Linköping University | Department of Electrical Engineering
Bachelor's thesis, 16 ECTS | Elektronik, Inbyggda system
2024 | LITH-ISY-EX-ET--24/0525--SE

State of Health measuring of NiMH batteries using simple electronic components.

Batterihälsa mätning av NiMH batterier med enkla komponenter

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Abstract

The possibility of measuring the state of health of a NiMH battery without doing it in a lab is evaluated, the goal was to see if it was possible to perceive any differences between batteries of different states of health and whether it's worth further exploring this solution in a more detailed manner.

In order to try and extract and analyze the state of health of the batteries a series of tests consisting of discharging batteries at different lengths of times and different resistive loads were made, the voltage of the batteries being captured by a multimeter.

The study shows that getting the state of health of a battery with simple components is a possibility and is useful for battery-powered items. Situations where batteries can't deliver enough energy for the item to function can be prevented by measuring the health of the batteries and then subsequently switching out the batteries if needed.

Acknowledgments

I am grateful to Daniel Jung from Linköpings University for being a great examiner.
Special thanks to Mark Willerton from Actia for the great support during the project.
I am also grateful to Arman Mohammadi from Linköpings University for the excellent help in providing feedback for this report.
Last of all thank you Actia Nordic for providing the equipment used in the project.

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1 Introduction

Batteries are widely used in many applications in the world, such as phones, cars, and embedded systems. Unfortunately, a problem with using batteries is the ageing of the batteries which causes the batteries to progressively get lower capacity and higher internal resistance, which means that eventually a battery cell or battery pack requires replacement. The problem is to decide when to replace the battery. The easiest solution would be to just measure the internal resistance or internal impedance, but this alone isn't enough, since it does not tell how much capacity is remaining in the battery. For measuring the capacity the battery needs to be discharged almost fully and from there it's possible to calculate the amount of Ampere Hours or Watt Hours a battery has in capacity left compared to when it was fresh and new. But discharging an entire battery in the field is not trivial, the battery is either being used or if it is a backup battery it needs to be ready to step in and start providing power at a moment's due.

NiMH batteries which are used in this thesis project are widely used in applications where a high amount of current is being used and is commonly found in AA battery form.

1.1 Motivation

The ability to get a reading of a battery's state of health is very useful in many applications where the battery life plays a big role in the application's function. If there is a way to measure the state of health of a battery while still keeping the components required simple, then that is a step closer to making sure that batteries don't get switched out too early or too late. This would be a great boon in not only reducing waste, but also making sure that the batteries are used as long as they can in their application. It can also help save lives in some applications where the battery is a backup battery to be used when necessary and it's extra important then to ensure that the battery is healthy enough to provide the power for the product's function.

1.2 Aim

The goal of this project is to investigate and test if there is a way to get an indication of the state of health a battery has without having to use a lab to do things like a full discharge in order to measure the capacity of a battery. If it is possible to measure or get a reading of the State of Health of a battery using mundane components like resistors to measure the current that is being drawn. Following that up by measuring the voltage across the battery when the current is being drawn, and then analysing the gathered data to see if there are any notable differences between batteries of different states of health.

1.3 Research questions

The goal of the thesis project is to investigate if it is possible to get a sense of the state of health of a battery by looking at the beginning of the voltage discharge curve of a battery, and if it is possible to see the difference between a healthy battery and a battery with poor health.

1. Is it possible to get a sense of the State of Health without discharging the entire battery?
2. Is it possible to see the differences between batteries at different stages of health by looking at the voltage curve and slope?

1.4 Delimitations

For this project, the battery chemistry will be limited to Nickel-Metal Hydride batteries.

2 Background

2.1 The NiMH battery

The Nickel-Metal Hydride battery was developed as a replacement for the older Nickel-Cadmium battery and is commonly found in high energy consuming applications. This is due to the fact that it comes with some advantages over the older battery type, such as:

- Higher energy density, which means more energy can be stored in the same amount of space as a NiCd battery.
- Easier manufacturing of batteries thanks to eliminating the toxic material such as Cadmium.
- It's easy to replace an old NiCd battery with a newer NiMH battery, since they share voltage characteristics.
- NiMH batteries are good at delivering high amounts of current for extended amounts of time, which makes them ideal for high energy consuming applications.

A healthy battery cell that is fully charged averages around 1.4 V in open circuit voltage. But when the battery is used the voltage goes down to around 1.2 V where it then continues falling slowly. When the battery voltage goes down close to 1 V it indicates that there is only a little bit of charge left in the battery. It is possible to continue discharging down further and extract some more energy, but discharging below 0.8 V would risk either killing the battery cell or damaging it, since the voltage starts dropping rapidly below 0.9 V [2]. This can be seen by looking at the discharge curve of a NiMH battery. NiMH batteries can be found as regular AA batteries and is what is used in this thesis project.

2.2 Battery ageing and life cycles

A battery life cycle is the amount of discharge cycles and charge cycles a battery can endure before losing performance. The battery life cycle can increase or decrease the amount of cycles it can endure depending on how the battery is used and cared for. A battery ages as it is used and from simply existing, as the battery ages its performance will go down, lowering its capacity and increasing its internal resistance. The amount of cycles a battery has endured will often be a big factor for speeding up the ageing of the battery.

2.3 Ampere Hour and Watt Hour

Watt-hour, often abbreviated as Wh is an energy unit often used when calculating the power usage of a machine or a circuit. A single Wh is equal to 3600 Joules, which is the unit for energy.

Ampere hour, often abbreviated as Ah is a measurement unit used to measure the amount of charge something has and is often used with batteries. If a battery has 2300 mAh in capacity, it means that the battery can theoretically deliver at most 2.3 ampere for a whole hour. Or it can deliver less current but for a longer time.

2.4 Octave

Octave is a software and language used in performing numerical computations and is as a language very similar to Matlab, another well known program used to simulate and perform numerical computations in many fields. The software can also be used to plot data into graphs, which is useful for visualising data and computed data.

2.5 LTSpice

LTSpice is a free software used for simulating analog electronic circuits and is very useful when designing circuits and verifying them.

2.6 Python

Python is a high-level interpreted programming language that is widely used around the world for its easy-to-read syntax and wide array of modules and packages.

easy_scpi package

easy_scpi[1] is a python library used to make communication with lab instruments such as digital multimeters easier. The library makes it easy to send instructions to the connected equipment.

2.7 Capacity measuring

Batteries have a standard rating which is often abbreviated as C, this standard rating represents the capacity of a new battery which after conditioning to achieve maximum capacity will be subjected to constant current discharge at room temperature and after that, it will be fully charged to an optimal level. The capacity of a battery has an inverse relationship with the discharge rate and for Nickel-Metal Hydride batteries the rated capacity according to Energizer's datasheet [2] is normally determined by a discharge rate which leaves the battery fully discharged after five hours.

2.8 Equations

Internal resistance is computed as:

$$R_i = (\frac{V_{oc}}{V_{cc}} - 1) \times R_{Load} \tag{2.1}$$

Where V_{oc} is the open circuit voltage measured between the terminals of the battery and V_{cc} is the closed circuit voltage measured between the terminals of the battery.

The capacity in Ampere hours is computed as:

$$AmpereHours = \int_0^T I(t)dt \times \frac{1}{3600} \tag{2.2}$$

where $I(t)$ is the current drawn at time t, and T is the time when the battery is depleted.

Watt hours is computed as:

$$WattHours = \int_0^T P(t)dt \times \frac{1}{3600} \tag{2.3}$$

where $P(t)$ is the power at time t, and T is the time when the battery is depleted.

Calculating the capacity can also be done by dividing Watt Hours by the nominal voltage of the batteries which in this case is 1.2 V for the NiMH type batteries.

$$AmpereHours = \int_0^T P(t)dt \times \frac{1}{3600 \times 1.2} \tag{2.4}$$

Internal resistance of a battery is computed as:

$$R_i(t) = (\frac{V_{oc}}{V_{cc}(t)} - 1) \times R_L \tag{2.5}$$

Where V_{oc} is the open circuit voltage of the battery and $V_{cc}(t)$ is the closed circuit voltage at time t of the battery. R_L is the load resistance connected to the battery.

Scaled voltage is computed as:

$$V_{scaled}(t) = V(t) \times \frac{V_{ref}}{V(1)} \tag{2.6}$$

where $V(t)$ is the voltage at time t and V_{ref} is the reference point the voltage is being scaled to.

Current is computed as:

$$I(t) = \frac{V(t)}{R_L} \tag{2.7}$$

where $V(t)$ is the voltage at time t and R_L is the load resistance.

Power is computed as:

$$P(t) = I(t) \times V(t) \tag{2.8}$$

Where $I(t)$ is the current at time t and $V(t)$ is the voltage at time t.

Amount of energy E extracted from the battery is computed as:

$$E(t) = \int_0^t P(s)ds \tag{2.9}$$

Where $P(s)$ is the power at time s.

2.9 State of Health

The State of Health of a battery for the purpose of this project is a combination of battery capacity and internal resistance. The internal resistance of a battery plays a significant role in deciding how much energy is possible to squeeze out of a battery. The higher the internal resistance gets, the higher the efficiency loss across the internal resistance will become. The capacity of a battery can be seen as the total amount of energy that is possible to be stored, which can be expressed in **Ampere Hours[Ah]** or **Watt Hours[Wh]**.

3 Method

3.1 Test Setup

In order to conduct the testing, some equipment is required. The test equipment used in this project is a digital multimeter which is required because it is able to log voltage values it measures, and it measures it accurately. In this project, a Keysight 34465a Truevolt Digital multimeter is used to measure the voltage across the battery. Then in order to record the voltage measured by the multimeter, a program is needed to log the values and the time that has passed, for this project the sampling happens once a second. For the logging program itself, a small python script is used to send commands to the multimeter in order to query for the voltage and then use the computer's internal clock system to note down the relative passed time. The **easy_scpi** [1] library is used in order to facilitate the communication between the instruments and handles nearly all the setup process in the background, all that's left to do is to tell the library the address of the instrument and then the program will be able to send **SCPI**[1] commands to the multimeter.

3.2 Capacity Testing

Measuring the capacity is an important step in order to try and get a better look at the batteries' states of health. The steps are the following:

1. Measure the open circuit voltage to make sure that the battery is fully charged.
2. Connect the battery to the circuit.
3. Start the logging software.

The load in the first tests is a 10 Ω load which will draw around 120 mA of current. Which is about 0.05C, the discharge itself takes many hours which makes it easy to accidentally over-discharge the batteries. In order to prevent this, the circuit mentioned in Section 5.2 is used to stop the discharge once the battery reaches 1 Volt across the battery's terminals.

