INVESTIGATION AND ANALYSIS OF PREMATURE FAILURE OF VALVE REGULATED LEAD ACID BATTERIES

by

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Abstract

Over the past fifty years Valve Regulated Lead Acid (VRLA) battery has been deployed with Uninterruptable Power Supplies (UPS) backup systems as a last line of defense against primary power outages, due to its affordability and maintainability. Although other newer battery technologies such as Lithium-Ion and Sodium Nickel Chloride are starting to take more space in the market, most of the safety-critical systems still depend on VRLA batteries for energy storage.

The usage of VRLA batteries with UPS backup systems continues to increase, although up to 40% of VRLA cells fail prematurely. This high failure rate compromises safety and it is also a substantial loss of revenue. The charging and discharging method on a battery is very crucial because it can affect the life span of a battery. When a lead-acid battery is discharging or charging, lead-sulfate crystals build up gradually on the electrodes, this could result in total loss of capacity if a battery is not charged properly.

In this study, a collection of ninety-six VRLA batteries based on GEL electrolyte and Absorbent Glass Matt (AGM) type were tested under float and cyclic applications. The battery strings were arranged in a series connection of 32 VRLA batteries at three different test sites. The specification of battery strings used is based on ampere-hour and voltage ratings of 170 AH and 12 V respectively. The batteries were continuously monitored for more than 600 days using Sentinel Battery Monitoring System (BMS) and the performance data were analyzed to identify the rate of premature failure.

The result obtained shows that VRLA batteries that are based on GEL electrolyte are more robust than those that are based on AGM technology. One battery out of thirty-two GEL electrolyte type batteries failed as compared to thirty-two batteries out of sixty-four AGM type batteries that failed within twenty-four months. It was also observed that the GEL type is more suitable for cyclic application, whereas AGM is more suitable for float application. In addition, it was also observed that the equalization charge proved to improve the life cycle of both types of VRLA batteries.

DECLARATION

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Exact wording of the title of the dissertation as appearing on the electronic copy submitted for examination:

INVESTIGATION AND ANALYSIS OF PREMATURE FAILURE OF VALVE REGULATED LEAD

ACID BATTERIES

I declare that the above dissertation is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

I further declare that I submitted the dissertation to originality checking software and that it falls within the accepted requirements for originality.

I further declare that I have not previously submitted this work, or part of it, for examination at Unisa for another qualification or at any other higher education institution.

(The dissertation will not be examined unless this statement has been submitted.)

29 January 2021

SIGNATURE DATE

Acknowledgments

Firstly, I would like to thank God the almighty for providing me with the strength and courage to complete this research.

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List of Abbreviations

AC - Alternating Current

AGM - Absorbent Glass Matt

Ah - Amp Hour

BMS - Battery Monitoring System

BU - Battery University

CCV - Constant Charge Voltage

DC - Direct Current

DOD - Depth of Discharge

GBA - Global Battery Alliance

Hz - Hertz

Li-ion - Lithium-Ion

MB - Monobloc

MCVC - Modified Constant-Voltage Charging

PC - Personal Computer

SCR - Silicon Controlled Rectifier

SOC - State of Charge

SOH - State of Health

UPS - Uninterruptable Power Supplies

V - Voltage

VRLA - Valve Regulated Lead

WEF - World Economic Forum

WHO - World Health Organization

1. CHAPTER 1: BACKGROUND

1.1 Introduction

Electricity has become a lifeline of operations and production for industries in the world. Companies rely on electric power to supply critical loads and store valuable data using electric dependant components. Industries such as Telecommunication companies, Railway companies, Financial Institutions and other electric utility companies use an uninterruptible power supply (UPS) in conjunction with Valve Regulated Lead Acid batteries (VRLA) to provide back-up power for critical loads during power outages. Since a continuous supply of power is crucial to industrial sensitive systems, a standby battery is used to maintain critical load for a duration the alternate power source (e.g. generator) requires to start up. In the absence of a generator, a battery is sized to last for an extended duration depending on the user's requirement. Batteries are also used for support in solar system installations and other renewable energy systems in areas that are not connected to the grid, in such instances, a battery is sized to last few days.

The Uninterruptible Power Supply (UPS) back-up systems normally consist of individual battery blocks connected in series to make up a string. The aim behind a series connection is to produce a DC voltage required to run a UPS inverter in the absence of the primary power source. A series connection of batteries means a failure of any one battery will affect the whole string and leave critical loads without any back-up power. Meaning, although a battery is the main source of back-up power, it can also be the weakest link of the UPS system.

According to the Global Battery Alliance (GBA) and World Economic Forum (WEF), the demand for batteries raised by 30% per annum between 2010 and 2018 and reached a capacity of 180 GWh in 2018 (Global Battery Alliance, 2019). The demand for batteries is projected to increase by 25% per annum and reach a global capacity of 2,600 GWh in 2030. Figure 1.1 presents the projected comparison of battery demands per application for the period between 2018 and 2030. From figure 1.1, it can be observed that the major contributing factors of growing demand are due to electrification of transportation followed by battery usage in standby applications/Energy storage. It can also be observed that battery installations are expected to contribute about 220 GWh of energy storage in 2030.

The fundamental causes of growth can be directly linked to an increase in the use of intermittent renewable energy sources and solar systems (Global Battery Alliance, 2019; IRENA, 2017; Kocer, 2019).

The World Economic Forum also suggests that every added GW of wind capacity means the necessity for approximately 1 GWh of battery capacity, and any extra GW of solar capacity means the need for 3 GWh of battery capacity (Global Battery Alliance, 2019).

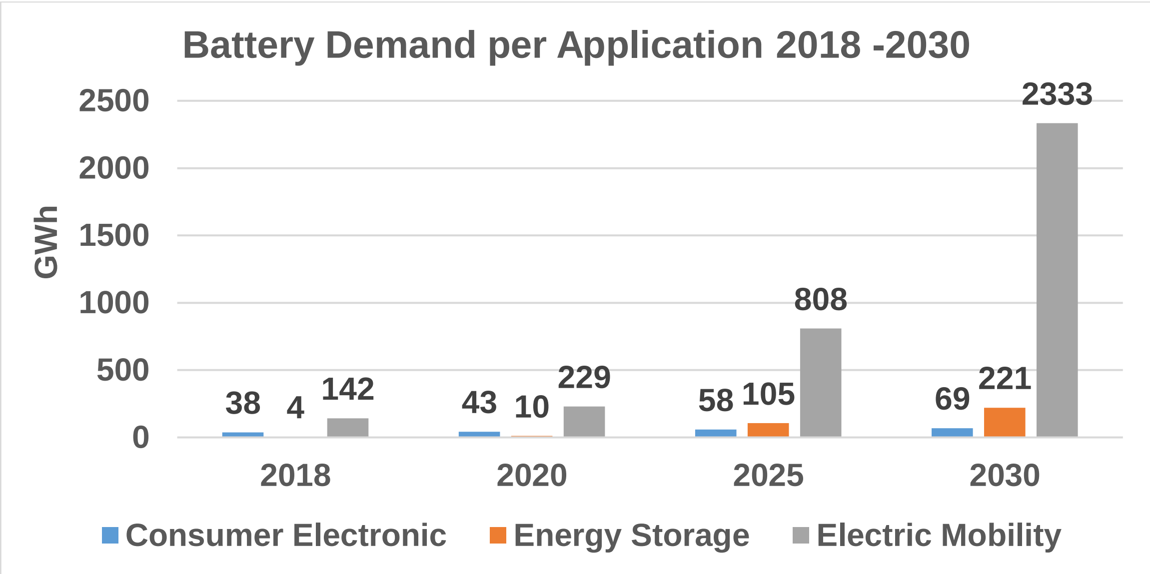


Figure 1.1: Battery demand per application 2018 to 2030
Source: (Global Battery Alliance, 2019).

Amongst other batteries, the lead-acid type covers the largest section of the market. In 2018, the lead-acid batteries provided over 72% of the global rechargeable battery capacity (in GWh). The total capacity delivered by lead-acid batteries was approximately 450 GWh by then. This capacity has been covering a wide range of applications such as industrial applications, vehicle starter batteries and stationary power applications (UPS and off-grid energy storage). The usage of lead-acid technology is expected to grow and reach between 487 GWh and 550 GWh by 2030. The global lead-acid battery demand per application for the period between 2018 and 2030 is shown in figure 1.2. It can be observed that the usage of lead-acid technology batteries for energy storage is expected to increase annually to reach 85 GWh in 2030. It can also be observed that a minor decline is expected per annum in the electric mobility usage of lead-acid technology from 417 GWh in 2020 to 406 GWh in 2030. However, this sector will still be dominating in the next decade (Global Battery Alliance, 2019; EUROBAT, 2020).

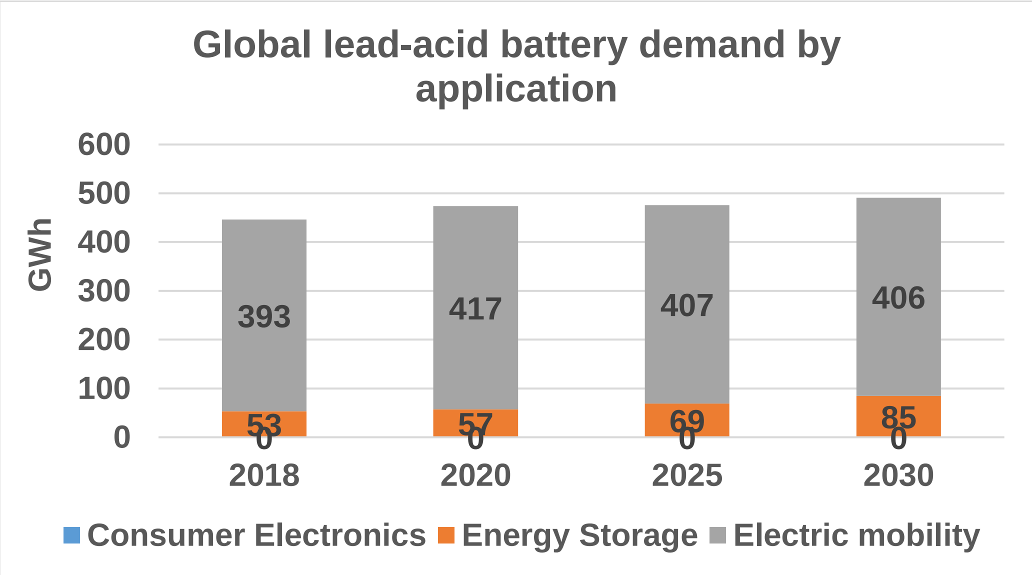


Figure 1.2: Global Lead-Acid battery demand per application 2018 – 2030
Source: (Global Battery Alliance, 2019)

Valve Regulated Lead Acid batteries (VRLA) battery is commonly used in Uninterruptible Power Supply (UPS) systems. The usage of VRLA batteries has since been increasing, many companies spend significant amounts of money purchasing VRLA batteries to cater for power outages. Since the VRLA battery technology was introduced, end users have encountered and are still experiencing varying degrees of performance and reliability, where VRLA batteries are being reported to fail prematurely. The premature failure of this battery type results in revenue loss and compromises safety to systems.

VRLA batteries are rechargeable in nature, charging a battery is a crucial process that ensures a battery can still deliver the power on the next discharge. The purpose of charging a battery is to replenish charges and keep it in a full state by maintaining a constant voltage. During a charge cycle, the conversion of lead sulfate to lead takes place and the process is reversed during a discharge cycle. A battery charging and discharging process has certain limitations that can positively or negatively affect a battery's cycle life. Irrespective of the application where a battery is deployed, an understanding of a battery's performance characteristic is of great importance. Performance testing and monitoring are essential to define the behavioural characteristics of a battery. Monitoring the voltage and current of a battery over an extended amount of time is important for assessing a battery for its capacity.

This study aims to analyze the performance of VRLA battery technologies under various charging parameters based on float and cyclic applications. The effect of charging parameters on the premature failure of VRLA technology will be identified. The evidence produced in this study will be significant in the ongoing development of the cycle life of Valve Regulated Lead Acid batteries. Although the railway industry's battery systems were targeted, the results apply to any circumstances where VRLA batteries are used, whether for cyclic or float applications. Protocols of the battery charging parameters were identified and a test, monitoring and analysis procedure was developed to provide the means of assessing the effectiveness of applied charging parameters under cyclic and float applications. A static UPS configured for Online Double Conversion mode is used to charge the VRLA batteries using Modified Constant-Voltage Charging Method and Constant Charge Voltage to determine the effect of both charging methods on VRLA performance. A Sentinel Battery Monitoring System (BMS) was used to monitors the batteries and provide real-time data, including the immediate detection of any bad cell in the battery bank. Gel and AGM types of VRLA technologies were tested.

1.2 Comparison of Lead Acid to Other Battery

Previous studies have shown that lead-acid batteries have been the utmost preferred choice since the 19th century. Thomas Edison performed tests with the aim of replacing lead-acid batteries with other technologies such as Nickel-Ion technology. However, lead-acid dominated due to its maintainability and affordability. Current studies indicate that lead acid is still widely used in stationary power applications, industrial applications and vehicle starter batteries, however other technologies such as Lithium-Ion technology are increasingly challenging lead-acid usage (Battery University, 2019; Enos, 2017; Lyu, 2018).

Figure 1.3 shows the features of Lithium-Ion (Li-ion) and lead-acid from a recent study on the cranking capabilities of the two technologies. The orange line represents lithium technology and the blue line represents a lead-acid type. From the figure, it can be observed that both technologies have nearly the same performance under cold cranking. It can also be observed that although lead acid is a little better in terms of power to weight ratio (W/kg), Lithium technology is more advanced in cycle life, improved specific energy in energy to weight ratio (Wh/kg) and very high charging capability. It was further observed that lead acid is cheaper, easy to recycle and safer than lithium-ion. Recognition was given to lead-acid for better performance under low temperature, low cost, effortlessness of recycling and good safety record (Battery University, 2019).

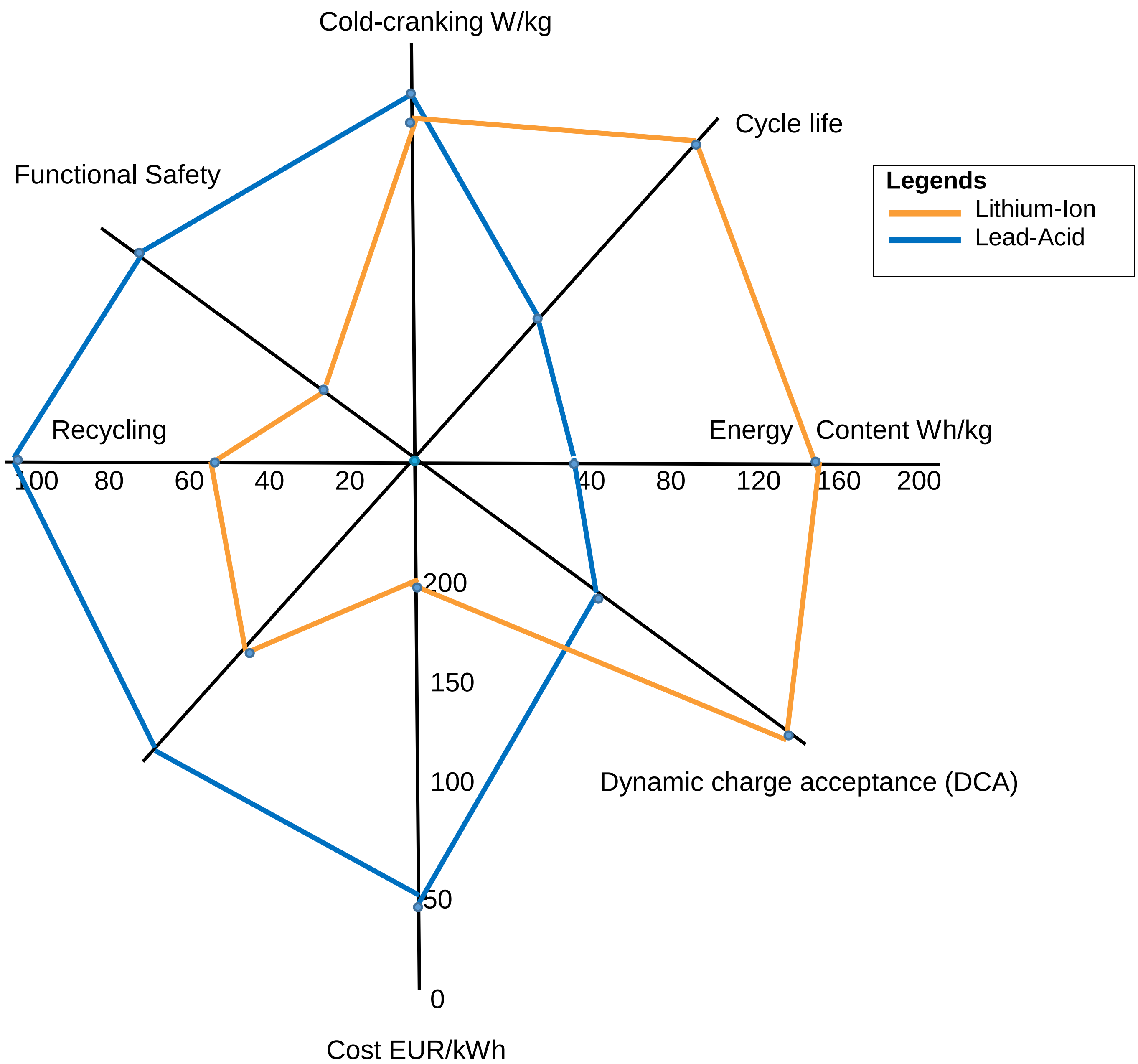


Figure 1.3: Comparison of lead-acid to lithium-ion.
Source: (Battery University, 2019)

1.3 Social and Environmental Effect of Lead Acid Battery Failures

About 85% of the entire global consumption of lead is for the manufacture of lead-acid batteries. The increasing demand for lead-acid batteries is presently maintained by the developments of both primary lead production from mines and lead recycling. About half of global lead production is obtained through the recycling process. The recycling and manufacturing of lead-acid batteries is a global practice performed in both formal and informal sectors (World Health Organisation, 2017; Lattanzio, 2020).

