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Method for Monitoring and Analyzing Lead-Acid Batteries

Development of a method for establishing an estimated battery health

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Bachelor’s Thesis

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Abstract

Lead-acid batteries today are commonly used in the automotive industry with a considerable span of purposes, yet historically, a primary purpose of cranking the engine at ignition which does demand a high current drainage from a battery. These high drainages later result in a health implication which can be hard to detect without the proper tools and this thesis focuses on the development of those tools.

To insure the health of a battery turns out to be a handy feature for most drivers today and early signs of deterioration may even warn a user in advance of damage or failure to insure that proper care is taken with a goal to extend every battery's lifespan.

The results of this thesis demonstrates great accuracy for the tools necessary for an accurate health estimation yet lacks extensive testing data to clearly verify an actual health estimation. Where the chapter of Further Work includes specific tests, error corrections and examples of how to achieve even greater accuracies.

Keywords

Lead-acid battery, BMU, Current sensing, Magneto resistive

Sammanfattning

Blybatterier används idag vanligen inom bilindustrin för ett stort antal ändamål, men historiskt sett har det ett primärt syfte att driva startmotorn vid tändning, vilket kräver en hög ström brukas från batteriet. Dessa höga strömmar resulterar senare i en hälsopåverkan som kan vara svår att upptäcka utan de korrekta verktygen och denna avhandling fokuserar på utvecklingen av just dessa verktyg.

Att fastställa batteriets hälsa är en användbar tillgång för de flesta förare idag och tidiga tecken på försämring kan till och med varna en användare i förväg om nära förestående skador och således försäkra sig om att lämpliga åtgärder vidtas, med ett mål att förlänga alla batteriernas livslängd.

Resultaten av denna avhandling visar en stor noggrannhet för de verktyg som behövs för en exakt hälsoestimering men saknar omfattande testdata för att tydligt verifiera denna estimering. I kapitlet “Further Work” ingår specifika tester, felkorrigeringar och exempel på hur man uppnår en ännu större noggrannhet.

Nyckelord

Blybatteri, BMU, Strömmätning, Magnetoresisitv

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List of Acronyms and Abbreviations

AC	Alternating Current
ADC	Analog-to-Digital Converter
BMU	Battery Monitoring Unit
CCA	Cold Cranking Amperes
DC	Direct Current
EOL	End of Life
IDE	Integrated Development Environment
LCR	Inductance(L), Capacitance(C), and Resistance®
NAM	Negative Active Mass
OCV	Open Circuit Voltage
PAM	Positive Active Mass
PCB	Printed Circuit Board
SOC	State of Charge
SOH	State of Health
SOL	State of Life

1 Introduction

For at least a century now, people have been relying on lead-acid batteries for a variety of applications, not in the least for automobiles. Where its original duty was cranking the engine[1] today it includes every single aspect of the electrical section of a car. The typical car battery is in between a phase shift where electrical cars are getting more and more popular and tend to use lithium-Ion based batteries for the reason of better efficiency, higher charge cycles etc. The shift of lead-acid batteries makes them less relevant for the scope of technology but the majority of people and industries still use the well-proven combustion engine and thus lead-acid based batteries. And forcing people to use electric cars for a faster transformation won't be viable and the lead-acid batteries will still be produced many years from now. But with an increase in lifespan for each battery should result in a decrease in the production since the market will adjust to it and thus affecting the environment in a healthy way.

1.1 Background

The lead-acid battery is crucial for every combustion vehicle today, independent of the type and yet only a handful of car manufactures can offer free insurance for the lead-acid based battery. This is most likely due to the unpredictability of failure where time, usage and random parameters make a too great of an affect. One company by the name “Candus” introduced a battery reconditioning product[2] designed for lead-acid batteries and EG Electronics is the distributor for that product in Sweden. And this thesis will provide a method which will be used in a collaboration with EG to develop a product that will work in parallel with the battery reconditioner in order to show a user the estimated State of Health of a battery.

1.2 Problem

When batteries are discharging, lead sulfate is formed in microcrystalline form which causes the battery to lose capacity due to the fact that some sulfate are not transformed back to its original form, thus occupying space in the battery. The result of this are changes in the internal resistance and the actual capacity of the battery’s specifications[1] which leads to a lower maximum voltage.

EG Electronics can unfortunately not ensure that the battery reconditioner is in fact restoring a lead-acid battery's health over time due to the fact that no extensive battery monitoring system has been implemented alongside it. A battery monitoring system where monitoring of the battery and the module would give a great overview of the whole battery.

1.3 Purpose

The purpose of this thesis is to provide the reader with extensive information considering an accurate health estimation of a lead-acid battery with a great focus on the necessary parameters. This health estimation includes the SOH, SOC and SOL of a lead-acid battery. With a focus on methodologies and hardware utilization possibilities for a future application development.

1.4 Goal

The essential goal for this thesis is to create a complete method to analyze a lead-acid battery’s health. To specify the goal; a reliable method to estimate a battery’s State of Health would be to, from measurements of the battery and knowledge of its specification, obtain an algorithm that returns the capacity and State of Charge from the battery. The goal subsequently would be to manufacture a product that works alongside the reconditioning product for EG Electronics. Thus for this thesis the goal is to provide that method and the calculations used to determine the battery’s State of Health, State of Charge, State of Life and eventual damage of the battery.

1.4.1 Benefits, Ethics and Sustainability

Since the lead-acid battery has not changed innovatively for the past decades the benefit of prolonging its State of Life can be crucial for the environment. If a lead-acid battery drops under a certain voltage it has more or less been irreversible damaged and is impossible to restore the battery back to its original capacity. When the battery is declared useless and replaced, the recycle process for the old battery will have lots of potential dangers to the environment[3].

A reconditioning product in combination with an app to provide its State of Health may imbalance the demand and supply model in a sense of decline in the production of lead-acid batteries and in conjunction to every circulating battery's lifetime prolonged, a deducted environmental impact can be achieved.

1.5 Methodology / Methods

The different methodologies chosen, act as a crucial basis for the subject at matter. Likewise to the developmental; the experimental part adopts at least one of the various methods elected, which are listed below. Note that all the methods are referring to Anne Håkanssons "Portal of Research Methods and Methodologies for Research Projects and Degree Projects"[4].

Quantitative: The quantitative research method is expressed in experiments and testing by measuring some sort of variable to verify or falsify theories or hypothesis. Which uses a big sample size in a statistical way.

Qualitative: The qualitative research method focuses on understanding meanings options and behaviors to attain tentative hypotheses and theories. Which usually uses a smaller sample size, just enough for reliable data.

Philosophical assumption, Realism: A Research method provide a specific procedure for accomplishing a research task, initiating, execution and completion are usually essential. Realism assumes that things in the reality exist with or without anyone thinking or perceiving it, where a phenomena provide credible data and facts. The results are regarded as accurate worldly experience in a sense of; what you see, is what you get.

Research method, Applied research: Applied research involves remarks about specific known practical problems. The method includes examination of circumstances in which the results can relate to a particular solution. It often builds upon existing research in combination with data from the real world and suites practical applications.

Research approach, Inductive: The Research approaches focuses on how to conclude and establish what is true and false. The inductive reasoning constructs theories and propositions based on alternative explanations with observations. Data is usually collected with qualitative methods and analyzed to gain different understandings of a phenomenon.

