CHALMERS

Parameterization of a 14.5 Ah $LiFePO_4$-battery cell

Master´s Thesis in the Master Degree Programme, Electric Power Engineering

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ABSTRACT

The environmental and economical issues with transportation have accelerated the development of plug-in hybrid electric driven vehicles. Amongst the most prominent techniques for energy storage within this field is the usage of Lithium Ion batteries. Because of this a study requested by *ETC Battery and Fuelcells Sweden AB*, has been made for investigating the performance of this technique. For this investigation a simulation model was used based on the physical parameters (*Internal Resistance* and *Open Circuit Voltage*) of the battery cell. These physical parameters were found through laboratory experiments and simulations methods which were verified through previously performed investigations. The battery cell types investigated in this study were $LiFePO_4$-ePLB F014 with capacity 14.5Ah and $LiNiCoMnO_2$-ePLB C020 with capacity 20Ah, which both are intended for a Plug-in hybrid vehicle.

Knowledge about the battery cell performance is needed for the battery system in the plug-in hybrid vehicle in order to determine its *State of Charge (SOC)* and *Power Limits* for charge and discharge. SOC is used as a fuel gauge for the battery package, i.e. it provides information on how much energy that is available in the battery. Power limits are important for the vehicle in order to limit the power outage from the battery cell.

The simulations showed a good overall accuracy of the battery model. Simulations for studying the State of Charge were also performed and these also showed an acceptable result. Since the accuracy of the model was well within acceptable error limits, the parameters may be used in a plug-in hybrid vehicle.

This project will not handle complex technical details of the battery cell, neither environmental nor economical aspects of the battery cell. Comparisons with other battery cells will not be performed nor will the simulation model be explained in detail.

Keywords: ***$LiFePO_4$-Lithium Ion battery cell, Plug-in hybrid vehicle, Battery monitoring unit, State of charge, Power limits, Battery simulation, Battery parameters***

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ABBREVIATIONS

Ah – Ampere Hours
BMU – Battery Monitoring Unit
C-Rate – Current Rate
C_{ref} – Rated capacity of the cell
DOD – Depth of Discharge
ETC – Energitekniskt Centrum
EV – Electric Vehicle
HEV – Hybrid Electric Vehicle
LiIon – Lithium Ion battery technology
$LiFePO_4$ – Cathode material with *Lithium-Iron-Phosphate* as active component
$LiCoO_2$ – Cathode material with *Lithium-Cobalt-Dioxide* as active component
$LiNiCoMnO_2$ – Cathode material with *Lithium-Nickel-Cobalt-Mangan-Dioxide* as active component
NiMH – Cathode material with *Nickel-Metal-Hydride* as active component
PHEV – Plug-In Hybrid Electric Vehicle
SOC – State of Charge
Matlab/Simulink – Mathematical software for calculation and simulation

INTRODUCTION

Chapter one gives an insight to what the report is based on, background to why the work has been made as well as what is strived for. The chapter also includes what is not handled.

1.1 Background

In the late 20th century and the beginning of the 21st the issue of global warming has been among the most frequently discussed topics. One of the most contributing factors to this problem is the usage of fossil fuel driven vehicles which release high levels of carbon dioxide into the atmosphere. Therefore the development of more environmentally friendly vehicles has emerged and is now more important than ever when the aim for a more sustainable society is set. The Hybrid technology is believed to be one of the most important solutions to this problem in the future due to its effective usage of both an electric motor and a combustion engine. This technique overcomes the problem with pure electric vehicles insufficiently short driving range due to the problem with storage of electric energy.

The storage of electric energy for transportation purposes is a modern problem and batteries are one of the solutions. But there is stil many questions and uncertainties that need to be explored in order to be fully functioning. The main issues for many of the battery cells that are used today is that the energy efficiency (energy/volume-ratio) is not as high as preferable as well as the battery weight being too high. This has resulted in the development of the powerful *Lithium-Ion (LiIon)* battery cells and this is the type of battery cell that was going to be studied in this project. A known problem with this battery technology is the safety issues related to them. Since explosions of LiIon battery cells have been known to occur, this subject is of course of mayor importance. These explosions are related to the cathodes poor ability to resist high voltage and/or high temperature, thus a new cathode material which resists maltreatment better is strived for. There are several new cathode materials on the market today and the performance of two battery cells with these new materials was investigated in this project, namely a 14.5Ah $LiFePO_4$-battery cell and a 20Ah $LiNiCoMnO_2$-battery cell. Since the method for investigation of these two and the expected result of these was similar, only the complete investigation of the 14.5Ah $LiFePO_4$-battery cell will be presented in this report. The results from the study of the 20Ah $LiNiCoMnO_2$-battery cell are available for ETC Battery and Fuelcells Sweden AB which the investigation was conducted for. Thus from now on in the report, all discussions regarding LiIon will refer to the $LiFePO_4$-battery cell unless other is stated.

ETC Battery and Fuelcells Sweden AB (will be referred to as ETC) was formed in 2003 and is a company specialized in battery technologies aimed for the car industry. ETC has together with the Ångström laboratory at Uppsala University introduced a new kind of LiIon battery cell incorporating the mentioned cathode material that can resist higher voltages than other battery cells existing on the market. This battery type is currently produced in Korea by the company EIG.

The car company also involved in this project is Volvo which is a worldwide car brand that is built around its safety thinking. Volvo is already using a similar type of battery cell but from another brand in their ongoing plug-in hybrid vehicle program. This battery cell was used in the beginning of this project in order to verify correct measurement proceedings. One of the goals for ETC is to support the introduction of the new type of LiIon battery cell on the market for hybrid vehicles.

The problem that was handled was how to perform the laboratory experiments on the battery cell in order to set the parameters needed to be able to run a Matlab/Simulink simulation model of a battery cell and a BMU. The parameters are *Internal Resistance* and *Open Circuit Voltage.* By doing this correct it was possible to find out the performance of the battery cell in an accurate manner. A state of the art simulation model has been developed in a previous project by another party and it has been supplied to this project through ETC. The simulated battery cell was intended to be used together with a simulated *Battery Monitoring Unit* (BMU). This is a component utilized in the control system between the vehicles main computer and the battery system. The BMU monitors the usage of the battery and its components, by surveillance of it. With this information the BMU calculates among others *State of Charge* (SOC) and *Power limits* for charge and discharge of the battery. SOC is a ratio between the momentarily available amount of charge in the battery and the total available charge of the battery when fully charged. SOC is a very important measure in the control of the battery since it gives information on how much energy that is still available in the battery, similar to a fuel gauge for gasoline. Previously SOC has been determined by measuring the voltage over the battery, but with LiIon battery cell technique this leaves too large inaccuracies. Thus a model which calculates SOC by using the amount of energy (current) leaving the battery during discharge had to be developed and this is the model used in this project. This model can deliver higher accuracy than previous methods. The power limits are important for the BMU in order to decide how much power that can be delivered from the battery during a specific time period. This is to avoid damage on the battery due to heavy discharging.

Since the knowledge about Lithium-Ion battery cell properties are partially unexplored territory this project has left some questions unanswered, e.g. regarding temperature damages. There are also uncertainties about dependence between degradation and SOC.

1.2 Purpose of the study

This project was a Master Thesis (30 ECTS) which is part of the fulfillment of the Master Education Electric Power Engineering at Chalmers University of Technology. The purpose of the study was to set the parameters (Internal resistance and Open Circuit Voltage) for the battery cells delivered by EIG in order to be able to use the supplied Matlab-model. The Matlab-model then provided a method to calculate SOC and the power limits for the battery cells.

The result of this study was the parameter outcome from the laboratory experiment and matlab modeling for the new type of battery cell. This enabled to use the simulation model to study the power limits and SOC. This is important to know for a real PHEV application, which the result is intended for.

1.3 Specification of the problem

The specification of the problem was to set the battery cell parameters (Internal Resistance and Open Circuit Voltage) for two battery cells by means of laboratory experiments and modeling.

1.4 Limitations

It was out of scope in this investigation to examine all of the complex technical details of the battery cell excluded in the simulation model. Environmental impacts of the different battery cells was neither examined and nor was the costs of producing these. Comparison between other battery cells than the ones used in this investigation was not made. The complex Matlab simulation model was neither a part of the purpose for this study and will not be explained in detail. This report solidly manages the setting and determination of battery cell parameters and to analyze the Matlab-model.

TECHNICAL BACKGROUND

This chapter will give background information on the subjects handled in this report. It will start with hybrid technology in general and proceed with more information concerning the actual batteries and their parameters. The battery chapter will also include a description of the LiIon batteries used in this work. After this it will deal with the BMU which also includes the complicated area of SOC. The subject on SOC will start with general facts about SOC and then handle how SOC is actually determined. Finally this chapter will handle power limits.

1.5 Hybrid Electric Vehicles and Plug-In Hybrid Electric Vehicles

The work to reach a more sustainable fuel economy in the vehicle sector emerged in the development of the *Hybrid Electric Vehicle (HEV)* market. The introduction of HEV would reduce the fuel consumption in the vehicle sector, thus reducing the fuel costs and also cut down on the serious environmentally hazardous emissions which are strongly dependant on the amount of gasoline, diesel etc. consumed by the vehicles. The major advantage of a HEV is the possibility to benefit from the use of a battery in the same way as an ordinary *Electric Vehicle (EV)* but without the need for a charging station nearby to ensure recharging possibilities. Instead an HEV uses both an electric drive system, often for acceleration of the vehicle and a gasoline drive system for higher speeds. Since the vehicle uses both of these propulsion methods it can consequently increase its action range substantially compared to an EV, although some fuel will be consumed. [1]

There are two different main types of configuration between the combustion engine and the electric drive system to provide for this recharging feature. The first type is called a *series hybrid* and in this type the combustion engine is connected directly to a generator which in turn supplies the battery pack and the electric motor with energy. Only the electric motor is then in connection with the wheels for movement of the car. I.e. in the series hybrid the combustion engine is only used to generate energy for the electric drive system. Opposite to a series hybrid is the *parallel hybrid* in which both the combustion engine and the electric drive system are utilized in the movement of the car as two separate drive systems which works together to optimize the fuel economy. These two schemes are illustrated in figure 2.1. During the operation of an HEV the car uses regenerative braking to recharge its battery by means of the electric motor thus saving fuel and energy. Of course there are great varieties in these propulsion schemes between the manufacturers and sometimes it is fair to talk about a *dual mode hybrid* or *series-parallel hybrid vehicle* which gives the possibility to switch between the two types depending on the situation. [1]

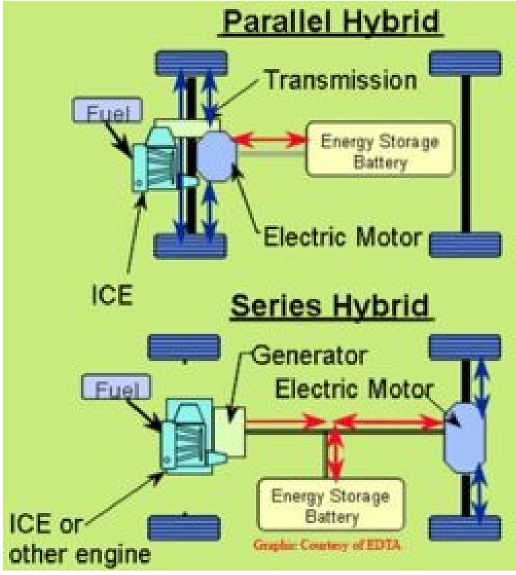

Figure 2.1 displaying the two operating schemes of parallel and series hybrid vehicles. [http://www.schleeter.com/images/series-parallel1.jpg]

The next generation of HEV is the so called *Plug-In Hybrid Electric Vehicle (PHEV)* which is one of the most discussed vehicle types the latest years due to its greater use of the battery and possibility to recharge in a simple way just by using an ordinary grid connection. The PHEV usually have a larger battery compared to a regular HEV to provide for a longer action range using pure electric driving hence decrease its fuel consumption further than a regular HEV. When the battery is low in energy the PHEV starts using its combustion engine for propulsion of the vehicle in the same way as a regular HEV. PHEV can also be divided in series hybrid, parallel hybrid and series-parallel hybrid. Some of the benefits from using PHEV, which many are similar to the ordinary HEV, are; economical fuel costs during operation and during pure electric driving the fuel costs are reduced to only the price of electricity and thereby also reduced air pollution and reduced dependence of the global fossil fuel resources. Another advantage is the convenient home recharging possibility which also opens for new future application such as home emergency power back-ups etc. [2][3]

The chemistry type used in the battery cell of HEV battery package may be of different types depending on the manufacturer but some of the most common ones are *Lead-Acid batteries*, *Nickel-Metal hydride (NiMH) batteries* and *Lithium-Ion batteries*. The latter, Lithium-Ion is nowadays most utilized and seems to be the dominating technique during the next years. LiIon cells popularity is due to their relatively high energy density compared to other cell types. This making it possible to use considerably smaller and lighter batteries but still get the same capacity from the battery compared to if used some other cell chemistry with the same capacity. The major drawback with LiIon cells is that it is a new technique that still needs several improvements in order to be reliable. [4][11]

1.5.1 Battery system

The battery package in a PHEV has larger capacity than an HEV which means that the vehicle can be driven on pure electric power for longer distances than an ordinary HEV. To ensure this capability the vehicle has an on-board main computer which controls the use of all the technical systems in the vehicle. This main computer decides on which propulsion system set up it should use for the moment. One such systems that it communicates with is the battery management system. This includes the actual battery cells, a Battery Monitoring Unit, a temperature regulating system and a chassis containing safety functions, communication and connection equipment. The BMU is the most central component in the battery system to ensure a healthy and appropriate usage of the sensitive battery cells. The BMU controls the usage of the battery cells by measuring variables such as voltage, current and temperature of each individual cell in the package. By means of this it calculates important state variables such as SOC and power limits for charge and discharge of the battery. This information along with other signals as alarm and status signals is sent from the BMU to the vehicles main computer which consequently is able to control the propulsion of the vehicle in a qualitative manner without damaging the battery package. The BMU can thus be seen as the vehicles interface between its battery system and its main computer. SOC is calculated inside the BMU by a complex algorithm, due to the many factors that SOC is dependent on and the numerous different operational scenarios that may occur. [2]

1.6 The Battery Cell

A battery is a connection of series/parallel stacks consisting of battery cells were one stack is at least two battery cells. An example of a battery can be seen in figure 2.2 below. The type of connections used is depending on what voltage level and current capability that is strived for at the output terminals of the battery. The voltage output from the battery cell is different from the theoretical output due to the internal resistance in the battery cell; this is explained in more detail later on in section 2.3. [2]

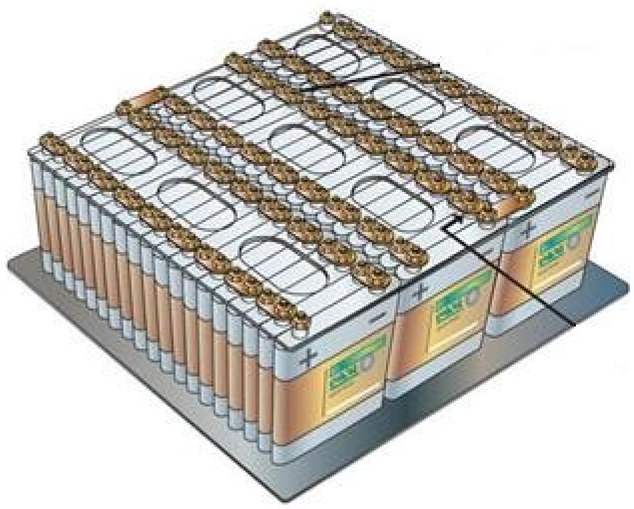

Figure 2.2 displays a battery with series/parallel connected cells. [http://www.linear.com/designtools/images/BatteryStack.jpg]

A battery cell converts chemical energy to electrical energy. This is done by oxidation at one electrode and reduction at the other electrode. The oxidation-reduction also known as redox is a reaction that occurs when the electrodes gets in contact with an electrolyte. When the electrodes are inserted in the electrolyte and the external circuit is closed i.e. discharging, electrons start to migrate from the negative anode to the positive cathode, when this occurs the ions in the anode start to diffuse into the electrolyte. This is due to the differences in ionic concentration between electrolyte and electrodes. If the concentration is higher in the electrode than in the electrolyte ions will pass into the electrolyte. The opposite will occur at the cathode where the ionic concentration is higher in the electrolyte than in the electrode, the cathode then strives for adding ions and the ions binds with the electrons arriving to the cathode from the external circuit.[1]

For a discharging battery the anode is the negative electrode releasing electrons to the external circuit and therefore is oxidized during the electrochemical reaction. The cathode is the positive electrode that accepts the electrons during the electrochemical reaction, the reduction electrode. The function of the electrolyte is that it conducts ions and not electrons. Thus the electrons has to migrate through the electrical conductor to be able to reach the cathode, the load (electric motor in a PHEV) is connected to this conductor.

When charging the battery cell this procedure is set in reverse, then the voltage applied from the charger has to be opposite and higher than the nominal voltage from the electrodes. In figure 2.3-2.4 these processes are shown for a LiIon cell. Notice that no lithium ions are lost in the reactions. [1]

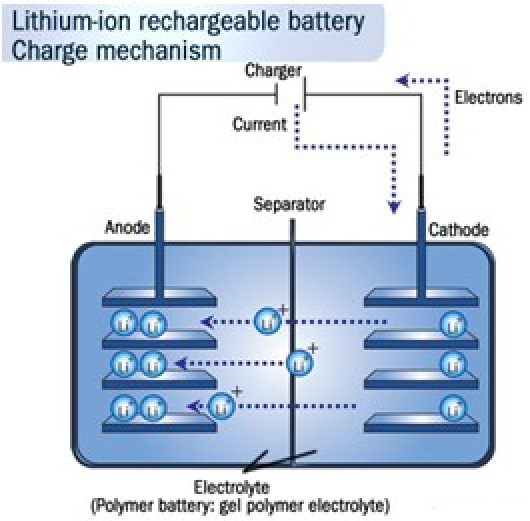

Figure 2.3 displaying the charge process in a LiIon-cell. [http://electronics.howstuffworks.com/lithium-ion-battery1.htm]

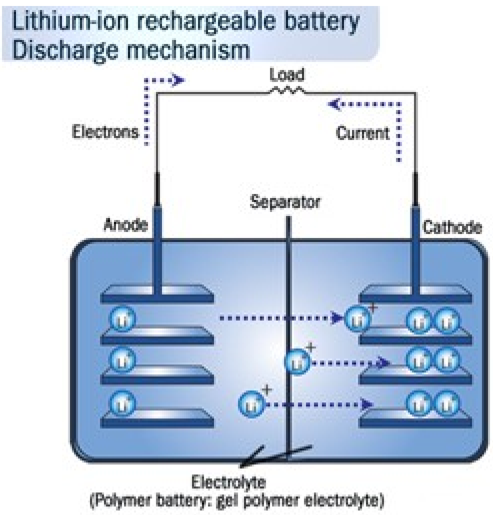

Figure 2.4 displaying the discharge process in a LiIon-cell. [http://electronics.howstuffworks.com/lithium-ion-battery1.htm]

There are two types of batteries, primary and secondary batteries. Primary batteries are the type of battery that cannot be recharged due to their chemical composition, the structure of a charged primary battery cannot be restructured after discharged. The advantage of primary batteries is that they are inexpensive and has a good *shelf life* meaning they can be stored without severe damage. The batteries can either be of *high energy density type* or *high power density type*. Energy density is the amount of energy with regards to kg or liters. Power density provides a good measure on how much energy that can be released due to discharge at a given time with regards to kg or liters. This is depending on several factors, for instance voltage, and the time it takes for the chemical reactions to react, many of these factors may be derived to the material used and its structure. High energy density is preferable in primary batteries due to their use in e.g. portable radios. [1]

The secondary batteries is rechargeable and the type of battery used in HEV´s. In contrary to the primary battery the secondary battery has the property of being able to reconstruct itself to the structure of a charged battery after being discharged. A high power density battery is useful in an application where a short but intensive power pulse is required e.g. in an ordinary HEV. This since in a HEV the electric motor often only assists the combustion engine short periods e.g. during acceleration. A high energy density battery is on the other hand useful in applications where a longer driving distance is desired e.g. in a PHEV which is intended to be driven on pure electricity for longer distances. [1]

1.7 Parameters of the battery cell

The parameters that are going to be determined in this project are Internal Resistance and cell Open Circuit Voltage (OCV). These parameters are of major importance when looking at the performance of the battery cell and are intended to be used in the simulation model of the battery cell. Another important parameter for many battery types is the Self-discharge current of the battery cell, but this is not the case for LiIon-cells. Here it is included only to give a complete explanation of the cell model. In figure 2.5 the cell model with all its parameters is shown. [6]

