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DYNAMIC MODELING, MONITORING AND CONTROL OF ENERGY STORAGE SYSTEM

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Abstract

Today there is a great interest on the small scale renewable electricity generation due to the changing economics and the demand for highly sustainable electricity generation. However, renewable energy sources are unreliable and fluctuating which causes variation of power flow. In this situation, there can be server problems such as frequency oscillations, violation of the power line capability jeopardizing the security of the power system. Batteries can be an emerging technology which acts as the fast acting spinning reserve that can balance between the load and generation. Conversely, it very difficult to accurately predict battery performance and the total cost of the investment of storage system by integrating batteries to the renewable system as batteries in this situation have to bear a wide range of the operational conditions. Henceforth, modeling of the battery is extremely important. This master thesis gives the dynamic modeling of the batteries which can replicate the relevant behavior of the battery.

The proposed methodology is the model based approach where the parameters are determined to develop a suitable model. In this thesis, the battery is modeled as an R-C circuit comprising of elements each of which represents certain battery characteristics. An appropriate model is selected based on the comparative study of the characteristics of experimental output of the battery using model identification. Parameters of the battery are computed in the MATLAB Simulink parameter estimation toolbox using least square estimation. The initial parameter values for the simulink are found with the help of the lab test. Validation results from the two experimental data shows that the model can accurately estimate the battery characteristics with an error of 0.3%. The aforementioned battery model is later used to make an appropriate charge controller.

The methods used in the thesis performed quite well within the limited tests performed during the experimental works. To use the model online in the future, further investigation is recommended in order to refine the model.
Table of Contents

CHAPTER 1 ................................................................................................................................. 1
Introduction ..................................................................................................................................... 1

1. 1. Background .......................................................................................................................... 1
    1.1.1. Energy storage system an enabling technology ............................................................. 2
    1.1.2. Overview of existing energy storage system ................................................................. 3
    1.1.3. Comparisons of Different Storage Techniques ............................................................. 4
    1.1.4. Types of batteries .......................................................................................................... 5

1.2. Problems and Solutions ....................................................................................................... 6

1.3. Objective of the thesis ......................................................................................................... 8

1.4. Limitations .......................................................................................................................... 8

1.5. Organization of the report .................................................................................................. 9

CHAPTER 2 .................................................................................................................................. 10

Lead Acid Battery ......................................................................................................................... 10

2.1. General Overview of Lead Acid Battery .............................................................................. 10
    2.1.1. Background .................................................................................................................. 10
    2.1.2. Structure and Operation ............................................................................................... 10
    2.1.3. Types of Lead acid Battery ......................................................................................... 11

2.2. Terminology used in batteries ............................................................................................ 12
    2.2.1. Battery Capacity .......................................................................................................... 12
    2.2.2. Cut off Voltage ............................................................................................................ 12
    2.2.3. Rate of Charge/Discharge ......................................................................................... 12
    2.2.4. Open Circuit Voltage ................................................................................................. 13
    2.2.5. Electromotive force ..................................................................................................... 13
    2.2.6. Depth of Discharge (DOD) ...................................................................................... 13
    2.2.7. State of charge (SOC) ............................................................................................... 13
    2.2.8. Internal Resistance ..................................................................................................... 13
    2.2.9. Self Discharge Rate .................................................................................................... 13
    2.2.10. State of Health .......................................................................................................... 14
    2.2.11. Battery Lifetime ........................................................................................................ 14
    2.2.12. Battery Efficiency ..................................................................................................... 15
    2.2.13. Thermal Runaway ..................................................................................................... 15
5.3. Discussion of the Results
5.4. Conclusion

CHAPTER 6
Final Model of the Lead acid battery
6.1. Capacity Model
6.1.2. Voltage Model
6.1.3. Thermal Model
6.2. Summary of the final Model

CHAPTER 7
Parameter Estimation of the Model
7.1. Parameter Estimation for the Project
7.2. Implementation of the parameter estimation
7.2.1. Parameter estimation using Lab Test
7.2.2. Model Parameter Identification using Simulink Parameter estimation
7.2.3. Validation of the model
7.4. Discussions
7.5. Summary

CHAPTER 8
Charge Controller Implemented in the Project
8.1. IUI\textsubscript{a} Charging
8.1.1. Bulk charging
8.1.2. Absorption Charging
8.1.3. Float charging
8.2. Charging Algorithm
8.3. Final System Block Diagram
8.4. Results after implementing the charge controller

Chapter 9
Conclusions and Future Research
9.1. Summary
List of Figures

Fig: 1 Energy Storage Diagram [6] ....................................................................................................................................... 2
Fig: 2 Existing Problems and solution for the problems ........................................................................................................... 7
Fig: 3 Lead Acid battery and its components.......................................................................................................................... 10
Fig: 4 Equivalent circuit model of simple model...................................................................................................................... 16
Fig: 5 Equivalent circuit of modified simple battery.................................................................................................................. 17
Fig: 6 Equivalent circuit of advanced simple battery ................................................................................................................ 18
Fig: 7 Equivalent circuit of Thevenin model [24] ....................................................................................................................... 19
Fig: 8 Equivalent model of modified Thevenin battery [24] ......................................................................................................... 20
Fig: 9 Equivalent circuit of Copetti model [26] ........................................................................................................................ 21
Fig: 10 Equivalent circuit of Randle’s model [27] ....................................................................................................................... 22
Fig: 11 Equivalent circuit of third model [28] .......................................................................................................................... 23
Fig: 12 Voltage and current characteristics for Wa charging .................................................................................................... 26
Fig: 13 Voltage and current characteristics for WOWa Charging ................................................................................................ 26
Fig: 14 Voltage and Current characteristics for IUIa Charging .................................................................................................. 27
Fig: 15 Current Characteristics for Pulsed charging .................................................................................................................. 27
Fig: 16 Voltage and Current Characteristics for quick charging ............................................................................................... 28
Fig: 17 Experimental Setup layouts........................................................................................................................................... 29
Fig: 18 Experimental setup .......................................................................................................................................................... 30
Fig: 19 charging curve from the Experiment ................................................................................................................................ 31
Fig: 20 Discharge curve for discharge current 18A ..................................................................................................................... 32
Fig: 21 Discharge curve for discharge current 10A ..................................................................................................................... 32
Fig: 22 Discharge curve for discharge current 15A ..................................................................................................................... 33
Fig: 23 Discharge curve from the experiment .......................................................................................................................... 34
Fig: 24 Simulink output for modified simple battery .................................................................................................................. 34
Fig: 25 Simulink output for linear variation for advanced simple model ....................................................................................... 35
Fig: 26 Simulink output for Non linear variation for the advanced simple battery .................................................................... 36
Fig: 27 Charging output from simulink for copetti model .......................................................................................................... 37
Fig: 28 discharging output for the Copetti model from Simulink ............................................................................................... 37
Fig: 29 Simulation Output for the Randle’s model ..................................................................................................................... 38
Fig: 30 Simulation result for the third order model .................................................................................................................. 39
Fig: 31 Final Structure model for the thesis

Fig: 32 Dynamic model of the battery

Fig: 33 Final Equivalent Circuit model for the system [28]

Fig: 34 typical voltage and current profile for a constant current discharge [21]

Fig: 35 Model based parameter Identification Algorithm

Fig: 36 The cost function for simulating the model in Simulink parameter estimation.

Fig: 37 the trajectories of the estimated parameters after the simulation

Fig: 38 Final estimated parameter values from the Simulink parameter estimation

Fig: 39 Plot of the measured and simulated result (Validation Data 1)

Fig: 40 Plot of the residual result (Validation Data 1)

Fig: 41 Plot of the measured and simulated result (Validation Data 2)

Fig: 42 Plot of Error voltage (Validation Data 2)

Fig: 43 Ideal three steps or IUIa Charging Method

Fig: 44 Algorithm for battery charging

Fig: 45 Final System Block Diagram implementing the battery model

Fig: 46 Output of the implementation of the algorithm in Simulink
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]. The population of the world is skyrocketing and the stored amount of the fossil fuel is diminishing. Fossil fuel has been very convenient way to power the energy demand but it also brings serve consequences. Two major problems that arise from the use of the fossil fuel are that the resources are limited and there is the serve impact on the environment.

Carbon dioxide is created while burning fossil fuel which in turn contributes to global warming. It is projected that by the year 2020, world energy consumption will increase by 50 percent, or an additional 207 quadrillion BTUs. If the same scenario of the fossil fuel consumption remains then the fossil fuel reserves will be finished in 104 years [2]. In addition to influence to the environment, derogating fossil fuels reserves and fluctuations of the global energy market, have increased the needs to explore renewable feedstock and to look for novel sustainable production systems.

Renewable energy sources include wind power, solar power (thermal, photovoltaic and concentrated), hydroelectric power, tidal power, geothermal energy and biomass. The global capacity of wind power has increased from 50 GW to 240 GW from 2005 to 2011 whereas solar power has increased from 5 GW to 60 GW [3]. In 2011, excluding the large hydropower plants, the installed worldwide capacity based on wind sources was estimated at 41.7 GW [4]. They are mainly installed in Europe, North America and Asia-Oceania. Taking the upcoming problems into consideration, the European Union (EU) by means of the SET Plan, will further support the energy production from renewable source. By 2020, the SET Plan have target to increase the energy production from the renewable energy sources to 20%. Also other countries, such as the USA and Canada, are going to increase the generation from renewable in the next decades [5].
1.1.1. Energy storage system an enabling technology

From the above statistics we can see that the overall structure of the electric power system is changing. The increasing demand for the alternative energy it is moving from fossil fuel to renewable energy that are more environmentally friendly and sustainable. In addition to that electric power systems should be more reliable and should meet the demand of the increasing energy. There is a great challenge when integrating renewable energy, as wind energy and photovoltaic do not behave like conventional power plants. Some major challenges with the use of renewable energy are:

- Weather dependent
- Non dispatchable
- Uncertainty of the time of generation
- Power quality and reliability issues
- Unable to produce electricity demand-driven
- Economic factors including tax and energy credits

This is where energy storage systems become an enabling technology. They provide the means to the non dispatchable resources into dispatchable energy sources. According to the technology selected they can provide spinning reserves, load leveling and shifting, load forecasting, frequency control, VAR support voltage regulation, relief of overloaded transmission line, and more effective and efficient use of the capital resources [6]. The principle energy storage applications and types of the energy storage system can be seen in fig. 1.

