Evaluating the Effects of AC Ripples on the Degradation of Lead Acid Battery

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CERTIFICATE OF APPROVAL

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DECLARATION OF AUTHORSHIP

It is hereby declared that this thesis report done by the students is only submitted to The Electrical and Electronic Engineering Department any part of it has not been submitted elsewhere for the award of any Degree or Diploma.

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Acknowledgments

In the name of Allah, the Most Gracious, the Most Merciful.

We dedicate our thesis to our families, friends, and everyone who has inspired and mentored us throughout this journey.

We wish them health and prosperity.

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Abstract

The growing use of battery-powered electric cars and equipment has sparked worries about the possible influence of charging station harmonics on battery deterioration. The lead acid battery is a well-known alternative among the different types of consumer batteries available. Despite having a low energy density, it is nonetheless commonly utilized due to its ease of use and inexpensive cost. Lead acid batteries are widely used in electric rickshaws, uninterruptible power supply (UPS), and home appliances in Bangladesh. Recognizing the rising concern about the impact of AC ripples on battery health, we conducted a thorough experimental analysis in our study to explore the impacts of different frequency harmonics on gel-type lead acid batteries. On lead acid batteries, frequencies of 100Hz, 1kHz, and pure DC have been measured. The experiment is repeated 35 cycles in constant current charging circumstances until a substantial change in battery performance is seen.

For a more accurate conclusion, the deterioration is compared to numerous characteristics, such as internal resistance and discharge capacity. The effect of AC harmonics on battery deterioration was shown to be more pronounced at the lower frequency of 100Hz, as internal resistance rose from 71m to 96m and discharge capacity decreased from 3.682Ah to 2.721Ah. Significant increases in both measurements showed faster aging and deterioration in the battery charged at 100.

Chapter 1

Introduction

Batteries are one type of galvanic cell. Galvanic cells are electrochemical devices that produce electricity in spontaneous reactions when their electrodes are connected through a load and in contact with an electrolyte.

The exponential advances in the battery industry's performance efficiency, reliability, and cost-effectiveness have enabled a new paradigm in electric energy storage [1]. The transition from non-renewable to renewable energy sources has increased demand for battery storage systems [2]. Lead-acid batteries have been and continue to be the most common rechargeable electrochemical batteries [3]. Despite their lower energy density and shorter lifespan than lithium-ion batteries, lead acid batteries (Lead Acid Batteries) are frequently used because to their great efficiency, accessibility, affordability, and simplicity [4].

These batteries are inexpensive, can be stored for a long period of time without adverse effects (as long as the acid is removed), have a low risk of explosion, do not produce much heat under normal conditions, and can be maintained and extended in this manner. They are generally among the most reliable batteries that are readily available. It is the most widely used rechargeable electrochemical device in automobiles, uninterrupted power supply (UPS), and backup systems for telecom and many other applications [5-9]. Lead acid battery systems are used in both mobile and stationary applications. Their typical applications are emergency power supply systems, stand-alone systems with PV, battery systems for mitigation of output fluctuations from wind power, and starter batteries in vehicles [10]. The lead-acid battery has a favorable cost/performance ratio, in addition to being easily recyclable.

For the majority of applications, rechargeable Lead Acid Batteries are charged directly from the grid or power supply. However, harmonics might be present in the background while charging since particular orders cannot be completely avoided under non-ideal settings [12]. Some of these ripples may be caused by the electric motor, while others may be caused by the switching frequency of the switched-mode power converter, raising worries that AC harmonics may degrade the battery [13].

Preventing the fast deterioration of Lead Acid Batteries not only gives a technological benefit but it also decreases hazardous waste generation [11,14]. Furthermore, if recycled in accordance with typical environments and circumstances, recycled Lead Acid Batteries might be more dangerous and cause explosions [15].

1.1 Problem Statement

Despite being a simple charging mechanism, lead-acid batteries have certain disadvantages. One significant drawback is that they are more prone to electrode plate sulfation. This effect happens when lead sulfate, a byproduct of the discharge reaction occurring on both electrodes, grows in particle size, decreasing the accessible surface area for future reactions. These reactions become irreversible over time, causing permanent harm to the battery. Furthermore, the capacity of lead acid batteries for complete discharge cycles is restricted, often ranging from 50 to 500 cycles. To avoid plate sulfation and eventual battery degeneration, these batteries should never be stored in a depleted condition, and their cell voltage should never go below the indicated cutoff value. Sulfation can increase the internal resistance of the battery as well as cause the battery to age. The charging current and ripples also have an impact on lead acid battery degradation and can result in premature aging. The ripples or fluctuations in current can increase the battery's internal resistance or decrease its charging capacity, resulting in premature aging.

1.2 Research Gap

The aging processes for lead acid batteries, which eventually reduce the capacity and shorten the life span of these batteries, have been the subject of extensive research. The aging mechanisms include grid corrosion, active mass degradation, less active mass utilization or sulfation, loss of water, short circuits, acid stratification, alternating current, and ripple current effects.

In the instance of lithium-ion batteries, extensive research has been conducted to identify whether AC ripples cause aging or not. Even in a few studies as [19,20], have identified specific frequency ranges that cause aging. Intensive research equipment such as impedance spectroscopy has also been used to identify aging in Lithium-ion batteries. However, the research conducted on these aging mechanisms due to AC ripples is relatively old [24,25]. In both papers, the experimental analysis was different and not conducted on a large scale, and it reached different conclusions. Previously, in [24], the influence of nonspecific frequency AC ripples on Lead Acid Batteries was examined, but no conclusions were achieved. Because of the rapid charging rate in [25], the influence of AC superimposed harmonics on Lead Acid Batteries may have been removed. Only against capacity is LAB deterioration shown in [24, 25].

Since the publishing of these papers, the structural composition of the Lead Acid Battery has changed also. Hence the validity of those investigations may be questionable at this current stage. No extensive research has been done on the effects of harmonics on the lifetime of Lead-acid batteries.

1.3 Research Motivation

A sinusoidal wave whose frequency is an integer multiple of the fundamental frequency is referred to as a harmonic in an electric power system. Non-linear loads like rectifiers, discharge lighting, or saturated electric machines produce harmonic frequencies. Due to harmonics, voltage, and current waveforms are distorted, moving away from their ideal sinusoidal shape. They occur by power semiconductors i.e diodes, triacs, thyristors, and transistors.

Battery damage could occur from ac harmonics from switching of power electronics and harmonics in electric machinery.

Hence, the motivations for our research are

1. An inadequate amount of research has been conducted on the impact of AC harmonics on Lead Acid Batteries
2. Lead Acid Batteries are the most commonly used batteries. Hence it is necessary to identify and avoid the factors that cause faster aging of batteries
3. Provide a refreshment on the previous studies and investigate the structural composition of the new lead acid batteries.

1.4 Scopes of Research

With the results of our study, we will be able to identify whether AC ripples have an impact on the acceleration of aging in batteries. Hence, we can determine and suggest the requirements of rectifications and capacitors in battery chargers. Through our research, we can also increase battery usage awareness and reduce battery wastage and toxic waste. Our research promises to be beneficial both economically and ecologically.

1.5 Research Objectives

1. To investigate the impact of AC ripples on the accelerated aging of Lead Acid Batteries
2. To compare the aging of the battery between AC and DC charging conditions
3. To provide a new and fresh perspective on the investigation of lead Acid Batteries
4. To identify specific ranges of frequencies that may cause battery degradation

1.6 Novelty of the research

In our thesis, a complete experimental examination of the deterioration of frequently used LABs owing to superimposed AC and DC current has been carried out in this work under cycle-use settings. In this study, the major characteristics that indicate aging is internal resistance and discharge capacity for 35 cycles. When batteries degrade, their discharge capacity decreases and their internal resistance increases [27]. While rising internal opposition impedes power, the quantity of energy that the battery can offer throughout each cycle is influenced by capacity decline. In previous studies, both of these parameters together have not been considered as the indicator aging. Using both parameters as indicators will not only solidify our results but also make our research more novel. Along with this, we have conducted our experiments on fixed frequencies of different spectrums instead of various ranges of frequencies, this will help us identify which end of frequencies have an impact on the degradation. The charging cycle duration and voltages are also compared to identify the battery performance of batteries evaluated in all three frequencies of 100Hz, 1kHz, and pure DC.