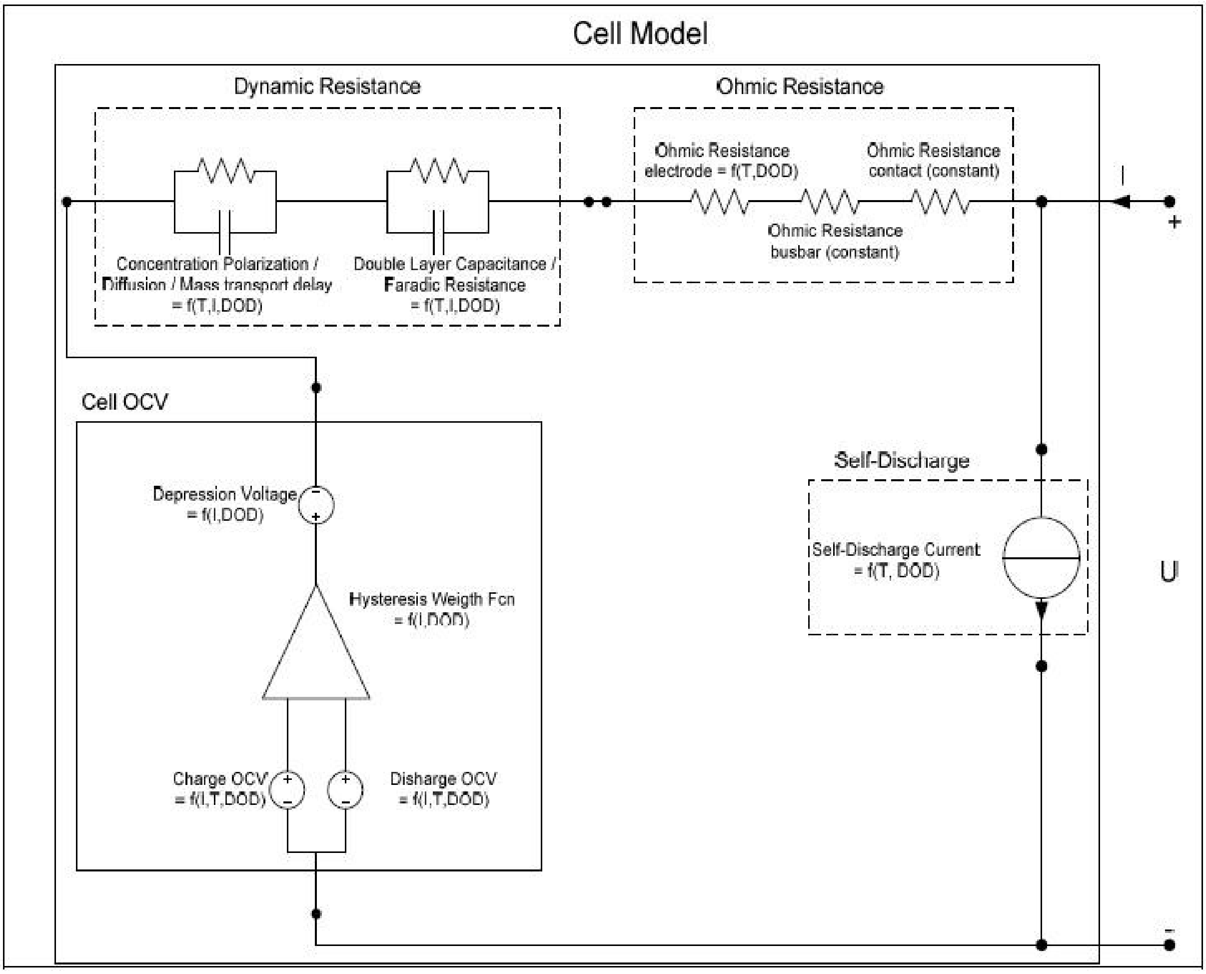

Figure 2.5 showing the cell model as it is implemented in Matlab/Simulink. [Internal material, ETC]

As noticed in figure 2.5 the internal resistance may be divided into dynamic resistance and ohmic resistance and the behavior of these is highly complicated. The internal resistance is modeled as an RC-circuit with different time-constants and dynamics which is partially empirically extracted. Empirically extracted means that the constants have been approximated from laboratory experiments performed in an earlier stage. This is to keep the model simple and relatively easy to measure and modify. Another advantage to model the internal resistance this way is the robustness of the model and the reduced calculations. For an exact theoretical calculation extensive calculations are necessary. [5]

1.7.1 Cell Open Circuit Voltage

The OCV is the voltage measured at the cell with the voltage drop over the internal resistance subtracted as can be seen in equation 2.1. By following Ohm´s law:

$$OCV = E - Dynamic\ Resistance\ voltage\ drop - Ohmic\ Resistance\ voltage\ drop\ [V]$$
[2.1]

Where E = cell voltage [V]

The difference between the OCV and the cell voltage is depending of the internal resistance which in turn is current-dependant. With no current through the cell, the open circuit voltage is equal to the cell voltage due to that the ohmic resistance term equals to zero. [5][1]

1.7.2 Ohmic resistance

The ohmic resistance is the current-dependent part of the internal resistance, this is the sum of the ionic resistance which is the resistance the ions face when wandering towards the cathode/anode and the electronic resistance from the electronically conducting material as well as the connections that connects the different materials e.g. the connection between cathode and conductor. [5][1]

1.7.3 Dynamic resistance

The dynamic resistance consists of several chemical phenomena, among these two contributes to the internal voltage drop more than the others and these two will be superficially dealt with. *Concentration Polarization* is a part of the ion mass diffusion losses. The mass diffusion is the ion migration that occurs due to the difference in ionic concentration. The other phenomenon is the *Double Layer Capacitance* which occurs at the electrodes. The time delay in the voltage profile which these phenomena create has been empirically extracted and modeled in the Matlab-model. [5][1]

1.7.3.1 Concentration polarization

Concentration polarization is the most dominant factor contributing to the battery cell voltage drop of the mass diffusion phenomenon. The concentration polarization is what occurs at the electrodes due to the different velocity of the ions depending on what distance these are from the electrode. The charges (ions) diffuse in the flux gradient to reach the equilibrium state. By that the charges depletes the region close to the electrode from charges due to the larger flux gradient in the nearby surroundings of the electrode. Leaving the area further away from the electrode more concentrated with charges a concentration difference will appear. The flux gradient increases with increased current supplied to the load, which leads to that the concentration difference of charges also increases. If no current is supplied to the load the natural state of the battery contains a certain concentration of charges in the area close to the electrodes due to diffusion. Now when current is supplied to the load the concentration of charges around the electrodes will drop as mentioned. When this concentration of charges is so reduced that it is lower than in the natural state, a voltage drop will occur. Higher rates of charging and discharging the battery cell leads to a higher voltage drop due to the higher flux gradient that depletes the region close to the electrode from charges faster. [5][6][1]

1.7.3.2 Double layer capacitance

For simplicity in this description of double layer capacitance the molecule refers to a water molecule that is shown in figure 2.6, which is commonly known to be a dipole. This means that the molecule has more positive charges in one end of the molecule than in the other, this forming a charge resultant. Although it is not possible with water as a solvent in a LiIon battery cell electrolyte due to the fact that lithium reacts with water. The electrolyte in LiIon battery cells solvents might not even contain dipoles but still the same behavior can be noticed.

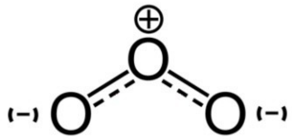

Figure 2.6 displays a water molecule (dipole). [http://upload.wikimedia.org/Wikipedia/common/e/ea/Dipole_water.png]

The double layer capacitance is what occurs between the electrolyte and the ion traveling through the electrolyte towards the anode/cathode. The molecules in the electrolyte bind with the ion during the ions travel through the electrolyte forming a layer of molecules surrounding the ion. At the electrodes the same phenomena occurs, i.e. that a layer of molecules from the electrolyte binds with the electrode. When the ion reaches the electrode the ion has a layer of molecules surrounding it as well as the cathode has a layer of molecules surrounding it. There are now two layers of molecules blocking the path of the ion. This is what is called double layer capacitance. There is now a potential from the ion striving for the electrode. And there is a potential between the molecules surrounding the ion/cathode and the ion which counteract the potential that is the driving force for the ion. This is represented in equation 2.2.

$$Vdrive = E - \emptyset^{e} \qquad \textbf{[2.2]}$$

Where V_{drive} = net voltage of the potential driving the ion.
E = potential between ion and electrode.
$\emptyset^{e}$= potential counteracting E from surrounding molecules attached to ion/electrode and ion.

When E increases, V_{drive} will be positive and the reaction between ion and electrode will be complete. This voltage can be resembled to a capacitor charging/discharging with a high frequency. This behavior is experimentally determined but has a physiological background which makes it important. [5][6][1][12]

This resultant of the water molecule is illustrated in the figures 2.7 and 2.8 with the arrows in the molecules (circles) where the front of the arrow is the positive end of the dipole.

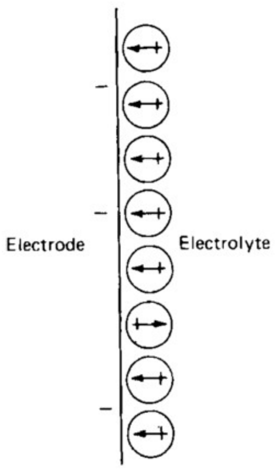

Figure 2.7 displays how the water molecules are attached to the negative electrode. [Linden D. & Reddy T.B: HANDBOOK OF BATTERIES-3rd edition, McGraw-Hill, 2001]

In figure 2.8 a positive ion travels towards the anode and tries to break the barrier of water molecules.

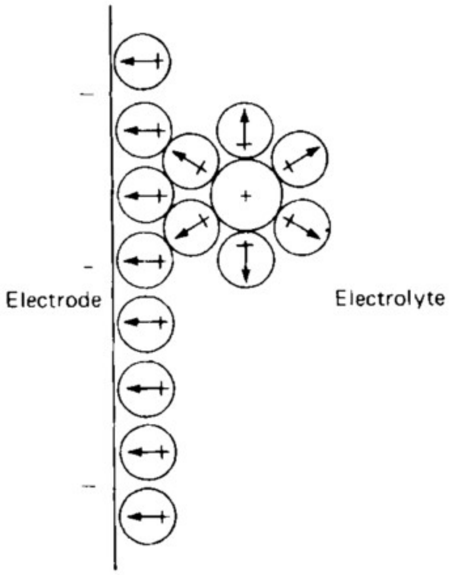

Figure 2.8 displays how the water molecules attach to both the electrode and the ion forming a double layer capacitance. This prevents the ion to reach the cathode. [Linden D. & Reddy T.B: HANDBOOK OF BATTERIES-3rd edition, McGraw-Hill, 2001]

1.7.4 Self Discharge Current

The self discharge current is the current leaking out of the battery cell when not active and is highly depending on the temperature. In a LiIon battery cell the self-discharge is negligible and because of this it is not taken into account when using the computer model for this cell technology. The self discharge current is only intended to be used when using the simulation model for other types of common cell chemistries such as NiMH-cells. [3]

1.7.5 Voltage drop/recovery due to internal resistance.

Figure 2.9 is displaying the different voltage drops that are simulated in the model and the explanation of these are following.

1. Voltage drop caused by ohmic resistance.
2. Voltage drop caused by dynamic resistance
3. Voltage recovery caused by ohmic resistance.
4. Voltage recovery caused by dynamic resistance.

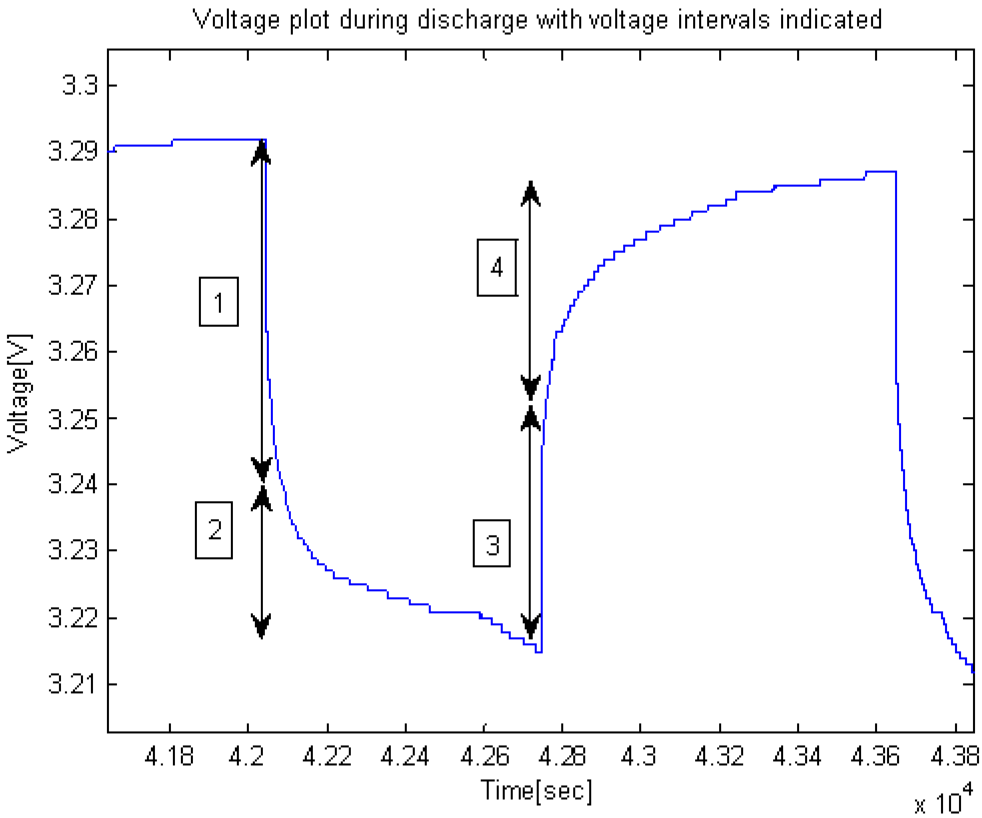

Figure 2.9 displaying the different voltage drops caused by the different resistances modeled.

At the moment the current start to flow in the circuit, an ohmic voltage drop (1) appears momentarily due to the pure ohmic resistive parts of the cell. The voltage drop from the dynamic resistance (2) is due to chemical and resistive parts and is modeled as a RC-circuit. This has a value which gives a corresponding time-delay in the voltage curve that is based on empirical experiments as previously explained. When the current stops flow the ohmic voltage drop (3) momentarily disappears. The time delay in the voltage curve during the recovery is due to the dynamic resistance (4) which also is empirically based. The empirical values are necessary for the model in order to model the battery cells time delayed voltage characteristics when applying a certain current cycle. As can be noticed in figure 2.9, in some intervals of the voltage curve, it takes longer time to change the voltage level, e.g. during the recovery (4). This is what is meant with a time delay and this is modeled by means of a capacitance. During the parameterization in Matlab the program identify and compare the dynamic behavior of the voltage curves from the laboratory experiment to be able to sort out the correct capacitance values for all different current rates. [5]

1.8 Lithium-Ion Batteries

The Lithium-Ion battery cell has several major advantages when compared to other batteries on the market today. There are today numerous different chemical compositions used in the cells but some of the more discussed are $LiCoO_2$, $LiNiCoMnO_2$ and $LiFePO_4$. The latter will be discussed more in detail in next section since this is the type that is parameterized in this project. All these types of names are referring to the different cathode materials used in the battery cell. [2]

When discussing LiIon batteries it is almost always the type secondary battery that is referred to. One of the reasons for this is the advantage that the LiIon battery resists degradation when exposed to numerous cycles, thus making them suitable for secondary batteries. A LiIon battery cell does not have much memory effect. Memory effect means that if the battery cell is repeatedly discharged to a certain amount several times, the battery capacity will appear to remember this smaller amount as its maximum capacity. Hence the capacity is decreased. A good LiIon cell can approximately stand 2000 cycles before a cell change is necessary due to the degradation of the active substances within the cell. This compared to 100-1000 cycles for other secondary batteries. The LiIon battery cell has a much higher energy density than many other batteries, because of the characteristics of the lithium in the electrodes. From this advantage the LiIon battery cells can be built smaller and lighter but with the same outputs as with a heavier and bigger battery with a different chemistry. This is very important in a HEV application for reducing the weight/energy-ratio. In addition to these advantages the LiIon battery cell can be charged/discharged rapidly and operate at a high spectrum of temperatures. [7]

There are also disadvantages with LiIon battery cells; if a cell is discharged under a limit of approximately 2 V the battery cell will be permanently degraded if not completely destroyed. This will also happen if the battery cell operates at a too high temperature (above approx. 65 degrees Celsius) during a longer period of time. The LiIon battery cell is also somewhat more expensive than other battery cells due to the material and composition. For not exceeding the limits for charging/discharging or temperature limits the LiIon battery cell needs a protection system for monitoring of the battery cells. For this a BMU is used, which further will increase the costs for LiIon applications.

The BMU also plays an important role as a protection system since LiIon cells may be instable due to their powerful chemistry, i.e. they may explode or start burning. Depending on which type of chemistry is used in the battery cells it will behave different when subject to abuse e.g. high voltage or high temperature. How the oxygen atoms in the molecules of the cathode material are bounded is the most important factor contributing to the cell stability. Some chemistry e.g. $LiFePO_4$ and $LiNiCoMnO_2$ are very stable since the oxygen atoms in these binds very well with the molecules. These types may be exposed to several hundred degrees of heat before any danger is apparent. [2]

1.8.1 $LiFePO_4$-cells

LiIon battery cells containing cathodes of the type $LiFePO_4$ is considered by many to be one of the most widely used types in future applications due to its stable nature and thus safe usage. The anode type used together with this cathode is often, as in many other cell chemistries, a layered carbon anode. This setup gives a somewhat lower nominal voltage of 3.2V compared to e.g. the more instable $LiCoO_2$, which has a voltage of 3.7V and is widely used on the market today. But the safety aspect is in many cases more important than the voltage profile. As mentioned above the $LiFePO_4$ metal-oxygen bonding is very stable and thus giving the cathode crystal the ability to maintain its structure even at high/low voltages and high temperatures.

The voltage profile of the $LiFePO_4$-cell used in this work is rather flat in the center of its operating region and has a maximum peak of 3.65V and minimum dip of 2.0V, the principle shape can be seen in figure 2.11. The maximum capacity is 14.5 Ah and the energy density is 220Wh/L. More detailed information may be found in the appendix B where the datasheet for the cell is attached. [8][9]

1.9 Battery Monitoring Unit

A BMU has several important tasks to manage. Depending on the application these may vary but three primary objectives every application have in common are; protection of the sensitive battery package from damage, prolonging the battery life length and preserving the battery package in an always functional state to ensure its intended function. The BMU is also responsible for accurately calculating SOC of the battery package; this topic will be covered in the next chapter. The BMU is also responsible for storage of the SOC when the vehicle is turned of until the next time it is used. This is particularly important in the case with LiIon-batteries since it is not possible to simply measure SOC on this type when the vehicle is started again. For some battery types it is possible to only measure the voltage of the battery and from this determining the SOC. [5][2]

1.9.1 Cell Protection

In order to avoid damaging the battery package during operation, one of the fundamental objectives of the BMU is to provide a monitoring system intended for this purpose. The battery cells are very sensitive to out of tolerance operations, i.e. to use them in an operating region where they are not intended to be used. Examples of this are at a too low battery voltage due to heavy discharge below preset voltage minimum limits or at a too high voltage because of incorrect charging, i.e. over charging. Another possibly harmful scenario is operation at a too high temperature which will cause reduction of battery cell life length etc. If protection is not done properly it will lead to a battery failure which could have catastrophic consequences since a PHEV battery package contains large amount of energy, therefore not only the inconvenience and costs of a battery package failure is of importance but also the safety of the surrounding environment and personal safety must be taken into account. In the case of working with LiIon batteries, as in most of the more modern PHEV, it is particularly important with the cell protection. This since many of today applications still is using the cell chemistry $LiCoO_2$ which is known to be more instable. Some of the events the protection system has to be able to deal with are:

- Over voltage – Due to over charging
- Under voltage – Exceeding preset minimum voltage-limits
- High ambient temperature
- Overheating – Exceeding preset cell temperature limits
- Excessive currents during charging and discharging.
- Short circuits
- Pressure build up inside the cell
- System isolation in case of an accident

The protection of the cell is done by means of different components connected to the battery cells and the BMU such as thermal fuses (thermistors), over current fuses, fast acting electronic protection circuits and vents. To be able to isolate the battery package during e.g. accidents, a system incorporating inertia switches is utilized to sense the emergency condition which will interrupt the main current path by sending a trigger signal to the current switch, thus isolating the battery from the rest of the drive system. The cell protection system itself needs a constant current drain to supply its own electric circuits and this drain will reduce the effective capacity of the battery cell, consequently it is of outmost importance to keep the current drain at its minimum to avoid unnecessary discharge of the battery. [2]

1.9.2 Cell balancing

A battery package in a PHEV is often containing several hundreds or thousands of series connected battery cells to be able to reach a sufficiently high system voltage. This fact means that there is a risk that one or several of the cell voltages becomes unsynchronized with the rest of the cells voltage level, since each cell is unique and their performance can vary from the production stage. If e.g. one cell starts a charging cycle on a higher voltage level than the rest of the cells it will reach the maximum allowed voltage before the other cells and also stop the entire charging cycle. This results in a premature charging stop initiated by the BMU to protect the battery cells and consequently leading to a poorly charged battery. A similar reasoning can be done regarding a discharge cycle. To avoid this phenomenon each cell in the series string need to be carefully monitored individually by the BMU and if some deviation is found this will be handled by C*ell Balancing*. Cell balancing is thus a way of compensating for the difference in performance between individual cells and is done by equalizing the charge on all the cells in the series. Cell balancing is extra important when LiIon cells are used, due to their sensitivity to over and under voltage. If one cell in the package would fail the whole package needs to be replaced because just changing the damaged cell with a new one would further increase the problem with cell-to-cell imbalance due, to the probably much larger capacity of a new cell than an old one. Since the failure of one battery cell in the string would cause a total failure of the battery package, cell balancing is considered crucial to prolong the lifetime of the battery, especially in a LiIon application.