![Energy Storage Diagram](Image)

**Fig: 1 Energy Storage Diagram [6]**
1.1.2. Overview of existing energy storage system

Depending on the variety of the applications a number of the energy storage system had been developed. Some of them are described below:

**Super capacitor or ultracapacitor**

In this kind of the storage system the energy is stored in an electric field between a pair of the conductors. The storing process is highly reversible and allows the ultracapacitor to charged and discharged hundreds of times. Further, it is also temperature resistant with an operating range between -40 to +65 degree and is also shock and vibration resistant [7]. With these attributes the ultracapacitor can be highly effective energy storage device. However, it has a low electric density and often used for short term energy storage. Current challenges are the low energy density and high cost of the system [8].

**Pumped Hydroelectricity (PHS)**

For more than 70 years pumped hydro storage has been used. The principle of the operation of pumped hydro is same as that of hydroelectric power plant. When there is no electric demand the surplus power water is pumped from a lower reservoir to a higher level reservoir. The stored water is released during the times of high electrical demand. The major drawback to this design is the amount of land required to create the reservoir and the elevation needed between them. Pumped hydro storage plants are costly and take long time to plan and build [9].

**Compressed air energy storage (CAES)**

During the off peak electricity produced is used to compress air into an underground reservoir or surface vessel/piping system. When there is demand for electricity the air is released so that it could be heated through combustion with any one of a variety of fuels which later on run through expansion turbines to drive an electric generator. About 85% of the efficiency can be achieved but the main problem with this type of system is the reservoir has to be air tight and very large [6].

**Flywheels**

In this kind of the energy storage system the energy is stored in the form of the kinetic energy. The energy is stored in rotor which is spinning in very high velocity and the amount of energy stored in the rotor is proportional to the square of its angular momentum. When the demand of the energy is high the flywheel switches operational modes to produce the power needed. Flywheels are mainly used and efficient for short duration storage cycles due to their fast response speed. These energy storage devices are mainly used in applications that require high numbers of deep discharge cycles [10].
**Superconducting Magnetic energy storage (SMES)**

In this kind of the energy storage system super conducting magnets are cooled to produce an essentially loss-less coil. These magnets stored as DC energy and when the demand is high this energy is to be released from the system the process is reversed. The efficiencies of these SMES systems have been reported to be in the range of 95 to 98%. In addition, it takes very small time to supply the power to the system [11].

**Hydrogen Fuel Cell**

The main working principle of hydrogen fuel cell is a very high energy density converts the chemical energy in a source fuel into an electrical current. It mainly consists of three stages: electrolyzing stage, hydrogen storage stage and the fuel cell stage. Hydrogen ion is created by the electrolyze water which is produced during the off peak. When there is need for the electricity hydrogen is combine with oxygen to make water and this reaction is converted to electrical energy. Hydrogen storage is relatively immature technology with efficiency between 50 to 60% with high cost of fuel cells [6].

**Chemical storage or Batteries**

Chemical storage is the most popular method of energy storage. The charge and discharge phase in the batteries helps to use batteries for double function i.e. storage and release of electricity. The main working principle of the battery is it converts chemical energy into electrical energy when the electrolytes flow through the electrochemical cell. They are often used in portable systems, but also in permanent applications such as emergency network back-up, renewable-energy storage in isolated areas, etc [6].

**1.1.3. Comparisons of Different Storage Techniques**

The storage system is selected on the basis of the necessity of system used. Some of the criteria included for the project are reliability, efficiency, cost technical maturity, life span and environmental impact. Efficiency and life expectancy plays a vital role while choosing any storage technology, as they affect the overall storage costs. Low efficiency increases the effective energy costs since only a fraction of the stored energy can be used in addition a short lifespan also increases long-term costs as the storage unit needs to be replaced more often. Further investment cost also affects the selection of the storage system. Comparison of different storage system is particularly important for the transmission industry, portable applications, and isolated sites.

SMES has the highest efficiency but it is relatively new technology with high cost. While hydrogen storage and super capacitor seems promising but their immaturity makes them unsuitable for the
system where support is not readily available. CAES and PHS have very large installation cost so they are not preferred for the small project. In addition to that CAES needs a wide amount of location to preserve it underground. Although flywheel is efficient and low cost system, their self discharge rate is high and supply energy density is low. Henceforth for small systems (a few kWh) and larger systems (a few 100kWh in isolated areas relying on intermittent renewable energy, the battery remains the best compromise between performance and cost.

1.1.4. Types of batteries
From the previous discussion we come to know that batteries are the most efficient storage system for a small system. There are various kind of batteries applied on the large range. The most popular batteries are discussed here and among them highly efficient battery is chosen.

Lead Acid Batteries
Lead acid batteries are the oldest rechargeable battery, invented by Planté in 1859. Battery cell has lead (Pb) and lead oxide (PbO₂) as electrodes and sulfuric acid (H₂SO₄) as electrolyte. These batteries are widely used as engine starting or backup power systems. Mostly popular for its low price but short lifetime (500-1000 cycles) makes energy management applications limited. In addition to its deep discharge quality it also have low self discharge rate. Largest installations of 40 MWh/10 MW can be seen in Chino, California, and 8.5 MWh in Berlin. Lead is toxic but is 98% recycled [12].

Lithium Ion (Li Ion) batteries
The cathode is made of lithiated metal oxide (e.g. LiCoO₂, LiNiO₂, LiMn₂O₄, LiFePO₄) and anode of graphited carbon. Electrolyte of lithium ion batteries is made of lithium salts like LiPF6 dissolved in organic carbonates. When battery is charged, lithium atoms in the cathode become ions and migrate through the electrolyte to the carbon anode where they combine with external electrons and are deposited between carbon layers as lithium atoms. High efficiency, energy density and long lifetime are the qualities seen in Li ion batteries. However, lithium ion battery have low economic efficiencies and stability of the chemicals should be considered because of the chemical activeness of lithium[13].

Sodium Sulphur (NaS) batteries
NaS battery consists of molten sulphur at the positive electrolyte and molten sodium at the negative electrode which are separated by a solid beta alumina ceramic electrolyte. NaS have efficiency of about 80-90% and lifetime of 2500 cycles at 100% discharge. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally-insulated enclosure that must keep it above 270°C, usually at 320°C to 340°C. One of the
greatest characteristics of NaS batteries is its ability to provide power in a single, continuous discharge. NaS batteries have also been used for deferring transmission upgrades. The major disadvantage of NaS batteries is retaining the device at elevated temperatures above 270°C. It is not only energy consuming, but it also brings with it problems such as thermal management and safety regulations [14].

**Nickel Cadmium (NiCd) Batteries**
Most common nickel battery is nickel-cadmium (NiCd) which has nickel as cathode and cadmium as anode with an alkaline like potassium hydroxide (KOH) as electrolyte. Because cadmium is toxic, metal hydrides are now replacing cadmium as anode. Metal is usually a compound of rare earth metals and Ni, Co, Mn and/or aluminium. NiMH have lower energy density than Li-ion batteries. Nickel batteries have a low internal resistance and can tolerate high discharge currents at deep discharge levels. Most application are portable like in power tools or in automobiles and other vehicles. A problem preventing the large scale application of this kind of battery is that nickel cadmium batteries suffer from faster self discharge rate and cadmium is toxic as well as expensive [15].

**Zinc Bromine (ZnBr) Batteries**
Anode is pure metal like zinc or aluminium whereas cathode is made of porous carbon structure or a metal mesh covered with catalysts and uses the incoming air as the oxidant. The electrolytes used in this kind of battery are good ion conductors like KOH liquid or saturated in solid polymer membrane. ZnBr are compact and potentially inexpensive but chargeable batteries are difficult to make. Efficiency is below 50% and lifetime 100-300 cycles which makes it less popular[14].

Battery selection criteria are basically performance and energy density versus life cycle cost and environment concerns. While NiCd batteries are well understood, but their relatively low density make them less popular. Similarly, due to energy management NaS and low efficiency of ZnBr makes them less popular in the battery market. However, Li ion and lead acid battery seems to be the idle choice. For storage system having small systems (a few kWh) and larger systems (a few 100kWh in isolated areas relying on intermittent renewable energy size is not the main concern so lead acid batteries are most economical choices with their recyclable capability which can double their life span.

### 1.2. Problems and Solutions
Today there is an increasing demand of new technology for standalone energy system in remote areas. Availability issues and environmental issues have shifted the interest of the people towards integration of renewable energy towards these systems. In contrast to this due to the intermittency and unpredictability nature of the renewable energy sources the integration of renewable energy system to the power system becomes more challenging. These challenges can be minimized by using batteries as
the storage system. Battery storage has proven to be necessary in the autonomous power supply where there is continuous power demand. So, in small scale off grid system battery performance is considered as the key for the overall system performance and the battery also contribute a significant investment cost.

Batteries that are integrated to the renewable system have to bear a wide range of operational conditions such as varying rates of charge and discharge, frequency and depth of discharges, temperature fluctuations etc [16]. These variables make it very difficult to accurately predict battery performance in renewable systems and also the total cost of the storage system. Therefore, premature failure and possibilities of extended life span of batteries are major concerns within the renewable industry. The major sources of battery premature failure are due to the high discharge rate, over charging, temperature etc. Taking these parameters into consideration, a proper charge and discharge controller is required for reliability and safe operation of the battery. Consequently, modeling of battery becomes very necessary in order to enhance the performance of the battery by integrating a controller and to determine the cost of the storage system.