Lead recycling is a major cause of environmental pollution and human exposure since it is often done without adequate care, methods and technologies to regulate lead emissions (Manhart, 2016; Crippa, 2019).

Recycling lead-acid batteries is of major concern to the health of society since the industry is linked to a high level of work-related exposures and environmental secretions. Based on information captured in 2016, the estimated number of deaths related to lead exposure amounts to half a million people (World Health Organisation, 2017).

The major challenge of lead exposure occurs as a result of the uncontrolled battery recycling process taking place in the informal recycling facilities. Informal lead recycling activities happen in various countries and contributes significantly to lead exposure and poisoning, thus posing risk to the public and environment. The highest corridors of exposure to lead arise from environmental emissions, where the elements of lead and gasses released into the air during the recycling process are deposited onto the soil, water forms and different surfaces such as parks, gardens, etc. This element pose risk to human beings and animals as they are inhalable. Also, if the proper battery disposal is not adhered to, chemicals with high concentrations of lead can contaminate land and water or even enter the food chain through crops rising on contaminated land. Animals grazing on contaminated crops could also be affected. Sea animals living in polluted water could also get severely affected. Every lead-acid battery that fails, means additional risk for lead emission.

1.4 Cost Implications Associated with VRLA Battery Failures

The premature failure of VRLA batteries in different applications presents problems associated with system total shutdown, data loss and compromised safety on critical systems. As such, end-users spend significant amounts of money trying to overcome the challenge. The costly replacement of failed VRLA batteries and increased maintenance cost has become a common practice to the majority of end-users. These facts identify the lead-acid battery as the weak link and the most expensive section of the UPS system.

1.5 Problem Statement

Industries such as Railway companies, Telecommunication companies and other electric utility companies use VRLA batteries in their operations. A battery bank is typically the last line of defense against total shutdown during power outages. Traditionally flooded lead-acid batteries used to be employed for power backup purposes, however over the past 30 years, VRLA type have been rapidly deployed in many different applications, of which the usage is increasing.

Over 90 percent of the VRLA battery end-users have experienced varying degrees of battery underperformance. Although the VRLA battery has a typical design life of 10 years, more and more VRLA batteries are continuously being identified/reported to have failed prematurely or within 12 to 24 months of installation. Most battery suppliers and end-users believe the cause of VRLA battery underperformances is a result of operational abuse, manufacturing errors, environmental conditions, improper charging or compatibility concerns with specific applications. However, due to the lack of battery monitoring system, the data available at hand is not sufficient to make any meaningful inference on the actual cause of VRLA battery premature failure. Most end users have the perception that VRLA batteries are maintenance-free, as a result, the majority of VRLA installations in multiple industries are not being monitored leading to declined warranty claims by manufacturers.

Although various studies have been conducted to look into the performance of VRLA batteries, the problems associated with premature failure of VRLA batteries continue to be a challenge for end-users such as Railway industries and telecommunication companies.

The underperformance of VRLA batteries is a global problem and it requires studies to be continually conducted to analyze the contributing factors to premature failure and provide guidelines to prolong the life cycle of VRLA batteries.

This research aims to identify VRLA battery failure mode associated with battery charging regime and provide recommendations suitable for VRLA battery charging parameters, factors of monitoring and maintenance activities required on Gel and AGM technologies under cyclic and float conditions. This will be achieved through analysis of the performance, relationships and operations of Valve Regulated Lead Acid (VRLA) technologies under different charging parameters based on float and cyclic applications.

1.6 Study Objectives

The objectives of this study are:

i. to analyze the charging characteristics of VRLA battery technology.
ii. to study the effect of fluctuating real-time temperature on VRLA life cycle
iii. to propose a scheme that will improve the life expectancy of VRLA batteries

1.7 Importance of the Study

As seen in section 1.3, every VRLA battery that fails increases the amount of lead being recycled. This has a negative impact on the health of the public society, soil contamination and water pollution. By improving the life cycle of VRLA batteries, the listed benefits could be achieved.

i. To reduce the amount of lead being emitted. The quantity of lead chemicals that affects members of the society through the inhalation process will reduce.
ii. To reduce the impact of lead on environmental structure such as land contamination and water pollution

iii. The reduction of VRLA battery failures means financial relief to the industries, which spend significant amounts of funds on the continuous replacement of the failed batteries. The saved funds, as a result of the extended VRLA life cycle, could positively contribute to empowering the industries and creating employment opportunities.

According to the global battery alliance and the consortium for battery innovation technical roadmap, battery energy storage is projected to be the leading technology in the reduction of carbon dependency systems over the next ten years. The demand for battery services is also projected to grow rapidly. Due to these reasons, there is a serious need to improve and exploit the lead-acid technology to ensure the growing demands of end-users are met (Global Battery Alliance, 2019).

The recommendations of this study will improve the reliability and life cycle of the valve regulated lead-acid batteries, thus yield positive results on the life expectancy and contribute to meeting the end-users growing demands.

1.8 Delimitations of the Study

The factors listed below will not be addressed in this study:

i. The analysis of electrolyte elements
ii. Battery internal structure decomposition

1.9 Overview of the Study

This Dissertation is arranged as follows:

The background of the study and introduction is given in chapter one.

In chapter two, a literature review of the operating principles of VRLA battery technology and failure modes are presented. The previous studies conducted concerning the charging regime on VRLA technology are also covered in this chapter.

The research method, experimental setup and the testing procedures and protocols of the experiment are presented in chapter three.

In chapter four, analysis of results and performance profiles obtained from the two VRLA battery technologies (Gel and AGM) are presented and discussed.

Conclusions and recommendations are outlined in chapter five. This is based on the practical results obtained through the Battery Monitoring System in comparison to the battery manufacture's specifications.

2. CHAPTER 2 LITERATURE REVIEW

Before starting a study on the analysis of the premature failure of VRLA batteries, it was important to review work that has been done on the charging regime as well as failure modes associated with the VRLA technology then outline the theoretical background of a VRLA battery. The first section of this chapter (section 2.1) will cover the literature review or previous studies on the development of VRLA battery and the second section (section 2.2) will address the theoretical background of a VRLA battery.

2.1 Previous Research

This section covers work that has been done on the charging regime as well as failure modes associated with the VRLA technology. This would provide a clear understanding and further justify the methodology developed herein.

2.1.1 Failure Modes of VRLA Battery

A substantial number of studies have been conducted concerning the performance of VRLA batteries and the factors involved in the VRLA technology failure modes (Badeda, 2018; Yahmadi, 2016). Most of the previous studies have identified that VRLA batteries fail much earlier than the expected time. In most studies, the Gel electrolyte VRLA type has been shown to perform better than the AGM VRLA type under various conditions. As a result, more studies were focused on improving the Gel technology based on its advantages over AGM technology. While studies were conducted, some chemical components have continually been added to the Gel type VRLA technology in order to improve its performance and cycle life under normal temperature and float conditions. However, little has been done to analyze the effect of the additive chemical components on the Gel battery type under varying temperature and charging conditions (Badeda, 2018; Pachano, 2016)

2.1.2 Influence of Float charge on VRLA Battery Life

Float charging refers to the battery charging fashion where a battery is charged with a constant voltage of about 2.25 V per VRLA cell. A battery charger maintains a battery in a full charge state without boiling/overcharging the electrolyte. The charger allows maximum current to be delivered to a battery until the battery voltage reaches about 80% of the full charge state. This type of charging requires a long period to fill up a battery and is suitable for applications where the power source is reliable or have minimum power outages, i.e. one power outage every few months (Wong, 2008; Chandrabose, 2019)

(Hunter, 2003) Conducted a study to analyze the efficiency of float charge on the life cycle of VRLA batteries. The benefits of float charging were identified and various testing procedures were established to assess the efficiency of the applied float voltage. The aim was to prolong the battery life by developing an approach to address the battery self-discharging process. In the study, gas venting and positive grid corrosion were kept to the lowest level. The challenges related to controlling the float charging as well as the electrode inequalities were investigated and detailed. Various tests were conducted based on the float voltage of 2.27 V per VRLA cell where the polarisation of 130 mV was assumed. The positive electrode polarization and that of the negative electrode were compared to assess the effect of float charging. The results of this study indicated that VRLA batteries can reach or exceed their design life expectancy when used under a float charge operation where the source of power is more reliable or available for months without outages. This is mainly because the batteries operating under float mode are kept fully charged for an extended period of time, which assists in avoiding battery self-discharging. However, with the status of the current power grid (frequent power outages), the battery application becomes cyclic rather than float and VRLA batteries are exposed to more frequent discharges which reveals poor performance (Hunter, 2003). Despite the recommendations of Hunter's, the VRLA batteries which are exposed to an unreliable power source continue to fail prematurely. This is mainly due to the fact that the applied charge voltage method is only effective under a stable power condition. Most of the charge voltage studies conducted in the past were based on ideal power conditions. Thus, it is critical to conduct a study to analyze and improve the performance of VRLA batteries under cyclic conditions.

2.1.3 Influence of Temperature on VRLA Battery Life

VRLA batteries degrade with time and without showing any sign of degradation. There are multiple issues that contribute to the VRLA battery's speed of degradation. This includes but not limited to design parameters, type of application and environmental influences. Temperature is the most critical environmental factor that has a significant impact on the life of a battery. Most VRLA batteries (especially in Africa) are installed at remote locations where temperature varies drastically. This makes temperature one of the biggest concerns on VRLA installations. Lead-acid batteries are designed to operate under a nominal temperature of 25 degrees. An increase of 10 degrees above or below the nominal can reduce the life of VRLA batteries by over 50% (Lu, 2011).

In 2016 a study was conducted to determine the effect of high temperature on the VRLA battery life. It was determined that high temperature speeds up the battery's chemical reaction which leads to loss of water, high cell current and fast corrosion on the positive grid material. Water gets transformed to hydrogen and oxygen gasses while current is passing through it and then get out of the battery through the vented holes, this result in battery drying out. It was determined that amount of corrosion on the plate is equivalent to the quantity of current flowing through the water and the corrosion intensifies based on temperature. The float currents, water losses per annum and life expectancy estimations were conducted for temperatures ranging from 25 to 50 degrees Celsius. This study has shown that each 10 degrees increment in temperature reduces the VRLA battery life by 50% and has further recommended that a catalyzer refresher is required to be added to the VRLA battery electrolyte to improve the life of VRLA battery (Gencten, 2016). Although many studies have been conducted to determine the influence of temperature on VRLA batteries, most are focused on the nominal temperature of 25 degrees and above. A little has been done to explore the influence of fluctuating temperatures.

As the demand for standby power increases, the usage of VRLA increases. The majority of the VRLA batteries are currently installed in remote areas where the reliability of the primary power source is very poor.

In many UPS systems, the battery and inverter are connected directly to the output of the charger in order to ensure the load is immediately transferred to batteries in the event of a primary power outage. An inverter converts a DC to AC power which supplies the load. The rectifier circuits are designed to produce a filtered DC signal of which the circuits contain capacitors, shunt and inductors. These DC filtering components have a significant possibility for generating an AC ripple current which may negatively affect the life and performance of the battery (Barros, 2019). The results of this study will give a clear picture concerning the VRLA battery life expectancy. Guidelines and mitigating factors to improve the VRLA battery life cycle will also be provided to benefit the users and manufacturers.

This study will determine the suitable battery charging parameters required for VRLA batteries operating under cyclic applications where the power grid is unstable and unreliable. The influence of fluctuating real-time temperatures on VRLA batteries will also be analyzed. The performance of Gel and AGM battery technology under different conditions will be compared and recommendations aiming to prolong the battery life will be established from the results.

2.2 Theoretical Background

To address matters relating to the performance of lead-acid battery technology, the critical principles of a lead-acid battery will be defined first. The basic operation of lead-acid battery, life cycle factors, charging topologies as well as failure modes are explained.

2.2.1 Lead Acid Battery

A battery is an electrochemical energy storage device that contains energy that can be transformed into electrical power. There are two categories of lead-acid batteries, Valve Regulated Lead Acid (VRLA) type and Vented Lead Acid type. Lead-acid batteries use a combination of electrolyte that contains sulphuric acid and lead plates for the conversion of chemical energy into electrical energy and vice versa. The lead-acid battery technologies provide a low energy-to-volume ratio, low energy-to-weight ratio and can produce a high surge current which shows the cells maintain a large power-to-weight ratio.

Irrespective of the electrolyte or cell design type, lead-acid battery technology has the same operating principles and similar reactions. For this reason, the VRLA type will be presented.

2.2.2 Valve Regulated Lead Acid

VRLA Batteries are the latest version of lead-acid technology. The major difference between VRLA battery type and other lead-acid batteries is that VRLA type contains less electrolyte and can combine hydrogen and oxygen to produce water and avoid dry out during charging and discharging cycles, thus preventing gases from escaping. The most common versions of VRLA batteries are **Gel** electrolyte and Absorbent Glass Mat **(AGM)** type. The AGM type uses a low resistance glass fiber separator to quarantine the positive and negative plates and to absorb the free electrolyte in the cell. On the other hand, the Gel type uses a tough polyethylene separator. Gel technology does not depend on the separator for absorbent because the chemical is gelled. The Gel electrolyte tolerates deep cycle than AGM. However, AGM can tolerate quick discharge and charge much better than the Gel type. The VRLA technology is more sensitive to environmental conditions than the vented type.

A VRLA battery is made of several cells where a nominal voltage per cell is 2 V. The cells within a battery are arranged in a series connection to obtain the voltage required. Each cell consists of an alternately gathered group of positive plates (whose active material is PbO2) and negative plates (Pb) where the number of plates of each polarity and their dimensions is the main parameters to define the cell capacity. A separator is placed between the plates to prevent direct contact for different polarities. The pack (negative & positive plates) are grouped and put in a polystyrene container filled with an electrolyte (sulfuric acid and distilled water or gelling agent) to form a battery. The positive and negative battery terminals are made of lead metal connected to the packs of each polarity (Sen, 2018).

2.1.2.1 Operating Principles

VRLA cell consists of two electrodes and a separator as shown in Figure 2.1. The positive plate is made of lead oxide material (PbO_2), a negative plate made of lead material (Pb) and the electrolyte is a sulphuric acid solution (H_2SO_4) (Sen, 2018). Lead-acid battery's principle of operation is based on the conversion between chemical and electrical energy, the process which takes place within a VRLA cell during energy conversion is known as oxidation-reduction reaction (Redox).

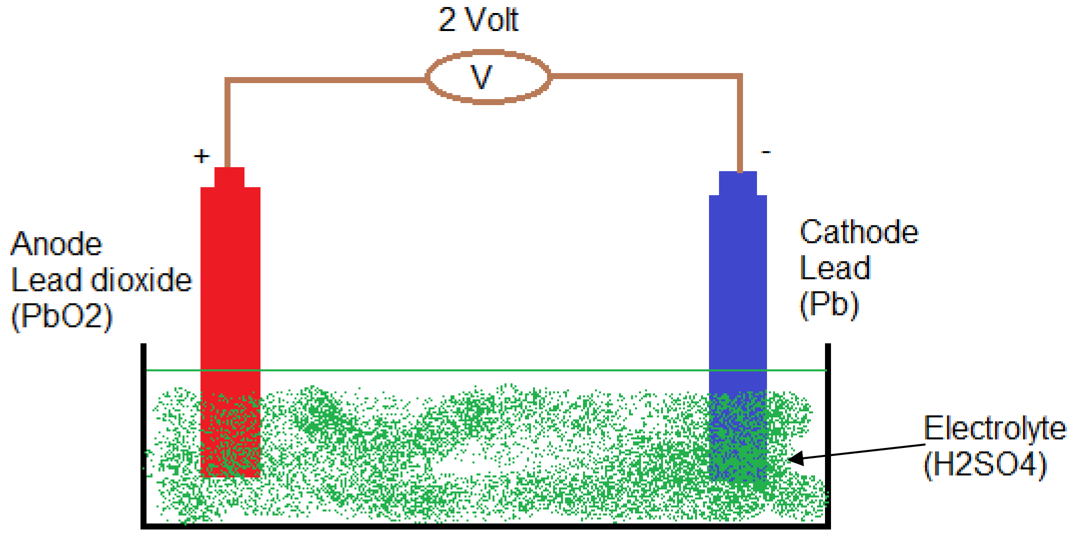


Figure 2.1: Battery chemical reaction.
Source: (Sen, 2018)

Once a VRLA cell is constructed, it is then ready for chemical energy conversion and to produce electrical energy based on a reduction-oxidation (REDOX) reaction. The key reaction of the positive plate electrode is given by:

$$PbO_2 + 3H_+ + HSO_{4-} + 2_{e-} \rightleftarrows PbSO_4 + 2H_2O \tag{2.1}$$

The key reaction of the negative plate is given by:

$$Pb + HSO_{4-} \rightleftarrows PbSO_4 + H_+ + 2_{e-} \tag{2.2}$$

The chemical reaction that takes place during the discharge cycle is shown in equation 2.1. When the battery is discharging, the flow of current follows is from negative to positive and the operation converts the chemical energy into electrical energy. From equation 2.1, during a discharging process, the negative plate's lead (Pb) and positive plate's lead dioxide (PbO_2) are transformed to lead sulfate ($PbSO_4$) while the sulphuric acid (H2SO_4) transform into water (H_2O) at the same time. The process increases the excess of negative charge on the electrode. This means, the $PbSO_4$ gradually develops in equal quantities at both positive and negative polarities, at the same time the concentration of the electrolyte solution decreases. Thus both electrodes react with sulfuric acid to form a non-conductive, solid product of lead sulfate ($PbSO_4$).