The problem is mostly encountered in series strings where the same current flows through all cells; a parallel string has a good self balancing ability inherent to the parallel structure. A potential danger is hence that an individual cell in the series string becomes overstressed during a charging cycle leading to damage of the cell by increased temperature inside the cell. The problem is exaggerated in a HEV application due to their many and short discharge cycles associated to them when accelerating as well as by their powerful charging pulses associated with regenerative breaking. [2]

1.9.3 Measures to minimize the problem with cell variations

There are several possibilities, more or less advanced, to minimize the problem related to cell-to-cell variations. The key to a healthy battery package is to treat all the cells in the stack in the same way and reach equilibrium between them, same production cycle, same environment in the application and same operation characteristics.

Since the underlying cause of this problem is that all battery cells are unique, the first measure to take in order to avoid this is to select the battery cells carefully. All cells used in a battery package should preferably origin from the same manufacturing batch to get an as uniform performance as possible. Also, testing of battery cell performance may be utilized to group them in suitable sets.

Next fundamental approach to avoid cell variation problems is to create a uniform operating environment for the cells in the battery. Most important is the temperature difference across the battery package since it is possible that e.g. cells in the outer regions of a large battery block are in contact with ambient temperature and thus obtain a better cooling effect compared to cells in the center of the block. Consequently it is important to use an effective cooling system in the battery.

During operation of the battery, actual dynamic cell balancing is acquired through cell equalization by the BMU in the series string to avoid overstressed battery cells. This is done by monitoring of each cell in the string and continually determines its State of Charge. Often this is obtained by only measuring the individual cell voltages and from this concludes the charge status. This way of determining SOC, in the case of LiIon-cells, is usually associated with large errors due to the flat voltage characteristics of the cell, as will be discussed later. The cell equalization is achieved by means of switching circuits controlled by the BMU, which direct the charging power away from the unbalanced cells to the rest of the cells to get a uniform charging of the battery. In practice this is often simplified to a more easily implemented balancing scheme which basically uses large resistors to attain the balancing effect. If a cell is unsynchronized and reaches a higher cell voltage than the other cells in the string during charging, the BMU will alarm on this and the charging will be paused. Next the BMU will control the unsynchronized cell to discharge some of its capacity over a large resistor and thus lower its voltage to the correct voltage level. When all unsynchronized cells in the string are on the correct and equal voltage level the charging can proceed. This type of cell balancing is rather inefficient but its simplicity is often a more heavy argument for it to be used. [11]

Both simple and advanced cell equalization schemes have in common that they need a good estimate of the State of Charge for each individual cell to be effective.

1.10 State of Charge

The next fundamental function that the BMU has is to determine the State of Charge of the battery package. A precise calculation of the SOC is very important for several reasons and the fact that the determination process is rather complicated makes this area important to understand. State of Charge is important to know both for the total battery package and the individual cells in the package. The use of State of Charge could be, as mentioned before, to increase the efficiency of cell balancing and the charging process or just as a measure of how much capacity the battery still has to provide to the user. A familiar example of the latter is the SOC indicator bar that all cellular phones show in the display. State of Charge of a battery is defined as the available capacity expressed as a percentage of its rated, nominal capacity. Another way of expressing the same thing is to use the *Depth of Discharge (DOD)* which is defined as 1-SOC, i.e. how much capacity of the battery that already has been used expressed in percentage of rated capacity. A representation of the SOC can be seen in figure 2.10 where also the operation area is indicated as 40-80% SOC. This area will give room for regenerative charging and at the same time not allow the battery to operate close to the damaging low voltage zone. This operating scheme is often used for ordinary HEV. [2][6]

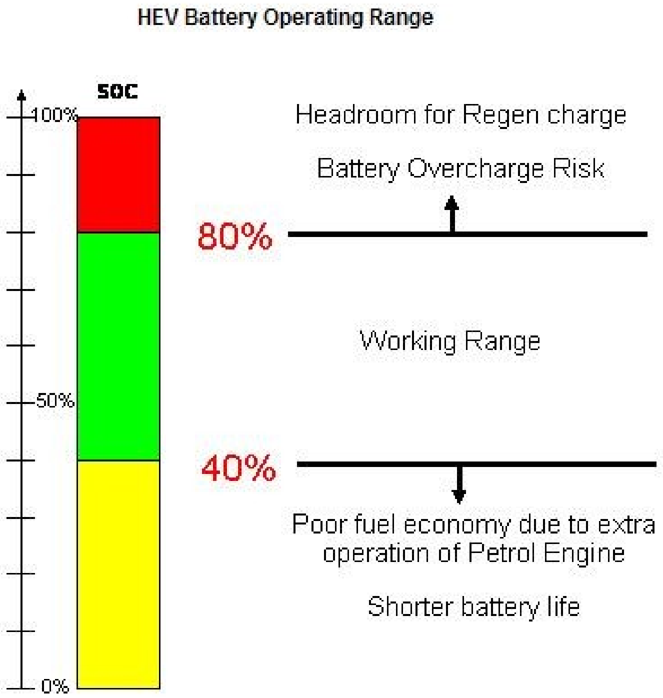

Figure 2.10 shows different operating regions for an HEV. [http://www.mpoweruk.com/bms.htm]

Since the capacity of a battery cell degrades over time due to the usage and the environment, it will not always be possible to charge it to rated capacity. This fact leads to the question on how to define maximum capacity, i.e. what 100% state of charge is. A common way to define SOC is to let the rated capacity of a new cell always be the SOC reference. By using this convention it follows that it not will be possible to charge the battery to a SOC of 100% after some usage, due to the degradation.

The other way of defining SOC is to always define the present maximum charge capacity i.e. of a fully charged battery, as the SOC reference and by doing so get the possibility to always charge the battery to SOC equal to 100%. The problem to use this method is that it will need the usage of adjustment factors to compensate for the degradation when determining the new SOC reference point. These adjustment factors are difficult to estimate since they must predict how much the battery has degraded due to its wearing from prior usage. [10][2]

There are several ways of determining SOC but in this text only the two most common methods will be discussed. Both methods are also functional for the Lithium-Ion cell chemistry. Common to both techniques is that both rely on measurements of some carefully chosen parameters, such as voltage, current and temperature, which all vary with the SOC.

1.10.1 Voltage based measurements

The voltage based method uses, as the name imply the voltage of the battery to determine the SOC. The method is based on the fact that the voltage of the battery will decrease as the SOC decreases. This phenomenon is very apparent in some battery chemistry types, as can be seen in figure 2.11, but unfortunately it is less apparent in a Lithium-Ion battery cell. Nevertheless it is also used for Lithium-Ion type batteries but often together with some other technique to get a more precise estimate. This method will provide a good measure of the desired cutoff points which is used during charging and discharging to know when the battery is fully charged respectively discharged. To only rely on this voltage based SOC calculation method in a Lithium-Ion application would probably give a large inaccuracy in the estimate of SOC. This due to the very flat voltage profile of the LiIon cell chemistry and thus it is not used in this way. The flat voltage profile can be seen in figure 2.11 and it is apparent at the capacity in the area around 50% SOC.

1.10.2 Current based measurements

The next method is often called *Coulomb Counting* and it utilizes the current to estimate the SOC. By integrating the current entering and leaving the battery it is possible to determine how much capacity it currently holds in a fairly accurate manner. The SOC is obtained by subtracting the accumulated current flow from the SOC reference point, i.e. the point where SOC is equal to 100%. An example on how to the SOC is calculated by integration of the current for a battery cell with reference capacity of 20 Ah is shown in equation 2.3.

$$SOC[\%] = \frac{20-\int_{t_0}^{t_0+T} i(t)dt}{20} \times 100 \qquad \textbf{[2.3]}$$

Problems that may be encountered are, as in previous method, compensation for different operating conditions and problem with the integrator which may lose its accuracy if the integrator is not restored to the reference value continuously. The latter problem could arise from different sources such as inaccurate measurements of current, inaccurate compensation factors which adjust for degradation of the cell or a too large number of small cycles between fully recharging. Fortunately this problem is not very severe in a PHEV application since this type of vehicle is recharged preferably every night and consequently is restored to its well defined 100 % SOC value when it is fully charged. The integrator can subsequently reset its counter and start a new counting cycle the next time it is used and any old inaccuracies are eliminated.

Another major issue when using a method like this is to keep the *Coulombic Efficiency* in mind when estimating the SOC. Coulombic efficiency is the relation between charged capacity and discharged capacity, i.e. a battery cell needs to be charged with more power than it is possible to deliver during a following discharge due to losses inside the cell. How much of the charged energy compared with how much of it that is available during a discharge is thus the coulombic efficiency. It can be expressed by equation 2.4.

$$Coulombic\ Efficiency = \frac{Discharged\ energy}{Charged\ energy} \qquad \textbf{[2.4]}$$

The coulombic efficiency also tends to vary with parameters such as current rate, temperature and SOC. Hence it needs to be measured and documented carefully in laboratory environment for different operating conditions in order to support an accurate SOC estimation. The current rate is one of the most dominating factors for how effective charging/discharging can be.

Lithium-Ion battery cells have a high charging efficiency and in the model used in this project, the charge efficiency is approximated to one. [6][5]

1.10.3 Other aspects influencing the SOC

To be able to get a reliable estimation of the SOC it is not enough to work alone with the above presented SOC calculation methods, it is also needed to include both the battery cells long time and short time operating environment/condition to reach a satisfying result. The next section will list some of the factors influencing the SOC.

1.10.3.1 Current rate

It is a known fact that charging with a low current leads to a more effectively charging of the battery cell than charging at a higher current, this phenomenon adhere from the battery cells chemical properties. The electric dynamics is much faster than the chemical and because of this the battery cell might not be possible to follow the electric loadings placed on it. Since the chemical reactions in the battery cell needs some time to complete it means that a very high current will stress the battery severely and there is a risk that not all chemical reactions will be completed. The same reasoning works for a discharge event. In a PHEV this is a common problem since its loading characteristics is very dynamic with high discharging current pulses during acceleration followed by regenerative breaking which causing high charging current pulses. If the battery is loaded with lower currents instead, the battery cells chemical reactions have more time to complete its actions and the charging will be more efficient.

When using coulomb counting to determine SOC it is therefore important to take the current rate into account in order to get an accurate estimation. The phenomena is often called Capacity offset and is shown in figure 2.11. Capacity offset is accordingly the change in how much capacity the battery cell has at different current rates. As can be seen in figure 2.11 the capacity is reduced when using a high current. What also may be noticed in figure 2.11 is the larger voltage drop for higher current rates. This is due to the internal resistance of the battery cell. [2] [6]

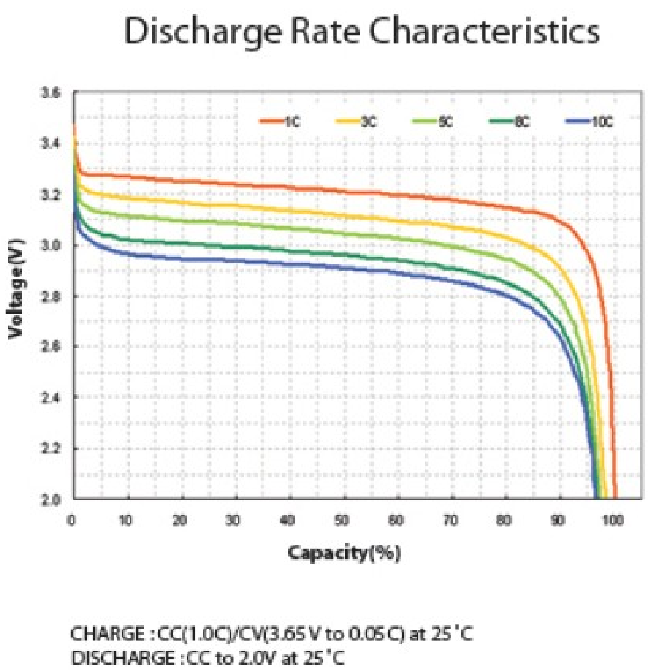

Figure 2.11 shows the flat voltage characteristic at different current rates against DOD. Notice that the capacity decreases with increasing current rate. Also an observation can be made that the voltage is reduced with increased DOD. [Data sheet EIG]

1.10.3.2 Temperature

All chemical reactions occur slower at lower temperatures than at higher temperatures. This is a familiar relation that is of great importance inside the battery cell which is exposed to varying operating conditions and hence the temperature characteristics are closely correlated with coulombic efficiency. The most severe case for a LiIon battery cell is to be operated at low temperatures with high current rates, because already the high current rate will stress the cell chemistry seriously and now also the low temperature slows down the chemical reactions further. This will lead to a very poor coulombic efficiency and can be seen in figure 2.12. Consequently the relation between temperature and cell capacity needs to be monitored closely and taken in to account when estimating the SOC. [2][6][5]

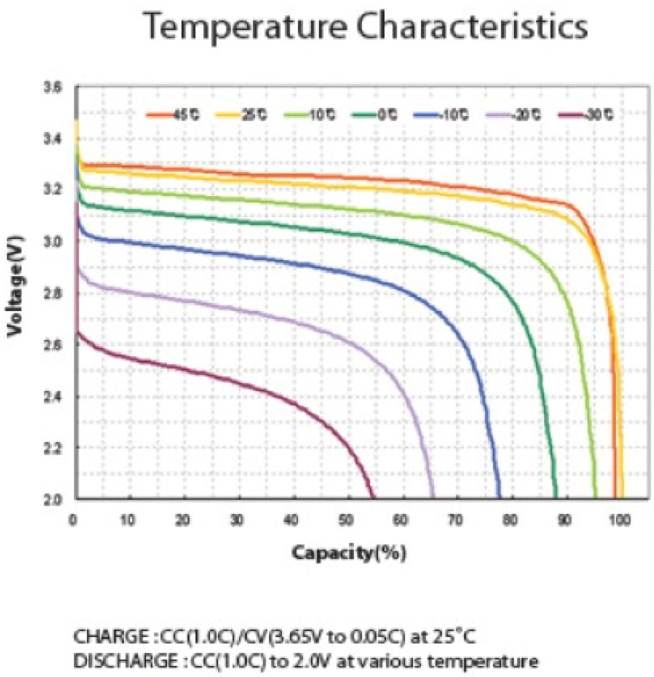

Figure 2.12 shows how the capacity of the cell is reduced with decreasing temperature. [Data sheet EIG]

1.10.3.3 Cell lifetime and State of Health

The algorithm used for determining the SOC must also take the battery cell age in to account. Due to long time wearing old used cells active substances has degraded which will decrease the battery cells maximum capacity. Also if the cell has a high shelf life which will cause the battery cell to decrease its capacity even though it has not been used. This is caused by an increase of internal resistance in the cell and is thus affecting the cells ability to deliver high current rates.

Usually when a cell has dropped 20% in capacity from its original maximum capacity it is considered to be used up and is discarded. After this point the deterioration starts to accelerate and the battery performance reduces drastically. A measure of the general condition of a cell compared to a new cell can be defined as the *State of Health (SOH)* which is a linear dependence between maximum capacity and the number of cycle it has completed. The cell capacity is decreasing with number of cycles it has completed as shown in figure 2.13. [2][6][5]

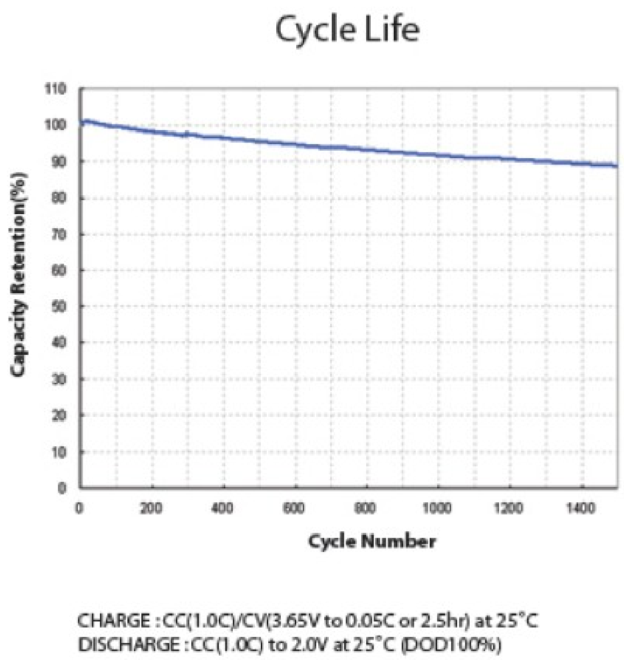

Figure 2.13 shows how the battery cell capacity is decreased with increased number of cycles. [Data sheet EIG]

Good LiIon cells are capable of completing approximately 2000 cycles, as mentioned above in the section 2.4 on LiIon batteries. The cell ageing phenomena is also strongly dependant on the history of operating conditions, i.e. DOD history, temperature and load profile. If the battery cell is deep cycled it means that a large amount of the battery capacity is discharged each cycle, i.e. DOD over 80%. This will wear out the cell rapidly if it is frequently repeated.
[6][5]

1.11 Implementation of State of Charge

The SOC is determined by a software algorithm in the Battery Management Unit. The determination process is usually done by starting measuring the real, physical battery variables which are voltage, current and temperature on the battery cells. These data are through Analog/ Digital-converters fed into a software model of the measured battery which give an accurate cell response to the BMU. The software model of the battery cell is developed in an appropriate computer program such as Matlab/Simulink and is intended to give the same dynamic voltage/capacity behavior as a real cell when loaded with a current. When using this type of set-up a sufficiently powerful hardware in the BMU is needed, i.e. accurate measurement sensors on the battery cells and a microprocessor to calculate the dynamic behavior also including a memory for storage of the software model.

Since the cell behavior is dependant of all the cell parameters named previously in section 2.3 it is necessary to construct parameter data tables for each cell type. The software model of the cell then incorporates these tables when calculating the cell response. The data tables are constructed in laboratory environment through measurements in a precise manner for different current rates, temperatures and DOD.

The SOC is finally calculated by integrating the current entering and leaving the cell and then subtracting the current integral from the known nominal (reference) capacity of a fully charged cell. A correction factor for the coulombic efficiency is also applied to further increase the accuracy. [5]

1.12 Power limits

The power limits calculated by the BMU is intended to be used in order to avoid any damages on the battery due to inaccuracies in the battery model. If the battery cell is discharged or charged with a higher power than the power limit allows the battery may be harmed. The power limits is calculated for three different time periods which are 1, 10 and 30 seconds of the battery cell use. The model underestimates the power limits in order to be sure that safe operation is maintained. If operating close to the power limits the thermal management must be carefully designed in order to keep the temperature down. [5]

METHOD

Chapter three describes how the project was planned and issues concerning the execution of it. In the next chapter the implementation of this method will be presented.

1.13 Preparations

In order to use the given Matlab-model input values of the measured quantities from the 14.5 Ah battery cell had to be found. These will be extracted through a series of laboratory experiments performed on the battery cell. In order to be able to complete this project in a satisfying way and to understand the outcome of the project given documentation about the Matlab-model is going to be studied in parallel with studies about the battery cell. Important issues to handle before executing this project are:

- Input data in Matlab-model.
- Output data from laboratory experiments.
- Hardware in order to obtain wanted ambient temperatures.
- Battery cell limitations for battery cell safety.

