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Influence of Shallow Cycling on the Ageing of SLI Batteries

MASTER THESIS

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Declaration

”I confirm that I prepared this work independently and without external help except for the supervision of the Institute for Power Electronics and Electrical Drives. The references and tools are completely stated, citations are indicated“.

Acknowledgements

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Contents

1 Introduction

Lead-acid batteries have different uses ever since they were invented. It is found interesting and usable to investigate the ageing of battery over time, and therefore to determine the batteries cycle life and performance in different situations, remarking the automotive industry and power supply systems, among others.

Nowadays lead-acid batteries with an infinite cycle life would be ideal for the applications where they are used. It is considered impossible to build an infinite cycle life battery, reason by which engineers have been looking forward to increase batteries' cycle life.

The main objective of the thesis is to analyse the effect of cycle depth for the measurements data provided by the ISEA Department and to obtain each battery's rate of ageing.

The finite life of the batteries is due to the occurrence of unwanted chemical or physical changes, or the loss of the active materials from which they are made; otherwise they would last indefinitely. These changes are usually irreversible and they affect the electrical performance of the cell, increasing the internal resistance, decreasing the capacity, and reducing the battery cycle life.

The report is structured by the following guideline:

- Chapter 2 explains in detail all information relating to lead-acid batteries as flooded and AGM batteries, ageing processes, applications, environmental impact and, manufacturers and suppliers.

- Chapter 3 discusses the conducted battery measurements as strategies for the capacity test procedures; the kinds of batteries used, and test characteristics at different temperatures for each measurement data.

- Chapter 4 here, there is an analysis of the test verification as maximum and minimum voltages observing all cycles, whether the amount of charge taken out of the battery relative to the nominal capacity is constant over time, as well as the real battery temperature for the measurement data.

- Chapter 5 will analyse the capacity over number of cycle depths for each measurement, to see if these obtained results are close to the expected results. Measurement data will be grouped with the same operational conditions to know how the number of cycle depths varies with the amount of charge taken out of the battery relative to the nominal capacity.

2 Lead-Acid Batteries

This chapter defines some general terms concerning lead-acid batteries, such as battery capacity, capacity test, battery cycle life, etc. Also explained in detail is all information relating to lead-acid batteries (flooded and AGM batteries, cycles in a battery, ageing processes, etc.).

2.1 Battery terms

“A device that converts the chemical energy contained in its active materials into electrical energy by means of an electrochemical reaction is known as cell. Two or more cells electrically connected in series forming a battery”. [1]

The battery capacity is the amount of charge that a charged battery can deliver under specified conditions of discharge. It is expressed in Ampere-hours (Ah).

A capacity test is used to determine the battery capacity. It consists of a discharge of a battery at a constant current or constant power to a specified terminal voltage. [2]

The battery cycle life is defined as the number of complete charge-discharge cycles a battery can perform before its nominal capacity falls below 50 % of its original capacity (this information will be found in each paper of the concrete battery).

State of Charge (SoC) is the charge in a specific time in respect to the nominal capacity of the used battery (expressed as a percentage) where C(t) is the leftover battery charge as a function of time and C_N is the nominal capacity for each battery used:

$$SoC(t) = \frac{C(t)}{C_N}, \tag{2.1}$$

Depth of Discharge (DoD) is the opposite of SoC and is the amount of charge taken out of the battery relative to the nominal capacity. It is usually expressed as a percentage.

- When the battery is completely charged: SoC = 100 %, DoD = 0 %.
- When the battery is completely discharged: SoC = 0 %, DoD = 100 %.

The number of full cycle equivalent (# FCE) is defined as the expected number of complete charges that a battery can stand.

2.2 Lead-acid batteries

The lead-acid battery is a type of rechargeable battery and uses lead alloy for the electrode grids, sulphuric acid for the electrolyte, and plastic for housing.

In a lead-acid battery the negative electrode supplies electrons to the external circuit and the positive electrode accepts electrons from the load during discharge. The separator is used to electrically isolate the positive and negative electrodes. It is made of a porous plastic or glass fibre material.

The lead-acid battery uses lead dioxide as active material in the positive electrode and metallic lead, in a high-surface-area porous structure, as negative active material. [3]

The lead-acid battery is the most used storage system due to its low price, low manufacturing cost, and high performance. It is used in many sizes and designs, ranging from less than one to over several thousand Ampere-hours, and in applications such as traction, SLI (Starting, Lighting, Ignition) and UPS (Uninterruptible Power Supply). Also, the lead-acid battery performs reliably over a wide temperature range and is easily recycled. However, the lead-acid batteries also have disadvantages like its relatively low cycle life (depending on the application type and the technology used).

Typically, lead-acid batteries can be divided on two different types depending on their method of construction, flooded or sealed. These two types also differ in their operation.

2.2.1 Flooded or wet cells

The most commonly used lead-acid battery type today is flooded (or wet) cells. They are built for a large variety of applications and offer the most options in size and design. So that, in the marine business, the user can replace any electrolyte the battery has vented while the battery is being recharged, these batteries are often not sealed.

Flooded lead-acid batteries are the least strong of all batteries mechanically, as the only support the grid has is at its edges. A single cell or several cells are attached to their plastic container.

“Hydro caps” allow for the combination of hydrogen and oxygen into water while the charging process occurs. Flooded cells require water but this amount can be cut down through “hydro cap” use.

Flooded cells are one of the less expensive sources of battery power and there are wide range of sizes and capacities available. They are reliable, robust and tolerant to overcharging. Also they have low internal impedance and can deliver very high currents.

However, in flooded batteries (see figure 2-1) the liquid electrolyte can be released from the cell and cause corrosions. Flooded cells must be periodically checked for fluid level and deionised water added as necessary to compensate the water loss through gassing while are being charged.

Figure 2-1: Casing of an internal flooded battery

2.2.2 Absorbed Glass Mat (AGM) batteries

AGM is a class of Valve-Regulated Lead-Acid (VRLA) batteries, which is a type of sealed battery. This type of battery confines the electrolyte which is absorbed in a matrix of glass fibres, immobilising the electrolyte, holding it next to the plate, and preventing a spill. If internal pressure exceeds a certain threshold, these batteries have a vent or a valve to allow excess gases to escape.

AGM batteries (see figure 2-2) are mature and reliable, but have higher manufacturing cost than flooded batteries. They have good power characteristics, low internal resistance, as well as lower self-discharge than other batteries, high vibration resistance and good behaviour during charging. They have high charge efficiency; about 98 % while flooded batteries have 85-95 %. They can also recombine 99 % of the oxygen and hydrogen, so there is almost no water loss. [4]

Figure 2-2: Casing of an AGM battery

AGM technology is used in spiral wound cells. Spiral wound is a particular design for the electrodes in lead-acid batteries where, instead of having the electrodes as flat plates, the electrodes are rolled up in a spiral.

However these batteries have several limitations. They have a low energy density and can be used only with flat plate electrodes or spiral wound cells. The large cell must also be installed horizontally to avoid stratification.

2.3 Ageing processes

The ageing mechanisms of the battery are processes that affect its correct performance. In lead-acid batteries these processes are corrosion and sulfation. Corrosion is irreversible and when it happens, the battery must be replaced. Also, gassing has an influence on water loss and reduces battery life. [5]

2.3.1 Corrosion

Corrosion occurs preferentially at the grain boundaries and is manifested as growth. When growth becomes excessive there is gradual loss of contact between the active material and the grid, resulting in a lowering of battery performance.

When the cell voltage reaches a certain level, the hydrogen involves at the negative electrode and the oxygen at the positive electrode, resulting in gassing.

Figure 2-3 shows a corrosion reaction in the external metal part of the lead-acid battery. When a chemical reaction between the battery terminals, lugs, and connectors occurs, electrolysis causes corrosion on the positive terminal. This a result of mismatched metal alloys used in cable connector and battery terminal production.

Figure 2-3: Corrosion in the external parts of the battery

Thermal expansion can cause some of the liquid from the battery to be pushed on to the top of the battery through its vents. This happens when the battery contains too much water and electrolytes, any substance that contains free ions and can conduct electricity, and results in the potential for corrosion through the reaction between metals such as lead in the battery connector and the solution. Where the battery terminals penetrate the plastic case, the electrolyte can leak through the plastic to lead seal.

The sulphuric acid fumes can build up and react with the exposed metals due to the overcharging of the acid fumes that vaporize through the vent caps and the insufficient battery box ventilation.

Aluminum connectors corrode to aluminum sulfate and copper connectors produce blue and white corrosion crystals (this last is usually lead or zinc sulfate crystals). This can be minimized by coating with a suitable rubber or plastic spray (see figure 2-4).

Figure 2-4: Plastic sprayed on to the external parts of the battery

2.3.2 Sulfation

Sulfation occurs when a battery is not fully charged, and therefore in all lead-acid batteries during normal operation. It is caused by usage and production of concentrated sulphuric acid during the charging and the discharging process, and also appears if a battery remains in a high depth of discharge. It clogs the grids, impedes recharging and ultimately expands, cracking the plates and destroying the battery.

Furthermore, the sulfate portion (of the lead sulfate) is not returned to the electrolyte as sulfuric acid. The large crystals physically block the electrolyte from entering the pores of the plates (see figure 2-5). Sulfation causes a loss of active mass and increase of overvoltage. Also, acid stratification has to be taken into account, as although it does not have an ageing effect it accelerates the ageing process.

Figure 2-5: Sulfation inside the battery

"Sulfation can be avoided if the battery is fully recharged immediately after a discharge cycle".

Sulfation also has an impact on the charging cycle. It can cause the battery to require more time for charging, as well as raise the temperature of the batteries and result in less efficient and complete charging.

Sulfation can be partially stopped or reversed however. This is done using a desulfation technique known as pulse conditioning. A damaged battery has brief but powerful current surges sent through it a number of times, causing the gradual breaking down and dissolution of sulfate crystals. Higher temperatures accelerate the desulfation process, however they speed up sulfation as well, and an excess of heat will damage the battery by increasing the speed of corrosion.

The forming of lead sulfate into crystals results in lead-acid batteries losing the ability to hold a charge when discharged for extended periods. Lead and lead (IV) oxide ($Pb0_2$) form lead sulfate in a reaction with the sulphuric acid in the electrolyte. The lead sulfate reverts back to lead and lead oxide (the active substances found on the plates of the battery) once the battery is charged again, as when the lead sulfate first forms it is amorphous (see figure 2-6).

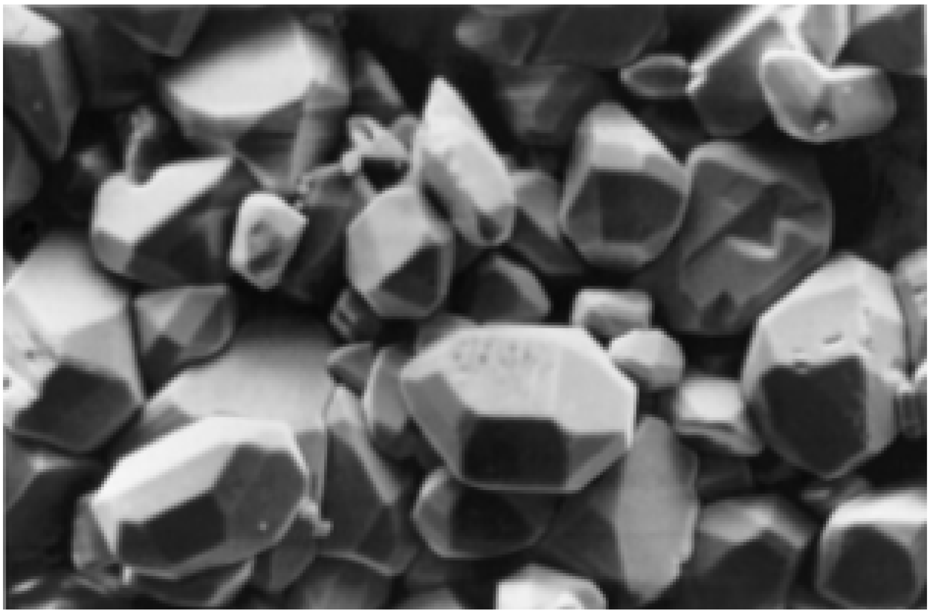

Figure 2-6: Battery plate coated by dense, hardened and crystalline lead sulfate

The lead-acid sulfate gradually is converted to a stable crystalline form that does not dissolve over time in the recharge as batteries cycle through numerous charges and discharges. Therefore, not all of the lead returns to the battery plates and the amount of usable active material required to generate electricity decreases over time.

2.4 Applications

Batteries are divided by construction (see in section 2.2.1 and 2.2.2 of this chapter) and application. The many uses (applications) of lead-acid batteries vary from the comparatively small batteries used in hand tools to the far larger kinds used by electric utility companies for load levelling.

Batteries can be kept on “float” and only be discharged infrequently, for example in an emergency lighting application. However they may also require deep and frequent cycling, such as when they are used for providing electrical vehicle power. As a result these different applications require different batteries. A number of restraints on parameters help to determine the type of battery to be used, for instance desired capacity, operating temperature, etc.

The major automotive, marine, and deep cycle applications of lead-acid batteries will be explained in sections 2.4.1, 2.4.2 and 2.4.3 respectively.

2.4.1 Starting batteries

Lead acid batteries, used in the starting of automotive engines, are not designed for deep discharge. They (sometimes called SLI for starting, lighting, ignition) can suffer damage from deep discharge easily, as they have a maximum current output due to numerous thin plates for maximum surface area. An automotive battery can last for thousands of cycles in normal 2-5 % discharge starting use, but normally will only survive 30-150 deep cycles. Repeated deep discharges will cause loss in capacity and eventual premature failure- due to electrode disintegration from the mechanical stresses that cycling results in.

In order to prevent sulfation it is necessary for batteries to be charged at least fortnightly and kept on an open circuit. Corrosion in the electrodes and premature failure will occur when starting batteries remain on continuous float charge.

2.4.2 Deep cycle batteries

Deep cycle cells are needed for applications where batteries are discharged regularly. These batteries have much thicker plates, allowing for a lower peak current but less susceptibility to frequent discharging.

Unlike other batteries the deep cycle battery has plates of solid lead rather than sponge. This provides less instant power, for example the amount that starting batteries need, as less surface area is provided. While these can be cycled down to a 20 % charge, keeping the average cycle at around 50 % discharge results in the best lifespan against cost method.

The applications for deep cycle cells include power supplies that can not be interrupted, photovoltaic systems and electric vehicles, and they are capable of being repetitively discharged down as much as 80 %.

2.4.3 Marine

Batteries used in the marine industry are usually a hybrid between the previously described deep-cycle and starting batteries. The plates can be composed of sponge as in starting batteries, but it is made from coarser and heavier lead. In some cases marine batteries can be true deep cycle batteries, but this is not common.

“CCA” or “MCA” (“Cold Cranking Amperes” or “Marine Cranking Amperes”) are the usual ratings for Marine batteries, with “MCA” being the same as “CA”. While CA and MCA ratings are at 32 degrees Fahrenheit (F), CCA is at zero degrees Fahrenheit (F). Any battery with MCA or CA behaviour can potentially be a true deep cycle battery. As the term deep cycle is frequently overused, it can be hard to tell which at times.

2.5 Environmental impact

Nowadays batteries (also lead-acid batteries) are the most used electrical energy storage devices worldwide. As a result there are serious disposal issues for these batteries due to their deteriorating effects on human health (long term exposure to even tiny amounts of lead can cause brain and kidney damage, hearing impairment, and learning problems in children) and the environment.

Therefore, cost-effective methods must be thought of to solve disposal issues for developing countries, and the complete recycling of batteries is necessary to ensure a cleaner and healthier world for future generations to live in.

Disposal of batteries is a key problem faced by both recycling organisations and manufacturers. It is unfortunate that one of the current means of disposal is to send used batteries to specialised landfills (see figure 2-7). This sort of disposal can clearly be seen to interfere with maintaining a clean and healthy environment. Nowadays, there are some countries that are implanting measures to reduce this problem.

Figure 2-7: Battery landfill

“According to a 2003 report entitled, "Getting the Lead Out", by Environmental Defence and the Ecology Center of Ann Arbor (Michigan) the batteries of vehicles on the road contained an estimated 2,600,000 metric tons of lead which is extremely toxic.

The automobile industry uses over 1,000,000 metric tons every year, with 90 % going to conventional lead-acid vehicle batteries.

While lead recycling is a well-established industry, more than 40,000 metric tons ends up in landfills every year. According to the federal Toxic Release Inventory, another 70,000 metric tons are released in the lead mining and manufacturing process”. [6]

2.6 Manufacturers and suppliers

There are a large number of lead-acid manufacturers and suppliers around the world, all providing for different applications. The following list provides some examples: [7]

- All Power is a Canadian manufacturer of sealed lead-acid batteries for commercial applications such as medical, security, lighting, ups, and scooters.
- Centurion Akku, a well-known company from Netherlands, found in initial assembly and in the replacement market. This company focus its production on the slogan "one size fits all", that includes super starter batteries for passenger cars, semi traction batteries from 40 to 180 Ah for power and lighting, heavy duty batteries for road and water transport and multifunctional batteries with patented carbon fibre technology for a range of applications.
- Global Technology Systems, Inc. is a company from USA that manufacture portable data collection device, portable printer, two-way radio, and uninterruptible power supply batteries.
- GS Battery (U.S.A.) Inc is a company which makes valve regulated lead-acid (VRLA) batteries and rechargeable motorcycle batteries. Also produces rechargeable lithium-ion batteries for use in electric vehicles, as well as for space and industrial applications.
- Hangzhou Haijiu Battery Co., Ltd. from China is a manufacturer of motorcycle batteries, electric bike batteries, riding mower, automobile, and UPS batteries.
- Hawker Energy Products, Inc. from USA produces flooded and valve regulated lead-acid (VRLA) batteries for telecommunications, UPS, security, emergency lighting, general electronics, medical, aviation, military and more applications.
- Hawker Powersource, Inc. (USA) is a company specialized in industrial lead-acid batteries for applications in telecommunications and aircraft, UPS systems and submarines.
- Hoppecke, from Germany, is a company specialized in industrial battery systems. This company develops and produces batteries and systems of lead-acid, nickel-technology, emission-free propulsion and hybrid-technology.
- Innergy Power Corporation, Inc. is an American company which designes and manufactures thin sealed lead batteries and high-quality flat-panel multicrystalline photovoltaic solar modules including unique solar/battery hybrid modules.
- Laor Industrial Batteries LTD was founded in Israel. Laor's product line includes special batteries for military applications, industrial stationary batteries and Nato type Batteries.