Chapter 2

Literature Review and Background Study

2.1 Aging Mechanisms in Lead-Acid Batteries

Lead-acid batteries (LABs) are widely used energy storage devices with significant implications for various applications. This literature review aims to provide a comprehensive overview of the aging process in LABs, focusing on key mechanisms such as anodic corrosion and loss of water that contribute to performance degradation. The authors of [1] emphasize that each battery design possesses a characteristic aging mechanism, which determines its achievable service life. Furthermore, it is highlighted that while LABs offer a favorable cost-to-performance ratio, they suffer from a short life cycle and pose environmental concerns due to their toxic nature.

2.2: Rechargeable LABs in E-rickshaws

Rechargeable LABs serve as the primary power source for traditional E-rickshaws, which have transformed transportability and become a traditional source of revenue, particularly in developing Asian nations [11]. These vehicles heavily rely on rechargeable LABs, often charged directly from the power source or the grid. However, concerns arise when AC harmonics are present during the charging process [12]. Harmonics can be attributed to the electric motor and the switching frequency of the power converter, potentially affecting the battery's performance [13].

Additionally, it is worth noting that preserving the longevity of LABs not only provides technological and economic advantages but also reduces the generation of hazardous waste [11,14]. The recycling of LABs must be conducted in adherence to industry standards to prevent the potential hazards and explosions associated with mishandling [15]. Previous research studies have extensively examined the effects of harmonics on batteries. For instance, [16] demonstrated that charging a lithium-ion battery while subject to AC harmonics from the electrical grid significantly increases its temperature, leading to accelerated degradation. Furthermore, [17] evaluated ripple currents ranging from 1Hz to 100kHz on 12 lithium-ion battery test groups and found that the frequency region between 1Hz and 10Hz induces rapid aging.

2.3 Impedance Analysis and Deterioration Studies

Impedance spectroscopy has been employed in [18] to identify indicators of degradation in lithium-ion batteries caused by high-frequency ripples, resulting in improper current distribution. Similarly, [19] and [20] identify specific frequency ranges that expedite the aging of lithium-ion batteries. In the context of LABs, deterioration analysis against various factors has been conducted. The authors of [21] investigated how temperature and discharge rate influence the rate of LAB degradation in relation to battery capacity. Moreover, [22] reviewed the impact of different charging methods on the lifetime of LABs, while [23] examined the performance of LABs under pulsed loads.

2.4 Harmonic-Induced Degradation of LABs

Despite extensive research in recent years, the precise impact of harmonics on the deterioration of LABs requires further investigation. Previous studies, such as [24], have examined the effects of nonspecific frequency AC ripples on LABs; however, conclusive results could not be drawn. It is suggested that the high charging rate employed in [25] may have minimized the impact of AC superimposed harmonics on LABs. Nonetheless, it is important to note that the decline in LABs is evident in terms of capacity, but internal resistance also serves as an indicator of aging [26]. As batteries age, their internal resistance increases, leading to a decrease in discharge capacity and limitations in power delivery [27].

2.5 Experimental Analysis of LABs under Superimposed AC and DC Current

This paper presents a comprehensive experimental analysis of commonly used LABs under conditions of superimposed AC and DC current. The study focuses on two main indicators of aging: internal resistance and 35-cycle discharge capacity. Furthermore, the charging cycle duration and voltages are compared to evaluate the battery performance at three different frequencies: 100Hz, 1kHz, and pure DC. The experiment demonstrates that batteries experience significant degradation when subjected to 100Hz charging harmonics.

Chapter 3

Methodology

3.1 Overall Workflow

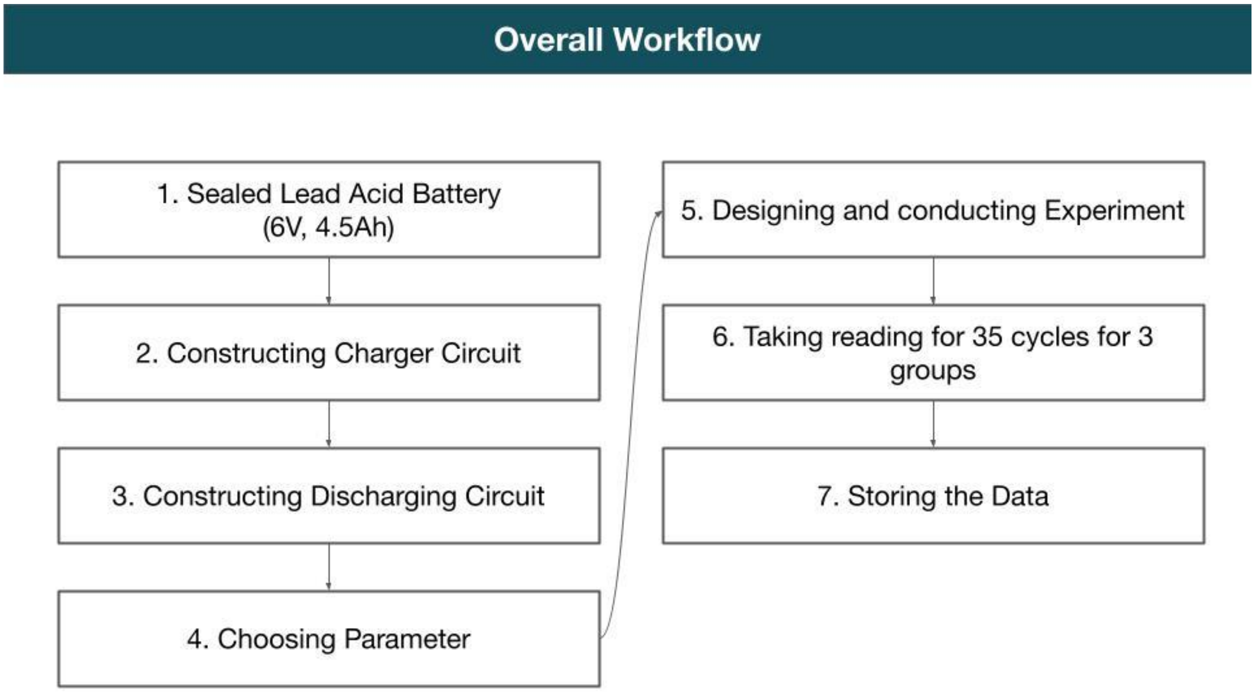


Figure 3.1. Overall Workflow of the Experiment

The aim of our experiment was to look into the impact of different charging currents on the aging process of lead-acid batteries. High charge currents are commonly acknowledged to have a stronger influence on battery aging than high discharge currents [26]. We used three easily accessible and inexpensive lead acid batteries with capacities of 6V and 4.5Ah for our investigation.

We used a constant current technique with a duty cycle during the charging period. This required the use of a pure direct current (DC) as well as the superimposition of alternating currents (AC) at frequencies of 100Hz and 1kHz. It's worth mentioning that all three charging currents had an RMS value of 0.83A, which is what the battery manufacturer recommends.

To guarantee consistency, we kept the charging voltage from the power supply between 7.5V and 8.5V throughout the trial. This range was chosen to comply with the manufacturer's recommendations and avoid any potential battery damage.

Each battery was exposed to a constant resistive load during the discharge phase. This totally resistive load was chosen to simplify the research and allow for a more concentrated look at the impact of charging currents on battery aging.

