and r.t.p

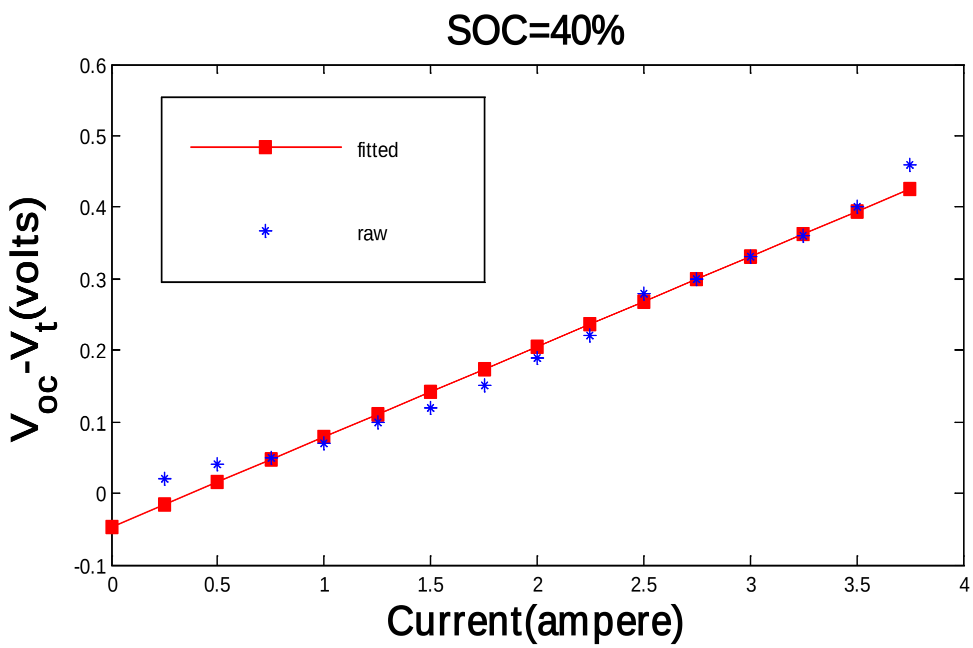


Fig 45: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 40% SOC and r.t.p

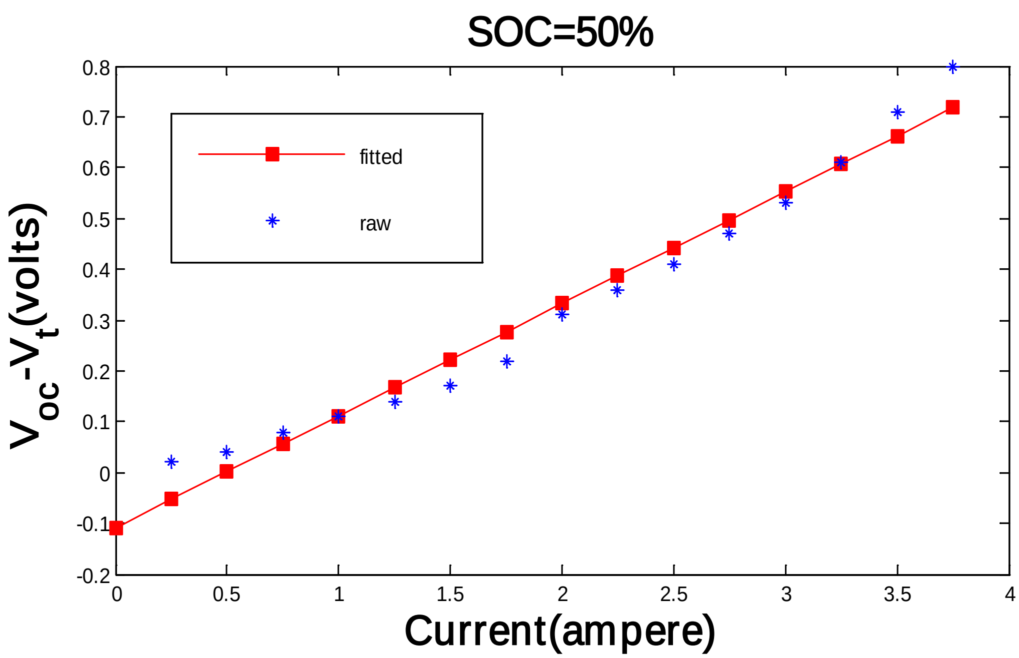


Fig 46: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 50% SOC and r.t.p

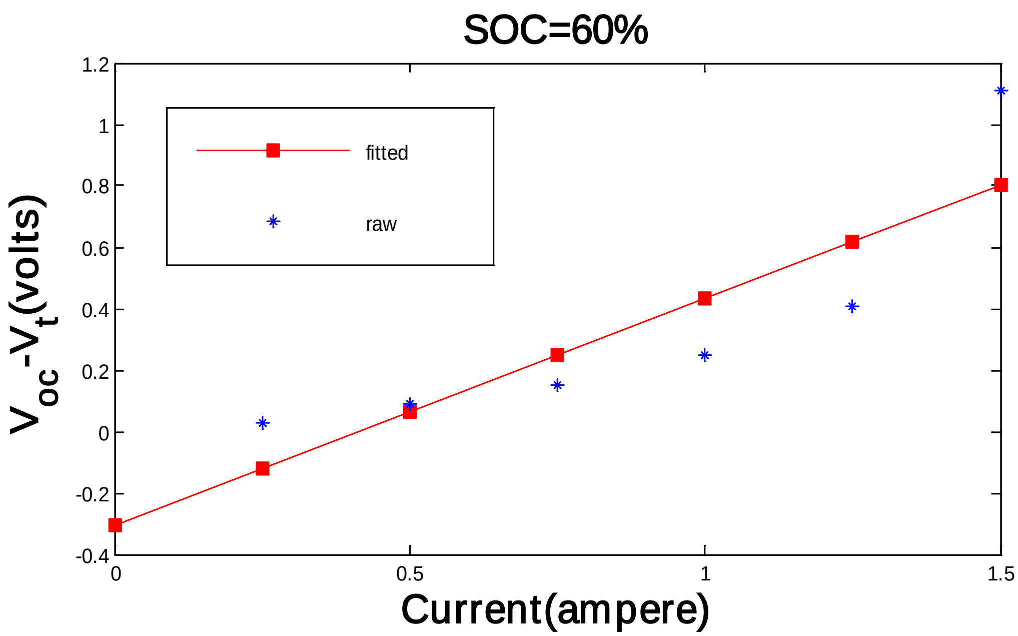


Fig 47: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 60% SOC and r.t.p

And their corresponding R, V_d and V_{OC} graphs:

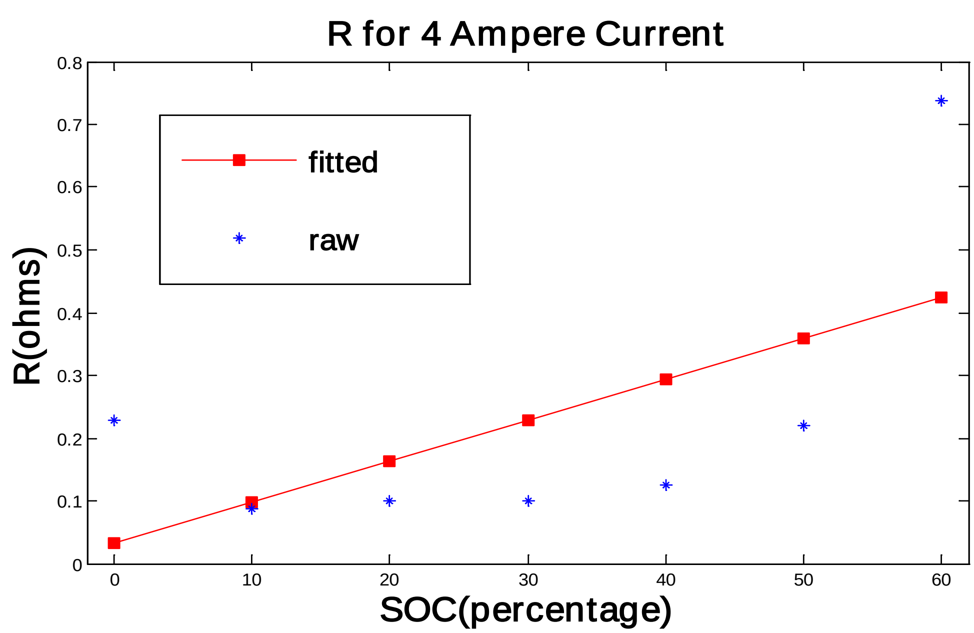


Fig 48: graph of R varying with SOC at r.t.p

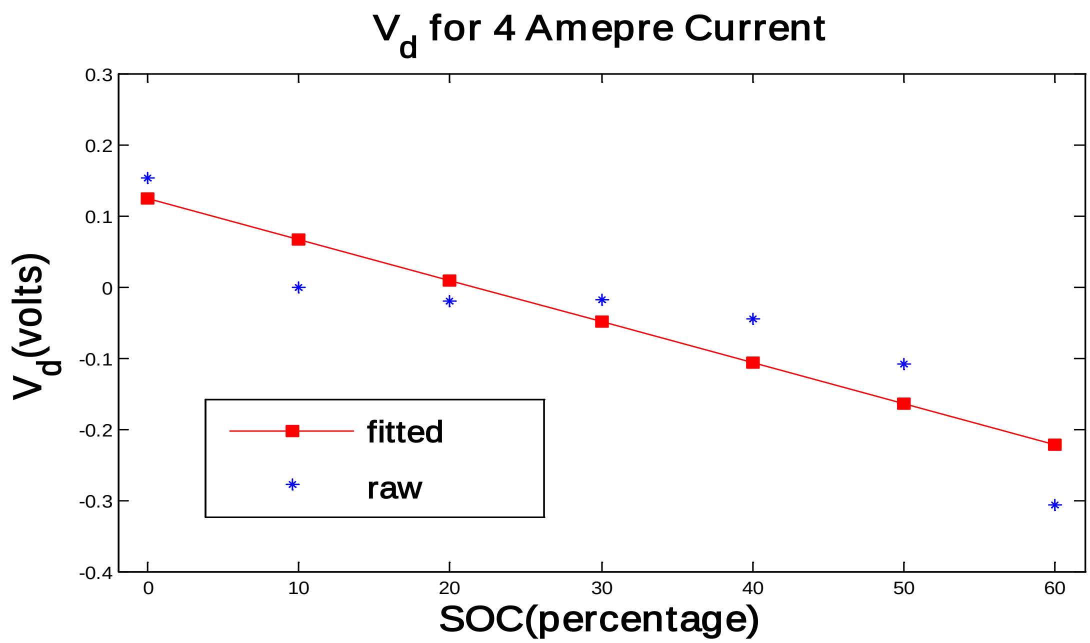


Fig 49: graph of V_d varying with SOC at r.t.p

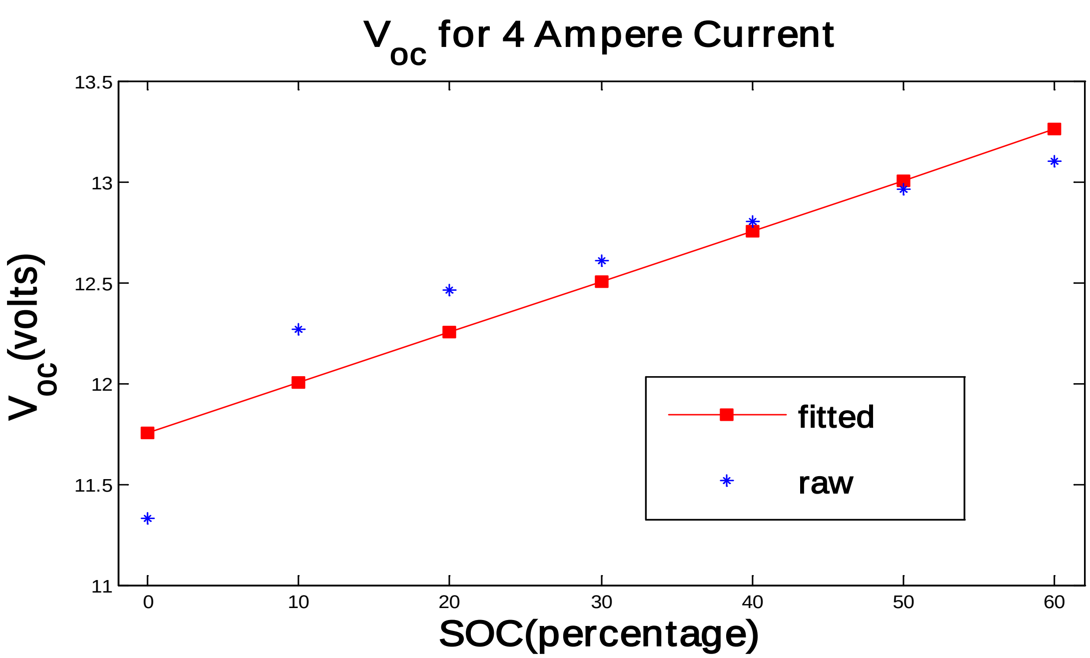


Fig 50: graph of V_{OC} varying with SOC at r.t.p

The Equations that were found using least square fitting from the graphs are:

For 4 Ampere

$$R(SOC) = 0.0065 * SOC + 0.03$$

$$Vd(SOC) = -0.0057 * SOC + 0.12$$

$$Voc(SOC) = 0.025 * SOC + 11.75$$

For 8 Ampere:

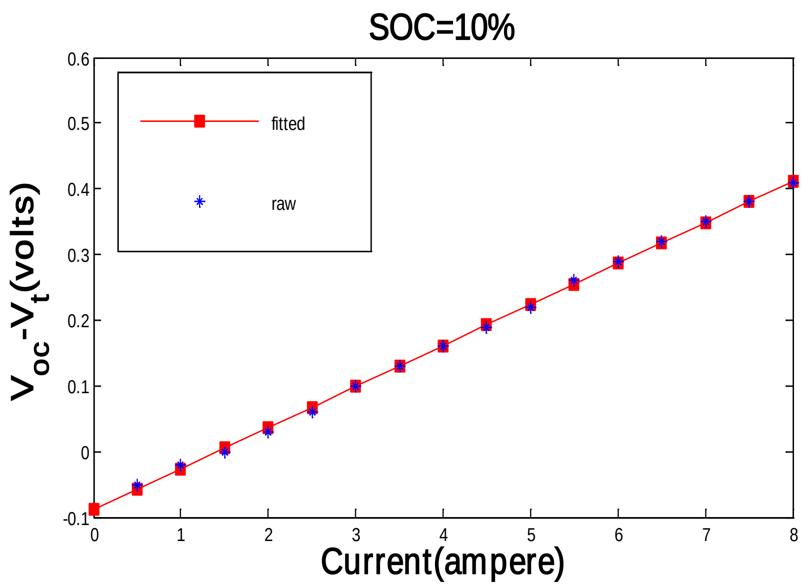


Fig 51: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 10% SOC and r.t.p

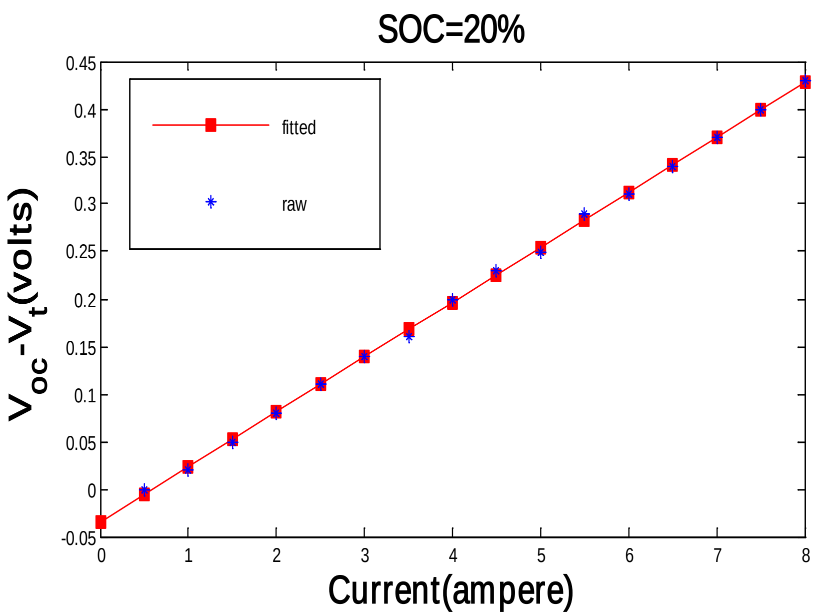


Fig 52: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 20% SOC and r.t.p

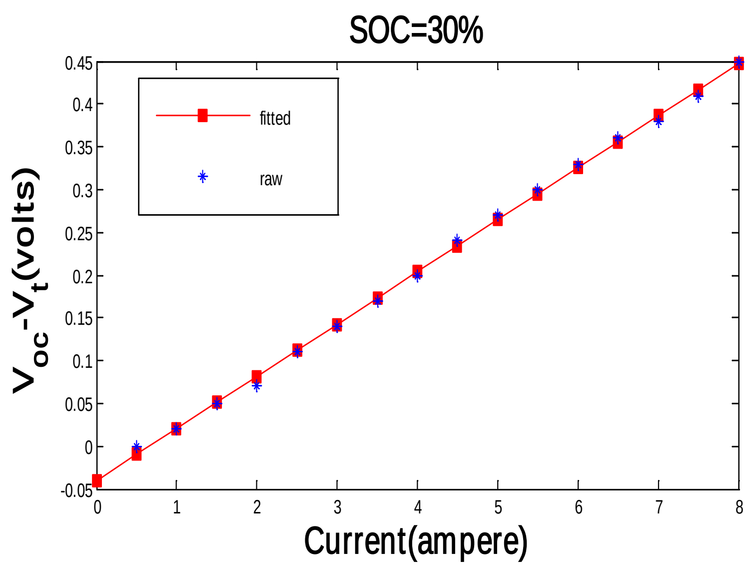


Fig 53: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 30% SOC and r.t.p

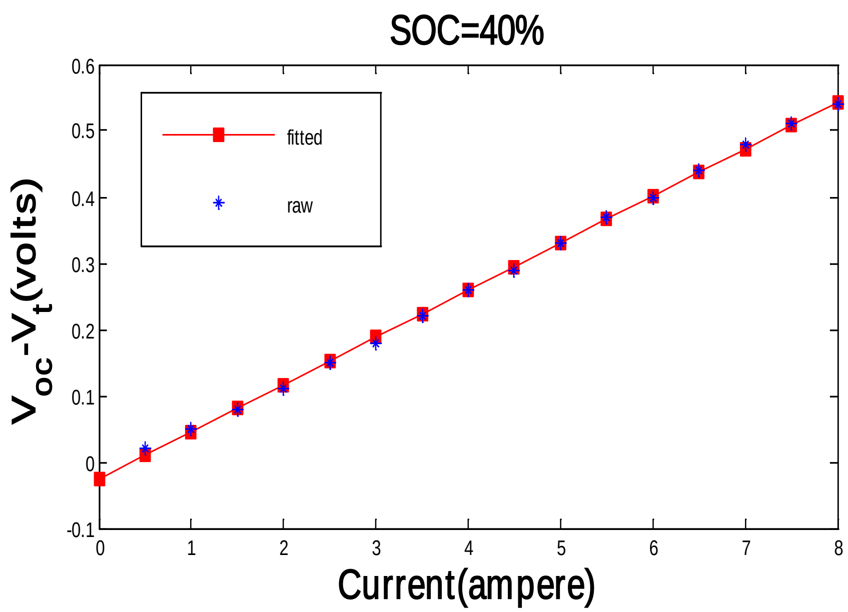


Fig 54: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 40% SOC and r.t.p

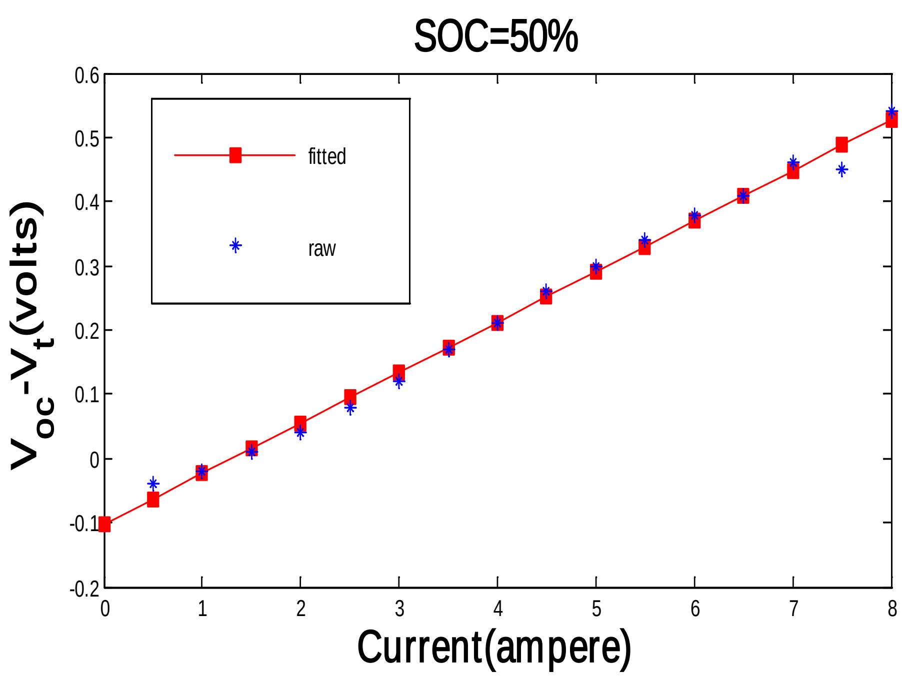


Fig 55: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 50% SOC and r.t.p

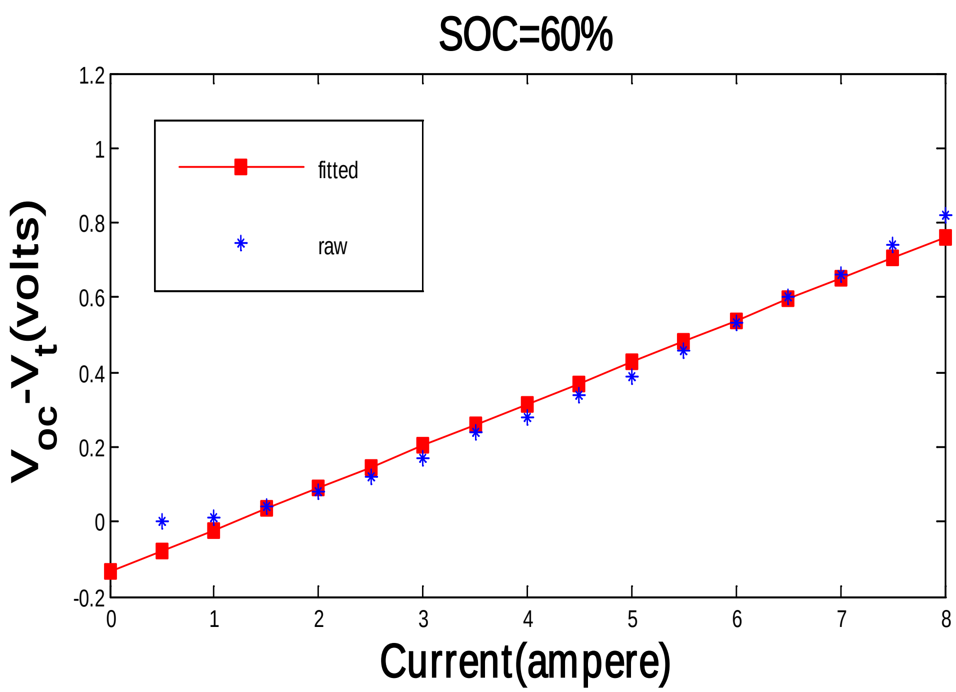


Fig 56: graph of difference between open circuit voltage and terminal voltage that is varying with battery current at 60% SOC and r.t.p

And their corresponding R, Vd and VOC graphs:

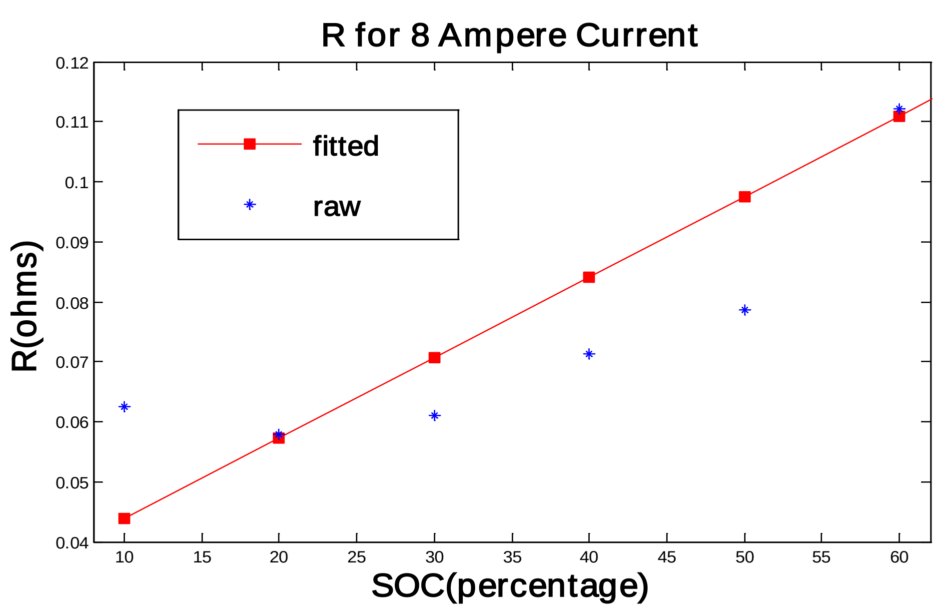


Fig 57: graph of R varying with SOC at r.t.p

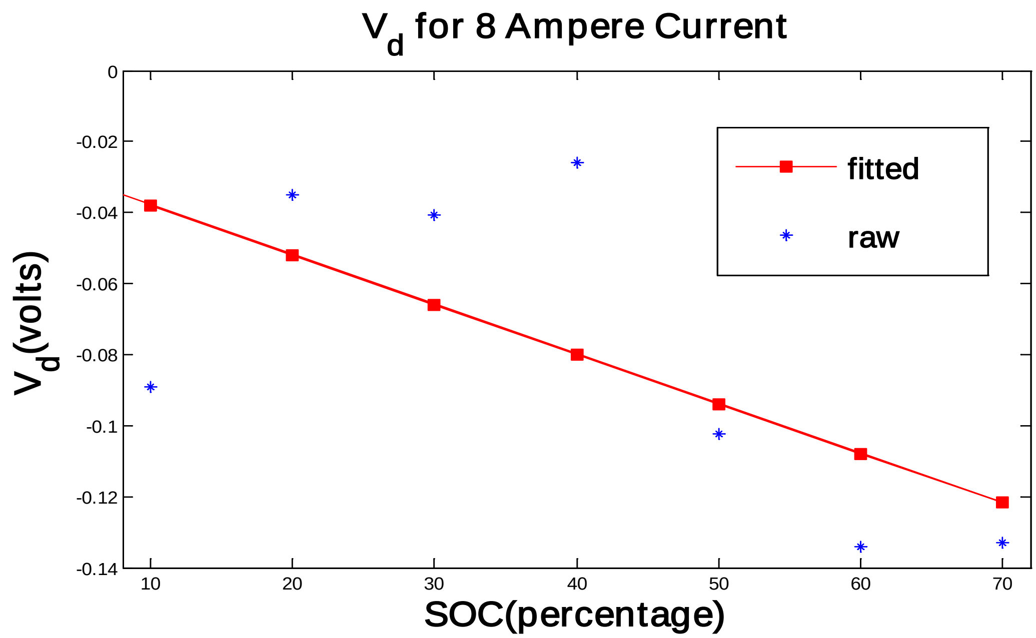


Fig 58: graph of V_d varying with SOC at r.t.p

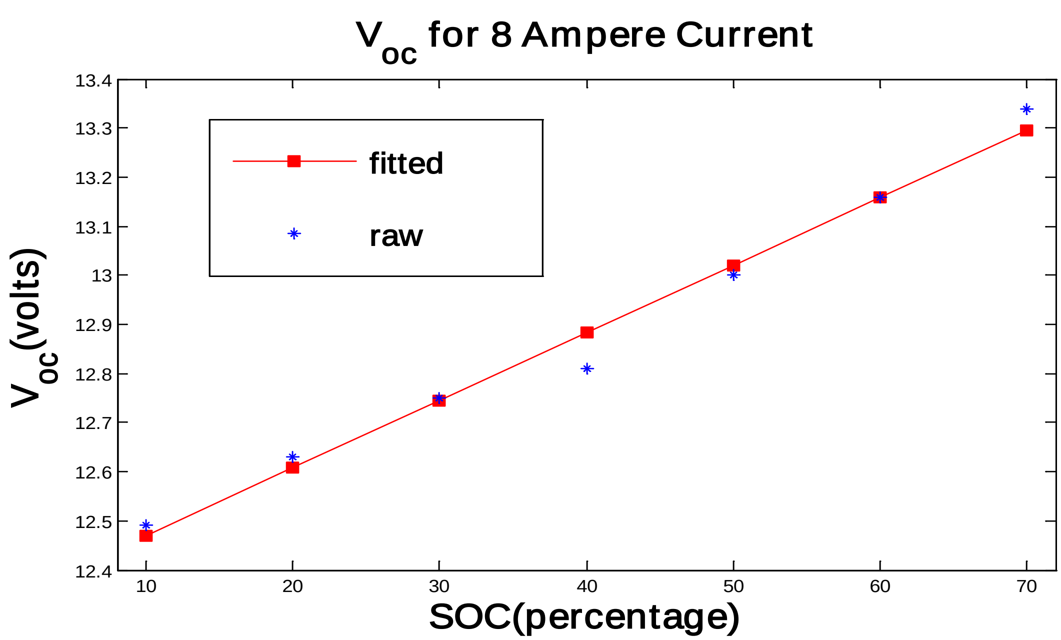


Fig 59: graph of V_{OC} varying with SOC at r.t.p

The Equations that were found using least square fitting from the graphs are:

For 8 Ampere

$$R(SOC) = 0.0013 * SOC + 0.03$$

$$Vd(SOC) = -0.0014 * SOC - 0.24$$

$$Voc(SOC) = 0.013 * SOC + 12.33$$

All these information were used to design the battery model.