Research strategy, Action research: Research strategy are guidelines for the research, which commonly includes organizing, planning, designing and conducting research. An Action research strategy is essentially a systematic cyclic method of planning, taking action, observing, evaluating and critical reflection.

1.6 Stakeholders

Aside from the authors, Simon A. Chobot and Johan Hanssen, and KTH, The Royal Institute of Technology in Stockholm, Sweden, the degree project is a collaboration with the company EG Electronics[5] who owns the distribution rights to the reconditioning product in Sweden and will be provided the final BMU product in which this developed method will apply to.

1.7 Scope

This thesis intends to spotlight the lead-acid battery used in the automotive industry, the operational aspect and the SOH; all with an aim towards the theoretical viewpoint.

One request from EG Electronics is to estimate the battery's health without breaking the already existing circuits and this initially means that no shunt for current measurement easily can be applied. This conveys a dilemma where our sub-goal would be to measure the current, however without a straightforward approach since a shunt would be the direct approach as the solution and indeed the only practical one in lack of perspectival solutions.

1.8 Outline

In the following chapters the method to estimate the battery's State of Health will be shown and explained. A thorough walkthrough of the chemical reactions in the battery when charging or discharging will be brought up to clarify how the calculations may be of value for the monitoring system.

The chapters of the thesis, excluding the current one, are described below.

Chapter 2: Theoretical background of lead-acid batteries – Here the background of lead-acid batteries will be presented, along with the fundamental anatomy, chemical processes and the definition of battery health which will lay a base for the the developmental process.

Chapter 3: Methodologies – In this chapter the methods used to obtain the data, how they are interpreted and its usefulness and replication will be discussed. This is of value to ensure the reader of the validity and trustworthiness of the results brought up in this thesis.

Chapter 4: Health Determination Parameters – The parameters chosen to be included in the battery SOH and SOC estimations are discussed and evaluated in this chapter. In order to provide the reader the answer to why these parameters has been chosen and why they are crucial in the overall estimation.

Chapter 5: Technical Procedures – In Chapter 5, the technical procedures of how the values are measured and interpreted are explained along with hardware descriptions and manipulations of the data from sensors to the value wanted.

Chapter 6: Resulting Quality of Estimation – The results are presented along with the sensors accuracy and precision.

Chapter 7: Conclusion and Further Work – Conclusions are discussed and the work itself is evaluated and criticised. Further work and improvements is discussed and analyzed.

2 Theoretical Background of Lead-Acid Battery Health

The information provided in this chapter is meant to be the foundation of what this thesis is meant to be built on. This chapter focuses on the fundamental aspects of the lead-acid battery which include the anatomy, the occurring chemical reactions related to a charge or discharge and different abstract as well as concrete definitions for the battery health.

2.1 The Fundamentals of Lead-Acid based batteries

In order for the battery to produce an electrical current, a natural chemical difference of ions between the anode and cathode has to exist. The lead-acid battery's anode and cathode are separated by an electrolyte solution which ions from the battery's chemical reactions are using as a medium of transportation when an electrical outer circuit current is present. This natural imbalance is what produces the electrical current due to the natural strive to equilibrate the ions between the chosen active chemical substances of the battery.

2.1.1 Battery Anatomy

The positive anode is connected with Positive Active Mass (PAM) which for the lead-acid battery is a paste of lead-oxide (PbO_2), whereas the Negative Active Mass (NAM) on the cathode is a porous sponge lead (Pb). The electrolyte separating the Pb from the PbO_2 is an aqueous solution of sulfuric acid (H_2SO_4).

When an outer circuit is connected to the anode and cathode, electrons from the NAM are creating an electrical current when transferred to the PAM via the outer circuit. And thus a chemical process are taking place inside the battery, positive ions are released from the Pb in the form H_3O^+ and then conveyed to the PbO_2 via the electrolyte of sulfuric acid. When electrons are added to the PbO_2 via the circuit $2H_2O$ is released in the sulfuric acid which creates the chemical reaction:

$$H_2SO_4 + H_2O \rightarrow HSO_4^- + H_3O^+$$

The negative ions HSO_4^- are reacting and absorbed in both the Pb and the PbO_2 while the H_3O^+ is absorbed only on the positive anode of PbO_2[1].

2.1.2 Chemical Reactions

When charging or discharging takes place, different types of chemical reactions occur. In order to fully comprehend the problem presented in chapter 1.2 a good understanding of the chemical processes the battery undergoes, needs to be studied.

The sulfuric acid hydration transpires at the battery factories where they dilute the electrolyte with water. And this since water is dipolar and enables the H^+ to break off from the sulfuric acids H_2SO_4, which will correspond to the H_3O^+ joined and the desired HSO_4.

Sulfuric acid hydration:

$$H_2SO_4 + H_2O \rightarrow HSO_4^- + H_3O^+$$

Discharge:

When energy is extracted from the battery, different reactions occur at the electrodes where $2H_2O$ is released around the PAM and H_3O^+ is released around the NAM.

Discharge at negative electrode:

$$Pb + HSO_4^- \rightarrow Pb_2^+ + SO_4^{2-} + {}^{2e-} + H^+$$

Discharge at positive electrode:

$$PbO_2 + HSO_4^- + {}^{2e-} + 3H^+ \rightarrow Pb_2^+ + SO_4^{2-} + 2H_2O$$

Charge:

The battery's chemical reactions when charging is reversed back to its original state as electrons are added to the Pb NAM causing the PbO_2 NAM to react with the electrolyte and SO_4^{2-} are released. Each of the following reactions are initiated by the lead sulfate dissolution reaction to lead and sulfate ions.

Charge at negative electrode:

$$Pb_2^+ + SO_4^{2-} + H^+ + {}^{2e-} \rightarrow Pb + HSO_4^-$$

Charge at positive electrode:

$$Pb_2^+ + SO_4^{2-} + 2H_2O \rightarrow PbO_2 + HSO_4^- + {}^{2e-} + 3H^+$$

2.2 Defining Battery Health

When it comes to monitor batteries and to analyze them, time is usually something that needs to be taken into consideration. The amount of charges and discharges can occasionally reach some substantial sums which in itself will affect the batteries in some dubious ways which in some manner have to be addressed. But it will also take a lot of time to evaluate different tests and developmental attempts. The corresponding methods will therefore have an undertone focus on time and faults in the calculations and tests in which specifically comes from charge cycles.

Furthermore, to estimate the health of a battery one may evaluate the internal resistance to then calculate an approximated amount of microcrystalline in which will correspond to a missing potential and thus an attribute to the overall health. Another important aspect to the health is the aging, in which both the sheer amount of cycles and the lifetime takes part.

Aging:

Grid corrosion – A grid is placed on the electrodes when manufactured in order to connect the active masses to the electrode. This lead alloy grid will naturally be exposed to corrosion as water is present in the electrolyte. The consequence of this is degeneration of the grid leading to higher internal resistance and lower SOC. If this grid corrodes too much it degrades the battery to a point where it is unusable.

Positive active mass degradation – The following occurs when particles of the PAM begin losing their attraction to one another causing them to break free and thus no longer be part of the electrochemical reactions of charging and discharging at the anode.