For confirmation of that the given Matlab-model is used properly and that the laboratory experiments are performed correctly a study of a 20 Ah battery cell from which results already exists will be made. If the results from this study agree with the existing results from the same battery cell the Matlab-model and the laboratory experiments can be seen as successful.

1.14 Software

In the project software for two different systems will be used. There are software for the battery testing equipment called Digatron and a second which is Matlab/Simulink in which all the simulations will be performed.

1.14.1 Digatron

In order to perform the laboratory experiments needed to collect data from the battery, the software Digatron has to be programmed according to given instructions. Digatron is the brand of the measurement system that is used in the laboratory and this is controlled by software in a computer. These software programs give instructions to charge/discharge the battery according to a given schedule that the Matlab-model is based upon. The outcome of this laboratory experiments is raw data sampled according to given instructions. These data files have to be formatted and converted to mat-files in order to fit in the Matlab-model.

1.14.2 The Matlab model

The Matlab model that is going to be used to simulate the battery and BMU response is composed of several different subroutines and block models implemented in Matlab/Simulink.

The main files in the model are the following:

- Init_battery_3_15.m
- Test_Battery_v3_15.m

- Test_Battery_BMU_3_15.mdl (Simulink model)
- Test_Example_GMPT_battery_3_15.mdl (Simulink model)
- Load_digatron.m

The Matlab model is created in such a way that it uses predefined input raw data from actual laboratory experiments to form a set of battery parameters that is used in the simulation. These battery parameters are then unique to the specific battery cell type, the type used in the laboratory, and hence the dynamics of the battery cell may be studied by means of the simulated battery model in a computer environment. In the Matlab model the battery cell is modeled as one part and the BMU as a separate part, the battery model may be analyzed alone or together with the BMU in order to obtain a full system response. In figure 3.1 the system setup is shown where the battery and BMU is interconnected in the Simulink environment.

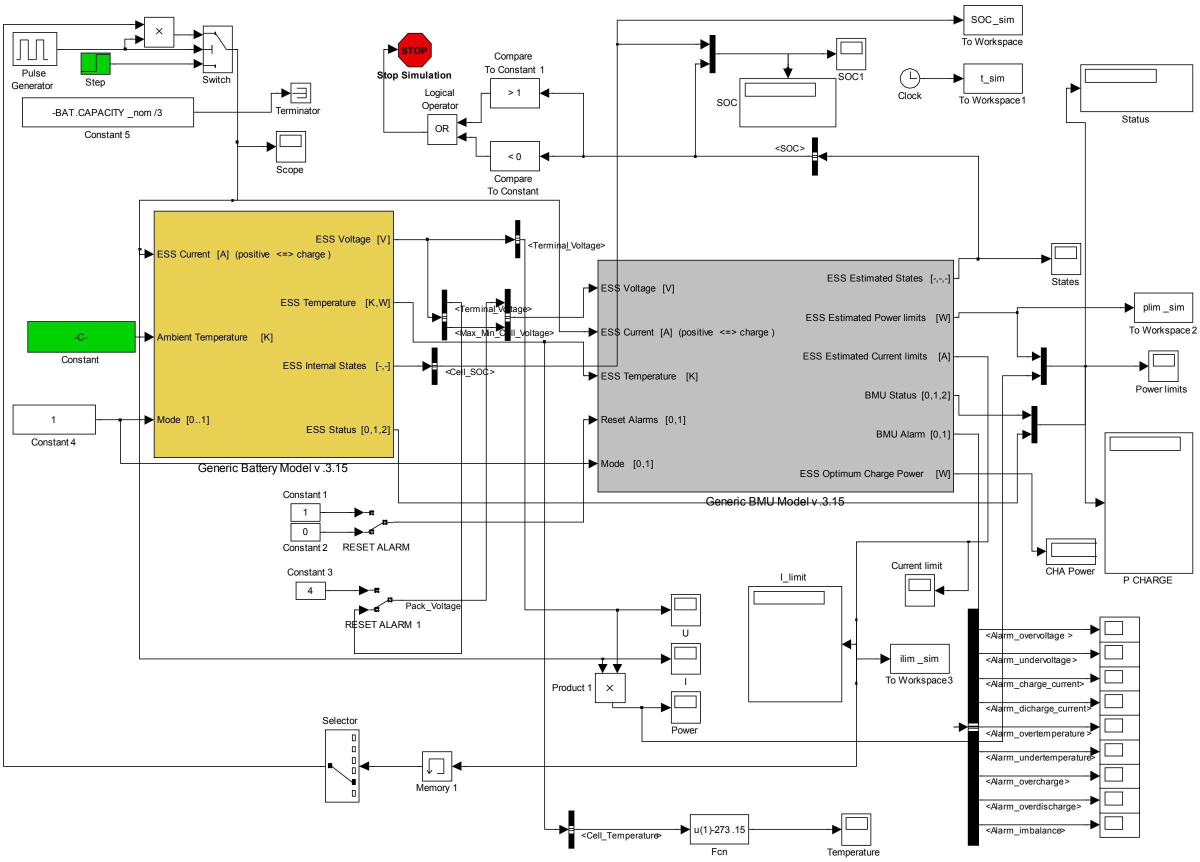

Figure 3.1 shows the simulation window in Simulink with the battery in series with the BMU. [Internal material, ETC]

To be able to use the model, the laboratory experiments which aim to extract the needed input data have to be performed first. The result from the experiments is then formatted, sorted into vectors and put into MAT-files with help from the file *load_digatron.m* which converts data to MAT-files and controls the time vector for duplicates which is forbidden in the script. MAT-files are then the file type that Matlab uses as data files. The input MAT-files will contain data values acquired from the physical experiments, measured variables are; Time, Voltage, Current, Cell Temperature and Ambient Temperature. Finally before executing the simulation model, the input MAT-files needs to be placed in the correct folder.

The first step in performing a simulation is to parameterize the model; this is done by running the script *Init_battery_3_15.m*. After setting the parameters *Test_Battery_v3_15.m* will provide information on how well the battery cell is parameterized by comparing a simulated battery cell performance with actual battery cell performance, the results from this will show the simulated voltage and the measured voltage. If these two has a perfect match the Matlab-model has set the battery cell parameters perfectly. For minimization of this error, manual changes can be done in the parameters to adjust the simulated curve and by this minimize the residual between the true and the simulated voltage. If the residual decreases the battery cell parameters will become more accurate. When satisfaction is reached with regards to the parameters another simulation will be done with a charge/discharge scheme corresponding to PHEV-usage. This is done in order to verify that the parameters also works with a current cycle that the model is not based upon. If the result of Test_Battery_v3_15.m is satisfying *Test_Battery_BMU_3_15.mdl* will be executed in order to find out SOC and Power limits for the battery cell.

1.15 Laboratory equipment

The measurement system *DIGATRON MCT 100-05-8* ME universal battery tester is used to perform all laboratory experiments. A picture of the battery tester can be seen in figure 3.2. It has eight different channels which may be connected to the test object i.e. the battery cell. Each channel is possible to handle up to 100 A current and voltages up to 5 V. Belonging to each channel is also a temperature sensor.

Figure 3.2 displaying the measurement setup

1.16 The laboratory experiments

When a series of measurements is about to be performed on a new battery cell it is necessary to format the battery cell. One complete discharge followed by a complete charge of the battery cell is referred to as a *Standard Cycle*. After charging/discharging a battery cell the voltage will decrease/increase slightly due to stabilization. Because of this behavior it is appropriate to insert a pause between the charge and discharge to be able to measure this stabilization process. A Standard charge in four cycles (repeated four times) is in our study referred to as *Battery*

Formation. This is made for the battery cell to stabilize so the battery cell performance becomes more representative. If taken directly from the packaging and tested on, the results might not be as representative as from a battery charged/discharged a couple of times due to stabilization in the battery cell. From the battery formation output data the battery cell reference capacity can be extracted. Reference capacity (C_{ref}) is set as 97,5 % of the total amount of Ampere-hours discharged during the last cycle in battery formation. This reference capacity is necessary for the following tests.

After the battery formation the *Dynamic Resistance and Open Circuit Voltage Test* is performed at the four temperatures -15˚C, 0˚C, 23˚C and 40˚C. Even though the actual temperatures during the measurements will deviate a couple of degrees from the intended test temperature, the different measurements will be referred according to the temperatures that were supposed to be used. The test is also done at different *C-rates*. C-rate is the expression for how high current that is used and is referring to the maximum reference capacity C_{ref} of the battery cell. If 1C-rate is used it means that it will discharge the battery completely in 1 hour, e.g. if C_{ref} is 20 Ah it means that 1 C-rate is equal to 20 A, ½C-rate equal to 10 A etc. The C-rate settings for both charging and discharging that will be used are 1C-rate, 5C-rate and 10C-rate. This test is performed to gain information about the OCV after charge and discharge. This test also gives information about the internal resistance. After each charge/discharge there is a pause of 15 minutes, this is to observe the stabilization process of the battery cell. All tests starts with one standard cycle as well as an acclimatization phase consisting of a 12 hour pause to ensure that the battery cell is fully charged and has the correct temperature. A charge/discharge for this test cycle is showed in figure 3.3.

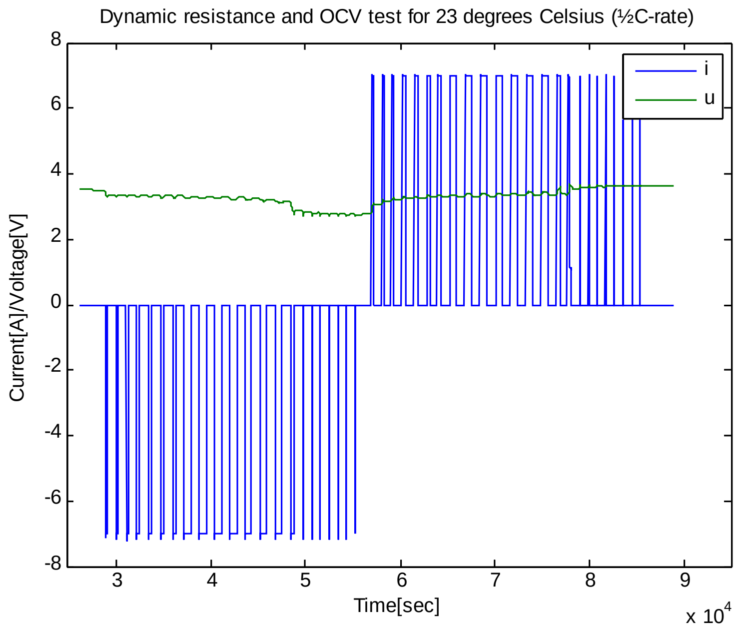

Figure 3.3 showing the current cycle for the Dynamic resistance and OCV test.

In the measurement that is below 0 degrees Celsius only 1C-rate is used to spare the battery cell from damage.

1.16.1 23 degrees Celsius

The laboratory experiment at room temperature is the first measurement that will be performed. Before performing this measurement the battery cell should be mounted on a stand in order to keep the thin electrodes from braking, the programming in Digatron should be finished and safety margins for the battery as well as for the other equipment considered. In this project the cable-capacity has to be considered and the safety-aspects when connecting/disconnecting the battery to prevent short-circuiting the battery cell.

1.16.2 **40 degrees Celsius**

This laboratory experiment demands that the ambient temperature of the battery cell is 40 degrees Celsius. This temperature issue is going to be solved by performing the measurements in a water tank which has a build in thermostat that control the water temperature. In this measurement it is important to know the time extent of the laboratory experiment as mentioned earlier. This due to that the water with a temperature of 40 degrees Celsius tends to evaporate. Since there is no control unit controlling the water level in the tank the battery will be continually more and more exposed to contact with air leaving the accuracy of the measurements questionable. This measurement is approximated to four days (4*24 hours) which probably will empty the whole water tank. This leads to that the water tank needs to be continually refilled with water in order to keep the ambient temperature correct. Also the water level cannot cover the battery cell complete due to short circuit if the water level establishes an electronically conducting connection between the electrodes.

1.16.3 **0 and -15 degrees Celsius**

For performing these laboratory experiments a freezer and a thermostat has to be used in order to keep the ambient temperature steady. It is probably advantageous to purchase a top-loaded freezer since it is easier to handle cables and connections from above. The measurements with 0 and -15 degrees Celsius are similar with the exception that the laboratory experiment with -15 degrees Celsius only is performed with a low current.

PARAMETERIZATION OF A LITHIUM-ION BATTERY CELL (14.5Ah)

Chapter four provides information concerning the execution of the project. It also describes problems that occurred during the execution as well as how these were overcome. Also errors that occurred in both Digatron and Matlab as well as how these were corrected are explained.

1.17 Software

Most problems that were encountered during the execution phase of the project were concerning programming in Digatron and Matlab.

1.17.1 Digatron

Digatron software was used to program charging/discharging schedules according to the battery test specification given. The given instructions of the schedule was handed in paper-format and had to be programmed into the Digatron software. The instructions did not include the Digatron commands, only stepwise instructions of what actions that were going to be performed on the battery cell. This had the consequence that several commands had to be understood before the programming could begin.

The first and least complex file that was programmed in Digatron was the formation file which was needed before any other tests could be performed. The second file that was programmed was the file that calculated the internal resistance and open circuit voltage. In every command that charged/discharged the battery cell safety commands was used that either forced the program to stop or jump to the following command. These safety commands activated if the cell became overheated respectively reached the voltage limit for charging/discharging. This file was programmed once and then packed and unpacked in three different files, these files was then slightly changed so they were performed at the three different C-rates. These Digatron files with different C-rates were named LC, MC, HC which is abbreviations for Low Current, Medium Current and High Current in order to easily separate the files.

1.17.2 Programming errors in Digatron

When the files in Digatron were programmed, the laboratory experiments on the 20 Ah battery cell that would confirm that the programming and the Matlab-model was correct could start. This was done by placing the files in a queue and activating the test-program.

Since the laboratory experiments were very time-consuming a decision was taken that only one laboratory experiment on one C-rate in one temperature should be done to begin with. This should be used with the already given existing files for confirmation of correct data settings/handling. After the first laboratory experiment was completed this data were extracted from Digatron, formatted and converted to mat-files. The files contained vectors with voltage, current, time, cell temperature and ambient temperature. When the mat-file from the now performed 1C-rate measurement with the ambient temperature of 23 degrees Celsius was inserted with the other two existing results (5C and 10C) from 23 degrees Celsius and the existing results from -15, 0 and 40 degrees Celsius a try to run the initiation file was made. Sampling was made on four different conditions, 1 sampel/sec, 1 sampel/0.05*nominal current, 1 sampel/0.005*nominal voltage or 1 sampel/Kelvin.

The outcome of the first laboratory experiment was not correct. According to the schedule a charging/discharging condition (Ahstep) that would precede the program when a certain amount of charge has been charged/discharged had been incorrectly written. The compilation of the program had been successful but the execution was not correct so this condition was not fulfilled. Instead of discharging the battery cell in a series of predetermined current-pulses (Ah-steps) the battery became completely discharged in the first pulse leaving the remaining discharge pulses very small due to that the voltage-condition almost instantly activated. After a discharging pulse the battery cell goes into a pause, during this pause the voltage increases before the next discharge pulse starts. So the low voltage condition is not fulfilled before the next discharging pulse starts and drastically reduces the voltage. In the settings the lower voltage limit was set to 2.0 Volts. Adjustments were made on the Ahstep-condition and another laboratory experiment was performed.

In the battery test specifications it was specified that the appropriate C-rates were 10C, 5C, 1C. But during the second laboratory experiment with these specified C-rates a problem with overheating of the battery cell occurred at MC. This due to the high current during a long time before the low voltage condition activated. An attempt to overcome this was made by adding a cooling fan which led the heat away from the battery cell. After adding the fan no overheating occurred at MC, but at HC the battery cell still became overheated. When comparing the results from the laboratory measurements and the existing files a discovery was made that the specified C-rates was not the C-rates used in the results from the 20 Ah battery cell. These results were founded on 5C, 2C and 1/2C which are about half the C-rates specified. Due to the fact that a comparison had to be made in order to conclude whether the work so far was correct or not a change in C-rates was made. The C-rates were changed to 5C, 2C and 1/2C. After changing the C-rates according to the C-rates used in the results given and changing the low voltage condition from 2 Volts to 2.7 Volts no overheating occurred. The amount of energy available in the battery cell with regards to the voltage difference of 0.7V is small; this small amount of energy compared to the increased safety margin makes this change appropriate.

A new laboratory experiment at 23 degrees Celsius was made. A misunderstanding had been made in the specifications causing that charging/discharging cycles were missing in the results due to incorrect interpretation of the specification. This was changed to the correct number of charging/discharging cycle.

A fourth laboratory experiment was made, this resulting in an error in the time-vector, the time-vector had to be monotonously increasing which was not the case due to a sampling error. Sampling had been made on four different conditions, namely voltage, current, temperature and time. This resulted in multiple samples per time unit leaving the time-vector not monotonously increasing. Changes in sampling conditions were made so only time was the sampling condition with a sampling frequency of 0.5 Hz.

During the fifth laboratory experiment which also was unsuccessful due to low sampling rate. The charging/discharging cycles was not enough clearly defined for the Matlab script to be able to interpret these as current pulses. An adjustment in sampling rate had to be made. The sampling rate was increased from 0.5 Hz to 10 Hz.

After the sixth laboratory experiment which also was unsuccessful a discovery was made that the charging cycles was incorrectly performed, instead of charging with "constant current/constant voltage" a charging with only constant current had been made. This was changed and finally the seventh laboratory experiment was successful. After achieving successful laboratory results on the 20 Ah battery cell laboratory experiments on the 14.5 Ah battery cell began.

The results from simulating with the 20 Ah battery cell is shown in figure 4.1 where the results without any manual changes in the parameters have been made. It clearly shows that the residual between the curves is small and thus the accuracy is good except from the points in proximity of SOC 100% and 0%. The SOC graph is shown in figure 4.2.

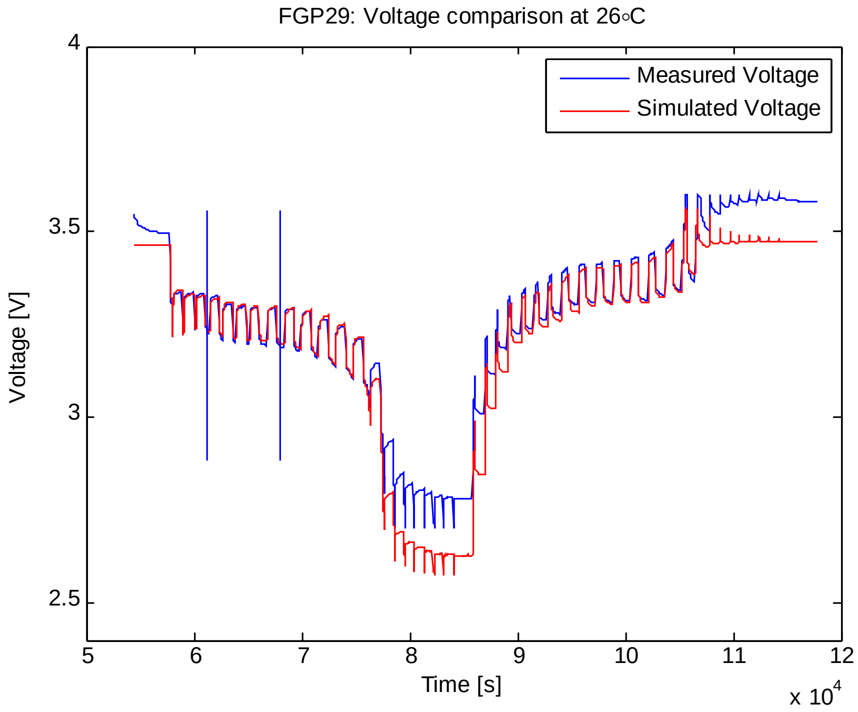

Figure 4.4 is showing the results from executing test_battery_v3_15.m with data from the 20 Ah cell in order to verify correct measurements.