In summary, we charged three 6V 4.5Ah lead acid batteries with three different charging currents: a constant DC current, a DC current superimposed with a 100Hz AC, and a DC current overlaid with a 1kHz AC.

The RMS value of all currents was 0.83A, as stipulated by the battery manufacturer. The charging voltage was kept between 7.5 and 8.5 volts. The batteries were depleted while being subjected to a steady purely resistive load. We were able to evaluate the effect of changing charge currents on the aging properties of lead acid batteries using this system.

To avoid deep draining and changing the conclusion, the 6V batteries are depleted up to 5.5V. The experiment in this study is carried out in an air-conditioned environment.

The room temperature should be between 22°C and 25°C. The resting interval between cycles was kept constant at 8 hours to eliminate inconsistencies, as resting times might affect battery performance, as shown in [28].

Table 3.1 Experimental Configuration

Test Set	**RMS Current (A)**	**Frequency (Hz)**	**Voltage range (V)**
DC	0.83	0	8.0
DC + AC (100Hz)	0.83	100	7.5-8.5
DC + AC (1KHz)	0.83	1000	7.5-8.5

During the conversion of AC to DC, the full wave bridge rectification could be better, as residual harmonics remain in the voltage supplied. The ripple factor for bridge rectifiers is

$$\gamma=\sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2-1} \tag{1}$$

Where v_{dc} is the DC voltage, v_{rms} is the root mean square of the AC voltage. Taking (1) into consideration, the alternating charging current is superimposed on direct charging current.

$$I_{DC}=I_o \tag{2}$$

Where I_{dc} is the direct current for charging. Following, for alternating current,

$$I_{ac}=I_o\sin\omega t \tag{3}$$

$$\omega=2\pi f \tag{4}$$

Where I_{ac} is the alternating current, ω is the angular frequency and f is the charging frequency.

$$I=I_o+I_o\sin\omega t \tag{5}$$

Where I is the super imposed current for charging the battery with frequency f.

3.2 Performance Parameters

Battery degradation is a critical concern in various fields, from consumer electronics to renewable energy systems. Monitoring performance parameters can provide valuable insights into the health and efficiency of batteries. This article delves into two key factors, namely capacity and internal resistance, and their relationship to battery degradation.

3.2.1 Capacity and its Decrease with Discharge Rate

Capacity, measured in ampere-hours (Ah), represents the energy storage capability of a battery. Lead-acid batteries (LABs) are widely used and have well-defined capacity characteristics [4]. Peukert's law [3] mathematically illustrates how a battery's capacity diminishes as the discharge rate increases. By considering the capacity at known and unknown discharge rates (Q1 and Q2, respectively), along with the Peukert coefficient (pc), rapid degradation in LABs can be identified [4].

3.2.2 Peukert Coefficient and its Influence on Battery Internal Resistance

The Peukert coefficient (pc) plays a crucial role in predicting battery capacity and is affected not only by the battery system but also by factors such as battery design, operating temperatures, and aging [4]. Internal resistance, a parameter closely linked to battery performance, can be measured using various techniques. The most straightforward approach is the DC load method, which utilizes ohmic data [29]. However, for more precise measurements, Electrochemical Impedance Spectroscopy (EIS) is preferred [30]. EIS involves injecting a sinusoidal signal into the battery and analyzing its response at different frequencies [27]. Although EIS provides comprehensive insights into battery behavior without distortion, it requires expensive equipment [13].

$$Q2 = Q1\left(\frac{I_1}{I_2}\right)^{pc-1} \tag{6}$$

3.3.3 Calculation of Internal Resistance using Ohm's Law and the DC Load Method

To determine the internal resistance (R) of a battery, Ohm's law can be applied in conjunction with the DC load method. The voltage difference between the load voltage and open circuit voltage (v10) and the applied current (I) are used in the following equation:

$$R = \frac{\Delta v_{10}}{I} \tag{7}$$

3.3 Experimental Set-up

The experimental setup plays a crucial role in investigating the effects of AC harmonics on lead-acid batteries. This section presents a detailed description of the experimental setup used in this study, including the equipment, battery specifications, charging methods, discharge setup, measurement techniques, and environmental conditions.

Table 3.2 Abbreviated data of alteration in internal resistance with no. of cycles

Measurement	**Parameters**	**Equipment**
Multimeter	Charging Time	Lead Acid Battery
Clamp Meter	Discharging Time	PCB Charger
Oscilloscope	Discharging Capacity	Oscilloscope
Battery Tester	Charging Current	Variable DC Supply
IR Thermometer	Discharging Current	Voltmeter
Stopwatch	Internal Resistance	Battery Tester
IMAX B6 80W 6A Charger 1-6 Cells	–	Load Resistor

Figure 3.2. Measurement Instruments

3.3.1 Battery Selection

For this study, three commonly used and cost-effective Sunca 6V 4.5Ah sealed lead acid batteries manufactured by Sun Fat Electric Products (Int'l) Co. Ltd., as shown in Figure 3.3, were chosen as the subjects. These batteries are frequently employed in various applications and offer a suitable representation of lead-acid batteries in general.

Figure 3.3. 6V Sunca Sealed Lead Acid Battery

3.3.2 Charging Setup

To prevent overcharging and mitigate the risk of disguising the effects of early degradation, a specific charging process was employed. The batteries were charged in the constant current phase, at the RMS value of 0.83A. The charging voltage was maintained between 7.2V and 7.5V, which is within the recommended range for cycle use. Figures 3.4 and3. 5 depict the arrangement of the equipment and connections required for each charging method.

3.3.2.1 DC charging

For DC charging, a voltage-regulated DC power supply, the MCH-305D-II, was utilized. This power supply ensures precise control of the charging process, allowing for accurate and consistent charging conditions throughout the experiment. Figure 3.4 illustrates the DC charging setup.

Figure 3.4. Experimental Setup for DC charging

3.3.2.2 AC charging

AC charging was performed by superimposing AC signals at 100 Hz and 1 kHz frequencies on the batteries. A signal generator, the UTG9005C-II, was employed to generate pure sinusoidal AC ripples. These AC signals were introduced to the batteries through an IRF540N switching circuit, enabling controlled AC charging. Figure 3.5 illustrates the AC charging setup.