- Power-Cell Battery Products, LLC (USA) is a manufacturer of sealed lead-acid and custom battery packs. Also offers electromagnetic services of pack assembly and ultrasonic welding.

- Power-Sonic Corporation produces rechargeable sealed lead-acid batteries, sealed nickel-cadmium batteries, nickel metal hydride batteries, custom battery packs, and battery chargers for SLA and NiCd batteries.

- Shamas Battery Co., Ltd. from China is a manufacturer and exporter of valve-controlled lead-acid batteries and electrode plates for lead acid batteries.

- Shenzhen Stand Power Industrial Co., Ltd. is a Chinese company which manufactures a wide range of VRLA batteries, mostly applicable for AGM and GEL batteries for long service life, deep cycle service and high rate discharge.

- Tong Yong Battery Co., Ltd. from China is a manufacturer of valve-regulated (sealed) lead-acid batteries, flooded and maintenance-free motorcycle batteries.

- Trojan Battery Company is an American manufacturer of lead-acid deep cycle batteries for use in floor machine, marine, renewable energy, RV and utility vehicle applications.

- Varta by Johnson Controls, from Germany, is the world’s leading manufacturer of car starter batteries and provides lots of other services and facilities as well. This company is the benchmark for battery quality in the automotive industry due to the battery package packs a powerful punch.

- Zhongshan Fengge Battery Co., Ltd. from China is a manufacturer of sealed lead-acid batteries including automobile batteries, motorcycle batteries, and valve regulated sealed lead acid batteries.

3 Conducted Battery Measurements

This chapter introduces two types of battery which are to be investigated in the thesis as well as the test characteristics at different temperatures (-10°C or 25°C) with 1C of constant current rate for the measurements data in order to obtain the number of full cycles for each file.

From these investigations, a table has been created containing the data for the most important topics: battery number and battery test, type test, temperature and constant current rate, battery type, SoC and DoD, and number of blocks (see attachment 8.1).

3.1 Cycle life investigations

The aim of the thesis is to investigate the cycle life as a function of DoD, constant current rate, temperature and SoC level for flooded and AGM lead-acid SLI batteries, in order to calculate the ageing in each measurement data.

3.1.1 Strategies for the capacity test procedures

Establishing a regular basis in which it is possible to perform the capacity tests and so gather sufficient information on the life time of the batteries during the cycling test. There are two strategies for this; with an EN full charge or with an OP full charge procedure:

- **EN full charge**

In this procedure, the batteries are charged with an operational charge first. The capacity is determined for the operational full charge. This is followed by an EN full charge with an additional capacity test. Thus, each capacity test procedure consists of one operational full charge, 2 EN full charges and 2 capacity tests. Before the tests, the battery is allowed to adjust its temperature to 25 °C over a period of 6 hours. The overall duration is approximately 77 hours.

- **OP full charge**

In this procedure, the batteries are also charged with an operational charge first, and the capacity for the operational full charge determined. This is followed again by an OP EN full charge. Thus, each capacity test procedure consists of 2 operational full charges and 1 capacity test. Before the tests, the battery is allowed to adjust its temperature to 25 °C over a period of 6 hours. The overall duration is approximately 30 hours.

The capacity test procedure will be performed with double frequency compared with the tests under similar conditions using the EN full charge characteristic. This ensures that the same total number of capacity tests occur in both cases.

SoC adjustment is made by discharging 5 % of EN after OP full charge; SoC_{max} can be calculated using pre-tests and is expected to be about 80 % with regard to an EN charged battery.

3.1.2 Investigating battery and capacity test parameters

The measurements obtained are referred to the investigations of cycle life as a function of DoD, constant current rate, temperature and SoC level for flooded and AGM lead-acid SLI batteries.

The following two kinds of batteries have been investigated:

- AGM Varta 70 Ah.
- Exide pan-brand 43 Ah, T4.

Previously explained in section 3.1.1 are the two strategies for achieving sufficient information on the life time of the batteries during the cycling test. The parameters that determine if the measures have been taken for EN full charge or OP full charge are showed in table 3-1:

	EN-charge	**OP-charge**
Flooded	**$5I_{20}$, 16 V** **24 h in total**	**$5I_{20}$, 14.7 V** **3h U-phase**
AGM	**$5I_{20}$, 14.7 V** **24 h in total**	**$5I_{20}$, 14.7 V** **3 h U-phase**
	Discharge until U = 10.5 V reached	

Table 3-1: EN-charge and OP-charge definitions

3.1.3 Test characteristics

Characteristic ageing curve (remaining capacity over cycle life time with different DoDs) will be measured for one set of conditions in detail. With a constant temperature (-10 °C and 25 °C) and a constant current rate (1C) during charging and discharging it has two possible combinations:

- At 25 °C water bath temperature and 1C current rate

Cycle life depending on cycle DoD and SoC_{max} will be investigated. Table 3-2 shows performed tests for flooded and AGM batteries with both strategies (EN-charge and OP-charge).

	Flooded	**Flooded**	**AGM**
SOC_{max}	**95%**	**80%**	**80%**
1%		X	
2%	X	X	X
5%		X	
10%			X
20%		X	
50%			X

Table 3-2: Tests at 25 °C and 1C

- At -10 °C ambient air temperature and 1C current rate

During the capacity test procedure, the temperature will return to 25 ºC during the capacity test procedure, with 12 hours temperature adaptation before the capacity test, and 12 hours temperature adaptation after the capacity test procedure.

During cycling, the temperature in a cell is expected to be about 15 ºC – 20 ºC higher than ambient temperature, and as ageing tests will be done at about +5 ºC real cell temperature, the ambient temperature will be set to –10 ºC. If the battery warming is stronger than expected, the ambient temperature will be lowered further.

Capacity tests are described in table 3-3, where the measurements data chosen can be seen.

	AGM
SOC_{max}	**80%**
2%	X
10%	X

Table 3-3: Tests at –10 ºC and 1C

3.2 MATLAB

For the thesis a mathematical program has been used to analyze the measurements data and to obtain graph results.

MATLAB is a commercial platform-independent software company of The MathWorks, Inc. It can be used to solve mathematical problems and graph the results. The graphs obtained provide basic information to obtain conclusions and assist in the development of the thesis.

Note that if ".mat" files extension have a large size (80 MB or higher) a high random-access memory (RAM) is required to simulate in MATLAB. For this reason, it uses a Virtual-Cluster Machine, provided by the Centre for Computing and Communication of the RWTH Aachen University (Rechenund kommunikationszentrum, RZ), with 40 GB of RAM in order to obtain graphs for large files with less execution time and without memory problems.

3.3 Measurement data available

If all of the above factors explained in this chapter are taken into account, a summary table showing the parameters of the simulation data available is created for the ".mat" files extension. The excel table (see attachment 8.1) contains the following topics:

- Battery number and Battery test.
- Type test: Pre-test, Error, or Cycling.
- Temperature (°C) and constant current rate.
- Battery type: Flooded or AGM.
- Start SoC (%) and DoD (%).
- Number of blocks for the simulated graphs.

Battery number, battery test and type test are observed in each measurement data script. The ambient temperature is taken in each case, only 25 °C and -10 °C, and 1C as a maximum constant current rate, because the battery capacity can only be 70 Ah or 43 Ah.

The charging strategy can be observed in section 3.1.1. To decide the battery type it uses sections 3.1.2 and 3.1.3 corresponding to the start SoC and the DoD, while the number of blocks is a set of charge-discharge cycles inside one block.

4 Test Verification

In this chapter the performance of the batteries is analyzed over time (seconds). To show this, a script to calculate the maximum and minimum voltage during cycling for each measurement data has been created. By observing these voltages (maximum and minimum), the capacity test points can be determined.

Also to be determined is whether the DoD remains constant along the measurements data or if it varies with the time during the cycling.

Furthermore, it is known that the ambient temperature will be -10 °C or 25 °C for all measurements data, but the real battery temperature will be different in each case because in an ideal situation, the real cell temperature is about 15-20 °C higher than the ambient temperature, and it is hoped that about 5-10 °C for the ambient temperature equivalent to -10 °C and about 30-35 °C for the ambient temperature of 25 °C will be obtained.

It would be interesting to explain and plot all measurements data for the next three topics included in this chapter; however it is better to choose one of them and to analyze it in detail. Thus, the file chosen has been explained in this chapter and the others have been explained in attachments 8.2, 8.3 and 8.4.

The operational conditions for the measurement data chosen in this chapter are:

- Type battery: AGM
- Temperature: 25 ºC
- Constant current rate: 1C
- Start SoC: 80 %
- DoD: 2 %

4.1 Maximum and minimum voltage (V) Vs. Time (s)

A script has been created to determine the maximum and minimum voltage in each measurement data. It is known that the maximum voltage corresponds to charging state and the minimum voltage to discharging state.

In figure 4-1 it is possible to observe the voltage over time plot and extract from this the charge and discharge voltages corresponding with the maximum and minimum voltages separated by two different colours, blue and red respectively. Note that there are very few points (in some cases none) under the minimum voltage value, 10.5 V.

In this case it can be observed how the voltage along the measurement data oscillates between the maximum value, 14.7 V, and the minimum, about 11.75 V. These two values correspond to the maximum voltage in charge and the minimum voltage in discharge cycles respectively, except when the value is exactly 10.5 V and the previous step was a pause in the maximum value because this is a capacity test point.

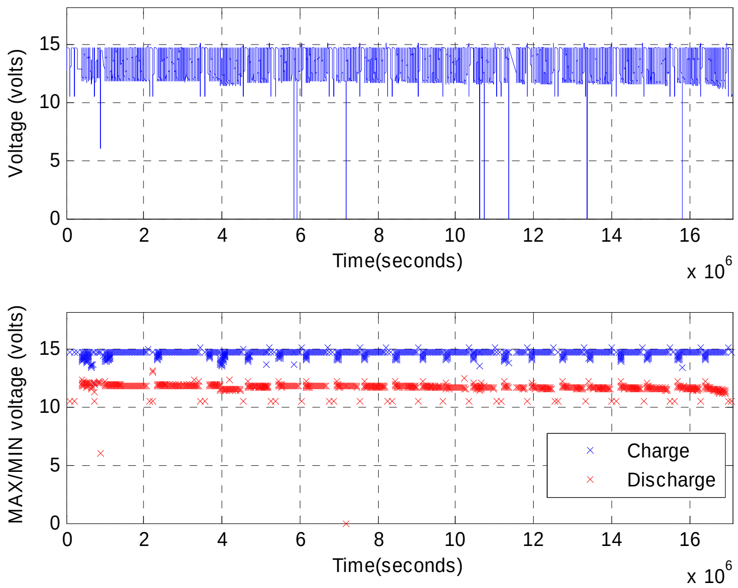

Figure 4-1: Voltage Vs. Time for the defined operational conditions

As can be seen in figure 4-2, maximum and minimum values along the measurement data are 14.7 V (for AGM batteries the charging value is always the same) and around 11.75 V respectively. This figure shows a close-up of a part of the measurement, of an area between 5 and 6 million seconds.

When the previous step is a discharge, the maximum voltage during cycling varies between 13.9 V and 14.5 V but never reaches 14.7 V. However, when the previous step is a charge, the maximum voltage during cycling is 14.7 V.

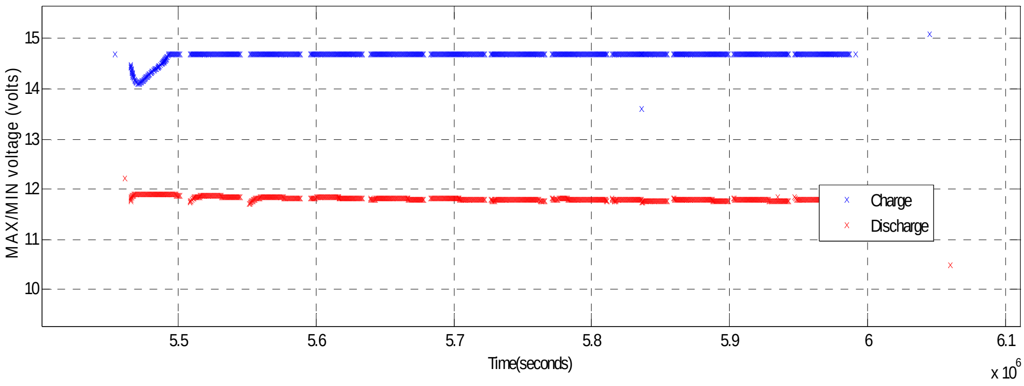

Figure 4-2: Voltage Vs. Time for the defined operational conditions

4.2 Depth of discharge (DoD) Vs. Time (s)

This section explains the DoD variation over time for the measurement data chosen (AGM battery, temperature of 25 ºC, constant current rate 1C, Start SoC of 80 % and DoD of 2 %). To extract good results from the graph it would be ideal to obtain a constant straight line corresponding to the DoD value; in this case 2 %.

In the following figure it can be observed that most of the points are on this straight line, but some points oscillate a little bit under or above the 2 % because there are some capacity test points or the battery state remained paused.

In figure 4-3 it is shown that the depth of discharge does not vary along the measurement data. Therefore it can be affirmed that the performance of this file is as expected because most of the points are on the 2 % line. This fact shows that measurements during cycling are appropriated.

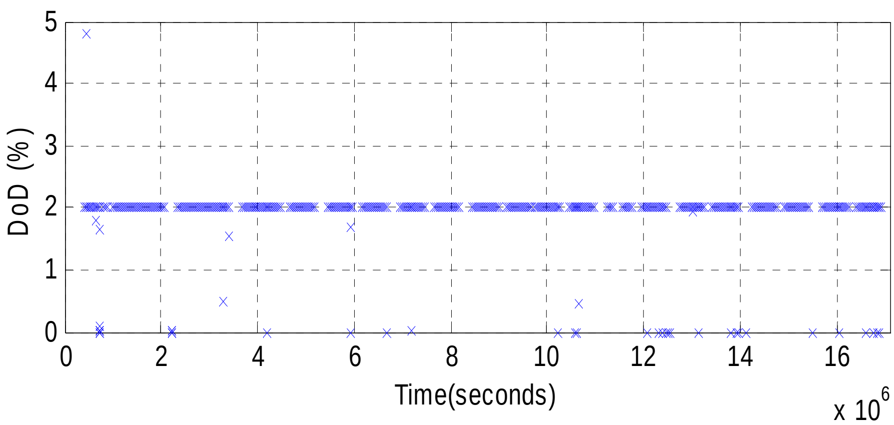

Figure 4-3: DoD Vs. Time for the defined operational conditions

4.3 Real battery temperature (ºC)

This section of chapter 4 investigates whether the real battery temperature for the obtained results in the measurement data chosen and analyzed is correct. This has been done by obtaining the average temperature for the file and comparing it with the expected real temperature of the battery, around 30-35 ºC.

In figure 4-4 the average temperature can be observed for different tests in the same measurement data that has a temperature higher than 25 ºC, and then compared with the total average temperature along the file.

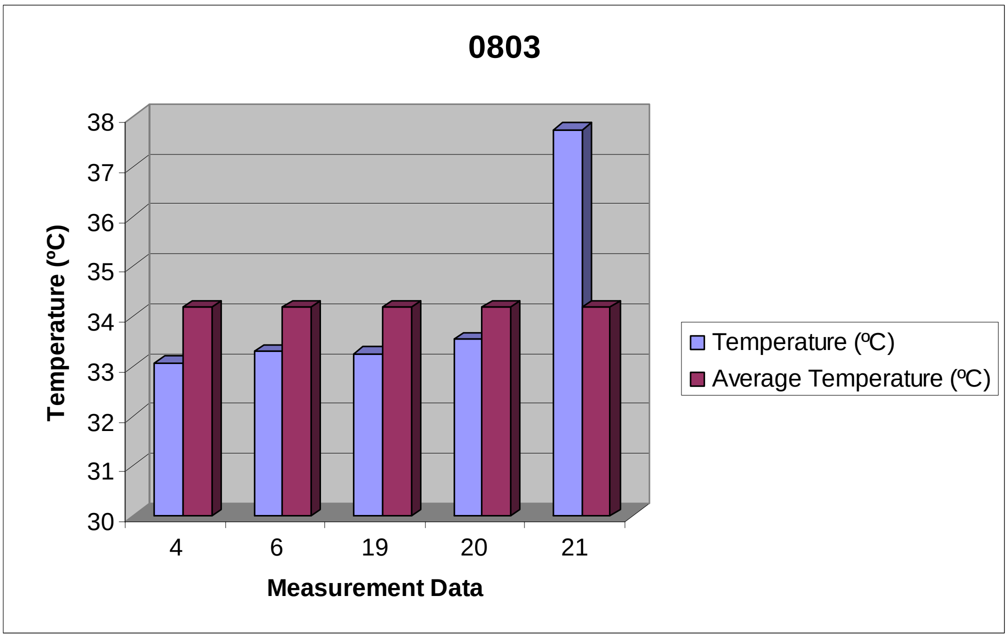

Figure 4-4: Real battery temperature for the defined operational conditions

Power losses influencing the battery temperature, specifically SoC, discharge current and ageing are the parameters that can cause variation in the real battery temperature, depending on the situation.