The process is reversed when the battery is charging. From equation 2.2, when a battery is charging, $PbSO_4$ and H_2O are electro-chemically transformed to H_2SO_4 and Pb. The current follows from positive to negative while the battery is charging. The charging process converts energy from electrical to chemical form (Sen, 2018; Pavlov, 2012).

2.2.3 Factors that affect the Life of a Battery

The life of a VRLA battery is affected by a number of factors. The factors listed below are considered the most critical in battery life (Lu, 2011; Sen, 2018; Abbas, 2016).

2.2.4 Number of Life Cycles

A cycle is a scenario where a battery gets discharged and then charged. A lifespan of a battery depends on the number of cycles and the depth of discharges a battery is exposed to. A typical Absorbed Glass Mat (AGM) battery is rated to have cycles of 250 to 1000 under normal conditions and a Gel type is rated to have 450 to 3500 cycles. A battery discharge table that is usually provided by the manufacture is used to estimate the number of cycles a battery can archive.

2.2.5 Depth of Discharge Effect (DOD)

The more a battery is used, the quicker the failure. This implies that a battery's life cycle is inversely proportional to capacity withdrawal. The data for AGM and Gel battery types is presented in table 2.1. Batteries life cycle are organized as column elements, while depths of discharge are organized as row elements. It can easily be seen from the table that a Gel battery that is drained to 80% of its capacity on each cycle will produce only 500 cycles, but the one drained to 20% at each cycle will produce up to 2000 cycles. A similar argument also holds for AGM batteries.

Table 2.1: Battery life cycle vs depth of discharge

Depth of Discharge	Gel Battery Life Cycle [Hours]	AGM Battery Life Cycle [Hours]
80 %	500	250
50 %	800	500
20 %	2000	1200

2.2.6 Temperature Influence

Temperature is the leading influential factor on battery performance characteristics such as charging parameters and shelf life. The battery's chemical reaction is more affected by higher temperatures than lower temperatures. The ideal performance of a VRLA battery is rated at 25 Degree Celsius. An increase of 10 degrees in temperature can reduce the battery life by over 50 %. Typical battery life versus temperature is shown in figure 2.2. It is observed that at a temperature of slightly above 20 degrees Celsius a VRLA battery's life expectancy is 100 %. It is further observed that an increase of 10 degrees in temperature reduces the battery life expectancy by about 50 % (Gencten, 2016).

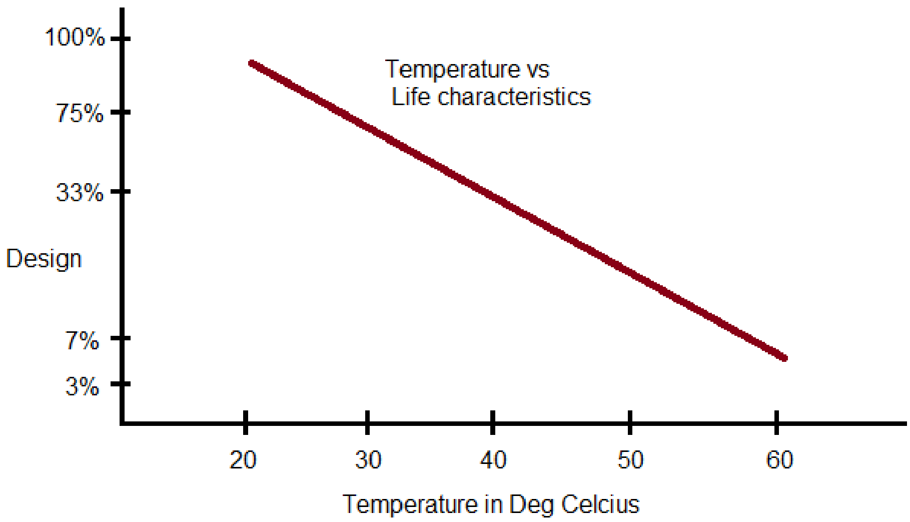


Figure 2.2: Temperature vs life characteristics
Source: (Gencten, 2016)

2.2.7 Recharge Voltage and Rate:

A VRLA battery charge voltage is also very crucial to the life of a VRLA battery. Too high voltage or overcharging the battery will cause a battery defect called thermal runaway. On the other hand, low charge voltage or undercharging will result in plate sulfating. Temperature plays a significant role in the charge voltage level, the two have to be looked at together.

2.2.8 VRLA Battery Failure Modes

Before going into details on the VRLA battery failure modes, it is important to outline the difference between catastrophic battery failures, as classified by immediate loss of capacity and inability to charge and produce energy, and progressive deterioration in performance as revealed by an ongoing deterioration in capacity.

Catastrophic failure is easier to diagnose since the battery will fail suddenly. This failure mode is commonly a consequence of the following factors:

i. Cell design deficiencies
ii. Poor quality control during manufacturing
iii. Operational abuse
iv. External or internal damage

On the other hand, progressive deterioration is difficult to predict, it represents an elusive nonconformity from the ideal performance that originates from small changes in plate features brought about by the influence of manufacturing variables and service conditions. This failure mode is commonly a consequence of the following factors:

i. Physical properties and the chemical composition of lead-acid
ii. Size of the plate
iii. Structure of formed plates
iv. Cell design
v. Shelf time
vi. Temperature
vii. Charging regime
viii. Type of separator

The performance degradation in VRLA batteries is more likely to be due to different damage mechanisms such as irreversible sulfation, plate corrosion, electrolyte stratification water loss, active material degradation and cell design deficiencies. The common failure modes are often a result of operational abuse such as partial cycling, high discharge rates, long periods at a low state of charge, overcharging, current and temperature history of the battery. The failure modes caused by operational abuse are of special concern when trying to improve the life cycle of a battery. These failure modes are more like to affect the VRLA type than all other lead-acid technologies. For this study, plate sulfation and voltage variation were considered.

2.2.9 Voltage Variation

Batteries connected in series and operating in cyclic mode are more likely to experience voltage variations between monoblocs (MB). When a battery string with unbalanced battery voltages is charged, the weak cells in a string will not reach a full state of charge and will be drained to a higher depth of discharge with the next discharge activity. Each discharge activity worsens the condition of the weak cells and will eventually result in loss of capacity to due undercharging. The same concept applies to batteries with higher voltage levels and the batteries could reach a gassing state due to overcharging. Thus voltage variation in a battery string could lead to premature loss of capacity for some of the batteries in the string.

2.2.10 Irreversible Sulfation

Irreversible sulfation is described as the most common and hazardous failure mode in the valve regulated lead-acid battery family. Sulfation is an electrochemical reaction that decreases the concentration of electrolyte in a VRLA cell. The voltage of a cell also gets decreased as a result of sulfation. The sulfation process can be summarised as the recrystallization of $PbSO_4$ into a substance that is no longer electroactive (Spanos, 2017; May, 2018). A reflection of the microscopic processes that take place between the electrolyte and electrode during $PbSO_4$ recrystallization as well as the charge and discharge of the negative plate is shown in figure 2.3.

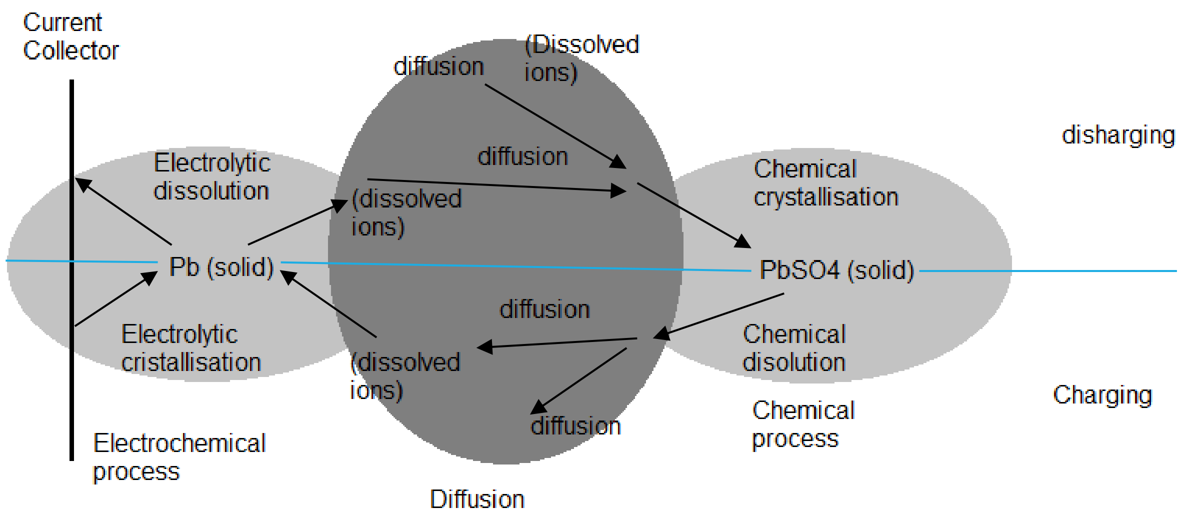


Figure 2.3: Microscopic level of the discharge and charge reaction in lead-acid cell
Source: (Journal of Power Sources, vol. 158)

From figure 2.3 it can be observed that when a battery is discharging the electrolytic dissolution produces the Pb2+ ions which engage in a chemical crystallization process with the sulfate ions to create lead sulfate (PbSO4) on the electrode's surface. This process is reversed during the charging cycle in which PbSO4 liquefies through chemical reaction into sulfate ion and Pb2+ ion. The sulfate ions diffuse back into the electrolyte and Pb2+ ion becomes vacant for electrolytic crystallization. If the battery is not recharged or left in a low state of charge for an extended period, the lead sulfate substance produced during the discharge cycle forms a solid crystal material that cannot be broken again, this is referred to as irreversible sulfation. The end result of sulfation is the permanent loss of capacity of a battery.

In VRLA batteries sulfation is more intensified on the negative electrode as a consequence of insufficient charging. Every discharge cycle accumulates a specific amount of irreversible $PbSO_4$ crystals as an outcome of the recrystallization of finely separated elements. The dissolution of lead sulfate crystals on the negative plate depends on their specific size based on the Ostwald-Freundlich equation which is given by:

$$In\left(\frac{CPb_{2+}}{C\infty\ Pb_{2+}}\right) = \frac{K}{T}.r \qquad (2.3)$$

where CPb_{2+} is the concentration of lead ion (Pb_{2+}) over small lead sulfate ($PbSO_4$) crystals, $C\infty Pb_{2+}$ is the concentration of lead ion (Pb_{2+}) over a huge lead sulfate ($PbSO_4$) crystals, r is the radius of lead sulfate ($PbSO_4$) crystals, T is temperature and K is a constant.

Sulfation is noted by a loss of battery capacity, deteriorations in open-circuit voltage, and decline in the concentration of acid and increases in the ohmic value of and temperature of the battery.

2.2.11 Battery Capacity

Battery capacity (**C**) denotes the total amount of power that can be drained from a battery under some specified conditions. The battery amp-hours rating (**Ah**) is the unit used to denote the rated capacity. The battery's actual capacity depends on the condition of the electro-chemical contents within a battery, as such when a battery is discharged at different current levels and temperature conditions the effective capacity varies from the rated capacity (**C**). The chemical contents within a battery strongly depend on the usage, discharge or charge parameters, temperature and age of the battery.

2.2.12 Battery Ratings

The amount of energy a battery can provide is measured in amp-hours (Ah). The Ah expresses the quantity of hours that a battery can deliver current equivalent to the discharge rate at the nominal battery voltage. For instance, a 12 V battery that is rated 170 AH is capable of delivering 170 A of current for one hour.

The rate at which a battery is charging or discharging is defined by **C-rate**. C-rate is a theoretical way of determining the amount of time a battery will last when discharged at a certain current. C-rate is determined by the division between the nominal rated capacity and the discharge current. For instance, 1C describes the current that can be drawn from a battery's rated capacity for 1 hour. 2 C is double that current and 0.5 C of C/2 is half the amount of that current. The expression used to determine C-rate is shown in equation 2.4.

$$C_{rate} = \frac{\text{AH}}{\text{Current drawn}} \tag{2.4}$$

Table 2.2 illustrate the different performance of a battery with a rated capacity of 170 AH when discharging under different C-rate. From the table, it can be observed that when a 170 AH battery is discharging at 1 C, it can deliver the current of 170 A for a period of 1 hour. It can also be seen that when the same battery is discharging at 2C it will deliver double the amount of current but only last half the time. It is further observed that when discharging at 0.5 C the battery will deliver 85 A for a period of two hours. This implies that, when a battery is discharged at a higher current, the duration for delivering the current is reduced and when charging at lower current levels the duration is extended.

Table 2.2: C-rate vs discharge time

C - Rate	Current Drawn [A]	Discharge Time [Minutes]
2 C	340	30
1 C	170	60
0.5C or C/2	85	120

2.2.13 Battery State of Health

State of Health (SOH) is a quantity that indicates the state of a battery and its capability to produce a specific performance compared to a brand new battery (Tran, 2017). The mathematical expression used to calculate the SOH is given in equation (2.5).

$$SOH = \frac{C_{max}}{C_{rt}} \text{ X } 100\% \tag{2.5}$$

Where C_{max} is the maximum capacity which the battery can produce, and
C_{rt} is the battery's rated capacity (Brunig, 2013; Kwiecien, 2018; Murmane, 2017).

2.2.14 Battery State of Charge (SOC)

The battery's releasable capacity (C_{rel}) is the total current that is released when the battery is completely discharged. The SOC is referred to as the percentage of the releasable capacity in relation to the battery rated capacity (C_{rt}) which is provided by the battery manufacturer. The SOC is calculated as follows (Brunig, 2013; Murmane, 2017)

$$SOC = \frac{C_{rel}}{C_{rt}} X\ 100\% \quad (2.6)$$

The battery state of charge is classified between 0% and 100% based on the battery voltage levels. The typical open circuit voltage levels which are used to classify the state of charge for a typical 12 V VRLA battery are shown in table 2.3 (Brunig, 2013; Murmane, 2017). From the table, it can be observed that a Gel battery measuring 12.85 V is classified as 100% charged while the one measuring 11.8 V is classified as 0% charged. A similar argument also holds for AGM batteries.

Table 2.3: Typical SOC open circuit voltage values for VRLA battery

State of Charge	AGM Battery [V]	GEL Battery [V]
100 %	12.80	12.85
75 %	12.60	12.65
50 %	12.30	12.35
25 %	12.0	12.0
0 %	11.8	11.8

3. CHAPTER 3 RESEARCH METHOD

3.1 Introduction

This chapter outlines the research method used in this project. Section 3.2 defines the experimental setup of the project. In section 3.3, the charging methods used in the study, the protocols of Constant Charge Voltage (CCV) and Modified Constant-Voltage Charging Method (MCVC) are defined in detail. The third section, section 3.4 presents the testing procedures and protocols. The last section, section 3.5 explains the hardware development of the material used in the project.

3.2 Experimental Setup

3.2.1 Block Diagram of the Experimental Setup

The block diagram of the experimental setup is shown in figure 3.1. Each experimental site consists of a 30 kVA UPS, BMS system and 32 series-connected VRLA batteries rated 170 AH of either Gel or AGM type. Measurement of factors such as individual battery voltages, bank voltage, load current, battery's internal resistance and temperature of battery banks are recorded on the BMS system. From figure 3.1 it can be observed that the UPS output DC cables which supply the battery charging voltage are connected directly to the VRLA battery bank. At the same time, the temperature and current sensors are connected from the BMS monitor to the battery bank and UPS cables respectively. The m-sensor also connects between the batteries and the BMS monitor. The BMS data is sent through an optic fibre network to the BMS server PC/Laptop for real-time monitoring. The functions of each component of the experimental setup will be described under the hardware development section (section 3.5).

