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d'Enginyeria Industrial de
Barcelona

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Autor: David Balaguer Escolano

Director: Dr. Iztok Kramberger

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Thermal analysis of a LiFePo4 Battery

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Abstract

The objective of this final thesis project was to study and test a 3,3V LiFePo4 battery in outer space conditions to be able to determine its working range, its limitations and its problems. To do so a measuring set-up to read and estimate the capacity of a battery was built and programmed. Then the $LiFePo_4$ battery was tested at different temperatures between -20°C and 40°C in a vacuum chamber at a pressure under 100 microbars.

The results showed that the battery can still operate properly at temperatures as low as -20°C. However a reduction of the capacity at low temperatures was observed: The battery's capacity at -20°C was 62% lower than the one at 20°C. The battery fully recovered its capacity after returning back to the nominal working range (20°C), and its performance barely changed thorough the whole range of temperatures studied.

1. Summary

1.1. Introduction

The Department of electronics of the University of Maribor, is currently working on the Tristat Project [1]. The main goal of this project is to launch a very small satellite (5Kg) and put it into orbit. This is a multidisciplinary project, which involves electronic, optic, mechanical, thermal and energetic analysis. Therefore, for the project to be successful, it is necessary to study, design and test every part of it.

The satellite that is being designed will need to get energy from the sun. To do so it will use solar panels. Unfortunately the satellite will not be getting energy all the time because during its orbit (sun-synchronous orbit), the satellite will be some time in the sun and some in the shade.

This diploma work is concerned with the study of the batteries of this small satellite. We will try to study the charge and discharge cycle of a LiFePo4 battery and see how it performs under different temperatures. The goal of this project is to test the batteries in the conditions at which they will be exposed in outer space and to stablish a nominal working range at which the batteries can operate correctly so that, in case we need it, we can supply heat to the batteries to keep them always inside this range.

1.2. Objectives

- Study the influence of the temperature on the battery's capacity
- Design and construct a measurement set-up to estimate the capacity
- Test the battery's capacity at a constant temperature
- Test the battery's capacity at different temperatures in a vacuum chamber

1.3. Materials and methods

To study the battery's cycle we will design a measurement set-up that will:

- Read and record values for the current and the voltage. These readings will be multiplied later to obtain the capacity.
- Either supply energy to the battery from a power source **RIGOL DP832** (charge), or dissipate it using an **active load** (discharge). We will switch between these two states using a relay.

To do so we will use a computer and write a little program in Python for the **Multifunction DAQ** that will switch the relay and store current and voltage values.

2. Theory

2.1. The satellite's orbit

The satellite will follow a sun-synchronous orbit at an altitude of 700km above sea level. One of the peculiarities of this orbit is that the satellite always passes over the earth at the same local solar time, and therefore the illumination conditions remain the same [2]. That's why the sun rays will reach the solar panels of the satellite at a constant angle during the whole orbit and will therefore be charging the battery with constant power. At its altitude the satellite will have an orbit period of about 1 hour with 40 minutes of sun and 20 minutes of shade.

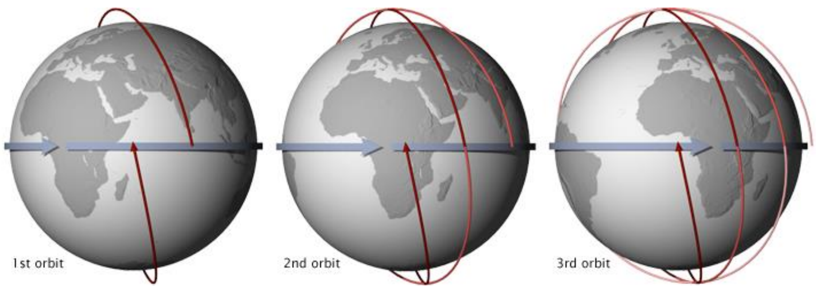


Image 1: Sun-synchronous orbit [3]

2.2. Heat transfer in space

In outer space there is no air, and thus there's no convection. That's why there are only two mechanisms of heat transfer. One of them is radiation (from the sun to the surface of our satellite and from the surface of our satellite to the vacuum); the other is conduction from the surface of the satellite to the surface of the battery and from the inside of the battery to the battery itself.

While our satellite is orbiting the earth we will distinguish two different scenarios:

1) The satellite is on the sunny side of the earth: In this case, we can consider the sun to be the only emitter from which our satellite receives irradiation (G), and the vacuum to be the rest of the space to which the satellite emits radiosity (J). The difference between this two values will be proportional to the heat flow through the battery surface. After some time this heat flow will become equal to the heat losses inside the battery and the temperature will remain constant (stationary state).

2) The satellite is on the shady side of the earth that is the earth is in-between the sun and the satellite and is blocking the sun's radiation from reaching our satellite: In this case the temperature will begin to drop and the battery should reach extremely cold temperatures. To avoid this we will use some energy from the battery to heat itself. This extra heat will prevent the battery to go to unwanted temperatures where the capacity would be to low and the battery would stop working. This would be the worst case scenario because since we are in space if the battery stops working there would be no one to restart it or replace it and the battery would die.

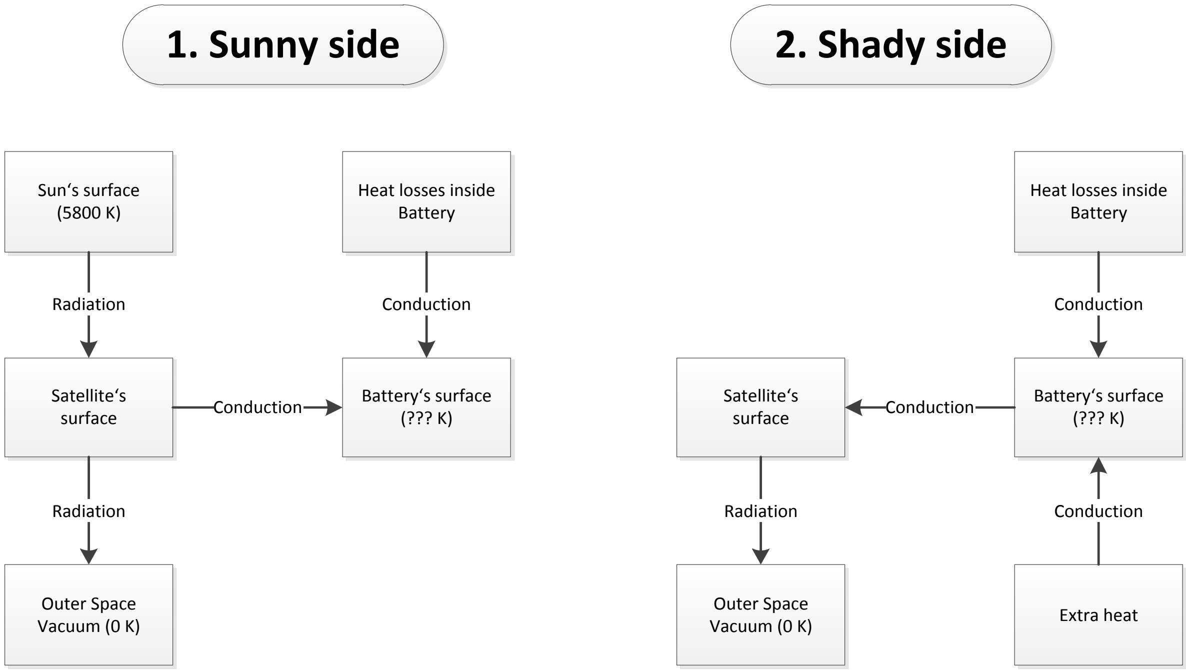


Image 2: Heat transfer diagram

2.3. Choosing the battery

When choosing a battery for a satellite we must take into account a lot of things to make sure that the battery will perform well in the harsh conditions at which it will be exposed during its whole life. For our battery we want good performance without worrying much about ecological reasons or price. Therefore we will look for a battery that offers [4]:

- **Safety**: We will choose a battery with very low risk of overheating, that it doesn't burn or heat much in case of an overcharge.

- **Durability and reliability**: When our battery dies, the satellite is over. That's why we will look for a battery with a long cycle life: that means that can do a lot of charge/discharge cycles (durability) without losing much of its properties (reliability). Also the battery must not require maintenance.
- **Low volume**: For small and medium satellites the launching price of a satellite increases with every extra kilogram of weight. Our satellite however is even smaller and falls into the nano category. That's why it has a fixed cost (independently of its weight), but a limited space. Because of that we will try to choose a battery which gives us the maximum capacity for that space, which means a battery with high energy density (capacity/volume ratio).
- **Broad working temperature range**: We want our battery to be able to perform well at different temperatures. The lower the temperatures it can reach the better, because we will use less energy for heating the battery.
- **Low Charging Time**: when the satellite is in the sunny side of the earth it will use part of the radiation that it receives from the sun for charging the battery.

The battery that matches more our needs is the $LiFePO_4$ battery. This type of battery is very safe, doesn't require maintenance during its whole life, has a very long life cycle (2000+), good temperature working range (-20°C to 70°C), can be charged quite fast and it has a theoretical specific capacity of about 170mAh/g [5]. Its actual capacity however is in reality smaller due to its poor electrical conductivity (10^{-9} S/cm) which causes the battery to have less discharge capacity and a worse performance [6]. However, although it has lower energy density (around 14% less) than other batteries like the $LiCoO_2$ (which means it must be bigger to store the same amount of energy), it has a longer lifetime and it's safer. There are other important advantages of this battery because they are not affected by vibrations that may happen during launching and are thus not fragile.

2.4. The battery $LiFePo_4$

The battery model that we are going to test is a 3,3V 3,3AH 26650 $LiFePo_4$ H2OLe battery. In this battery the cell consist of two electrodes (anode and cathode) with an electrolyte in between. The material in the positive electrolyte is the $LiFePo_4$. The negative electrolyte is made out of porous carbon (graphite).

When the battery charges the lithium ions move from the cathode to anode. During discharge the anode undergoes oxidation (electron loss) and the anode undergoes reduction (electron gain) and the lithium ions go back through the electrolyte to the cathode [7]. The movement of lithium ions generates a flow of electrons in the circuit in the opposite direction (electricity). The chemical reactions inside the battery are the following:

Discharge : $Li_{(1-x)}FePO_4 + xLi + xe \rightarrow LiFePO_4$

Charge : $Li_xC_6 \rightarrow 6C + xLi + xe$

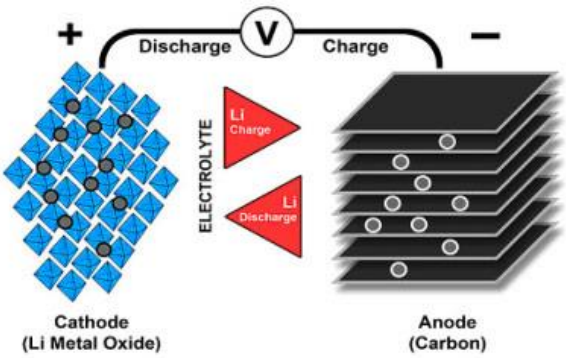


Image 3: Working principle of an ion battery

Image 4: LiFePo$_4$ battery

2.5. The power supply

The electric power used for charging our battery will come from the Rigol DP832 equipment. This equipment allow us as we have explained before to set a maximum current and a voltage. The supplied voltage will always be the one that we set unless the current reaches the value that we have put, in which case the limiting variable will be the current and the voltage will drop to keep the current inside of range.

This way of charging the battery although it sounds complicated, it's mostly a constant voltage (CV) charge, because except from the first couple of minutes the voltage applied will be maximum.

Following the instructions of the manufacturer we will charge this battery with a voltage of 3,65V (although it is possible with this type of batteries to apply an overvoltage), and let the maximum limiting current be 3,2A (the maximum that our equipment allows).

Image 5: Rigol DP832

2.6. The active load

The active load is a current stable non-linear resistor, which means that that it controls the current passing through it to keep it constant all the time no matter what is the voltage.

2.7. The multifunction DAQ

With the computer we can control the multifunction DAQ. We will be able to read or set a voltage between different pins using different functions to communicate with the device. The pins we will be used in the following way:

1) Analog inputs

- Differential voltage between pins 1 and 2 to measure and get the voltage of the battery
- Differential voltage between pins 4 and 5 to measure the voltage between the extremes of a 0,02Ω resistance and get the current.

2) Analog Outputs

- We will set the voltage between pins 15 and 16 to control the relay and switch from charge to discharge cycle.

The DAQ is a device that provide us with accurate small-scale measurements. And it allow us to read the voltage accurately and with precision. It can be programmed and customized in different software languages (in our case Python).

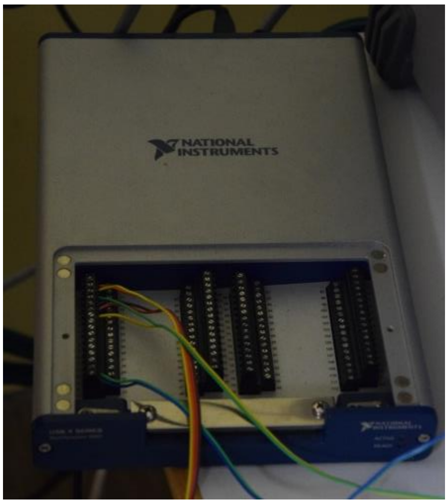


Image 6: Multifunction DAQ

In the NI-DAQmx Library we can find a lot of functions that will help us with this task. Here we present the ones that we have used in this project [8]:

DAQmxStarttask(): puts the task into the running state, which begins measurement or generation.

DAQmxStoptask(): returns the task to the state at which it was before calling DAQmxStarttask().

DAQmxCleartask(): It aborts the task and releases any resources reserved by the task.

DAQmxCreateAIVoltageChan(): It creates a channel to measure voltage and adds this channel to a specified task.