Chapter 6

Charging and Discharging Characteristics

6.1Charging and Discharging Characteristics of the battery

Experiment 3: Charging the battery to its full capacity.

Apparatus:

- A DC source
- Diamec Battery (12V 40 Ahr)
- Multimeters
- Connecting wires

Circuit diagram:

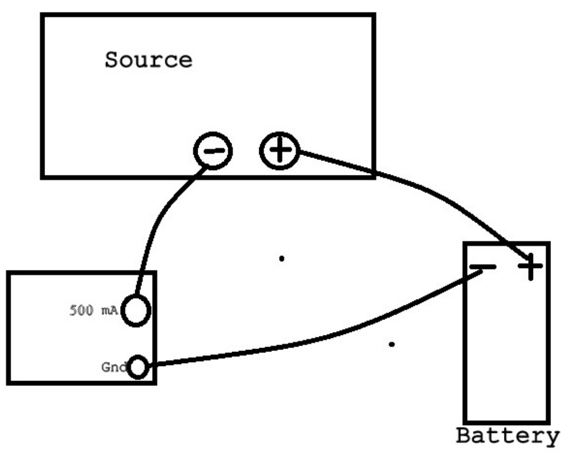


Fig : The simple circuit setup for battery charging without using a commercial recharger.

Method:

According to the setup of the diagram as mentioned in the previous page the battery was charged at first at a high current enough to charge 80% of the total capacity. The mode of charging was constant current charging where the current was kept constant as the voltage increased to a certain level. The threshold Voltage for CC charging was decided at 15 V and current was decreased by 50% when the voltage reached 15 V. As current was decreased the threshold voltage was also decreased. These charging experiments were done to find the total capacity of the battery and they were done for different current values to determine internal loses as well.

<u>Results and Analysis:</u>

The graph below is the charging graph for current against time for different values of current. The current was decreased every time the voltage went over the threshold voltage.

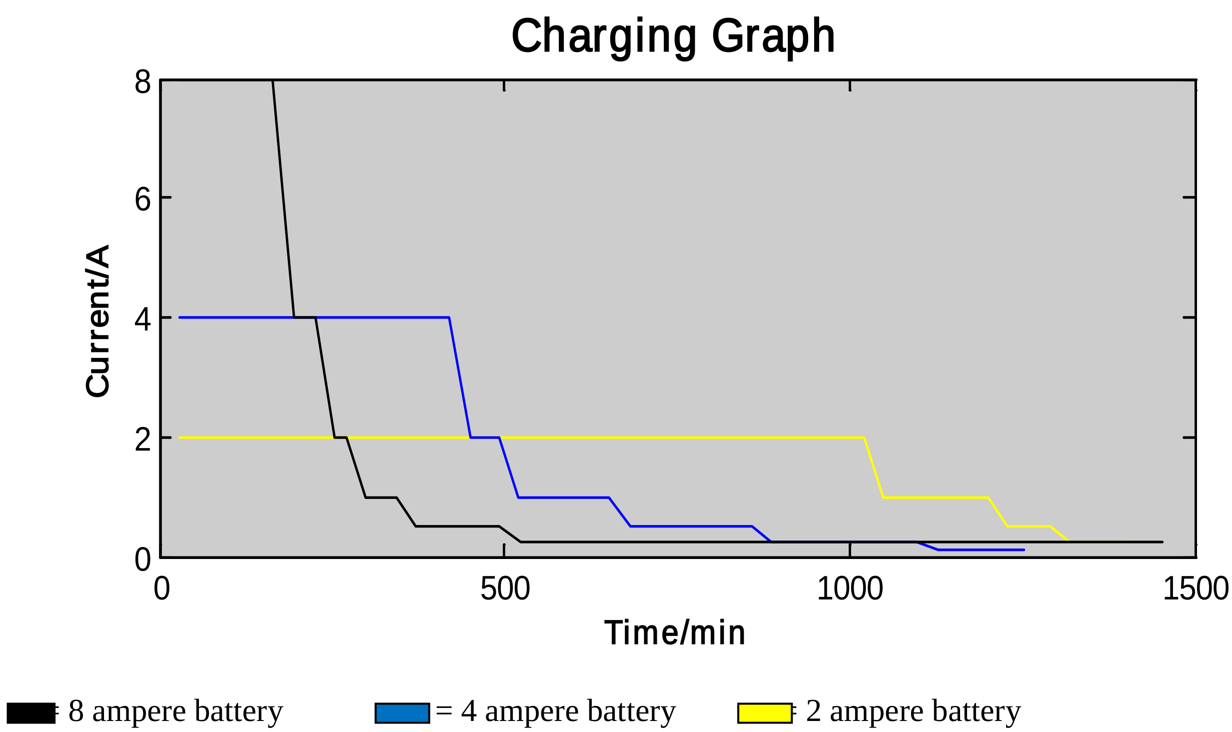


Fig 60: graph of current varying with time at r.t.p

The graph below is the same charging data plotted against SOC.

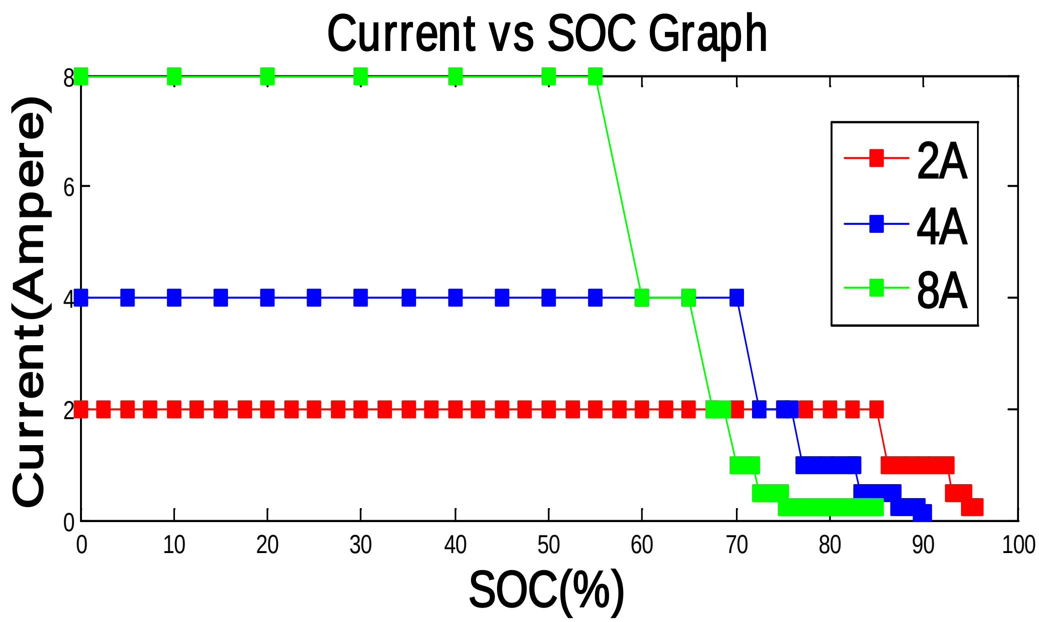


Fig 61: graph of current varying with SOC at r.t.p

During the experiment the V_t was also measured and below are the graphs of Vt against time for 3 different currents and also the graph of Vt against SOC was also plotted.