It is known that for an ambient temperature equivalent to 25 ºC, the real battery temperature should be between 30-35 ºC, but this is not certain because if the discharge current decreases the real temperature can be less than the expected temperature. Therefore, as a conclusion it can be confirmed that the discharge current marks the real temperature in the battery.

The real temperature along the measurements data varies in each cycle but is always higher than 25 ºC. As observed in figure 4-5, the average real battery temperature around 34 °C, which is considered a good value because this temperature is found between the expected values to be observed on the discharge current values.

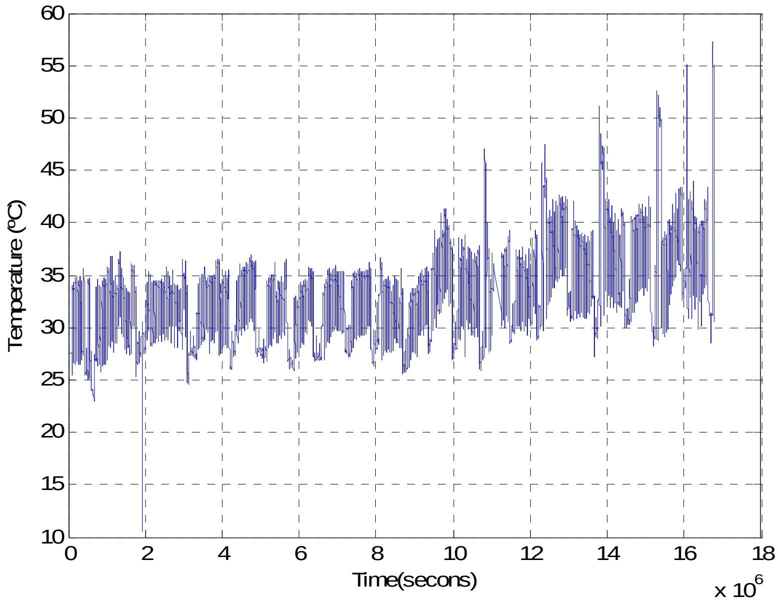

Figure 4-5: Real temperature Vs. Time for the defined operational conditions

The times of the temperature envelope obtained in figure 4-5 correspond with the obtained values for measurement data in figure 4-4 for each test.

5 Analysis

After several tests it has been concluded that the behaviour of lead-acid batteries can be approximated by a linear model. To use this model it is necessary to obtain the constant values (K_0 and K_1) for each measurement data.

Chapter 5 also shows the capacity (Ah) over a number of full cycle equivalents to observe how this capacity decreases following the linear model. Then, it can be seen that the performance in the measurement data depends on temperature, SoC and DoD in each case. The constant current rate will be always 1C (70 Ah for AGM batteries and 43 Ah for Flooded batteries).

The last topic in this chapter will look at how the number of full cycle equivalents varies depending on the DoD for the same battery type (AGM or Flooded) in the similar operational conditions of temperature, SoC and constant current rate (always 1C).

5.1 Linear model

The purpose of the relationship between the battery behaviour and the linear model is to determine the ageing battery over time. Ideally, the real curve obtained through the measurement data can be approximated by a linear curve. The formula for this linear curve is:

$$y = K_0 \cdot x + K_1 \text{ ,} \tag{5.1}$$

where 'y' is the capacity (Ah) and 'x' is the number of full cycle equivalents. K_0 and K_1 are constant values for each measurement data but have different values for the EN and OP charging strategies.

K_0 is the slope of the line curve and this value always will be negative because the obtained line curve is decreasing. This is so because the capacity of the battery decreases over time. K_1 is the term that marks the offset in the linear graph and these values will always be positive because the line is always above the zero mark on the 'y axis'.

To achieve the constant values an excel function is used to approximate the real curve, graphing the linear formula. Therefore, a linear tendency line is added to the obtained graph and the following values are obtained for each measurement data (see table 5-1):

Battery file	DoD (%)	Charging Strategy	K_0	K_1
803	2%	EN	-0,0241	67,581
		OP	-0,0255	59,351
804	50%	EN	-0,2395	66,793
		OP	-0,1749	60,317
805	2%	EN	-0,1038	68,259
		OP	-0,0587	53,673
808	2%	EN	-0,0927	68,484
		OP	-0,0747	66,611
809	10%	EN	-0,0749	68,551
		OP	-0,0706	69,999
902	2%	EN	-0,0754	41,094
		OP	-0,0538	30,888
918	1%	EN	-0,0691	40,359
		OP	-0,0711	37,999
919	5%	EN	-0,2174	41,056
		OP	-0,1254	22,391
921	2%	EN	-0,0775	41,072
		OP	-0,0691	33,587

Table 5-1: Model constant values, K_0 and K_1

5.2 Capacity (Ah) Vs. Number of full cycle equivalent (# FCE)

A script has been created to determine the capacity test points in each test of the measurement data. When these points have been obtained the excel script conditions will be observed to determine if these points belong to an EN full charge or an OP full charge.

Then, each measurement data will have two graphs depending on this full charge and therefore, two lines (EN and OP) formed from K_0 and K_1. These values can be observed in table 5-1. In investigating these values some points have been deleted due to some possible measurement errors. In figure 5-1 it can be observed that and all of the values have been taken to create the capacity graph over a number of FCE, and that the line curve without some values has been used to create the linear equation.

In attachment 8.5 there are the figures and tables (It can be observed in these tables the different points to obtain a linear equation for each measurement data) associated to measurement data, except for the one defined in this chapter.

The operational conditions for the measurement data chosen in this section of the chapter 5 are:

- Type battery: Flooded
- Temperature: 25 ºC

- Constant current rate: 1C
- Start SoC: 80 %
- DoD: 1 %

In the measurement data are found some testes with capacity test points with the conditions mentioned above. By observing the capacity profile, it is found that a suitable line curve has been obtained because it passes through approximately all capacity test points. Therefore, as can be seen in figure 5-1, the expected FCE at 50 % of capacity is approximately 250, the frequency for EN full charge is 60, and the OP full charge is 30.

It is known that for OP full charge the frequency of capacity tests procedure is higher than for EN full charge. Conversely, the number of full cycle equivalents is higher when the DoD cycles (%) is less.

Also it is important to know that for AGM batteries the number of full cycle equivalents will always be higher than for flooded batteries, independent of the DoD (%) cycles.

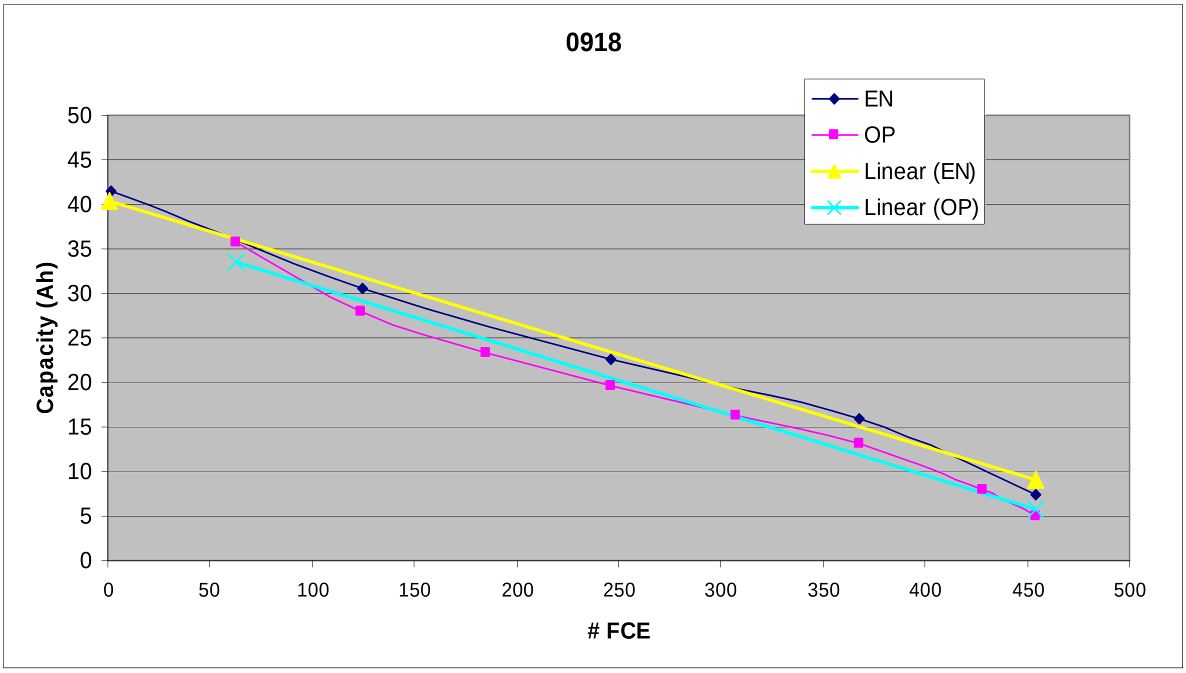

Figure 5-1: Capacity Vs. # FCE for the defined operational conditions

As can be seen in table 5-2, three points have been removed in total; one point for the EN full charge and two points for the OP full charge. Without these three points a straight line has been obtained that passes through all capacity test points.

EN		OP	
# FCE	Capacity (Ah)	# FCE	Capacity (Ah)
1	40,1019	63	35,736
2	41,5506	124	28,0301
124	30,505	185	23,3791
246	22,5028	246	19,5492
368	15,9893	307	16,3655
454	7,3294	367	13,2366
		428	7,888
		454	4,9926

Table 5-2: Measurement data for the defined operational conditions

5.3 Number of full cycle equivalent (# FCE) Vs. Depth of discharge (DoD)

This section explains how the depth of discharge in different measurement data can be plotted on a graph to observe the variation in the number of FCE over DoD. This is made possible by comparing the measurement data with the same operational conditions (flooded batteries, temperature = 25 ºC, current rate = 1C and SoC = 80 %), with changes only in the DoD.

In this case, it has been chosen measurements data with 1 % of DoD, with 2 % of DoD and with 5 % of DoD.

Therefore, it is necessary to know the constant values, K_0 and K_1 (see table 5-1), for these three measurement data, because the aim is to determine the number of FCE when the capacity is exactly 50 %, as it is up until this point that the battery will work correctly; when below 50 % of the battery capacity the cycle life deteriorates.

To obtain the capacity just at 50 % K_1 is divided (the offset in the equation line) by 2 and this value is introduced in the formula of the equation line. By determining the line slope (K_0) the number of FCE ($X_{50\%}$) is obtained. This procedure can be observed in the following formulas (5.2, 5.3 and 5.4):

$$y = K_0 \cdot x + K_1 \tag{5.2}$$

$$y_{50\%} = \frac{K_1}{2} \tag{5.3}$$

$$x_{50\%} = \frac{(y_{50\%} - K_1)}{K_0} \tag{5.4}$$

The next step is to take the measurement data with the same operational conditions, changing only the DoD, and plot the graph to observe how the number of FCE varies.

As can be seen in figure 5-2, for EN full charge the number of FCE decreases when the DoD is higher. This happens because in small DoDs the amount of charge respect to the nominal capacity is less, reason by which the battery cycle life is higher and there is also a higher number of FCE.

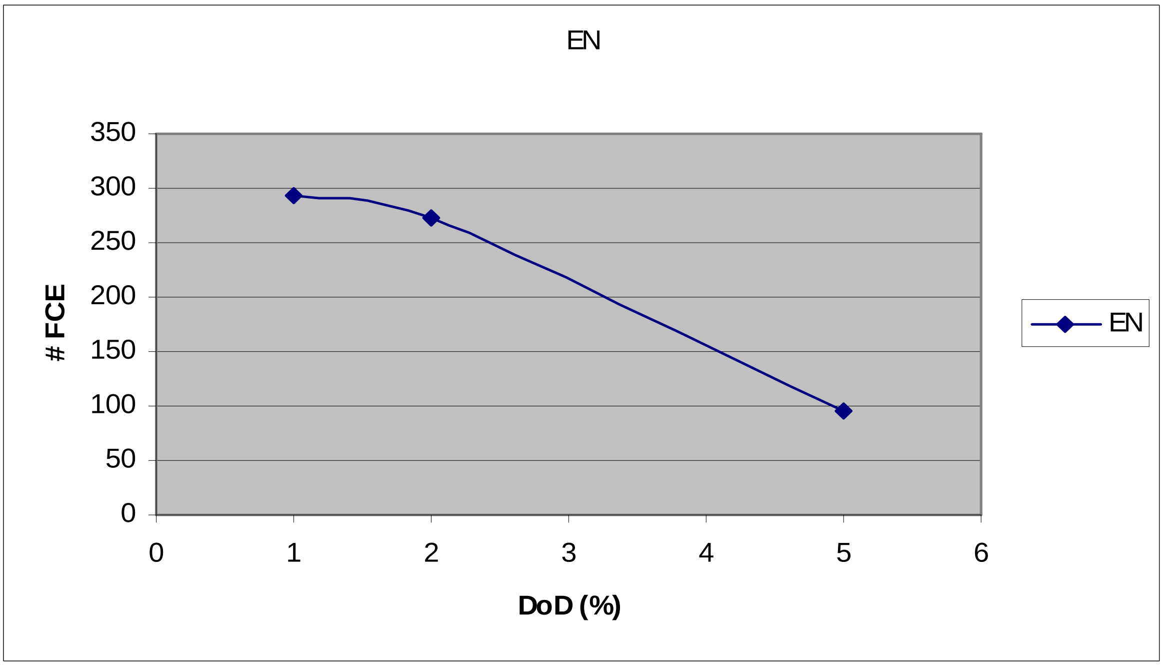

Figure 5-2: # FCE Vs. DoD for EN full charge

Conversely, figure 5-3 is the opposite because the number of FCE is higher when the DoD is higher and therefore this is not possible because with higher DoDs the cycle life of the battery is smaller as with less DoDs. The reason for this is that there are few valid capacity test points. The battery temperature is also very important because it has a big influence on the obtained results.

Therefore it can be concluded that figure 5-3 does not correspond well with the actual situation, perhaps because more capacity test points and/or a different real temperature in the battery are required.

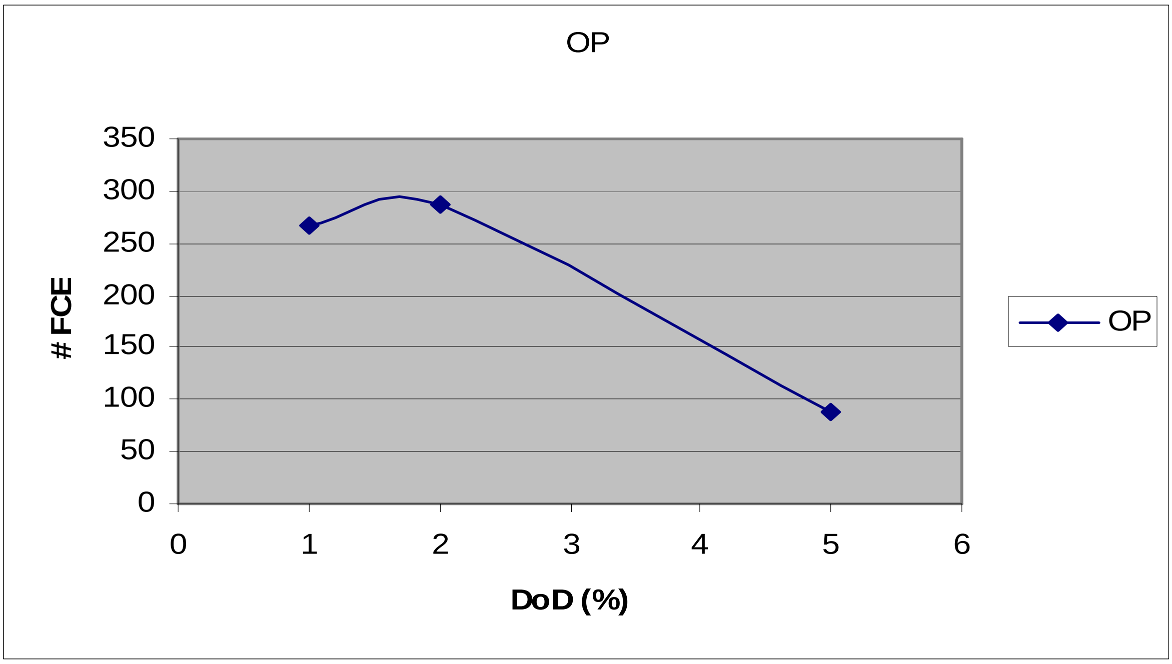

Figure 5-3: # FCE Vs. DoD for OP full charge

In table 5-3 the capacities at 50 % for EN and OP full charge can be seen for the operational conditions chosen and the DoDs corresponding with these capacities. Also included is the measurement data chosen.

File	DoD (%)	$X_{50\%}$ EN full charge	$X_{50\%}$ OP full charge
918	1	292,4565	267,5986
902	2	272,5066	287,0632
919	5	94,425023	89,2743222

Table 5-3: Flooded batteries, temperature = 25 °C, current rate = 1C and SoC = 80 %

In attachment 8.6 there are the figures and tables associated with the other measurement data, except for the explained in this chapter.