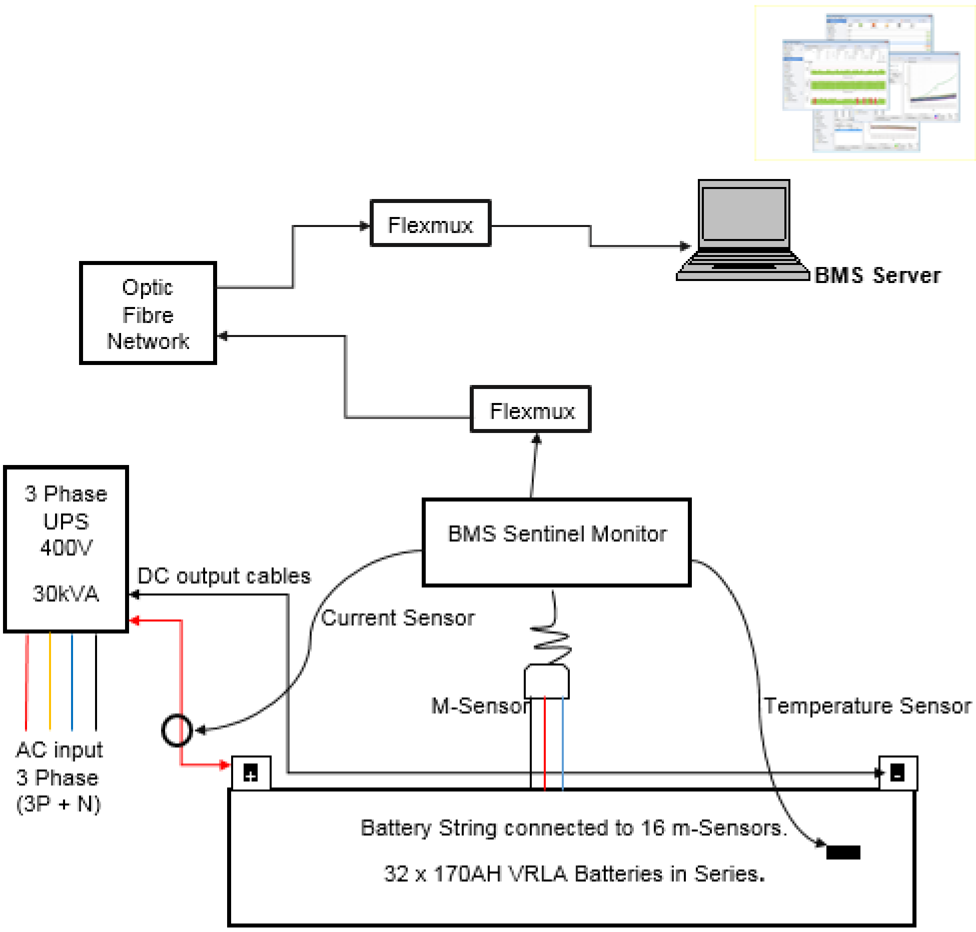


Figure 3.1: Block diagram of the experimental setup

3.2.2 Site Configurations

This study was conducted at three experimental sites. The nominal values of battery capacity, voltage and current limits of the three experimental sites are shown in table 3.1. The sites are classified as site A, B and C. The charging and discharging parameters are very important for the safe operation of VRLA battery banks (Chandrabose, 2019; Murmane, 2017). From the table provided, it can be observed that sites A and B have the same charging parameters (voltage and current). However, the batteries used at site A is Gel electrolyte and site B has AGM type batteries. Site B is fitted with a generator, this means the AGM batteries installed at site B will have short and minimum discharge durations which are mostly used for enabling the generator to start up and take over when the primary power fails, thus the mode of operation under site B is float application. No generator is installed at site A, which means the batteries are subjected to providing back-up power each time the primary power fails. The experiment is conducted under conditions where the primary source of power has more frequent outages of varying durations. Thus the mode of operation applicable to site A is cyclic application. The charging protocol used under Site A and B is based on the Constant Charge Voltage method (CCV) where the float voltage is set to 2.29 volt per cell. The maximum charging current for site A is set at 30 A and at 34 A for site B. this concept is explained further in section 3.3.

Table 3.1 also illustrates that site C is installed with AGM batteries under cyclic application. However, the charging protocol at this site is based on Modified Constant-Voltage Charging Method (MCVC) method. The float voltage at site C is set to 2.29 V per cell at charging at a charging rate of 5A or below, and the boost charge voltage is set at 2.34 V per cell at a charging rate of 34 A. The MCVC protocol is also defined in detail under section 3.3. The configuration of this site allows the effect of CCV and MCVC charging topology on VRLA batteries to be analyzed.

Table 3.1: CCV and MCVC method rating tabulation

Parameters	Site A	Site B	Site C
Battery Arrangement	VRLA – Gel 170 AH	VRLA – AGM 170 AH	VRLA – AGM 170 AH
Charge Regime	CCV	CCV with a generator	MCVC
Charge Voltage [V]	440	440	440 – Float 449 – Boost
Charge Current [A]	30	34	34 (float) 5 (boost)

3.3 Charging Regime

A VRLA battery requires to be properly charged to ensure that all chemical reactions formed during the discharge and charge cycles are re-combined when a battery is fully charged. When a VRLA battery is overcharged, the electrolyte gets transformed to a huge amount of oxygen and hydrogen gasses which cannot be rectified by the normal battery charging process. When the VRLA battery is undercharged, the capacity gets permanently lost due to low voltage which enables the lead sulfate created during the discharge cycle to crystallize on the plates. Thus, incorrect charge voltage has a direct and significant impact on the premature failure of a VRLA cell. Although there are numerous methods used for charging lead-acid batteries, this study focuses on the two charging methods, i.e. Constant Charge Voltage Method and Modified Constant-Voltage Charging Method (Chandrabose, 2019). The main effect of the charging topology is to bring a battery to a high state of charge (SoC). The charging topology is designed to charge the Valve Regulated Lead Acid battery in a specific technique from the lower SoC throughout to a higher SoC status (Sun, 2020; Sharma, 2016).

3.3.1 Constant Charging Voltage Method (CCV)

As seen in table 3.1, the constant charge voltage method is applied in experimental sites A and B to reinstate the battery to a float level. This method provides a regulated output voltage and larger current capacity. A high amount of current is permitted to flow during the first stage of the charging process when the battery's voltage level is still low. A large amount of current is delivered until a battery reaches about 70% state of charge, then the current reduces as the battery reaches saturation. For this method, the large initial current is controlled or limited by a device within a battery charger (or a UPS in this case). The automatic decrease of current with the rise in battery voltage is critical to ensure the battery's water decomposition is kept at a minimum level. The charge profile for the constant charge voltage method is shown in Figures 3.2 and 3.3. These figures show the battery charging profile of one monobloc that was extracted from real-time battery monitoring system data at experimental site A. The data was sampled every 10 minutes for a period of four hours during a charge cycle. The UPS float charge voltage at this site is set at 2.29 volt per cell which means a battery will be considered 100% SOC at the voltage level of 13.75 V. The maximum charging current is set at 34 A. From figure 3.2 it can be observed that from the beginning of the charge cycle the battery voltage is increasing rapidly from 11.8 V to about 13.75 V in the first two and half hours of the charge cycle. At the same time figure 3.2 shows the amount of current (32 A) being delivered to the battery. It can also be seen in figure 3.2 that, immediately the battery reaches saturation, the level of current in figure 3.3 drops drastically. This is a typical concept of the CCV charge method.

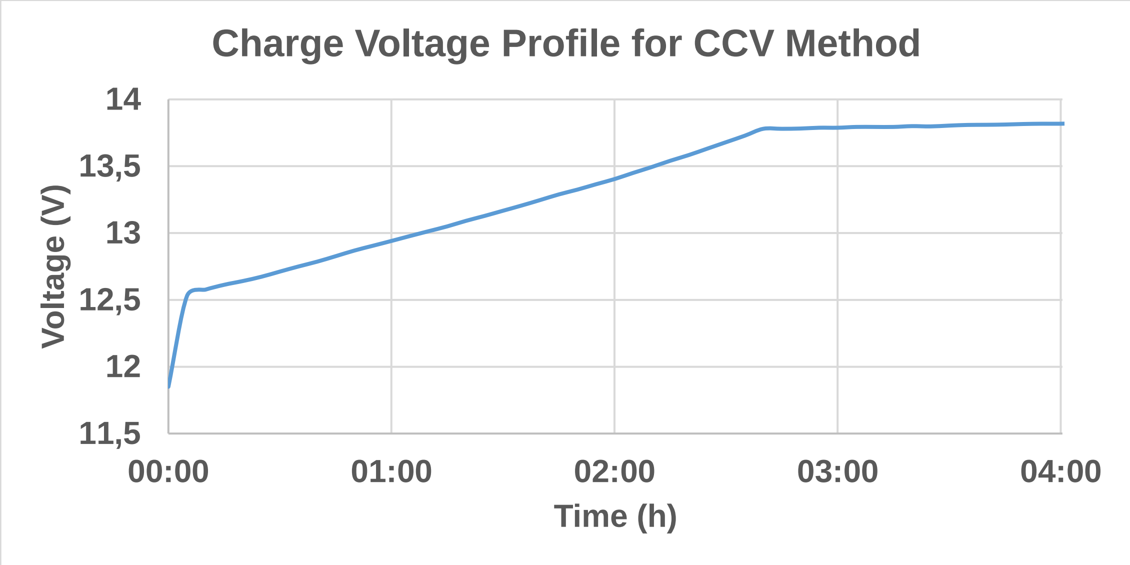


Figure 3.2: Charge voltage profile for CCV method at Site A

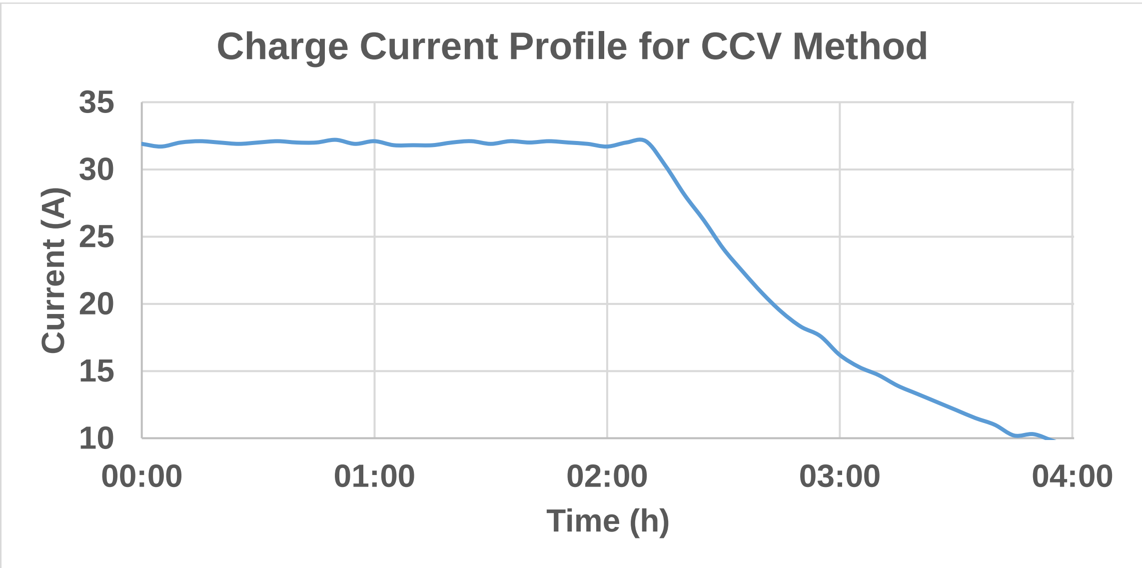


Figure 3.3: Charge current profile for CCV method at Site A

The float voltage (V_{Float}) refers to the UPS dc output voltage that is adjusted to the level depending on the battery manufacturer's recommendations to charge the battery bank. Float voltage is derived from the total number of VRLA cells in a battery bank (C_T) and the recommended charge voltage per cell (V_{PC}) which is given as 2.29 V. The formula to calculate float voltage is given as:

$$V_{Float} = V_{PC} \, . \, C_T \tag{3.1}$$

Where V_{PC} is the manufacturer's recommended charge voltage per cell and C_T is the total number of VRLA cells in a battery bank. A battery bank consists of 32 blocks of 12 V VRLA batteries, thus the formula to calculate C_T yields:

$$C_T = (No. of\ batt\ per\ bank) . (No. of\ cells\ in\ a\ battery) \tag{3.2}$$

Since a 12 V battery consists of 6 VRLA cells. By substituting the stated values in equation (3.2), C_T becomes:

C_T = 32 x 6

= 192 VRLA cell per battery bank

And by substituting C_T into equation (3.1), float voltage (V_{Float}) becomes:

V_{Float} = 2.29 x 192= 440 V

The normal charge current for VRLA battery is recommended at C/10. Where C is the battery's rated capacity (170 AH in this case). However, for batteries operating under cyclic application, most battery manufacturers recommends 2 x C/10 depending on the battery type. This is to enable the battery to recharge quicker. The batteries used in this study are rated 170 AH. Thus battery charge current (C_{Charge}) considering 2 x C/10 yields:

$$C_{Charge} = 2 \text{ x } \frac{\mathrm{C}}{10} \tag{3.3}$$

when substituting the battery capacity into equation (3.3), the charge current value yields: C_{Charge} = 2 (170 /10) = 34 A.

Thus, for sites A and B where the charging regime of the Constant Charge Voltage method (CICV) method is applied, a fixed UPS output voltage of 440V is applied to a series of 32 VRLA batteries (170AH batteries). Since AGM battery is capable of accepting high current levels, the maximum UPS charge current for the sites with AGM batteries is set to 34 A. At the site with Gel batteries, the maximum charge current is set to 30 A due to current limit factors stated by the manufacture's manual. The effect of the CCV charging regime on VRLA batteries under float and cyclic application was determined at sites A and B.

3.3.2 Modified Constant-Voltage Charging Method (MCVC)

For site C, the modified constant-voltage charging method is applied. This method is applied to boost the battery before settling to float condition to address the voltage variation problem in the string. This method requires control circuits equipped with current limiting resistors within the rectifier assembly to the charging process. The charging process takes place in three phases namely, constant-current charge, boost charge and float charge. The first phase delivers the majority of the charge and takes about half the total charge time. The boost charge proceeds at a relatively low current to saturation which is set at a higher voltage than float level. The boost voltage level on this method is set at 2.34 V per cell or 14.04 V per battery. As the battery voltage rises the current decreases, at a certain set limit the control circuit reduces the charge voltage to float level and maintains it. The float charge keeps the battery at a full state of charge. The charging profile for the modified constant-voltage charging method is illustrated in figure 3.4 and 3.5. These graphs are also extracted from the real-time BMS measurements from site C with the same sampling rate. For this site, the float charge voltage is set at 2.29 V per cell (13.75 V per battery), boost charge voltage set at 2.34 V per cell (14.04 V per battery) and the maximum charge current set at 34 A. From figure 3.4, it can be observed that the first phase of charging (constant-current charge) takes place during the first 50 minutes where the battery voltage increase rapidly from 12.9 V to about 14.04 V, during the same period the maximum charge current is also observed on figure 3.5. The second phase (boost charge) is observed on both graphs between 50 minutes and 2 hours period. As the battery is reaching saturation the charge current declines significantly and the voltage level decrease to float level, this is the third charging phase (float charge) and can be seen on both figures between 2 hours, 10 minutes and 4 hours period

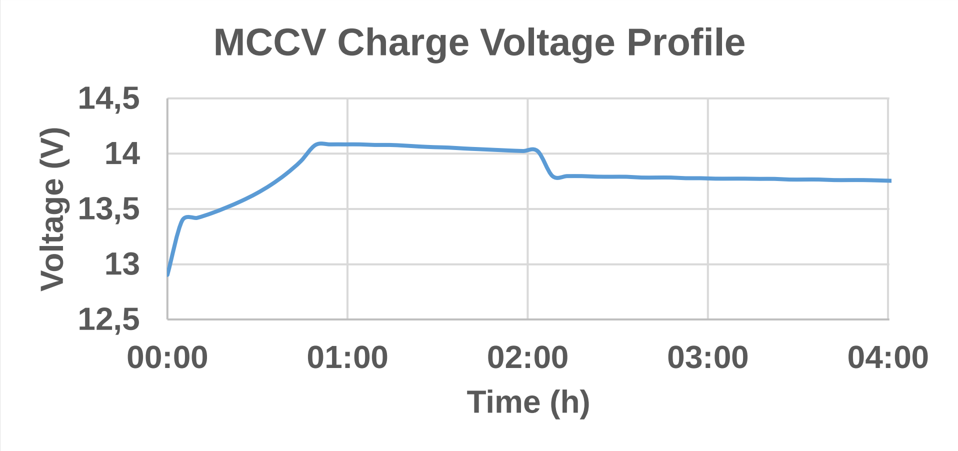


Figure 3.4: Charge voltage profile for MCVC method at Site C.