Irreversible formation of lead sulfate in the active masses – This behaviour is known as "Hard Sulfation" and is the most commonly known cause of battery failure. After a discharge, $Pb_2^+ + SO_4^{2-}$ will transform into Lead(II) sulfate ($PbSO_4$) in the form of microcrystalline. If the lead sulfate becomes crystallized it is therefore no longer electrochemical active. The crystalized lead sulfate is also larger than the active material it replaces and clogs up the pores in the active masses. And thus, the capacity of the battery will be reduced over time and use cycles, the lead sulfate has a negative effect on the battery's capacity and will also increase the internal resistance of the battery.

Loss of water – Newer sealed batteries often do not need to refill water, instead a gas chamber provided at the positive electrode transports the formed O2 at the positive electrode to the negative electrode where it is recombined back to water. If, however, the gas would leak from the security valve of the sealed battery, due to high temperature or over charging, a loss of H2O will happen since O2 is absent for the chemical reaction.

State of Charge:

This state denotes the percentual capacity of electrons that is at disposal for an external circuit. If the lead-acid battery has a nominal capacity then the SOC would be 100% when fully charged. Every battery has a lower OCV that it should stay above in order to be protected from taking damage, this voltage is known in SOC as 0%.

To define State of Health, Christopher Suozzo[1] writes in his thesis that a step change in load when the battery has not been in use for eight hours could be a practical test to estimate the state of charge. A current is being drawn from the battery of the size of half the battery capacity in Ampere. This load should be connected to the battery for a few minutes in order for the voltage to settle. The "delta voltage" is what is measured and then later applied in the calculations.

Another test from Suozzo's thesis is taking measurement from when the driver cranks the engine where a load is naturally used and measure the voltage and current differences.

Another thesis, "Development of an algorithm for estimating Lead-Acid Battery State of Charge and State of Health" by Mateusz Michal Samolyk & Jakub Sobczak[6], states the following methods for estimating SOC:

Open Circuit Voltage – The OCV method uses voltage measurement of the battery's cell as an indicator of the battery's SOC. Even though this is a decent pointer of the SOC a lot of parameters have to be taken into consideration as the true voltage measured from the battery will have to be a resting OCV-value. Parameters to be aware of are temperature, actual voltage level, discharge rate and age of the battery.

Specific Gravity (SG) Method – This method is focused on measuring the concentration of sulfuric acid in the electrolyte. This is a problematic method in a real life scenario, because the use of a hydrometer inside the battery, if no sensor is already placed inside the battery. The only way to measure a sealed battery is to tamper with its original implementation.

Coulomb Counting Method – This method is also known as Direct Method as its straightforward approach is the summation of current to and from the battery.

Impedance Measurement Method – The internal impedance of the battery changes after it's charging cycles and usage. This measurement is a way to estimate the SOC, but is not commonly used due to its complexity and temperature dependency.

State of Health and End of Life:

State of Health is not to be confused with State of Charge even though State of Health affects the total capacity of the battery. If a battery has low SOH due to aging or damage its SOC can still be 100% but only for the capacity that the SOH allows. Therefore a battery with high capacity charged to 100% for SOC the SOH can lower that capacity to much lower numbers than stated in the specifications of the battery.

A new battery never used before then has a SOH of 100% and when the battery degenerate with aspect to time and usage and reached End of Life(EOL) its SOH is said to be 0%. For more information about SOH and EOL read the section called Aging above.

2.3 Applicable Methods for Monitor Parameters

The following subchapter sheds light on the methods that can be used to estimate the SOH and SOC to understand the battery's condition.

Internal Resistance – Internal resistance is used in order to measure the capability of the battery to handle a load that is greatly larger than its internal resistance. The internal resistance depends heavily on the SOH and SOC and can be calculated using the following formula:

$$\mathrm{R}_i = \frac{U_1 - U_2}{i_1 - i_2} = \frac{\Delta U}{\Delta i} \qquad \text{(Equation 1)}$$

The measurements of voltage and current has to be the difference of them when a change in current is applied with aspect to time. This formula is true and valid under certain circumstances such as temperature and SOC. This is derived from a basic electrical model of the battery in the form of an ideal DC power source and a resistance on the anode wiring.

The internal resistance is also used by the battery manufacturer to calculate the CCA specified on the product, which is the maximum amount of current, in Ampere, that can be utilized from the battery.

Electrode Grid Corrosion – Identifying the grid corrosion on anode or loss of active mass at the cathode could be hard to fully isolate due to the fact that using the simple basic electric model has a lumped component for the resistance in a stable DC current. It is not quite simple to pinpoint what is causing the resistance when the parameters could be; sulfuric acid, corrosion, loss of NAM(PbO_2) or loss of water due to gas leakage. Therefore another model can be introduced called the Randle model. This model has added a resistance parallel with a capacitor to the circuit to give a more realistic reflection of the battery. The R1 resistance in Figure 1 is symbolized as the resistance between the grid and the active masses. The R2 resistance's impact is stable when a steady-state DC current is flowing. But when transient AC currents are occurring the resistance will be determined by the capacitance parameters of the battery, as Suozzo writes in his thesis, such as; charge-transfer processes, ionic diffusion, electrolyte concentration gradients and active material abundance.

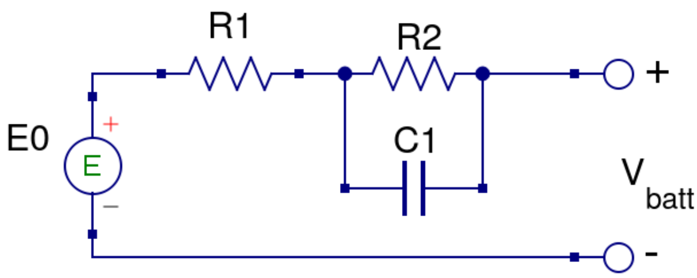


Figure 1: Randle model for a Lead-acid Battery

Capacity – To get a clear capacity estimation of a battery; one must measure the incoming current in addition to the drainage. This simple principle is the best chance to an accurate estimation and will indicate that any fault observed must be from the measurement instruments. Other methods that implements parameters such as the internal resistance (amongst others) to calculate the current tend to have a more diffuse origin of errors which can make it cumbersome to achieve a correction for any error, likewise the total likelihood of error which is certain to increase.

The methods below are representing the different approaches of estimating the capacity and will be evaluated later on, in reference to the specific application which is developed in parallel of this thesis.

- *Internal resistance* – The capacity can be accessed by measuring the load at two occasions with an offset in time which then can be used to calculate the internal resistance. The capacity can then be extracted by using the battery's, most recent, lowest SOH resistance and thus obtaining the SOC which is equivalent to the current capacity.