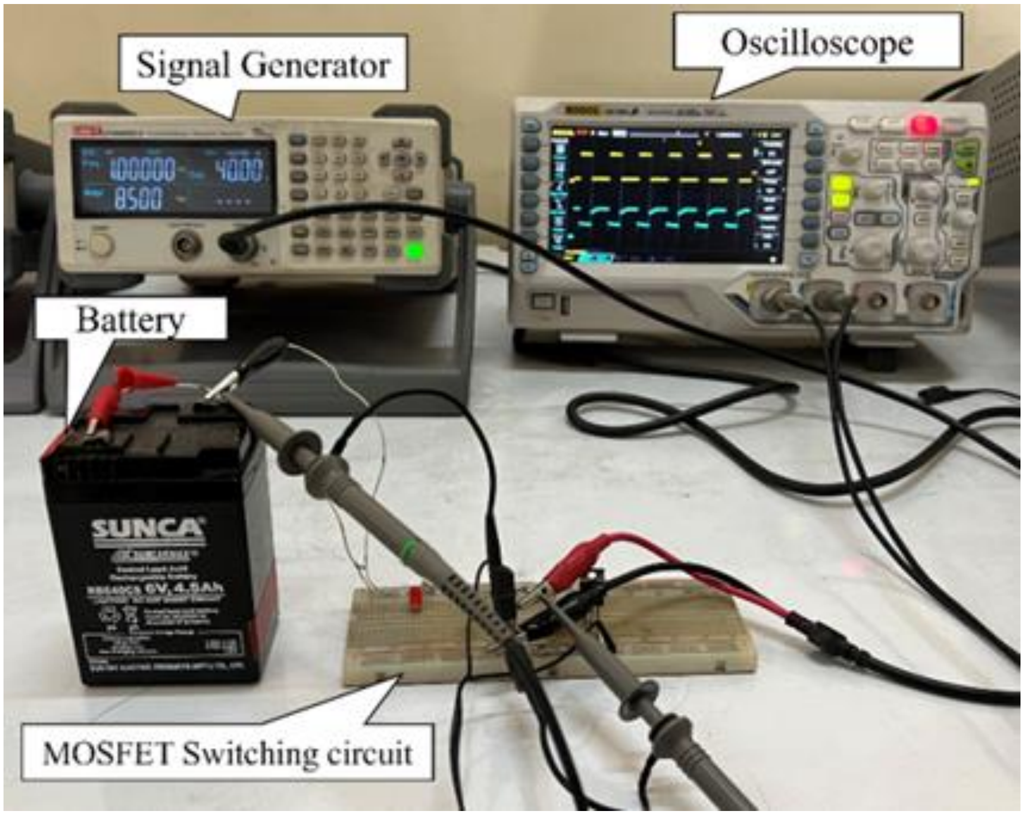


Figure 3.5. Experimental Setup for AC charging

3.3.3 Discharge Setup

To discharge the batteries and evaluate their capacity, a 5W 7.5-ohm resistor load coupled with the battery discharge capacity module HW-586 was used. The setup as illustrated by Figure 3.6, ensured a consistent and controlled discharge process for accurate comparison of battery performance.

3.3.3.1 Preventing deep discharge

Deep discharge can lead to mechanical stress and reduce battery lifespan. In this study, deep discharge was prevented by limiting the battery discharge to a voltage of 5.5V. This threshold ensured the batteries were not subjected to excessive discharge, preserving their longevity.

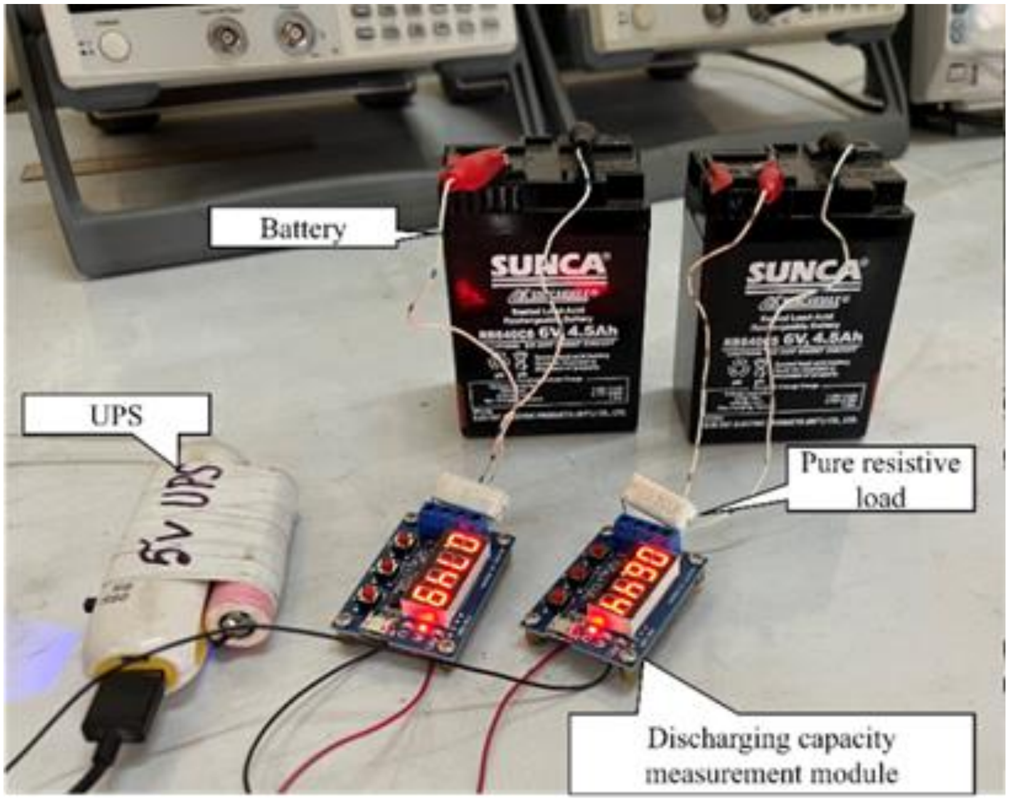


Fig. 3.6. Experimental Setup for Discharging with Purely Resistive Load

3.3.4 Temperature Control

Temperature is a critical factor that can impact battery performance and longevity. To maintain consistent and controlled environmental conditions, an AR320 infrared thermometer was employed to measure the temperature. Throughout the experiment, the temperature was carefully regulated within the range of 22 to 25 degrees Celsius.

3.4 Measurement Techniques

Accurate measurement techniques were employed throughout the experimental setup to gather reliable data on battery performance. This section outlines the measurement techniques used and their significance in assessing the effects of AC harmonics on lead-acid batteries.

3.4.1 Voltage Measurement

Voltage measurements were a crucial aspect of evaluating battery behavior. The CD800A digital multimeter was used to measure the voltage levels of the batteries during the charging and discharging cycles. Stable voltage readings were taken 15 minutes after each charge and discharge process to ensure that the battery had reached a stable state. These voltage measurements provided valuable information on the battery's electrical potential and its response to different charging methods.

3.4.2 Internal Resistance Measurement

The internal resistance of the batteries was measured using the iMAX B6mini device. Internal resistance values were recorded at both the fully charged and depleted states of the batteries. These measurements served as indicators of battery health and performance. Formula (7) was applied to confirm the accuracy of the internal resistance measurements.

3.4.3 Current Monitoring

Continuous monitoring of the current flowing through the batteries was essential to ensure consistency and accuracy in the experimental results. The UNI-T UT203 digital clamp meter was used to measure and record the current values throughout the charging and discharging cycles. This monitoring allowed for the assessment of the battery's electrical flow and the detection of any abnormalities or fluctuations in current behavior.

3.4.4 Oscilloscope Measurements

In addition to voltage and current measurements obtained from the CD800A and UNI-T UT203 digital clamp meter, respectively, the charging voltage waveforms were captured using an oscilloscope. The oscilloscope provided detailed visual representations of voltage fluctuations over time during the charging process as shown in Figures 3.7 and 3.8. These waveforms were synchronized with the voltage measurements recorded by the CD800A, enabling a comprehensive analysis of the battery's response to the charging methods. The oscilloscope measurements offered insights into the dynamics and characteristics of the charging process, contributing to a more detailed understanding of the battery's behavior.