Fig: 2 Existing Problems and solution for the problems
1.3. Objective of the thesis
The main objective of the thesis is to come up with the dynamic model which can replicate the battery energy storage system. The dynamic model will replicate the relevant behavior of the battery such as state of charge, depth of discharge, terminal voltage and cell temperature as that in the real battery. These outputs from the model are then used to design a charge controller in order to prolong the life time of the battery.

The proposed methodology is the model based approach where the parameters are determined to develop a suitable model. The main steps taken during the project are; a various models are studied first from the literature in order to be familiar with battery and the selection of the model is done according to the requirement of the battery model. Then the unknown parameter of the dynamic model is found using the methodology of the experimental test. These values were used as the initial parameter to find the optimum value of the parameter from the MATLAB Simulink parameter estimation toolbox. Later, the model is used to design appropriate charge controller.

The intension of the battery modeling is to integrate it with the PV simulation platform in the small scale off grid system specially developed for remote areas. A complete system simulation is necessary to predict the performance and the cost of the system.

1.4. Limitations
The key limitation of the thesis is the proposed model can determine the state of charge of the battery but cannot determine the state of the health of the battery. Because for determining state of health different types of battery are necessary and various experimental tests needed to be conducted. A battery needs at least six months to become weak even continuously charged and discharged. Due to the time limitations and lack of resources the battery state of health was not studied in the project. A charge controller is designed to prolong the battery life but discharge controller is not discussed.
1.5. Organization of the report

The thesis is organized into nine chapters. First chapter gives the general background of the project and objective of the thesis. The over view of remaining chapters are described as below:

Chapter 2 gives an overview of the lead acid batteries such as its structure and types of lead acid batteries. In order to be familiar with the battery terms and concept various terminology used in the batteries are briefly described in the second part of the chapter.

Chapter 3 gives the theoretical introduction of different existing lead acid battery model. The model is introduced systematically from a simple model to the complex model. The detailed analysis of the selected model is presented in chapter 6.

Chapter 4 starts with the description of importance of the charging methodology. The methods and techniques used for charging lead acid batteries are described in this chapter. A comparison is done between the different charging techniques to come up with the appropriate charging technique for our system.

Chapter 5 is the experiment and model selection. The experimental setup used in the project is briefly described and the output from the experiment is presented. The simulated output of the existing theoretical models is presented. At the end section a comparison is made between the model outputs and the experimental output. Based on the comparisons an appropriate model is selected for the project.

Chapter 6 deals with the final model of the lead acid battery. A detailed analysis of the model is presented.

Chapter 7 presents the model parameter identification. The chapter provides a detailed analysis of the estimation method used. The chapter is divided into two parts. Firstly, the parameters are analyzed according to the lab test. In the second part principle of Simulink parameter estimation is introduced. The parameter is estimated using the Matlab Simulink toolbox using the experimental value of the parameter as the initial value. The validation of the model is also presented.

Chapter 8 develops an algorithm for the design of the charge controller used in the project. The algorithm is implemented in the Simulink and the output is discussed.

Chapter 9 gives the future work and improvements that can be implemented are projected.
CHAPTER 2
Lead Acid Battery

2.1. General Overview of Lead Acid Battery

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 [12].

2.1.2. Structure and Operation
Lead acid batteries are constructed with the positive electrode (anode) made from lead dioxide and the negative electrode (cathode) is made from pure lead. Both electrodes are immersed into the electrolyte which is sulphuric acid for lead acid batteries. These structures make the battery energy storage device, as they can convert electrical energy into chemical energy and vice versa [17].

Fig: 3 Lead Acid battery and its components
**Discharging**

During discharging the negative plate acts as the anode and the positive plate act as the cathode. When a load is connected between two electrodes the excess electrons move from anode to cathode as a current and electricity is generated.

At Anode

\[ Pb + HSO_4^- \rightarrow PbSO_4 + H^+ \]

At Cathode

\[ PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O \]

**Charging**

During charging an external power supply is connected to the electrodes. The lead sulphate is changed back to lead and lead dioxide as the electrons are forced to flow backward against the electro potential. Sulphuric acid is restored back to the liquid electrolyte.

At Anode

\[ PbSO_4 + 2H_2O - 2e^- \rightarrow PbO_2 + HSO_4^- + 3H^+ \]

At Cathode

\[ PbSO_4 + H^+ + 2e^- \rightarrow Pb + HSO_4^- \]

**2.1.3. 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 centres, offgrid system etc. Flooded lead acid batteries are less sensitive to the charging and should be kept upright [17].

*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 [17].

*Valve Regulated Lead Avid Battery (VRLA)*

The electrolyte in VRLA batteries are sealed in the container. The plates, size and weight of these kind 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 [17].
Absorbed Glass Mat (AGM) Batteries
The electrolyte in these kind 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 [17].

2.2. Terminology used in batteries

2.2.1. Battery Capacity
Battery capacity is the measure of a battery’s ability to store or deliver electrical energy and is commonly expressed in units of ampere-hours. Ampere-Hour is calculated by integrating the discharge current in amperes over a specific time period. The transfer of one-ampere over one-hour is equal to an ampere hour or is equal to 3600 coulombs of charge. Let’s say if a battery delivers 5-amps for 20-hours it is said to have delivered 100 ampere-hours. The quantity of active material, the number, design and physical dimensions of the plates, and the electrolyte specific gravity etc determines the capacity of the battery. Generally, capacity is specified at a specific discharge rate or over a certain time period [18]. According to Peukert’s law:

\[ C_p = I^k t \]

Where \( C_p \) = capacity on one ampere discharge rate

\[ I = \text{Discharge current} \]

\[ K = \text{Peukert’s constant} \]

\[ t = \text{Time of discharge} \]

Battery capacity is always referred as “\( C_n \)” which means to complete discharge the battery in n hours. The capacity under ten hour discharge rate “\( C_{10} \)” is always taken as the nominal capacity.

2.2.2. Cut off Voltage
It is the lowest voltage which a battery system is allowed to reach in operation. It is provided by the manufacturing datasheet at a defined discharge rate.

2.2.3. Rate of Charge/Discharge
It is the ratio of the nominal battery capacity to the charge or discharge time period in hours. For example, a 5-amp discharge for a nominal 100 ampere-hour battery would be considered a C/20 discharge rate.
2.2.4. 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, the open circuit voltage of a fully charged lead-acid battery is typically about 2.1-volts.

2.2.5. Electromotive force
Energy is transferred to the electron by the batteries so that they flow around a circuit. Total amount of energy per coulomb of charge supplied by the battery is referred as electromotive force. It is calculated by the difference between the electric potential of the two electrodes of each cell. This electromotive force is numerically equal to the battery open circuit voltage.

2.2.6. 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.

2.2.7. 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.

2.2.8. Internal Resistance
The path of the electron while flowing through the battery will have internal resistance. This internal resistance depends on the cells design, construction, age and condition. Therefore, on discharge this internal resistance causes the voltage measured across the cells terminal to be less than the EMF voltage. Thus when the current flows the resistance is given by
\[ r = \frac{V_{oc} - V_t}{t} \]
Various factors cause the increase in internal resistance of the battery such as sulphation, temperature, complete or deep discharge leading to excessive use of the active material. Sulphation is a process of formation of the stable crystalline form of the lead sulphate which cannot be converted to lead, lead oxide and sulphuric acid and cannot conduct electricity [19]. High temperature operation increase the aging rate of the battery therefore increasing the internal resistance.

2.2.9. Self Discharge Rate
Even if the battery is not charged or discharged in open-circuit mode a battery undergoes a reduction in state of charge, due to internal mechanisms and losses within the battery. Self discharge rate depends
on the active materials and grid alloying elements used in the design so different batteries have different self discharge rate.

2.2.10. State of Health
State of health is defined to show how weak the battery is and represents the percentage of remaining capacity to the initial capacity when the battery is brand new.

2.2.11. Battery Lifetime
Battery lifetime will be affected in different ways depending on the conditions they are treated and in a number of design factors. The stress factor of the battery is a function of the design, selection of the materials and manufacturing processes. Generally, the battery life span is quoted by the number of cycles that it is expected to perform. Some of the major damaged factors are discussed below:

Positive Grid Corrosion
The available capacity and internal resistance of the battery is affected by the corrosion of the positive grid. As the grid corrodes some of the active mass has reduced connection to the terminal as a result the capacity is decreased. The internal resistance increases as the corrosion increases because of the reduced connectivity of the corroded material and decrease in the cross section of the positive grid. The corrosion of the positive grid takes place with the increase in the voltage, acid concentration and temperature. Generally, as the temperature increases by 10°C the rate of an electrochemical reaction doubles, battery life decreases by a factor of two for every 10°C increase in average operating temperature [17].

Irreversible sulphation
Sulphate crystals are formed while the battery is discharged and these crystals are dissolved during charging. However, if the battery is not operated properly the sulphate crystals grow in size and resulting in irreversible sulphation. This leads the loss in capacity of the battery and low battery lifetime as the large sulphate crystals will not take part in chemical reaction and also will leave part of active material insulated from the terminal [19].

Shedding
The process of detachment of the active material from the electrode due to overcharging and sulphation reducing the battery capacity is called shedding. While sulphation creates the difference in volume of the sulphate crystals and lead oxide on the positive electrode leading to shedding, gassing bubbles created during overcharging detach the active material from electrode [19].
Softening of the electrodes

It is the change in the mechanical structure of the electrodes and active material due to overcharging and undercharging. Softening of the electrodes decreases the capacity of the battery as the porosity and surface area of the electrolyte is decreased as the chemical reaction is concentrated to less space [19].