- *Current sensing* – By frequently measuring current along with its polarity and using timestamps of one second, for example, we can obtain the current per second (Isec). Furthermore, by multiplying with 1000 and then dividing by 3600 we can receive the change of capacity occurring which will then be portrayed in mAh. The following example is the capacity change of 'x' ampere drainage during one second:

$$\mathrm{C}_{mAh} = C_{mAh} - x(A)/3.6 \qquad \text{(Equation 2)}$$

- *Open Circuit Voltage* – The voltage of a battery without a load can portray a certain capacity with a specific correlation depending on each battery and will either be specified in the datasheet or calculable from the datasheet. Though this method has a debatable accuracy and thus the result may be misleading.[7]

3 Methodology

This chapter will explore the methods used in the development of the BMU and how research data is collected to ensure that the information used in this thesis is of value and necessity for academic purposes. The foundation of the structure for the methodologies is based, as earlier mentioned in chapter 1.5, on Anne Håkanssons paper[4]. However, the chosen methods for data collection, data analysis and quality assurance has not yet been chosen and discussed, but will be under the following subsections. This is to ensure the reader that certain precautions has been taking into account to provide trustworthy results, replicable methods and non-biased intentions.

3.1 Data Collection Method

Since this thesis is based on a qualitative approach with realism as philosophical assumption there are several data collections methods that are excluded, among them; Experiments, Interviews and Language & Text.

And since there is not enough time for Observations method, due to the fact that charging and discharging several batteries and testing them at different temperatures is time consuming work, the one most preferred method for this thesis is Case Study. In a test environment the batteries will be examined under certain predefined conditions and data for these scenarios will be gathered for further use and as a foundation for this thesis as an empirical evidence for the evaluation of lead-acid batteries health and capacity.

3.2 Data Analysis Method

The data analysis methods are used on collected data for processing or viewing. As the data can be manipulated by cleaning, transforming or model it to draw conclusions and make decisions. The methods Håkansson suggests are Statistics, Computational Mathematics, Coding, Analytic Induction, Grounded Theory and Narrative Analysis[4]. Since this thesis is based on a qualitative approach it is focused on analytic induction where certain scenarios will be examined and data will be collected iteratively for evaluation until the hypothesis of the test cannot be ruled out as false. Some Computational Mathematics will be applied as well to find out the accuracy and precision of the sensors used in this thesis.

3.3 Quality Assurance

To ensure that the result from this thesis is of trustworthy measure, quality assurance has to be applied to the data collected from the case study. Anne Håkansson is stating that for a qualitative inductive approach, validity, dependability, confirmability, transferability and ethics must be applied and discussed[4].

Validity – The data collection is following certain rules and makes sure that the right parameter is measured or analyzed.

Dependability – The trustworthiness of the data and how it has been extracted.

Confirmability – Confirms that the authors have not tampered with the data or in some way manipulated the result for personal gain.

Transferability – Create informative descriptions of the data so that it can be reused or transferred to other projects.

Ethics – The thesis is following ethical foundations, ensuring integrity and confidentiality.

In order to validate the data achieved from current sensing, voltage readings and internal resistance, several different electrical testers has been used, mostly a FLUKE 45 and FLUKE 123 Scopemeter, to ensure that the data extracted and read from ESP32 is within the chosen accuracy for the readings to be of value. Along with this the mathematical formulas used has been analyzed and cross-referenced for further validity.

4 System Implementation

In this chapter, the strategies for battery health estimation are chosen and discussed along with how the chosen values and parameters is obtained and their importance. In order to get a trustworthy result for estimating battery health under a limited work and evaluation period, the approaches that have been chosen is made with the assumption that they are the most dependable and straightforward techniques in order not to compromise the result given.

In order to estimate SOH and SOC of a lead-acid battery, as discussed earlier, several approaches could be used, in this chapter these approaches will be evaluated and discussed why they are chosen.

4.1 Developing Environment and Hardware

For replication and/or skepticism purposes the following subchapter is included.

The whole development is executed on a ESP32-WROOM-32 module, partly on one that has been soldered on to a custom designed PCB made for EG Electronics and partly on an ESP32 DevKitC-board under early and testing stages[7].

The ESP32 module has an internal 12-bit ADC which is used for sensor readings. It also has built in Bluetooth and Bluetooth Low Energy which was of high necessity for low power consumption and wireless communication from remote locations.

The software used for programming is the Arduino Software (IDE), which works on most common operating systems by today's standards.

4.2 Health Determination Parameters

The following approaches have been chosen to be the foundation for lead-acid battery SOH and SOC estimation.

Open Circuit Voltage:

Since this method is the most commonly used as well as the easiest approach to get a general overview on the lead-acid battery's health it should almost be mandatory to include this parameter for the overall health estimation. Since the fact that the lead-acid battery in the automotive field is, mostly, not in use when the vehicle is parked means that the battery has time to find a resting OCV-value[9].

$$\text{SOC}=\alpha_1 V_{cell} + \alpha_0, \quad \alpha_1 = 429,\ \alpha_0 = -836 \qquad \text{(Equation 3)}$$

The equation above is derived from the thesis "State-of-Charge Estimation for Lead-Acid Batteries Based on Dynamic Open-Circuit Voltage"[9], from measurements of a single 4Ah cell which a regular 12V lead-acid battery is built with. With this estimation a general estimation of the battery's SOC can be calculated. There is usual 6 cells connected in a general 12V battery. Another approach to calculate the SOC from OCV is to connect the BMU to a battery that has been fully charged, ideally one that is brand new and charged, and save that value as an OCV reference value. This value will be referenced and compared to during the battery's life to see whether the new OCV is higher or lower than that, meaning that the SOC and SOH has increased or declined, showing that the Canadus product has improved the battery's performance.

Current Sensing measurement:

The first approach to the current sensing included a Hall-Effect sensor but was swiftly discontinued due to the fact that the sensors velocity influenced the prompted magnetic field and thus would required a means for obtaining it accurately which would lay outside of this project's scope. And in addition to that, a phenomena, which is sometimes called "drifting" occur from the Hall effect sensor. Which corresponds to a change from the sensors readings and will result in a faulty value.

This can be solved by calculating the increasing offset but will also require too much work endeavor outside of this projects scope. Instead, a magnetoresistive sensor was adopted which will respond to a magnetic field with a specific resistance. The output of this sensor consists of two signals where the difference in the voltages signifies a certain magnetic field as well as a specific kA/m and this distinct measurement is often used in contactless current reading. The chosen sensor for this application is the G-MRCO-001 where its output response characteristics is shown in Figure 2.

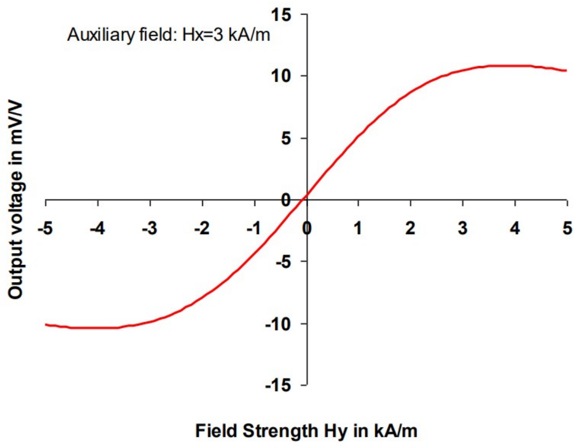


Figure 2: Output characteristics from magneticfield sensor

The G-MRCO-001 also known as KMY20M was chosen for reasons like availability but also since it has a great hysteresis relative to the sensitivity with a maximum hysteresis of 50µV/V and a typical sensitivity of 5.5 mV/V / kA/m. This would give a ratio of ~9% which unfortunately would be noticeable yet manageable without any error correction. And since the dynamic range of possible current drainages can vary from roughly 0 - 200 A and above for certain automotive vehicles, a respective magnetic field will emit and thus require a dynamic range for the sensor. Unfortunately this was not easily achievable since only one of, the precision or the dynamic range needed, could be met. In this situation it was clear that precision was of greater importance and thus achieved to maintain a dynamic range of 0 ~ 7.4 A. This in turn would not be acceptable in a finalized product since the dynamic range would leave out too much information but for academic purposes, it is both convenient and appropriate since a more a correct reading is more important than being able to read high values. This could be achieved by placing the sensor close to the measuring cable at a distance of ~1 mm was arranged using a 3D-printed design.