---

[1] **Standard Commands for Programmable Instruments**.

A standard capacity test for Nickel Metal Hydride batteries is to discharge the battery at a rate that leaves the battery discharged after 5 hours according to Energizer's datasheet [2]. For the batteries rated 2300 mAh this would be roughly 460 mA current draw and this would require a load of roughly 2.6 Ω but the closest power resistor available during this project would be 3 Ω which is close enough to use while keeping the circuit simple. The test with 3 Ω load will be done to see if it's possible to get closer to the standard capacity test even without having a constant current load.

3.3 State of Health Testing

The purpose of this section is to describe the tests made to gather the data needed to try and differentiate batteries of different states of health. All the discharge tests use the same setup, with only the load resistance varying amongst the tests. The basic steps for these tests are the following:

1. Connect the intended load resistance.
2. Measure the open circuit voltage of the battery.
3. Connect the battery to the circuit and start the logging software.

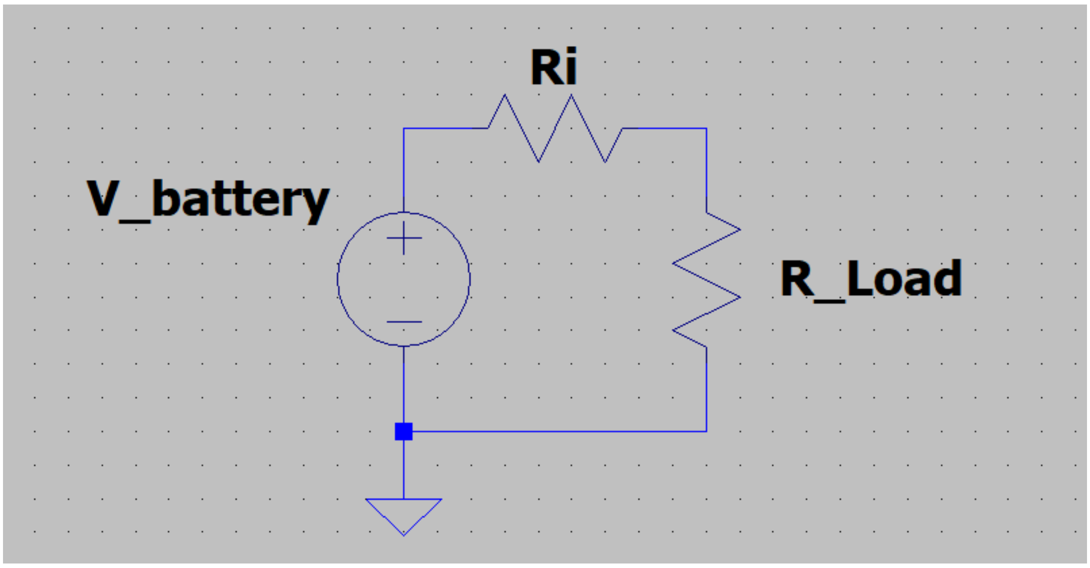

Figure 3.1: Schematic of the test setup without the multimeter connected.

30 Minute Tests

For these tests, the idea is that the battery is fully charged and then discharged for 30 minutes where the voltage across the battery's terminals is sampled in 1 Hz. From these voltage samples, the current and power usage are calculated since the load resistance is known. The load resistances used in the tests are 1 Ω, 2 Ω, and 10 Ω.

Measuring Internal Resistance

In order to get a better grasp on the state of health of the batteries, the internal resistance of the batteries is measured by a **YR1035+**. This device utilizes 4 wire technology to measure internal resistance by connecting four probes to the terminals of the battery, two on each side when the batteries are fully charged. This is important since it helps verify the data gathered, since the state of health of the old batteries is mostly unknown.

Analysis And Data Extraction

After the voltage curves have been sampled and collected some calculations need to be done, since the load resistance is known and the voltage is measured across the battery terminals as well as across the load resistance the current can be calculated as well as the internal resistance by taking the open circuit voltage of the battery. The resistance of other components such as cables is not taken into consideration and while it will introduce some errors, especially under high current, it will not change the differences between the batteries change of internal resistance much. All calculations are done in Octave.

A battery with worse health should drop its voltage faster but whether it's because of the internal resistance, if it is because of the capacity of the battery or if it is a combination of both is not possible to tell just from looking at the slope, but differentiating the state of health is possible to observe. A way to automatically differentiate the state of health of the batteries is needed. The first way to look at the differences between the curves is to look at the numerical differentiation of voltage over time: $\frac{\Delta V}{\Delta t}$.

In an attempt to normalize the gathered data and make it have the same starting point the data is scaled to begin at the same referense point. With the computed scaled data, the next step is to compute the numerical differentiation of the voltage over time.

The benefit of doing this type of scaling is that the starting point matters less and the curves themselves aren't changed too much, as long as the reference starting point isn't too far away from the individual curves starting points they won't be amplified or dampened much. From the tests the scaling factor averages around 2% to 5% in amplification and dampening.

Another point of interest would be to have a look at the change in voltage over change joule: $\frac{\Delta V}{\Delta J}$ where the change in joule is derived from the previously calculated energy extracted over time. The idea of using this derivation is to try and extract health data that are more biased towards the energy capacity of the batteries by looking at the change in voltage as energy has been extracted.

But something else that might be important to look at is the internal resistance and how it changes during the discharge test and a way to extract the differences between batteries is to once again do a numerical derivation $\frac{\Delta \Omega}{\Delta t}$. This set of data is interesting because if a battery increases its internal resistance faster during use compared to other batteries, this indicates that it is less healthy on the internal resistance front.

By using a numerical integration of the calculated Watts per second it's possible to see differences between batteries and the amount of energy extracted for the same duration of time. A healthy battery should be able to deliver more energy than a less healthy battery.

4 Results

In this chapter the results of the test will be shown. The batteries used are named after their previously known capacity. Note that the current capacity of the batteries aren't fully known.

4.1 Capacity Testing

This section will show the results from the capacity tests that were done in order to try and measure the capacity of the batteries. The tables below will show the measured capacities of the batteries. The battery capacity in mAH is estimated using equation 2.2 and from Wh using equation 2.4.

3 Ω

Table 4.1 shows the calculated capacity for each battery. The table shows that most of them are around similar levels with the 1611 Battery being of the best out of the old batteries.

Table 4.1: 3 Ω Capacity test results

Battery	mAh	mAh computed from Wh
1611	2359.8	2375.0
1727	2289.5	2313.3
1810	2280.9	2296.3
1915	2240.6	2254.4
2600 Damaged	2622.1	2622.4
2600	2650.5	2702.6

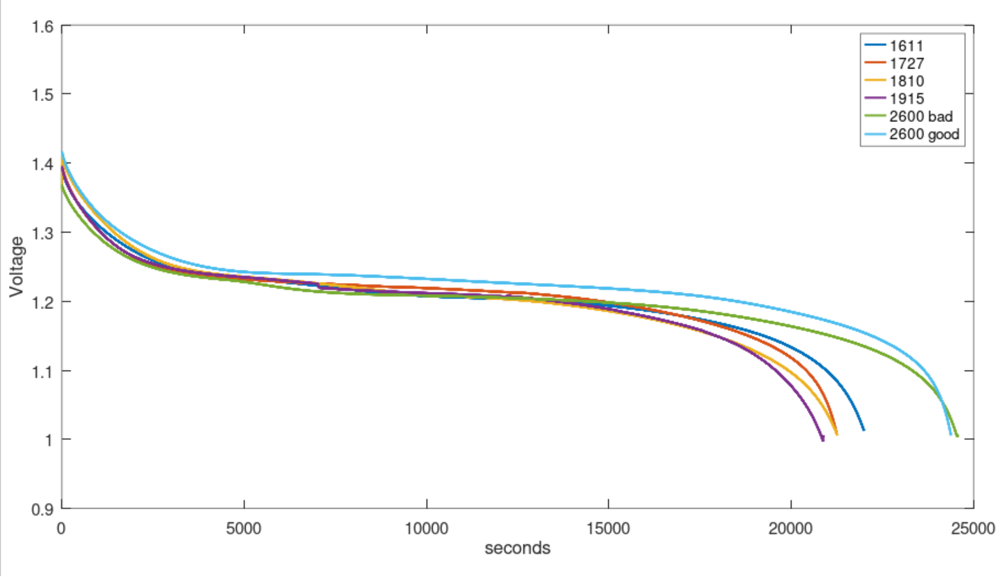

Figure 4.1: 3 Ω Capacity discharge voltage curves.

Figure 4.1 shows the voltage level on the battery during the test. From looking at the graph it's possible to see that the 1611 lasts the longest amongst the old batteries, while the new ones are further away where the voltage starts dipping faster.

10 Ω

Table 4.2 shows the calculated capacity of each battery from the test, where the 1611 battery has the largest capacity of the batteries with only the newer batteries 2600 and 2600 damaged being larger which isn't strange considering they are supposed to be bigger.

Table 4.2: 10 Ω Capacity test results

Battery	mAh	mAh computed from Wh
1611	2359.9	2455.4
1727	2226.2	2283.9
1810	2225.4	2284.0
1915	2276.6	2354.2
2600 Damaged	2596.5	2653.1
2600	2573.6	2638.7

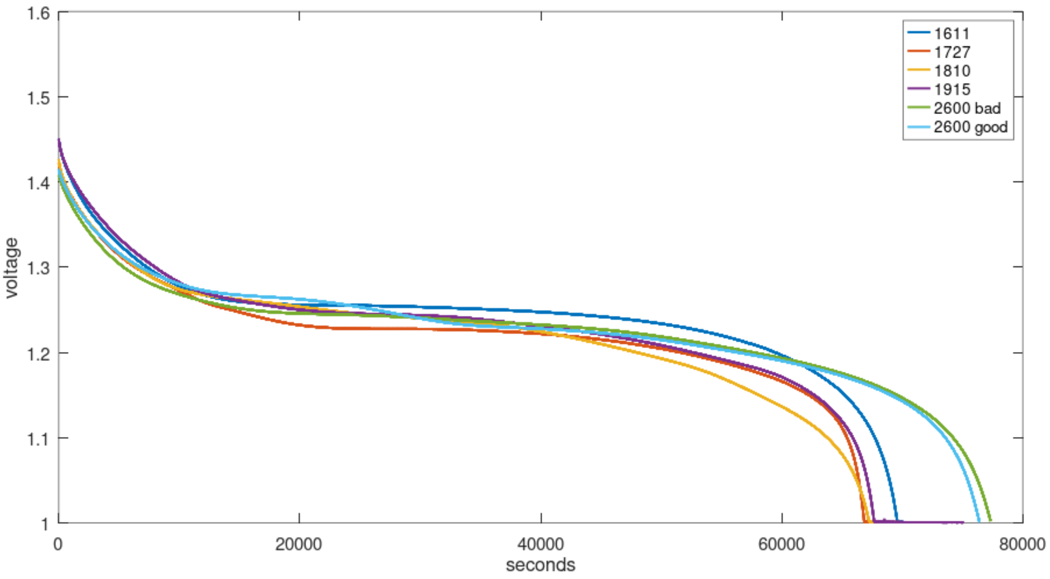

Figure 4.2: 10 Ω Capacity discharge voltage curves.