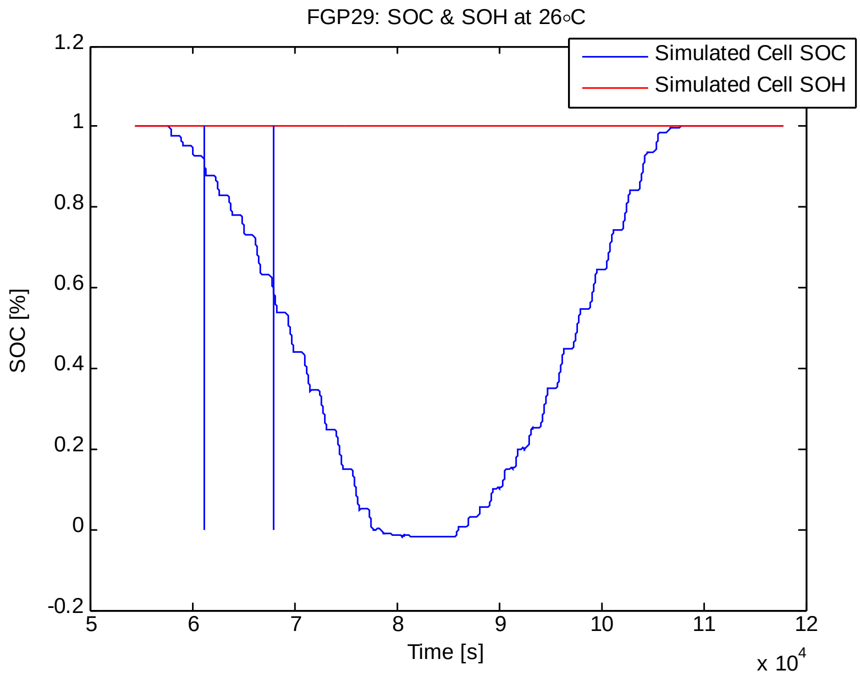

Figure 4.5 is showing the SOC from executing test_battery_v3_15.m with data from the 20 Ah cell in order to verify correct measurements.

A problem that was noticed throughout all the results from the parameterization laboratory experiments was that the battery cell became fully charged / discharged to early in the test cycles. The current cycle can be seen in figure 4.3 and the problem can be clearly noticed in the close up in figure 4.4. This caused that the last current pulses became very short which makes them difficult to for the model to identify. This will force the model to extrapolate and interpolate these values based on other data from the same measurement. This interpolation/extrapolation has less accuracy and by this the results will be less accurate in these regions, which can be seen in figure 4.1.

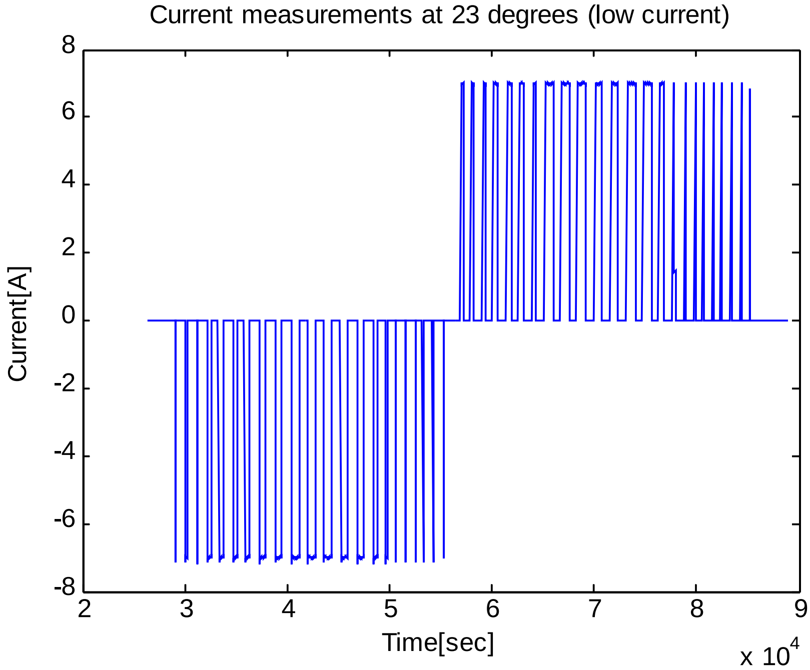

Figure 4.3 displaying the current graph obtained during the laboratory experiments on the 14.5 Ah cell.

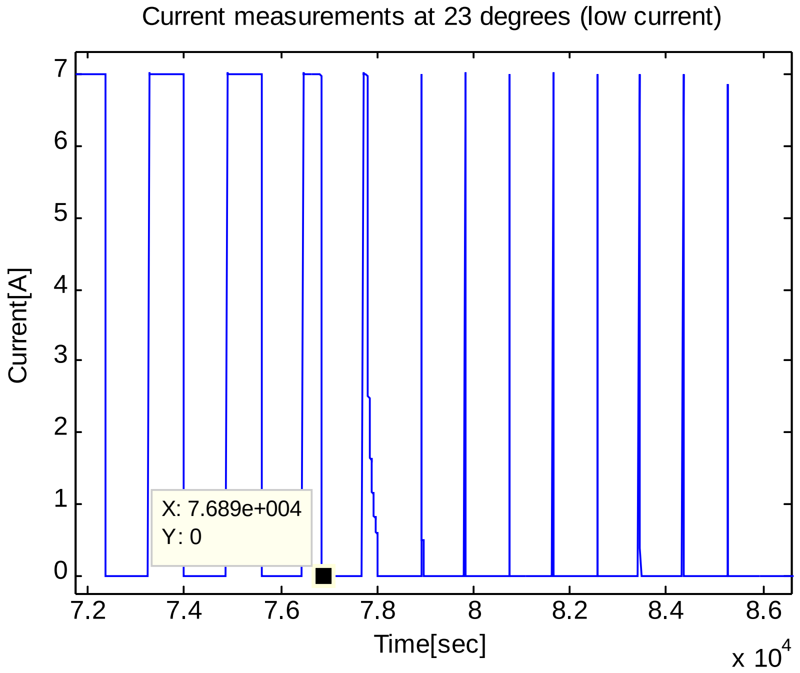

Figure 4.4 showing a close up of the current graph from figure 4.3 displaying the short current pulses beginning at 7.689e+4 sec due to the premature fully charged battery.

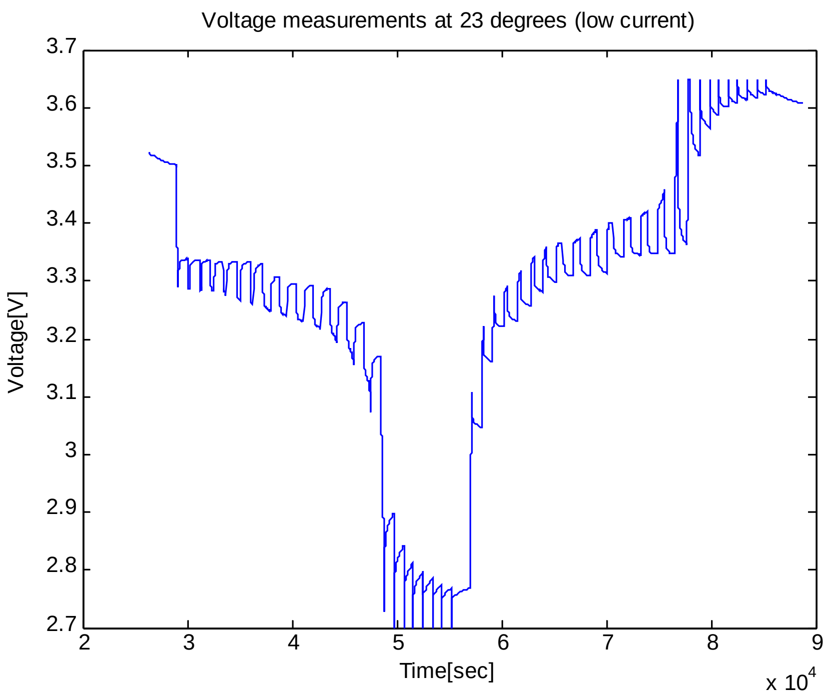

Figure 4.5 The voltage graph obtained from the laboratory experiments. Notice the significant voltage changes when the cell is totally discharged (t=4.6e4) respectively charged (t=7.8e4).

Another observation was that the ambient temperature during the measurements did not stay constant. This was due to the relatively simple laboratory equipment used. This probably will cause some inaccuracies in the model. The temperatures during the tests are shown in figures 4.6-4.9.

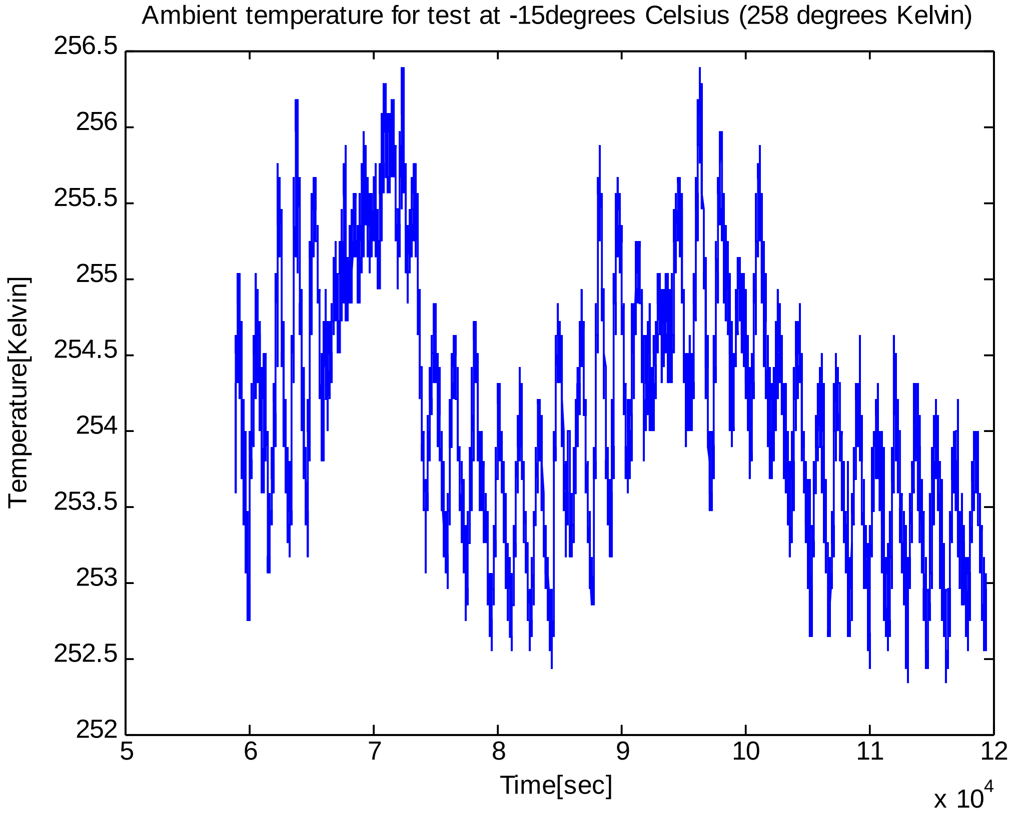

Figure 4.6 displaying the temperature during test at -15 degrees Celsius.

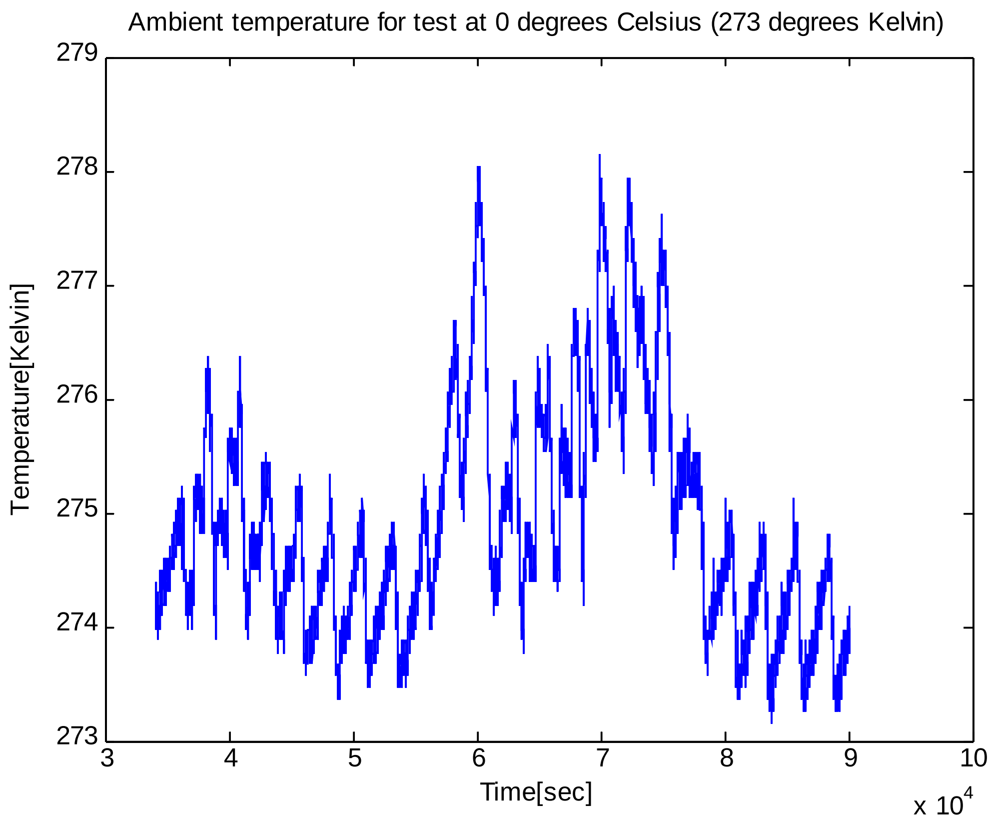

Figure 4.7 displaying the temperature during test at 0 degrees Celsius.

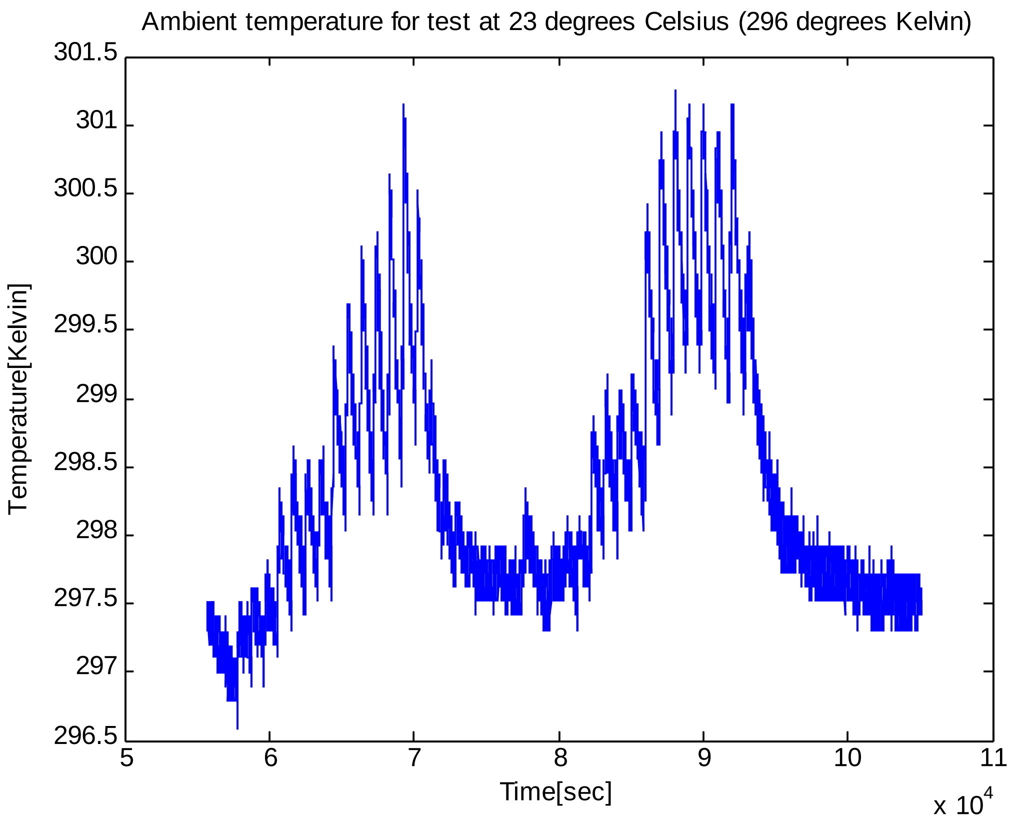

Figure 4.8 displaying the temperature during test at 23 degrees Celsius.

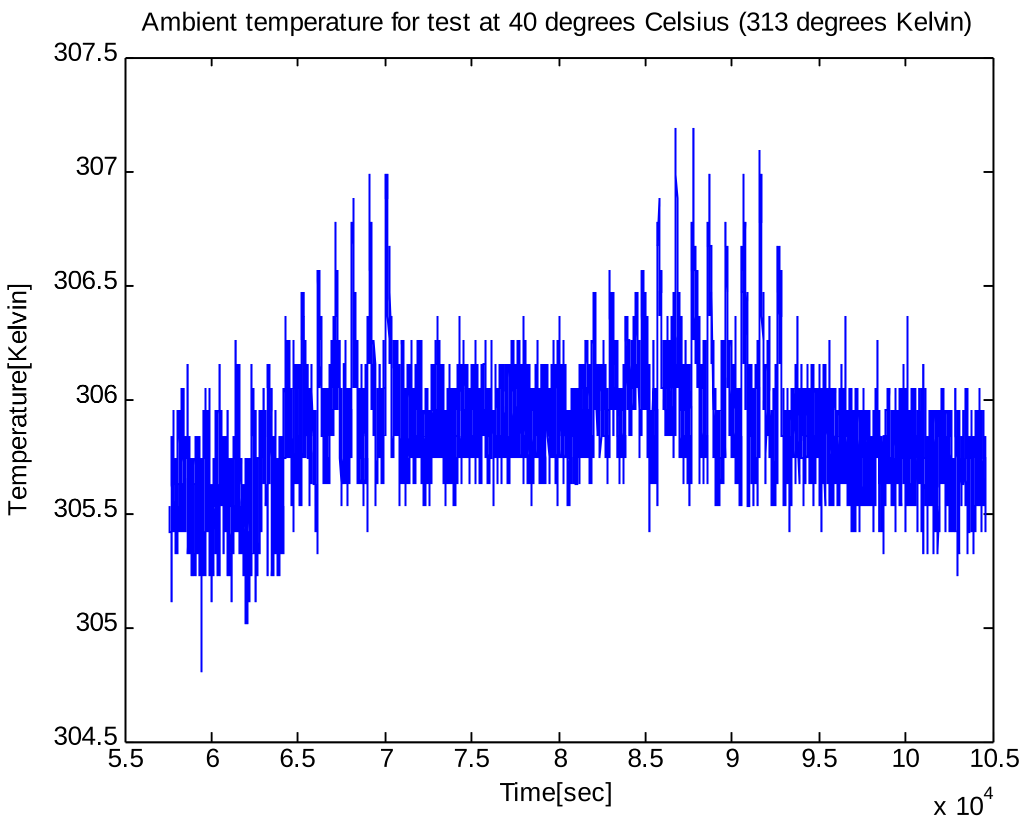

Figure 4.9 displaying the temperature during test at 40 degrees Celsius.

1.17.3 Matlab errors

After execution of laboratory experiments on the 14.5 Ah battery cell, the data was implemented in Matlab. Despite that previous tests had confirmed the laboratory experiments correctness and data handling the Matlab-script did not work. Error messages still appeared when the scripts were executed. After studying and searching in the Matlab-scripts a constant concerning data-filtering was found (break limit). By changing this constant no error message appeared when the script was executed. Another error occurred when implementing the data for -15 degrees Celsius laboratory experiment which only was performed with 1/2C-rate in order to spare the battery cell. Conclusions was made that charging constants needed in the Matlab script for the laboratory experiments with 2C and 5C not performed for -15 degrees was founded on charging constants for 0 degrees. And since the 0-degrees laboratory experiment not yet had been preformed, existing files for 0 degrees from the 20 Ah battery cell was used for confirmation.

1.18 The laboratory experiments implementation

The work with implementation of the laboratory experiments was straight forward and did not cause any major problems.

1.18.1 23 degrees Celsius

From experiences of laboratory experiments on the 20 Ah battery cell were the electrodes came loose from the battery cell due to their fragileness, a conclusion that a stand was necessary was made.

1.18.2 **40 degrees Celsius**

In this laboratory experiment the battery cell and the stand holding it had to be lowered into a water tank. The water tank was not that big leaving a limited number of ways to use it. The stand and the battery were simply lowered into the tank in the way that was possible with this construction. One disadvantage in this laboratory experiment was that the stand was composed of wood which absorbed water and expanded/became electrically conductive. When performing measurements of the complete setting of the water tank including battery a voltage drop between electrode and water tank appeared. A current flowing through the poorly isolated bolts on the backside of the stand to the water tank was noticed. The measurements had to restart with better isolation. Also measurements on the conductivity of the stand when water had been absorbed were made, but the resistance in the water absorbed stand still prevented current from flowing.