6 Conclusions

The study of the influence of shallow cycling on the ageing of SLI batteries has been the main aim of the thesis during the last six months. By doing the thesis, some battery measurements data provided by the ISEA Department has been analyzed.

Firstly, a study of the general terms about lead-acid batteries and the different ageing processes that affect them to analyze the measurements data of batteries was done. Different characteristics of batteries have been analyzed in this thesis, in which were included the following characteristics, the battery type, the temperature, the current rate, the State of Charge and the Depth of Discharge.

Once the initial specifications were known, the behavior of the batteries over time was analyzed. With MATLAB program, a script which allows us to analyze the maximum and minimum voltage (V) over time, depth of discharge (DoD) over time and the real temperature of the battery (°C) of the measurement data was created.

After three verification tests for the measurement data chosen, it is concluded that maximum and minimum voltages for AGM batteries were properly used because they always were between 14.7 V for the charge and 10.5 V for the discharge in both charging strategies; EN and OP full charge. By following, the depth of discharge (DoD) remained constant over time at 2 % for the measurement data. Finally, the average real temperature of the battery was close to the expected value when the ambient temperature was 25 °C. By observing this last test, the temperature envelope over time was determined and it coincided with the average temperature values in each test of the measurement data.

The behaviour of lead-acid batteries was approximated by a linear curve. Also, the capacity (Ah) over number of full cycle equivalent and number of full cycle equivalent over depth of discharge (DoD) were analyzed through a new script created in MATLAB program.

With these script it was prove that the number of full cycle equivalents for an AGM batteries is higher than for flooded batteries and also that is higher when the DoD is less, independently of the battery type. There were some difficulties to determine the linear model due to the lack of capacity test in some measurement data.

The realization of this thesis has provided us new knowledge about the lead-acid battery, as well as, to analyze its behaviour at different specifications of temperature, SoC and DoD in order to increase its cycle life in the future by using the thesis as a starting point.

By following with this thesis a possible next step would be to implement the linear model in the Simulink program and, therefore determining the ageing battery plot for a current input measurement data.

Figures Content

Tables Content

7 Bibliography

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8 Attachments

8.1 Measurement data available

The following table shows the information of the measurements data used in the thesis.

Battery #	Test #	Type Test	Temperature (°C)	Current rate	Type	StartSoC (%)	DoD (%)	# of blocks
803	1	Vortest						
803	2	Cycling	25	1C	AGM	80	2	
803	3	Cycling	25	1C	AGM	80	2	
803	4	Cycling	25	1C	AGM	80	2	8
803	5	Cycling	25	1C	AGM	80	2	
803	6	Cycling	25	1C	AGM	80	2	24
803	7	Cycling	25	1C	AGM	80	2	
803	8	Cycling	25	1C	AGM	80	2	
803	9	Cycling	25	1C	AGM	80	2	
803	10	Cycling	25	1C	AGM	80	2	
803	11	Cycling	25	1C	AGM	80	2	
803	12	Cycling	25	1C	AGM	80	2	
803	13	Cycling	25	1C	AGM	80	2	
803	14	Cycling	25	1C	AGM	80	2	
803	15	Cycling	25	1C	AGM	80	2	
803	16	Cycling	25	1C	AGM	80	2	
803	17	Cycling	25	1C	AGM	80	2	
803	18	Cycling	25	1C	AGM	80	2	
803	19	Cycling	25	1C	AGM	80	2	28
803	20	Cycling	25	1C	AGM	80	2	8
803	21	Cycling	25	1C	AGM	80	2	11
804	1	Vortest						
804	2	Cycling	25	1C	AGM	80	50	
804	3	Cycling	25	1C	AGM	80	50	
804	4	Cycling	25	1C	AGM	80	50	
804	5	Cycling	25	1C	AGM	80	50	7
804	6	Cycling	25	1C	AGM	80	50	7
804	7	Cycling	25	1C	AGM	80	50	7
805	1	Vortest						
805	2	Cycling	25	1C	AGM	80	10	3
805	3	Cycling	25	1C	AGM	80	10	4
808	1	Vortest						
808	2	Cycling	-10	1C	AGM	80	2	
808	3	Cycling	-10	1C	AGM	80	2	6
808	4	Cycling	-10	1C	AGM	80	2	
808	5	Cycling	-10	1C	AGM	80	2	
808	6	Cycling	-10	1C	AGM	80	2	
808	7	Cycling	-10	1C	AGM	80	2	

Battery #	Test #	Type Test	Temperature (ºC)	Current rate	Type	StartSoc (%)	DoD (%)	# of blocks
808	8	Cycling	-10	1C	AGM	80	2	
808	9	Cycling	-10	1C	AGM	80	2	
808	10	Cycling	-10	1C	AGM	80	2	
808	11	Cycling	-10	1C	AGM	80	2	
808	12	Cycling	-10	1C	AGM	80	2	8
808	13	Cycling	-10	1C	AGM	80	2	6
808	14	Cycling	-10	1C	AGM	80	2	4
809	1	Vortest						
809	2	Cycling	-10	1C	AGM	80	10	
809	3	Cycling	-10	1C	AGM	80	10	
809	4	Cycling	-10	1C	AGM	80	10	
809	5	Cycling	-10	1C	AGM	80	10	
809	6	Cycling	-10	1C	AGM	80	10	
809	7	Cycling	-10	1C	AGM	80	10	
809	8	Cycling	-10	1C	AGM	80	10	
809	9	Cycling	-10	1C	AGM	80	10	
809	10	Cycling	-10	1C	AGM	80	10	
809	11	Cycling	-10	1C	AGM	80	10	
809	12	Cycling	-10	1C	AGM	80	10	
809	13	Cycling	-10	1C	AGM	80	10	
809	14	Cycling	-10	1C	AGM	80	10	
809	15	Cycling	-10	1C	AGM	80	10	
809	16	Cycling	-10	1C	AGM	80	10	
809	17	Cycling	-10	1C	AGM	80	10	
809	18	Cycling	-10	1C	AGM	80	10	4
809	19	Cycling	-10	1C	AGM	80	10	2
902	1	Vortest	25		Flooded			3
902	2	Cycling	25	1C	Flooded	80	2	10
902	3	Cycling	25	1C	Flooded	80	2	
902	4	Cycling	25	1C	Flooded	80	2	
914	1	Vortest	25		Flooded			3
914	2	Cycling	25	1 C	Flooded	80	20	
914	3	Cycling	25	1 C	Flooded	80	20	4
914	4	Error	-	-	-	-	-	-
914	5	Cycling	25	1 C	Flooded	80	20	2
918	1	Vortest	25		Flooded			3
918	2	Cycling	25	1 C	Flooded	80	1	8
918	3	Kaptest	25	1 C	Flooded			3
919	1	Vortest	25		Flooded			3
919	2	Cycling	25	1 C	Flooded	80	5	24
921	1	Vortest	25		Flooded			3
921	2	Cycling	25	1 C	Flooded	95	2	6

Table 8-1: Measurement data available

8.2 Maximum and minimum voltage (V) Vs. Time (s)

The following figures show the maximum and minimum voltage in the measurements data used in the thesis. The method to obtain the voltages and the explanation about these voltages are the same than in chapter 4, but the obtained results are different in each case.

- AGM battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 50 %

The maximum voltage varies during cycling, which is 12.53 V at the beginning, and the minimum voltage in discharge cycles is about 10.5 V (see figure 8-1).

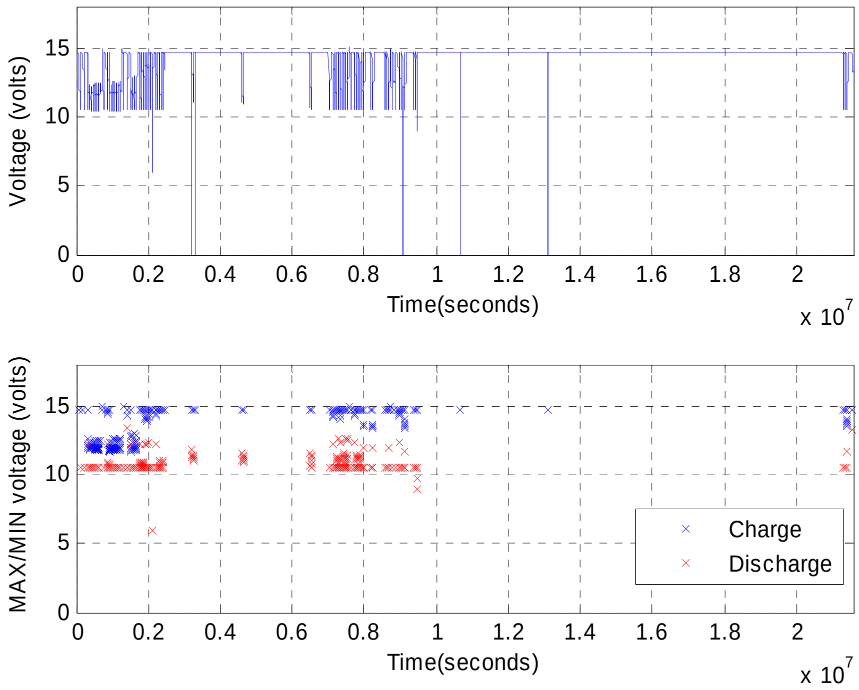

Figure 8-1: Voltage Vs. Time for the defined operational conditions

- AGM battery, temperature = 25 ºC, current rate = 1C, SoC = 80 % and DoD = 10 %

As observed in figure 8-2, the obtained results have a 14.7 V maximum voltage for charge cycles, and for discharge cycles the minimum voltage varies from 11.7 V to 10.5 V. The cycling duration on the first block is long.

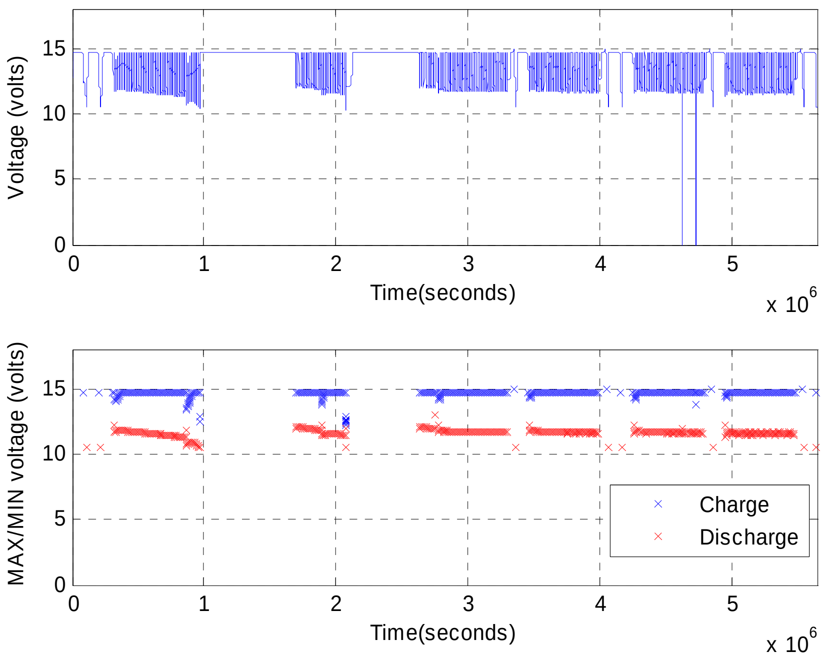

Figure 8-2: Voltage Vs. Time for the defined operational conditions

- AGM battery, temperature = -10 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

As observed in figure 8-3, the maximum voltage is 14.7 V, and between 11.5 V and 12 V for the minimum. The maximum voltage decreases as cycling occurs, which is somewhere around 13.5 V in the last cycles of this measurement data.

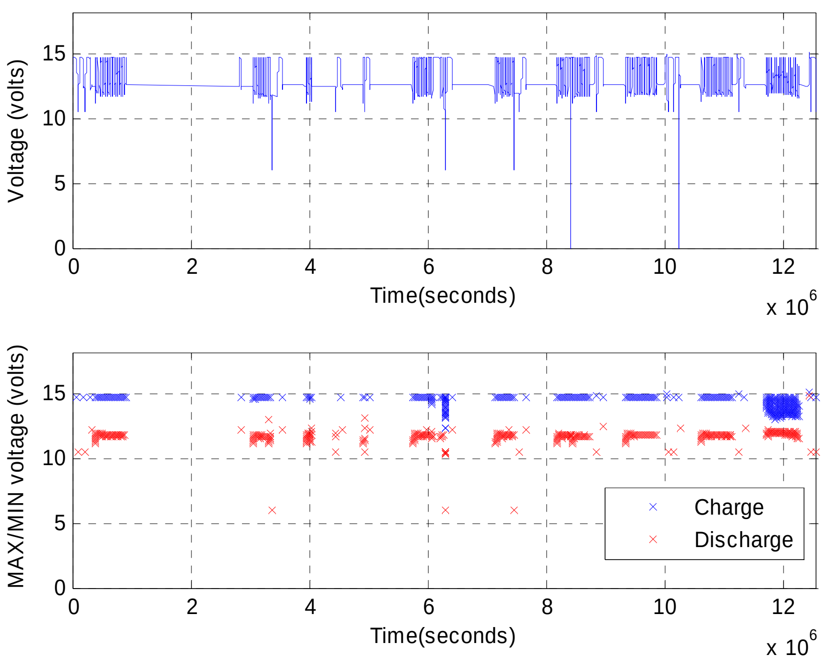

Figure 8-3: Voltage Vs. Time for the defined operational conditions

- AGM battery, temperature = -10 ºC, current rate = 1C, SoC = 80 % and DoD = 10 %

The values obtained for the maximum voltage are between 14.7 V and 13 V during the charge cycles while in discharge cycles the minimum voltage is between 11.81 V and 10 V (see figure 8-4).

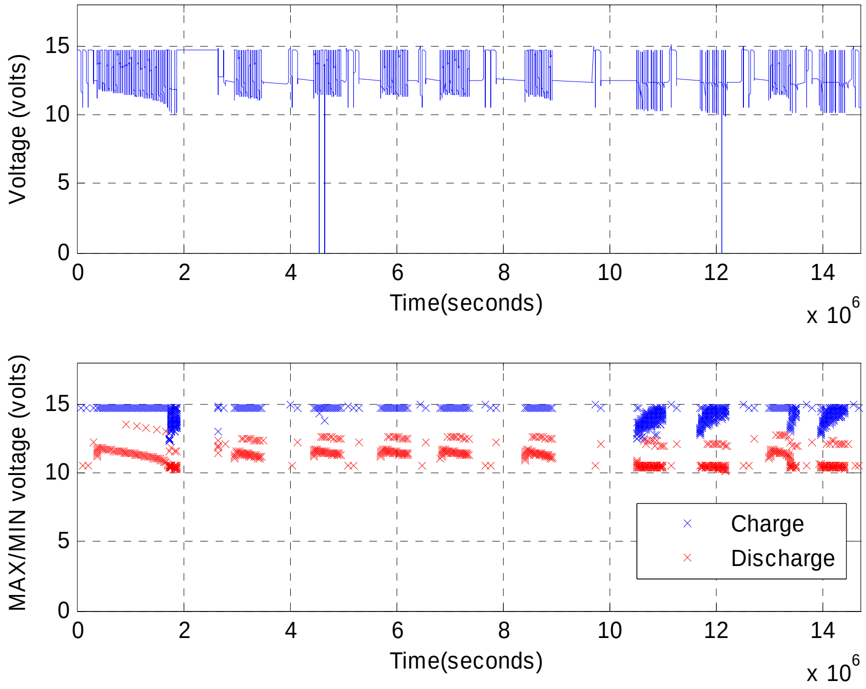

Figure 8-4: Voltage Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

The maximum voltage in charge cycles is 14.7 V, while the minimum voltage varies from 12 V to 10.5 V during discharge cycles. As observed in figure 8-5, the minimum values decrease when the number of charge and discharge cycles increase.

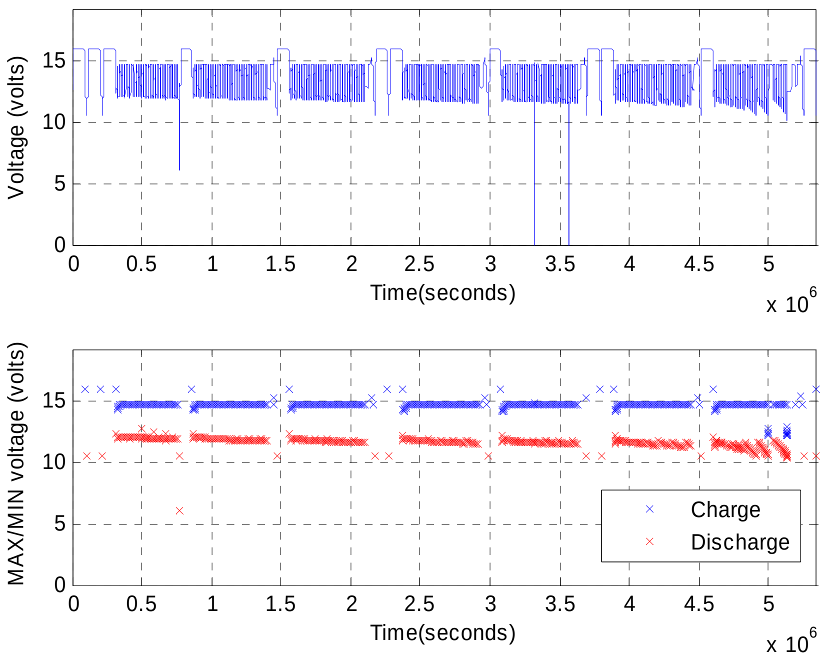

Figure 8-5: Voltage Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 ºC, current rate = 1C, SoC = 80 % and DoD = 1%.