Figure 4.2 shows the voltage of the batteries during the test and from looking at the plot here it's possible to once again discern that the 1611 has the bigger capacity compared to the other older batteries while the two 2600 batteries are still bigger in capacity as they should be.

4.2 State of Health Testing

Measuring Internal Resistance

Results of measuring the internal resistance using the **YR1035+** internal resistance meter:

- 2600: 25.8 mΩ.
- 2600 Damaged: 24.3 mΩ.
- 1915: 36.6 mΩ.
- 1810: 54.6 mΩ.
- 1727: 37.0 mΩ.
- 1611: 30.06 mΩ.

30 Minute Tests

Below are the results from the thirty-minute tests that were performed in Section 3.3

1 Ω test number 1

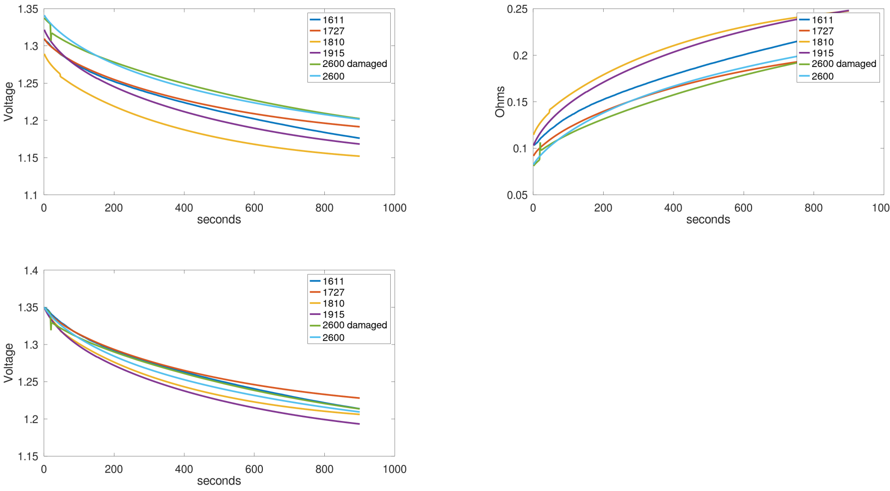

Figure 4.3: Results from 1Ω test using the voltage, scaled voltage and internal resistance signals.

In Figure 4.3, the voltage, scaled voltage and internal resistance signals show that there are differences between the different batteries, some batteries drop voltage faster than others and they start with different internal resistance values. Looking at the third subplot it shows that the differences between the batteries become easier to discern after the samples from each battery have been scaled to start at the same voltage reference point as the others. The plots also show the change in internal resistance over time as well as the voltage drops over time.

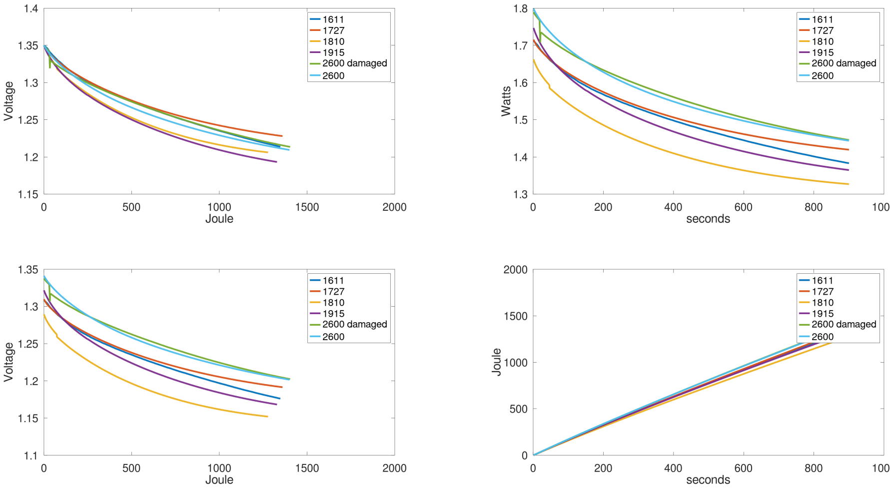

Figure 4.4: Results from 1Ω test using the voltage, scaled voltage, power and energy signals.

In Figure 4.4 the plots show the voltage, scaled voltag, power and energy signals. The first plot shows the scaled voltage level per joule extracted and by looking at the differences it's possible to see how some batteries drop in voltage faster than the other batteries. The second plot shows the change in power for the duration of the test. A healthy battery can deliver more power than a battery with worse health. The third plot shows the voltage level per joule and is interesting to look at in comparison with the scaled variant. The fourth and final plot shows the amount of total energy extracted per second passed.

1 Ω test number 2

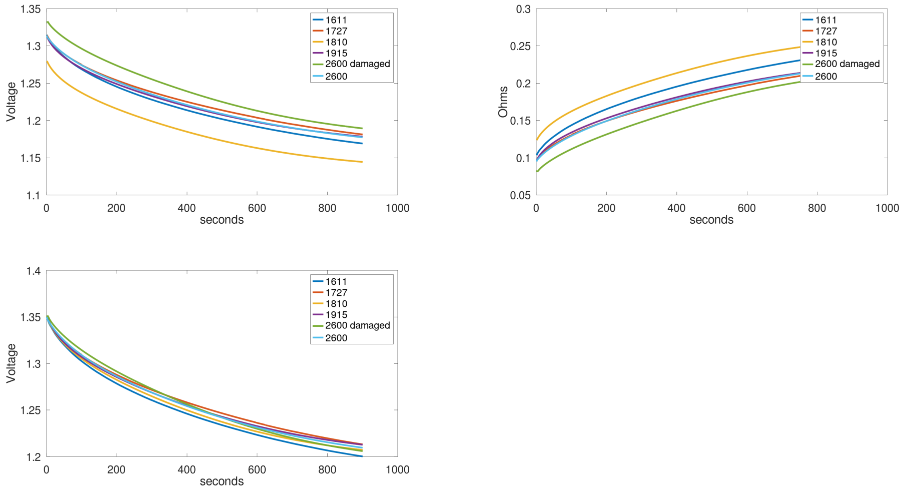

Figure 4.5: Results from 1Ω test 2 using the voltage, scaled voltage and internal resistance signals.

In Figure 4.5 the first plot shows the voltage samples collected during the test, the difference between this test and the previous test is the order of when the voltage logging starts and a different charger which charges the batteries close to the same level of voltage as the others. The result of using the charger and starting the voltage sampling before connecting the battery shows that they don't have any spikes in the graph as they had in the first version of the test. The second plot shows the change in internal resistance over time. The third plot shows the voltage change over time where the voltage curves have been scaled to start at the same reference point.

In Figure 4.6 the first plot shows the change in volts per amount of energy extracted for each of the batteries, the voltage in this plot is the scaled voltage. Looking at the way the voltage changes when extracting energy from the battery shows that some batteries like the 1611 mAh battery could deliver slightly more energy than the 1810 mAh. The second plot shows the change in power over time. The third plot shows the change in voltage per amount of energy extracted but uses the unchanged voltage samples. The fourth and last plot simply shows the amount of energy extracted over time, in most cases looking at the final value would give the most valuable information from the plot since it tells the total amount of energy extracted during the test, more energy extracted is better.

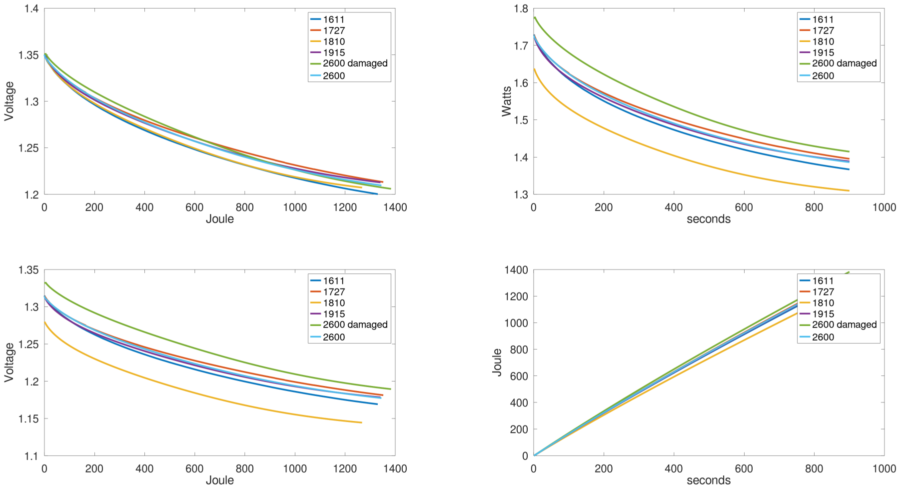

Figure 4.6: Results from 1Ω test 2 using the voltage, scaled voltage, power and energy signals.

2 Ω

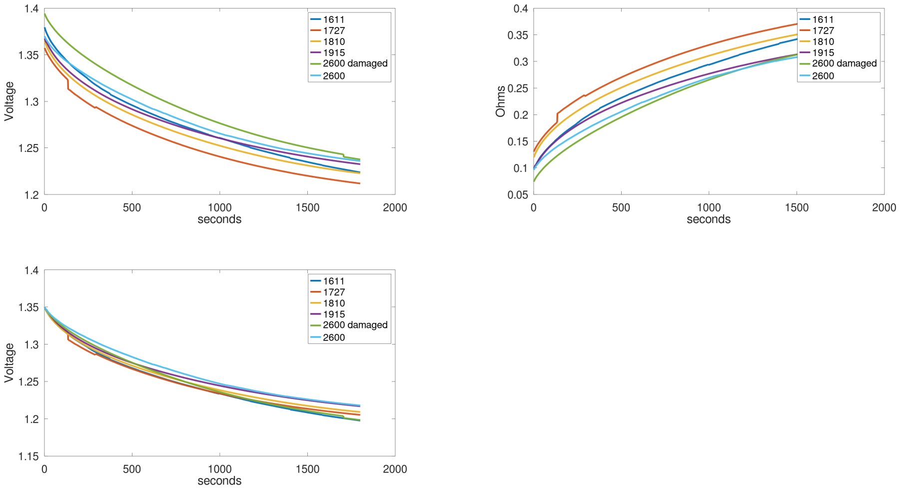

Figure 4.7: Results from 2Ω test using the voltage, scaled voltage and internal resistance signals.