2.2.12. Battery Efficiency

Due to the internal resistance and the fact that the charging voltage is greater than the discharge voltage the energy returned by the battery upon discharge will be less than the energy used for recharging. Typically a lead acid battery will be 80 to 90% efficient when considering ampere hours [17].

\[
\text{ampere–hour efficiency} = \frac{\text{discharged Ah} \times 100 \%}{\text{charging Ah}}
\]

2.2.13. Thermal Runaway

Thermal runaway is the extreme example of battery getting heated, at which point the battery is almost certain to be damaged beyond repair. If the battery is not operated properly like operating in high temperature, high voltage beyond gassing voltage which results in extreme gas evolution, high increased water loss, excessive shedding of positive active material and increased positive grid corrosion. At thermal runaway, the heat generated internally in the battery is more than that can be dissipated to the surrounding so this can also damage the surrounding equipment. Henceforth, it is extremely important that the battery’s temperature is not high a while charging at high voltage [17].
CHAPTER 3
Types of Lead Acid Battery models

Modeling of the lead acid batteries can be done in numerous ways depending on the system requirement and accuracy [20]. These include Electrochemical Models, Computational Fluid Dynamics Models, Finite Element Models and Electrical Equivalent model. These models need experimentation to ascertain the characteristics and plot response curves for the battery, measuring voltage and currents during charge and discharging process. Electrochemical Models, Computational Fluid Dynamics Models, Finite Element Models are effective in gaining technical knowledge on the battery, but not very helpful in actual simulation and system behavior analysis purposes. But Electrical equivalent circuit Model represents the various parameters and characteristics of the battery by the electrical equation and is useful in simulation and system behavior analysis purpose.

Modeling of the lead acid battery is a new topic for me. The study of the various models is done from a very simple battery model to a complex battery model. The study is done in order to gain in depth knowledge of the electrical behavior of the battery. Hence, various electrical battery models are described below:

3.1 Simple Battery Model

![Equivalent circuit model of simple model](image-url)
If battery was linear then it acts as an electric bipole. A simple ideal model consists of $E_0$ as the electromotive force of the battery and a constant equivalent resistor ESR connected in series as an internal resistance. $V_0$ is the terminal voltage of the battery [21]. $V_0$ 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.

### 3.2. Modified Simple Battery Model

![Equivalent circuit of modified simple battery](image)

Fig: 5 Equivalent circuit of modified simple battery

It is the modified form of the simple battery model. The fixed resistance from the simple battery model is changed into a variable resistance which is dependent on state of charge. Here the resistance ESR is varying accordance with the battery state of charge [22].

$$ESR = \frac{R_0}{S^K}$$

Where, $E_0$ is the open circuit voltage, $R_0$ is the internal resistance R with the battery fully charged, $C_{10}$ is the nominal battery capacity given by the manufacture, $K$ is the capacity coefficient and $S$ is the state of charge varying from 0 to 1.
3.3. Advanced simple battery model

![Equivalent circuit of advanced simple battery](image)

Similar to the modified battery model more advanced simple battery model is presented in [23].

In this model the constant resistance is no longer constant but varies with the depth of discharge. The variation upon depth of discharge is either linear or non linear.

\[ V_{\text{terminal}} = V_{oc} - I_{\text{bat}} \times R_i \]

\( V_{\text{terminal}} \) is the output voltage, \( V_{oc} \) is the open circuit voltage, \( I_{\text{bat}} \) is the battery current and \( R_i \) is the resistance.

\( V_{oc} \) and \( R_i \) vary with the depth of discharge (\( Q \)), where \( Q = \frac{q}{q_{\text{max}}} \) and \( q = I_{\text{bat}} \times t \).

The variation upon depth of discharge is either linear or non linear which is given below:

**For linear variation:**

\( V_{oc} \) and \( R_i \) vary linearly with depth of discharge (\( Q \)).

\[ V_{oc} = a_0 + b_0 Q \]

\[ R_i = a_1 + b_1 Q \]

Here, \( a_0, a_1, b_0, \) and \( b_1 \) are the coefficient and the values are found experimentally in [23]. The internal resistance of the battery was given by

\[ R_i = \frac{V_{oc} - V_{\text{terminal}}}{I_{\text{bat}}} \]
For Nonlinear variation:

The $V_{oc}$ and $R_i$ vary non-linearly with the depth of discharge (Q).

$$V_{oc} = a_0 + a_1 Q + a_2 Q^2 + a_3 Q^3 + a_4 Q^4 + a_5 Q^5$$

$$R_i = b_0 + b_1 Q + b_3 Q^3 + b_4 Q^4 + b_5 Q^5$$

Here, $a_0$, $a_1$, $a_2$, $a_3$, $a_4$, $a_5$, $b_0$, $b_1$, $b_3$, $b_4$ and $b_5$ are the coefficient and the values are found experimentally in [23].

3.3. Thevenin Battery Model

![Fig: 7 Equivalent circuit of Thevenin model [24]](image)

Thevenin battery model is one of the most commonly used battery model. The model consists of ideal no-load battery voltage $V_{oc}$, internal resistance ($R$), Capacitance ($C_o$) and over voltage resistance ($R_0$). Capacitance between electrolyte and electrodes is given by ($C_0$) whereas $R_0$ represents the battery overvoltage due to the contact resistance of plate to electrolyte [24].

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

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

3.4. 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 [25].
The internal resistance is given by \( \frac{k}{soc} \).

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

Where, \( V_b \) is the terminal battery voltage, \( V_{oc} \) is the open circuit voltage and \( R_b \) is the battery terminal resistor.

3.5. Modified Thevenin Equivalent battery model

![Equivalent model of modified Thevenin battery](image)

Thevenin Battery Model was modified to improve accuracy so the modified Thevenin equivalent battery model is introduced. This model uses a capacitor \( C \), to represent the polarization capacitance and a shunt resistor \( R_b \) to represent its self-discharge. \( R_d \) and \( R_w \) are the resistors connected to the two parallel branches of the circuit and each diode facing the opposite direction respectively. This type of construction is to enable different resistances to be used to model the charging and discharging behavior of the internal resistance of the battery.

\[
\frac{dV_p}{dt} = -V_p \frac{1}{R_d C} + V_0 \frac{1}{R_d C} - I_b \frac{1}{C} , V_p \leq V_0
\]

\[
\frac{dV_p}{dt} = -V_p \frac{1}{R_c C} + V_0 \frac{1}{R_c C} - I_b \frac{1}{C} , V_p > V_0
\]
3.6. Copetti Model:

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

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

Fig: 9 Equivalent circuit of Copetti model [26]
\[
C_b(t) = \frac{1.67 \ C_{10}}{1 + 0.67 \left(\frac{i_{bat}(t)}{I_{10}}\right)^{0.9}} n^{0.16} \frac{1}{10}
\]

Here, \(i_{bat}\) is the battery current, \(u_{bat}\) is the battery voltage, \(n\) is the number of the cells, \(V_g = 2.35V\) is the gassing voltage, \(V_{cp}\) is the polarization voltage, \(V_{cb}\) is the electromotive force, \(R\) is the internal resistance, \(C_p\) is the polarization capacitor, \(C_{10}\) is the nominal capacity and \(I_{10}\) is the charge current corresponding to \(C_{10}\).

### 3.7. Randle’s Battery Model

![Fig: 10 Equivalent circuit of Randle’s model [27]](image)

The fig 15 represents the Randles model circuit where \(R_i\) is the resistance of the battery’s terminals and inter-cell connections. Similarly, \(R_t\) and \(C_s\) describe transient effects due to shifting ion concentrations and plate current densities. While \(R_d\) represents the self-discharging resistance, \(C_b\) 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 \(C_b\) [27].

\[
V'_{cb} = \frac{l_{in} R_d - V_{cb}}{C_b R_d}
\]

\[
V'_{cs} = \frac{l_{in} R_t - V_{cs}}{C_s R_t}
\]

A large time constants is involved with typical combinations of \(C_b\) and \(R_d\), 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 $C_b R_d$ is assumed to be large, hence neglected. Likewise, $R_d$ 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 [25]:

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

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

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

Where $C_s, R_t, C_b$ and $R_i$ are the parameters to be estimated.

### 3.8. Third Order Model

![Fig: 11 Equivalent circuit of third model [28]](image)

The model is described by equivalent electric network as shown in figure 10. The dynamic equation of the model represents the charge storage process in the battery and the electrolyte heating which is given as follows [28]:

$$\frac{dI_1}{dt} = \frac{1}{\tau_1} (I_m - I_1)$$

$$Q_e = \int_{0}^{t} -I_m(\tau) d\tau$$

$$C_\theta \frac{d\theta}{dt} = \frac{\theta - \theta_e}{R_\theta} + P_s$$

where
$Q_e$ = “extracted charge,” i.e., the charge that has been actually extracted from the battery starting from a battery completely full, $C_0$ = battery thermal capacitance, $R_\theta$ = thermal resistance and $P_s$ = heating power generated inside the battery by conversion from electrical or chemical energy.

Where $\tau_1 = R_1 C_1$

\[
SOC = 1 - \frac{Q_e}{C(0, \theta)}
\]

\[
DOC = 1 - \frac{Q_e}{C(I_{avg}, \theta)}
\]

\[
I_{avg} = \frac{I_m}{(\tau_1 s + 1)}
\]

\[
E_m = E_{m0} - K_e (273 + \theta) (1 - SOC)
\]

\[
R_0 = R_{00} [1 + A_0 (1 - SOC)]
\]

\[
R_1 = -R_{10} \ln (DOC)
\]

\[
R_2 = R_{20} \frac{\exp [A_{21} (1 - SOC)]}{1 + \exp (A_{22} \frac{I_m}{T})}
\]

\[
I_p = V_{PN} G_{PO} \exp \left[ \frac{V_{PN} (r_P S + 1)}{V_{po}} + A_p \left( 1 + \frac{\theta}{\theta_f} \right) \right]
\]

Where $E_{m0}$, $R_{00}$, $R_{10}$, $R_{20}$, $V_{PN}$, $G_{PO}$, $A_p$ and $A_{21}$ are the constants for the particular battery. The detailed analysis and the explanation of the model are presented in chapter 6.
CHAPTER 4
Charging/discharging methods and technique

The charging of lead acid battery is done with direct current. The charging and discharging of the battery plays a vital role on the battery lifetime. During discharge the chemical reaction is such that the active components of the battery plate i.e. lead and lead dioxide in the negative plate and positive plate respectively converts into free electrons, water and lead sulphate. The tricky part is during recharge, these sulphates are eliminated by recombining water into acid; however this should be carried on without losing hydrogen and oxygen gases which makes up water. The major reason of the losses of the gases is if the charging is done beyond the gassing voltage (2.54 V) and charging at higher temperature.