In this case, the maximum voltage is 14.7 V for charge cycles and, for discharge cycles the minimum voltage decrease from 12.43 V to 10 V (see figure 8-6).

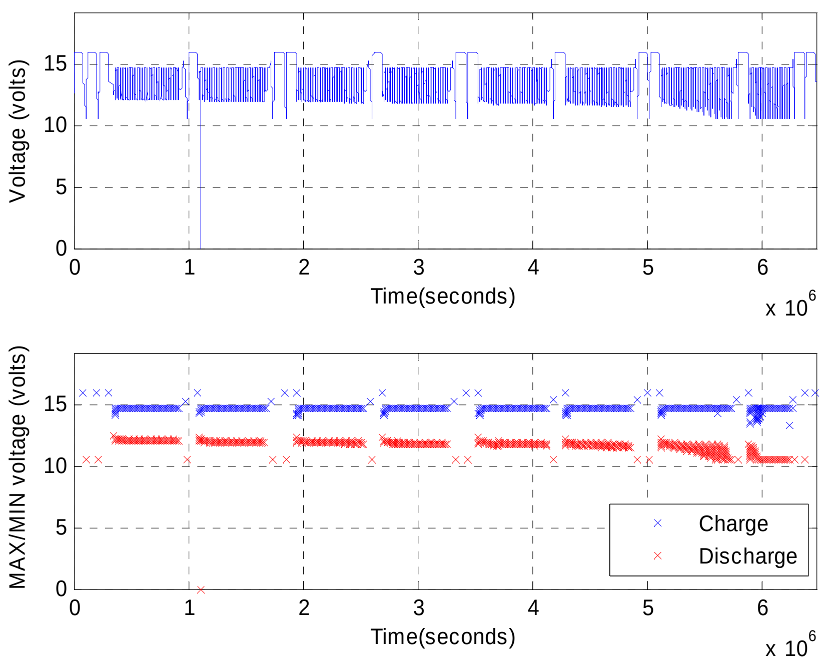

Figure 8-6: Voltage Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 5 %

The maximum voltage obtained in charge cycles is 14.7 V, while the minimum voltage varies from 12.1 V to 10.5 V during discharge cycles. The minimum values decrease when the number of charge and discharge cycles increase (see figure 8-7).

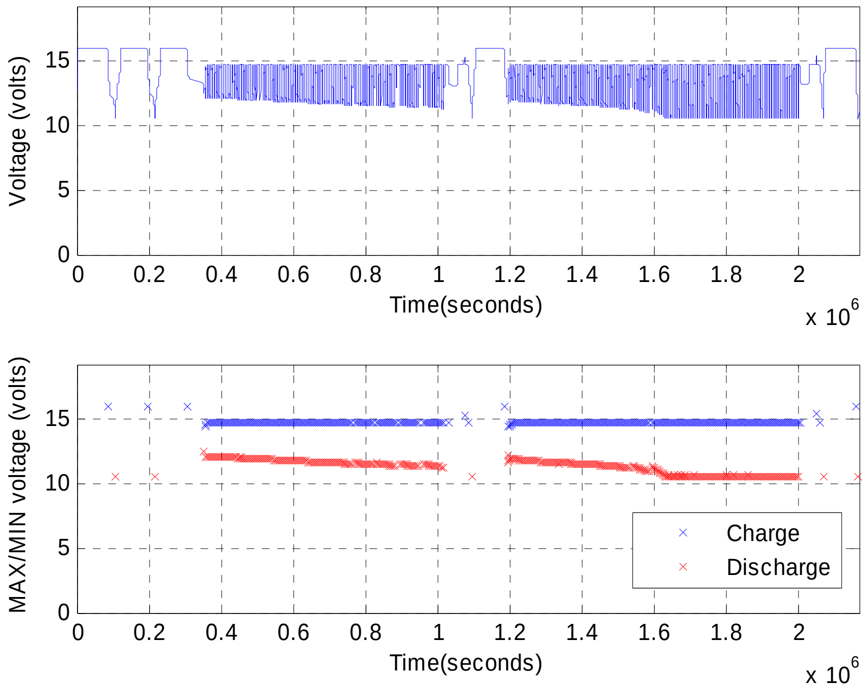

Figure 8-7: Voltage Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 95 % and DoD = 2 %

This measurement data has a higher SoC (%). In this case, it has been obtained a maximum voltage during the charge cycles of 14.7 V and a minimum voltage that varies from 12.5 V to 10.5 V in the last cycles of the measurement data (see figure 8-8).

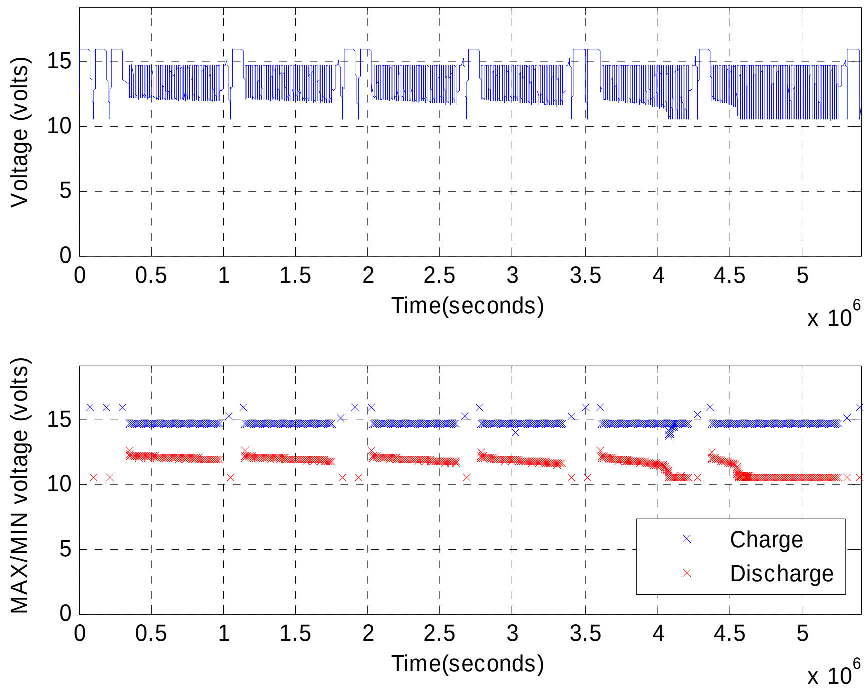

Figure 8-8: Voltage Vs. Time for the defined operational conditions

8.3 Depth of discharge (DoD) Vs. Time (s)

The following figures determine if the DoD (%) is constant over time. Depending of the defined operational conditions, different results for each measurement data had been determined.

- AGM battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 50 %

The DoD during cycling is constant but along the measurement data for the defined operational conditions is changing continuously due to the capacity test points or because the battery state is paused. Therefore the obtained results are not correct due to that there is not enough cycling (see figure 8-9).

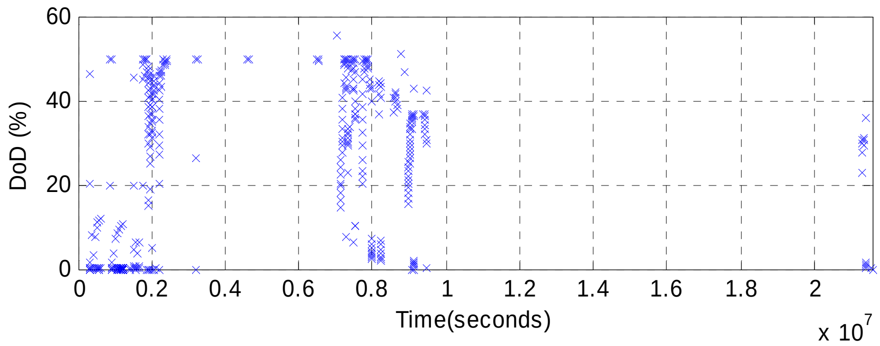

Figure 8-9: DoD Vs. Time for the defined operational conditions

- AGM battery, temperature = 25 ºC, current rate = 1C, SoC = 80 % and DoD = 10 %

In this case, the DoD remains constant at 10 % (see figure 8-10).

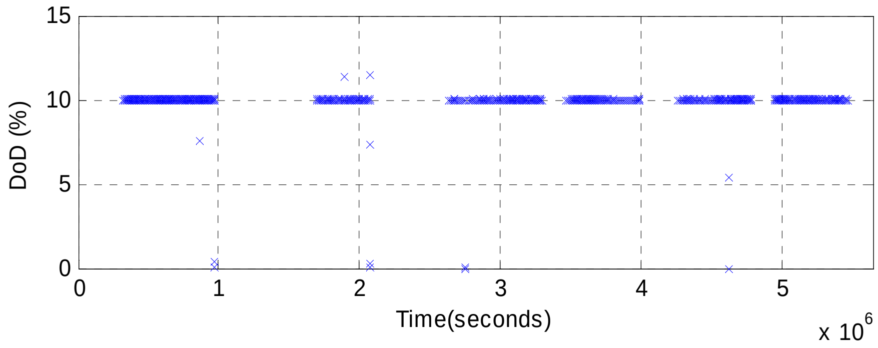

Figure 8-10: DoD Vs. Time for the defined operational conditions

- AGM battery, temperature = -10 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

During cycling the DoD is 2 % along the measurement data but there are some points under the normal value, this can be caused by the battery state being paused (see figure 8-11).

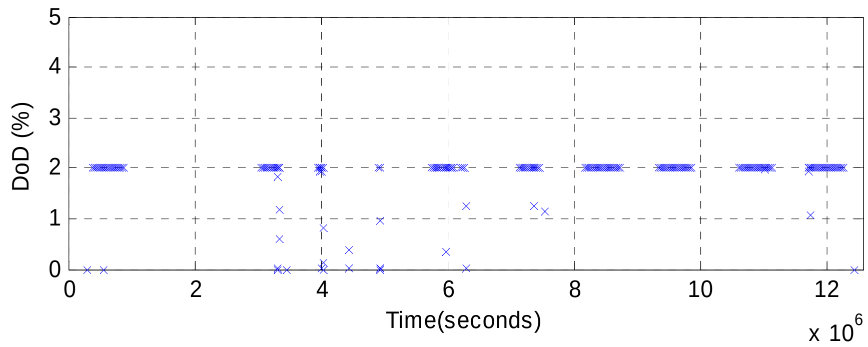

Figure 8-11: DoD Vs. Time for the defined operational conditions

- AGM battery, temperature = -10 °C, current rate = 1C, SoC = 80 % and DoD = 10 %

There are a lot of cycles and the DoD during cycling is constant but there are some points out of the modelled DoD at 10 % because the battery state remained paused or capacity test points have been done (see figure 8-12).

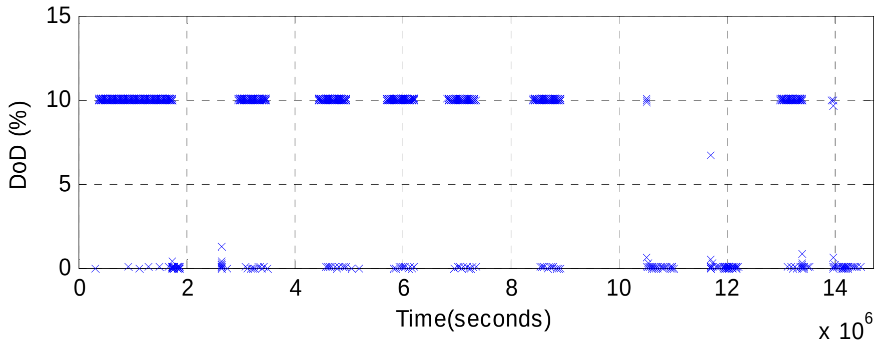

Figure 8-12: DoD Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

During cycling the DoD is constant at 2 % (see figure 8-13).

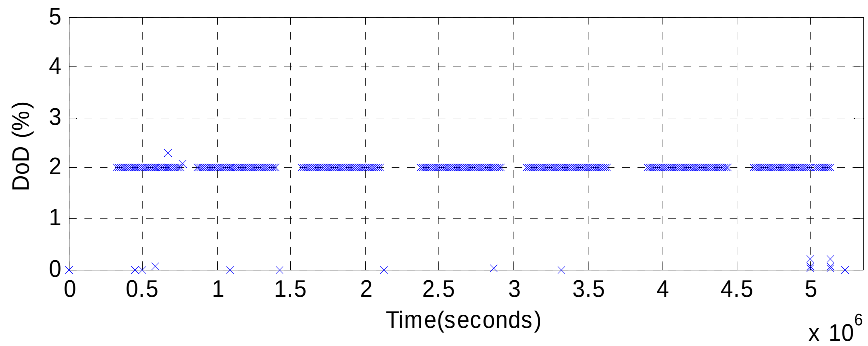

Figure 8-13: DoD Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 1 %

The DoD is just 1 % along the measurement data but at the end of it the DoD decreases due to the battery capacity is less than 50 % of its original value (see figure 8-14).

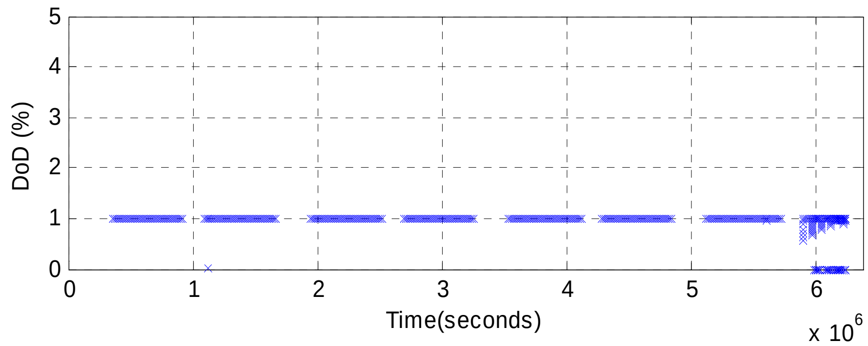

Figure 8-14: DoD Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 5 %

During cycling the DoD is constant at 5 % (see figure 8-15).

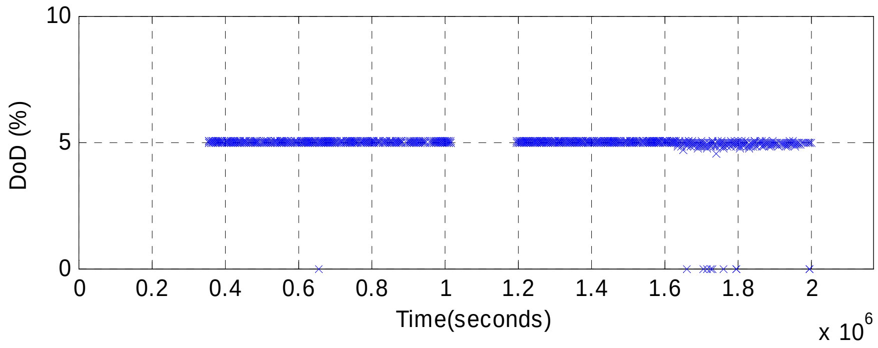

Figure 8-15: DoD Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 95 % and DoD = 2 %

Figure 8-16 shows the DoD exactly at 2 % during the cycling but in the last points of the measurement data it decreases exponentially until 0.25 % because the battery capacity is less than 50 % of its original value.

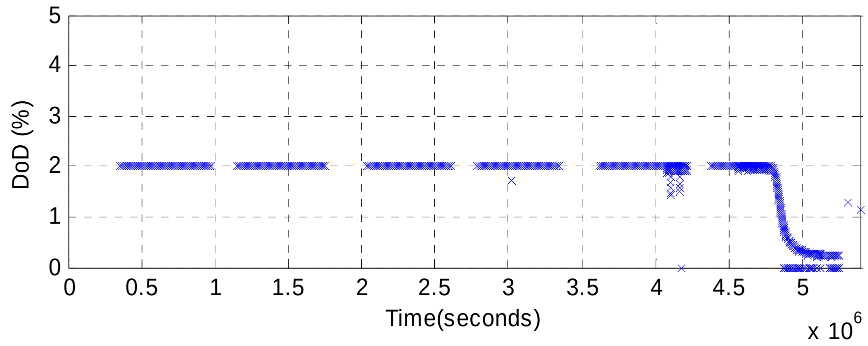

Figure 8-16: DoD Vs. Time for the defined operational conditions

8.4 Real battery temperature (°C)

The following figures show the real battery temperature in each measurement data. There is shown the temperature over time; its envelope has to match with the values obtained for the tests.

- AGM battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 50 %

As observed in figure 8-17 the temperature reaches around -260 ºC and this is due to a measurement error, but in figure 8-18 is possible to observe the same graph without that measurement error.