Figure 4.7 shows in its first plot the voltage change of the battery for the duration of the test. By looking at the first plot it would seem that the 1810 battery is the one with the worst state of health since it starts at the lowest voltage and ends at the lowest voltage. Looking at the second plot also indicates that since the change in internal resistance grows much faster and to a higher final number compared to the other batteries. Looking at the third plot it's no longer that easy to discern the differences between the batteries but the 1810 battery is somewhere in the middle.

Figure 4.8 shows the scaled voltage per joule extracted in the first plot and the voltage per joule in the third plot while the second plot shows the power throughout the discharge.

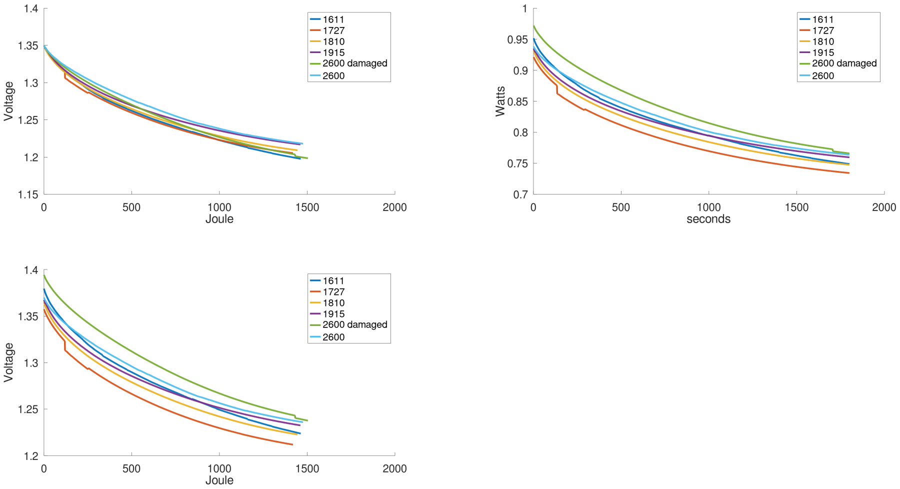

Figure 4.8: Results from 2Ω test using the voltage, scaled voltage, power and energy signals.

Looking at the graphs it would seem that the 1727 battery is the worst off since it drops in voltage faster per joule extracted and it drops in power over time faster.

10 Ω

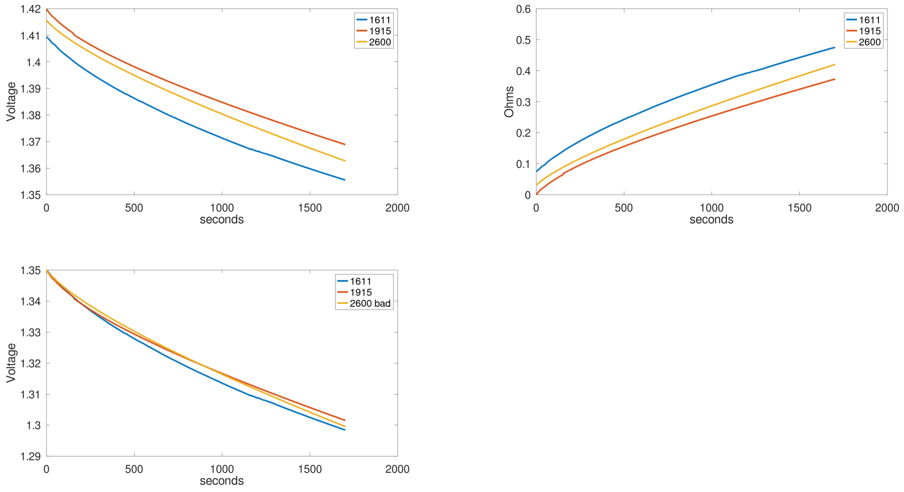

Figure 4.9: Results from 10Ω test using the voltage, scaled voltage and internal resistance signals.

Figure 4.9 shows the voltage of the battery during the test in the first plot. The second plot shows the increase in internal resistance of the batteries as they went on. The third and final plot shows the voltage scaled to start on the same voltage level and how it changed during the test. From these graphs, it would seem that the 1915 battery is better off than the 1611 battery while the 2600 battery is omitted since it's unknown if it is of the same battery chemistry type as the older batteries.

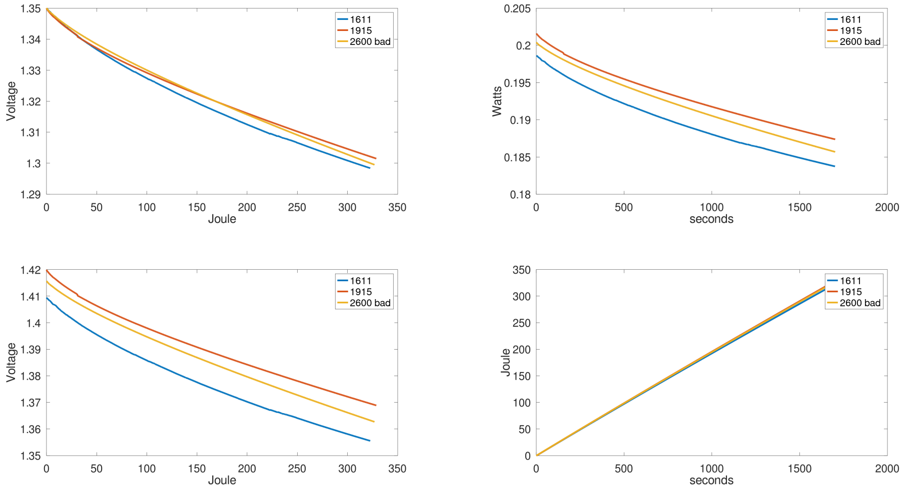

Figure 4.10: Results from 10Ω test using the voltage, scaled voltage, power and energy signals.

Figure 4.10 shows the voltage in relation to the energy extracted and from looking at it the 1611 battery is the worst off on both the first plot where the battery voltage has been scaled to start on the same voltage level, and the third plot shows the normal voltage over the batteries relative to the amount of energy extracted. The second plot shows the power extracted during the test and the fourth plot shows the total amount of energy extracted after a certain amount of time.

Analysis and Data Extraction

In this section, the result of the calculations done from the different test data is shown for each test.

Results calculated from the 1 Ohm 30-minute test number 1

Table 4.3 shows the calculated values from the voltage samples collected from the different tests. A lower drop in voltage is better than a higher one when looking at the values since it indicates that it can more easily deliver energy without dropping as much voltage as a battery with a worse state of health might. By looking at the different derivatives it would appear that the 1727 has the best state of health out of the older batteries.

Table 4.3: 1 Ω test 1 analysis results from derivative data set 1.

Battery	$\frac{\Delta Volts}{\Delta time}$	$\frac{\Delta ScaledVoltage}{\Delta time}$	$\frac{\Delta ScaledVoltage}{\Delta Joule}$
1611	-1.4689×10^{-04}	-1.5159×10^{-04}	-1.0113×10^{-04}
1727	-1.3163×10^{-04}	-1.3568×10^{-04}	-8.9689×10^{-05}
1810	-1.5285×10^{-04}	-1.6004×10^{-04}	-1.1262×10^{-04}
1915	-1.7071×10^{-04}	-1.7437×10^{-04}	-1.1799×10^{-04}
2600 Damaged	-1.5043×10^{-04}	-1.5183×10^{-04}	-9.7254×10^{-05}
2600	-1.5536×10^{-04}	-1.5638×10^{-04}	-1.0046×10^{-04}

Table 4.4 shows the calculated derivatives in relation to energy, power, and internal resistance, and by looking at their values it should be possible to determine which batteries have a better state of health compared to the others. The slower the values drop the better, and the 1727 battery once again has the best state of health of the older batteries.

Table 4.4: 1 Ω test 1 analysis results from derivative data set 2.

Battery	$\frac{\Delta Volts}{\Delta Joule}$	$\frac{\Delta Ohms}{\Delta time}$	$\frac{\Delta Watt}{\Delta time}$
1611	-9.7991×10^{-05}	1.3777×10^{-04}	-3.6489×10^{-04}
1727	-8.7015×10^{-05}	1.2063×10^{-04}	-3.2924×10^{-04}
1810	-1.0756×10^{-04}	1.4789×10^{-04}	-3.7313×10^{-04}
1915	-1.1552×10^{-04}	1.6120×10^{-04}	-4.2504×10^{-04}
2600 Damaged	-9.6357×10^{-05}	1.3526×10^{-04}	-3.8206×10^{-04}
2600	-9.9803×10^{-05}	1.3998×10^{-04}	-3.9504×10^{-04}

Even here by looking at the table 4.5 that shows the energy extracted in mAh and Wh, it is clear that 1727 provided the most energy out of the older batteries even if it's just small differences.

Table 4.5: 1 Ω test 1 analysis results from derivative data set 3.

Battery	mAh	mAh computed from Wh	mWh
1611	305.6	311.9	374.3
1727	307.1	314.8	377.8
1810	297.6	297.6	354.9
1915	303.4	307.5	369.0
2600 Damaged	311.9	324.9	389.9
2600	311.4	323.9	388.7

Results calculated from the 1 Ohm 30-minute test number 2

Table 4.6 shows the calculated derivative values from the second improved version of the 1Ω test. The table shows how fast the voltage changes over time to how fast the voltage changes from extracting energy for each of the batteries and by looking at the table it's possible to pick out which battery has the best state of health from the table. From the older batteries, it would seem that both 1915 and 1727 are the best of with how close they are together in their metrics with 1810 coming at a third place and 1611 coming last. The 2600 battery is slightly better off than the damaged 2600 battery. The damage to said battery is not known, just that it got discharged down to around 0.2 V.

Table 4.6: 1 Ω test 2 analysis results from derivative data set 1.