DAQmxCfgSampClkTiming(): It sets the rate of the sample clock and the number of samples to adquire.

DAQmxReadAnalogF64(): It reads samples from a task that has analog input channels.

DAQmxWriteAnalogF64 (): It writes samples to a task that has analog output channels.

3. Set up

3.1. Components connection

Here we can see how the testing equipment is connected. We have:

- The LiFePo4 battery we want to test
- Two resistance of 0.02Ω and 10KΩ respectively
- A two-state relay RT114005
- A NPN BJT transistor C547C
- A diode (to protect the transistor)
- An active load
- A power supply Rigol DP832
- A Multifunction DAQ (to connect with the computer)

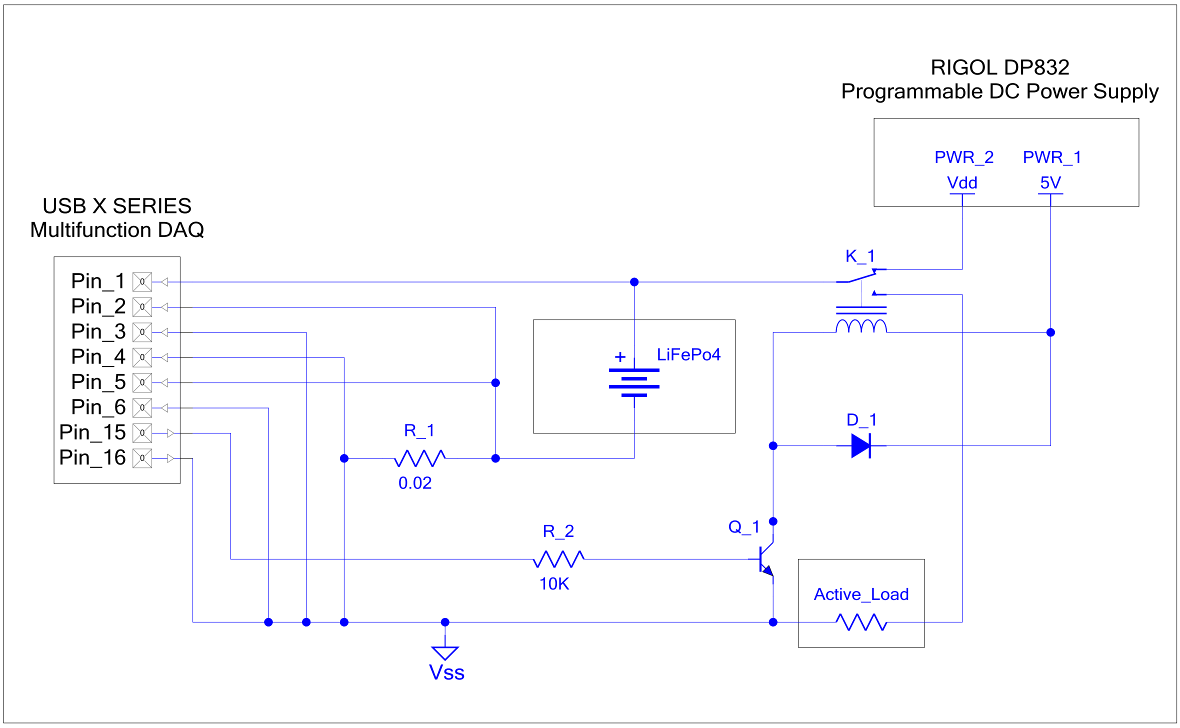


Image 7: Block diagram of the testing equipment

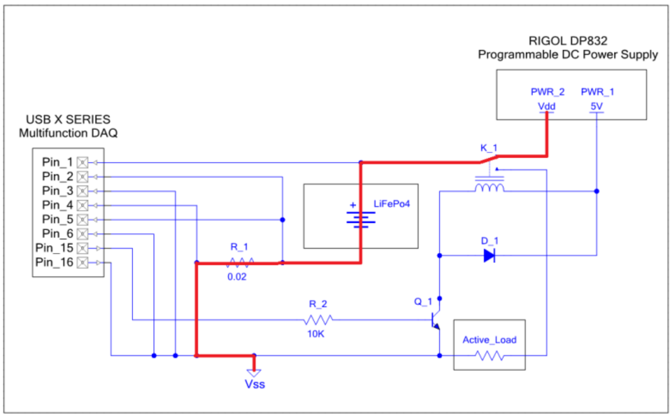


Image 8: electric circuit with the relay opened

When the relay is opened the battery will be connected to the power source and it will charge.