Internal Resistance:

The key to successfully calculating the internal resistance of the lead-acid battery is accurate voltage and current measurements. The internal resistance, as mentioned earlier, can not be measured with a LCR-meter since there is a natural occurring potential between the anode and cathode where the wanted resistance exists, if the battery has not reached EOL, that is. In order to calculate the internal resistance, the OCV has to be obtained first to have a reference point for the voltage. After that, a significant change in current has to occur to induce a voltage drop on the battery's cells which corresponds to the resistance. After that the voltage on the battery should be read again and the resistance can be calculated by taking the differences of voltage divided by the current differences, see Equation 1. The temperature has a considerable effect on the resistance correlation to SOH, for all tests on batteries in this thesis an environment of ~22 degrees Celsius has been used to rule out temperature from the equation, more on this in the chapter "Conclusions and Further work". The value of the internal resistance is of high importance for the SOH and will be directly linked to the battery's improvement or degeneration, as the first internal resistance value obtained will be used as a reference value to use in the estimation of the battery's evolution with the Canadus product connected to it.

5 Technical Procedures

This chapter provides information on how the sensors and their data is used along with mathematical calculations needed for an estimation of the SOC and the SOH.

5.1 Sensors and Peripherals

The sensors and peripherals used in this project has been explained for their purposes in the previous chapter, here they are explained in detail on how they are used and how the raw data is manipulated to give accurate results.

Battery Voltage Divider:

The OCV can easily be measured by scaling down the battery voltage via a voltage divider and interpreted by the ESP32. Since the BMU is going to be powered by the battery it is evaluating, the input may range from 12-24V, add the Canadus-product connected alongside and voltage may be up to 50V for shorter peaks and disturbances caused by the Canadus-product. With this in mind the voltage divider resistors can be calculated to be 100kΩ and 7.15kΩ with Equation 4, making sure that input voltage for the ESP32 stays between 0-3.3V for measured battery voltage 0-50V.

$$\mathrm{V}_{out} = \frac{V_{in}R_2}{(R_1+R_2)} \qquad \text{(Equation 4)}$$

Since its only of interest to know battery voltage levels between 0-27V the ADC in the ESP32 is used with 6dB attenuation instead of the standard 11dB to get a better resolution for logical voltage levels between 0-1.8V, which corresponds to battery voltage, Vout, being 0-27V [10]. In order to get trustworthy results from these bits converted into a voltage, several data points was gathered by reading bits on the ESP32 and using a Powerbox 3000 to simulate battery voltage, Vin, to the voltage divider, verified by the FLUKE multimeter. From there the data points where scatter plotted in MATLAB and an equation was fitted to the data points using MATLAB's function “polyfit” to get a polynomial function of 3rd degree, which was the most accurate polynomial degree for the data points. This function will be used as a correction curve in order to provide accurate volt values from the bits read from the ESP32. The column named “Error” in Table I is the difference between the measured value and the calculated value using the correction curve achieved from MATLAB.

Table I: ESP32 bits achieved from applied voltage to the voltage divider and calculated errors.

Bits read by ESP32(x)	Voltage (V_{in})	Error, V_{in}-Y(x), in Volt
1264	10	0.0046
1415	11	-0.0106
1573	12	0.0150
1726	13	0.0038
1879	14	-0.0108
2033	15	-0.0220
2193	16	0.0027
2351	17	0.0127
2505	18	-0.0042
2666	19	0.0230
2818	20	-0.0074
2975	21	-0.0053
3135	22	0.0172
3287	23	-0.0097
3443	24	-0.0087
3597	25	-0.0176
3757	26	0.0158
3909	27	0.0016

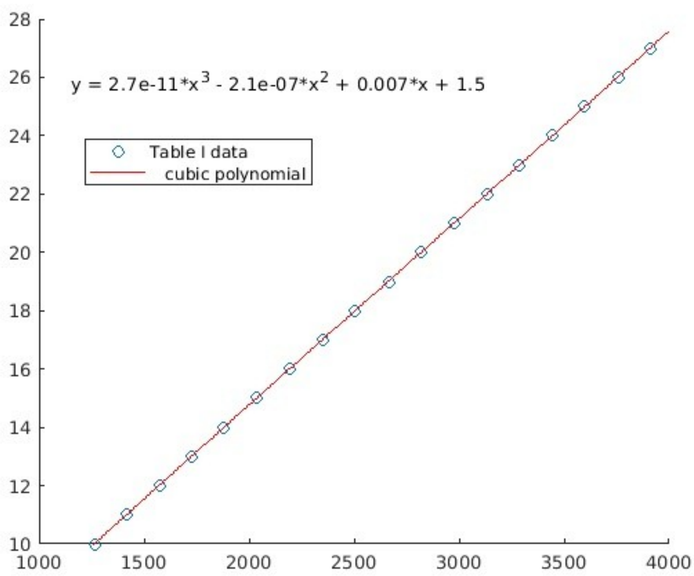


Figure 3: Plot of the polynomial equation and the scatter plot from Table I data.

MATLAB polynomial result: $V(x)=2.7*10\text{-}11x^3-2.1*10\text{-}7x+0.007x+1.5$

shown plotted in Figure 3 above. As can be seen above in Table 1, the cubic polynomial shows an acceptable result giving the highest error of ~-0.023V at 19V.

The ESP32 is used with standard analog cycles which is 8 samples to receive one bit value.

Applied Current Sensing Method:

The output from the magnetoresistive sensor will be in the range of millivolts and will thus need an amplifier to be detectable from the microcontroller and this can in turn be achieved from an Operation Amplifier, also known as op-amp.

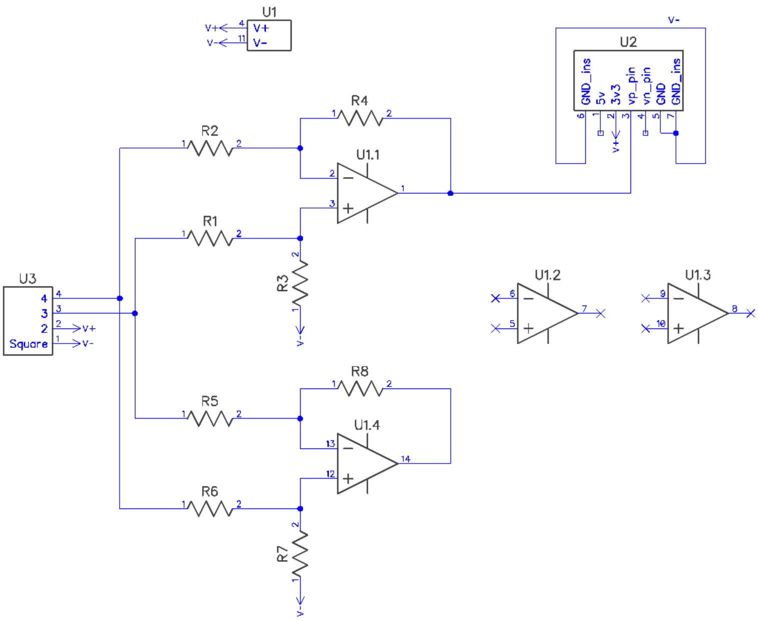


Figure 4: The differential amplifier for the magnetoresistive sensor.