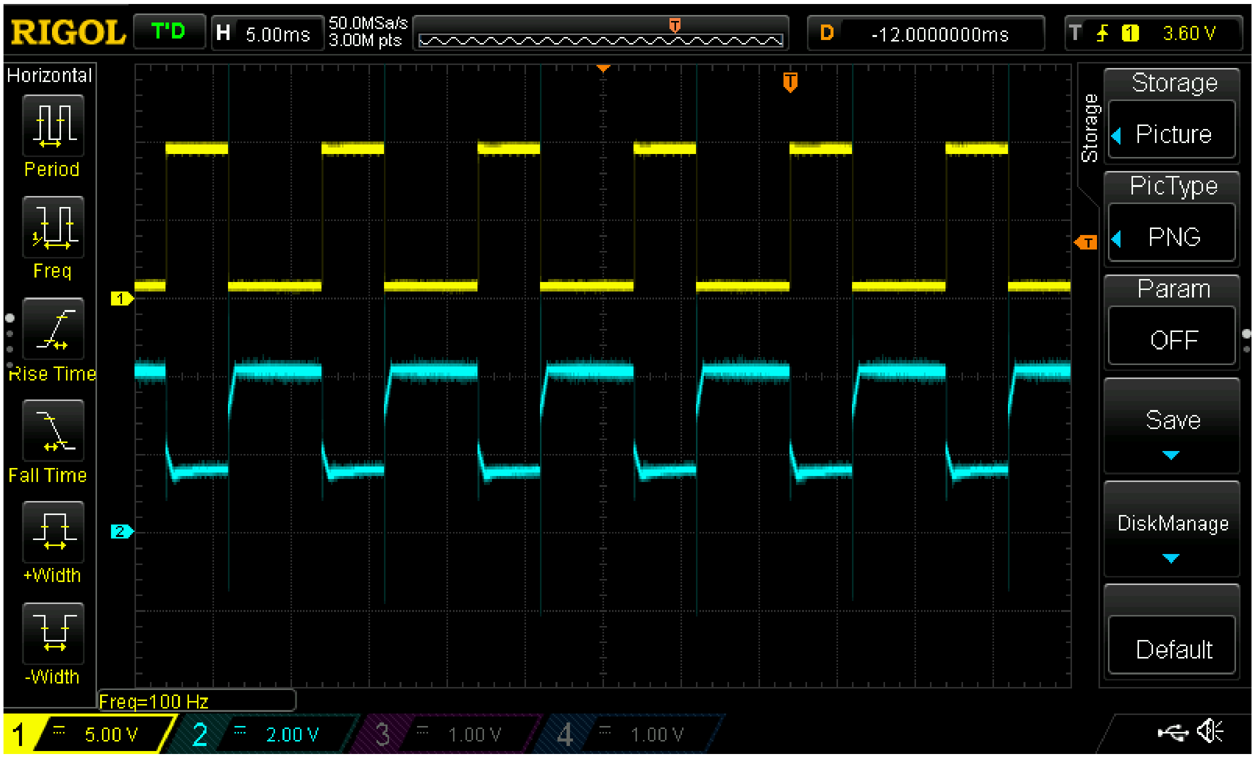
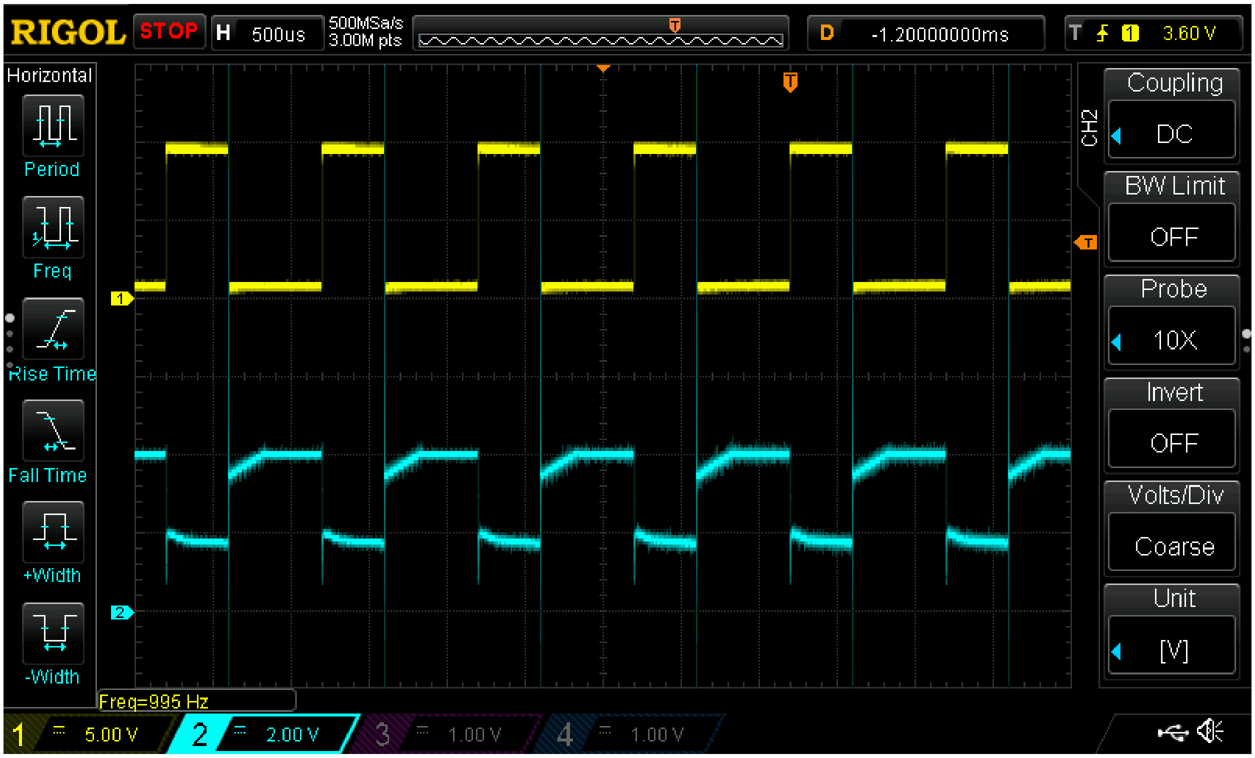


Figure 3.7. Charging Voltage Waveforms for 100 Hz setup



Freq=995 Hz

Coupling DC

BW Limit OFF

Probe 10X

Invert OFF

Volts/Div Coarse

Unit [V]

Figure 3.8. Charging Voltage Waveforms for 1 kHz setup

By employing these measurement techniques, the study was able to collect accurate and comprehensive data on voltage, internal resistance, and current. These measurements facilitated a thorough analysis of the effects of AC harmonics on lead-acid batteries and provided valuable insights into battery behavior and performance characteristics.

3.5 Experimental Procedure

The experimental procedure followed a structured approach to ensure consistency and reliability in the data obtained. The following steps were carried out:

(i) Battery Preparation: The Sunca 6V 4.5Ah sealed lead-acid batteries were initially conditioned by fully charging them using the DC charging method. This step ensured that all batteries started the experiment in a consistent state.

(ii) Initial Measurements: Internal resistance values were recorded using the iMAX B6mini at the fully charged state for each battery. These measurements provided a baseline for comparison throughout the experiment.

(iii) Charging Cycle: The batteries were subjected to a series of charging and discharging cycles. Each cycle consisted of charging the batteries using either the DC or AC method, followed by a controlled discharge using the resistor load setup. The current was monitored continuously using the UNI-T UT203 digital clamp meter.

(iv) Measurement and Recording: After each charging and discharging cycle, stable voltage readings and internal resistance measurements were taken 15 minutes later. These readings were recorded using the CD800A and a timer. Additionally, voltage readings at predetermined time intervals were documented for comparison purposes.

(v) Rest Period: Following each cycle, an 8-hour rest period was observed to allow the batteries to stabilize and minimize the effects of sulfation. This rest period ensured consistent conditions for subsequent cycles.

Chapter 4

Results and Discussion

Three lead acid batteries, BAT1, BAT2, and BAT3, each having a capacity of 6V and 4.5Ah, were exposed to varied charging circumstances in this investigation. The batteries were tested using both pure DC and superimposed AC impulses at frequencies of 100Hz and 1kHz.

Internal resistance values were evaluated over many charging cycles to assess battery performance. Internal resistance values were obtained for each battery (BAT1, BAT2, and BAT3) and listed in Table 4.1. This procedure was done 35 times to ensure that any significant discrepancies in performance were detected.

For all three batteries, the change in internal resistance was studied and compared throughout increasing cycles. This comparison is depicted in Figure 4.1, which displays the numerical data from Table 4.1.

The overall goal of this study was to look into the effect of different charging conditions on the internal resistance of lead-acid batteries. The researchers hoped to get insight into the performance and endurance of the batteries under varied charging settings by evaluating changes in internal resistance across numerous cycles.