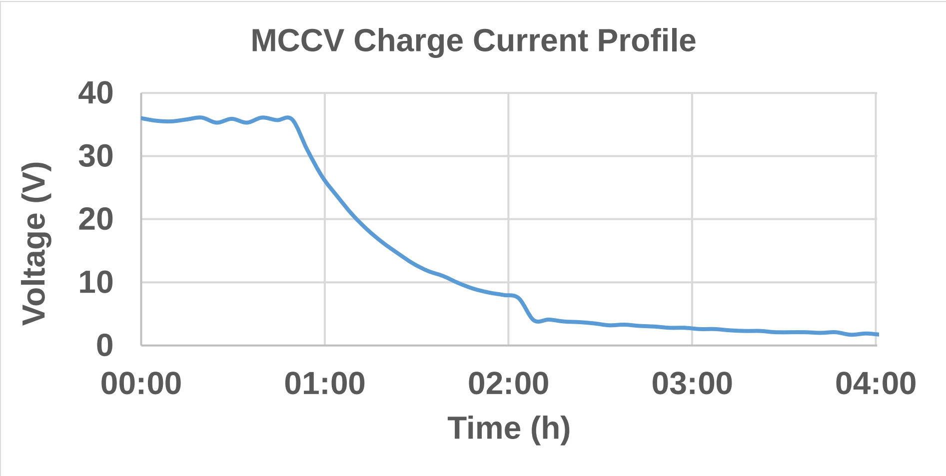


Figure 3.5: Current profile for MCVC method at Site C.

3.4 Testing Protocols

According to (He, 2017), assessing the usable capacity of a battery is the most accurate way of analyzing performance and estimating the degradation factors of a battery. (He, 2017) Further indicates that the traditional method of fully discharging a battery for capacity assessment is time-consuming and causing damage to the batteries. A large amount of current could be drawn from a battery in order to shorten the discharge duration. However, drawing a large amount of current can cause permanent damage to the VRLA cell and lead to premature failure. Also, a long discharge of batteries connected in series will be terminated should any one battery in the string fail (Howell, 2013). (Vishnupriyan, 2014) Suggest that, the analysis based on a data-driven framework over a given amount of time is the safest and most effective way of assessing a battery performance and for predicting capacity.

In this study, the BMS data obtained from real live events of the relationship between fully discharging time and partially discharging voltage curve is considered for usable capacity analysis. The analysis of discharge/charge cycles ranging from 30 minutes to a maximum of 8 hours on both AGM and Gel VRLA batteries is used to analyze performance. Capacity degradation is the main form of identification of a failed VRLA battery. Thus, cycle life is the most critical key to quantify battery performance. Cycle life is basically represented by the total number of discharge/charge cycles that the battery undergoes before reaching the end of life. A VRLA battery is considered to have failed or reached end of life if the remaining capacity is below 80% of its rated capacity (Sen, 2018; He, 2017). It is also commonly knowns that a rapid increase of the battery’s internal impedance under discharging process is a positive indication of capacity loss. The BMS data of battery internal resistance/ohmic value and real-live temperature over time are also analyzed to identify the batteries aging factors.

3.4.1 Discharge Voltage Sampling

The discharge voltage curvature of a fully charged VRLA battery is shown in figure 3.6. From this figure, it can be observed that the discharge voltage curve has three phases, under the initial phase. The voltage undergoes a steep drop in a short period of time (typically 5 minutes). It can also be observed that, the discharge voltage follows a linear decrease during the second phase and then a rapid drop to the cut-off voltage during the third phase. According to (He, et al 2017), the steep drop during the initial phase is caused by the battery's internal resistance and, the electrochemical reaction inside the battery is stable during the second phase. In this study, the variation of discharge voltage curves in different cycles obtained from the BMS system data are analyzed to assess the battery performance and estimate the remaining capacity.

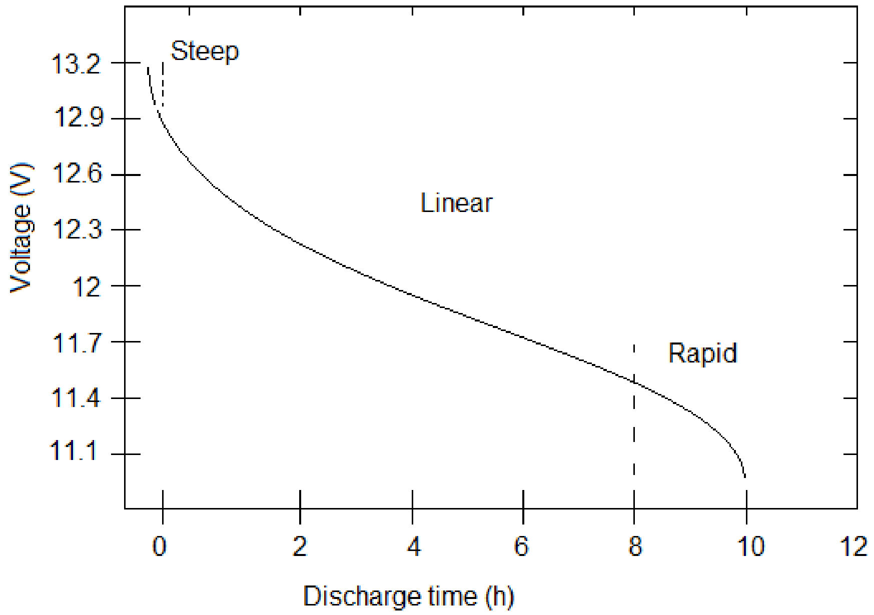


Figure 3.6: Discharge voltage in one cycle.
Source: (He, 2017)

3.4.1.1 Discharge Voltage Modelling

A battery discharge voltage data obtained from the Battery Monitoring System contains crucial evidence concerning the battery performance and condition of the battery. Thus forming an accurate discharge model, which can assist in predicting the usable capacity. The initial discharge phase is excluded in the model since it is a very short portion of the discharge activity. The equation for charge and recharge modeling of VRLA battery is given by Rynkiewicz as shown in equation 3.4 (He, 2017).

$$U_{(t)} = k_0 - I.k_1.t - k_2/(k_3 - I.t) \tag{3.4}$$

where $U(t)$ is the discharge voltage over time, t is the discharge duration in hours (h), I is the discharge current in ampere (A), $k0$ is a constant for the initial volt (V), $k1$ is a constant for the effective resistance in ohm, $k2$ captures the concentration of electrolyte, and $k3$ represents the final capacity of all active materials.

Theoretically, the voltages of each cycle are fitted into equation (3.4) to generate analytic graphs. However, for the purpose of this study, the BMS system data provides already calculated data and graphs. The performance of each battery under different cycles is obtained from the BMS system data and analyzed.

3.4.1.2 Capacity Prediction

Ideally, the battery capacity may be measured by discharging a battery until it reaches its cut-off voltage level of 1.85 volts per cell (Vishnupriyan, 2014; Hu, 2019). However, this method is time consuming as mentioned earlier. The BMS system provides a fast capacity prediction method based on equation 3.5.

$$C = I.t_c \tag{3.5}$$

where *C* denotes capacity, I denotes the discharge current and t_c is the time taken to reach the cut-off voltage.

For every charge and discharge cycle, the BMS system provides readily calculated parameters including, the age, number of cycles, discharged capacity, depth of discharge, power in kW, battery start and end voltage for individual batteries, current, discharge duration, ohmic value and most importantly the estimated life remaining for the battery. This crucial information provides a clear concept relating to the performance and condition of the battery and is thus used for analysis. The data is extractable in CSV/excel values and pdf graphics format for simplified analysis.

3.4.1.3 Model Validation

A battery monitoring system (BMS) provides real-time measurements and calculated values of the required information. To validate BMS and battery model, an analysis of battery data sheets from the battery manufacturers and actual calculations were done. This enabled the validation of the model. The state of charge of AGM and Gel types batteries are classified between 0% and 100% based on the battery voltage levels. The voltage readings which are used for classifying the battery SOC are shown in table 3.2. From the table, it is observed that a Gel battery measuring 12.85 V is classified as 100% charged, while the one measuring 11.8 V is classified as 0% charged. A similar argument also holds for AGM batteries

Table 3.2: Classification of state of charge (SOC) based on voltage readings.

State of Charge	AGM Battery	GEL Battery
100 %	12.80 V	12.85 V
75 %	12.60 V	12.65 V
50 %	12.30 V	12.35 V
25 %	12.00 V	12.00 V
0 %	11.80 V	11.80 V

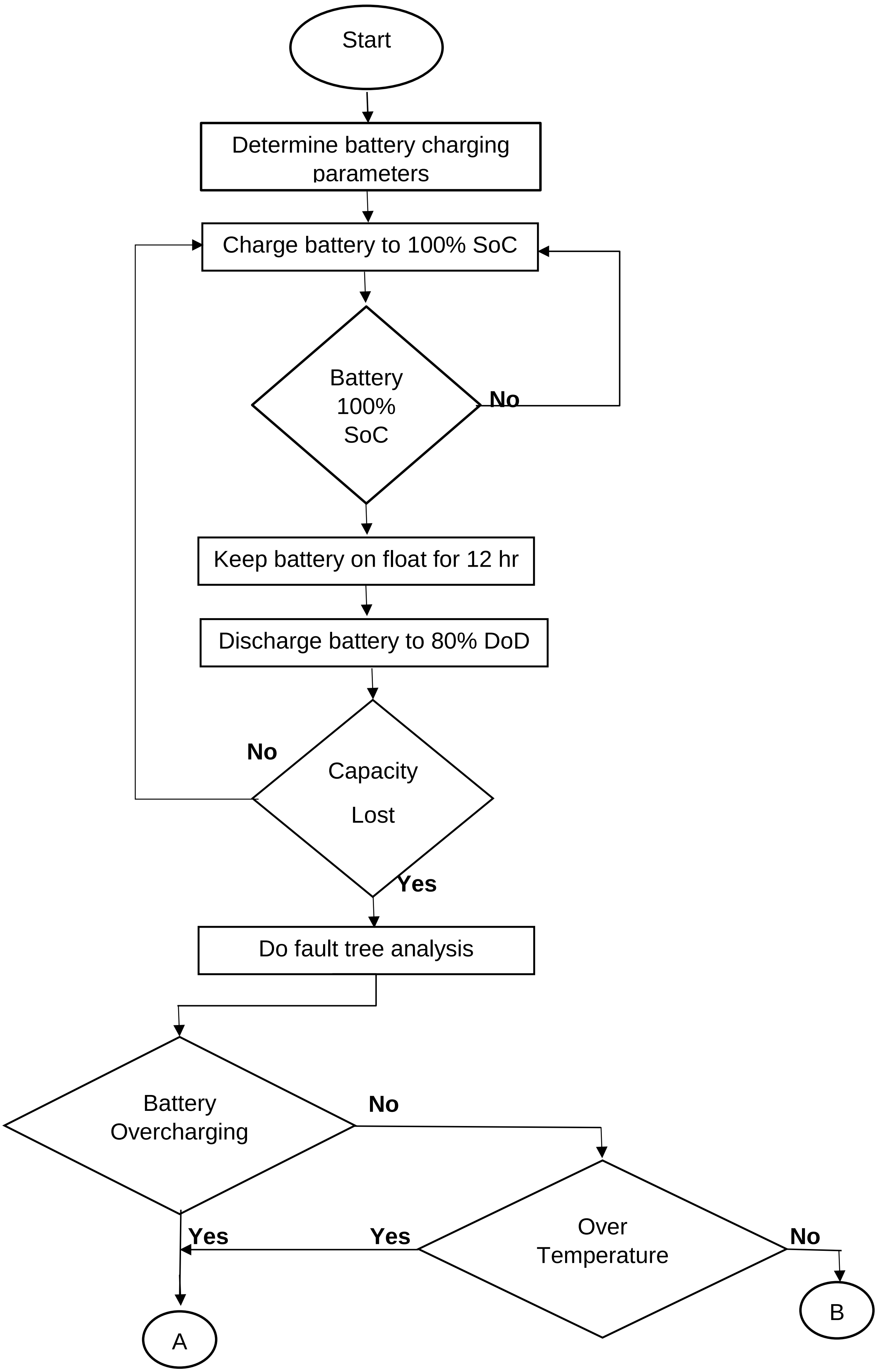
3.4.2 Testing Procedures

To analyze the performance of VRLA batteries, Gel and AGM type batteries rated at 170 AH were used. Although a battery bank contains 32 batteries connected in series, the BMS system provides data for individual batteries which enables analysis to be conducted for each battery when required. The nominal voltage of VRLA batteries used in this study is 12 V. The end of discharge cut-off voltage is 1.85 V per cell or 11.1 V per battery and the maximum cut-off charge voltage is 2.29 volt per cell or 2.34 volt per cell for CCV and MCVC topology respectively. The charging regime considered in this study is CCV and MCVC topologies. The battery test procedures involving a constant current discharge have proven to be effective (Chandrabose, 2019; Vishnupriyan, 2014). The test procedures followed in this study are presented on the steps below:

1. Charge a battery with a constant current of 0.2 C until the voltage reaches 2.29 V per cell. Under the MCVC regime, continue charging the battery with a constant voltage of 2.34 V per cell until the current below 5 A.
2. Keep the battery on float charge of 2.29 V per cell for at least 12 hours. Since the tests are conducted under a real live system, this fact is verified by observing that, the primary source of power was steadily available for a minimum duration of 12 hours before step 3 is conducted.
3. Discharge the battery with a constant current level of between 0.05 C and 0.1 C for the duration ranging between 30 minutes and 8 hours or until the battery reaches a cut-off voltage of 1.85 V per cell.
4. Repeat step 1 and 2
5. If a battery fails, follow the fault tree analysis steps as shown in figure 3.7
6. Repeat the process as per the test plan

During testing, parameters of interest such as voltage, current, ohmic value and discharge capacity are monitored and recorded automatically by the BMS system. The discharge voltage curves in different cycles were plotted and will be discussed in chapter 4.

An electrochemical cell completes a cycle each time a battery is discharged and then charged. A life cycle of a battery is determined by these cycles. Loss of capacity in VRLA battery can be classified by several failure modes: Irreversible sulfation, plate corrosion, water loss, active material degradation and cell design deficiencies. A flow diagram of the investigation method used to link the stress factor to a failure mode associated with loss of capacity is shown in figure 3.7. Typical stress factors include overcharging and undercharging which are factors derived from the voltage, current and temperature history of the battery. A battery is classified as failed when its capacity decreases beyond a threshold specified by the manufacturer.


Start
Determine battery charging parameters
Charge battery to 100% SoC
Battery 100% SoC
No
Keep battery on float for 12 hr
Discharge battery to 80% DoD
No
Capacity Lost
Yes
Do fault tree analysis
Battery Overcharging
No
Yes
Yes
Over Temperature
No
A
B

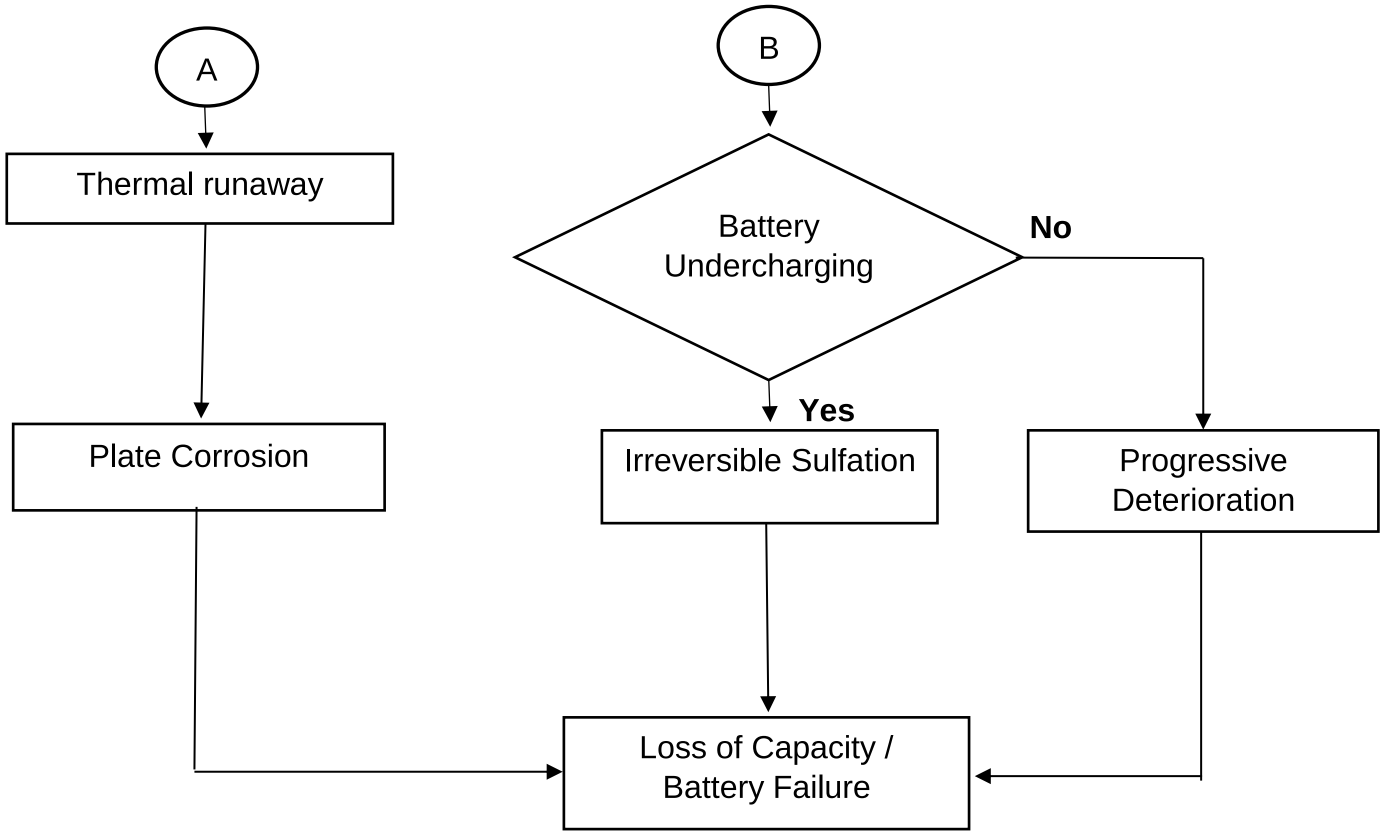


Figure 3 7: Fault tree analysis process

3.5 Hardware Composition

3.5.1 Uninterruptable Power Supply Unit

The type of UPS system that is used at the three sites is a standalone online double conversion static UPS sized 30 kVA. The typical block diagram of the UPS is shown in figure 3.8. From the figure, the bold line indicates the flow of power under normal operation. The rectifier converts the incoming primary AC power (3 Phase, 380 V) to DC output voltage which charges the batteries and supplies the inverter at the same time. The rectifier's output voltage level is adjusted to match the relevant battery charging protocol. The inverter converts the DC signal to a clean AC signal, which supplies the critical load. If the primary AC input voltage fails or becomes unavailable, the battery immediately supplies the necessary DC voltage to the inverter without interruption, for a limited time, depending upon the size of the battery. With the restoration of the primary AC input voltage, the rectifier will resume operation and again supply DC voltage to the inverter and charge the batteries. Thus, it is critical to ensure that, the UPS/rectifier is sized correctly to supply the critical loads and charge the batteries at the desired rate. In this study, the UPS's rectifier is the only component that will be described in detail amongst other components of the UPS, this is mainly because the rectifier/charger is the major component that is directly linked to or affecting the performance of batteries.