Battery charging technique also should consider the complete conversion of the active components. Battery can accept very high current energy but the chemical process in the battery is very slow. Pumping electrical energy faster than the chemicals can react to it can cause local overcharge, overheating, and unwanted chemical reaction near to the electrodes thus damaging the cell. Henceforth, a rest period is desirable so that the chemical process can propagate throughout the battery. As an analogy battery charging is like pouring a beer into the glass. If the beer is pour very quickly then a lot of froth can be seen and a very little beer at the bottom but if the beer is poured very slowly the beer settle till the forth disperses and then topping up results in completely filled glass [30].

4.1 Various Charging Methods and Techniques used for lead acid batteries
Usually the charging time of the sealed lead acid battery is 12-16 hours, up to 36-48 hours for the stationary batteries .But the charging time can be reduced to 10 hours or less with higher and multistage charging methods, the topping charge may not be complete [30]. Therefore, the charging techniques and methodology of lead acid vary with demand and charging time. Some of the charging techniques are discussed below:

4.1. Wa charging
This is the simplest kind of the charging method. The charger is built according to the type of the battery. If there is large amount of the charging time (10 hours) available then this kind of the charging technique is used. The battery is initially charged with the high current defined by the manufacture and then exponentially decreased as the voltage rises until the battery is fully charged. The charger is then deactivated. The efficiency is around 70 to 75% and the temperature increases up to +70°C. With this kind of charging method the battery lifetime is approximately 5 to 6 years [29].
4.1.1. WOWa Charging
In this type of the charging method the battery is initially charged at the constant current (nominal current) until the gassing voltage is reached then the current is decreased exponentially as in the Wa characteristics. The charge efficiency is about 85% and the temperature increases up to +7°C. The charging time is usually 6-7 hours. The battery lifetime is usually 5 years from this kind of the charging methods [29].

4.1.2. IUla Charging
In this kind of charging methods initially the battery is charged at a constant current until the cell voltage is reached to pre-set value. This type of charging is called the bulk phase. The second part is as the voltage reaches to the pre-set value the voltage is made constant and the current decreases exponentially until it reaches another pre-set value this is called the absorption. In this phase the saturation is provided to the battery. Finally the charger switches to the constant current mode until the voltage reached up to another pre-set value which is called the float charge. During this phase the losses due to self discharge is compensated. Finally the charger is switched off. This kind of the charger is
highly efficient with efficiency about 95% and the battery is charged 5 to 6 hours. The temperature rises up to 15°C and the life expectancy is about 3 to 4 years [29].

4.1.3. Pulsed charging
The battery is charged by the pulse current. The battery is initially charged by a constant current and then there is no current. After a small rest period the battery is again charged. These rest periods allows the chemical actions in the battery to stabilize by equalizing the reaction throughout the bulk of the electrode. It also helps in reducing the gas formation, crystal growth and passivation. It takes long time to charge the battery however the battery lifetime can be increased from this kind of charger [30].

4.1.4. Quick Charging
The battery is charged with constant current above the current limit from the manufacture data sheet taking temperature into consideration. The battery is stopped charging before the gassing voltage is reached. With this kind of the charger the battery is charged only 80% but the battery can be charged
within an hour. The battery life time is about 2 to 2.5 years. It is mostly applicable where there is no time to charge the battery [30].

Fig: 16 Voltage and Current Characteristics for quick charging.

4.2. Discharging
The battery should be discharged at the rated nominal current and the discharged rate is maintained constant. When the state of charge of the battery reaches 20 % then the discharging should be stopped. If the battery is over discharged then the sulphuric acid electrolyte can be depleted of the sulphate ion and becomes essentially water. The deficiency of the sulphate ion will cause cell impedance to rise and the resistance there will be hindrance in current flow.

4.3. Choice of appropriate charging method
The charging method depends on the demand and the available of charging time. For our project the charging is done by the renewable sources and generally for PV module the battery can be charged during the day and discharged during the night. Our main concern is the efficiency of the battery and the battery lifetime. Using Wa requires large amount of time while WOWa is least efficient compared to IUla. Pulse charging requires large amount of time and quick charging is not possible as the huge current cannot be produced by small PV module. Henceforth, the choice for appropriate charging method will be IUla with its advantages of high efficiency, charging time and life expectancy.
CHAPTER 5

Experiment and Model Selection

Experimental test based on 12V lead acid battery having a nominal capacity of 100 Ah was carried out. Some of the characteristics of the battery can be found in the tests. The data’s from the test will be used to select the appropriate model and the parameters for the model. Basically charging and discharging of the battery at different temperature was done.

5.1. Experimental Setup:
In the experiment, SMP charger 120 V/10A was used to charge the battery, a multimeter to log the data and Torkel 820 Battery load Unit was used as a discharger whose specification are provided in the appendix. Two temperature sensors were employed in the experiment and a heater was used to vary the temperature. The state of charge of the battery was measured with the help of specific gravity hydrometer. The equivalent circuit of the test designed for the experiment is shown in figure:

Fig: 17 Experimental Setup layouts
Fig: 18 Experimental setup
Charging:

During charging the Torkel load unit was disconnected and the SMP charger was connected to the battery. The battery was charged from the charger at a constant voltage of 14 V at normal room temperature and the current was maintained constant so that the charging voltage was constant. Once the charging voltage remain constant the battery starts charging the charging current steadily decreases. When the battery is empty the battery takes sufficiently large current however when the charge inside the battery increases, the charging current starts decreasing. The initial 90% of the charge was charged quickly but the remaining 10% took sufficiently large time to charge.

![Charging curve from the Experiment](image)

Discharging:

During discharging SMP charger was disconnected and Torkel load unit was connected. A constant load was applied on the battery and the performance of the battery was recorded. Four test were done for the discharging

i. Discharge at 18A at 25°C
ii. Discharge at 18A at 35°C
iii. Discharge at 10A at 25°C
iv. Discharge at 15A at 25°C

When the load was applied the battery terminal voltage drops significantly at the beginning. When the battery was approaching its minimum voltage the terminal voltage starts decreasing rapidly. The
temperature in the battery cell was also recorded and it shows that for normal temperature (25°C) the cell temperature was also same however for the same load the discharge time decreases with the increasing in the temperature.

Fig: 20 Discharge curve for discharge current 18A

Fig: 21 Discharge curve for discharge current 10A
5.2. 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 which is shown in fig 23 and the key output such as terminal voltage, cell temperature and state of charge of the battery.
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.

5.2.2. Modified Simple Battery Model
The output from the simulation of the battery with capacity is given as

![Modified Battery Model](image)

Fig: 23 Discharge curve from the experiment

![Simulink output for modified simple battery](image)

Fig: 24 Simulink output for modified simple battery
The output from this model fails to give the similar behavior as we required and also this model fails to describe the transient behavior of the battery. This kind of model can be used for the application where state of charge irrelevant to calculation such as sizing a system where the system has a fairly constant charge.

5.2.2. Advanced simple battery model

For linear variation:

\[ V_{oc} = a_0 + b_0 Q \]
\[ R_i = a_1 + b_1 Q \]

Here, \( a_0, a_1, b_0, \) and \( b_1 \) are the coefficient and the values are found experimentally in [23]. The internal resistance of the battery was given by

\[ R_i = \frac{V_{oc} - V_{terminal}}{I_{bat}} \]

The simulation result is shown below

![Fig: 25 Simulink output for linear variation for advanced simple model](image)

For Nonlinear variation:

The \( V_{oc} \) and \( R_i \) vary non-linearly with the depth of discharge (Q).

\[ V_{oc} = a_0 + a_1 Q + a_2 Q^2 + a_3 Q^3 + a_4 Q^4 + a_5 Q^5 \]
\[ R_i = b_0 + b_1 Q + b_3 Q^3 + b_4 Q^4 + b_5 Q^5 \]
Here, $a_0$, $a_1$, $a_2$, $a_3$, $a_4$, $b_0$, $b_1$, $b_2$, $b_3$, $b_4$ and $b_5$ are the coefficient and the values are found experimentally in [23]. The experimental procedure mentioned in [23] consisted of a motorcycle battery and it was made to discharge under a constant current of 2A. The terminal voltage of the battery was monitored and the open circuit voltage was measured at regular time intervals. Thus, simulating the battery model with the nonlinear relation with the values given in [23] gave us the following graph.

![Non linear Advanced Simple Battery Model](image)

**Fig: 26 Simulink output for Non linear variation for the advanced simple battery**

The advanced modified battery model also cannot give the output as we desired. The output of the battery did not match with the output we found experimentally so the model was discarded.

**5.2.4. 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. This model can be used which do not consider the dynamic state of charge. Hence, it is not suitable for our project.

**5.2.5. Copetti Model**

As described in section 3.6 the Copetti model was simulated in the Matlab Simulink with the provided equation and the model was tested with the constant discharged battery current of 18A. And found the output as shown in fig 27.
The charging curve was similar to the charging curve found experimentally however the discharge curve was not similar to our experimental output. The discharge curve should have been decreasing and when the minimum voltage approaches it should have been increasing but the output from the model is constant and then it starts decreasing linearly. So the model was also discarded as it could not fulfill our requirement.
5.2.7. Randle’s Battery Model

The above equation can be represented in state space matrix form as

\[
\begin{bmatrix}
0 & 0 \\
0 & \frac{1}{C_s R_t}
\end{bmatrix}
\begin{bmatrix}
V_{cb} \\
V_{cs}
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{C_b} & \frac{1}{C_s}
\end{bmatrix}
I_{in}
\]

\[
V_0 = [1 \ 1] \begin{bmatrix}
V_{cb} \\
V_{cs}
\end{bmatrix}
+ [R_t]I_{in}
\]

The simulation output for the Randles model is given as

![Discharge Curve for the Randle’s Model](image)

**Fig: 29 Simulation Output for the Randle’s model**

The output from this model is very similar to the output we got from the experimental observation. Initially the output voltage decreases rapidly and then starts decreasing rapidly, when the battery reaches the minimum voltage there is a sharp decrease and then the terminal voltage increase at the end and then the output voltage stops. However, in this model the temperature is considered to be constant during the whole process. So, the model is not appropriate for the system.