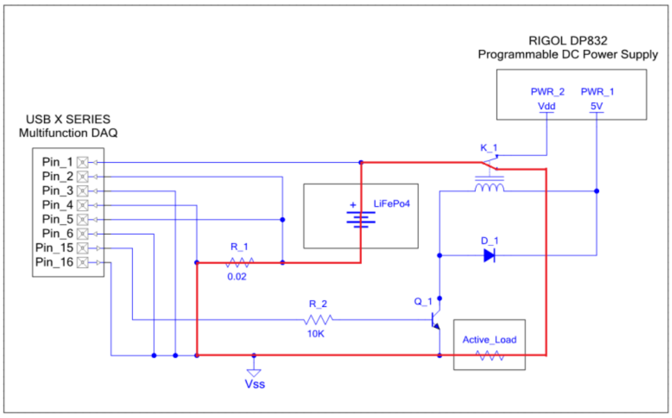


Image 9: electric circuit with the relay closed

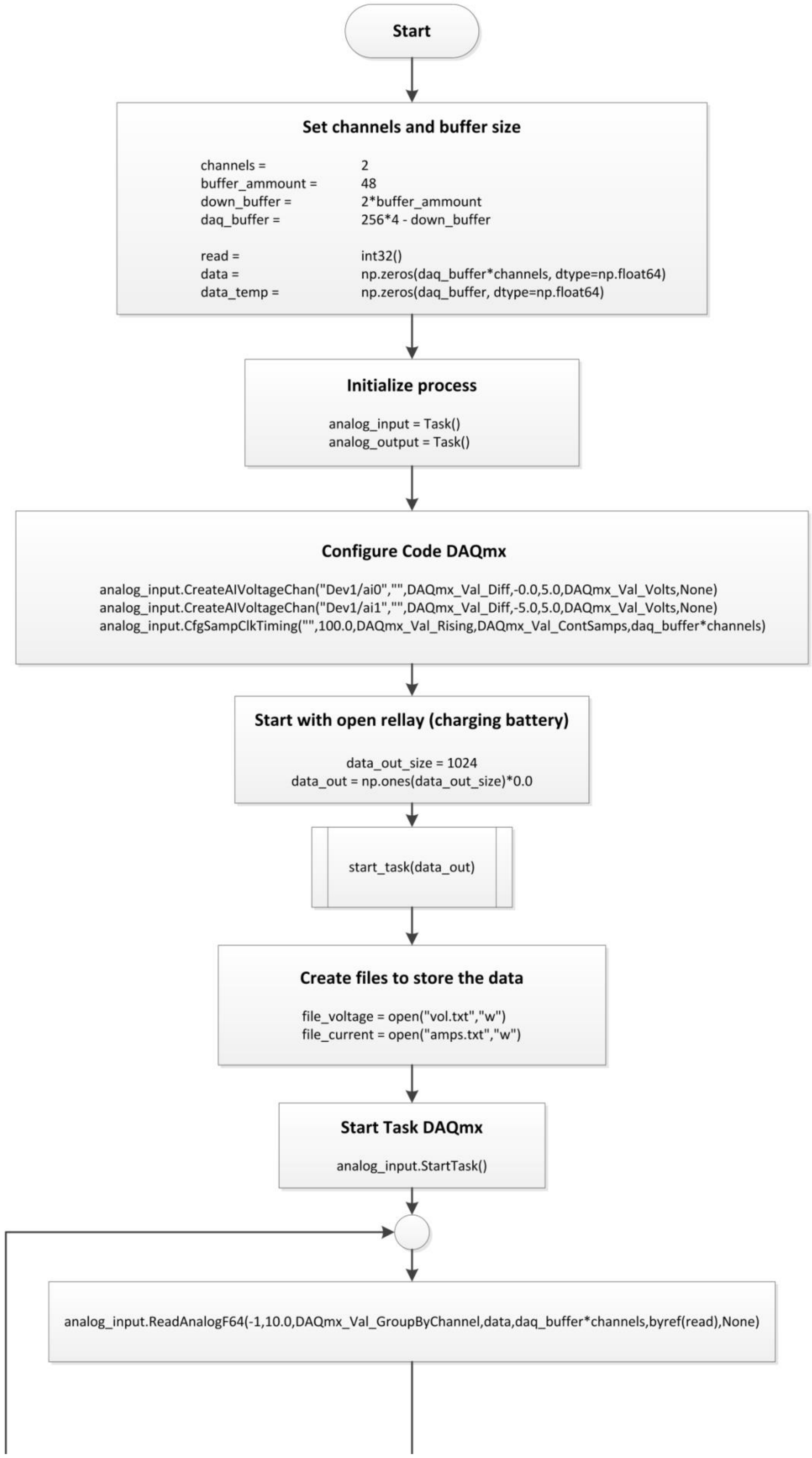
When the relay is closed the battery will be connected to the active load and it will discharge with constant current.