Battery	$\frac{\Delta Volts}{\Delta time}$	$\frac{\Delta ScaledVoltage}{\Delta time}$	$\frac{\Delta ScaledVoltage}{\Delta Joule}$
1611	-1.6224×10^{-04}	-1.6656×10^{-04}	-1.1258×10^{-04}
1727	-1.4817×10^{-04}	-1.5218×10^{-04}	-1.0118×10^{-04}
1810	-1.5053×10^{-04}	-1.5880×10^{-04}	-1.1263×10^{-04}
1915	-1.4831×10^{-04}	-1.5264×10^{-04}	-1.0233×10^{-04}
2600 Damaged	-1.5805×10^{-04}	-1.6024×10^{-04}	-1.0416×10^{-04}
2600	-1.5204×10^{-04}	-1.5620×10^{-04}	-1.0443×10^{-04}

Table 4.7 shows the calculated derivatives for the speed in which the voltage changes per extracted joule, the speed of the growth of the internal resistance over time, and the speed of the change of power over time. Looking at this table shows similar results to the previous table but the differences between the 1727 and 1915 are bigger because the voltage hasn't been scaled. The 1727 battery is best with 1915 second, 1810 third, and 1611 last in fourth place. The 2600 is once again better than the 2600 battery that is damaged.

Table 4.7: 1 Ω test 2 analysis results from derivative data set 2.

Battery	$\frac{\Delta Volts}{\Delta Joule}$	$\frac{\Delta Ohms}{\Delta time}$	$\frac{\Delta Watt}{\Delta time}$
1611	-1.0966×10^{-04}	1.7084×10^{-04}	-4.0303×10^{-04}
1727	-9.8517×10^{-05}	1.4958×10^{-04}	-3.6980×10^{-04}
1810	-1.0677×10^{-04}	1.8339×10^{-04}	-3.6492×10^{-04}
1915	-9.9424×10^{-05}	1.9989×10^{-04}	-3.6930×10^{-04}
2600 Damaged	-1.0273×10^{-04}	1.6772×10^{-04}	-3.9842×10^{-04}
2600	-1.0165×10^{-04}	1.7358×10^{-04}	-3.7880×10^{-04}

Table 4.8 shows the amount of energy extracted in Ampere hours and Watt-hours. One thing of note when looking at the values here is that the 1810 battery is worse off than the 1611 battery which breaks the pattern of the previous tables but coincides with the fact that the 1810 battery has the highest internal resistance of them all.

Table 4.8: 1 Ω test 2 analysis results from derivative data set 3.

Battery	mAh	mAh computed from Wh	mWh
1611	303.6	307.9	369.5
1727	306.1	313.0	375.6
1810	296.4	293.4	352.1
1915	304.9	310.4	372.5
2600 Damaged	309.6	320.1	384.2
2600	305.3	311.3	373.5

Results calculated from the 2 Ohms 30-minute test

Table 4.9 shows the calculated derivatives for this test, with the speed voltage changes over time as well as the speed that the voltage changes per joule extracted. In this test, it seems 1915 is the best battery compared to the other older batteries since it has the lowest speed in each of the different derivative values. The 2600 battery is also better than its damaged counterpart.

Table 4.9: 2 Ω analysis results from derivative data set 1.

Battery	$\frac{\Delta Volts}{\Delta time}$	$\frac{\Delta ScaledVoltage}{\Delta time}$	$\frac{\Delta ScaledVoltage}{\Delta Joule}$
1611	-8.6532×10^{-05}	-8.4685×10^{-05}	-1.0416×10^{-04}
1727	-8.0846×10^{-05}	-8.0410×10^{-05}	-1.0199×10^{-04}
1810	-7.9126×10^{-05}	-7.8248×10^{-05}	-9.7488×10^{-05}
1915	-7.4917×10^{-05}	-7.3967×10^{-05}	-9.1087×10^{-05}
2600 Damaged	-8.7013×10^{-05}	-8.4253×10^{-05}	-1.0080×10^{-04}
2600	-7.4443×10^{-05}	-7.3362×10^{-05}	-8.9414×10^{-05}

Table 4.10 shows the calculated values of this table and once again shows that the 1915 battery is the battery with the best values with 1810 coming in second, 1727 third, and 1611 in last place.

Table 4.10: 2 Ω analysis results from derivative data set 2.

Battery	$\frac{\Delta Volts}{\Delta Joule}$	$\frac{\Delta Ohms}{\Delta time}$	$\frac{\Delta Watt}{\Delta time}$
1611	-1.0643×10^{-04}	1.4824×10^{-04}	-1.1263×10^{-04}
1727	-1.0254×10^{-04}	1.4214×10^{-04}	-1.0385×10^{-04}
1810	-9.8581×10^{-05}	1.3718×10^{-04}	-1.0239×10^{-04}
1915	-9.2257×10^{-05}	1.2758×10^{-04}	-9.7388×10^{-05}
2600 Damaged	-1.0410×10^{-04}	1.4583×10^{-04}	-1.1451×10^{-04}
2600	-9.0733×10^{-05}	1.2627×10^{-04}	-9.6996×10^{-05}

Table 4.11 shows the total amount of energy extracted during the test per battery expressed in ampere-hours and watt-hours. While all of the batteries are similar in the amount of energy extracted the 1915 battery managed to deliver slightly less than 1611 which means that 1611 is the best battery from this table with 1915 second, 1810 third, and 1727 in last place. The damaged 2600 battery managed to deliver more energy than the regular 2600 battery.

Table 4.11: 2 Ω analysis results from derivative data set 3.

Battery	mAh	mAh computed from Wh	mWh
1611	318.5	338.6	406.3
1727	313.6	328.3	394.0
1810	316.5	334.3	401.1
1915	318.3	338.2	405.8
2600 Damaged	322.9	348.1	417.7
2600	319.9	341.7	410.0

Results calculated from the 10 Ω 30-minute

Table 4.12 shows the result from calculated derivatives and from looking at the different values the 1915 battery is better than the 1611 and the 2600.

Table 4.12: 10 Ω analysis results from derivative data set 1.

Battery	$\frac{\Delta Volts}{\Delta time}$	$\frac{\Delta ScaledVoltage}{\Delta time}$	$\frac{\Delta ScaledVoltage}{\Delta Joule}$
1611	-3.1666×10^{-05}	-3.0331×10^{-05}	-1.5984×10^{-04}
1915	-2.9978×10^{-05}	-2.8502×10^{-05}	-1.4752×10^{-04}
2600	-3.1087×10^{-05}	-2.9646×10^{-05}	-1.5438×10^{-04}

Table 4.13 shows the speed at which the batteries changed in volts and ohms per joule respectively as well as the speed at which the power changes per second. Here it's clear again that the 1915 battery is better off than the 1611.

Table 4.13: 10 Ω analysis results from derivative data set 2.

Battery	$\frac{\Delta Volts}{\Delta Joule}$	$\frac{\Delta Ohms}{\Delta time}$	$\frac{\Delta Watt}{\Delta time}$
1611	-1.6688×10^{-04}	2.3536×10^{-04}	-8.7556×10^{-06}
1915	-1.5516×10^{-04}	2.1901×10^{-04}	-8.3600×10^{-06}
2600	-1.6188×10^{-04}	2.2883×10^{-04}	-8.6371×10^{-06}

Table 4.14 shows the total amount of energy extracted expressed in ampere hours and watt hours where the 1915 battery managed to deliver the most amount of energy in the same amount of time as the others with the 1611 being last and the 2600 coming second.

Table 4.14: 10 Ω analysis results from derivative data set 3.

Battery	mAh	mAh computed from Wh	mWh
1611	65.046	74.672	89.607
1915	65.673	76.073	91.288
2600	65.512	75.658	90.790

5 Discussion

In this chapter, the method and results of the project will be discussed and analysed and after that, it will be discussed on what can be improved upon.

5.1 Results

Capacity Testing

This test unfortunately didn't show any meaningful results for what their capacity might be. The calculated capacity of the batteries using numerical integration were too similar in value and too close to the rated battery capacity of 2300 mAh. This when considering that they are all aged batteries and have been tested by the previous owner to have lower capacity than what the test showed means that the method of testing said capacity is flawed. The first thing that comes to mind is that during these tests the discharge rate wasn't constant which is because the load was just a simple power resistor. In Energizer's datasheet[2] it is said that when measuring capacity the battery is put under a constant current discharge, this means that no matter the voltage across the terminals the current drawn will stay the same, which would give different results from what was shown in the results section.

State of Health Testing

30-minute tests

Looking through the results shows that with the higher current draw, the differences between the batteries become more obvious, for example, the battery labeled 1810 is shown to be in clear poor health which is also backed up by the internal resistance measuring that was done before the tests. But the battery still has a relatively high capacity and the internal resistance plays a lesser role when drawing less current.

The 1Ω tests were the best at showing the differences between the state of health of the batteries, as well as requiring the shortest amount of time with only fifteen minutes needed to perform the test.

Analysis and Data Extraction

Looking at the energy drawn from the batteries under a certain amount of time is a good indication of health since a healthy battery will deliver more energy than a less healthy one, although it's important to consider the current draw as a factor to how much the internal resistance has to play compared to rated capacity. Unfortunately, the newer batteries with a rated capacity of 2600 mAh seem to have slightly different behaviors. For example, the batteries drop their voltage faster than some of the older aged batteries despite being pretty new with the highest capacity and lowest internal resistance of all the batteries. For this reason, when comparing the differences between batteries they are not taken into much consideration. Looking at the differences between the old batteries shows much more promise in being able to single out a bad battery. Another complicating factor is that the aged batteries' capacity isn't really known, what is known about their capacities is that they were measured around three to four years ago, and since the capacity tests didn't really work out it was decided to assume that the batteries were close to their previously measured capacities or lower and that they all aged in a way that leaves the capacity in a similar order of 1915 having the highest and 1611 the lowest.

Looking at the voltage per second derivative results in Section3.3 in **1 Ohms test number 2** both the scaled and normal one, it becomes apparent that the two worst batteries are the battery labeled **1611** and **1810**. The 1810 battery loses voltage faster because of its high internal resistance of 54.6 mΩ compared to the 1611 battery's internal resistance of 30 mΩ. The reason why 1611 loses voltage faster than the other batteries seems to have to do more with the fact that it has the lowest capacity of the old batteries. Looking at the voltage over joule derivative shows that the batteries 1727 and 1915 once again have better health since they lose voltage slower from the amount of energy extracted compared to 1611 and 1810 which drop in voltage faster. Looking at the difference in watt over time it would seem that it has the closest connection to the capacity part of the battery's state of health, 1611 has the fastest drop in power with 1727 coming after followed by 1810 with 1915 being close to 1727 which might be because it got discharged to around 0.2 V for an extended period of time which most likely damaged it in some way.