5.2.8. Third Order Model

Using the parameter given in [21] the model was simulated and the output was generated which is given in fig 29.
Fig: 30 Simulation result for the third order model

The experimental curve fig 23 and the model output fig 30 are very similar. On comparison of these two figures the characteristic of the curves are very similar and suits more approximately than the previous model discussed above.

5.3. Discussion of the Results
The main purpose of the theoretical simulation of the model is to find the model that best suits the experimental observation of our battery. Henceforth, we compare the simulation results with our experimental results to find the model which can describe our system.

In accordingly, let us discuss each of the results obtained. Considering the model output from the modified simple battery model from fig 23, we see that the terminal voltage decreases exponentially. However, our experimental observation shows that the voltage decreases rapidly but at the end it again increases so this model cannot be used.

When considering the advanced simple battery model for the linear case from fig 25 we see that the terminal voltage decreases linearly till the end. However from our actual experiment result from fig 23, here there is linear decrease for majority of discharge but for the last few percentage of discharge the decrease is non linear. Hence this model is discarded. Similarly, for non linear case of the same model in fig 26 the terminal voltage decreases nonlinearly throughout the experiment. In contrast to this in our
experiment non linearity is felt only at the end of the discharge. Hence the model cannot be used for our system.

From Copetti model from fig 28 we see that the terminal voltage is constant and then starts decreasing linearly. But from fig 23 the output should have been decreasing and when the minimum voltage approaches it should have been increasing. Hence, the model is discarded.

When we consider the result from the Randle’s battery model in fig 29, the result is very similar to our experimental observation. The battery decreases linearly and at certain point there is a sharp decrease in battery and then the terminal voltage increases at the end. The model can be used as our model as this gives the similar output as we needed. However the model fails to describe the state of charge of the battery and cell temperature. The model assumes the cell temperature to be constant throughout the process. But this is not the case hence the model is discarded.

When comparing fig 30 of the third order model with the experimental output in fig 23, the output is very similar and the model also describe about the state of charge, cell temperature and value of the resistance. Hence this model is the appropriate model to describe our system.

5.4. Conclusion

Simulation were performed for the model given in [22],[23],[26],[27] and [28]. On comparison with the experimental data we found that model in [27] and [28] is very similar to the experimental data. However, model [27] considers the battery temperature constant but our model should give the variation of the output with respect to the temperature. In regard of this Randles model is not suitable for our project. Hence the final battery model for the project is chosen as the third order model.
CHAPTER 6

Final Model of the Lead acid battery

From chapter 4 we found that the third order model is the appropriate model for our system. In section 3.8 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 final model is divided into three sub models Capacity model, Voltage model and Thermal model. The following structure model gives the detailed analysis of the model.

Fig: 31 Final Structure model for the thesis
The model can be divided into three sub models:

6.1.1. Capacity Model

The input for the model is charge/discharge current. The rated capacity, Used capacity and Actual capacity is calculated with the help of this input current and under different state of charge. The modeling of battery requires various circuit elements. The dependence of the capacity in the electrolyte temperature during fixed discharge current is given by:

\[
C(I_n, \theta_n) = C_0^* \left(1 + \frac{\theta_n}{\theta_f}\right)^\epsilon
\]

\(\theta_f\) is the electrolyte freezing temperature and \(C_0^*\) is the rated capacity at the rated discharge current in 0°C.

The capacity based on the discharge can be calculated as below [28]:

\[
C(I, \theta) = \frac{K_c C_0^*}{1 + (K_c - 1) \left(\frac{I}{I^*}\right)^\delta \left(1 + \frac{\theta_n}{\theta_f}\right)^\epsilon}
\]

Where \(K_c\) is a constant, \(C_0^*\) is the no load capacity, \(\theta\) is the electrolyte temperature, \(I^*\) is the nominal battery current and \(I\) is the discharge current. With the help of these capacities the state of charge and depth of discharge is calculated.

The charge extracted from the battery was a simple integration of the current flowing into and out of the battery. The initial value of the extracted charge is necessary for the simulation purpose [28].

\[
Q_e(t) = Q_{einit} + \int_0^t -I_m(\tau) d\tau
\]
Q_e is the extracted charge, Q_{eint} is the initial extracted charge, I_m is the main branch current τ is an integration variable and t is the simulation time.

State of charge (SOC)

State of charge measure the fraction of charge remaining in the battery

\[ SOC = 1 - \frac{Q_e}{C(0, \theta)} \]

Depth of charge (DOC)

Depth of charge measure the fraction of the usable charge remaining in the battery

\[ DOC = 1 - \frac{Q_e}{C(I_{avg}, \theta)} \]

6.1.2. Voltage Model

The state of charge and depth of discharge from the capacity model is used to find the resistance (R_0, R_1, R_2) and electromotive force (E_m) of the battery.

Electromotive force (E_m)

When fully charged the electromotive force (emf) was assumed to be constant. The emf varied with temperature and state of charge (SOC) and is given by the equation [28]:

\[ E_m = E_{m0} - K_e(273 + \theta)(1 - SOC) \]

Where, E_m is the open-circuit voltage (EMF) in volts, E_{m0} is the open-circuit voltage at full charge in volts, K_e is a constant, θ is electrolyte temperature in °C, and SOC is battery state of charge.

Resistance (R_1)

This resistance depends on the depth of discharge increases exponentially during discharge is given by:

\[ R_1 = -R_{10}.\ln(DOC) \]

Where R_1 is the resistance, R_{10} is a constant, and DOC is the depth of discharge.

Resistance (R2)

The resistance increased exponentially as the battery state of charge increased. The resistance primarily affected the battery during charging. The resistance became relatively insignificant for discharge currents
\[ R_2 = R_{20} \frac{\exp \left[ A_{21} (1 - SOC) \right]}{1 + \exp \left( A_{22} \frac{l_m}{I^*} \right)} \]

Where \( R_2 \) is a main branch resistance in Ohms, \( R_{20} \) is a constant in Ohms, \( A_{21} \) is a constant, \( A_{22} \) is a constant, \( E_m \) is the open-circuit voltage (EMF) in volts, \( SOC \) is the battery state of charge, \( l_m \) is the main branch current in Amps, \( I^* \) is the nominal battery current in Amps.

**Terminal resistance (RO)**

The resistance was assumed constant at all temperatures, and varied with the state of charge and is given by

\[ R_0 = R_{00} [1 + A_0 (1 - SOC)] \]

Where \( R_0 \) is a resistance in Ohms, \( R_{00} \) is the value of RO at SOC=1 in Ohms, \( A_0 \) is a constant, SOC was the battery state of charge.

**Terminal Voltage (V0)**

The terminal voltage is given by

\[ V_{out} = V_{pn} - R_0 l \]

Where \( V_{pn} \) is the voltage at the parasitic branch and is given by

\[ V_{pn} = IR_1 + E_m \]

Where \( E_m \) is the EMF voltage and \( R_1 \) is the resistance.

### 6.1.3. Thermal Model

The thermal model estimates the change in electrolyte due to internal resistive losses and due to ambient temperature \([28]\).

\[ \theta(t) = \theta_{int} + \int_0^t \frac{P_s - (\theta - \theta_{a})}{C_\theta} \, d\tau \]

Where \( P_s \) is the power loss of \( R_0 \) and \( R_2 \), \( R_\theta \) is the thermal resistance, \( C_\theta \) is the thermal capacitance and \( \theta_a \) is the ambient temperature.

\[ P_s = \frac{V_{pn}^2}{R_1} + l^2 R_0 + l^2 R_2 \]
6.2. Summary of the final Model

This model is constituted by:

- The electrical equivalent of the model consist of main branch (two RC block) and a parasitic branch.
- Capacity model gives state of charge and depth of charge, Voltage model gives the resistances as a function of state of charge and depth of charge, Thermal model gives the internal temperature.

The dynamic equations of the model are therefore:

\[
\frac{dI_1}{dt} = \frac{1}{\tau_1} (I_m - I_1)
\]

\[
Q_e = \int_0^t -I_m(\tau) d\tau
\]

\[
C_\theta \frac{d\theta}{dt} = \frac{\theta - \theta_e}{R_\theta} + P_s
\]

Fig : 33 Final Equivalent Circuit model for the system [28]
CHAPTER 7

Parameter Estimation of the Model

Estimation theory one of the branches of statistics and signal processing where parameters are estimated based on measured data. These parameters describe the whole physical setting such that the parameters affect the distribution of the measured data. Using the measured data the estimator estimates the unknown parameter. Thus, estimation is a process where the measured data is the input and output is the estimate of parameter. However, an optimal estimator is always desirable [31].

Estimation process consists of following steps:
1. Firstly, a model is found from the probability distribution of the measured data. The model shows how the measured data depends on parameter to be estimated.
2. A theoretical precision is found by the model.
3. An estimator is developed. A comparison is done between optimal performances in step 2.
4. Finally, simulation is run using the estimation to test the performance.

Parameter estimation is a discipline that provides tools for the efficient use of data for aiding in mathematically modeling of phenomena and the estimation of constants appearing in these models [32].