TABLE 4.1 ABBREVIATED DATA OF ALTERATION IN INTERNAL RESISTANCE WITH NO. OF CYCLES

No. of Cycle	BAT1	BAT2	BAT3
1	71	71	75
5	70	73	62
10	66	74	69
20	73	81	77
30	74	89	81
35	72	96	81

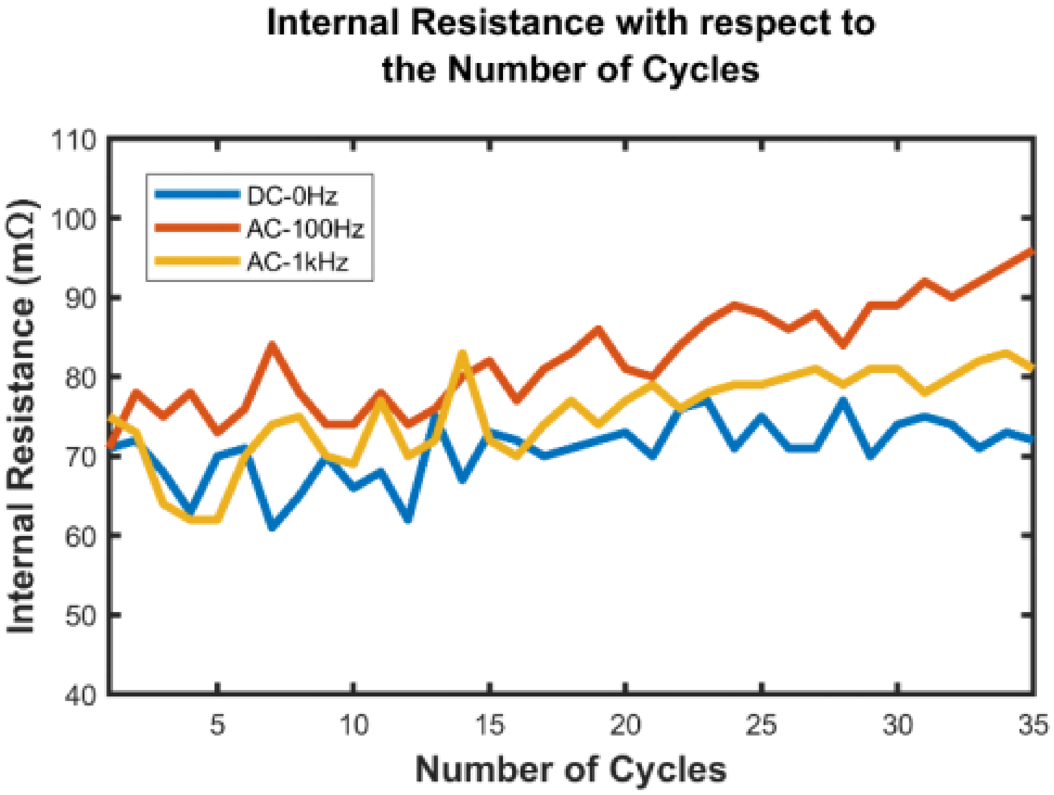


Figure 4.1. Internal Resistance plotted against No. of Cycles

Table 4.2 summarizes the results for discharge capacity at the discharge termination at 5.5V. Fig. 6 shows how the change in discharge capacity at the conclusion of each cycle of BAT1, BAT2, and BAT3 is associated using data from Table 4.2. Furthermore, Figs. 4.3, 4.4, and 4.5 provide consistent recordings of charging voltage characteristics at defined time intervals to gather further verification in the battery performances for the course of the experiment for each test group.

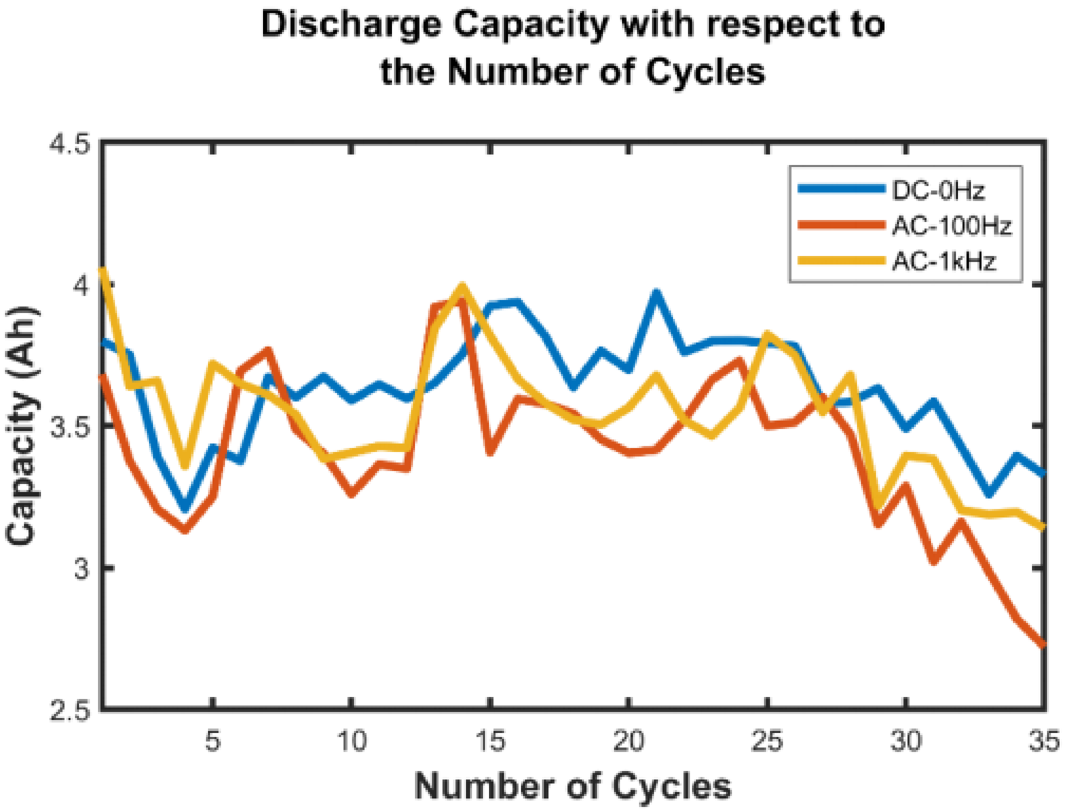


Figure 4.2. Discharge Capacity plotted against Number of Cycles

A comparison of the graphical representations of increasing internal resistance with each cycle of each test group in Fig. 5 shows that BAT2, charged with the superimposed AC of 100Hz, exhibits the largest rise in internal resistance.

Similarly, as seen in Fig. 6, BAT2 exhibits a higher decline in discharge capacity than the other test groups.. In addition to this, Fig. 7 to Fig. 9 demonstrate three graphs representing the charging voltage characteristics of each test group throughout the experiment. It can be observed in Fig. 7 and Fig. 9 that BAT1 and BAT3 display consistent changes in voltage characteristics, whereas, in the case of BAT2 in Fig. 8, voltage characteristics appear to be conflicting, indicating inconsistent performance from the test group.

The evolution of data indicating rising internal resistance and a rapid decrease in discharge capacity suggests symptoms of quicker deterioration. However, larger sample size experiments, additional cycles, and the use of EIS might offer more statistically reliable data and more meaningful conclusions.