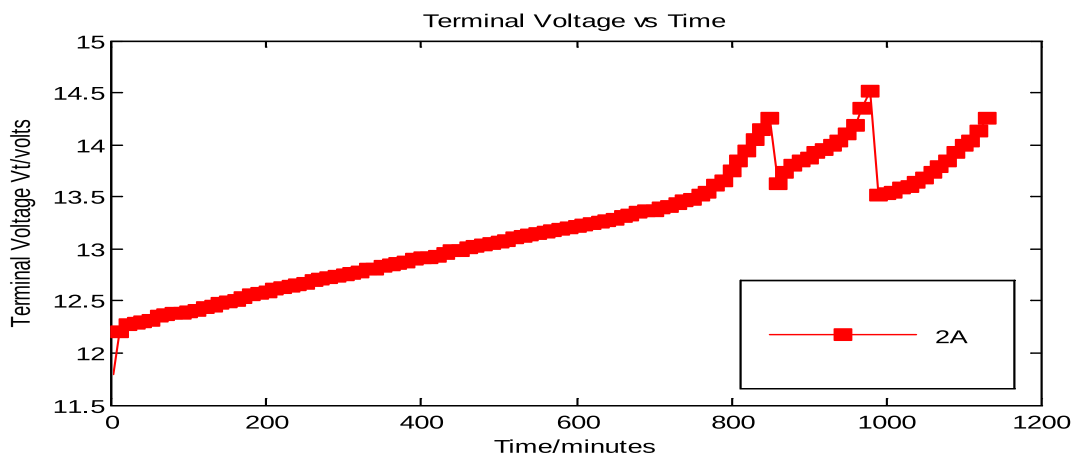


Fig 62: graph of terminal voltage varying with time for 2 A at r.t.p

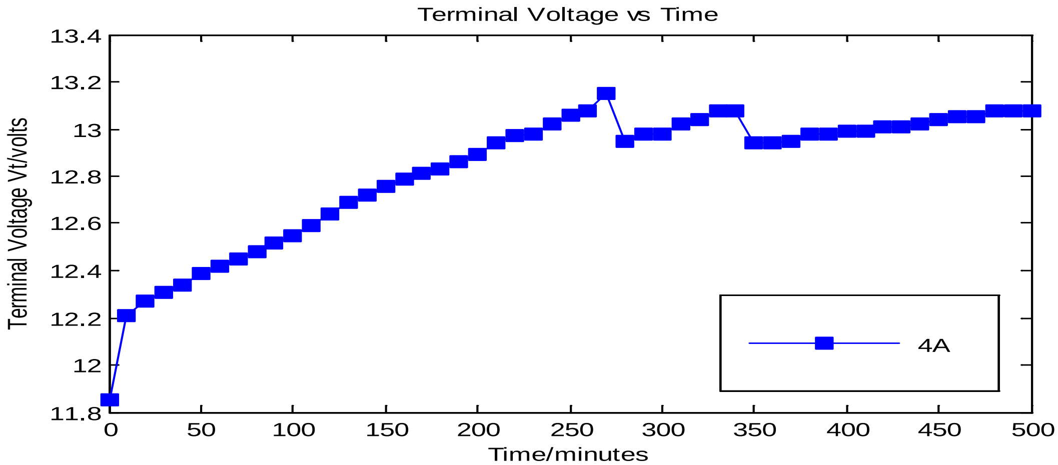


Fig 63: graph of terminal voltage varying with time for 4 A at r.t.p

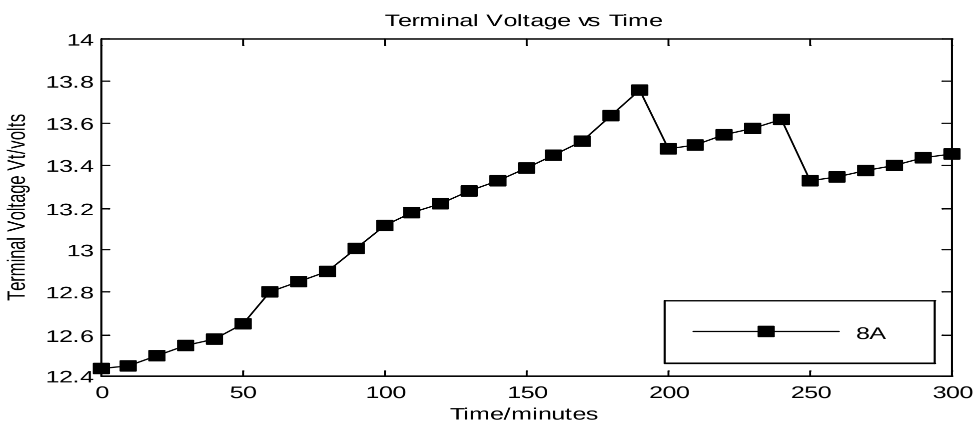


Fig 64: graph of terminal voltage varying with time for 8 A at r.t.p

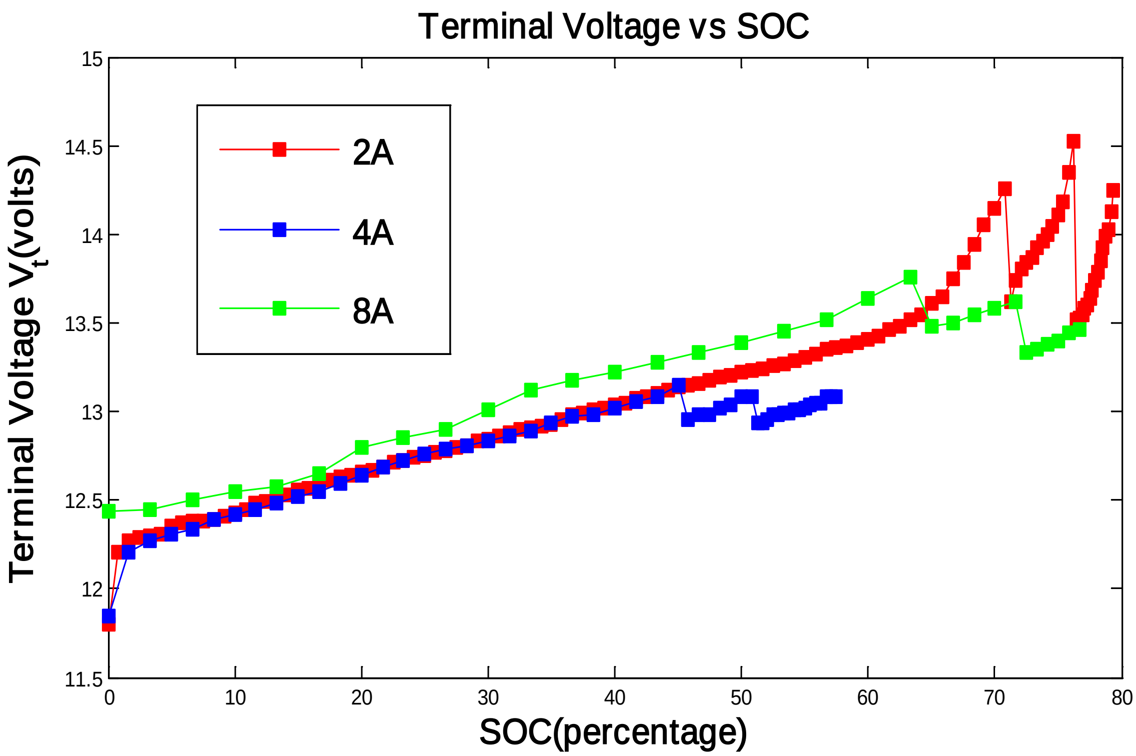


Fig 65: graph of terminal voltage varying with SOC at r.t.p

Experiment 4: Discharging the battery by its entire capacity.

Apparatus:

- A DC source
- Diamec Battery (12V 40 Ahr)
- Multimeters
- Rheostat
- Connecting wires

Circuit diagram:

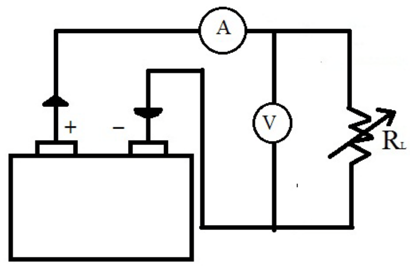
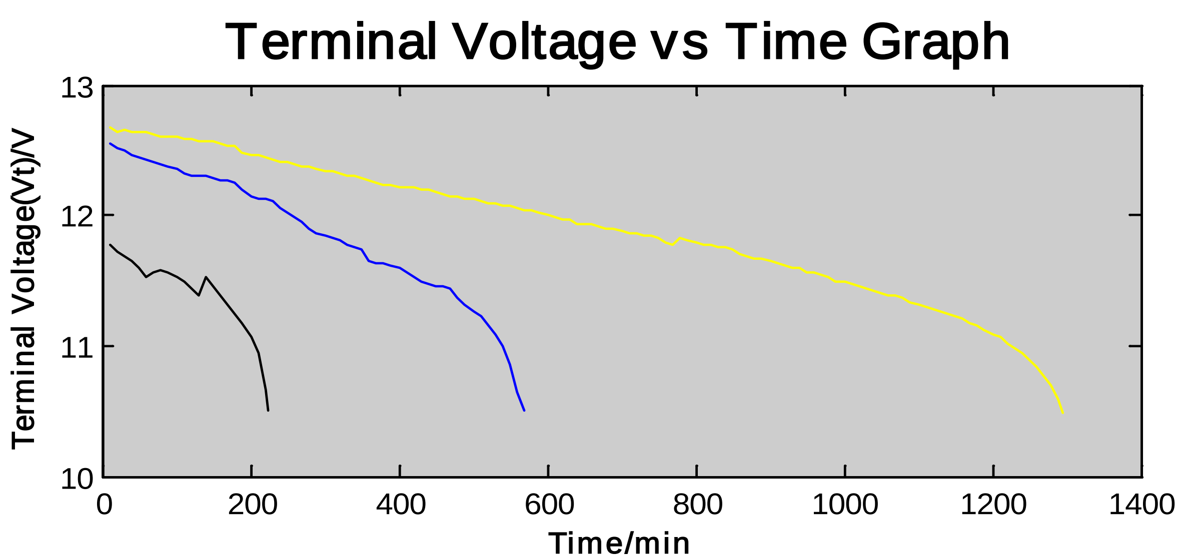


Fig : The simple circuit setup for battery discharging with a variable load.

Method:

As mentioned in the previous chapter the experiment was carried out just as explained and the battery was discharged for 3 different current levels and the terminal voltage drop was recorded with time accordingly. The graphs below illustrates the terminal voltage pattern of the battery with respect to time and SOC respectively.