5.2 Method

Design of experimental setup

When the test setup was completed a few tests were run on some of the newer AA batteries with a rated capacity of 2600 mAh to verify that logging the voltage over time works using the script. Then, in order to help visualize the change over time, the voltage and internal resistance were plotted using **Octave**.

Later on, the need to be able to do a full discharge became apparent in order to try and calculate the capacity of the aged AA batteries, and it needs to be done without accidentally killing the batteries, which happens if they go too far below 1V. In order to solve this, a small and simple circuit, see Figure 5.1 was put together in LTSpice to verify if it would work as intended to stop discharging the battery once it reached 1V in theory.

Once the schematic, in Figure 5.1 was finished it was time to start simulating to see if the circuit would work as intended. In the simulation, the voltage source VBat represents the battery and pulses between 1V and 1.3V in order to simulate the battery discharging. Putting voltage probes across the resistance R_Load and ground as well as putting an ampere probe on the resistance will show how the circuit behaves under different battery voltages.

Looking at the transient simulation in Figure 5.2 it is possible to see that the current going through R_Load which is the current extracted from the battery and is drawn as the red line

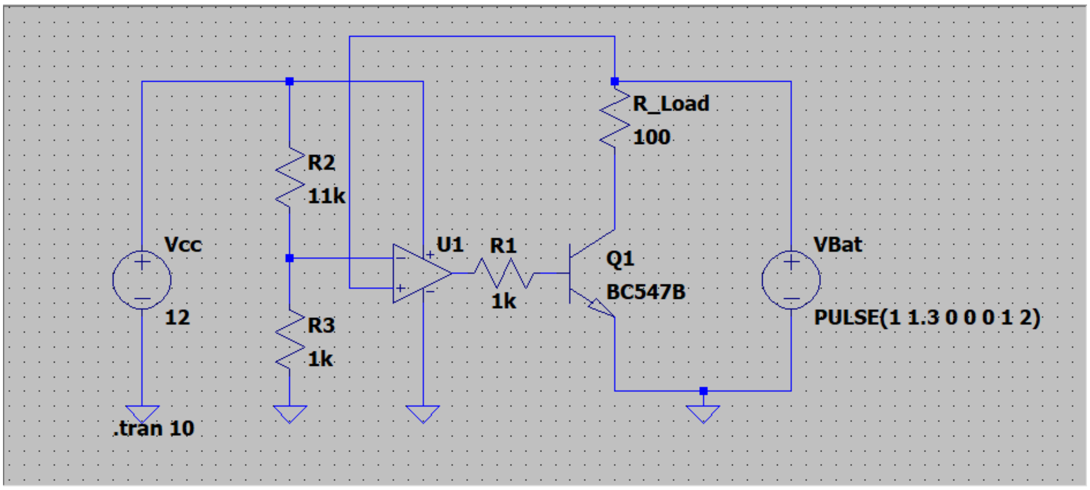

Figure 5.1: Discharge battery protector circuit V1.

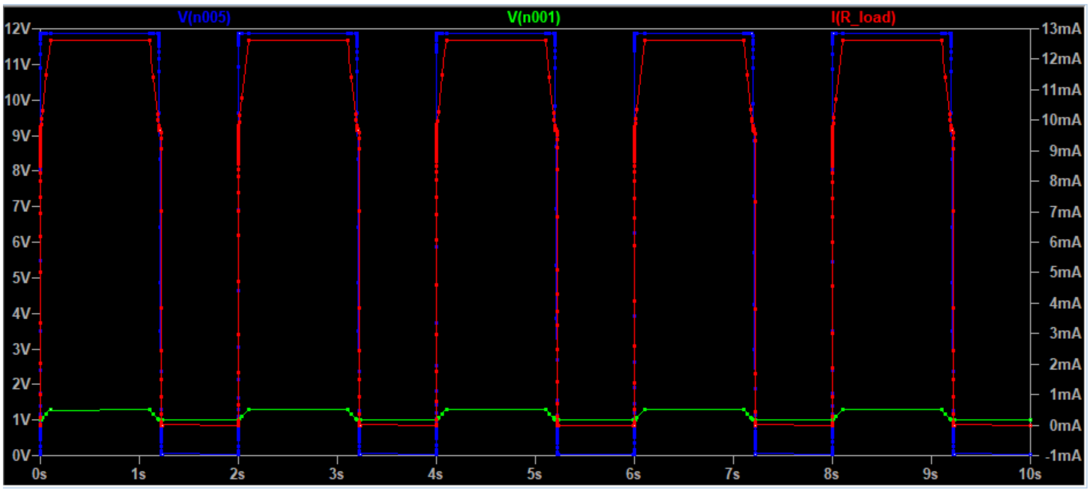

Figure 5.2: Transient simulation of the discharge voltage protector circuit V1.

in the graph. By looking at the graph it shows that the current drops close to zero when the voltage from the output of the OP-Amp which is drawn as a blue line goes down close to 0 V. This is because the output of the OP-Amp acts like a switch and when the voltage gets below 0.7 V the NPN transistor turns off.

During the first capacity test that was done on a new battery, it was observed that the under-voltage protector did not work. With some probing of the circuit board with it connected to batteries with voltages over and under 1 V. When probing the transistor with a multimeter and reading the voltage, it showed that the problem was that the transistor did not turn off when it should. When the voltage across the battery went below 1 Volt, the transistor was supposed to turn off, but it did not. After looking through the datasheet for the transistor once again, it would seem to be that the NPN transistor **BC547B** is rated for 100 mA normally and with a peak of 200 mA for shorter times. Since the battery was being drained around 120 mA on average for 22 hours, this could have broken the transistor, causing it to leak current and no longer turn off. It was noticed that the OP-Amp itself did not lower its voltage on the output pin, but it was believed the transistor could be a cause of that.

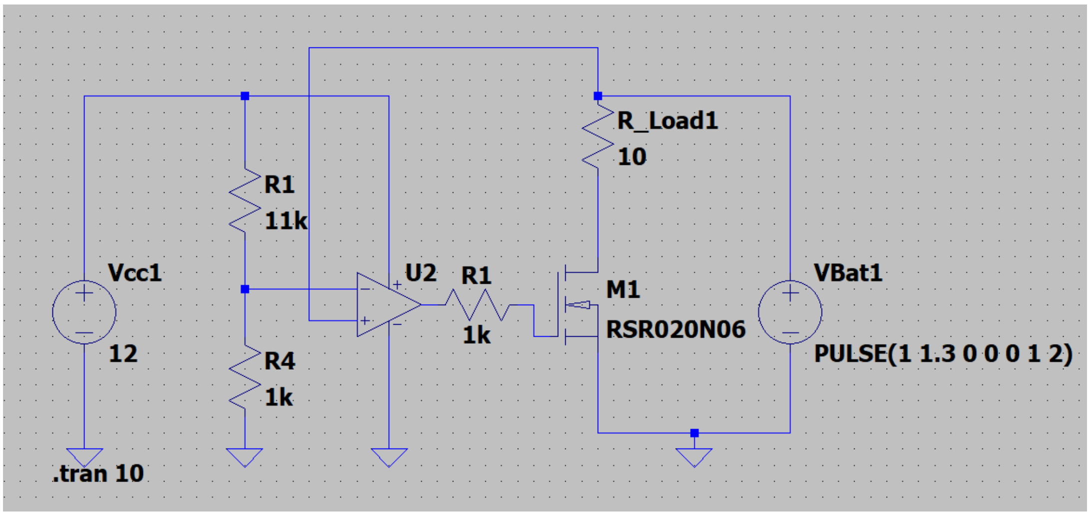

Figure 5.3: Discharge battery protector circuit V2.

Since the problem with the circuit was thought to be identified, what was left to do was simply switch out the transistor with a MOSFET able to handle the amount of current being drawn. The MOSFET that ended up being used was an old **MTD3055VL** that could handle up to 12 A DC and handle a continuous gate-source voltage of ±15 V DC and with an ON resistance of 120 mΩ, the voltage drop over the MOSFET is small. Now ideally, a MOSFET with lower resistance would be better, but this was not available. The modified circuit is shown in Figure 5.3.

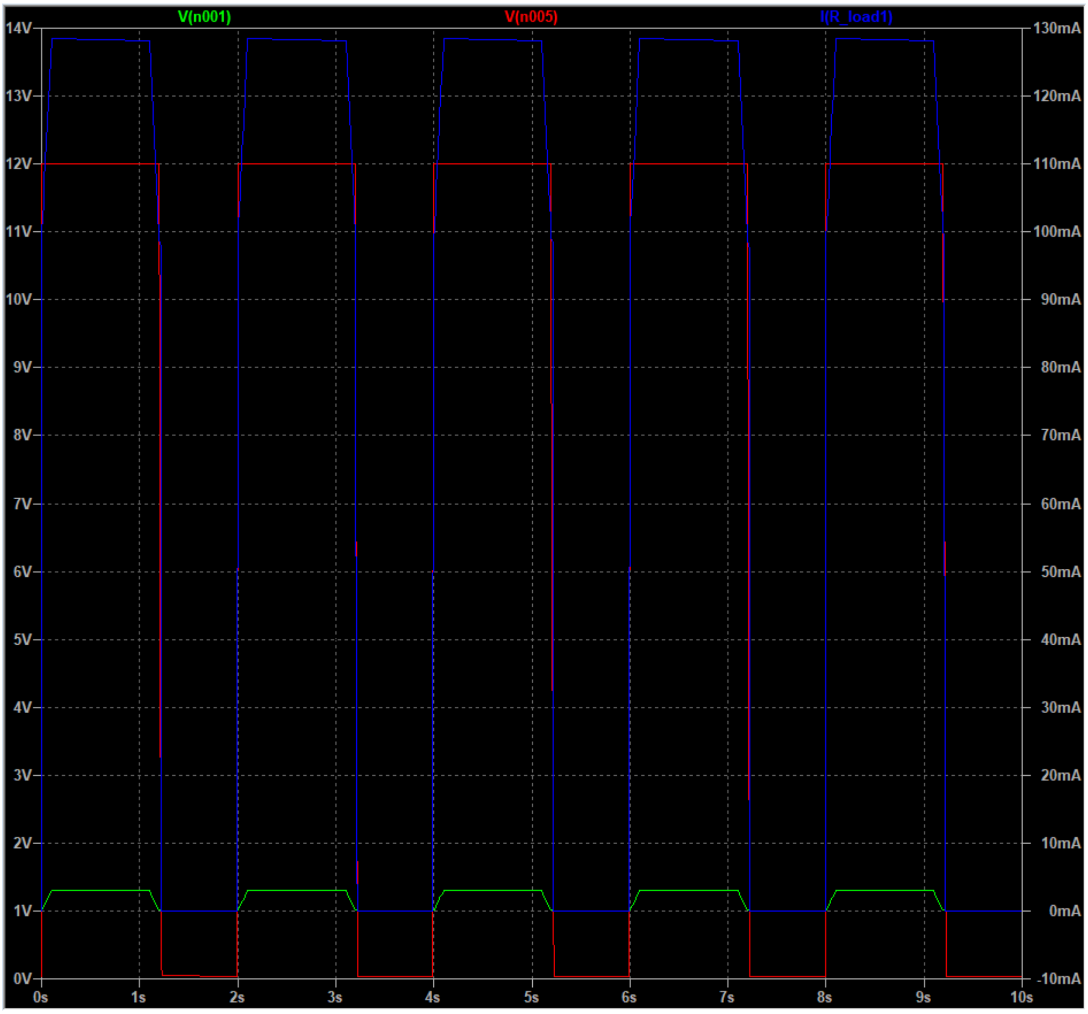

Figure 5.4: Transient simulation of the discharge battery protector V2.