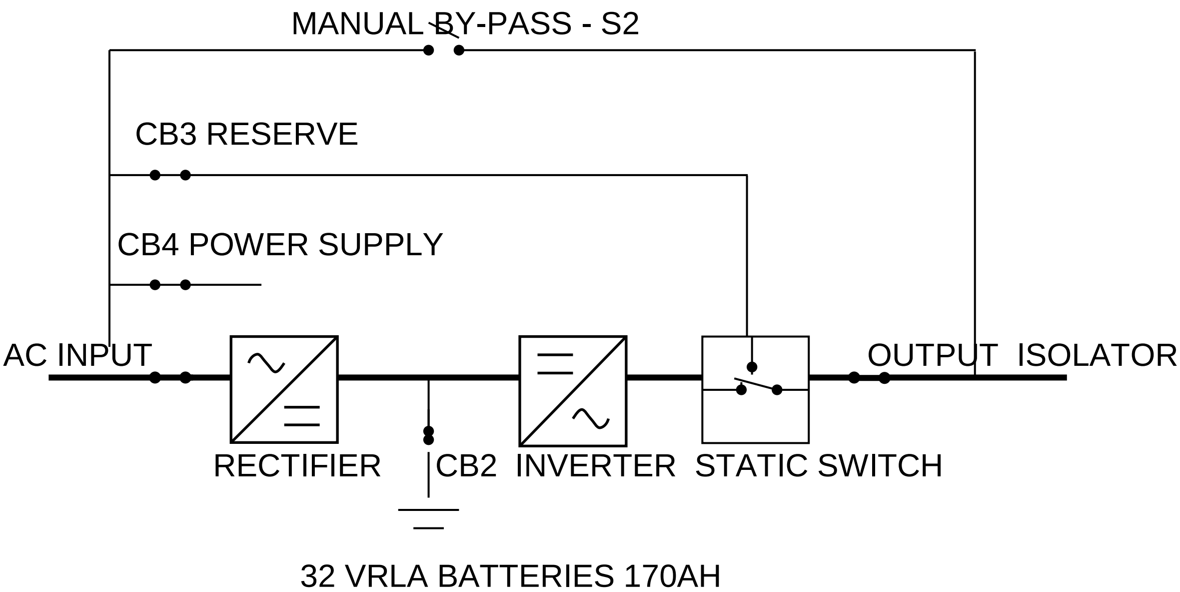


Figure 3.8: Block diagram of UPS system
(Source: Manufacturer's UPS specifications/manual)

3.5.1.1 The Rectifier/Charger Assembly

The rectifier is the main source of DC voltage. Its major function is to maintain the batteries in a charged condition and supply the inverter. The rectifier is equipped with a soft start circuit to prevent disturbances from the input AC power source and to prevent potentially dangerous power surges within the system. The rectifier can function in two different modes, namely, float mode and boost mode. This enables operations under the CCV and MCVC charge regime. The specifications of the rectifier assembly used in all the experimental sites are shown in table 3.3. Normally, a rectifier is designed with 1.2 factor over the normal UPS size to accommodate the demand to produce enough current for charging the batteries. Thus, for a 30 kVA UPS, the rectifier assembly will be sized 36 kW. From table 3.3, it can be observed that the rectifier assembly operates from a three-phase power with a tolerance of 10 % below and above 400 V at 50 Hz. The minimum DC output of 330 V and up to a maximum DC voltage of 450V can be supplied to charge a battery bank. Thus, the rectifier used is capable of producing any voltage ranging from 1.72 volts per VRLA cell to 2.35 volts per VRLA cell. The rectifier has 1 % stability, which means that the battery charging voltage will not be affected by the fluctuations of the AC primary input.

Table 3.3: Rectifier specifications

Size	30 kVA
Rectifier Input	Three Phase 400 VAC, ±10%
Input frequency	50 Hz ±5%
DC output voltage	Min 330 V, Max 450 V
Stability	±1 %
Float level	As per end-user requirements

A schematic diagram of the rectifier assembly is shown in figure 3.9. The major components of the rectifier assembly are rectifier control, rectifier drive and the Silicon Controlled Rectifier (SCR). The rectifier control communicates with the rectifier drive through a ribbon cable and the drive assembly is connected directly to the SCR, which converts the AC signal to a DC signal. The control facility is equipped with adjustable ports which enable the setting of charging parameters such as float voltage, boost voltage, maximum current, low and high dc cut-off to be adjusted. The control assembly is also equipped with a DC sensing circuit which will switch the rectifier off to protect the batteries in case the DC voltage rise above 2.6 V per cell. The drive assembly controls the switching activities of the SCR.

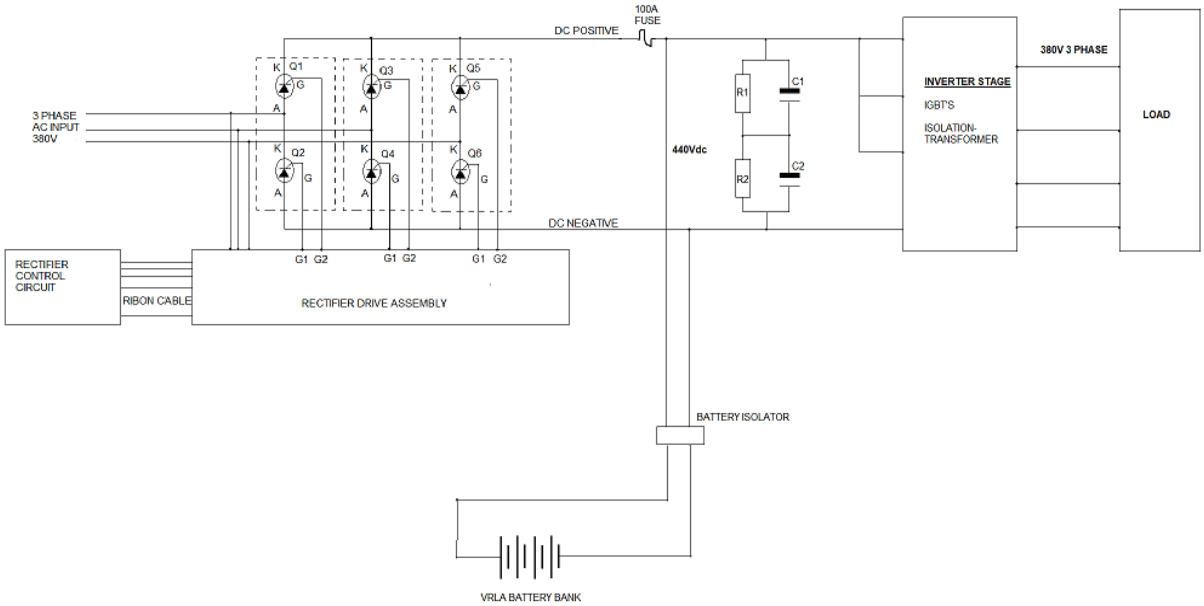


Figure 3.9: Schematic diagram of the rectifier assembly.
(*Figure drawn using paint with reference to the UPS manufacture's design)*

3.5.2 Battery Monitoring System

BMS system provides the most advanced tool for monitoring and managing battery banks. Its continuous data sampling and reporting capabilities provide the stuffiest data for battery analysis and detect any failing battery before they affect the performance of the entire system. Continuous monitoring provides the accumulation of data, the ability to report and spot trends, and the ability to make a sound analysis of battery performance (Vishnupriyan, 2014). The data obtainable from the BMS system can be summarized as:

i. **String Voltage**: The string voltage/ battery bank voltage is monitored to ensure the UPS rectifier/charger is online and performing properly.
ii. **Individual Battery Voltage**: Voltage identifies catastrophic failures, such as short circuit cells, and gives true visibility of performance under discharge. Therefore it is important to monitor the individual battery voltage

iii. **Ambient Temperature:** Temperature plays a critical role in the life cycle of a battery. A VRLA battery's lifespan is normally specified at 25 degrees. Every 10 degrees temperature increase can decrease battery life by 50%. Thus it is critical to monitor the temperature

iv. **String Current:** String current monitoring allows the detection of incorrect battery charging and also assists in measuring the energy delivered or accepted by the battery string.

v. **Individual Battery Impedance (Ohmic Value):** Monitoring the battery impedance is important for analyzing battery end-of-life trends and also allows detection of faulty batteries without the need for discharging (Kwiecien, 2019).

vi. **Individual Battery Temperature:** Measuring the temperature of each battery allows the early detection of thermal runaway.

3.5.2.1 BMS Hardware Components

The BMS hardware components consist of Sentinel Monitor, Monobloc sensors, Temperature sensor, Current sensor and a Personal Computer (PC) or Laptop.

3.5.2.1.1 Sentinel Monitor

The monitor captures, processes and stores data from a range of sensors. This includes monobloc voltage, impedance, individual battery temperature, string voltage and current and ambient temperature. The specifications of the BMS sentinel monitor used in this study are given in table 3.4. From the information provided in table 3.4, it can be observed that the monitor is power efficient, consuming only 10W or less and is capable of monitoring the battery voltages ranging from 2V to 1000V which allows a maximum of up to 1280 batteries to be monitored at a time. For the purpose of this study all sites are consist of 32 batteries in a bank. It can also be observed that the system also allows a variety of current and temperature levels to be monitored while providing sufficient communication mediums such as Ethernet, RS232, RS485 to be configured.

Table 3.4: Specifications of a BMS monitor

Input Power (10 W)	AC input 110 V to 240 Vac, 50/60Hz, 0.15 A max
Battery details	VRLA type, String voltage 2 V to 1000 V, m-sensor type, up to 1280 batteries
Current	0 A to 2000 A, Hall Effect type
Temperature range	0 °C to 80 °C measurement range
System accuracy	±1 % sensor accuracy, ±1 °C accuracy, maximum sensor cable distance 15m
Operating temperature	0° C to 50 °C
Communication ports	Ethernet, RS232, RS485
Relay outputs	4 programmable voltage free contacts, 1.25 A @ 24VDC
Physical dimension	Width: 430 mm, depth: 270 mm, height: 45 mm

3.5.2.1.2 Monobloc Sensor

The m-sensors are directly connected to battery terminals. They are used to measure the individual monoblock voltage, impedance and temperature. In this study, dual-type m-sensors are used. Each sensor monitors two monoblocs. The specifications of the m-sensor are tabulated in table 3.5. From the table, it can be observed that the M sensor obtain power from the batteries being monitored. It is capable of reading battery voltages in the range of 9.6 V to 15.6 V and can read the internal resistance ranging from 1 to 40 m ohms. The temperature range of up to 70 degrees Celsius can also be measured. This parameter identifies dual-type m-sensor as the most suitable for this study.

Table 3.5: Specifications of the m-sensor

M-sensor parameters	**Parameters specifications**
Type	Dual series – measures two monoblocs
Application	VRLA, 12 V nominal
Power supply	Powered by monoblock being monitored
Voltage measurement range	9.6 V to 15.6 V, 0.2 % accuracy
Impedance measurement range	1.00-40.00 mΩ, ±2.5 %
Temperature measurement range	-4 °C to 7 0°C
Maximum input voltage	65 V
Power supply current	18 mA

3.5.2.1.3 BMS Software Configurations

The BMS system uses the Configuration and Link windows-based software for setting up the system and monitoring the sites respectively. Both software applications allow for remote and direct local connections. The configuration software is used to program the BMS system and set the alarm limits for all monitored parameters.

4. CHAPTER 4 RESULTS

4.1 Introduction

This chapter provides an analysis of the results obtained from VRLA batteries with a rated capacity of 170 AH and nominal voltage of 12 V. In section 4.2 the results obtained at Site A are outlined. Section 4.3 and section 4.4 presents results for site B and site C respectively. The last section (section 4.5) of this chapter gives a summary of the results. Although each site contains thirty-two batteries, the performance results of six batteries identified as the top and low performers of the specific discharge cycle are presented. The results are provided in the form of graphs and tables. The performance profile obtained from the manufacturer's specifications for Gel and AGM VRLA battery with a rated capacity of 170 AH is shown in table 4.1.

The characteristics stipulated in table 4.1 were used to analyze the battery's actual performance against the manufacture's specified characteristics. The manufacturer's specified discharge durations are organized as row elements, while relevant discharge current levels are organized as column elements. From table 4.1 it can easily be seen that according to the manufacturer's specifications AGM battery with a nominal capacity of 170 AH is expected to last for ten hours when discharged at a current level of 17.3 A and last 5 hours if the discharge current is increased to 33.4 A. It can also be seen that a Gel type battery with a similar capacity rating will last for ten and five hours when discharged at a current level of 16 A and 28.2 A respectively.

Table 4.1: Performance characteristics of 170 AH AGM and Gel VRLA battery

Discharge Duration [Hours]	Discharge Current - AGM [A]	Discharge Current - Gel [A]
20	8.4	8.5
10	17.3	16.0
8	21.5	19.3
5	33.4	28.2
4	40.8	33.6
3	52.3	42.6

4.2 Experimental Results - Site A

4.2.1 Discharge Test after 18 Months of Operation – Site A

The results obtained during an eight-hour discharge test on VRLA Gel batteries after eighteen months of operation at Site A are presented. As defined in chapter 3, Site A is configured with the Constant Charge Voltage method and functioning under cyclic application. The discharge voltage profile of six batteries during the eight-hour discharge activity is shown in figure 4.1. The batteries are named MB 1 .. MB 32. However, the discharge curve for only batteries named MB 3, MB 8, MB 12, MB 17, MB 24 and MB 32 are shown in figure 4.1. It can easily be seen that the voltage of all batteries in a string was still well balanced after eight hours of discharge. At the same time, the battery with minimum voltage reading was MB 17 at 12.055 V and the highest was battery MB 12 at 12.167 V. During this discharge activity none of the batteries reached the low cut-off voltage of 11.1 volts. These results indicate a good state of health for all the batteries.