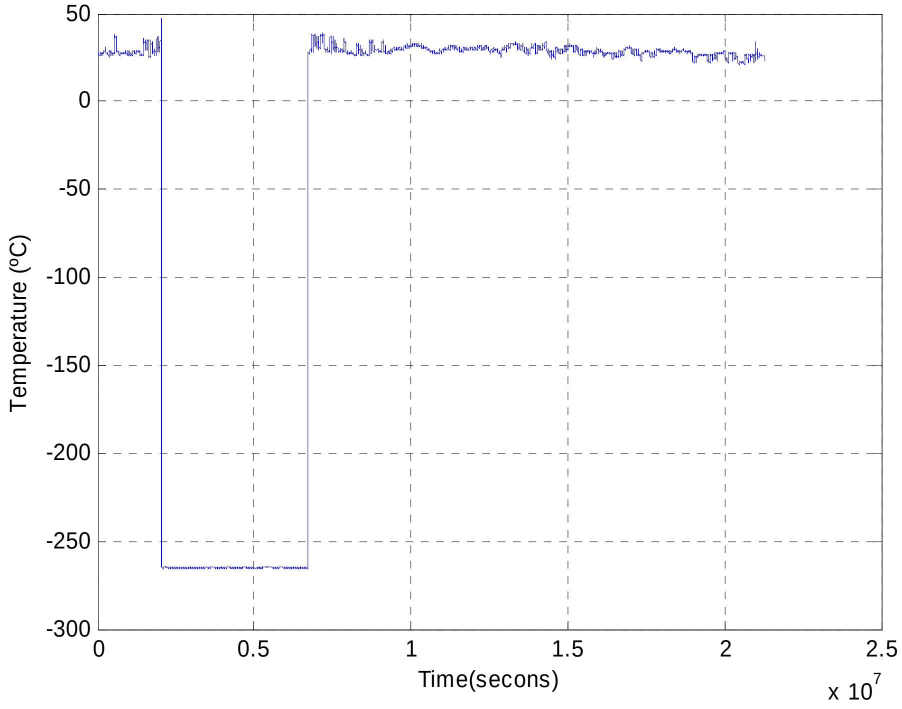

Figure 8-17: Real temperature Vs. Time for the defined operational conditions (zoom)

The real battery temperature varies from 21 ºC to 39 ºC. The average real battery temperature over time (without the measurement error) for the defined operational conditions is around 31 °C (see figure 8-18).

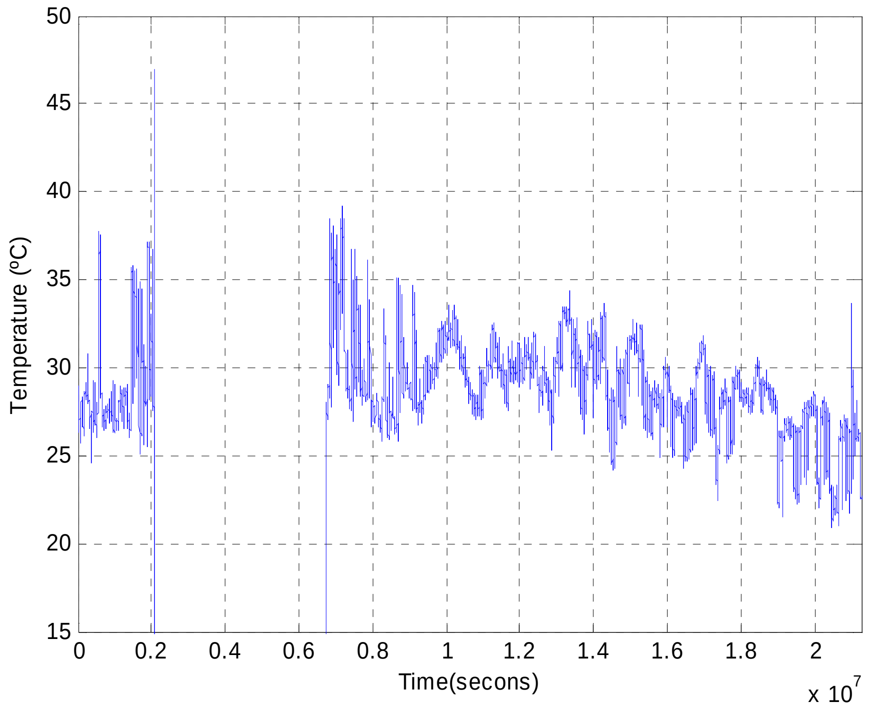

Figure 8-18: Real temperature Vs. Time for the defined operational conditions

- AGM battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 10 %

For these operational conditions has been obtained an average real battery temperature equivalent to 34 °C (see figure 8-19).

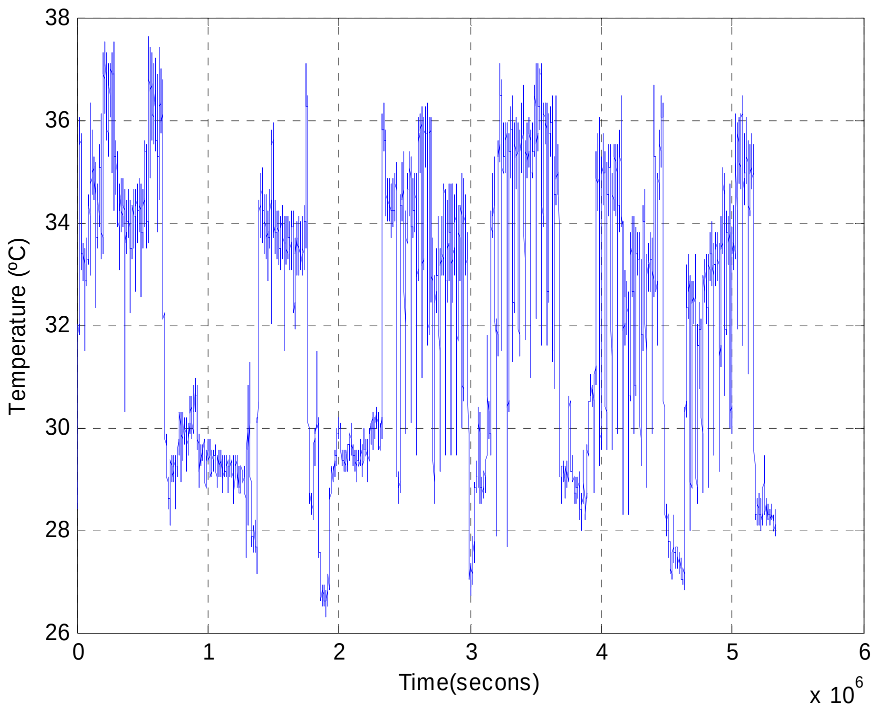

Figure 8-19: Real temperature Vs. Time for the defined operational conditions

- AGM battery, temperature = -10 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

In this case, it can be observed as the real temperature along the measurement data varies during cycling between -4.7 °C to 6.3 ºC; except for the capacity tests which value is 25 °C and, at the end of the measurement is observed a measurement error. The average real battery temperature is around 0.5 °C (see figure 8-20).

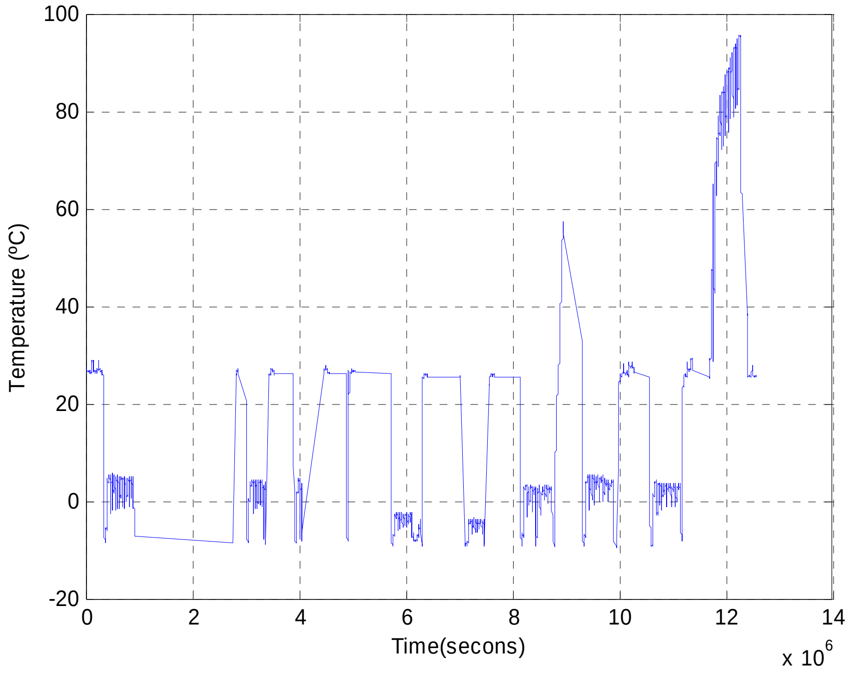

Figure 8-20: Real temperature Vs. Time for the defined operational conditions

- AGM battery, temperature = -10 °C, current rate = 1C, SoC = 80 % and DoD = 10 %

The real battery temperature for the defined operational conditions oscillates between -8 ºC to 6 ºC. Therefore, the average real battery temperature is around 3 °C, removing the capacity test points and the measurement error temperature (see figure 8-21).

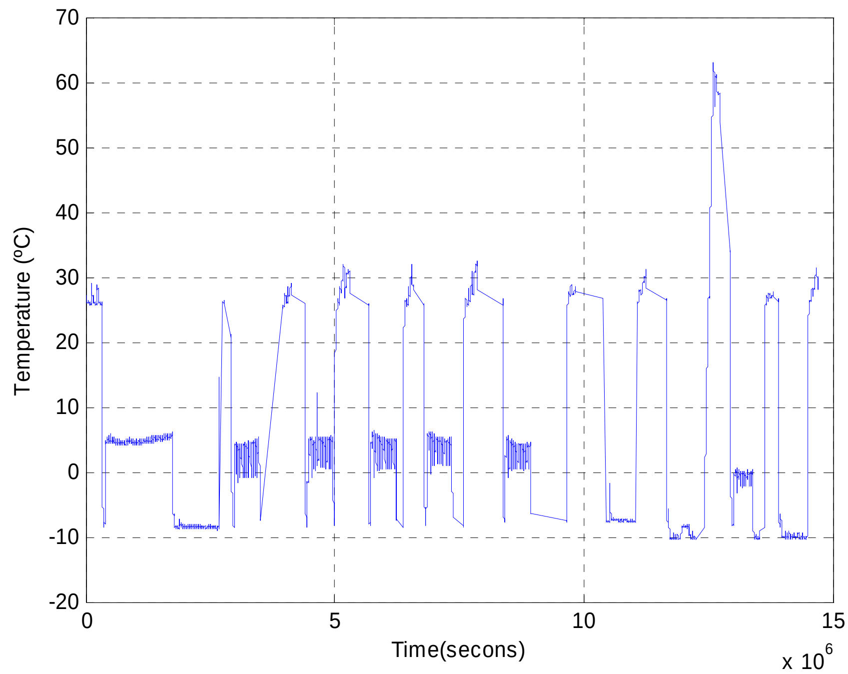

Figure 8-21: Real temperature Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

Temperatures in figure 8-22 oscillate between 22 °C and 34 °C. Therefore, the average real battery temperature is around 28.5 °C.

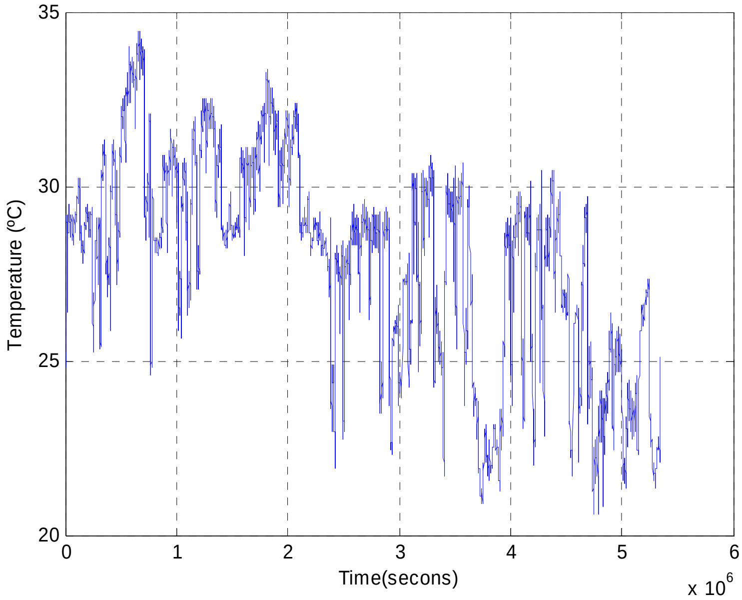

Figure 8-22: Real temperature Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 1 %

The average real battery temperature in this measurement data is around 28 °C (temperature values between 23.5 °C to 31 °C). See figure 8-23:

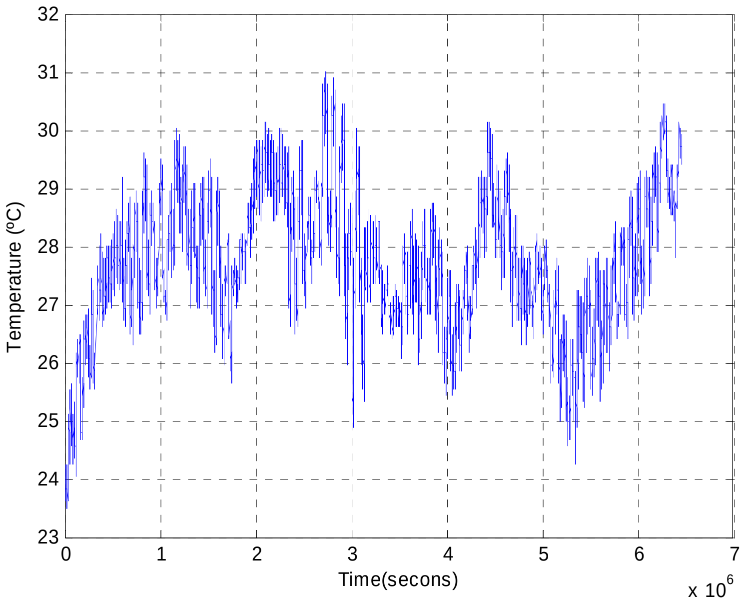

Figure 8-23: Real temperature Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 5 %

The average real battery temperature in this measurement data is around 27.8 °C (temperature values between 23.5 °C to 30 °C). See figure 8-24:

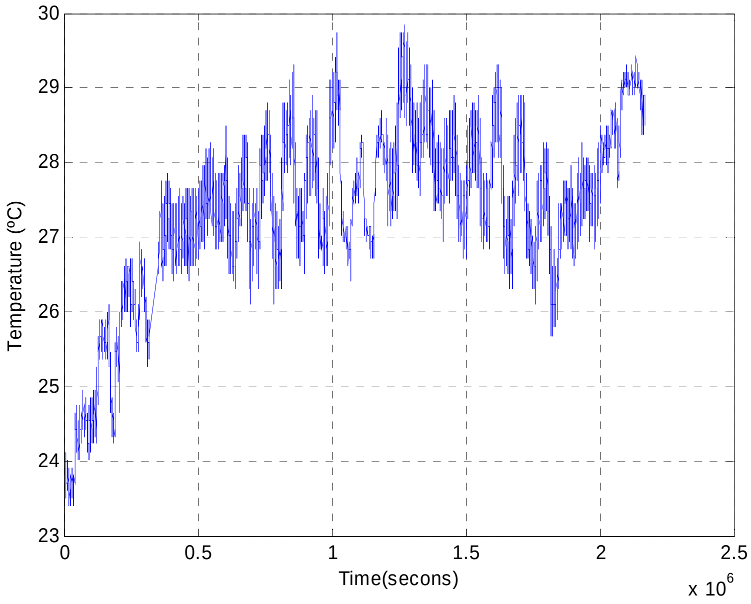

Figure 8-24: Real temperature Vs. Time for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 95 % and DoD = 2 %

The average real battery temperature obtained in this case is around 26.7 °C. The maximum temperature is 32 °C and, 21 °C for the minimum (see figure 8-25).

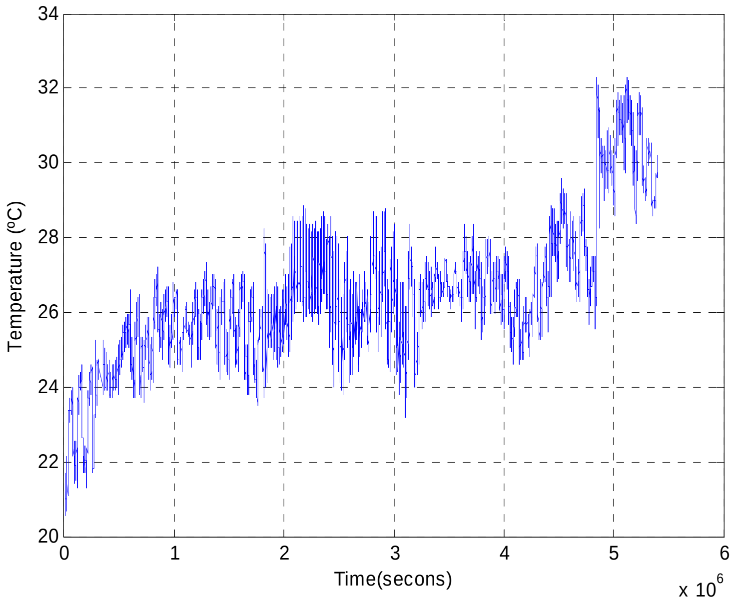

Figure 8-25: Real temperature Vs. Time for the defined operational conditions

8.5 Capacity (Ah) Vs. Number of full cycle equivalent (# FCE)

The following figures and tables (they are associated at each figure) determine all capacity test points obtained for each measurement data used in EN and OP full charge.

- AGM battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

Figure 8-26 determines the capacity profile (capacity test points) for these operational conditions and the frequency at 50 % capacity for EN full charge and OP full charge, being these values 1400 FCE and 1000 FCE, respectively.