1.18.3 **0 and -15 degrees Celsius**

In this laboratory experiment a freezer had to be purchased. Since no thermostat had been purchased yet the temperature setting that could be done was on the freezer which only could be set at a scale from 1-6 were 6 is coldest. This complicated the setting of -15 degrees Celsius. When performing measurements at 0 degrees Celsius a thermostat was needed in order to switch the current to the freezer on and off so a temperature close to 0 degrees Celsius would be kept, this since the maximum temperature of the freezer was about -10 degrees Celsius. A thermostat was purchased and at delivery it was discovered that no cables/components that was necessary for connections was included. After searching the ETC storage rooms after materials an extension cord and coupling-material were found so mounting became possible.

1.19 Accuracy of the simulations

During investigations of the extracted parameters concerning the accuracy of these it was concluded that improvements could be made. The most critical deviation between simulated and measured voltage could be observed in data from the laboratory experiments performed in low temperatures. Especially during -15 degrees Celsius the deviation became substantial. To make these improvements, manual changes in the parameters had to be made. The parameter changes were accomplished by trial and error. The parameter which gave the best improvement was the open circuit voltage which adjusted the voltage level. Changes in other parameters were also made but this did not have any large impact on the curve. The increased accuracy that was obtained at simulations in 0 degrees Celsius can be observed if comparing figure 4.10 and 4.11 and for -15 degrees Celsius in figure 4.12 and 4.13 . The accuracy of the simulations for the 23 and 40 degrees Celsius are similar to the accuracy at 0 degrees Celsius, although somewhat better.

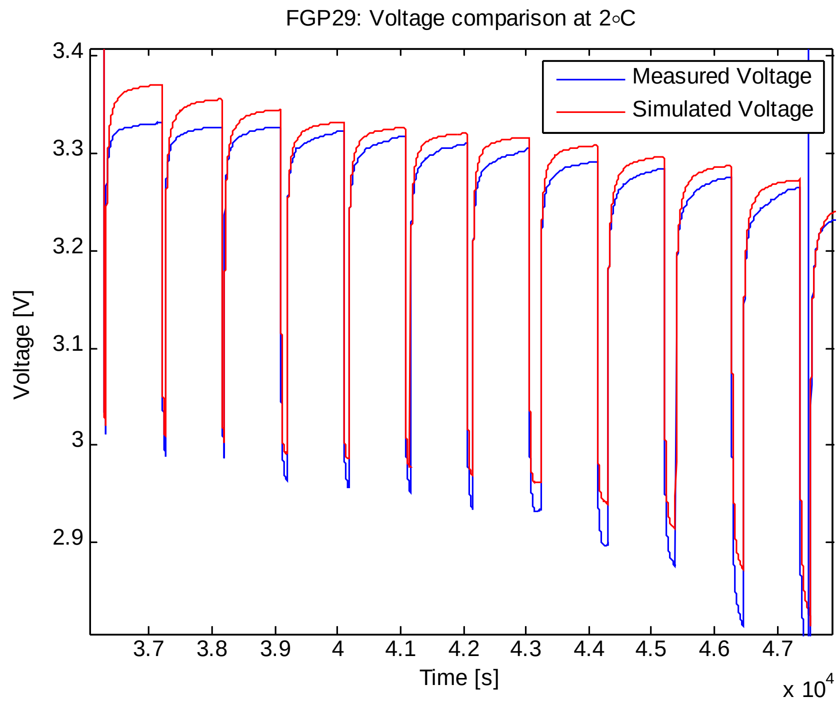

Figure 4.10 displaying the voltage comparison between laboratory experiment and simulation, 2C-rate, SOC 100-20%, during 0 degrees Celsius without manual adjustments.

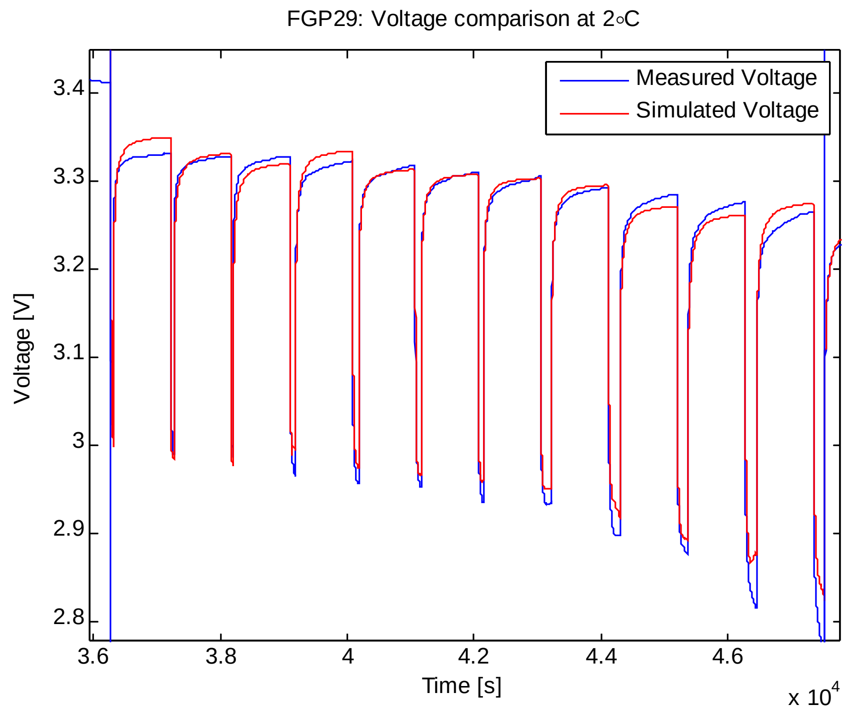

Figure 4.11 displaying the voltage comparison between laboratory experiment and simulation, 2C-rate, SOC 100-20%, during 0 degrees Celsius with manual adjustments.

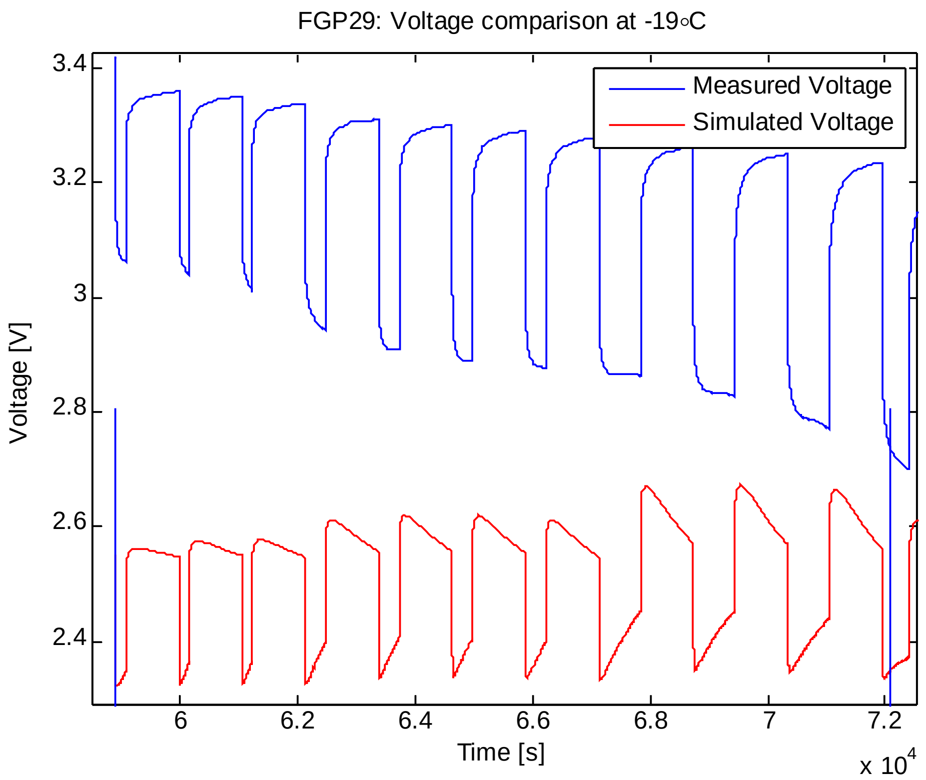

Figure 4.12 displaying the voltage comparison between laboratory experiment and simulation, SOC 100-20%, during -15 degrees Celsius without manual adjustments.

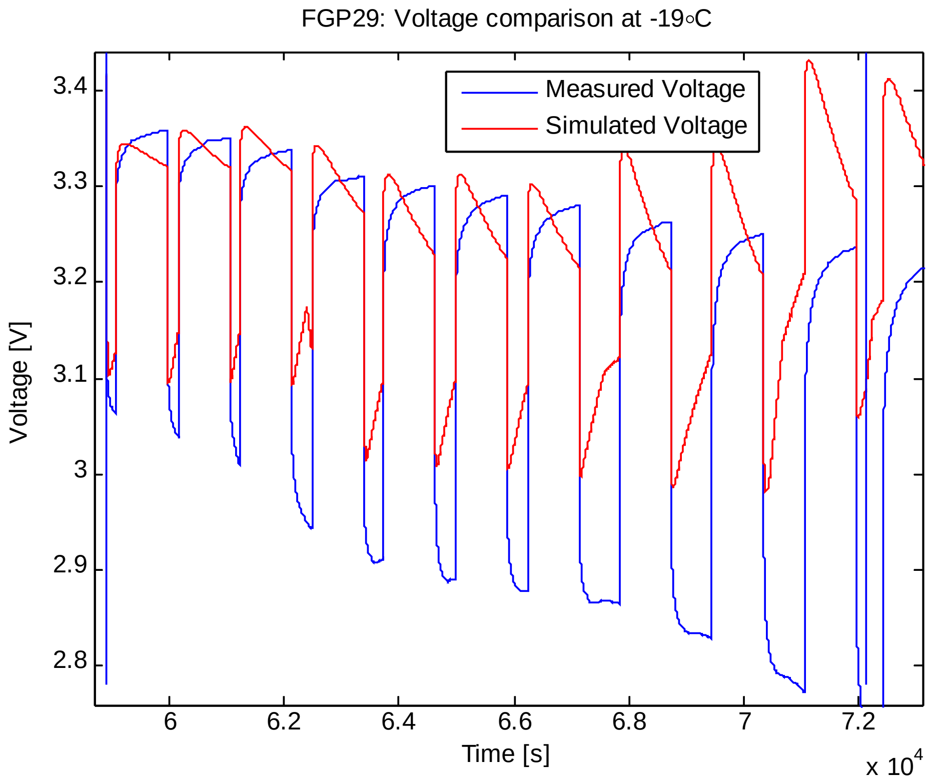

Figure 4.13 displaying the voltage comparison between laboratory experiment and simulation, SOC 100-20%, during -15 degrees Celsius with manual adjustments.

A Matlab script simulating the current cycle of an everyday driving scenario of a plug-in hybrid vehicle was constructed and used as input to Test_battery_v3_15.m. This was for confirmation that the accuracy is kept for a more general driving scenarios also. This would also enable the possibility to study how well the accuracy of the model was maintained after a complete recharge event. This simulation can be observed in figures 4.14 - 4.17. Figure 4.14 shows the complete voltage response obtained from the current cycle used. The current cycle used consisted of two series of 50 repeated identical discharge events separated with a complete recharge in between. A close up of the current cycle is shown in figure 4.15. In order to study how the accuracy is changed with the SOC, figure 4.16 and 4.17 are displaying the voltage comparison in the beginning respectively the end of the second half of figure 4.14. These show clearly how the accuracy is decreased when the battery cell starts to become discharged. Notice also how the accuracy is restored after the complete recharge of the battery.

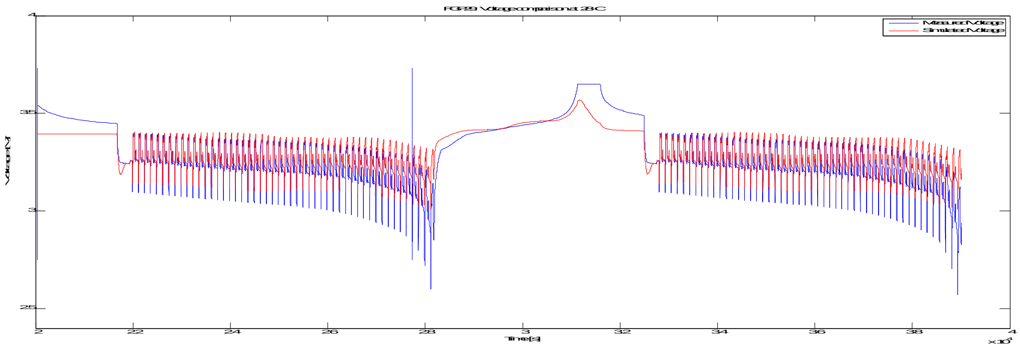

Figure 4.14 displaying the voltage response from a general current cycle that was used to confirm the accuracy of the model. The cycle consists of two series of 50 repeated identical discharge events separated with a complete recharge in between. A close up of the current cycle used, is shown in figure 4.15.

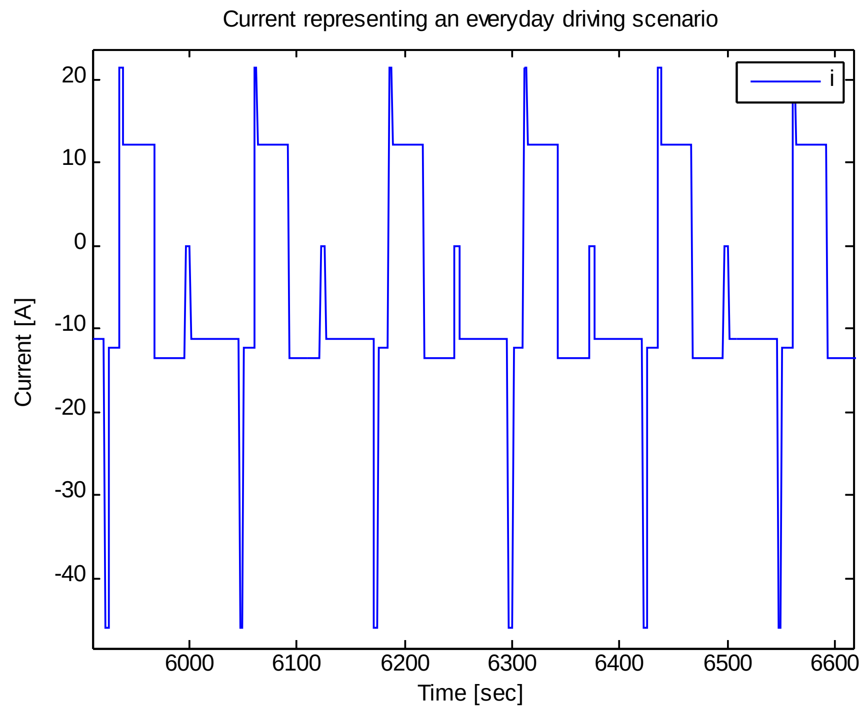

Figure 4.15 displaying a close up of the current drawn from the battery representing a general driving scenario used in figure 4.14.

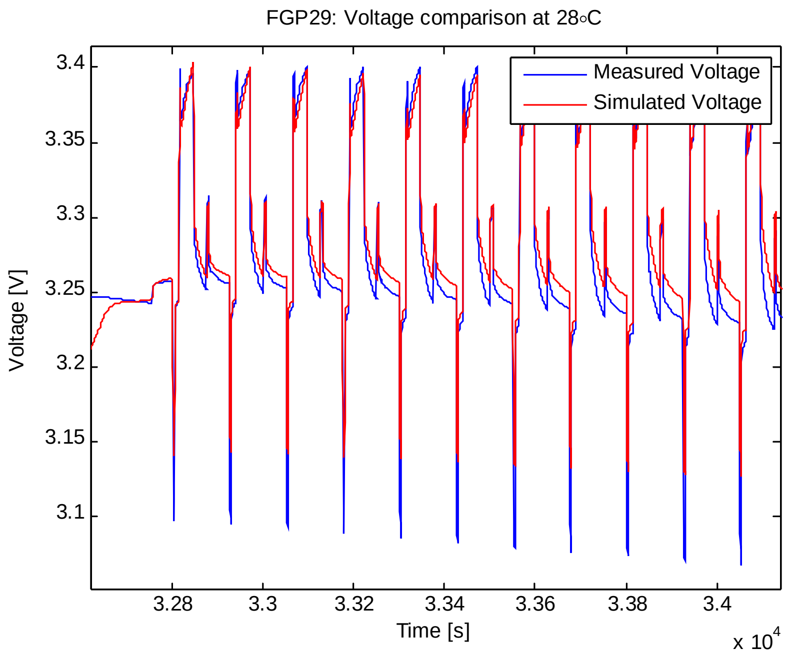

Figure 4.16 displaying a close up of the beginning of the second discharge series in figure 4.14. Notice the small residual between the measured and simulated voltage response.

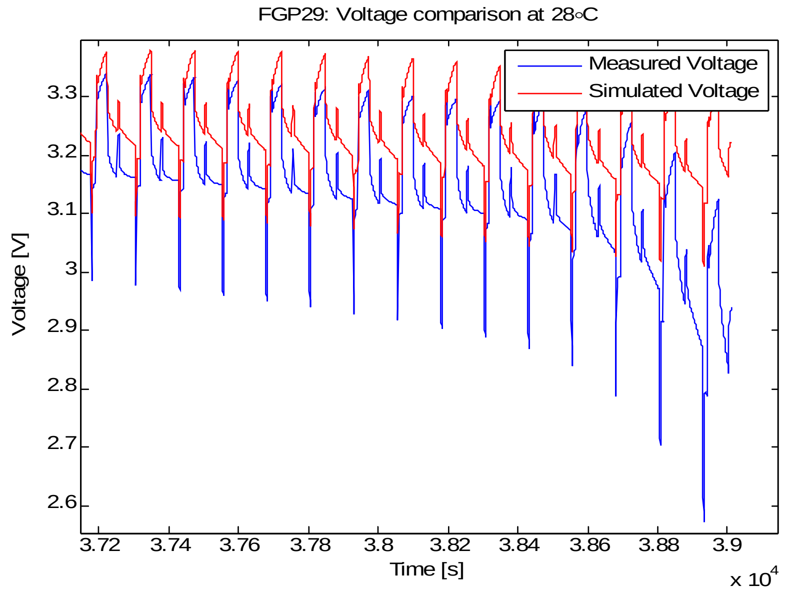

Figure 4.17 displaying a close up of the end of the second discharge series in figure 4.14. Notice the increased residual between the measured and the simulated voltage response.

For analyzing the precision of the simulation of the general driving cycle the error between the measured and the simulated curves has been plotted in figure 4.18. In this figure the mean value of the plotted error within the optimized region (SOC 100%-20%) is determined to 1.4% and the overall error to 1.5%. These errors are well within the set error limit that is set to 5% by the commissioner of this project. Notice figure 4.19 where the SOC is plotted for this simulation how the SOC increases to about 1 (100%) at t = 3.3e4 sec where the complete recharging occurs.

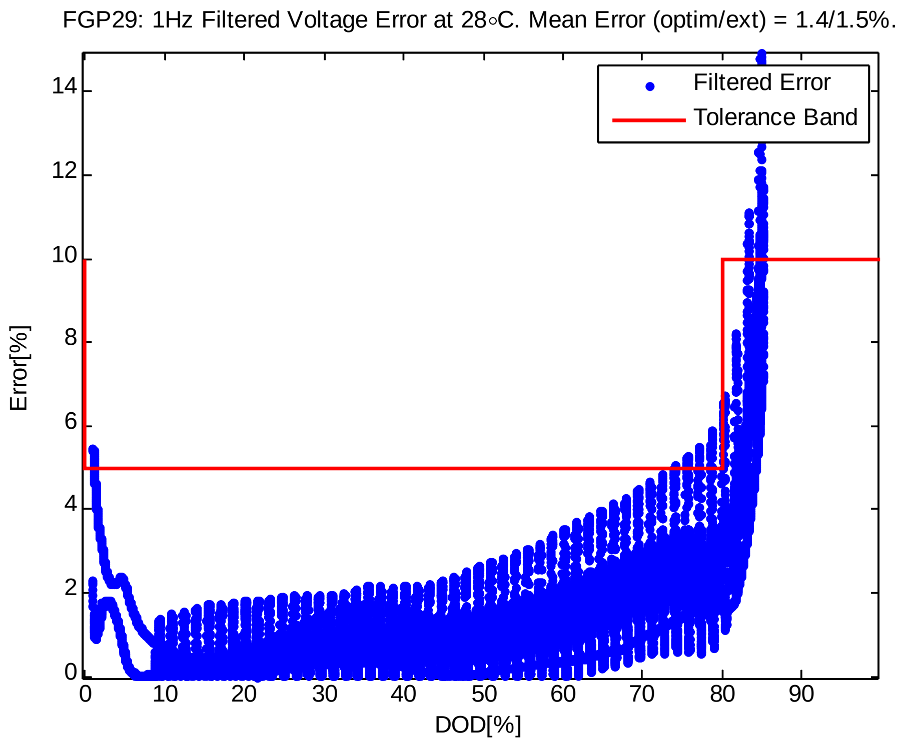

Figure 4.18 displaying the error between the measured curve and the simulated curve. Notice the increased error as the DOD reaches higher states.