From the simple schematic in Figure 4, we can see two of those amplifiers implemented but only one is used but is later on explained how both of them could collaborate to achieve higher readings of the current. The first op-amp, which again is the only one used, have a scaling factor of R3/R1 since R1=R2 and R3=R4. Where R1=1 kΩ and R3=830kΩ. This would be equivalent to a scaling of x830 times and in combination with the operational amplifier-array LM324, this schematic constitutes a differential amplifier. The case of this necessity is strictly correlated to the Magnetoresistive sensors dual-output configuration which in turn is used due to the full-bridge inside of the sensor. This dual-output delivers a difference in voltage between them to a corresponding magnetic field and since the LM342 is only provided with 3.3V and 0V to V+ and V- respectively, it will only amplify the difference up and until 3.3V but is ~2.7V due to the amplifiers specification, which is well suited for the input pin of the ESP32.

The ESP32 included ADC was in this case stepped down with an attenuation of 6dB to both protect the controller yet also to obtain a stabilized input with predictable readings, errors and offsets. This configuration was later used on a wide jumper cable to resemble a real car-battery cable. To obtain stable reading from the cable, a 3D-printed casing was constructed and thus eliminated the distance factor out of the equation. This was crucial due to the fact that distance is one of the most dominant factor when it comes to magnetic fields emitted from cables and to obtain an exact distance to every kind of car cable would have been close to impossible. To even obtain the exact distance for only one configuration would have been too complicated, not at least for every single car cable used.

So once this configuration was established, readings where made, the input bits and corresponding current stream applied through the cable is printed in Table II. To obtain a stable value from a sensor, a large sample size is necessary and was in this case set to 8000 were the final average is presented:

Table II:ESP32 input relative to a current flow in a cable

Bits read by ESP32 (x)	Current drainage (I)
0	0
132.8	0.252
272.8	0.503
406.2	0.750
549.4	1.003
668.2	1.250
805.4	1.505
938.7	1.750
1074.2	2.002
1208.7	2.250
1357.8	2.517

Table II was then used to calculate the Cubic Regression for an overall estimation of a certain current, in which a broad span of 0-5.56A can be measured. The reason for not linearly The following expression is the resulting Cubic Regression:

$$I_{xbits} = -76.55 * 10^{-12} * x^3 + 152.9 * 10^{-9} * x^2 - 4.762 * 10^{-3} \quad \text{(Equation 5)}$$

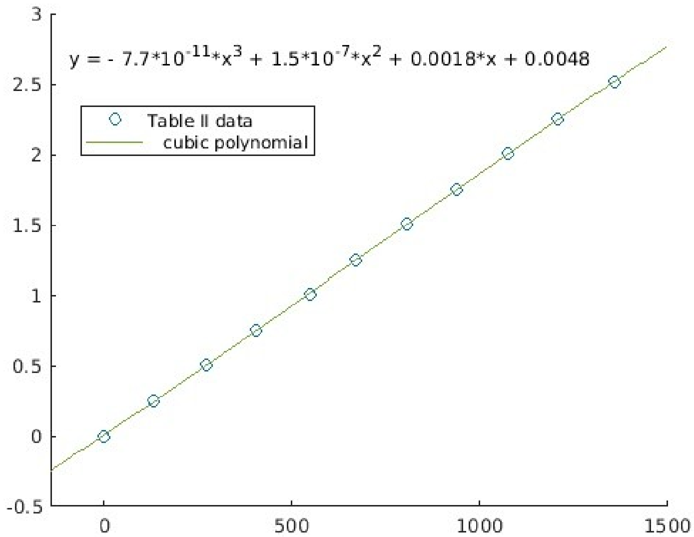


Figure 5: Plot of the polynomial equation and the scatter plot from Table II data.

5.2 Internal Resistance from Cranking Test

For the internal resistance, extensive testing has to be done in order to prove useful, the following procedure will be provided but has not yet been fully evaluated and should therefore be taken with a bit of skepticism. Several cranking tests have been performed on a 30Ah battery in different conditions using the OCV and a 2.2Ohms resistor as a load. Firstly the OCV is taken from the battery, then internal resistance is calculated by applying the 2.2Ohms load to the battery, which gives a current of 5.45A at 12V and, with coding on the ESP32, ensuring that the current is stable within 3%, the current is measured along with the voltage drop value. With these values the resistance is calculated with Equation 1. The battery is then drained, along with the current being measured every second to calculate the Ah drainage, with the same 2.2Ohm load for 30 minutes and then rested to obtain the new OCV value. This procedure is repeated to receive the correlation between the OCV, SOC and Internal Resistance. This will be used as part of the estimation to see how the internal resistance is changing with SOH, and how the internal resistance can be used to calculate the SOC of a battery as well.

Another way to estimate the SOH on an old used battery is to charge the battery fully and perform a cranking test. The OCV from the fully charged battery divided by the internal resistance gives, by Ohm's Law, the CCA which is stated on most batteries. The value received would then give an estimation on the battery’s condition to supply the Amps needed for starting a vehicle. The fraction of the calculated CCA and the CCA stated on the battery to give in percentage how much of the health the battery has lost during its lifespan.

5.3 Health

To estimate a health of a battery, one could set out to measure the difference from a brand-new to where it is now. More specifically, to start the monitoring when the battery is new and use the initial information as reference points to when further information is needed. The variables relevant in this case would be the voltage, capacity and resistance where the introduction voltage can be directly correlated to the mentioned capacity of the battery and this since no measurement before the first introduction may have occurred. This rapid procedure will surely result in an initial error since the actual capacity can never be measured nor received nor truly be the exact value of the battery’s specifications.

Yet, to ensure the user to only apply this product onto a brand-new battery, is a small cost to where user experience will surely be minimally impacted in a negative way. Where forcing the user to measure the capacity by themselves and later deliver that information to the product would be inadequate.

To obtain the health in an accurate and reliable manner is of great importance and to trust certain variables blindly could result in faulty estimation. To avoid that faultily, many precise tests needs to be taken and unfortunately not enough time was accessible for that.