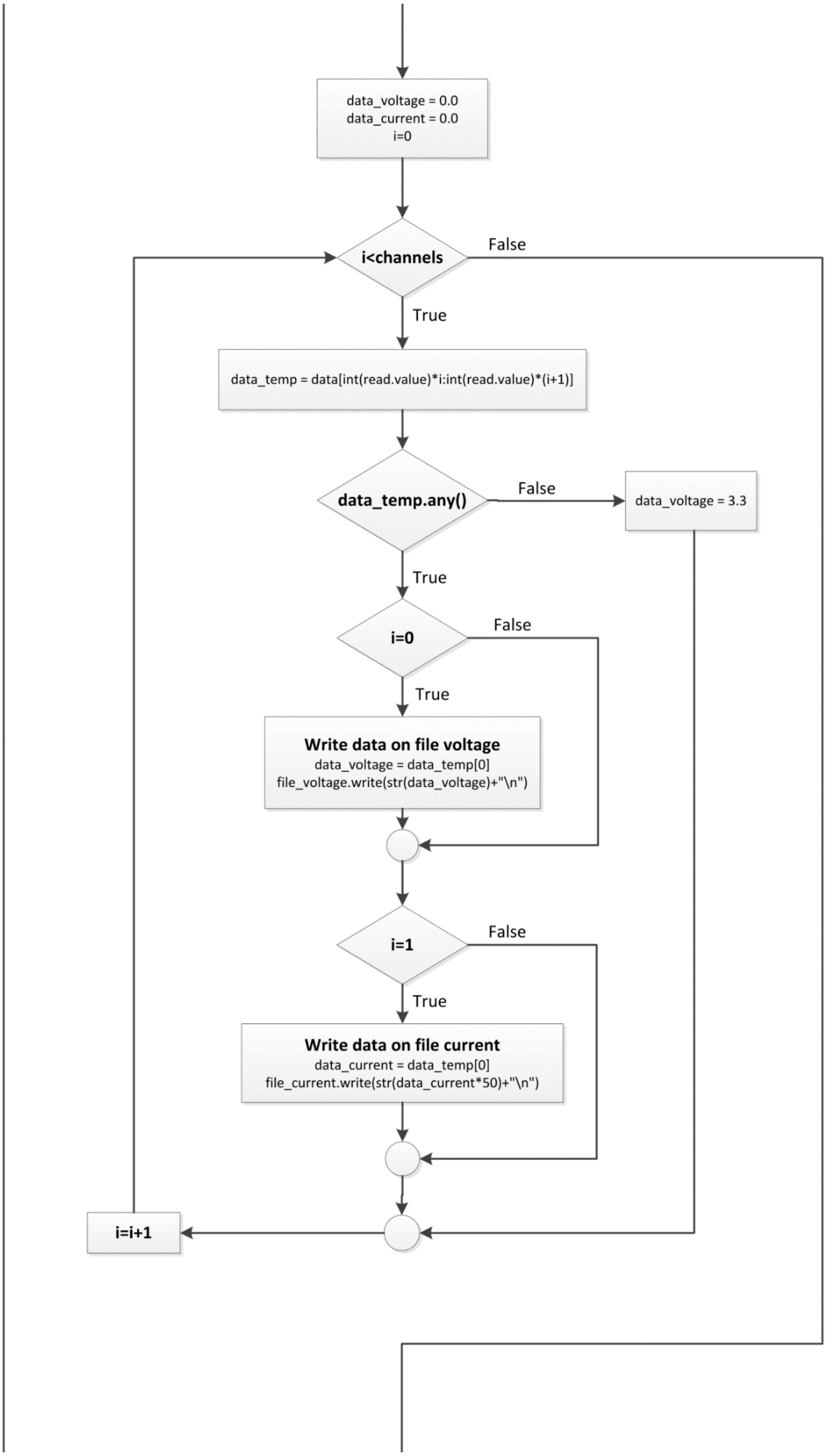
3.2. Program implementation

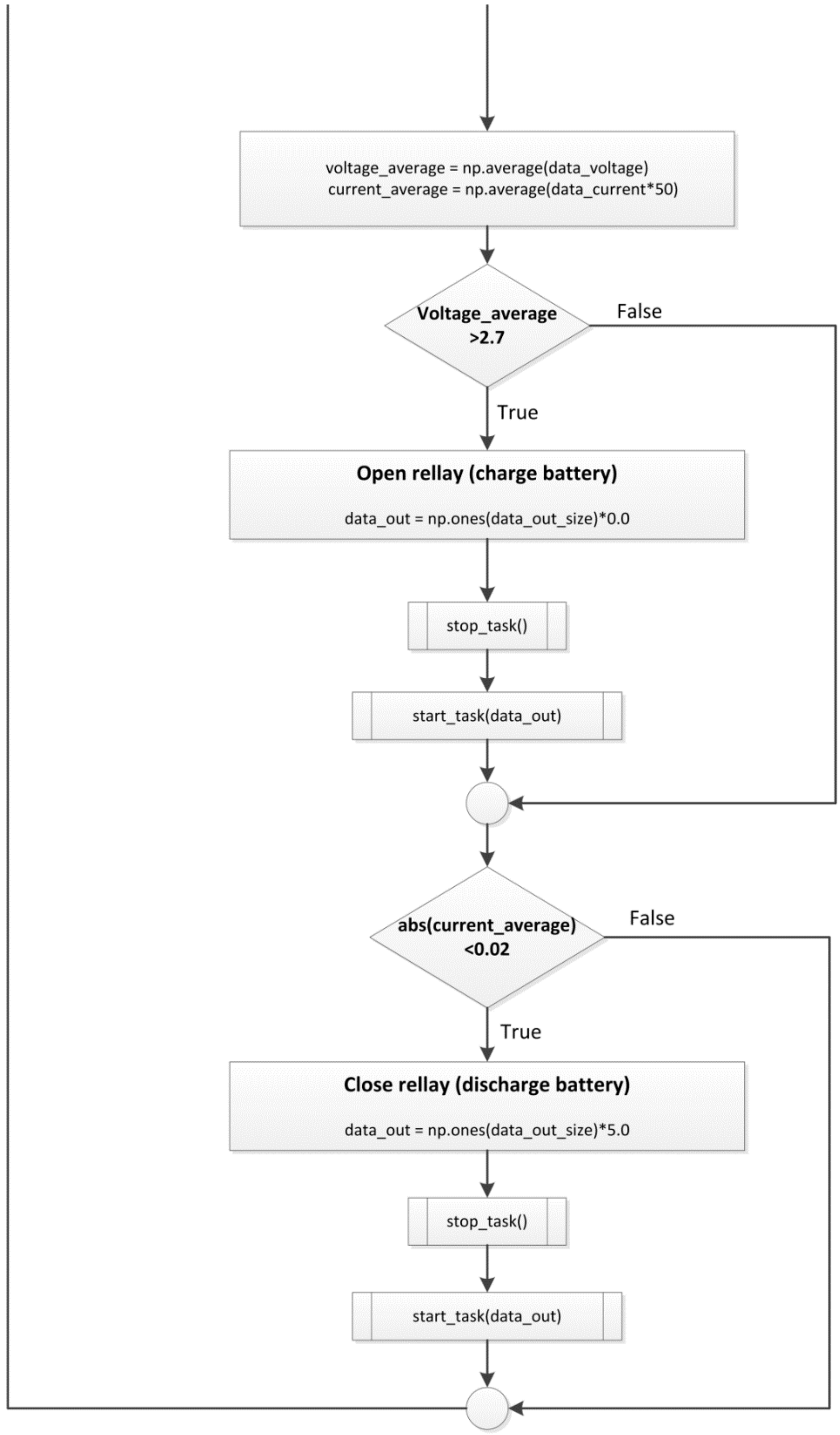
Using the functions previously described, I wrote with python a little program that stores data of the voltage between the battery terminals and of the current going through it. All this data is written in files named vol.txt and amp.txt respectively. Also while the program is storing all this information at the same time is able to do the following:

- Keep the relay opened to charge the battery until the current charging the battery is really low (that is until the battery is fully charged). We will get the information
- Then open the relay to let the battery discharge until the voltage between the battery terminals is lower than 2.7 V.
- After this the program will repeat itself doing charge-discharge cycles indefinitely until the user manually interrupts the program.

In the following three pages there is the flow diagram of the written program:




data_voltage = 0.0
data_current = 0.0
i=0
i<channels
False
True
data_temp = data[int(read.value)*i:int(read.value)*(i+1)]
data_temp.any()
False
data_voltage = 3.3
True
i=0
False
True
Write data on file voltage
data_voltage = data_temp[0]
file_voltage.write(str(data_voltage)+"\n")
i=1
False
True
Write data on file current
data_current = data_temp[0]
file_current.write(str(data_current*50)+"\n")
i=i+1



voltage_average = np.average(data_voltage)
current_average = np.average(data_current*50)
Voltage_average >2.7
False
True
Open rellay (charge battery)
data_out = np.ones(data_out_size)*0.0
stop_task()
start_task(data_out)
abs(current_average) <0.02
False
True
Close rellay (discharge battery)
data_out = np.ones(data_out_size)*5.0
stop_task()
start_task(data_out)

4. Results

4.1 Results testing the battery at room temperature

For the first part of our experiment, to test how everything works and to get some standard values, we will test our battery at room temperature and atmospheric pressure. We will do several cycles that allow us to obtain some basic parameters like the capacity, the performance or the charge and discharge time.

The relay will take care of switching from charge to discharge when the battery is fully charged and vice versa. This way we can automatize the process and let it work alone when testing.

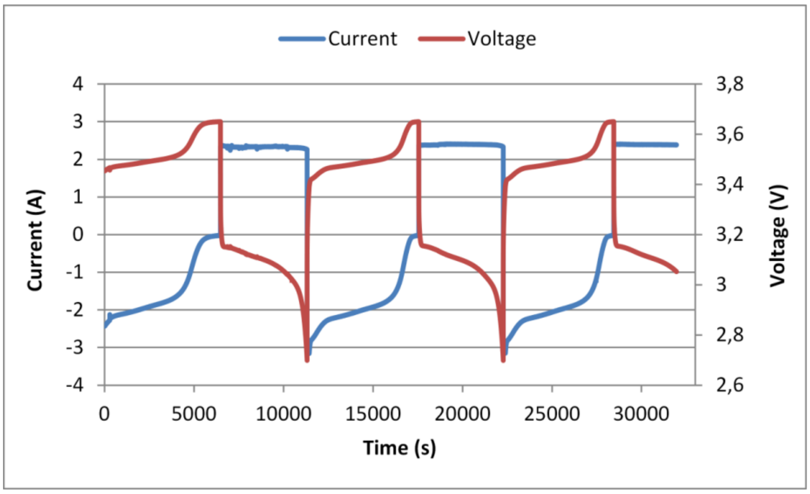


Image 10: charge-discharge cycles at room temperature

After charging the battery we get something like this:

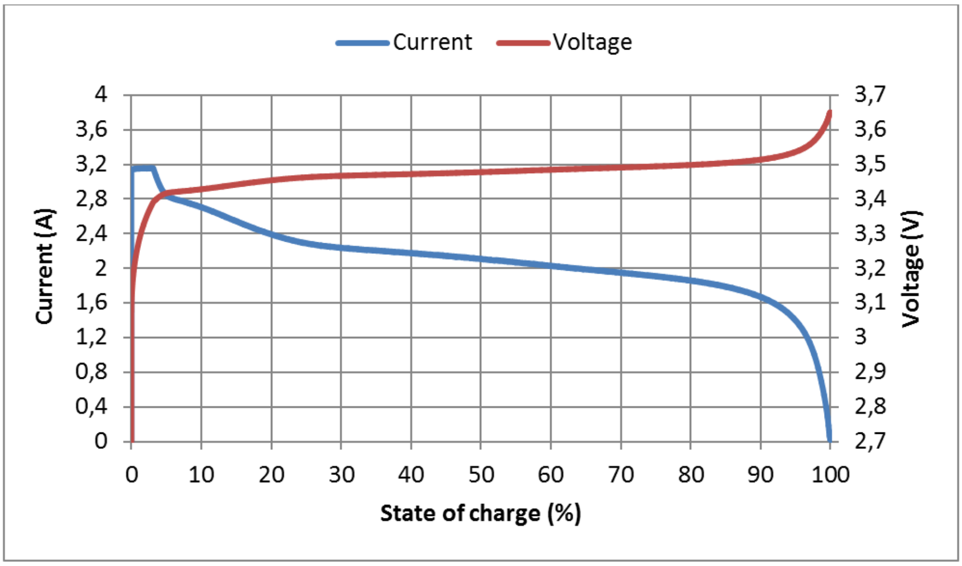


Image 11: charge of the battery at room temperature

The state of charge 100% equals that of the battery having 3,65V and 0% is 2,7V. Discharging the battery to less than 2,7V would be too much depth of discharge for this type of battery and would reduce it's lifespan and capacity greatly.

To discharge the battery we will use an active load that will mantain the current drawn from the battery constant. That's why the discharge will be constant current CC.

After discharging the battery we get something like this:

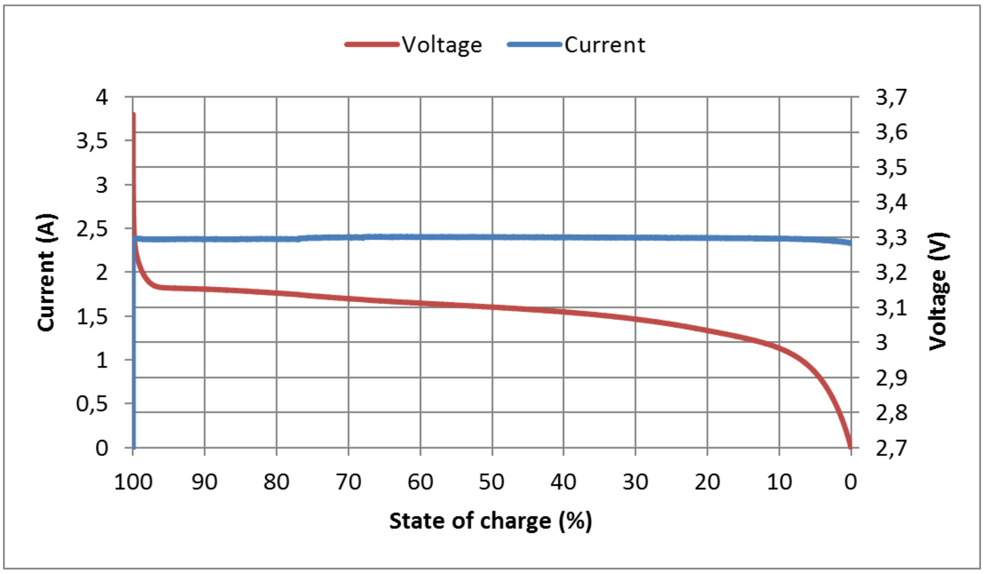


Image 12: discharge of the battery at room temperature

Making the product of the Voltage and the current we can get the electrical power that we are putting or withdrawing from the battery in VA or watts. We can see how $LiFePO_4$ batteries deliver us virtually full power until the battery is discharged (*image 12*). This is very positive because simplifies all the voltage regulation circuitry.

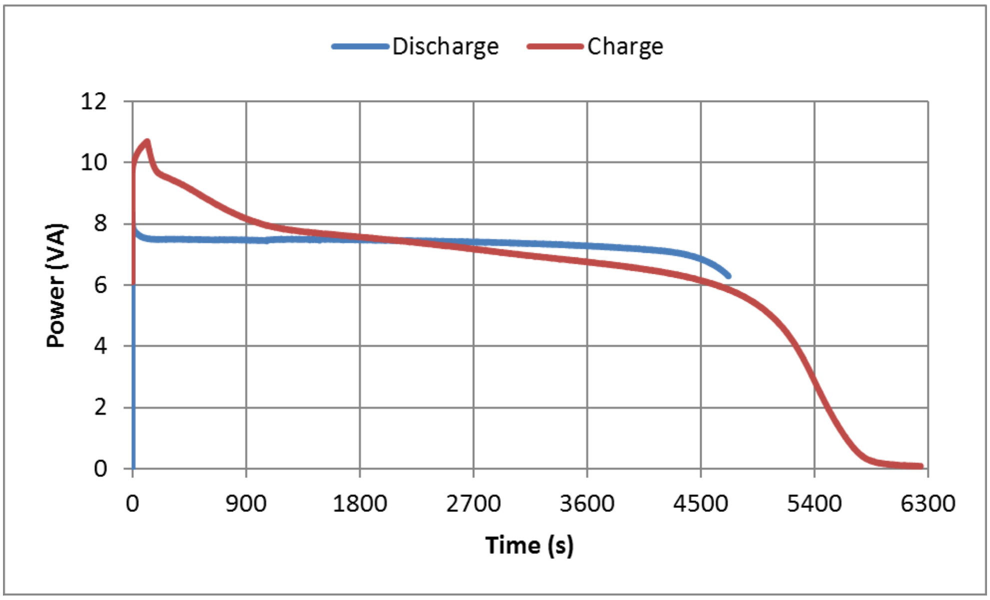


Image 13: power given by the battery during a discharge cycle

By integrating the discharge curve we get the capacity of the battery which is **9,64 VAh.**

We can also get the performance as the ratio between energy that we put and energy that we receive. We get a performance of **88,35%.**

4.2. Results testing the battery in the vacuum chamber

Now that all the equipment has been tested and it works successfully, we will try to repeat the process inside a vacuum chamber (*image 14*). The vacuum chamber basically allows to:

- Set a temperature: To achieve that the vacuum chamber has some heaters and a refrigeration cycle that allow to give or take heat from inside. It has four temperature sensors that make sure that the temperature in the center is the same as the selected one.
- Set a pressure: The vacuum chamber is sealed and it has a pump to take out the air. We can select pressures of the order of a few microbars.