TABLE 4.2 Abbreviated data of alteration in discharge capacity with no. of cycles

No. of Cycle	**BAT1**	**BAT2**	**BAT3**
1	3.799	3.682	4.060
5	3.423	3.251	3.720
10	3.590	3.260	3.406
20	3.698	3.405	3.564
30	3.490	3.289	3.395
35	3.327	2.721	3.139

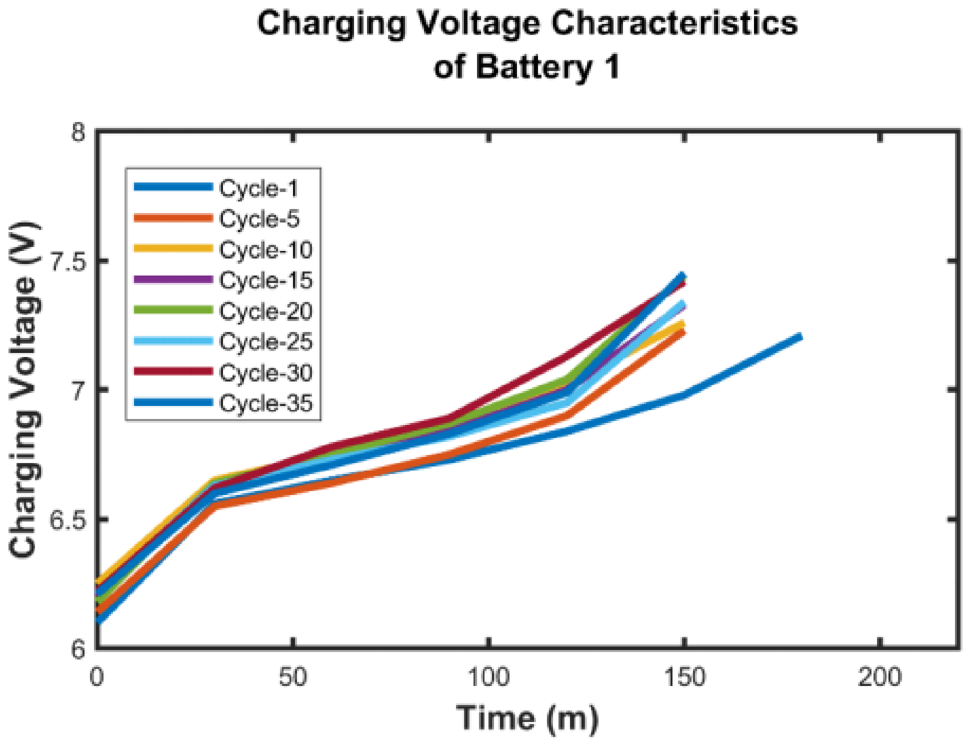


Figure 4.3. Charging Voltage Characteristics vs Charging time of Battery 1

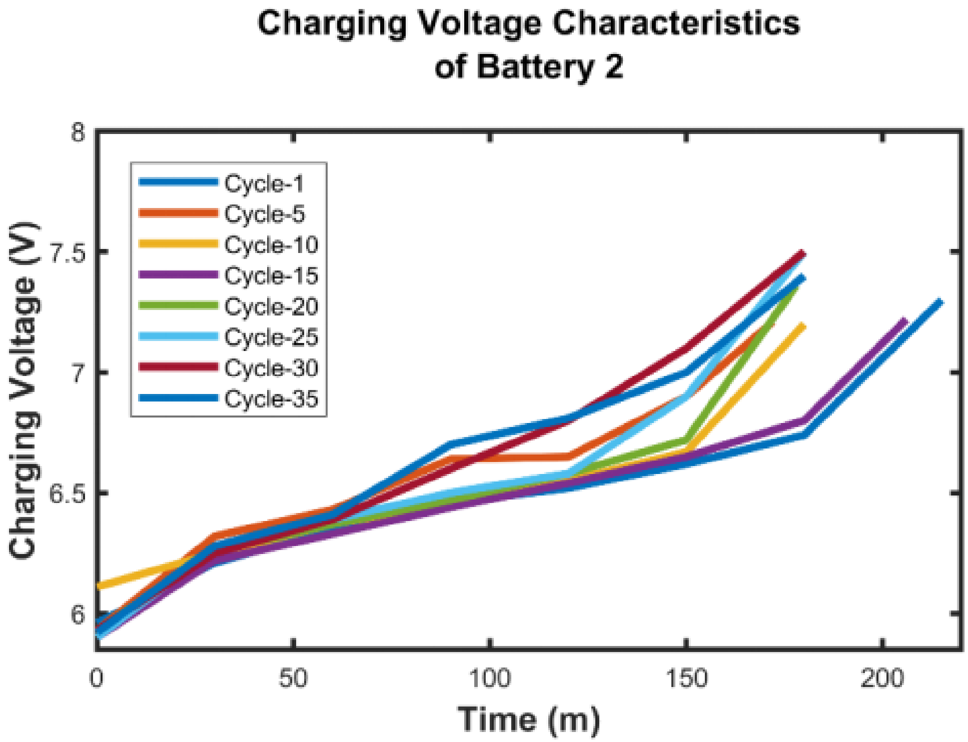


Figure 4.4. Charging Voltage Characteristics vs Charging time of Battery 2

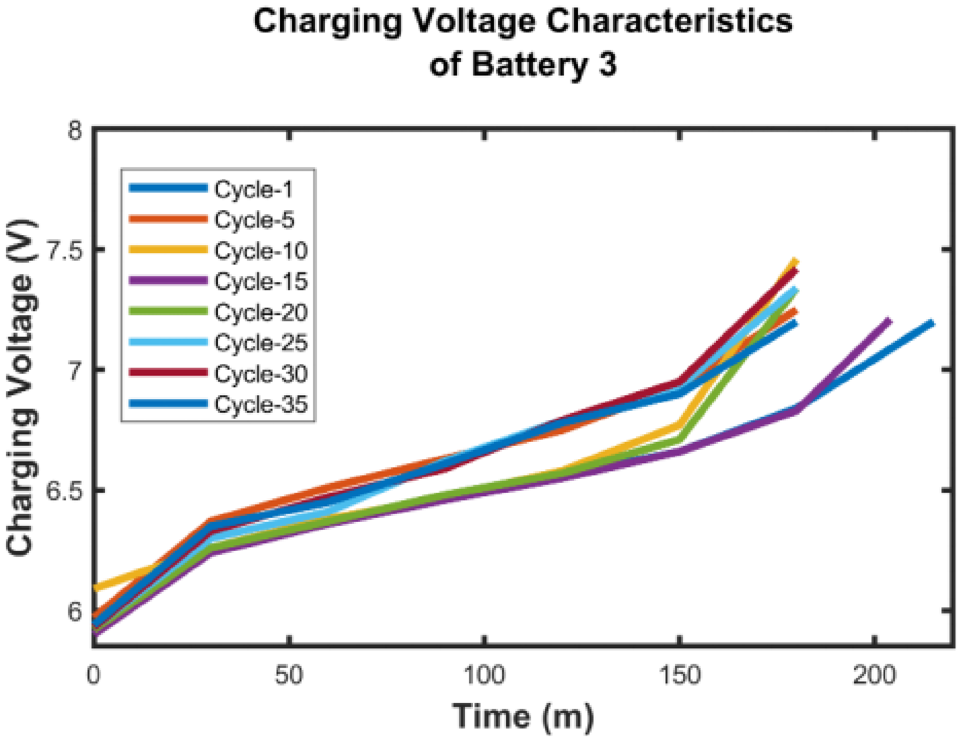


Figure 4.5. Charging Voltage Characteristics vs. Charging time of Battery 3

Chapter 5

Future Work

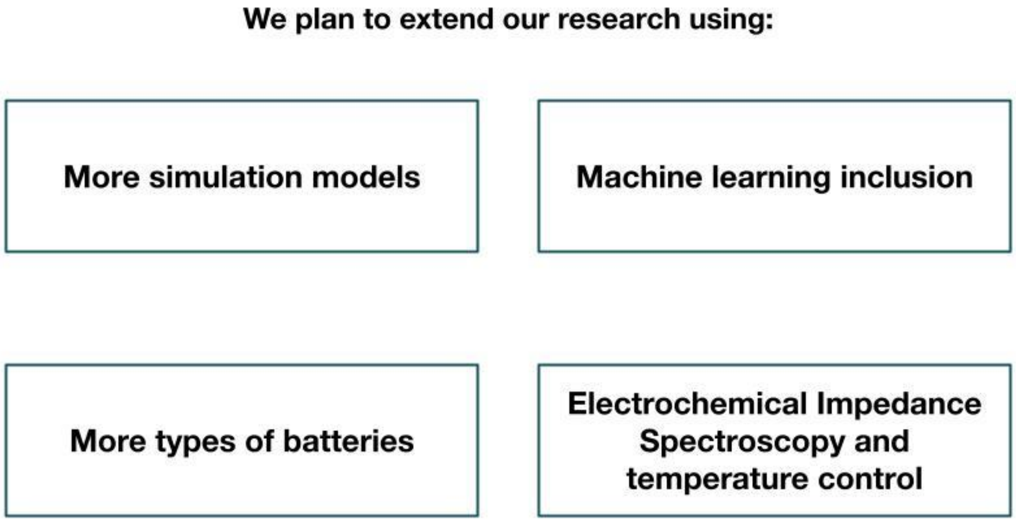


Figure 5.1. Future Work

5.1 Simulation Models

Computational approaches are used in lead acid battery simulation models to mimic battery performance under various situations, offering significant insights beyond the given data.