<u>Results and Analysis:</u>



= 8 ampere battery = 4 ampere battery = 2 ampere battery

Fig 66: graph of terminal voltage varying with time at r.t.p

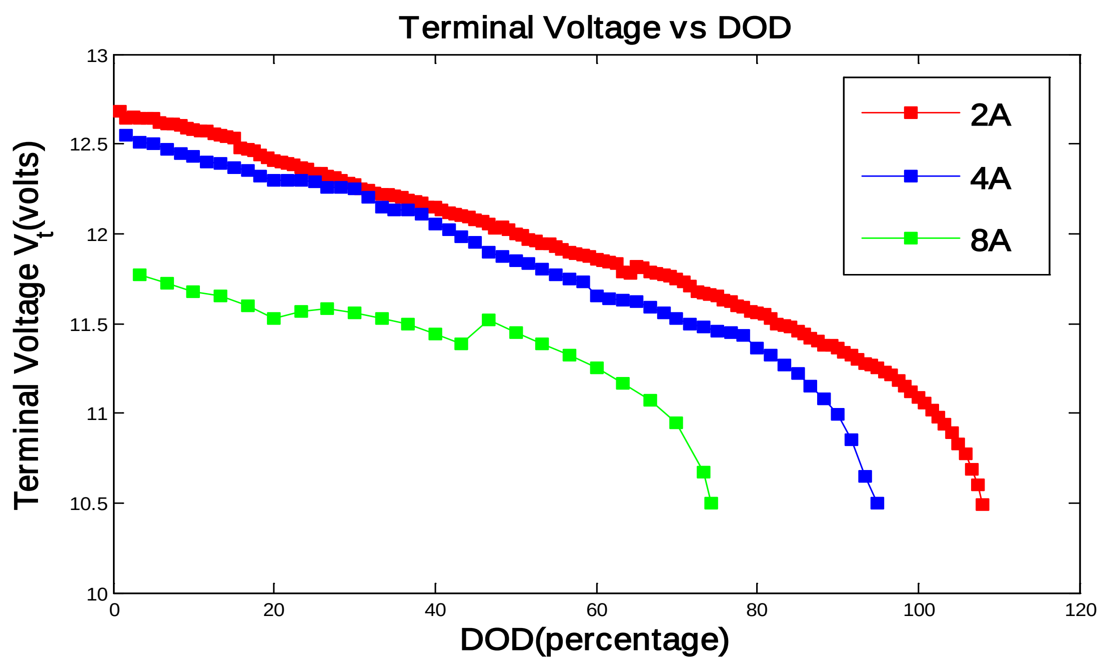


Fig 67: graph of terminal voltage varying with DOD at r.t.p

Summary of the results:

From the above graphs it can be seen that at lower current the battery has higher capacity and at lower internal loss.

Consequently, at higher current the battery has lower capacity and higher internal loss.

Experiment 5: Analyzing the voltage recovery of battery.

Apparatus:

- A DC source
- Diamec Battery (12V 40 A-hr)
- Multimeters
- Rheostat
- Connecting wires

Circuit diagram:

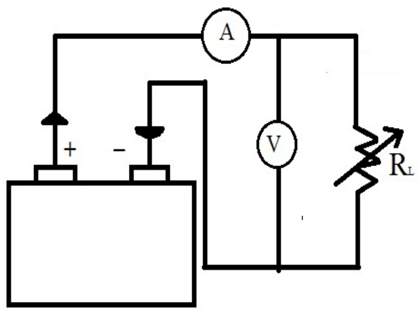


Fig : The simple circuit setup for battery discharging with a variable load.

Method:

As mentioned in the previous chapter the experiment was carried out just as explained and the battery was discharged for 2 different current levels and after every 20% removal of charge from the battery of its total capacity, the data for Vt and T etc were recorded.

Results and Analysis

The graph below illustrates the data taken from the battery.

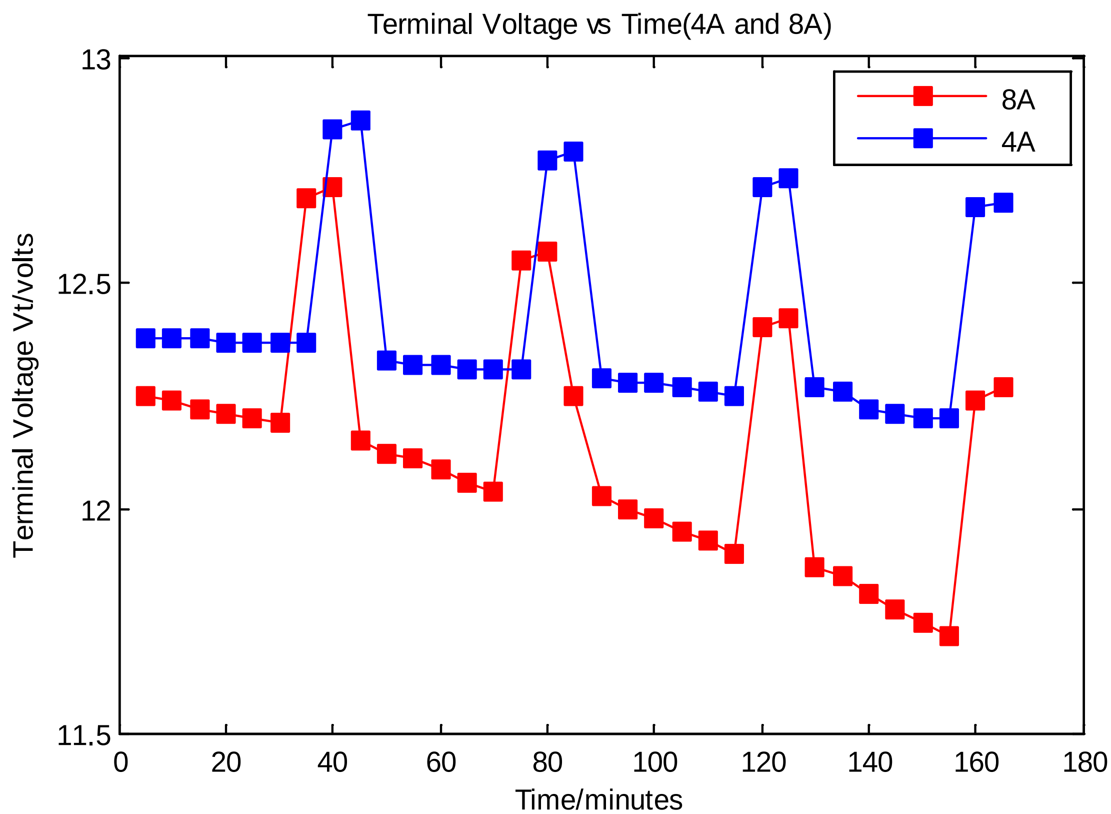


Fig 68: graph of terminal voltage varying with time at r.t.p

The graph illustrates the effect of voltage recovery for two different currents.

The results show that the battery had negligible voltage recovery

Chapter 7

Proposed Model and its Verification

7.1 Proposed Model:

From chapter 4 we found that the Thevenin model is the appropriate model for our system. In section 4.1.2 a brief introduction of the model is given. However, a detailed analysis of the model is given in this chapter. A slight modification is done in the model. The following structure model gives the detailed analysis of the model.

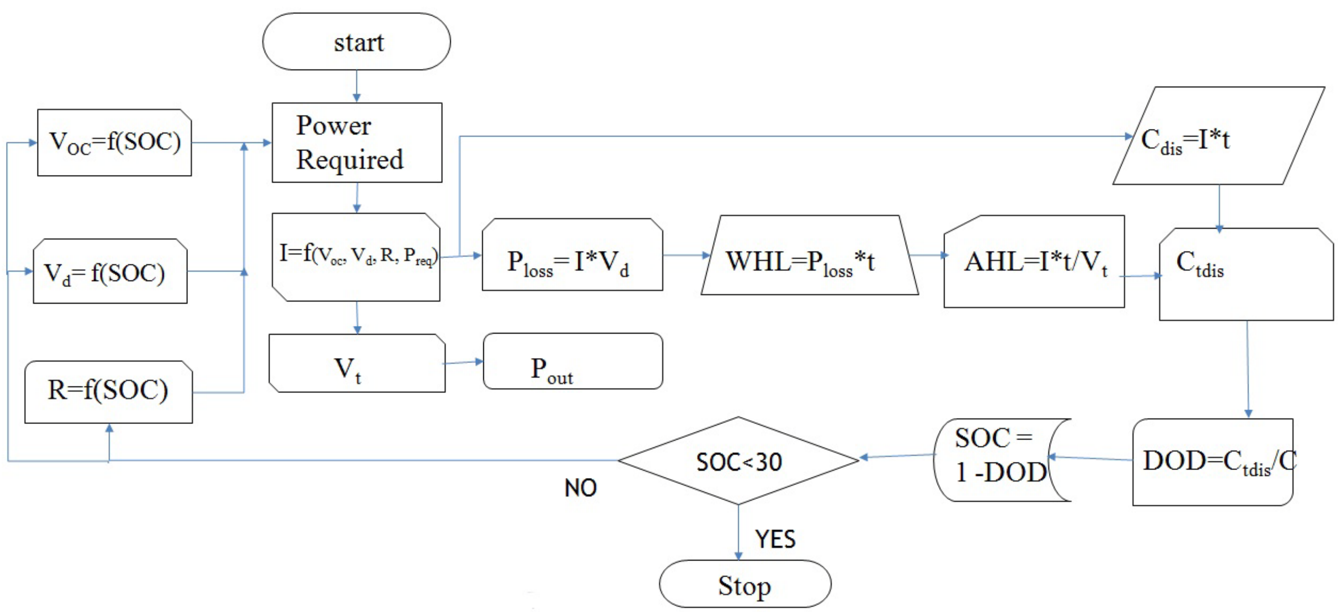


Fig 69: power flowchart of the model

As it can be seen in the flowchart, the current is calculated at a given point in SOC and from the power required to run the motor and then this current is used to calculate the terminal voltage at any time. Terminal voltage is then used to calculate the output power.

In order to find the battery health or the capacity of the battery the internal losses are also calculated. The battery current, I, is used to calculate the internal charge loss in the battery which is known as Q_{dis} and from the same battery current we also get the internal power loss that is due to the internal voltage drop in the metal plates of the battery. We also calculate the watt-hr loss and ampere-hr loss in the battery which is added to this power loss and hence we get the total power lost in the battery internally.

Once the internal losses are determined, the depth of discharge is calculated and the state of charge is also calculated. The flow chart then is fed into a decision where if the SOC is more than 30% then it will return to the starting point and calculate the new current and other parameters of the model and if it is less than 30% then the motor will stop and go on to the charging state.

A noteworthy mention here is that the dynamic response of the battery is not included in the power flow diagram but it is observed in the experiment that there is relaxation and voltage suppression occurring in the battery when it is in open circuit.