7.1. Parameter Estimation for the Project

In our project let \( X = [X_1, X_2, \ldots, X_k] \) is the input vector (charging current or the discharging current) and \( Y = [Y_1, Y_2, \ldots, Y_k] \) is the output vector (terminal voltage) observed. Let us consider \( \theta = (\theta_1, \theta_2, \ldots, \theta_k) \) be the vector of the parameters that need to be determined (thirteen parameters that needed to be determined). Then,

\[ Y = \theta^T X \]

Our main objective is to find the value of parameter vector (\( \theta \)) when both the input vector (\( X \)) and output vector (\( Y \)) is known.

In order to estimate \( \theta \), let \( T = (t_1, t_2, \ldots, t_k) \) be the vector of the estimated parameters for the same input (\( X \)) and for the estimated output (\( \hat{Y} \)). Then,

\[ \hat{Y} = T^T X \]
Let \( \varepsilon \) is the error between the observed output and estimated output.

Then,

\[
\varepsilon = \hat{Y} - Y
\]

i.e.

\[
\varepsilon = (T - \theta)^T X
\]

The values of \( T \) is updated in such a way that the error \( (\varepsilon) \) tends to zero and hence the estimated output converges to observed output. Hence the mean square error is given by

\[
 mse \ varepsilon = E(t_k - \theta_k)^2
\]

Hence, \( \varepsilon \rightarrow 0 \).

Implies \( \hat{Y} \rightarrow Y \) and \( T \rightarrow \theta \).

Thus, our estimated parameters converge to the actual parameters.

### 7.2. Implementation of the parameter estimation

The parameter estimation used in this project can be divided into two parts. Firstly the parameter is estimated with the lab test using the instruction given in [28] and then using Simulink parameter estimation. The Simulink parameter estimation needs an initial value of the parameters. But the parameter that defines the final model is very large and the initial values cannot be guessed. Therefore, the parameter estimation of the battery was firstly done with the lab test as instructed in [26] and these data were used as the initial values for the parameter estimation using the Simulink parameter estimation.

#### 7.2.1. Parameter estimation using Lab Test

The equation mentioned in the mathematical model contains constant that must be determined experimentally. These constants or parameters can be divided in three categories:

- The capacitance parameters
- The voltage parameters
- The thermal parameters
Parameters referring to Battery Capacity

To find the parameters four test were performed using different currents and temperature. The data’s are given in table 1.

Table: 1 Parameters referring to battery capacity

<table>
<thead>
<tr>
<th>Discharge Current</th>
<th>Temperature (degree Celsius)</th>
<th>Capacity(Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 A</td>
<td>25</td>
<td>68.1</td>
</tr>
<tr>
<td>18 A</td>
<td>35</td>
<td>75</td>
</tr>
<tr>
<td>10 A</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>15 A</td>
<td>25</td>
<td>76.6</td>
</tr>
</tbody>
</table>

Battery freezing temperature is -40 degree Celsius. These four couples \((I_1, \theta_1), (I_2, \theta_2), (I_3, \theta_3),\) and \((I_4, \theta_4)\) are used in the system of four equations to find the constants \(C_0^*, K_c, \varepsilon\) and \(\delta\).

Using \(C(I, \theta) = (1 + \alpha \Delta \theta)C(I_0, \theta)\) the value of the temperature coefficient \(\alpha\) was found. \(\varepsilon\) and \(\alpha\) are related as \(\varepsilon = \alpha(\theta_n - \theta_f)\). So the value of \(\varepsilon\) is found. Similarly, \(C_0^*\) was found by the relation

\[
C(I_n, \theta_n) = C_0^* \left(1 + \frac{\theta_n}{\theta_f}\right)^\varepsilon.
\]

Hence \(K_c\) and \(\delta\) were found by the relation

\[
C(I, \theta) = \frac{K_c C_0^* K_t}{1 + (K_c - 1) \left(\frac{I}{I^*}\right)\delta}.
\]

Table: 2 Final parameter value from the experiment

<table>
<thead>
<tr>
<th>Parameters</th>
<th>(C_0^*)</th>
<th>(K_c)</th>
<th>(\varepsilon)</th>
<th>(\delta)</th>
<th>(\alpha)</th>
<th>(K_t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>72.37 Ah</td>
<td>1.2</td>
<td>0.75</td>
<td>2</td>
<td>0.011</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Parameters referring to the voltage parameters

Fig: 34 typical voltage and current profile for a constant current discharge [21]
To identify $E_{mo}$ and $K_e$ one needs two equations, these equations were obtained while measuring the voltage at the beginning and end of the discharge test, $V_0$ and $V_1$. The corresponding state of charge at the beginning and end was measured. Similarly, $R1$ was identified by making the difference of ($V_4-V_3$). From the lab test following values were obtained.

Table: 3 Voltage found at the end and beginning of the experiment

<table>
<thead>
<tr>
<th>Discharge Currents</th>
<th>$V_0$</th>
<th>$V_2$</th>
<th>$V_3$</th>
<th>$V_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 A</td>
<td>12.95</td>
<td>12.30</td>
<td>11.14</td>
<td>12.32</td>
</tr>
<tr>
<td>15 A</td>
<td>12.95</td>
<td>12.6</td>
<td>11.3</td>
<td>12.03</td>
</tr>
<tr>
<td>10 A</td>
<td>12.95</td>
<td>12.7</td>
<td>11.57</td>
<td>12.04</td>
</tr>
</tbody>
</table>

Table: 4 Parameters found experimentally

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$R_{00}$</th>
<th>$A_{0}$</th>
<th>$R_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>0.0047</td>
<td>2</td>
<td>0.049</td>
</tr>
</tbody>
</table>

Parameters referring to the battery thermal model
The two parameters are identified from manufactured data sheets:

Table: 5 Parameters found in the manufacture data sheet

<table>
<thead>
<tr>
<th>Thermal Capacitance ($C_θ$)</th>
<th>Thermal Reactance ($R_θ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1.8</td>
</tr>
</tbody>
</table>

7.2.2. Model Parameter Identification using Simulink Parameter estimation
The parameters found experimentally are not the optimum parameter and all of the parameters cannot be found experimentally. Therefore optimum parameter identification becomes an integral part of the project. The parameter estimation in the project was done using Simulink parameter estimation method.

The Simulink parameter estimation method is an optimization process that adjusts the parameter by comparing the data generated by Simulink model with the measured experimental data. The parameter estimation method estimates the parameter to minimize the user selected cost function that typically calculates a least square error between the empirical and model data signals. The set of the parameters to achieve the least value of the objective function is considered to be the fittest set.
The cost function in the project is the difference between the output voltage from the experimental data and the simulated output. The parameter is identified in such a way that the cost function is minimized and the simulated output is fitted to the experimental output.

\[
\text{Cost function} = \left( \sum_{t_0}^{t_n} W(t)(V_{\text{experiment}} - V_{\text{simulated}}) \right)
\]

Where,

\(W(t)\) = weights of the difference in the simulated and experimental results

\(V_{\text{experiment}}\) = experimental voltage data

\(V_{\text{simulated}}\) = simulated voltage data
The cost function represents the sum of error values at each time interval. Fig 36 shows the cost function of the simulated voltage data and the experimental data after the Simulink parameter estimation. Fig 37 shows the adjustment of the parameter in order to minimize the cost function. The simulation is stopped when the local minimum is obtained and the parameter values converge.

Fig: 36 The cost function for simulating the model in Simulink parameter estimation.
As the parameter value improve, the simulation curve gets closer to the experimental curve. Once the simulation is completed the estimated parameter value was inspected.

Fig: 37 the trajectories of the estimated parameters after the simulation

Fig: 38 Final estimated parameter values from the Simulink parameter estimation.
7.2.3. Validation of the model

In order to validate the model two sets of experimental test have been adopted to compare with the simulation results. The validation results using two experimental tests are shown in fig 36 and 38.

From the simulation result fig 39 and 40, the discharge begins at the voltage 12.62 and the simulation result shows a little variation at the first 300s. While the experimental terminal voltage decreases linearly the simulated result is constant for 50s. Then both 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 1750s. The error voltage is 0.01%.
From fig 41 and 42, the discharge starts at 13.2 V and the experimental terminal voltage decreases linearly from 12.6V but the simulated voltage is not uniform at the beginning of the discharge. However, the voltage starts decreasing linearly after 200s. The error between simulated and experimental voltage
is increasing after 1000s. However at the end of the discharge the outputs show a reasonable agreement. The error is 0.3%.

7.4. Discussions
Two sets of experimental data’s were used in order to validate the mathematical model of the battery. The first validation data shows a reasonable agreement with the simulation result with an error of 0.01% at the beginning of the data. This is due to the ‘coup de fouet’, a phenomenon associated with the voltage drop at the beginning of the discharge [33]. In addition to this ‘coup de fouet’ can be also seen in the second validation data. There was however an error of 0.3% between simulated and experimental voltage. This is due to the fact that the initial thermal parameters were taken directly from the manufactured data sheet instead from the experiment. Also, the experiment was carried out immediately after being charged so the lead acid battery was not stable enough. Hence the deviation can be observed between simulated and experimental voltage.

7.5. Summary
Estimation theory and parameter estimation is discussed and two methods to estimate parameters are described in this chapter. Parameter estimation of the final model is done by two methods. Firstly the parameters are estimated by the Lab test and then the values obtained are used as the initial value for the Simulink Parameter Estimation. The algorithm of Simulink Parameter Estimation is discussed and implemented to find the values of the parameters. The parameters identified are validated by the two sets of other experimental test results. The average result found is 0.2%. The two results show the same transient but with different time scale.