Existing data on lead acid batteries, such as charging patterns, temperature fluctuations, discharge rates, and internal resistance measurements, may be used to train simulation models. The simulation model may understand the underlying patterns and relationships in the battery system by feeding this data into it.

Once trained, the simulation model may extend data by making predictions and modeling battery behavior in conditions that have not been seen or tested directly. This extrapolation feature is particularly beneficial for comprehending battery performance under various operating settings, improving charging procedures, and projecting battery health and longevity.

For modeling the aging of lead-acid batteries, numerous electrical circuit simulation models are routinely utilized. Some of these models are

Peukert's model: The Peukert equation, which specifies the link between battery capacity, discharge current, and battery efficiency, serves as the foundation for this model. It compensates for capacity loss owing to the Peukert effect, which occurs when discharge currents are high and effective capacity is low.

The Equivalent Circuit Model: This model depicts the battery as an electrical circuit made up of resistors, capacitors, and current sources. The circuit parts are tweaked to mimic the behavior of a lead acid battery, including aging effects like capacity loss and increases in internal resistance.

These simulation models may be used in applications such as MATLAB Acid Batteries/Simulink SPICE, or dedicated battery modeling software. They enable scientists and engineers to investigate the aging behavior of lead acid batteries, optimize battery and management systems, and investigate techniques for prolonging battery life and enhancing performance.

5.2 Extension of research using Machine Learning

Machine learning is a strong technique that may dramatically increase data analysis and extrapolation accuracy. Machine learning algorithms may discover patterns, correlations, and trends from existing data and make predictions or provide insights for new, unknown data by applying complex algorithms and statistical models.

One of machine learning's primary capabilities is its capacity to extrapolate data beyond previous observations. However, machine learning algorithms can go beyond the given data range and make predictions or produce important information.

Furthermore, by continually learning from fresh data, machine learning algorithms may adapt and enhance their performance over time. As they meet increasingly diverse and representative datasets, their adaptive nature allows them to refine their predictions and provide more accurate extrapolations. Here, for our experimental data, Adaboost can be used easily to extend the readings of internal resistance and discharge capacity.

5.3 Increasing Number of Test Groups

Increasing the number of battery test groups in an experiment can considerably improve its validity and reliability. A higher number of test groups reduces the influence of individual differences and gives a more representative sample of the population. A greater sample size boosts statistical power and the generalizability of the results.

Researchers can use more rigorous statistical analyses to reach valid results when there are more test groups. To examine the significance of differences and correlations between variables, statistical procedures such as hypothesis testing, analysis of variance (ANOVA), and regression analysis can be used. The results of a larger number of test groups can give more evidence and lower the possibility of chance discoveries. It also reduces anomalies and outliers

5.4 EIS and Temperature Control

Electrochemical Impedance Spectroscopy (EIS) is a powerful technique that enhances battery examination greatly by offering precise insights into battery performance and health. It enables full evaluation of battery behavior across a wide frequency range and offers information about numerous electrochemical processes occurring within the battery.

It enables the quantitative evaluation of battery parameters such as internal resistance, capacitance, and impedance spectra. These characteristics can give information about the battery's health, level of charge, and aging. Researchers can discover particular frequency-dependent patterns associated with certain battery degradation processes, such as electrode/electrolyte interface deterioration or electrode surface passivation, by examining impedance spectra.

Early identification of battery degradation: Because EIS is very sensitive to changes in battery performance, it is a useful technique for detecting battery degeneration early on. Researchers can detect minor changes in battery behavior that may suggest the start of deterioration processes by measuring impedance spectra over time.

Battery state-of-health (SOH) assessment: EIS may be used to determine the health of batteries. Changes in SOH, such as capacity fading, internal resistance rise, or electrolyte deterioration, may be evaluated by comparing impedance data from multiple or the same battery over time. This data is critical for estimating battery life, developing energy management tactics, and guaranteeing dependable functioning in a variety of applications.

High temperatures accelerate chemical processes within the battery. As a result, battery components such as electrodes, electrolytes, and separators degrade more quickly. As does ionic migration, electrode deterioration, and self-discharge, internal resistance increases. The higher internal resistance diminishes the battery's efficiency, useful capacity, and power output.

Thermal stress occurs in batteries as a result of temperature fluctuations. Cycling between high and low temperatures causes battery components to expand and contract, causing mechanical stress on the electrodes and separators.

Chapter 6

Conclusion

This project has conducted an extensive experimental analysis to investigate the effects of harmonics on lead-acid batteries. The study focused on 6V 4.5Ah lead-acid batteries subjected to both DC and superimposed AC charging currents at frequencies of 100Hz and 1kHz. By utilizing high-performance laboratory equipment and ensuring precise control over charging conditions, the research aimed to evaluate the impact of AC harmonics on battery aging.

Throughout the experimental setup, several important findings emerged. By comparing batteries charged with DC and high-frequency AC currents, it was observed that lower-frequency harmonics had a detrimental effect on the premature aging of the batteries. This was evident from the increase in internal resistance and the decrease in discharge capacity over the course of the cycles. These results suggest that AC harmonics can accelerate the degradation of lead-acid batteries, compromising their lifespan and overall performance.

However, it is important to acknowledge the limitations of this study. The research was conducted under specific conditions and with a limited sample size. To strengthen the conclusions drawn from this study, further investigations could incorporate larger sample sizes, additional cycles, and the integration of machine learning techniques. This would provide more comprehensive and robust data to support the observed effects of AC harmonics on battery aging.

The significance of this research lies in the growing popularity of lead-acid batteries in various applications, such as electric vehicles, energy storage systems, telecommunication power supplies, home appliances, and uninterruptible power supplies (UPS). Premature aging and reduced battery life not only pose risks to health but also contribute to pollution and financial losses. Consequently, manufacturers have taken measures to protect batteries during charging, considering the potential damage that AC harmonics can inflict on lead-acid cells. The attention researchers give to the analysis of deterioration caused by AC harmonics reflects the importance of understanding and mitigating these effects.

In conclusion, this project contributes to the existing knowledge on lead-acid battery behavior and provides valuable insights into the impact of AC harmonics on battery aging. The results highlight the need for further research and development to enhance battery performance, extend their lifespan, and ensure their safe and efficient operation in various applications. By gaining a deeper understanding of the mechanisms and effects of AC harmonics, future advancements can be made in battery technology and charging strategies to optimize battery performance and durability.

In summary, this study emphasizes the importance of considering the effects of AC harmonics on lead-acid batteries and provides a foundation for further investigations in this field. By addressing the limitations and incorporating more comprehensive data, future research endeavors can build upon these findings to enhance our understanding of battery aging and develop strategies to mitigate its negative effects. Ultimately, this research contributes to the advancement of battery technology, supporting the widespread adoption of lead-acid batteries in various industries while ensuring their long-term sustainability and reliability.

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