7.2 Battery Model Validation and Verification:

The two Diamec batteries were tested separately and were discharged against a load to determine the V_{oc} -SOC relationship of the battery. The batteries were discharged from a full SOC and then recharged with a DC source. As shown in the figure below the V_{oc} increased with increase in SOC. Using the least-square fitting method the open circuit voltage Voc was coordinated with SOC. This gave the equation:

V_{oc}=1.51*SOC+11.5

In the previous models the open circuit voltage Voc was modeled using the equation:

$V_{oc}-V_t = I*R$

However in the new model we are taking an internal voltage drop into account and rewriting the equation as

$V_{oc}-V_t = V_{drop}+I*R$

So the current equation can also now be written as:

$$I= \frac{Voc - Vdrop \pm\sqrt{(Voc-Vdrop)^2-4RP}}{2R}$$

And the equation for R in terms of SOC is found to be:

R= 0.031SOC+0.047

The equation of Vdrop in terms of SOC is found to be:

V_{drop} = 0.086*SOC-0.011

The other equations needed for the modeling are:

$P_{loss} = I^2*R + V_{drop}*I$

With accordance to flowchart the individual subsystems were created:

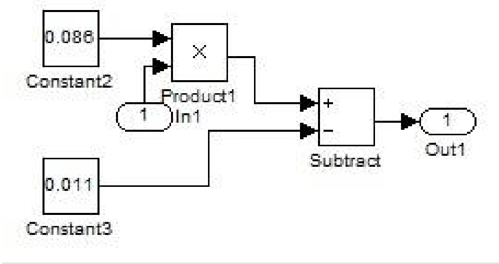


Fig 70: The V_{drop} calculation block

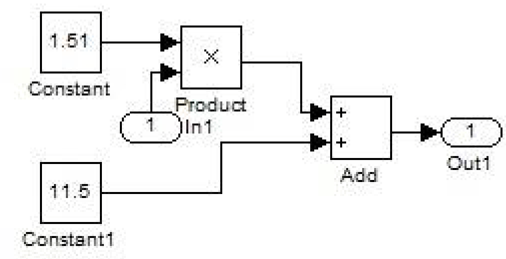


Fig 71: the V_{oc} calculation block

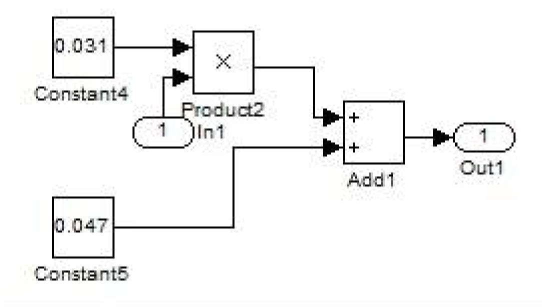


Fig 72: the R calculation block

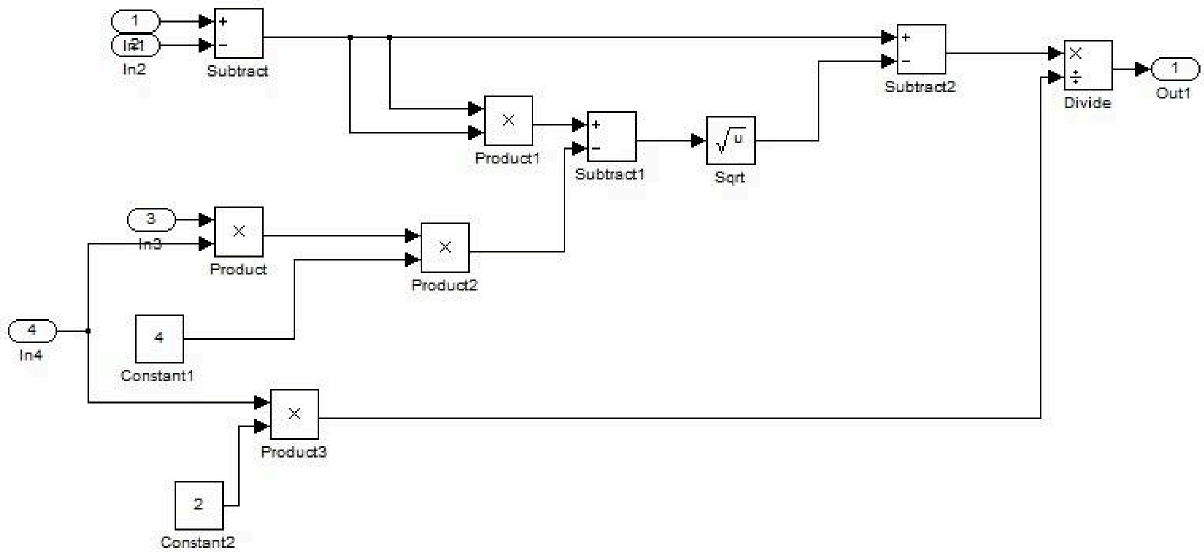


Fig 73: The I calculation block

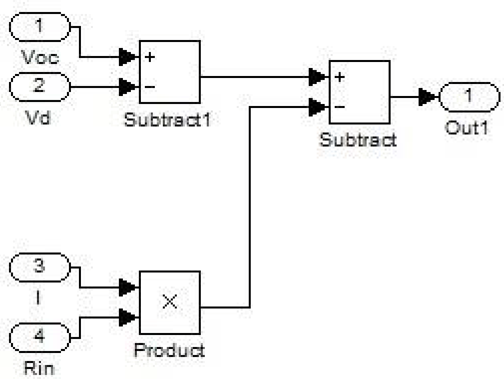


Fig 74: The V_t calculation block

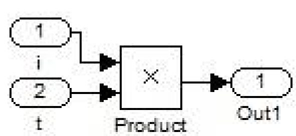


Fig 75: The Q_{dis} calculation block

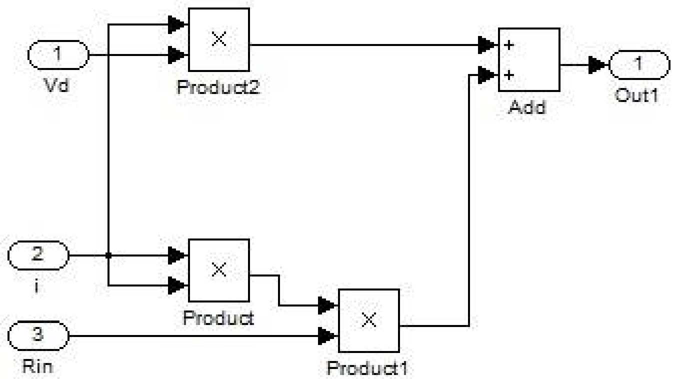


Fig 76: The P_{loss} calculation block

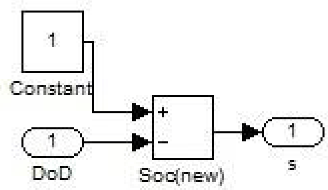


Fig 77: The SOC calculation block

All these parameters were then incorporated into the model using MATLAB/Simulink:

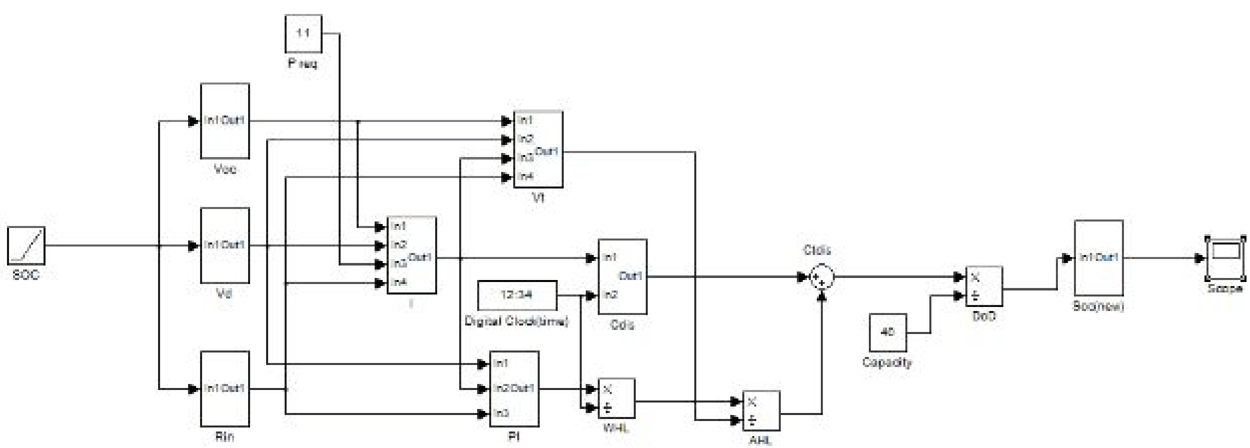


Fig 78: The complete model in Simulink

Nomenclature:

V_{oc} = Open Circuit Voltage

V_{drop} = Internal Voltage Drop of the Battery

V_t= Terminal Voltage of the battery

R = Internal resistance of the battery

I= Battery current

P_{req}= Power required from the battery

C_{dis}= The amount of charge dissipated from the battery

P_{loss}= Power lost internally

WH_{loss}= total watt hour lost

AH_{loss}= the total ampere-hour lost

C_{tdis} = the total amount of charge dissipated including all internal losses

DoD= depth of discharge

SOC= State of Charge

P_{out}= The output power provided by the battery.

Summary: Although the Simulink model was designed but due to time constraint, it was not tested. However this has been added as a further research work in the later section.