Simulations were also done to ensure that switching out the transistor for a MOSFET wouldn't change anything, and is shown in Figure 5.4 and show similar results in behaviour compared to Figure 5.2 which indicates that the circuit's function is working.

After switching the transistor out for a MOSFET transistor, the circuit still did not appear to work after another discharge test. After some investigating and measuring voltages it would seem that the OP-Amp might have been damaged, possibly from the NPN transistor if it started leaking from drawing too much current through it. To test this, a second variable power supply was connected to the **in+** pin with the power supply set to 1 V and below to see if the output would go close to 0 V or not. It did not go down but stayed at 11.38 V and no matter whether the input voltage went up or down, the output voltage stayed the same. Believing the OP-Amp was broken it got switched out for a new one, this after testing did not fix the circuit. This was confusing since all the simulations showed no such problems.

After further investigation, it would appear that the problem was that the reference voltage on pin **in-**. The reference voltage which is set to 1 V was outside the common mode input voltage range of the OP-Amp. This voltage range is usually 2 to 3 V inside the **Vcc-** and **Vcc+** voltage range. The problem was that since **Vcc-** was set to ground/0 V the reference voltage on **in-** was too close to the supply voltage and therefore the OP-Amp could not switch when the **in+** got down to reference voltage levels. To fix this issue, the circuit was modified to

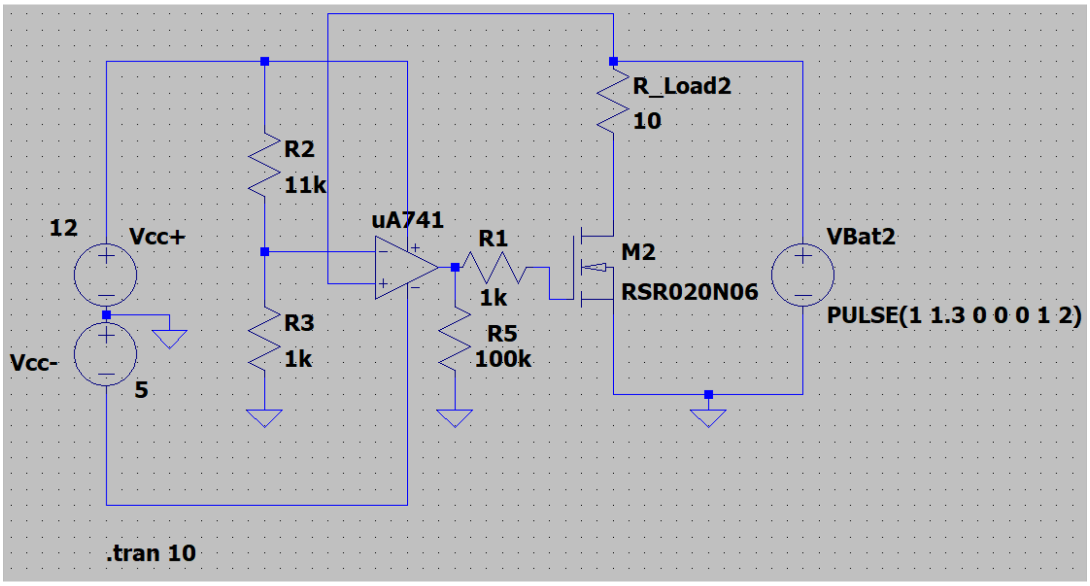

Figure 5.5: Discharge battery protector circuit V3.

take a negative and positive voltage supply that then connects to the OP-Amp. After this modification, the circuit is complete and working after some testing with different input voltages.

A simulation was also done on LTSpice with the modified circuit shown in Figure 5.5, the transient simulation on this circuit gave similar results to earlier versions of the circuit and can be seen in Figure 5.6.

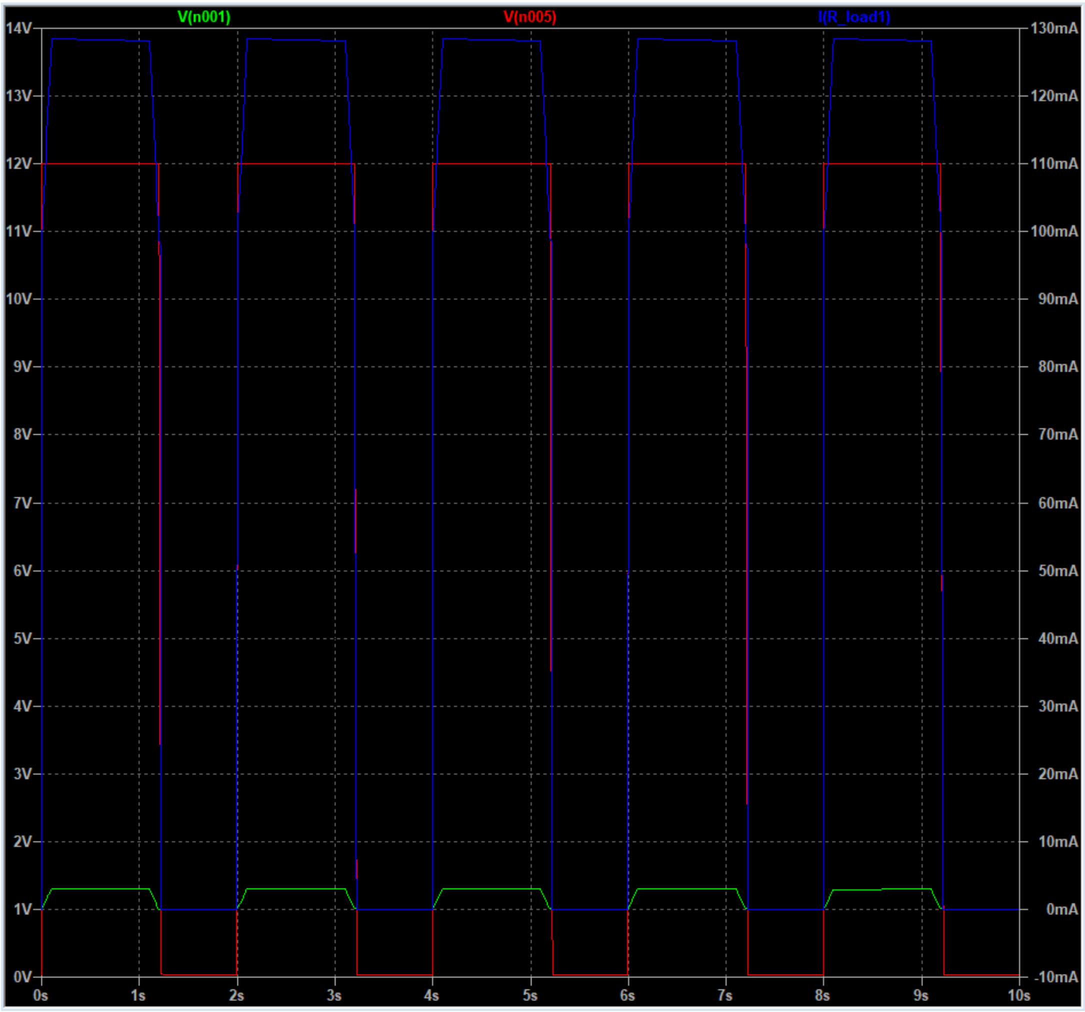

Figure 5.6: Transient simulation of the discharge battery protector V3.

So to summarise the tests:

- The purpose of the first test was to check how well a prolonged discharge test would go on a battery, with consideration for the voltage logging software and the voltage level of the battery. From this test, it became apparent that doing prolonged discharge tests at higher currents would not be doable without some form of a protection circuit.

- The second test's purpose was to test out the newly built circuit to verify if it worked in reality and not only in the LTSpice simulator, and here multiple problems arose, the circuit did not stop the discharge of the battery when it reached below 1 V. The first believed source of the problem was that the transistor acting like a switch had broken from drawing more current than it could handle and therefore started leaking current. But after switching the NPN transistor to a MOSFET, nothing seemed to have changed. To make sure that the OP-Amp did not somehow get damaged from any leaked current that could have come from the previous transistor, it got replaced. Unfortunately, that still did not change the situation, the OP-Amp still did not change its output voltage no matter the input voltage. The problem in the end was that the reference voltage was too close to the negative and positive supply voltage. This was solved by modifying the circuit to also take in a negative voltage supply, and then testing the response of the OP-Amp when it got above and below 1 Voltage input.

- The third and final test's purpose was to do a final check that all the equipment worked as intended, including the undervoltage protection circuit. The circuit after a long discharge test ended up working as intended and with that verified a second time it was time to move on.

Capacity Testing

The capacity tests obvious flaw is that the load wasn't drawing a constant current which would have given a different result since it would draw the same current no matter the voltage across the battery, on the tests described in the method section the current discharging the battery was in relation to the voltage, when the voltage dropped the current drawn would drop too.

State of Health Testing

The tests performed under this section could have been better, what would be ideal would be to have an automatic setup where the open circuit voltage is measured automatically and then the battery gets connected to the load like how it was in the original test. By doing it automatically it eliminates any human error that might have been introduced in the original tests since the battery had to get connected manually, the open circuit voltage was measured manually and the logging had to be started manually. All of which cost time and missed samples. An effort to rectify this was made in the second 30-minute test by starting the voltage sampling before connecting the battery and then manipulating the time data a bit in Octave. Another point of improvement would be to make sure the batteries after they've been fully charged wait a few minutes before any test is run on them to equalize the starting point for the batteries as much as possible.