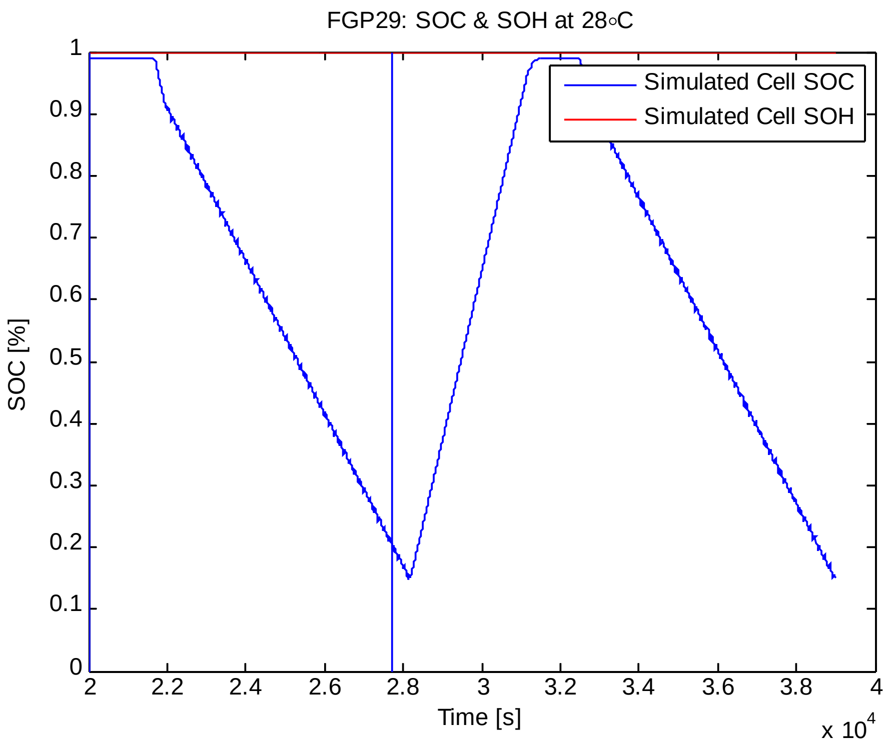

Figure 4.19 displaying how the SOC changes during the simulation of the general driving scenario displayed in figure 4.14.

VALIDITY

This result is valid to be used as parameters in a PHEV with battery cells of the type $LiFePO_4$-ePLB F014 with capacity 14.5 Ah from manufacturer EIG until an updated simulation model is released that can provide more accurate results.

RESULTS

In this chapter the final results from only the 23 degrees Celsius parameterization is presented, the results for the other temperatures will be presented in appendix A. First the parameters are presented, next the SOC and finally the power limits. In terms of internal resistance only the ohmic resistance will be presented since this is the most interesting part.The results in this report are graphically presented, the results are also obtained in numerical format but this will not be included in the report.

1.20 Parameter results

Figure 6.1 displays the ohmic resistance, the values are showing a good concentration between 3-3.5 mOhm which is a reasonable level, according to experts at ETC. The resistance map also plotted is a second order polynomial adjusted curve fitted to the resistance value.

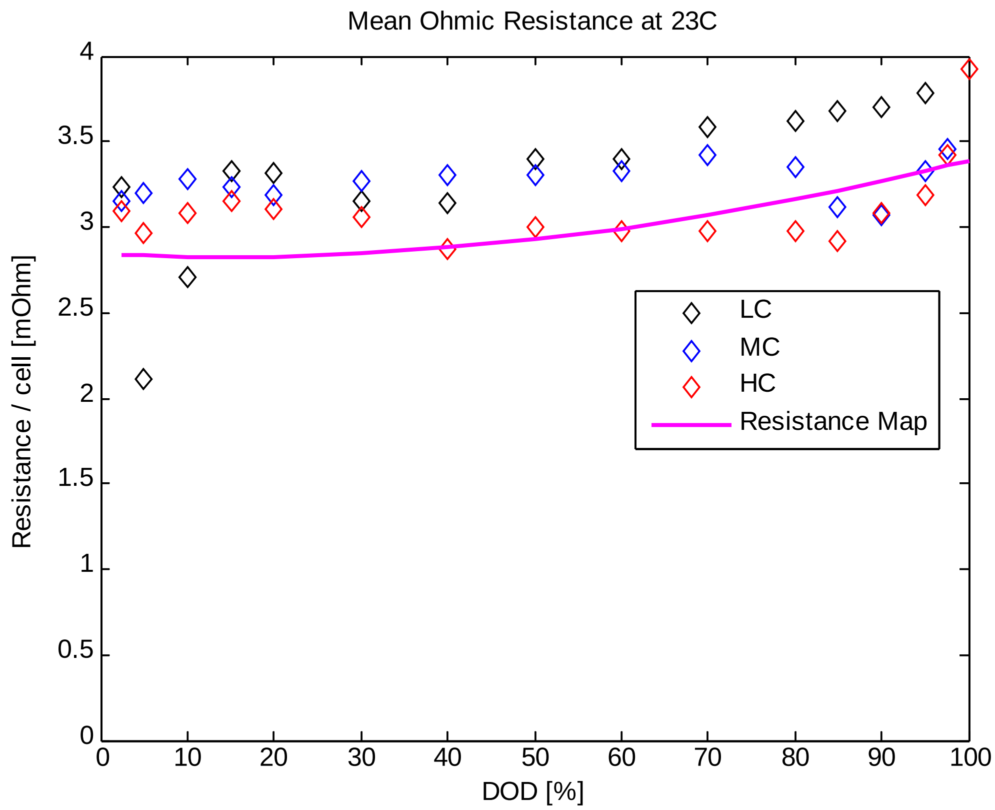

Figure 6.6 diplaying the parameter results for the ohmic resistance.

Figure 6.2 shows the OCV-curve for the simulated battery. The characteristic flat curve with distinct cutoff points as described in section 2.6.1 and shown in figure 2.11, is easily recognized. Also the voltage levels in the figure are good since according to data sheet the nominal voltage should be 3.2V and the maximum voltage is 3.65V for this cell. A slightly higher voltage may be observed but this is due to the models overestimation in order to leave margins for inaccuracies in the battery model.

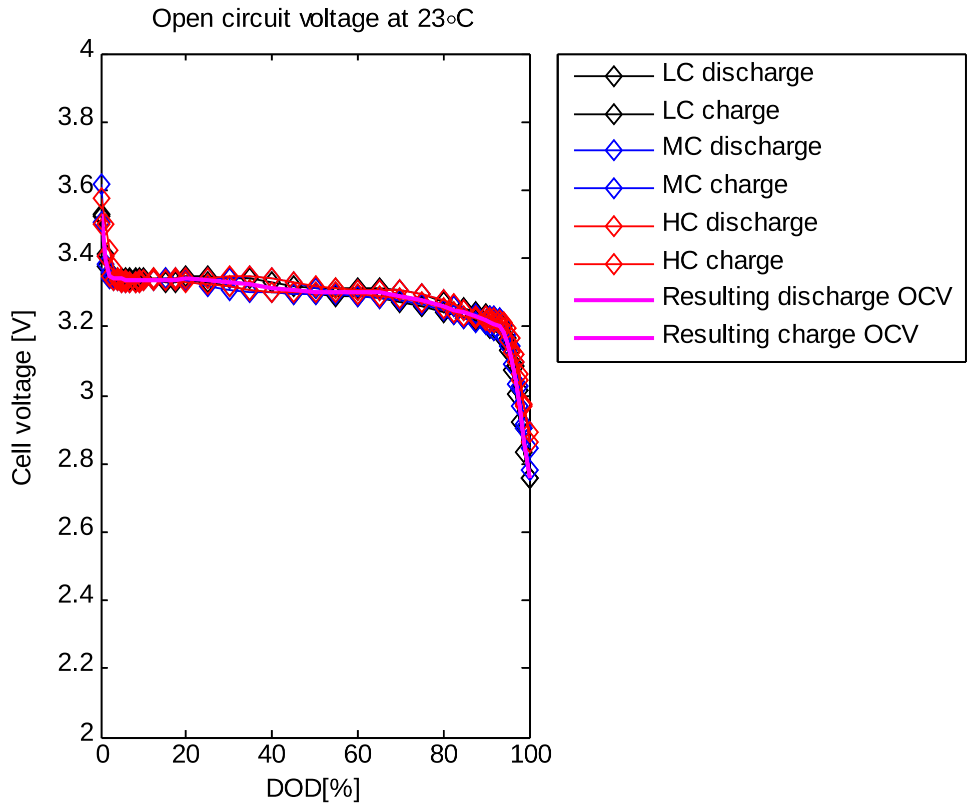

Figure 6.7 displaying the parameter results for the OCV-estimation.

1.21 SOC and power limit results

Figure 6.3 shows the current during complete discharge of the battery cell from SOC 100% until SOC 0%. This cycle is pre-set in the model for testing that the SOC algorithm with the chosen parameters is behaving as expected. In the end the current pulse is reduced due to that the power limits is reduced because of low capacity in the battery.

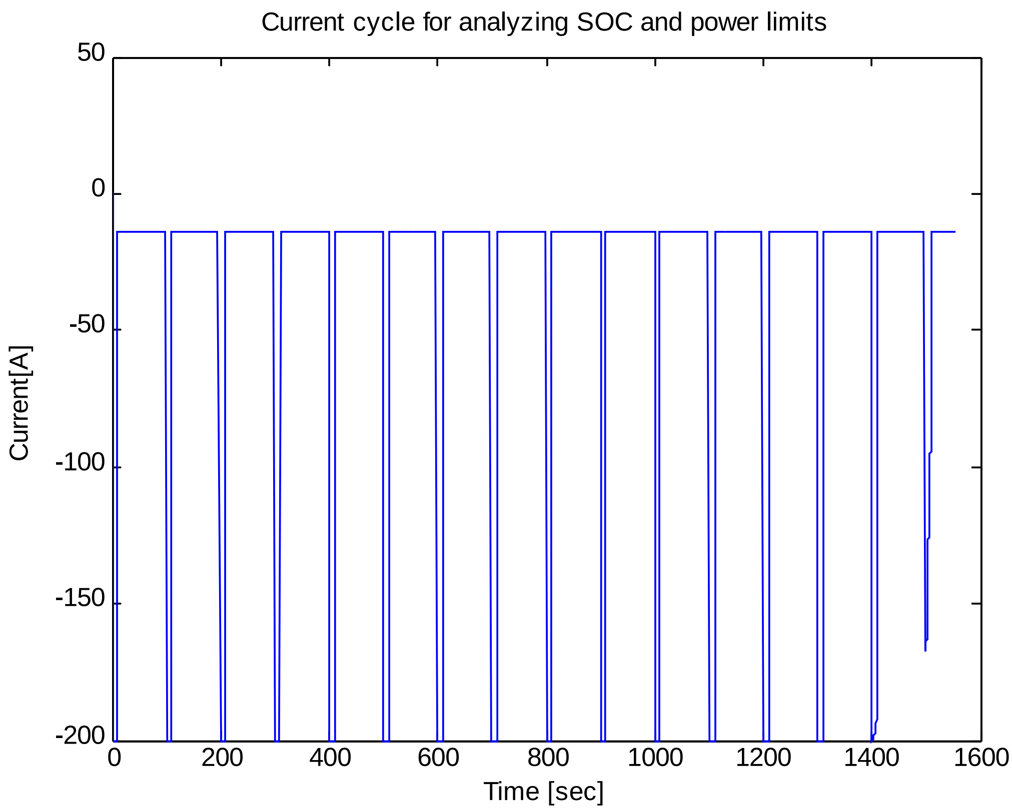

Figure 6.3 displaying the current cycle during complete discharge of the simulated battery cell.

Figure 6.4 shows the calculated SOC during the current cycle in figure 6.3 which was done in the simulation model. Notice that SOC is decreased more drastically when a higher current is applied.

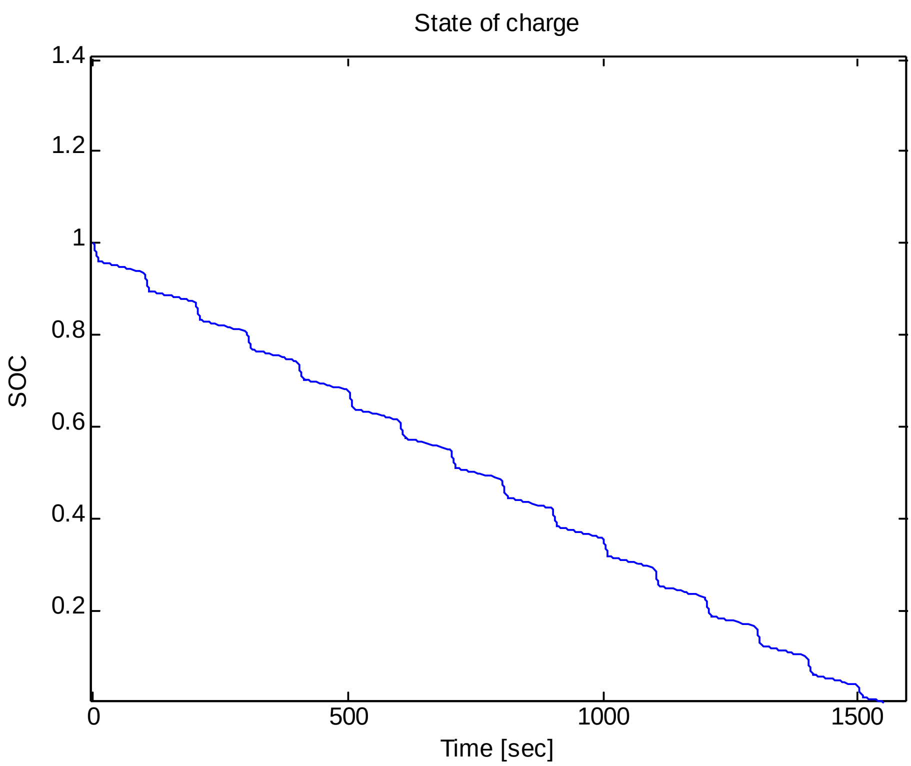

Figure 6.4 displaying SOC during complete discharge.

Figure 6.5 shows the power limits during charge and discharge for three different time intervals, 30, 10 and 1 second. The lower curves represent the discharge limit and the upper curves represents charge limit at the different time intervals. If studying the upper curve during discharge an observation can be made that this power limit represents lower discharge during a longer period of time (30 sec) which is realistic. With similar reasoning the lowest power limit curve represents a discharge at a higher rate during a shorter time interval (1 sec).

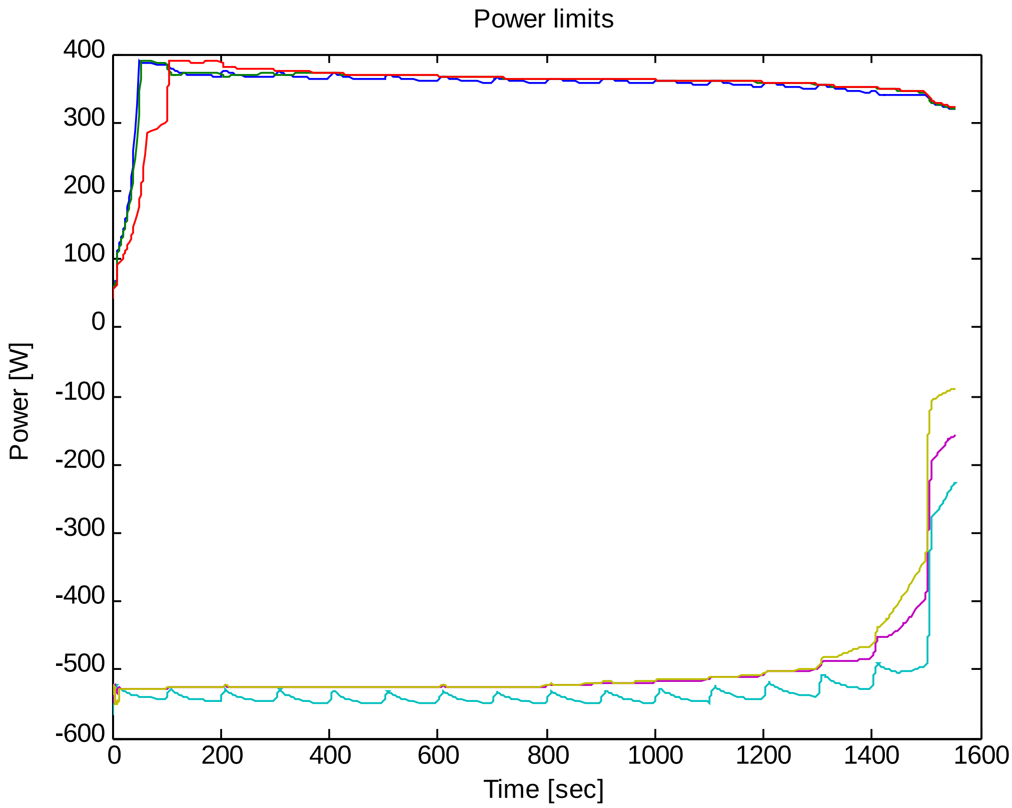

Figure 6.5 displaying the power limits during discharge (3 lower curves) and charge (3 upper curves) for three different time intervals, 30, 10 and 1 sec.

DISCUSSION

If the material provided in this project is assumed to be perfect, the main source of errors will be in the temperature measurements and in the measurement values at high/low SOC since these are the only things influenced during the project.

Inaccuracies adhering to the temperature measurements are probably due to that low precision measuring and laboratory equipment for the temperature controlling has been used which caused the temperature to oscillate. Especially in the case for -15 degrees Celsius when the freezer was used together with the simple thermostat this may have been a problem. Also the model is less accurate in low temperatures according to the model developer.

A theory concerning the errors during high/low SOC was that the schedule for discharge/charge provided too large pulses which led to that the battery cell became charged/discharged before the program was finished. This making the charging/discharging pulses in the end of the program to small for the model to use. This problem forced the model to interpolate/extrapolate these values. This interpolation/extrapolation has less accuracy and by this the results will be less accurate. This theory was tested by reducing the amount of energy in each pulse in order to secure that the battery capacity was neither depleted nor fully charged in advance. The theory failed when looking at the outcome and thus the model could not be adjusted for the battery cell in this way.

One explanation may also be that the accuracy of the current control in the measurement system Digatron was insufficient, since current is a very important variable. Thus a small error in the current would lead to large errors in the end when using the simulation model. But after talking to cooperating parties which previously has performed this type of laboratory experiment, it showed that they also had used this type of measurement system, although with another model. Thus this explanation seems vague.

Another theory regarding why the results not are perfectly accurate, is that the simulation model is originally developed for other types of battery technologies such as NiMH. Since LiIon battery cells have many unique phenomena that might not have been accounted for in the model, this may cause the inaccuracies noticed in the results.

The working method was verified by first implementing it on a battery cell which the results already was at hand for, before the work with the new cell type could begin. This verification showed that the working method should give a good accuracy and because of this it is difficult to exactly determine where the errors come from.

What is important to notice is that the simulations of the general driving cycle in figures 4.14-4.19 shows that the errors are uncorrelated between the recharging events. Thus there are no errors reproducing between the current cycles and the theory discussed in section 2.6.2 on how the BMU´s SOC algorithm is reset after a complete recharge holds.

After discussions with battery experts at ETC and the model developers the maintained parameter results are acceptable and as expected.

CONCLUSIONS

It may be concluded that the simulation model is not optimized for this type of battery cell. However the final results are acceptable even though there are larger errors at high/low SOC. It should be remembered that the PHEV most often operates in the SOC interval between 20-100%. In the region of 100% SOC the battery will always be fully charged and less accuracy is needed. Also since the errors starts to grow only at the very lowest SOC it means that at around 20% SOC and above the accuracy is good. Thus the parameter results may be used in a plug-in hybrid application.

FUTURE OUTLOOK

For future work a higher precision in temperature measurement can be achieved with help of improved laboratory equipment, e.g. temperature controlled cabinet which can keep the ambient temperature more stable. Also new series of measurements with some adjustments for this battery cell (14.5 Ah $LiFePO_4$) can be necessary to improve the results in the critical areas, e.g. try new sampling criteria etc.

The next step would be to develop a simulation model in Matlab/Simulink similar to the model used in this study but which is optimized for usage together with Lithium Ion battery cells, especially $LiFePO_4$-cells. This is to be able to take account for the unique phenomena which are related to this technique.