The battery was simulated using the following Matlab program and the results were compared with the experimental data.

```
============================PROGARM STARTS=======================

%%                   Dynamic Calculation for Battery SOC

%%                 for Constant Current Discharge I_dis = A

clear all

close all

clc

load Vt_SOC_2A.txt      % Load the experimenal Vt vs SOC data, I_dis=2A
```

```
Vt_raw=Vt_SOC_2A(:,2);

SOC_raw=Vt_SOC_2A(:,5);

load Vt_SOC_4A.txt      % Load the experimenal Vt vs SOC data, I_dis=4A

Vt4_raw=Vt_SOC_4A(:,2);

SOC4_raw=Vt_SOC_4A(:,5);

I=2;                    % Discharge Current in ampere

fc=43.2/40;             % Rate Capacity factor for I_discharge = 2A

C=40*fc;                % Ampere-hour capacity

SOC(1)=1;

DOD(1)=0;

Qd=0;                   % AH discharged

SOC_a(1)=1;             % apparent SOC, Does not include internal loss

DOD_a(1)=0;             % apparent DOD

Qd_a=0;

t(1)=0;                 % time

n=1;

Dt=10/60;               % time interval 10 min

%% Calculation of Terminal Voltage Vt until DOD reaches 100%

while (DOD<=1)

    Voc(n)=1.51*SOC(n)+11.5;

    Vd=0.086*SOC(n)-0.011;

    R=0.031*SOC(n)+0.047;

    Vt(n)=Voc(n)-Vd-I*R;            % Terminal Voltage

    Ploss=(Vd+I*R)*I;               % Internal loss in W

    AHloss=Ploss*Dt/Vt(n);          % Internal loss in AH
```

```
    Qdn = Qd + I*Dt + AHloss;        % Total AH discharged
    DOD(n+1) = Qdn/C;                % Depth of Discharge
    Qd = Qdn;
    Qdn_a = Qdn + I*Dt;              % Charge delivered in Dt time interval, does not include internal
losses
    DOD_a(n+1) = Qdn_a/C;            % Depth of Discharge
    Qd_a = Qdn_a;
    SOC(n+1) = 1 - DOD(n+1);
    SOC_a(n+1)= 1-DOD_a(n+1);
    t(n+1)=t(n)+Dt;
    n=n+1;
end
Voc(n)=1.51*SOC(n)+11.5;
Vd=0.086*SOC(n)-0.011;
R=0.031*SOC(n)+0.047;
Vt(n)=Voc(n)-Vd-I*R;    % Terminal Voltage
%%  Adjustment for SOC measurement data to 0 to 100%
SOC_raw=(40*SOC_raw+3.17)/43.17;
%%
DOD_raw=1-SOC_raw;
disp('n=')
disp(n)
%=============Calculating Error==============================
%========between calculated and experimental data===========
yi = interp1(DOD_raw,Vt_raw,DOD,'cubic');    % interpolating the experimental data to have the
```

```
error=100*(Vt-yi)./yi;                    % same matrix dimension as the calculated ones

%===================Plotting==================================

%==============Terminal Voltage vs DOD==========================

subplot(2,1,1)

plot(DOD_a*100,Vt,'--',DOD_raw*100,Vt_raw,'linewidth',2)

xlim([-5 110])

ylim([4 14])

ylabel('\bf Terminal Voltage V_t (V)','FontSize',10)

h = legend('Calculated','Experimental',3);

set(h,'Interpreter','none','EdgeColor','red','FontSize',14)

%======================Plotting==================================

%===================%Error vs DOD==========================

subplot(2,1,2)

plot(DOD*100,error,'--k','linewidth',2)

xlim([-5 110])

ylim([0 10])

ylabel('\bf  %Error (Calculated-Experimental)','FontSize',10)

xlabel('\bf Depth of Discharge, DOD (%)','FontSize',14)

=========================PROGRAM ENDS============================
```

7.3 Calculated vs Experimental Results:

In order to validate the model two sets of experimental test have been adopted to compare with the simulation results.

For 2 Ampere Current

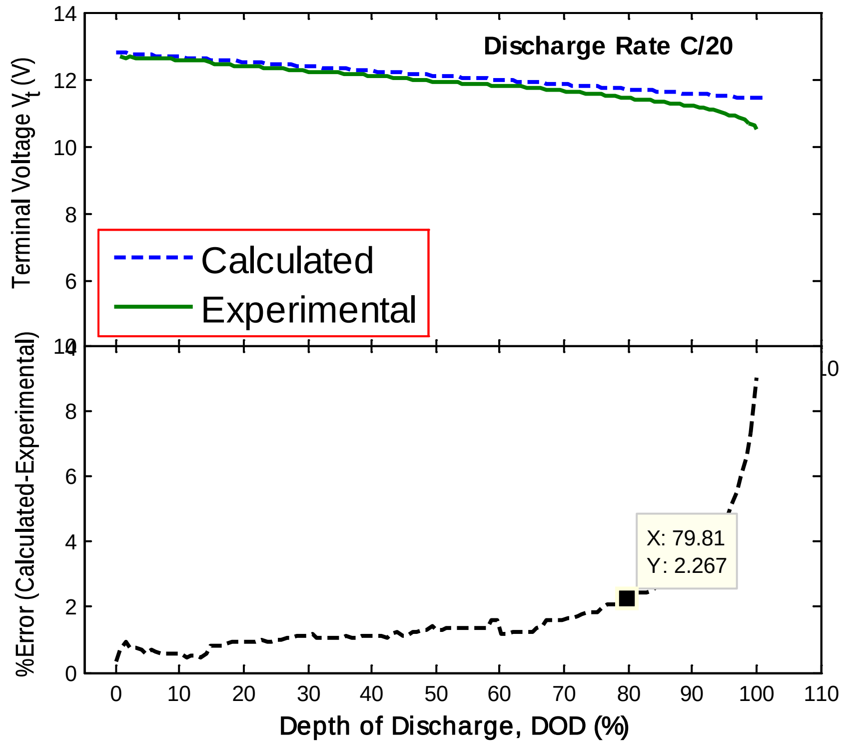


Fig 79: graph of experimental vs calculated data and error calculation of experimental vs calculated data for 2 Ampere current

For 4 Ampere Current

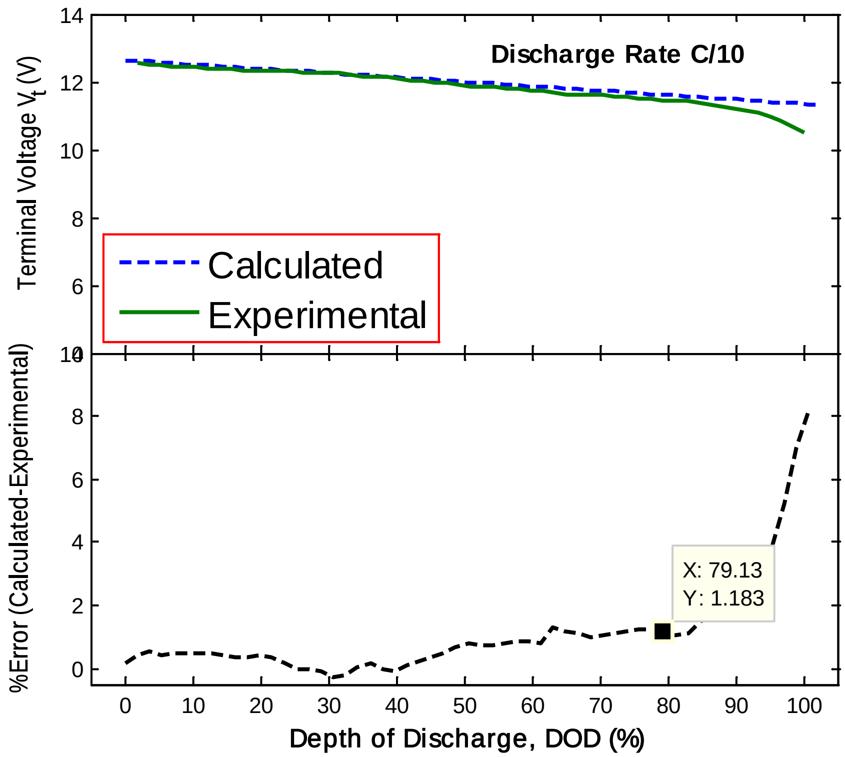


Fig 80: graph of experimental vs calculated data and error calculation of experimental vs calculated data for 4 Ampere current

7.4 Summary of the results:

From the simulation result in fig 70, the discharge begins at the voltage 12.62 and the simulation result shows a little variation with the experimental data. Both the simulated result and experimental result decreases linearly. It can be seen that the experimental terminal voltage and simulated terminal voltage shows a reasonable agreements for 80% of the DOD. The error voltage is 2%.

The error between simulated and experimental voltage is increasing after 80%. The marginal error lies within 0.3~1.2%

The graphs generated with the equations and the experimental data give marginal error thus validating our battery model.

Chapter 8

Conclusion and Future Work

This chapter gives the summary of the achievement of the project work in battery modeling.

The possible direction of the future work is also described in this chapter.

8.1 Summary:

Lead acid batteries are used as the storage system in renewable energy due to the intermittency nature of the renewable energy system. The capacity loss is observed in these batteries due to the repeated charge and discharge cycle. As a result it is very essential to know the performance of the battery.

In this thesis, the capacity status of the battery is studied in relation to the internal resistance, open circuit voltage, and internal voltage of the battery. Based on the experimental testing of the battery, various models were studied first and a suitable model was chosen for estimating battery parameter. An equivalent final model of lead acid battery has been developed and implemented under Matlab/Simulink software. The model consists of important concept of battery that reflects the dynamic response of terminal voltage. The model was then validated with two of the experimental data. From the validation result it is found that the model can accurately estimate the battery characteristics with an error of 1.2~0.3%.

8.2 Future Research Work

In the future-

- Effect of temperature on the model can be studied.
- Discharge rate has an effect on capacity of battery. SOC changes with capacity and R, V_t and V_{OC} are all function of SOC so all these parameters can be related to discharge rate.
- Using the model the state of health of the battery can be tested by deep cycle discharge of the battery for their whole lifetime. The state of health can be determined by the internal resistance. Hence, an improvement in the model to find the internal resistance at various discharge rates so that the model can be done in the future.

- A charge/discharge controller can be designed using the model for the storage system can be designed.
- The model can be integrated with the PV module so that a complete storage system can be designed. These kinds of system consist of PV array, battery, the converters and the controllers. Hence a digitally controlled stand alone photovoltaic power supply can be designed using the model presented in the thesis.

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