30-minute tests

These tests were the ones that were done the most mostly because of the limited amount of time of this project but also because of the goal of having this technique workable for ACTIA's product. In their product, a single test can't take hours to complete and has to be able to be done as fast as possible. When under a one ohm load the test time was reduced to fifteen minutes which is a very good time. But something that would be interesting would be to try these tests using constant current draw loads. Doing that might show the differences even more and even if not it would be possible to draw even more current as well as following the C standard of discharge rate.

The 10 Ω test is unfortunately a very early test and wasn't completely finished but it does have some interesting data nonetheless. It's possible to see the differences between the 1915 battery and the 1611 battery from roughly 15 to 20 minutes of discharging. The time samples for those tests were unfortunately done with the old logging software that had a bit of time drifting. The good thing about this test though is that it seems that it's possible to see the difference in capacity since the current is so low compared to the 1 Ω tests the capacity will play a much bigger part when it comes to the voltage drop. It was an oversight to not try and do shorter tests on 10 Ω for sure since it seems to have given some results after all. The reason for not doing that was that since it was drawing such little current the curve wouldn't reach the part where voltage is close to flat-lining which is where the test was supposed to end. This test shows that sampling the entire curve before it reaches the close-to-flat parts might not be necessary. More tests on this would be needed to verify this though.

60-minute tests

This type of test wasn't done much and that was because it was a test made on the way of deciding to go down to thirty-minute tests. Maybe doing sixty-minute tests could give some more information simply by drawing currents for a longer time but unlikely since from looking at the results the higher the discharge current the more the differences in health become apparent.

Analysis and Data Extraction

The analysis and data extraction techniques under this section are pretty simple in nature and while they seem to work to show the differences between the batteries their strong weakness is that it's difficult to know what part of the the state of health of the batteries weigh in the most. Then again capacity and internal resistance of a battery are linked in the way that the internal resistance limits the capacity depending on the intended discharge rate of an application. Two batteries with the same energy capacity but with different internal resistances will have different real capacities for the same discharge rate.

Scaling the voltage to make it seem like all the batteries started at the same starting point is a very useful tool since it helps both visually and mathematically to discern the differences between the batteries. Unfortunately by doing this the curves get either amplified or dampened and if the batteries are too far apart in relation to where the starting voltage is placed then some curves risk getting amplified more than is reasonable like more than five percent which is already pushing it. Ideally, the scaling factor should be around two percent maximum.

By looking at all the calculated parameters from the 1 Ohm 30-minute test number 2 and if they were to be ranked by their State of Health without taking the 2600 batteries into consideration then they'd be ranked like this:

1. The 1727 battery has the best State of Health overall, the only obvious flaw compared to 1915 which is the second best is that it has lower capacity otherwise they are similar in most cases. It's the best on both the voltage and scaled voltage derivative parameters, it has the lowest internal resistance growth and the lowest voltage drop per joule. Where it isn't the best is on the power drop over time but that's most likely to do with how much capacity it has. This battery seems to have mostly deteriorated mostly by normal aging and not as much by usage or excessive cycling of the battery and it is in great health except for the lowered capacity.
2. 1915 since it has the best capacity and it loses voltage over time slower than the others except for 1727 and it has close to equal internal resistance with 1727. 1915 also drew the second highest amount of Watt Hours although most of them were pretty close to each other in their values. 1915 also lost the second least voltage per joule extracted.
3. 1611 is in third place but even with the best internal resistance of them all and that's because it has the lowest capacity of them all and that causes it to rank lower. It loses more voltage per joule than the 1810 battery that has the worst internal resistance of them all and that has to do with the capacity difference between the two batteries. It drops voltage per second faster than the 1810 one as well as power per second but it does deliver slightly more energy in the end by looking at the Watt Hours and Ampere Hours. Its internal resistance grows slower per second compared to 1810 in these tests.
4. 1810 is the worst battery not only because of its initially high internal resistance but also because of its higher internal resistance growth per second. It also is the second worst on the voltage drop per joule extracted as well as being the second worst on voltage drop per second. This battery is really not suited for high current loads with its current State of Health because of its high internal resistance.

On the other hand, the results from the 2 Ohms 30-minute test will differ from the previously mentioned test simply because since the current drawn from the batteries is lower, the internal resistance of the batteries will have less impact on the voltage drop and the capacity will affect the voltage drop more. Just by looking at the voltage drop per second will rank the batteries like this:

1. 1915 is first because it drops voltage per second the slowest, in both normal and scaled voltage.
2. 1810 is second because it's second on the above-mentioned things.
3. 1727 is the third in voltage drop per second.
4. 1611 is in last place in voltage drop per second.

This means that the capacity has a bigger effect on the voltage drop the lower the current you draw and this is the reason why a battery with pretty bad internal resistance like 1810 can appear second to best in the State of Health ranking in this test. Even in the other areas calculated the order follows the ranking above where 1915 is the best and 1611 is the worst.

Alternative methods

One way of measuring the State of Health would be to do an Electrochemical Impedance Spectroscopy as described in **"Diagnostic methods for the evaluation of the state of health (SOH) of NiMH batteries through electrochemical impedance spectroscopy"**[3]. This technique has the benefits of being usable in the fields and while the battery is being used actively by measuring the impedance of a battery and comparing it to a new battery. This is great for applications like for example Electric Vehicles at the cost of extra equipment and sensors to implement the Spectroscopy.

Another way to do it is also the classic way of simply performing a normal capacity test on a battery and using that as a way to measure health, together with measuring the internal resistance of a battery. This however requires the battery to be cycled in order to do a full discharge and then charge since leaving the battery nearly fully depleted will harm the battery. This means that it's not very useful in the field or while actively using the battery.

It's also possible to estimate the State of Health of a battery by integrating the battery voltage during charging as shown in **"An Online State of Health Estimation Method for Lithium-ion Batteries Based on Integrated Voltage"** [8]. The study shows that the charging voltage curve changes with the State of Health of a lithium-ion battery and by integrating the voltage over time the differences can be mathematically computed. The benefit of using this technique is that it is possible to estimate the State of Health of a battery every time it charges. The technique mentioned in this study could be used on other battery types, for example, Nickel-metal Hydride batteries, especially since they have similar discharge voltage curves.

Another way to estimate the State of Health of batteries is to measure the voltage variation during the rest period after discharge of a battery. The study **"Novel state-of-health prediction method for lithium-ion batteries in battery storage system by using voltage variation at rest period after discharge"**[4] shows how the method was developed for lithium-ion batteries in storage systems. In the study, tests were done on the batteries where they got cycled with varying C-rates and ambient temperatures. From the results of the study, it was concluded that the voltage variation had a strong correlation with the State of Health of the batteries during the rest period after a discharge. The State of Health could be estimated and predicted using the slope $\frac{\Delta V_t}{\Delta t}$ at the rest period after a discharge as long as the ambient temperature and the discharge rate could be controlled.

Using a Thevenin battery model the study **"State of Charge (SOC) and State of Health (SOH) estimation on lithium polymer battery via Kalman filter"**[6] developed a way to estimate the State of Health of the battery by focusing on the internal resistance part of a battery. The study sets up the equations necessary to compute the internal resistance using the Thevenin battery model for its accuracy and complexity. With the equations, they then get transformed using a bilinear transformation method which then gets used in a Kalman filter. The results show that the State of Health can be estimated using this filter with a mean relative error of 5.26%. This technique and using the Thevenin battery model is interesting since it would seem that it gives more detailed and accurate internal resistance results which in return will make the State of Health estimation more accurate.

Another novel way of estimating the State of Health of a battery was shown in the study **"Gaussian Process Regression based State of Health Estimation of Lithium-Ion Batteries using Indirect Battery Health Indicators"**[5] where using a list of indirect health indicators from both discharging and charging was used in conjunction with Gaussian process regression is used to estimate the State of Health. The technique used in reading the health indicators is something that can be applied to online applications where the battery is always online. In the study, the indirect health indicators aren't limited to just the change in voltage or current, but they also include the temperature of the battery and the time needed to charge the battery. Like for example the indicator where the time taken to charge a battery from 3.8 V to 4.1 V.

Finally, there is also a way to get an indication of the State of Health of a battery by looking at the frequencies where the complex impedance of a battery's phase is zero and is explored in the study **"State-of-health indication method for Li-Ion batteries"**[7]. In the study, it is shown that the frequencies where the phase of the complex impedance of the battery is zero change with the age of the battery. The State of Health indicator computed using this method is useful to adjust the estimated capacity of a battery as well as correcting the State of Charge estimation which is shown in the study where the voltage reached 3.8 V faster than the State of Charge would indicate when not correcting the State of Charge with this technique. As the study mentions this technique together with online impedance measuring techniques can make it possible to do online State of Health estimations which are both fast and real-time which is useful in many of today's applications like electric vehicles or cellphones.

5.3 The work in a wider context

The technique discussed and shown in this project has been focused on looking for differences in State of Health between different aged batteries and with in mind that the battery type itself is used as a backup battery in Actia's ACU6 unit. This means that the battery can be ensured to be fully charged which is necessary to do the short tests in Section 3.3. This also means that it's fully available when it's not needed to perform this type of test and since it doesn't discharge more than $15 - 20\%$ during the test it can be aborted safely if the backup battery is needed and it'll have plenty of charge left.

As for the technique itself, it would be good to have it more thoroughly validated by aging the Nickel-Metal Hydride batteries in a controlled environment as well as having dedicated equipment that can measure the capacity, internal resistance, and internal impedance to get a more absolute grasp on the different States of Health of the batteries and then perform the tests and compare those results with what is known from the previous tests done by dedicated equipment. Doing that will help verifying the accuracy of the technique.

It might also be possible to do this type of test on an actively used battery it is quite important then to start measuring the voltage when it is fully charged and depending on the current draw it might show enough differences compared to a previously mapped healthy battery. But for measuring health on an actively used battery the **electrochemical impedance spectroscopy**[3] technique mentioned in the theory chapter might be a better alternative at the cost of some more advanced electronic parts that might be needed since it's a more advanced and accurate type of State of Health measurement. Another benefit of this technique is that it was intended for use on for example electric vehicles which means that it can handle high amounts of power drawn.

6 Conclusion

The results show that it is possible to estimate and differentiate between batteries with different States of Health. The technique shows promise in doing fast State of Health tests in the field since it requires only simple electronics. What remains to be done is to verify the technique by doing controlled aging of batteries as mentioned before and doing proper capacity tests with a constant current load and some automated way to measure the open circuit voltage and then automatically start the logging at the same time as the battery gets connected to the circuit.

This technique can have great use, especially in situations where the State of Health of backup batteries needs to be checked occasionally and even possibly on batteries that are used actively as long as the logging starts when the battery is fully charged.

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