The final values of the parameters found are:

<table>
<thead>
<tr>
<th>Parameter referring to Capacity Model</th>
<th>$K_e = 1.2,$ $K_t = 0.47,$ $\delta = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter referring to Voltage Model</td>
<td>$K_e = 6e - 04, R_{10} = 1.00e - 03$ $R_{00} = 0.0042, A_0 = 2, E_{mo} = 2.18$ $V_{po} = 0.12, G_{po} = 2e - 11$</td>
</tr>
<tr>
<td>Parameter referring to Thermal Model</td>
<td>$C_{theta} = 2$ $R_{theta} = 0.3$</td>
</tr>
</tbody>
</table>
CHAPTER 8
Charge Controller Implemented in the Project

In chapter 4 we discussed the various charging and discharging methods and techniques. We also discuss the application of various charging techniques. From the discussion we came to the conclusion that IUIₐ method is the appropriate charging method for our system. In this chapter a detailed overview of the method is discussed and the algorithm for the method is discussed and the implemented in the Simulink is discussed.

8.1. IUIₐ Charging
This charging method is also known as the three step charging method [30]. The three steps taken are

8.1.1. Bulk charging
In this step the battery is charged with the constant rated current and the output voltage is increased. In this step the battery refills all the energy drawn during the discharge process. However this is done without losing water. In this step the battery replenished up to 80 to 90 percent. The output voltage increases until the desired voltage then the charging process is changed to next step.

8.1.2. Absorption Charging
In this process the current is decreased and the output voltage is constant. In this step the water loss is minimized. This process balance 10 to 20 percent of charge.

8.1.3. Float charging
When the current decreases to 3% of the rated current the float charging occurs. In this step a constant voltage is applied to prevent the self discharge of the battery.

Fig: 43 Ideal three steps or IUIₐ Charging Method
8.2. Charging Algorithm

Start

Check the state of charge of battery

Charge the battery with constant rated current

<60%

Yes

Decrease the current

< 3% of rated current

Yes

Charge the battery with constant current

Check the state of charge of battery

>80%

No

No

Stop

Fig: 44 Algorithm for battery charging
The algorithm developed to charge the battery is shown in the fig 44. At the starting the state of charge is determined and the steps that need to be implemented are determined. The battery is charged initially with the rated current. When the battery’s state of charge is more than 60 percent then the charging current is decreased until the current decreases to 3 % of the rated current. Then the battery is charged with constant current until the state of charge of the battery is more than 80 percent. Finally the charging process is stop when the battery reaches more than 80 percent.

8.3. Final System Block Diagram

![Final System Block Diagram](image)

Fig: 45 Final System Block Diagram implementing the battery model

Fig 45 shows the final block diagram of the system after implementing the charge controller and the battery model. The system is an open loop charge controller. Here the system input is the discharge/charge input current (U) and the system output is terminal voltage (V). The output (Y) is the state of charge of the battery that triggers the set point and the input is then given to the charge controller according to the set point.
8.4. Results after implementing the charge controller

The algorithm was implemented in the Matlab Simulink using the output from the final model. Fig 46 shows the output obtained from the implementation of the algorithm. When a constant rated current was applied the terminal voltage increases until the output voltage is 14.8V or 2.46V per cell. This shows the bulk charging phase of the charge controller. The current is decreased and the output of the battery remains constant showing the absorption state and when the current is 3% of the rated current the battery is charged with constant current. The battery is in float state and in the fig 46 a slight change can be seen and then the charging was stopped when the battery was fully charged.

In nutshell, the charge controller was successfully implemented in the simulink using the battery model.
Chapter 9

Conclusions and Future Research

This chapter gives the summary of the achievement of the project work in battery modeling and charge controller design. The possible direction of the future work is also described in this chapter.

9.1. 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, their time of replacement and a significant investment cost needed for the system installation.

In this thesis, the capacity status of the battery is studied in relation to the internal resistance 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 0.3%.

A charging methods and technology were studied and an appropriate charge controller was implemented for the storage system based on the model designed in Matlab Simulink. Henceforth, the design of the battery storage system was successfully done.

9.2. Future Research Work

Taking the limitation of the project from section 1.4 into consideration in the future 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 used for the online application can be done in the future. A 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.
BIBLIOGRAPHY


Appendix A

Fig: A1 Simulink diagram for the modified simple battery model

Fig: A2 Simulink diagram for the advanced linear battery model
Fig: A3 Simulink diagram for non linear battery variation for advanced simple battery model

Fig: A4 Simulink diagram for Copetti model for discharge
Fig: A5 Simulation of Copetti model for Charge

Fig: A6 Simulation of the Randle’s model
Appendix B

Final Model

Fig: B1 Simulink diagram for Final Battery Model
Capacity Model

Fig: B1 Simulink diagram for Actual Capacity

Fig: B2 Simulink diagram for Used Capacity
Fig: B3 Simulink diagram for Rated Capacity

Fig: B5 Simulink diagram for DOC

Fig: B6 Simulink diagram for SOC
Voltage Model

Fig: B7 Simulink diagram for R1

Fig: B8 Simulink diagram for EMF
Fig: B9 Simulink diagram for R0

Fig: B9 Simulink diagram for Ip

Fig: B9 Simulink diagram for Terminal voltage
Thermal Model

Fig: B10 Simulink Diagram for Power

Fig: B11 Simulink Diagram for Cell temperature
Charge Controller

Fig: B12 Simulink Diagram for Charge Controller
### Appendix C

From manufacturer data sheet

<table>
<thead>
<tr>
<th>Cell Voltage (OCV)</th>
<th>Specific Gravity (SG)</th>
<th>Remaining Capacity</th>
<th>Voltage at 5/h Load Current for 100% of allowed, 80% of nominal capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.13</td>
<td>1.29</td>
<td>100%</td>
<td>1.990</td>
</tr>
<tr>
<td>2.12</td>
<td>1.28</td>
<td>94%</td>
<td>1.975</td>
</tr>
<tr>
<td>2.11</td>
<td>1.27</td>
<td>87%</td>
<td>1.960</td>
</tr>
<tr>
<td>2.10</td>
<td>1.26</td>
<td>81%</td>
<td>1.945</td>
</tr>
<tr>
<td>2.09</td>
<td>1.25</td>
<td>74%</td>
<td>1.930</td>
</tr>
<tr>
<td>2.08</td>
<td>1.24</td>
<td>68%</td>
<td>1.915</td>
</tr>
<tr>
<td>2.07</td>
<td>1.23</td>
<td>61%</td>
<td>1.900</td>
</tr>
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<td>2.06</td>
<td>1.22</td>
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<td>2.05</td>
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<td>1.870</td>
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<td>2.04</td>
<td>1.20</td>
<td>42%</td>
<td>1.855</td>
</tr>
<tr>
<td>2.03</td>
<td>1.19</td>
<td>35%</td>
<td>1.840</td>
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<td>2.02</td>
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<td>1.825</td>
</tr>
<tr>
<td>2.01</td>
<td>1.17</td>
<td>22%</td>
<td>1.810</td>
</tr>
<tr>
<td>2.00</td>
<td>1.16</td>
<td>16%</td>
<td>1.795</td>
</tr>
<tr>
<td>1.99</td>
<td>1.15</td>
<td>9%</td>
<td>1.780</td>
</tr>
<tr>
<td>1.98</td>
<td>1.14</td>
<td>3%</td>
<td>1.765</td>
</tr>
<tr>
<td>1.97</td>
<td>1.13</td>
<td>-4%</td>
<td>1.750</td>
</tr>
<tr>
<td>1.96</td>
<td>1.12</td>
<td>-11%</td>
<td>1.735</td>
</tr>
<tr>
<td>1.95</td>
<td>1.11</td>
<td>-17%</td>
<td>1.720</td>
</tr>
<tr>
<td>1.94</td>
<td>1.10</td>
<td>-22%</td>
<td>1.705</td>
</tr>
</tbody>
</table>
**SPECIFICATIONS**

**Load section**

<table>
<thead>
<tr>
<th>Maximum voltage:</th>
<th>80 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum current:</td>
<td>270 A</td>
</tr>
<tr>
<td>Maximum power:</td>
<td>15 kW</td>
</tr>
<tr>
<td>Load patterns:</td>
<td>Constant current, constant power, constant resistance, current profile and power profile</td>
</tr>
<tr>
<td>Current setting:</td>
<td>0-270.0 A (2999.9 A)(^1)</td>
</tr>
<tr>
<td>Power setting:</td>
<td>0-15.00 kW (299.99 kW)(^1)</td>
</tr>
<tr>
<td>Resistance setting:</td>
<td>0.1-2999.8 Ω</td>
</tr>
<tr>
<td>Battery voltage ranges:</td>
<td>2, set automatically at start of test.</td>
</tr>
<tr>
<td>Stabilization(^2):</td>
<td>± (0.5% of reading + 0.5 A)</td>
</tr>
</tbody>
</table>

\(^1\) Maximum value for a multi-unit system.

\(^2\) For internal current measurement

<table>
<thead>
<tr>
<th>Range</th>
<th>Battery voltage</th>
<th>Resistor element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range 1</td>
<td>10-27.6 V</td>
<td>0.069 Ω</td>
</tr>
<tr>
<td>Range 2</td>
<td>10-55.2 V</td>
<td>0.138 Ω</td>
</tr>
</tbody>
</table>
Charger for the experiment

**Technical Specification**

- **Mains supply:** 220-240VAC 50-60Hz (90-200 power limited)
- **Current draw:** 4,5A
- **Power factor:** ~1 (PFC)

<table>
<thead>
<tr>
<th>Output Power</th>
<th>36/30</th>
<th>54/20</th>
<th>72/15</th>
<th>120/10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Current</td>
<td>30A</td>
<td>20A</td>
<td>15A</td>
<td>10A</td>
</tr>
<tr>
<td>Max. Voltage</td>
<td>36V</td>
<td>54V</td>
<td>72V</td>
<td>120V</td>
</tr>
</tbody>
</table>

- **Max. Power:** 800W
- **Max. Ripple out:** 30mV RMS
- **Efficiency:** >86%
- **Frequency:** >100kHz
- **Cooling:** Temp. Controlled fan
- **Weight:** 1,6kg
- **Dimension:** 258 x 136 x 89mm
- **Protection:** IP21, Electrically II (with or Without earth)

**Cables:** One set of laboratory cables is included.
Battery characteristics from the manufacturer data sheet