However, a few different health aspects equations, not fully tested are mentioned as $\text{SOH}_{\text{A-E}}$ where:

$$\text{SOH}_A = \frac{C_{if}}{C} \quad \text{(Equation 6)}$$

$$\text{SOH}_B = \frac{R_i}{R} \quad \text{(Equation 7)}$$

$$\text{SOH}_C = \frac{CC_i - C_iC_{if}}{CC_{if}} \quad \text{(Equation 8)}$$

$$\text{SOH}_D = \frac{V_i/R_i}{V/R} \quad \text{(Equation 9)}$$

$$\text{SOH}_E = \frac{V_{if}/R_{if}}{V_{ref}/R_{ref}} \quad \text{(Equation 10)}$$

Table III:List of variables for State of Health

C_{ref}	*Capacity reference (new)*
C_{if}	*Current maximum capacity*
C_i	*Current capacity*
R_{ref}	*Resistance reference (new)*
R_{if}	*Current maximum resistance*
R_i	*Current resistance*
V_{ref}	*Open Circuit Voltage (new)*
V_{if}	*Open Circuit Voltage (now)*

Where,

SOH_A = is the maximum capacity deviation in which health implications can be detected.

SOH_B = Is the resistance deviation subtracted with the SOC implication of the resistance which hopefully is equal to the actual faltcity.

SOH_C = Is the capacity deviation subtracted with the SOC implication of the capacity which hopefully is equal to the actual faltcity and gives another aspect of the faulticity which can work like a verification with the SOHB but from different sources.

SOH_D = Is the highest amount discharge current right now divided by the highest discharge rate from when its new, which is usually stated on the battery.

SOH_E = Is the specified CCA (often stated on the battery) divided by the present CCA.

6 Resulting Quality of Estimation

This chapter evaluates the results provided, along with its accuracy and precision for each type of sensor and measurement.

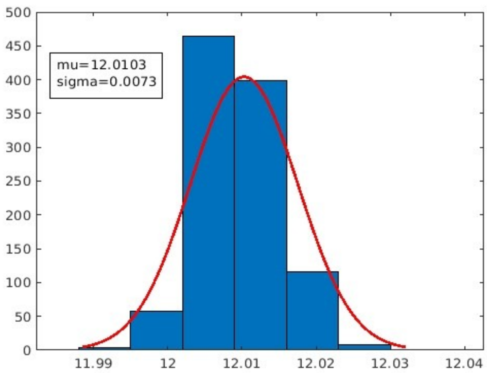
6.1 Result from Sensors

The following sensors are evaluated with a sample size of 8000 and is represented with a normal distribution. For information on how accuracy and precision is defined, a visual representation can be seen in the Appendix, Figure 9.

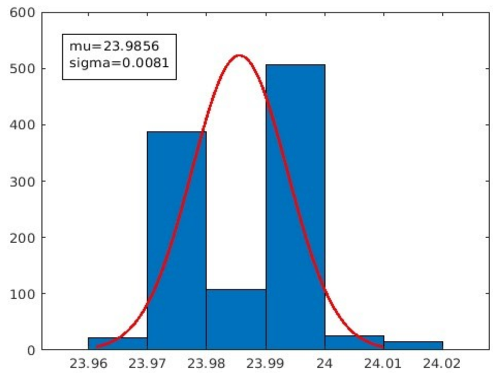
Battery Voltage Divider:

For these statistical models shown in Figure 6(a) and (b), the battery voltage is constant, fabricated by a "Powerbox 3000" to act as the battery voltage, at 12 V (a) or 24 V (b). Bit-values are read from the microcontroller and then converted and normally distributed in MATLAB to show the expected value(mu, μ) to be 12.0103 V (a) and 23.9856 V (b) and the standard deviation(sigma, σ), to be 0.0073 V (a) and 0.0081 V (b).

Accuracy has more errors then precision, precision is predicted to be between ±0.0073 V or, worst case, ±0.0081 V, but accuracy is, depending on what voltage will be measured, at worst case ~0.0230 V for 19 V. For the worst case scenario, with the accuracy having an offset of 0.0230 V and the precision an offset of 0.0081 V, the error, if we sum these values, in percentage per volt would be ~3%.



(a) Samples taken from 12V measurements



(b) Samples taken from 24 V measurements.

Figure 6: Gaussian Distribution of >1000 samples of measurements at 12 V/24 V read and interpreted by the ESP32.

Current Sensing Evaluation:

To obtain a result of the current sensor, a rig had to be set up, where one thermally durable resistor with 1Ohms for effortless calculations was chosen, where 1 V would result with 1 A through the resistor. The power supply of this test was yet again the "Powerbox 3000" and the measurement of the "true" ampere was provided by a "Fluke 45 Dual Display Multimeter".

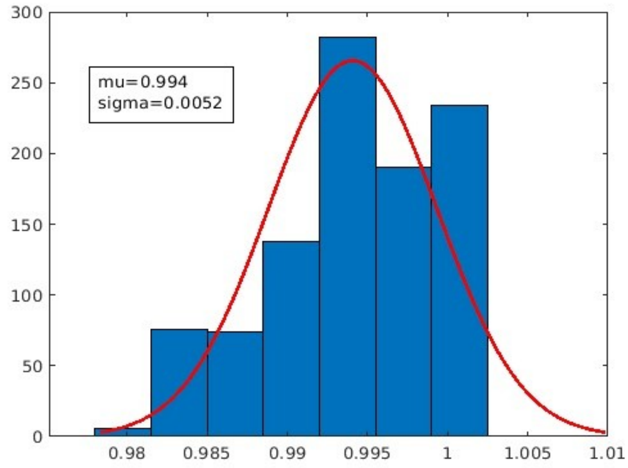


Figure 7: Gaussian Distribution of measuring a stable 1 A flow.

6.2 Result for Battery Estimation

In order to provide an accurate battery estimation the capacity should be known, the battery should also be fully charged and ideally brand new. When the BMU connects to the battery an OCV reference point will be taken and coulomb counting initialized to measure the draining current and thus keep track of the ongoing capacity changes. When the next opportunity is given to check the OCV it should be taken and compared to the referenced OCV and then validated against the drained capacity. Since the OCV is the easiest, but also most vague SOC/SOH-estimation, comparing this estimation with the remaining capacity achieved with coulomb counting gives a more trustworthy estimation, along with a greater insight in SOH. Because here lies the key to isolate SOC and SOH, for a lower OCV value and little capacity being drained the SOH is now known to be low and therefore bringing down the SOC fast while few Ampere hours has been used. With this in mind the current measuring implemented the knowledge of the batteries health would increase significant compared to only relying on OCV.

Internal Resistance:

For the overall estimation of the battery's health, the SOH for example, will only be accurate if the battery is brand new so the internal resistance value can be saved for future comparison. If a battery has unknown SOC and SOH, the estimations tend to be equally diffuse, the internal resistance could however be used to see if any improvements occur with the Canadus reconditioner connected alongside. Several cranking test were performed, but due to lack of time and trustworthiness the data from these were discarded. However, a cranking test was performed on the fully charged new 30 Ah battery, and the internal resistance obtained from this test where verified with the CCA stated on the battery using Ohm's law. The values can be found below in Table IV.

Table IV:. Data from cranking test on a 30 Ah charged new lead-acid battery.

OCV (V)	**Int. Res. (mOhm)**	**CCA(Stated) (A)**	**CCA(Calculated) (A)**
13.115	48.61	270	269.8

7 Conclusions and Further Work

This thesis has focused on the estimation of a lead-acid battery, with the methods stated above and the procedures to estimate the battery's health, the overall estimation is able to find out if the battery's SOH is increasing or decreasing. Along with coulomb counting to keep track of the capacity, which is directly linked to SOC. The main part of this BMU is the contactless current sensing method which proved to be reliable and since part of the project specification was to ensure that the original battery circuit does not need to be broken or tampered with, such as appling a shunt for current measurement, this contactless measuring technique would be a great feature for enabling an easy approach to monitor a lead-acid battery during its lifespan.