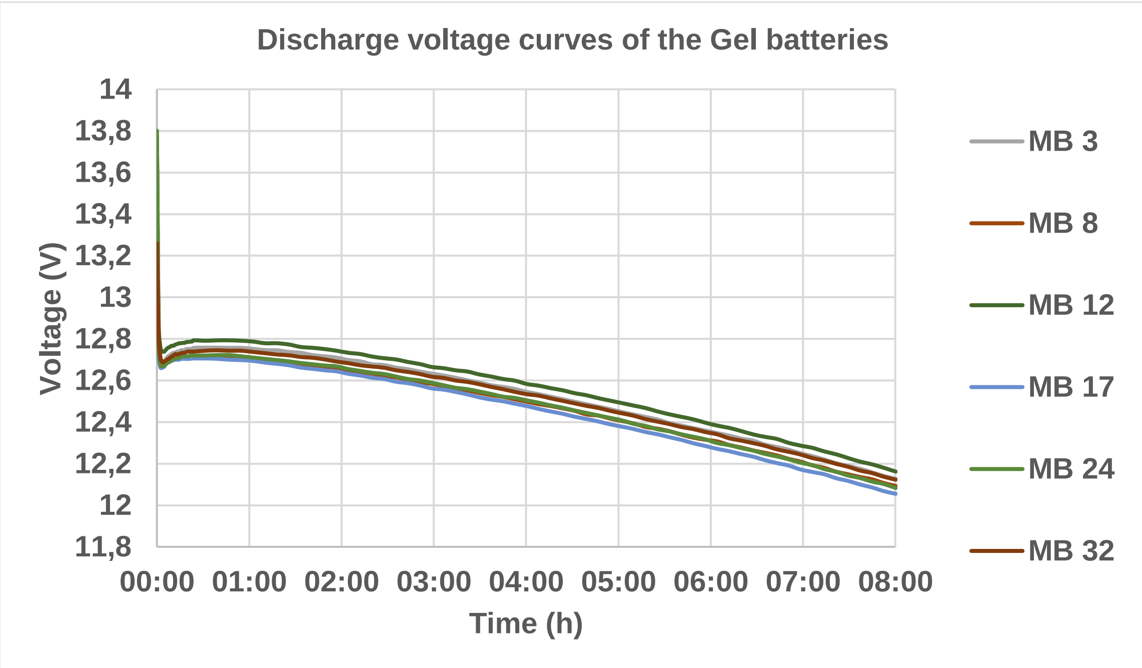


Figure 4.1: Discharge voltage curves of 170 AH Gel batteries, 83 % DoD at Site A

The performance summary data obtained from the Battery Monitoring System during the discharge activity is tabulated in table 4.2. Operating parameters and discharge parameters values are organized as column elements.

Table 4.2: Discharge data summary of Gel batteries @ 83% DoD at Site A

Operating parameters	Discharge Parameters Values
Nominal Voltage [V]	12
Nominal Capacity [AH]	170
Discharge Current [A]	17.6
Capacity used [AH]	140.9
Average temp [oC]	20 oC
Depth of Discharge [DoD]	83 %
Duration [Hours]	08:00:16
Voltage variation [V]	0.112

From table 4.2, it can be seen that the battery bank with a nominal capacity of 170 AH was discharged for a duration of eight hours and sixteen minutes with a load current of 17.6 A. It can also be observed that the used capacity during this discharge activity is 140.9 AH, the used capacity is a multiplication factor between the discharge duration and load current. This means the batteries were discharged to 83 % depth of discharge (DoD). The Depth of Discharge (DoD) used during a discharge activity can be verified by using the mathematical expression given in equation 4.1:

$$DoD = (D_T . I_D)/(C) .100 \qquad 4.1$$

Where D_T is the discharge duration, I_D represents the discharge current and C is the battery capacity. By substituting the values stated in table 4.2 into equation 4.1 the Depth of Discharge becomes:

DoD = (8 x 17.6) / 170 x 100 = 83 %

The capacity provided by the batteries is verified by the multiplication factor between discharge duration (D_T) and the discharge current (I_D).

It can also be observed that the average voltage variation of the battery bank was 0.112 V at the end of the 8-hour discharge test. This provides further evidence of a well-balanced and good battery state of health.

The temperature profile obtained for MB 16, MB 22 and MB 29 from the BMS system during the eight-hour discharge activity are shown in figure 4.2. It can be seen that the string temperature increases gradually from 18.5 ^{o}C to reach 20.8 ^{o}C after 8 hours. The low variation of temperatures during the discharge cycle also proves the good condition of batteries.

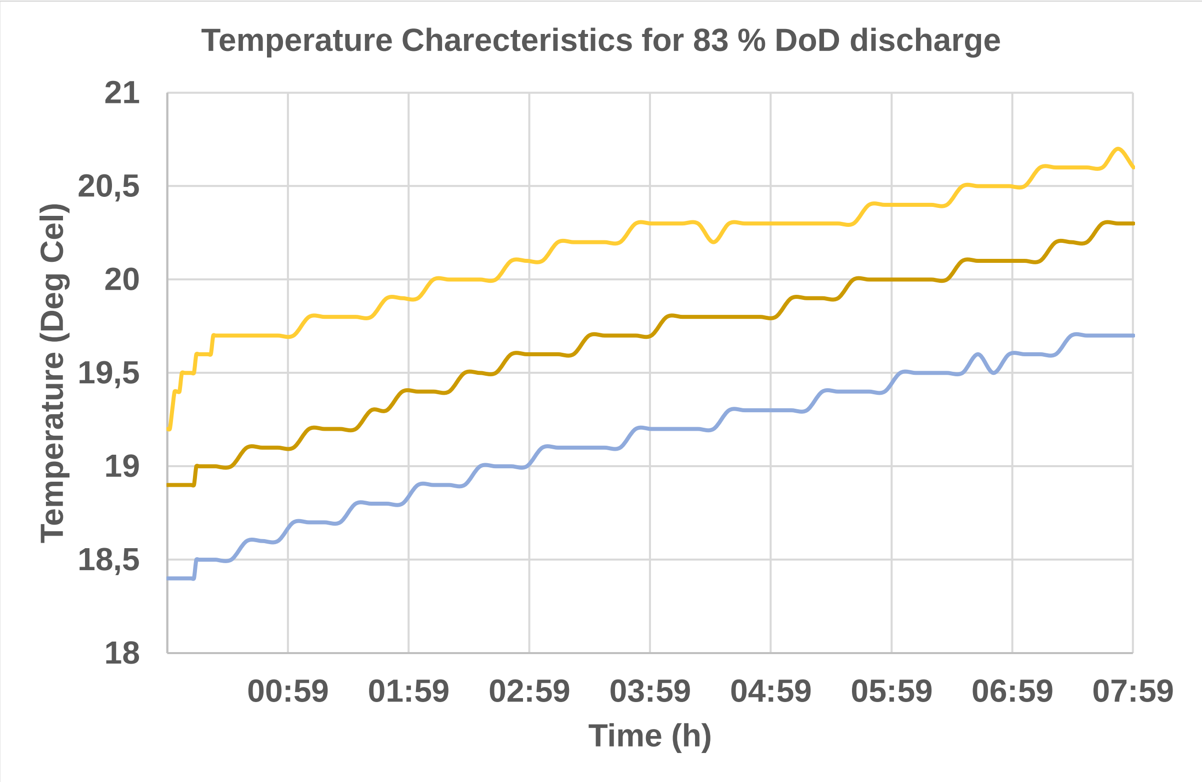


Figure 4.2: Discharge temperature profile of MB 22 (Gel) after 18 months at Site A

4.2.2 Discharge Test at 24 Months – Site A

The results obtained from the same Gel battery after 24 months of operation are presented in this section. The discharge voltage curves obtained from the BMS system during the discharge activity are shown in figure 4.3. It can be seen that the voltage of MB 27 drops rapidly and reaches the cut-off voltage of 1.85 volts per cell or 11.1 V per battery after one hour and thirty minutes of discharge. It was also observed that the voltage of MB 26 reaches the cut-off voltage of 11.1 V after 4 hours and 50 minutes of discharge. At the end of discharge activity, the voltage of MB 25 is no longer balance with the rest of the batteries in the bank. At the same time it can be seen that batteries lasted for seven hours and sixteen minutes before reaching the low cut-off voltage of 355 V. By observing the manufactures' specifications stated in table 4.1, it can be determined that a 170 AH Gel battery discharging at a load current of 17 A should easily last nine hours of discharge duration. This means the Gel battery bank did not meet its specified performance during this discharge activity. By analyzing the voltage profiles shown in figure 4.3, it can be easily be seen that battery MB 26 and MB 27 were bad cells in the string and have affected the performance of the entire battery string.

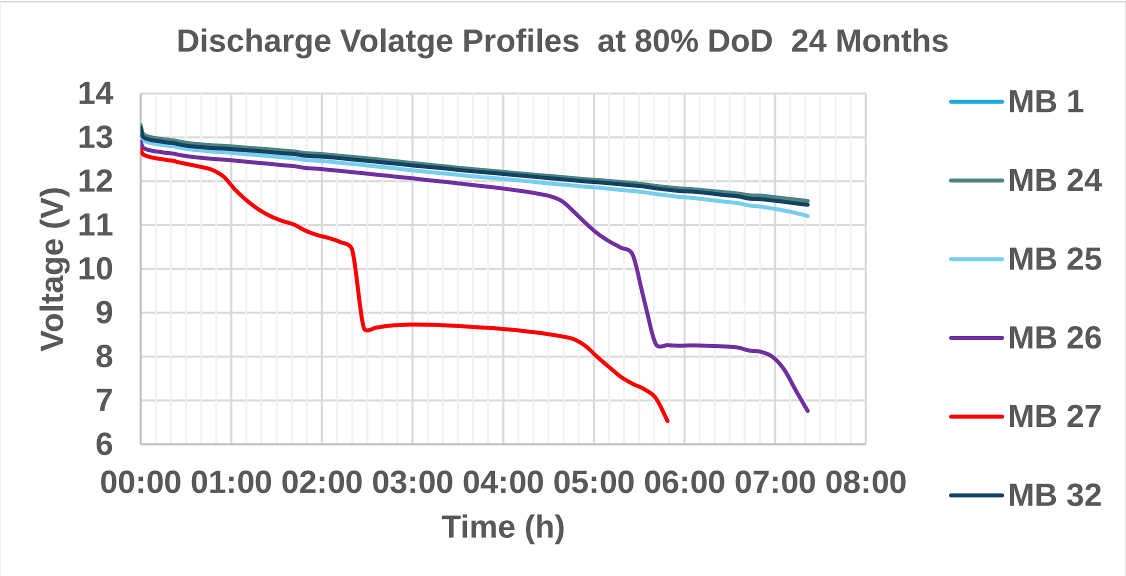


Figure 4.3: Discharge voltage curves of Gel batteries, 24 months old at Site A

The temperature variations of the individual batteries during the same discharge activity are shown in figure 4.4. It can be observed that the temperature levels of all other batteries in the string increases gradually from 22 ^{o}C to 25 ^{o}C during the discharge activity. At the same time, the temperature level of MB 27 increases rapidly from 45 ^{o}C and reaches 56 ^{o}C at the end of discharge. From the voltage and temperature profiles, it can be seen that MB 27 is a bad cell and it affects the performance of the whole bank.

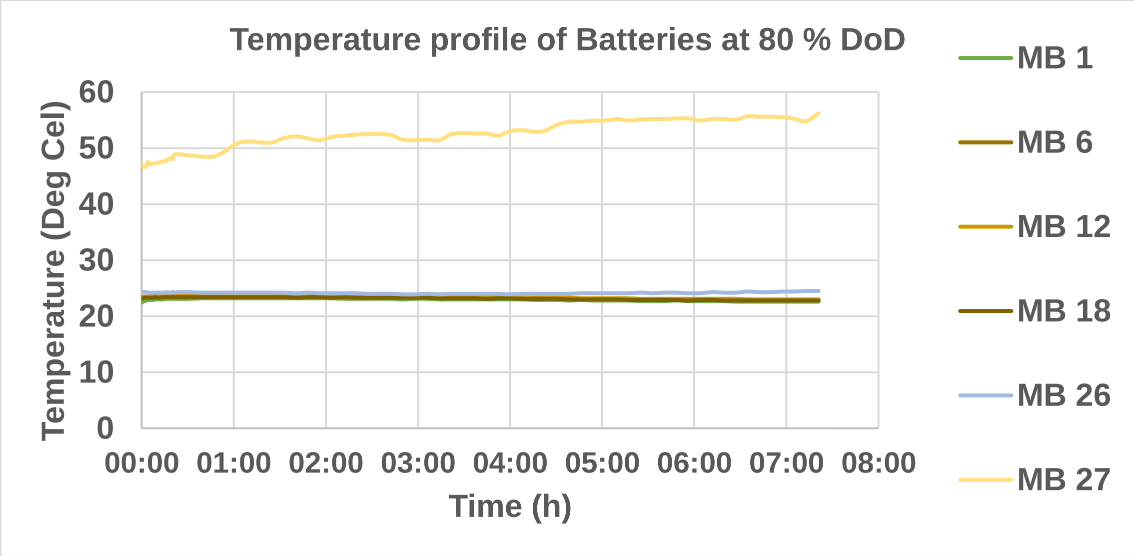


Figure 4.4: Discharge temperature profiles of Gel batteries at Site A

4.2.3 Equalization Charge test at 24 Months – Site A

The discharge activity results obtained from the same Gel battery bank after performing an equalization charge on the battery bank are shown in figure 4.5. The equalization charge was performed by applying the charge voltage of 2.4 per cell at a current level of 0.2 A for a period of 24 hours in order to address the voltage imbalances and recover the capacity of the bad performing batteries in the bank.

From figure 4.5, it can be seen that MB 27 reaches the low cut-off voltage of 11.1 V volt after two and half hours of discharge, which means its discharge time has improved by one hour as compared to the previous discharge activity. At the same time, MB 26 has been fully recovered and is well balanced with the rest of the batteries in the bank. Although MB 27 has improved, its performance was still not sufficient to meet the expected manufacture's specifications stated in table 4.1. MB 27 was replaced with a new 170 AH Gel battery of similar specifications. The cause of premature failure of MB 27 was classified as catastrophic failure associated with handling issues during installation.

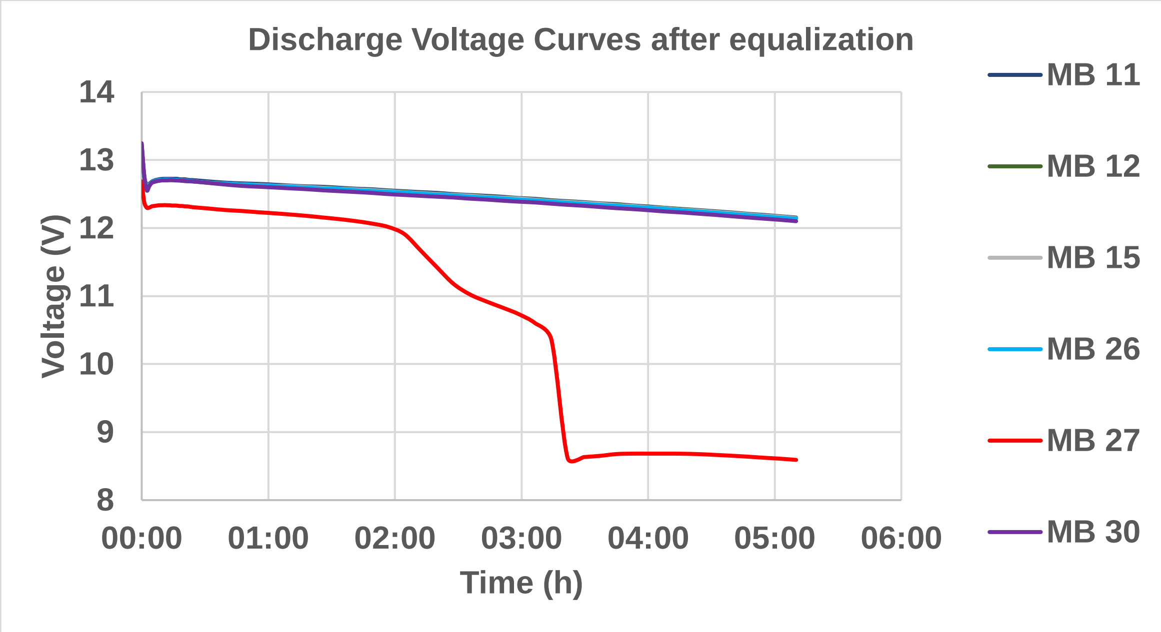


Figure 4.5: Discharge voltage curves of after equalization charge Site A

4.3 Experimental Results - Site B

4.3.1 Eight Hour Discharge Activity after 24 Months – Site B

The experimental results of AGM batteries operating under float application are presented in this section. The discharge voltage profile of six batteries during the eight-hour discharge activity is shown in figure 4.6. The batteries were discharged for a duration of eight hours with a load current of 16 A. It can easily be seen that after eight hours, the voltage of all batteries was still balanced. At the same time, the battery with minimum voltage reading was MB 29 at 12.23 V and the highest was battery MB 32 at 12.25 V. Thus the voltage levels of all batteries were still well balanced and above 12.2 V after 8 hours of discharge. This is an indication of good health and stable condition.