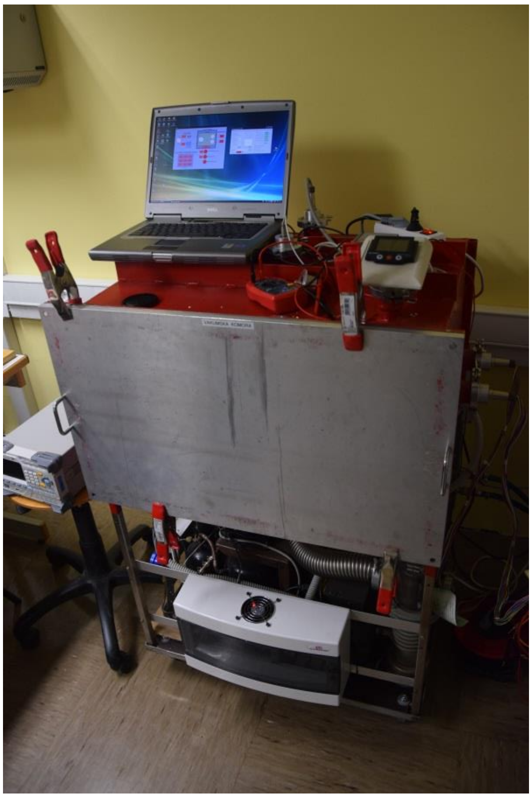


Image 14: vacuum chamber

For this next experiment we will test the battery at different temperatures and at a pressure as low as the vacuum machine allows (this pressure will be almost zero). The manufacturer specifications sets 0°C as the lowest recommended temperature at which the battery should work. However we want to see:

- If the battery can also perform well at temperatures below the one recommended by the manufacturer.
- If there is any permanent damage to the battery after working (doing charge/discharge cycles) with this low temperatures.

Since we only have one battery, the tests done must be non-destructive. That's why we will do the experiments in the following order:

Experiment number	Temperature	Observations
1	40 °C	Temperatures recommended by the manufacturer (the battery should perform well under this conditions)
2	20 °C	
3	0 °C	
4	-10 °C	Temperatures outside recommended range
5	-20 °C	
6	20 °C	Back to nominal temperature

Testing in the vacuum chamber we can obtain the discharge curves of the battery at different temperatures (experiments 1 to 5). In the following graph we can see the results obtained:

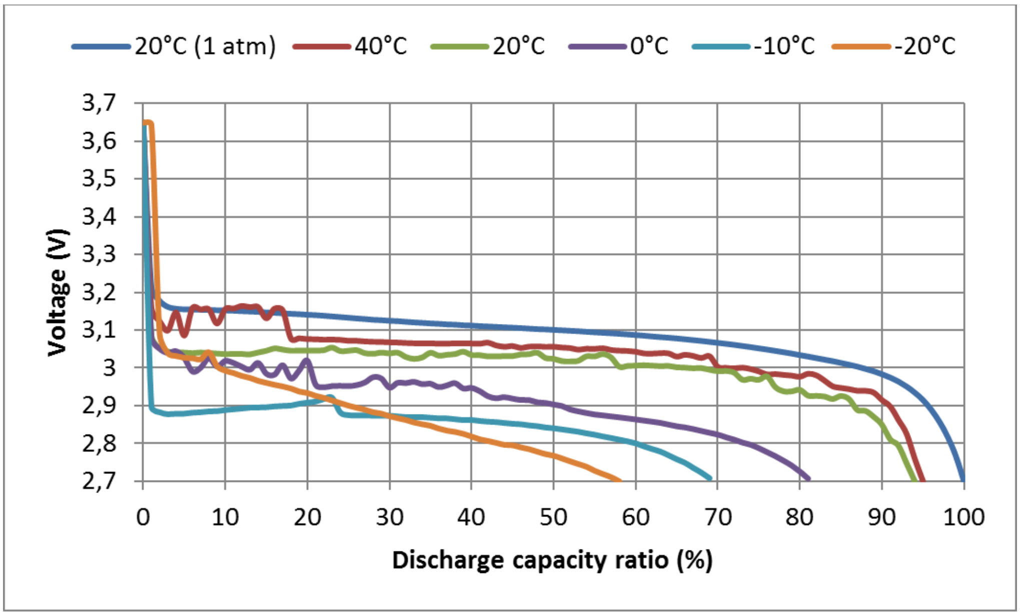


Image 15: Discharge of the battery at different temperatures

Also to see if the battery loses any performance we will repeat the experiment again at 20°C in the vacuum chamber (experiment 6). The results show very little variation between both tests.

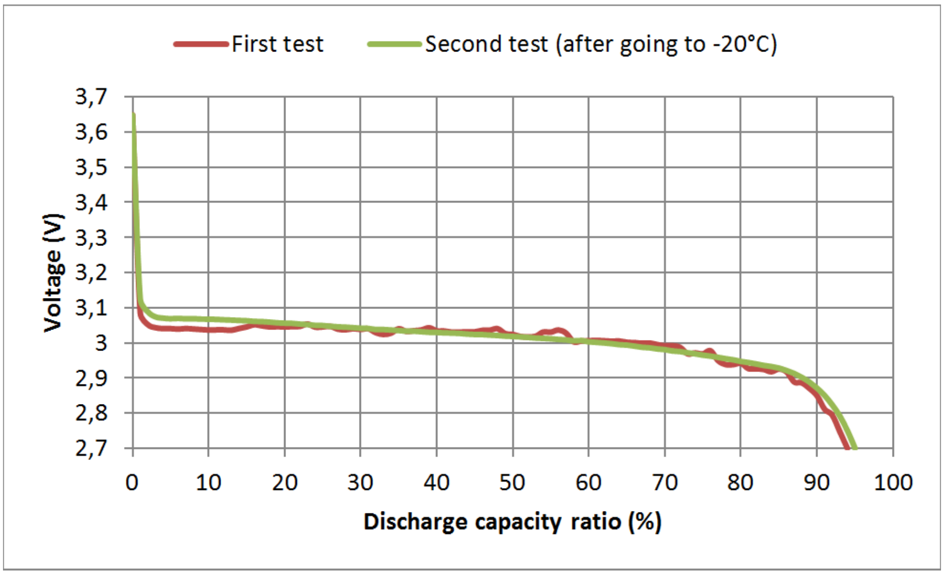


Image 16: Discharge of the battery before and after going to -20°C

After getting these curves we calculated the capacity and the performance of the battery in the vacuum chamber and the results obtained were the following:

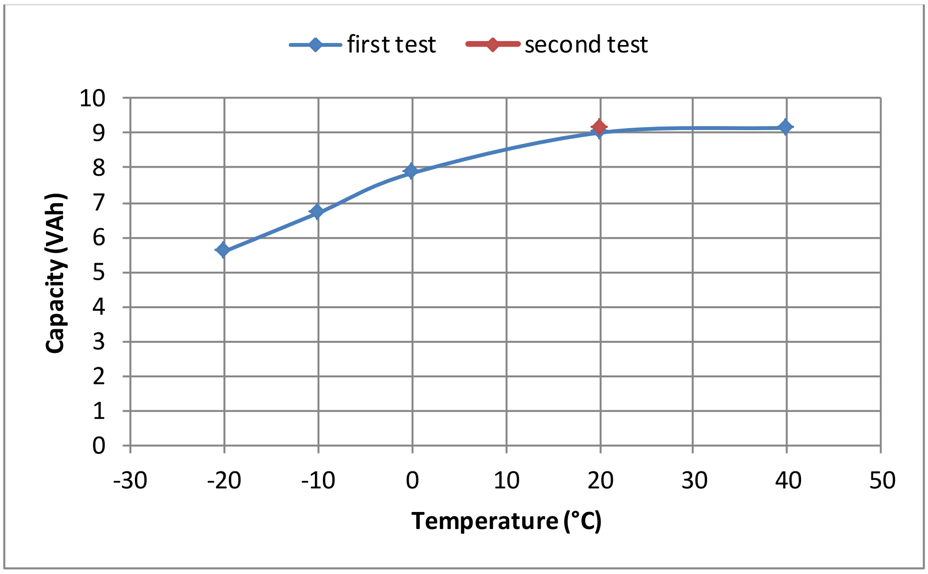


Image 17: Capacity of the battery at different temperatures

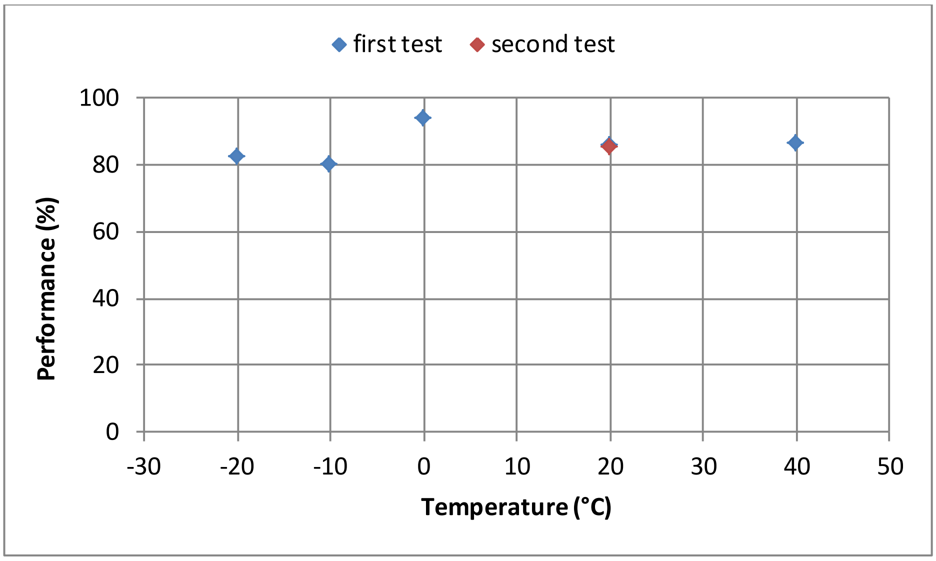


Image 18: Performance of the battery at different temperatures

When we calculated the capacity we can see how the capacity decreases outside the manufacturer's nominal range. The capacity at -20°C is much lower and has a value of only 62% of the nominal capacity at 20°C (*image 17*). From this data we can extrapolate that if we get a temperature lower than -20°C the capacity will keep on decreasing and that although it's not recommended to go below 0°C the battery still works with reduced capacity. The performance does barely change for this whole range although we could observed a little bit less performance for lower temperatures (*image 18*).

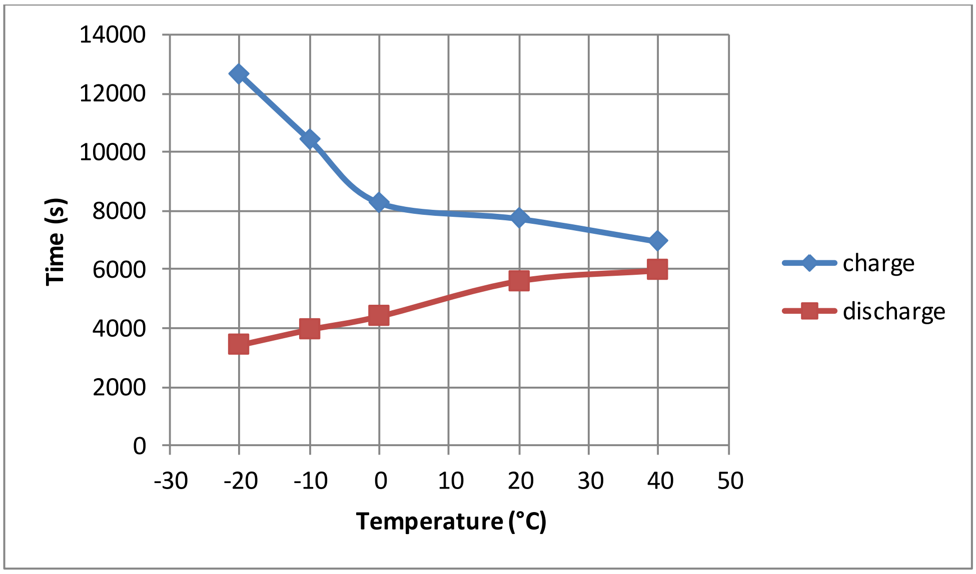


Image 19: Charge/discharge time of the battery at different temperatures

In this other graph (*image 19*) we can see how the battery charge and discharge times change for different temperatures. We can observe that:

- The discharge time decreases for colder temperatures. That's because the battery has a lower capacity and thus it takes less time to discharge it.
- The charge time increases as we lower the temperature due to the increasing internal resistance that lowers the charging current that goes through.

5. Conclusions

In this project we have been working with a LiFePo4 battery. This is a new, modern type of battery that hasn't been used in space satellites. This type of battery is safe and has a long life cycle although it still has fewer capacity than other lithium ion batteries like the $LiCoO_2$.

We have tested the battery at temperatures as low as -20°C and at a pressure under 100 microbars (almost vacuum) and from the results of the experiments made, we can see that the battery can still work properly at lower temperatures than those recommended by the manufacturer (0°C). We see that the battery's capacity decreases when we lower the temperature (being the capacity at -20 the 62% of the capacity at 20). That decrease is quite significant but not big enough to stop the satellite from performing its vital functions. What's more, even when the battery goes to -20 if later is returned to 20 degrees it recovers its previous capacity and no permanent damage is made.

We can also see, that the performance of the battery (charge/discharge capacity) barely changes and it almost remains constant thorough the whole range of temperatures studied. The changes are also only temporary and the battery is fully recovered after it is put back to the nominal temperature range.

With all the results obtained we can conclude then that this battery is ideal for its purpose since it gives great performance and capacity for the range at which it will be working, and even in the possible event that the heating system malfunction and the temperature dropped below 0°C the battery would still work although with fewer capacity.

For further analysis of the $LiFePo_4$ battery we should also measure capacity and performance but considering the variable number of cycles. With this we could be able to see how affected is the battery when performing hundreds of cycles and in what way do the charge and discharge cycles change. This analysis however would be destructive, it would require several batteries and it would take much more time.

Other possible tests could be testing the battery charging/discharching it with different amounts of current. This way we could see how the battery's capacity and performance are affected by a fast charge/discharge or an overvoltage.

6. References

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