The estimation per se has not yet been fully verified but the measurement tools needed for the estimation has proven to work well within the wanted requirements. This thesis purpose was to provide the reader an extensive procedure of estimating the State of Health and State of Charge of a lead-acid battery and to evaluate a contactless current measuring technique to investigate whether it is possible to implement this technique over a well proven shunt measuring technique. And, as shown from the results, it has proven to be useful under the lab circumstances that has been used for this report.

7.1 Further Work

Improvements and further testing should be done to ensure that the estimations taken are valid. Here are some of the improvements and further work that can be done so the overall estimation gets more dynamic and accurate.

Regarding the input from sensors to the ESP32, the use of some capacitors could be an improvement for stabilizing the bit-value and decrease the fluctuations shown in the normal distribution graphs in chapter 6. For the function used for bit-to-volt calculations, a separate function for 12 V and another for 24 V could be implemented to get more accurate results and minimize the errors from mathematical calculations.

In order to save power consumption and minimize the impact of self drainage from the battery, the amplifier circuit should be powered by the ESP32 so that the whole system could be put in deep sleep which only consumes 10 µA. With this setting the self drainage would be roughly 1 Ah after 600 weeks of sleep, but note that the linear voltage regulators are not included in that calculation, and with the present voltage regulators the minimum load current is 1mA so therefore a new voltage regulator has to be chosen which fits the requirements.

Some more evaluation has to take place so that the estimation can be verified and analyzed, this is time consuming work due to the charging/discharging-cycles that naturally will take time. If the Canadus product should be evaluated the battery has to be used in a car or manually charged/discharged under months for the result to be of value. Moreover the temperature plays a big part in estimations discussed in this thesis, and to include this parameter into the mixture of estimations would require more data from batteries at certain conditions and temperatures to analyze and evaluate. If a correlation is found between temperature and internal resistance or temperature and open circuit voltage and ideally is linear to the temperature then this function would be easily implemented in the overall system of estimation.

For the current sensing technique the sensor could be amplified with different amplifications to provide one for precise measuring and one for higher currents.

Another way is to implement several current sensors at different distances from the cable, thus accessing a wider span of currents to be measured.

References

[1] C. Suozzo, "LEAD-ACID BATTERY AGING AND STATE OF HEALTH DIAGNOSIS," The Ohio State University, 2008.

[2] "Canadus HD-1224 ‹ Canadus." .[Online]. Available: https://canadus.com/canadus-hd1224/. [Accessed: 01-Apr-2019].

[3] "WHO | Recycling used lead-acid batteries:," WHO. [Online]. Available: http://www.who.int/ipcs/publications/ulab/en/. [Accessed: 01-Apr-2019].

[4] A. Håkansson, "Portal of Research Methods and Methodologies for Research Projects and Degree Projects," Computer Engineering, p. 8, 2013.

[5] "EG Electronics - Sweden," EG Electronics, [Online]. Available: http://www.egelectronics.com/sweden/. [Accessed: 01-Apr-2019].

[6] M. M. Samolyk and J. Sobczak, "Development of an algorithm for estimating Lead-Acid Battery State of Charge and State of Health.," p. 81.

[7] Z. M. Salameh, M. A. Casacca, and W. A. Lynch, "A mathematical model for lead-acid batteries," IEEE Transactions on Energy Conversion, vol. 7, no. 1, pp. 93–98, Mar. 1992.

[8] "ESP32 Overview | Espressif Systems." [Online]. Available: https://www.espressif.com/en/products/hardware/esp32/overview. [Accessed: 28-May-2019].

[9] K. Ng, C. Moo, Yi-Ping Chen, and Y. Hsieh, "State-of-charge estimation for lead-acid batteries based on dynamic open-circuit voltage," in 2008 IEEE 2nd International Power and Energy Conference, 2008, pp. 972–976.

[10] A. Maier, A. Sharp, and Y. Vagapov, "Comparative analysis and practical implementation of the ESP32 microcontroller module for the internet of things," in 2017 Internet Technologies and Applications (ITA), Wrexham, 2017, pp. 143–148.

Appendix A:

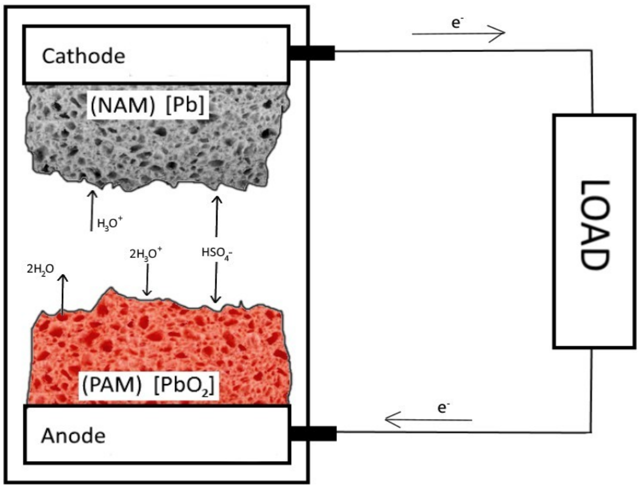


Figure 8: Illustration of the chemical reactions inside a lead-acid battery.

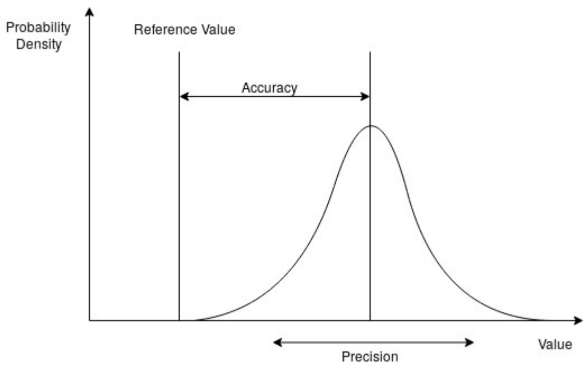


Figure 9: Visual representation of the definition for precision and accuracy

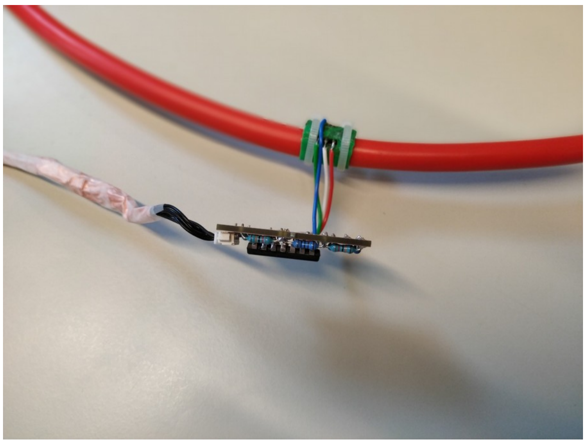


Figure 10: 3D-printed case for sensor with amplifier circuit.

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