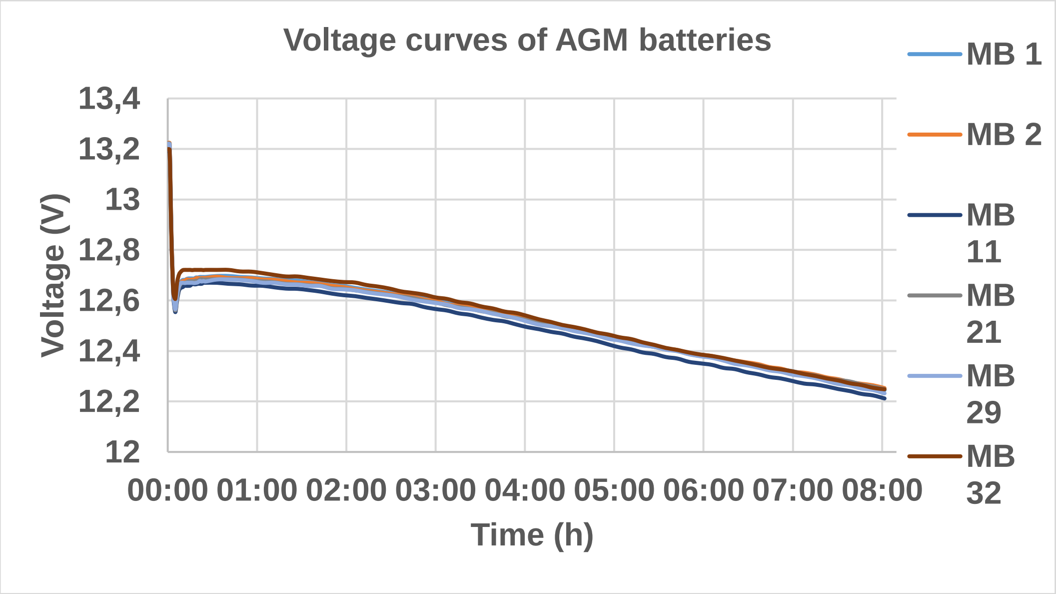


Figure 4.6: Discharge voltage curves of AGM batteries, 24 months at site B

4.4 Experimental Results – Site C

4.4.1 Five Hour Discharge Activity after 18 Months

The result obtained from AGM type battery after 18 months of operation under cyclic application and Modified Constant-Voltage Charging method is presented in the section. The discharge voltage curve of the six highest and lowest performing batteries during the discharge activity is shown in figure 4.7. The batteries were discharged with a constant current of 20 A. By observing the battery manufacturer's specification tabulated in table 4.1, it can be seen that a 170 AH AGM battery supplying a load current of 20 A is expected to last for a period not less than eight hours. From figure 4.7 it can be observed that the voltage of all batteries declines rapidly during discharge activity. At the same time, it can be seen that all batteries reach the low cut-off voltage of 11.1 V in less than five hours of discharge. This implies that the AGM battery operating under cyclic application did not meet the manufacturer-specified performance during this discharge activity.

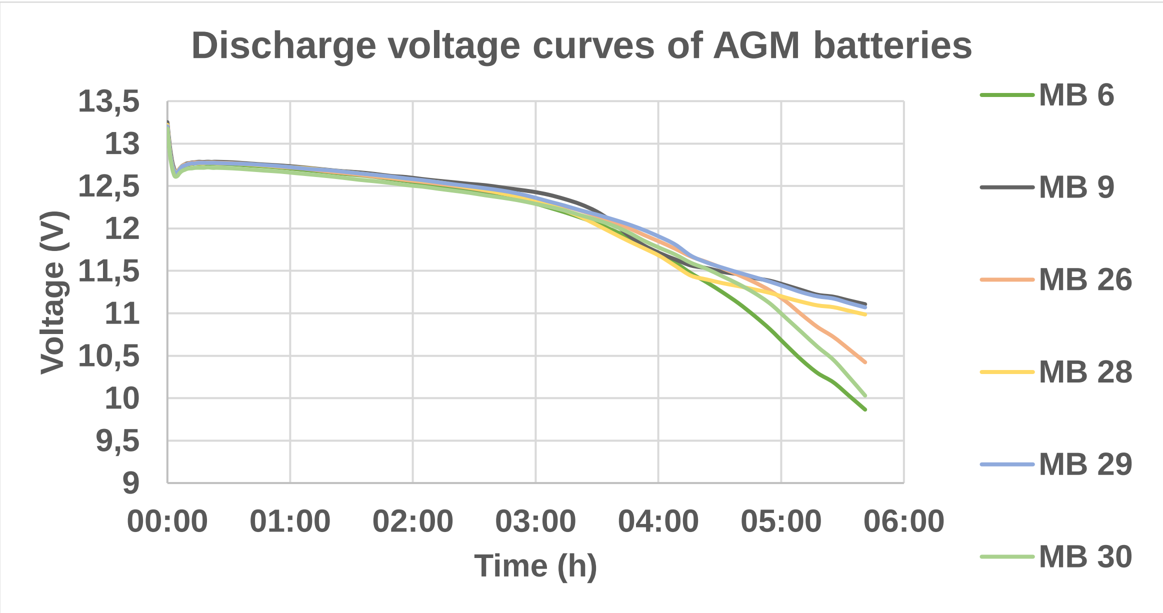


Figure 4.7: Discharge voltage curves of AGM batteries at site C

The string temperature trend of the same discharge activity is shown in figure 4.8. According to battery manufacture's specifications discussed in chapter 2 under figure 2.2, the ideal performance of a VRLA battery is rated at between 23 to 25 Degree Celsius, and an increase of 10 degrees in temperature reduces the battery life by over 50 %. From figure 4.8, it can be observed that during the discharge activity the battery string temperature increased rapidly from 25 ^{o}C to 45 ^{o}C within five hours. The VRLA failure mode associated with a rapid decline of battery voltage and rising temperature while discharging is classified as sulfation of batteries. Thus all AGM batteries at site C have failed within eighteen months of operation.

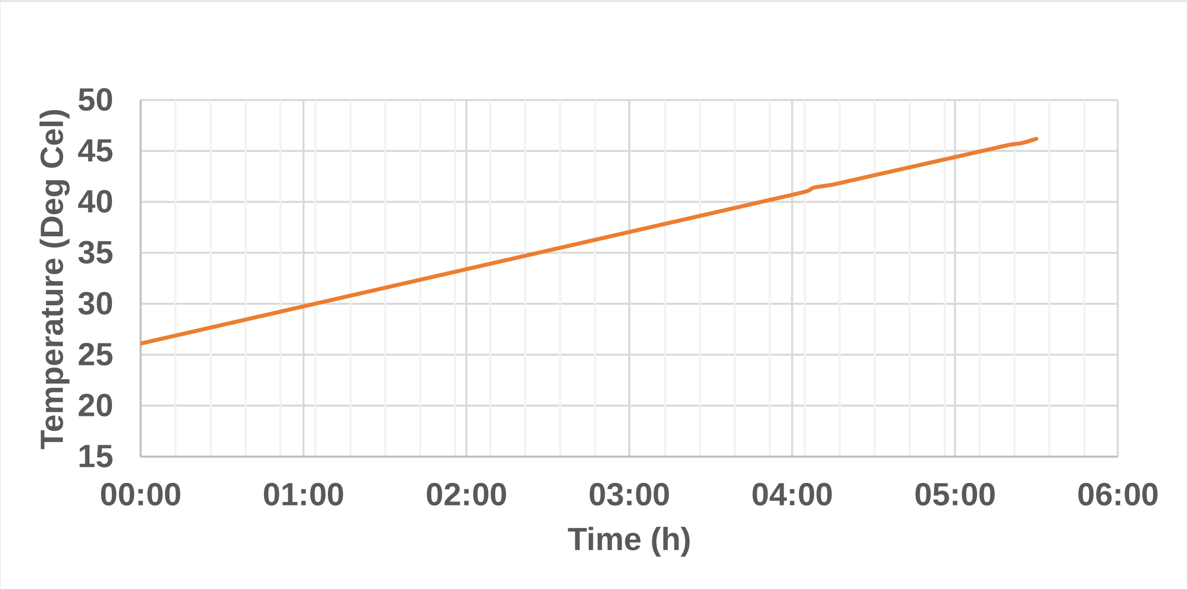


Figure 4.8: String temperature profile during discharge activity at site C

4.5 Summary of Experimental Results

The summary of performance results obtained from three sites over a period of 24 months are presented. A comparison between battery technologies and actual battery performances against manufactures' specifications is presented.

The parameters delivered by the Gel batteries over a period of 24 months are shown in table 4.3. The performance parameters are organized as row elements, while actual performance and manufacturer-specified performance are organized as column elements.

Table 4.3: Performance of 170 AH Gel battery vs manufacture's specifications

Performance Parameter	Manufacturer's Specifications	Actual performance – Gel battery
Discharge duration @ 17A	9 hours	9 hours
No. of discharge Cycles @ 50% DoD	800	289
Est. Remaining Life [Cycles at av. DoD]	-	486

From table 4.3 it can be observed that according to manufactures specifications a 170 AH Gel battery discharging at a load current of 17 A should last nine hours. By observing the actual performance results obtained during the discharge activities (i.e. section 4.2.1) it can be seen that the Gel battery provided an eight-hour discharge duration and all batteries remained in good condition, thus the battery bank could easily reach nine hours discharge time if drained more than 80 % DoD.

It can also be seen that according to the Gel battery manufacture, a Gel battery with a rated capacity of 170 AH is capable of producing 800 discharge cycles if drained to 50% depth of discharge. The number of actual discharge cycles delivered by the Gel battery during the experimental period amounts to 289 times at an average of 50 % depth of discharge. At the same time, it can be seen that the remaining life cycle calculated by the BMS system is estimated to be 486 cycles at the same depth of discharge. Thus according to the BMS state of heath calculations, this Gel battery bank will provide a total of 775 discharge cycles if discharged at 50% DoD. By comparing the BMS estimated values to manufacture specification it can be concluded that the Gel batteries at experimental site A will reach 96.9 % of its rated performance specifications by end of life. From the performance data analyzed over two years, it evident that the Gel type VRLA batteries have successfully indicated the robustness of its kind under cyclic application. Out of the 32 tested batteries, only one battery was replaced due to catastrophic failure.

The parameters delivered by the AGM batteries operating under cyclic application over a period of 24 months are shown in table 4.4. The performance parameters are organized as row elements, while actual performance and manufacturer specified performances are organized as column elements.

Table 4.4: Performance of 170 AH AGM battery vs manufacture's specifications

Performance Parameter	Manufacturer's Specifications	Actual performance Cyclic Application
Maximum discharge period @ 20 A	9 hours	5 hours
No. of discharge Cycles @ 50% DoD	500	234
Est. Remaining Life [Cycles at av. DoD]	-	61

From table 4.4 it can be seen that according to the AGM battery manufacture, an AGM battery with a rated capacity of 170 AH is capable of producing 500 discharge cycles if drained to 50% depth of discharge and is expected to last up to nine hours if discharged at a load current of 20 A. By comparing the actual delivered parameters against the AGM battery manufactures specifications, it can be seen that the AGM batteries operating under cyclic application provided only 234 discharge cycles of an average of 50 % depth of discharge. It can also be seen that the same battery under cyclic application lasted less than five hours when discharged at 20 A (in section 4.4.1). At the same time, the remaining life cycle calculated by the BMS system is estimated to be 61 cycles at 50% DoD. Thus according to the BMS state of heath calculations, the AGM battery under cyclic application will reach a total of 295 discharge cycles at end of life. By observing the actual performance results and analyzing the manufacture specification, it can be concluded that the AGM batteries at site C have failed prematurely. By looking at the voltage and temperature profiles of the batteries during the discharge cycles, it can be confirmed that the AGM batteries at site C failed due to sulfation.

A comparison of the Gel and AGM VRLA battery technologies is presented. The performance parameters of Gel and AGM type based on age, number of discharge cycles and estimated remaining life is shown in table 4.5. The parameters delivered by the Gel and AGM VRLA batteries over a period of 24 months are organized as row elements, while specific parameters are organized as column elements.

Table 4.5: Summary of experimental results

Performance Parameter	**Site A**	**Site B**	**Site C**
Battery Type	Gel	AGM	AGM
Application	Cyclic	Float	Cyclic
Age [days]	738	731	544
No. of Cycles	289	101	234
Average DoD	50%	5 %	50 %
Est. Remaining Life [Cycles at av. DoD]	486	6429	61

By observing the number of actual discharges cycles produced by Gel and AGM type over 24 months and also taking into considerations the BMS estimated calculated data, it can be seen that the Gel type VRLA operating under cyclic application has successfully produced 58% of its specified performance and is still capable of producing 38% more discharges. This means the Gel battery would easily meet up to 96 % of the manufacturer's specified performance. At the same time, it can be seen that the AGM battery operating under cyclic application has provided 47% of its specified performance and the estimated remaining life is only 12%, thus meeting only 59% of its rated specifications under cyclic application. All 32 tested AGM batteries failed prematurely under cyclic application. The failure mode was identified as sulfation. It can also be seen that the AGM battery operating under float application has provided 5 % of its specified performance and still capable of producing over 95 % of its specified performance, thus the AGM battery has better chances of exceeding its rated performance if operating under float application. This further proves that the CCC charging method is suitable for VRLA batteries operating under float application.

5. CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the findings of the study, conclusions and recommendations are outline based on the practical results obtained through the Battery Monitoring System in comparison to the battery manufacturer's specifications.

The primary aim of this study was to analyze the performance of VRLA battery technologies under various charging parameters based on float and cyclic applications. One of the objectives was to identify the effect of charging parameters on the premature failure of VRLA technology. In this study, two charging protocols (Constant Charge Voltage Method and Modified Constant-Voltage Charging) were implemented to observe the premature failure of two types of VRLA batteries.

The active capacity of a battery is a vital pointer for measuring the performance degradation of lead-acid batteries. In this study, the performance analysis based on a data-driven framework over a given amount of time was considered. It has been shown that, through the analysis of the charging and discharging features of individual batteries within a battery bank, the effect of charging parameters on the performance of VRLA batteries can be identified. The performance of Gel and AGM under float and cyclic applications can be classified and the suitable VRLA technology for a specific application can be chosen.

Premature failure of VRLA batteries constitutes a significant amount of operational cost in power critical applications, due to its high level of failure rates. A significant amount of funds can be saved by selecting the correct VRLA technology relevant to the application and applying correct battery charging parameters.

A battery monitoring system can play a major role in all maintenance and monitoring factors of the VRLA batteries. It was observed that the Gel type VRLA batteries are suitable for application where the primary source of power is unstable. Under unstable power condition that requires a high frequency of cyclic charging and discharging, Gel type VRLA batteries were able to perform better than the AGM type VRLA batteries. In addition, it was observed that AGM-type VRLA batteries provide excellent performance under float application.

Furthermore, VRLA batteries offer improved performance when equalize charge is done. Thus indicating the need to opt for the Modified Constant-Voltage Charging Method. The sulfation is the major cause of the premature failure of VRLA batteries.

5.1 Findings of the Study

i. **Effect of temperature:** The effect of temperature on VRLA operation has been verified. It was observed that an increase in the temperature of cells has a significant negative impact on the performance of VRLA batteries. The lack of a temperature compensation system against charge regimes plays a significant role in the improper operation of the VRLA battery.

ii. **Charging regime:** The Modified Constant-Voltage Charging Method proves to be effective for VRLA batteries operating under cyclic application. The Constant Charge Voltage Method has been observed to be working well on VRLA batteries operating under float application.

iii. **Gel-based VRLA battery:** Based on analysis of the experimental results, it has been identified that Gel type VRLA batteries have successfully indicated the robustness of its kind under cyclic application with increased durability, deep cycle ability and high tolerance to discharges. It has also been pointed out that the Gel type is more likely to meet its rated performance even when operating under cyclic application. Out of the 32 tested Gel batteries, only one battery was replaced due to a catastrophic fault.

iv. **AGM-based VRLA Battery:** It has been identified that the AGM type performs better under float application and has minimum tolerance to deep discharges. The AGM type has shown increased capacity over a shorter discharge period which makes it more suitable to operate under float application. It has also been proven that the AGM type is not suitable for operation under cyclic application. All 32 AGM batteries operating under cyclic application have failed prematurely due to sulfation.

v. **Series connection of battery**: It has been proven any bad cell is a weak link to the whole battery system for batteries operating under a series connection system.

5.2 Recommendations

Based on the results of the study, the recommendations are as follows:

i. **Battery Monitoring System (BMS):** The BMS system should be installed on every VRLA battery bank to ensure that bad cells are identified before they cause damage to the rest of a batteries string. Maintenance costs can be reduced by using the BMS system.
ii. **Equalizing Charge:** Equalisation charge of 2.4 volts per VRLA cell for a minimum period of 24 hours should be done on regular basis, to eliminate voltage imbalances in the string. This has proven to improve the performance of VRLA batteries.
iii. **Battery Application:** It is recommended that the Gel electrolyte VRLA batteries should be used only in cyclic applications and the AGM type should be used only in float applications.
iv. **Charging Protocol:** It is recommended that the Modified Constant-Voltage Charging Method should be applied to VRLA batteries operating in areas where the primary power source have more frequent and long outages and the Constant Charge Voltage Method should be applied in areas where VRLA batteries are exposed to minimum power outages, typically not more than one outage in a month. This is to ensure an improved life cycle of the batteries.
v. **Temperature compensation method:** It is highly recommended that a temperature compensation system be incorporated in the charging system to automatically adjust the float voltage level based on the fluctuation of temperature.

5.3 Future Research

Although charging parameters of VRLA batteries based on GEL electrolyte and AGM type were studied in this work. There's still significant work that needs to be done on the analysis of electrolyte elements and battery internal structure decomposition of VRLA battery.

Further studies on the failure rates of technologies such as Lithium-Ion and Sodium Nickel Chloride batteries need to be conducted as these technologies are starting to fill up the power backup system spaces.

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Appendix A – Data Sheets

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