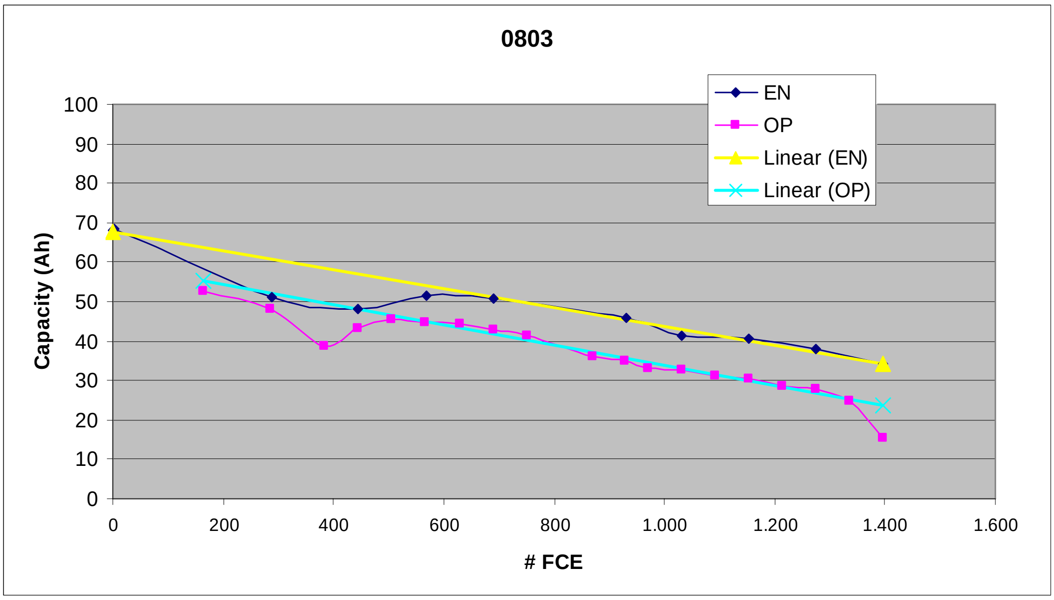

Figure 8-26: Capacity Vs. # FCE for the defined operational conditions

Table associated at the operational conditions obtained in figure 8-26:

EN		OP	
# FCE	**Capacity (Ah)**	**# FCE**	**Capacity (Ah)**
1	**68,2301**	**165**	**52,758**
2	**68,2743**	**287**	**48,1595**
288	**51,1855**	**383**	**38,718**
445	**48,1331**	**444**	**43,2202**
567	**51,6757**	**506**	**45,3349**
690	**50,7279**	**567**	**44,7496**
930	**45,6956**	**628**	**44,332**

1.032	41,5132	689	42,8303
1.153	40,648	751	41,4907
1.275	37,9633	869	36,2203
1.397	34,0255	930	35,1477
		970	33,1876
		1.031	32,6014
		1.092	31,1528
		1.153	30,461
		1.214	28,6463
		1.275	27,7555
		1.336	24,875
		1.396	15,5327

Table 8-2: Measurement data for the defined operational conditions

- AGM battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 50 %

In this case, there are a few capacity test points for the defined operational conditions. By observing the capacity profile at 50 % of it, it is determined close to 145 FCE in both full charges (see figure 8-27).

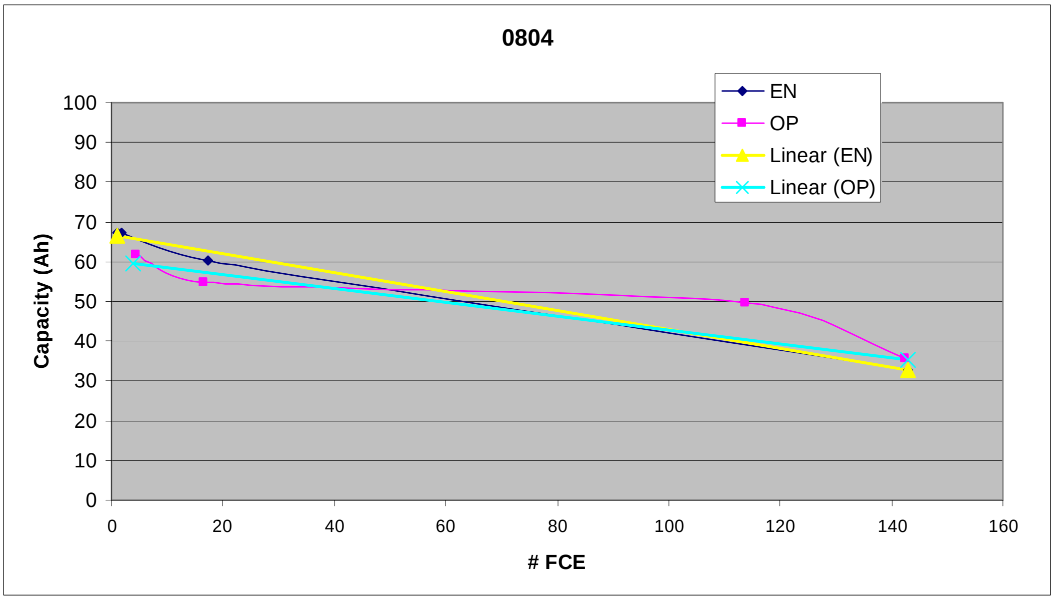

Figure 8-27: Capacity Vs. # FCE for the defined operational conditions

Table associated at the operational conditions obtained in figure 8-27:

EN		OP	
# FCE	**Capacity (Ah)**	**# FCE**	**Capacity (Ah)**
1	**67,4557**	**4**	**61,8617**
2	**67,4106**	**17**	**54,9052**
17	**60,4082**	**114**	**49,8104**
143	**32,7895**	**143**	**35,6167**

Table 8-3: Measurement data for the defined operational conditions

- AGM battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 10 %

There are only three tests in this measurement data, therefore a few capacity test points. The obtained result at 50 % capacity is around 320 FCE for EN full charge (see figure 8-28).

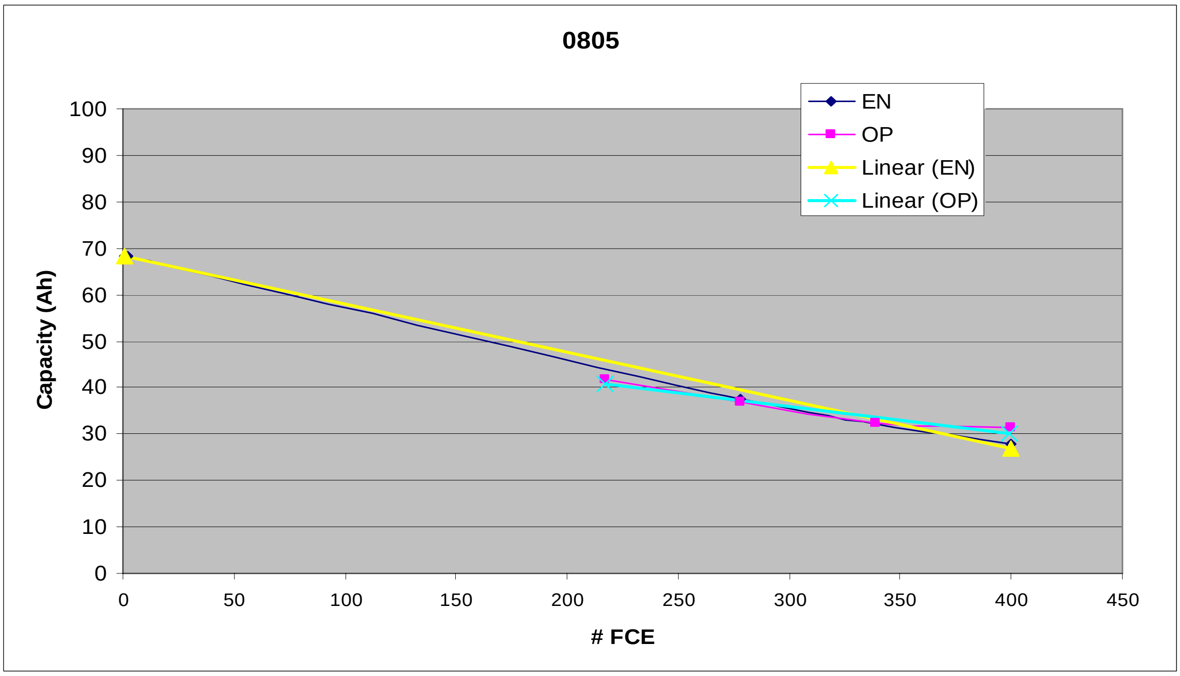

Figure 8-28: Capacity Vs.# FCE for the defined operational conditions

Table associated at the operational conditions obtained in figure 8-28:

EN		OP	
# FCE	Capacity (Ah)	# FCE	Capacity (Ah)
1	68,3711	217	41,6841
2	68,3704	278	36,8848
278	37,6503	339	32,442
400	27,9479	399	31,2475

Table 8-4: Measurement data for the defined operational conditions

- AGM battery, temperature = -10 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

In this case the temperature changed to -10 ºC. Figure 8-29 shows an incorrect model because the tendency lines in both cases (EN and OP full charge) do not pass through the capacity test points. Therefore it is not possible to calculate the frequency.

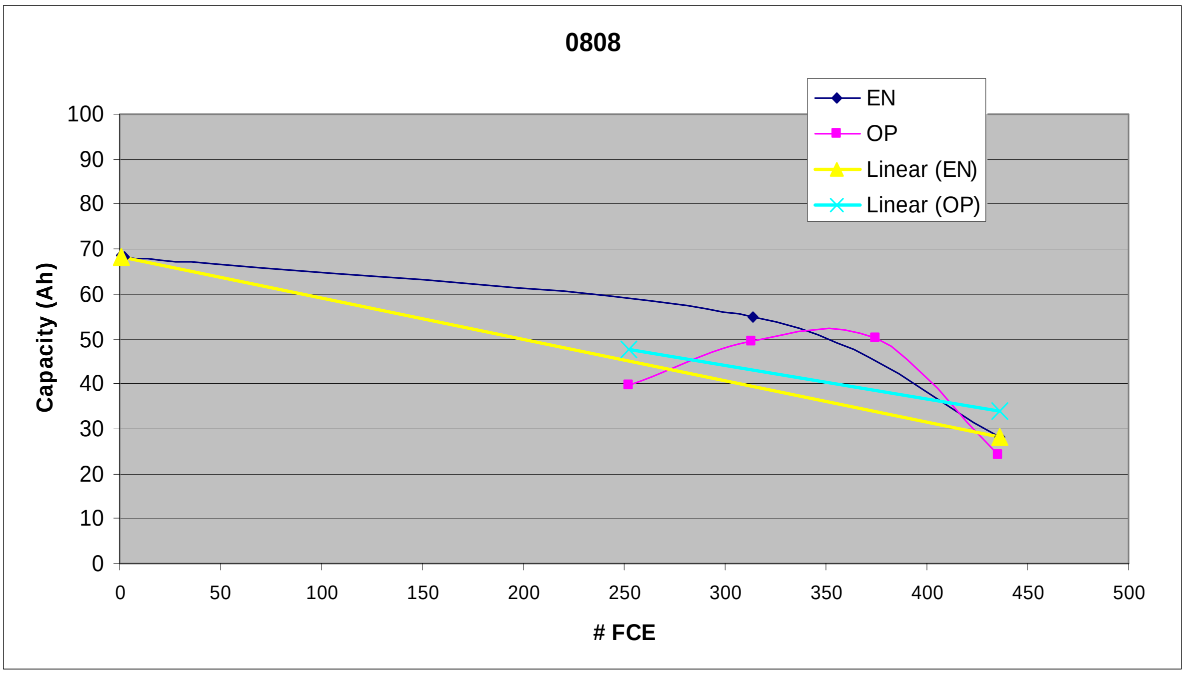

Figure 8-29: Capacity Vs. # FCE for the defined operational conditions

Table associated at the operational conditions obtained in figure 8-29:

EN		OP	
# FCE	Capacity (Ah)	# FCE	Capacity (Ah)
1	68,4202	252	39,7581
2	68,2766	313	49,4454
314	54,9336	375	50,2244
436	28,0543	436	24,2255

Table 8-5: Measurement data for the defined operational conditions

- AGM battery, temperature = -10 °C, current rate = 1C, SoC = 80 % and DoD = 10 %

The temperature is also -10 ºC and the obtained frequency values for EN and OP full charge are 460 FCE and 500 FCE, respectively (figure 8-30).

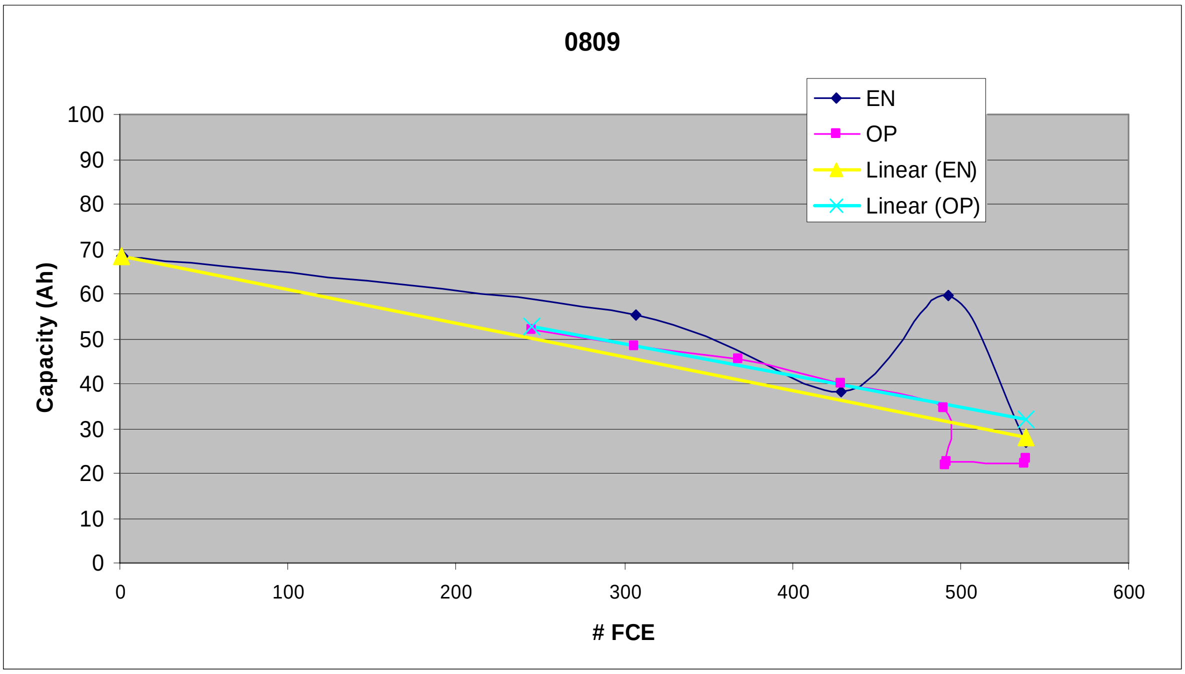

Figure 8-30: Capacity Vs. # FCE for the defined operational conditions

Table associated at the operational conditions obtained in figure 8-30:

EN		OP	
# FCE	Capacity (Ah)	# FCE	Capacity (Ah)
1	68,3085	245	51,8684
2	68,2018	306	48,4664
307	55,2812	368	45,3526
429	38,2179	429	40,1333
493	59,5229	490	34,4545
539	26,7374	491	21,8912
		492	22,6279
		538	22,1083
		539	23,3449

Table 8-6: Measurement data for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 2 %

The capacity profile for these operational conditions shows how the tendency line passes through almost every capacity test points. The frequency in this situation is 280 FCE for an EN full charge and 240 FCE for an OP full charge.

For these conditions the type battery is flooded and values for the FCE are less than in AGM batteries (see figure 8-31).

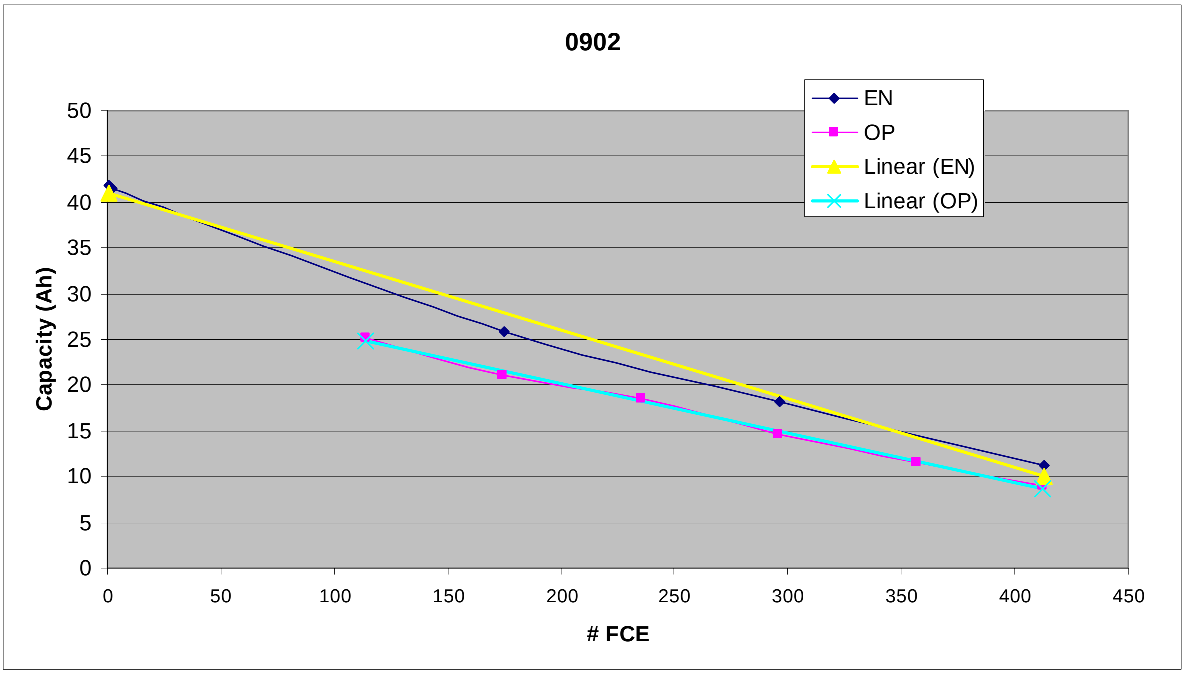

Figure 8-31: Capacity Vs. # FCE for the defined operational conditions

Table associated at the operational conditions obtained in figure 8-31:

EN		OP	
# FCE	**Capacity (Ah)**	**# FCE**	**Capacity (Ah)**
1	**41,8114**	**114**	**25,107**
2	**41,4593**	**174**	**21,0262**
175	**25,8916**	**235**	**18,552**
296	**18,248**	**296**	**14,6936**
413	**11,1602**	**357**	**11,5601**
		412	**8,9411**

Table 8-7: Measurement data for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 80 % and DoD = 5 %

In this case the line curve passes exactly through all capacity test points but it is not a good approximation because there only exist three points for EN full charge and two for OP full charge (see figure 8-32); two points defines a straight line.

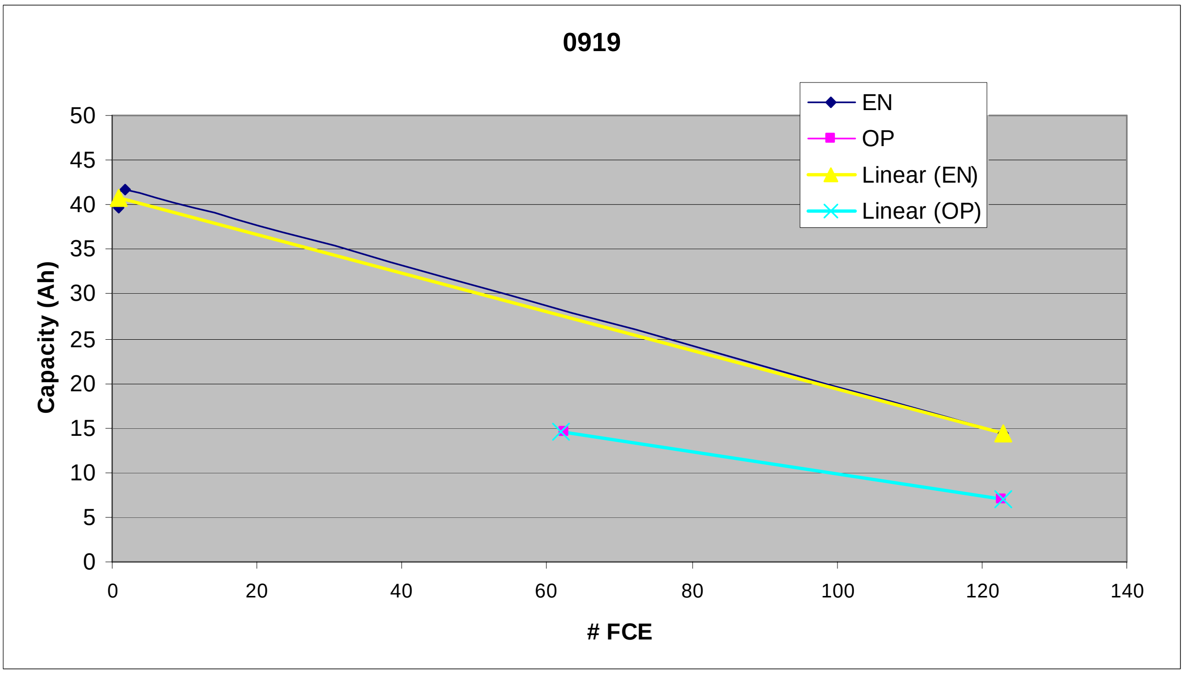

Figure 8-32: Capacity Vs. # FCE for the defined operational conditions

Table associated at the operational conditions obtained in figure 8-32:

EN		OP	
# FCE	**Capacity (Ah)**	**# FCE**	**Capacity (Ah)**
1	**39,7184**	**62**	**14,5622**
2	**41,7893**	**123**	**7,0157**
123	**14,3131**		

Table 8-8: Measurement data for the defined operational conditions

- Flooded battery, temperature = 25 °C, current rate = 1C, SoC = 95 % and DoD = 2 %

Until 250 FCE the tendency line passes through the capacity test points. After that, the linear model do not follows these points (see figure 8-33). Therefore it would not be reasonable to obtain the values of the FCE for both strategies; EN and OP full charge.

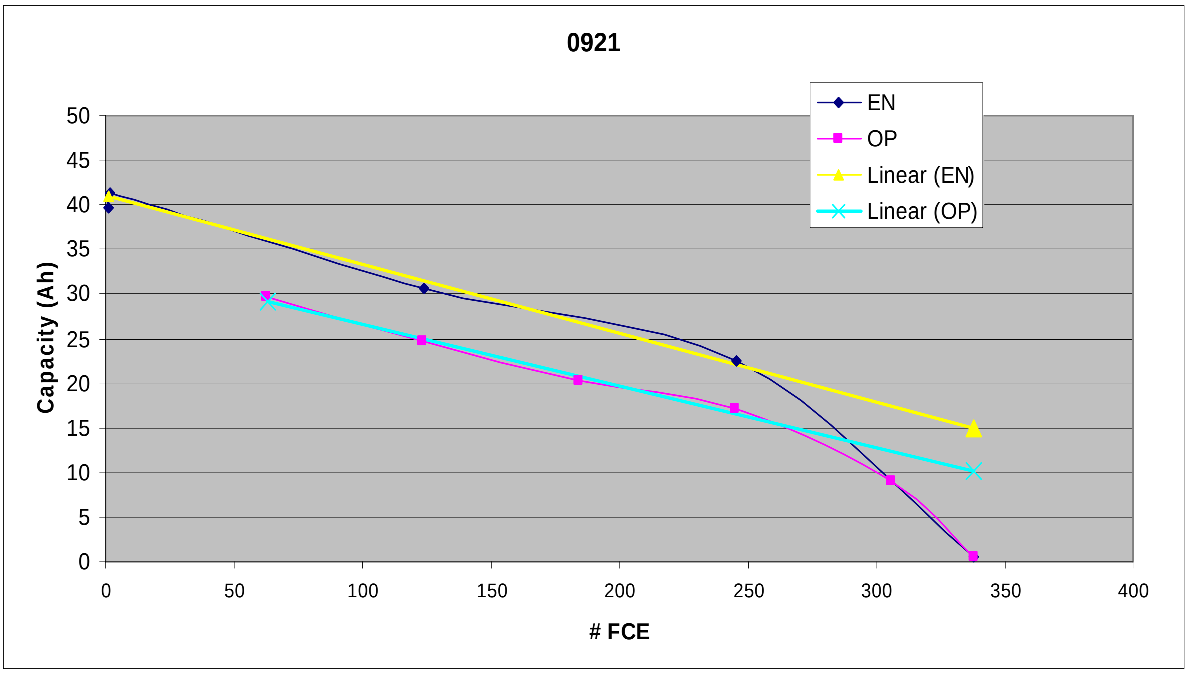

Figure 8-33: Capacity Vs. # FCE for the defined operational conditions

Table associated at the operational conditions obtained in figure 8-33:

EN		OP	
# FCE	**Capacity (Ah)**	**# FCE**	**Capacity (Ah)**
1	**39,7276**	**63**	**29,6795**
2	**41,3383**	**123**	**24,7433**
124	**30,6406**	**184**	**20,2156**
245	**22,4657**	**245**	**17,176**
338	**0,4962**	**306**	**9,0645**
		338	**0,55984**

Table 8-9: Measurement data for the defined operational conditions

8.6 Number of full cycle equivalent (# FCE) Vs. Depth of discharge (DoD)

The following figures and tables show measurements data with the same operational conditions only changing their DoDs, which value is corresponded when the capacity is just at 50 % for EN and OP full charge.

- AGM batteries, temperature = 25 °C, current rate = 1C and SoC = 80 %

As observed in figures 8-34 and 8-35, number of FCE in EN and OP full charge decreases when the DoD is higher, because in small DoDs the amount of charge respecting to the nominal capacity is less, and for this reason the battery cycle life is higher and there are a higher number of FCE.

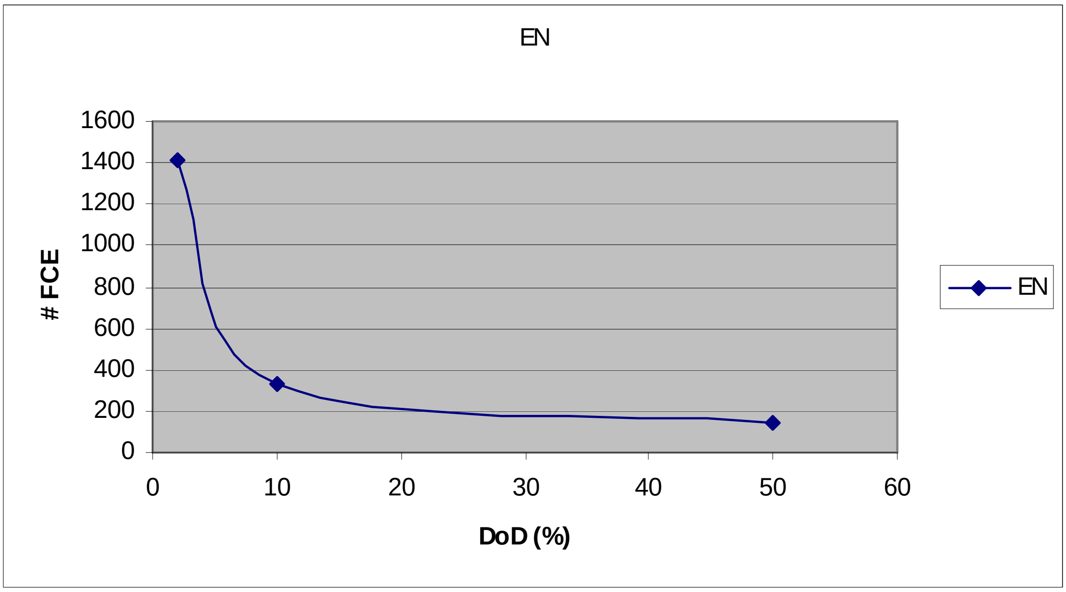

Figure 8-34: # FCE Vs. DoD for EN full charge

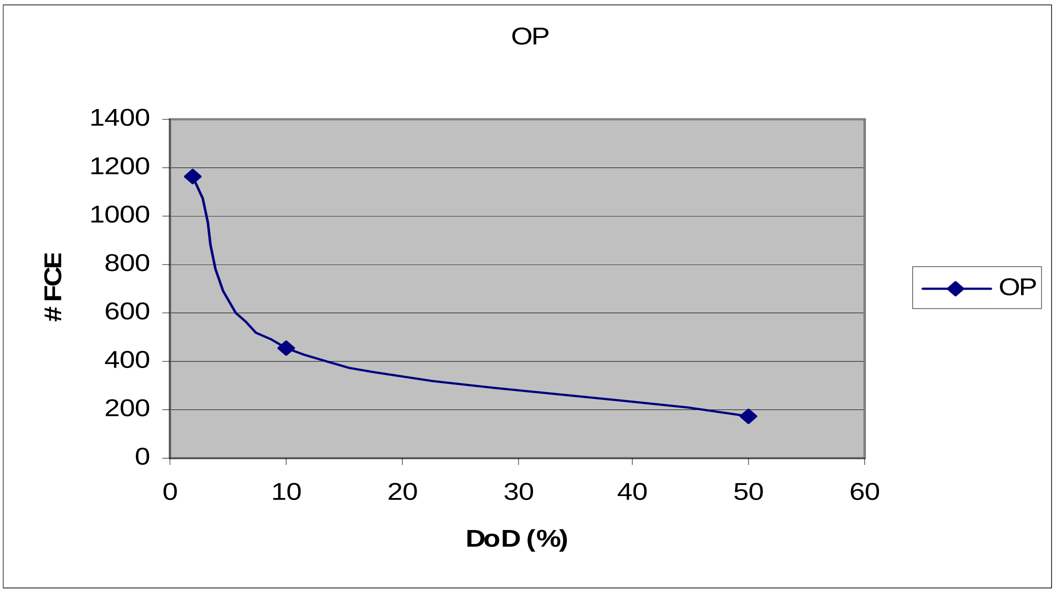

Figure 8-35: # FCE Vs. DoD for OP full charge

Table associated at the operational conditions obtained in figures 8-34 and 8-35:

File	DoD (%)	$X_{50\%}$ EN full charge	$X_{50\%}$ OP full charge
803	2	1407,9375	1163,72549
805	10	328,800578	457,180579
804	50	139,44259	172,432819

Table 8-10: AGM batteries, temperature = 25 °C, current rate = 1C and SoC = 80 %

- AGM batteries, temperature = -10 °C, current rate = 1C and SoC = 80 %

In this case, figures 8-36 and 8-37 show a less number of FCE when the DoD is higher. This situation is opposite to the actual situation that it must have.

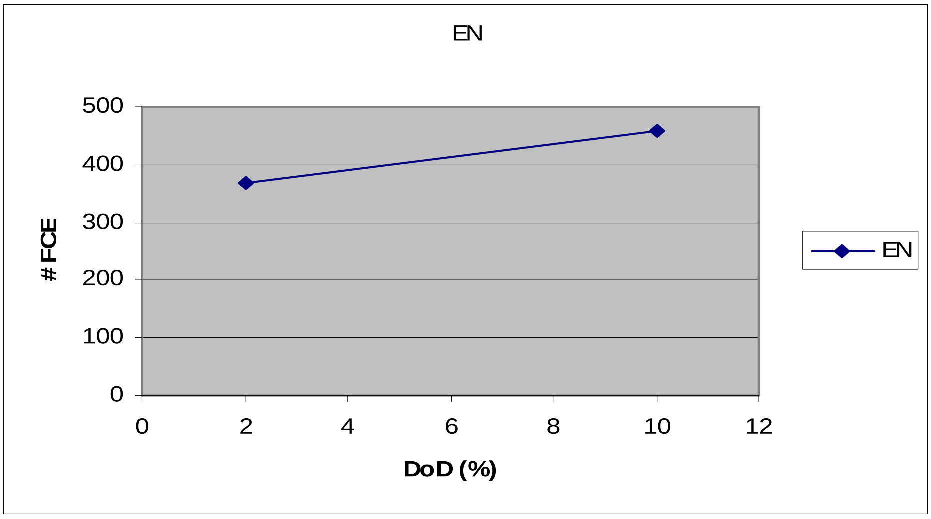

Figure 8-36: # FCE Vs. DoD for EN full charge

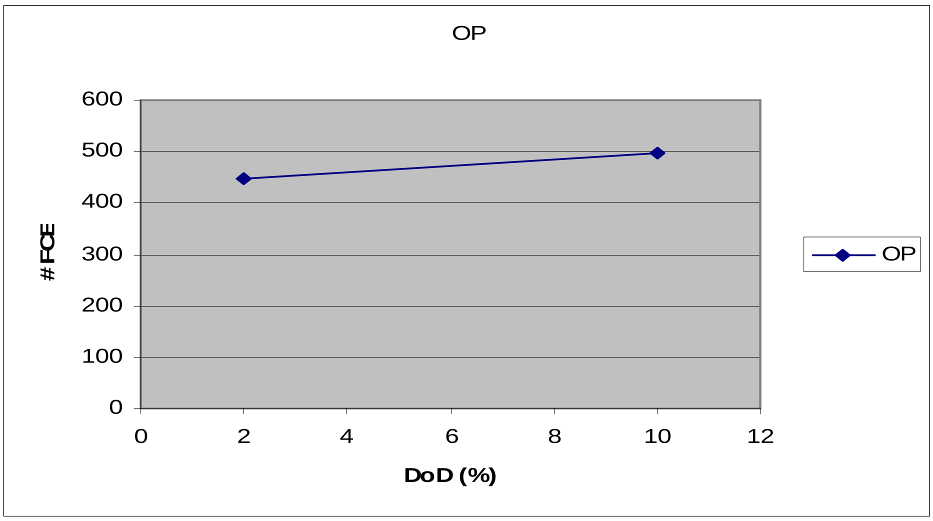

Figure 8-37: # FCE Vs. DoD for OP full charge

Table associated at the operational conditions obtained in figures 8-36 and 8-37:

File	DoD (%)	$X_{50\%}$ EN full charge	$X_{50\%}$ OP full charge
808	2	369,3851	445,8501
809	10	457,6101	495,7436

Table 8-11: AGM batteries, temperature = -10 °C, current rate = 1C and SoC = 80 %

Note that these operational conditions are not a group because there are not more measurements data in the same situation. Therefore, it can not be compared with anyone.

File	DoD (%)	$X_{50\%}$ EN full charge	$X_{50\%}$ OP full charge
921	2	264,9806	243,0318

Table 8-12: Flooded batteries, temperature = 25 °C, current rate = 1C and SoC = 95 %