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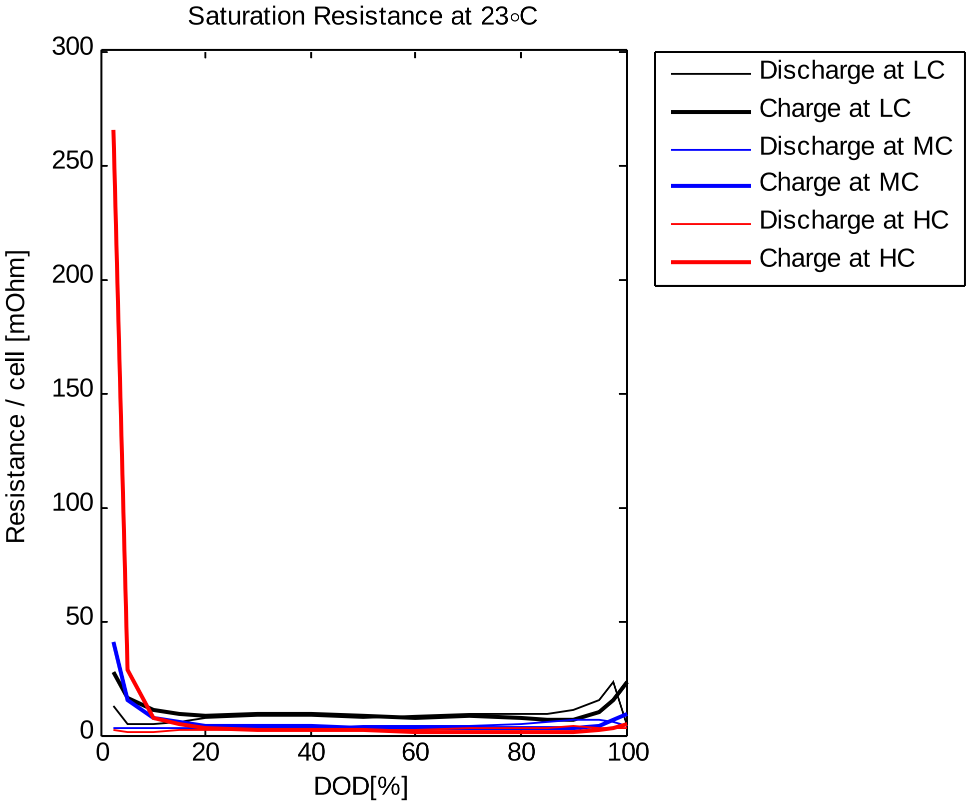
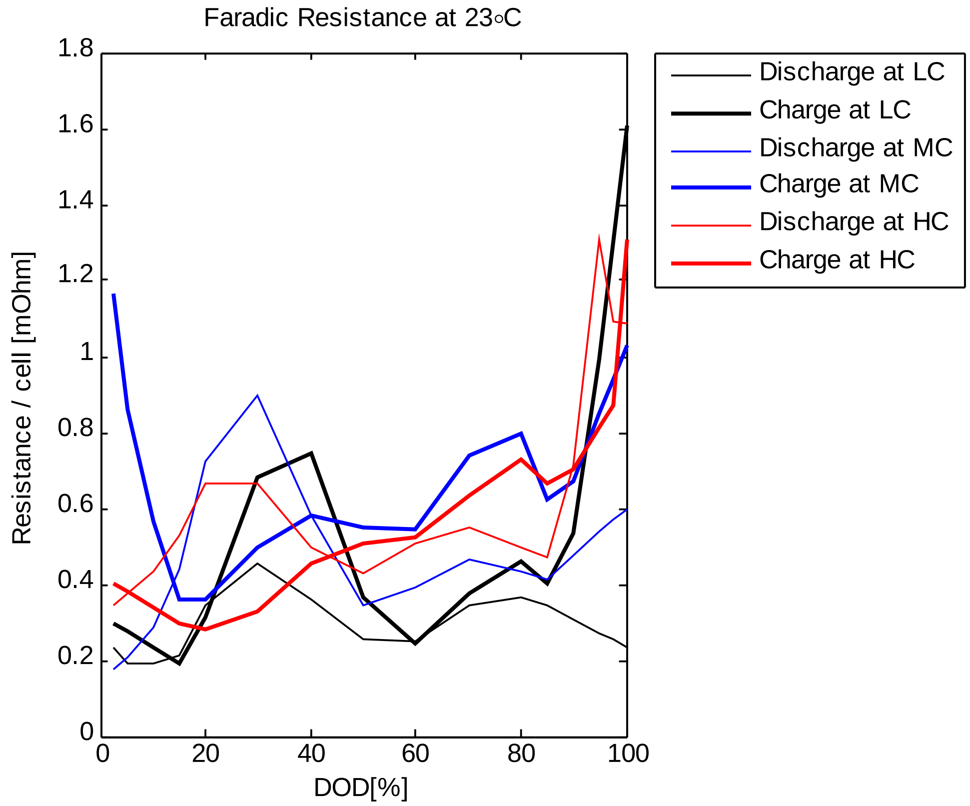
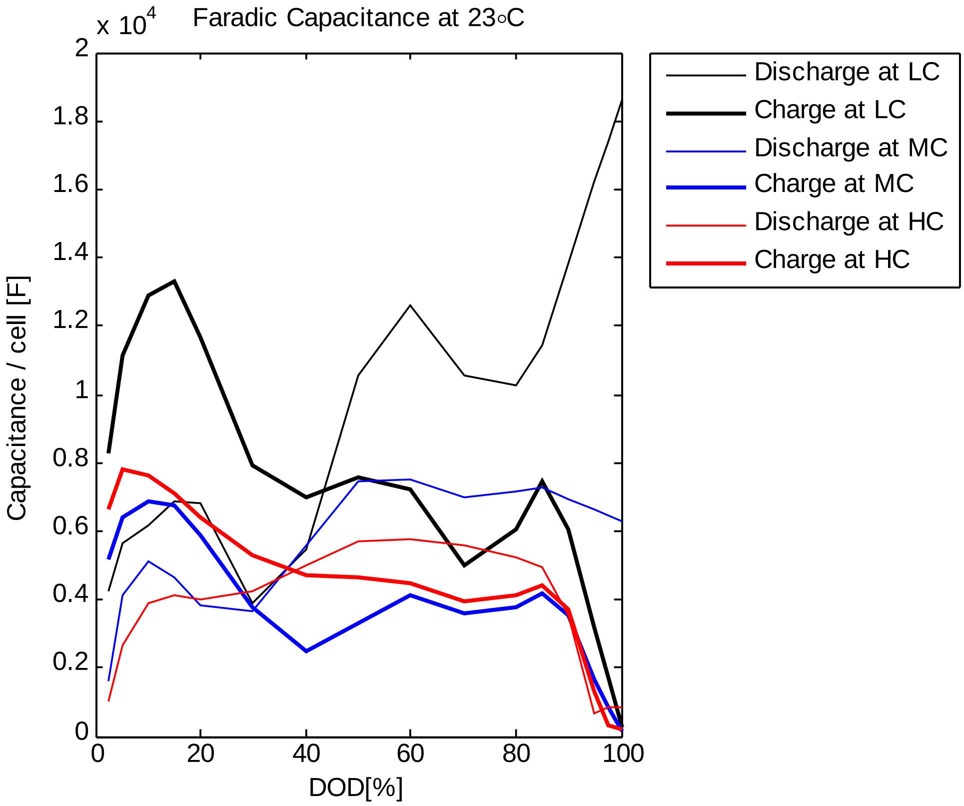
http://www.eigbattery.com/eng/technology/about_epb.htm, (Acc. 2009-07-28)
(OBS. New characteristics, see attached data sheet for old version)
[9] Nazri G-A & Pistoia G: LITHIUM BATTERIES Science and Technology, Kluwer Academic Publishers, 2004
[10] The Electropaedia, http://www.mpoweruk.com/index.htm (Acc. 2009-07-28)
[11] Robert Aronsson , ETC Battery and Fuelcells Sweden AB, Nol
[12] Bard A.J & Faulkner L.R: ELECTROCHEMICAL METHODS Fundamentals and Applications-2nd edition, Wiley and Sons Inc., 2001

APPENDIX A

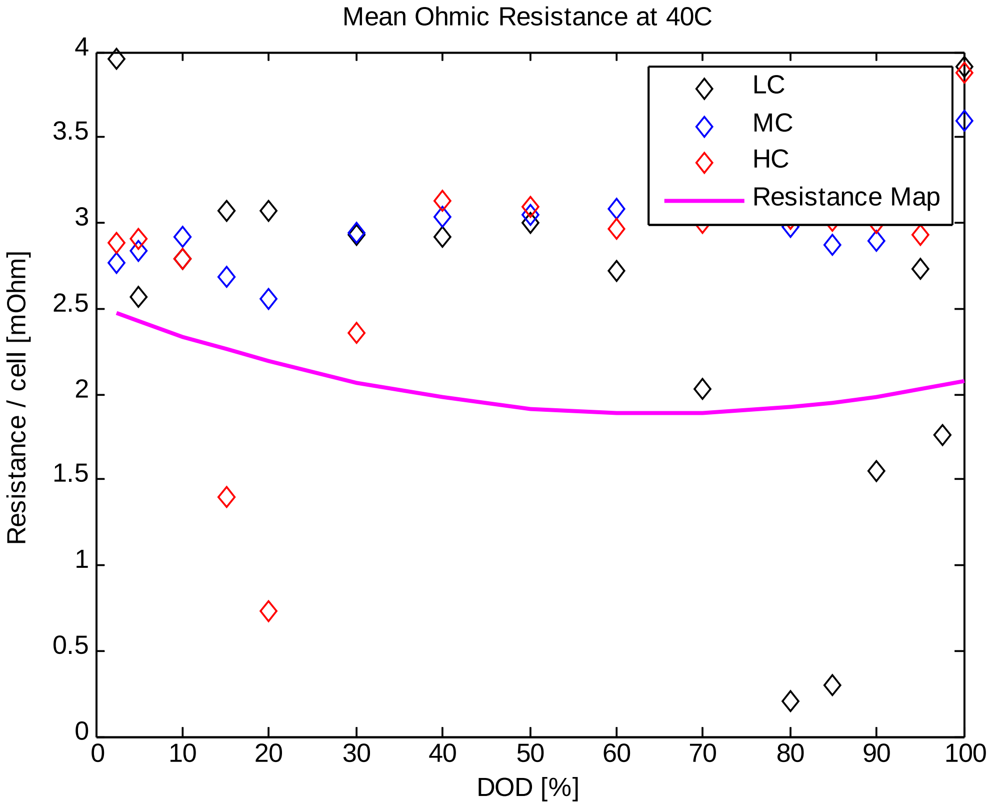
Parameters for 23 degrees Celsius

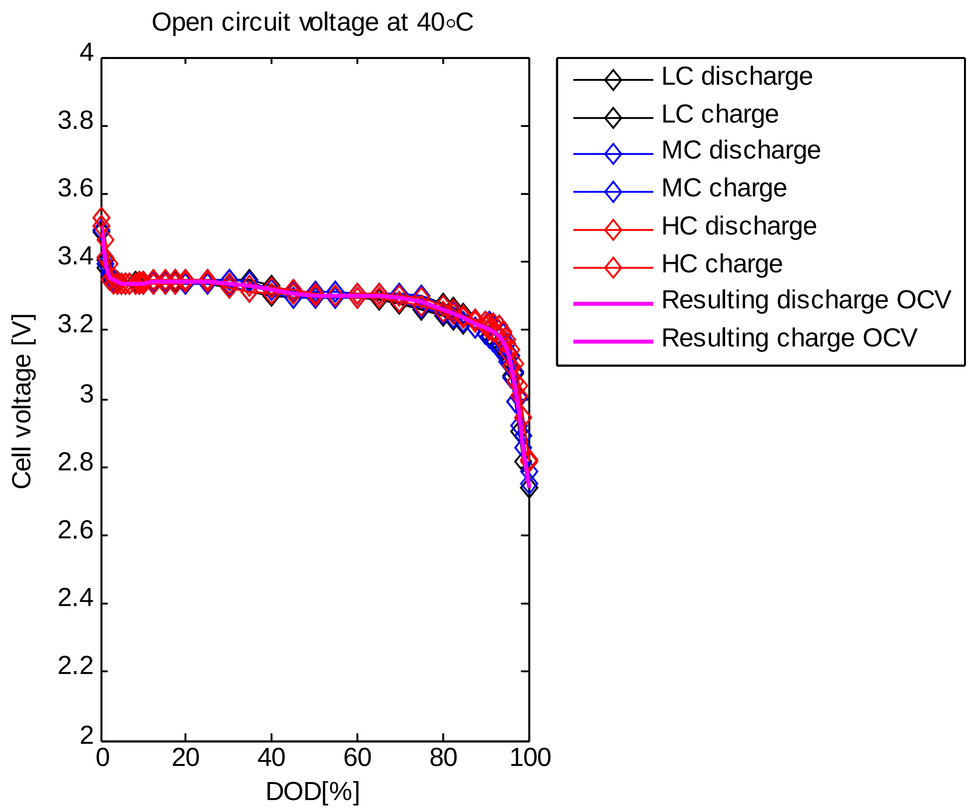


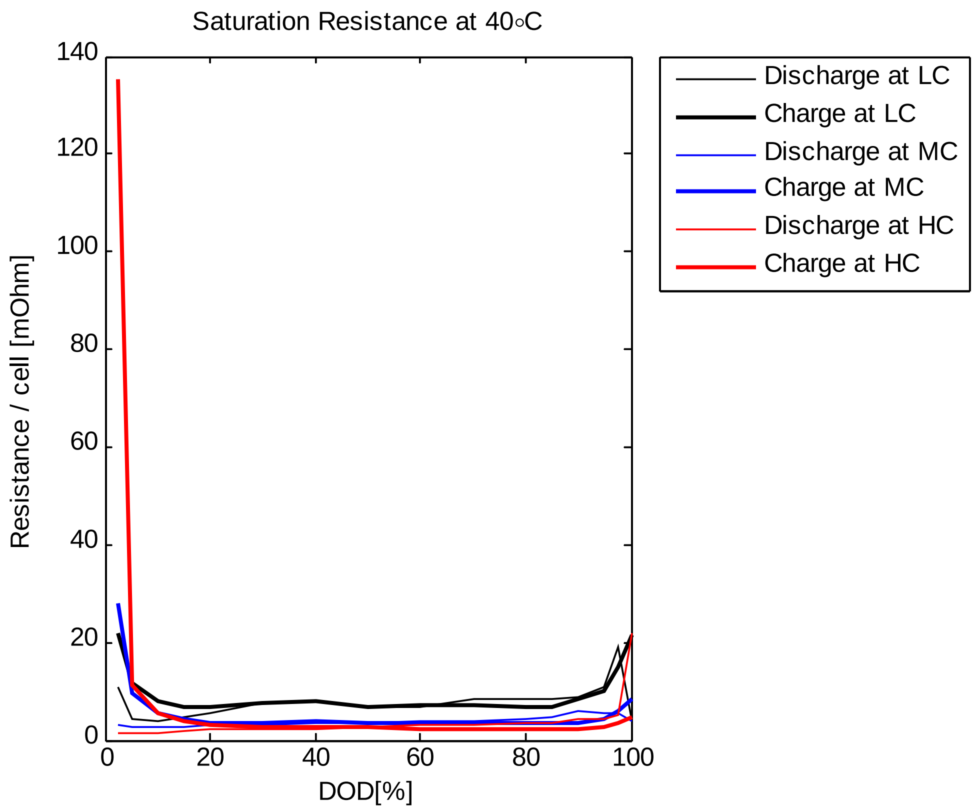


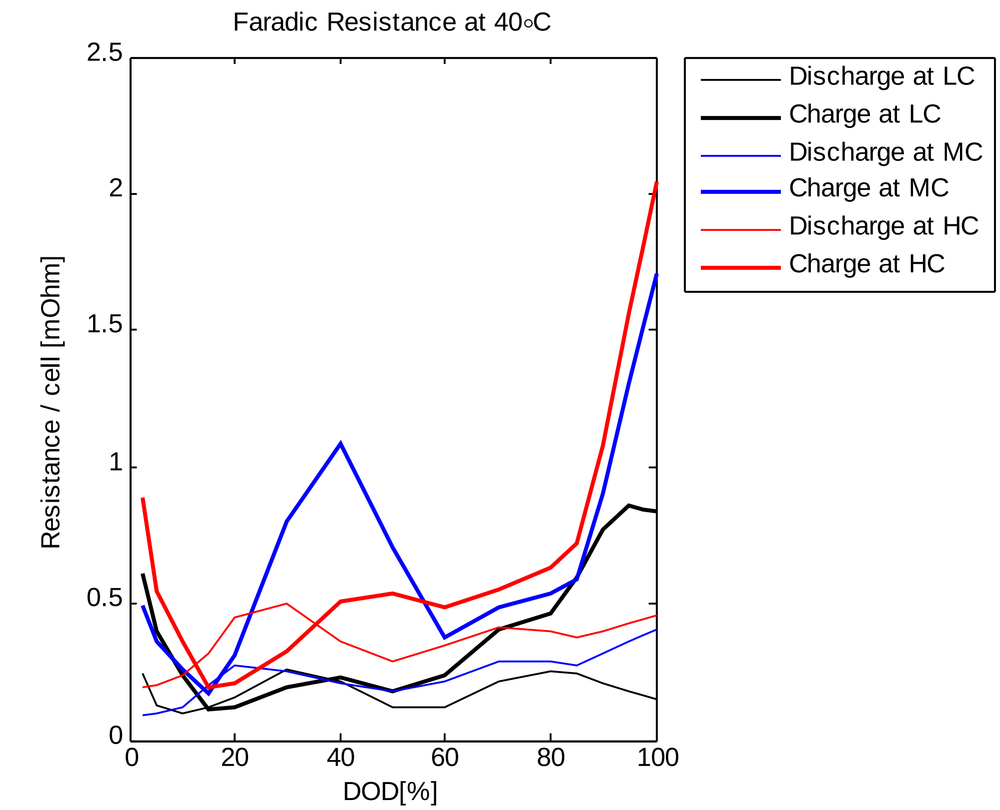


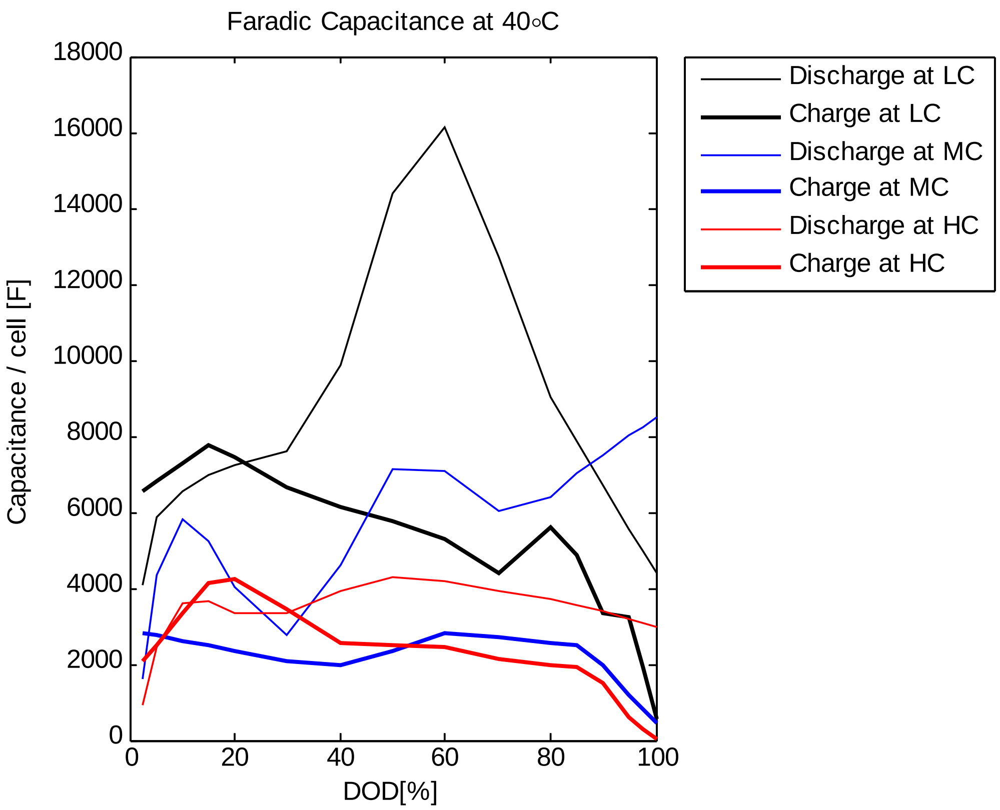
Parameters for 40 degrees Celsius



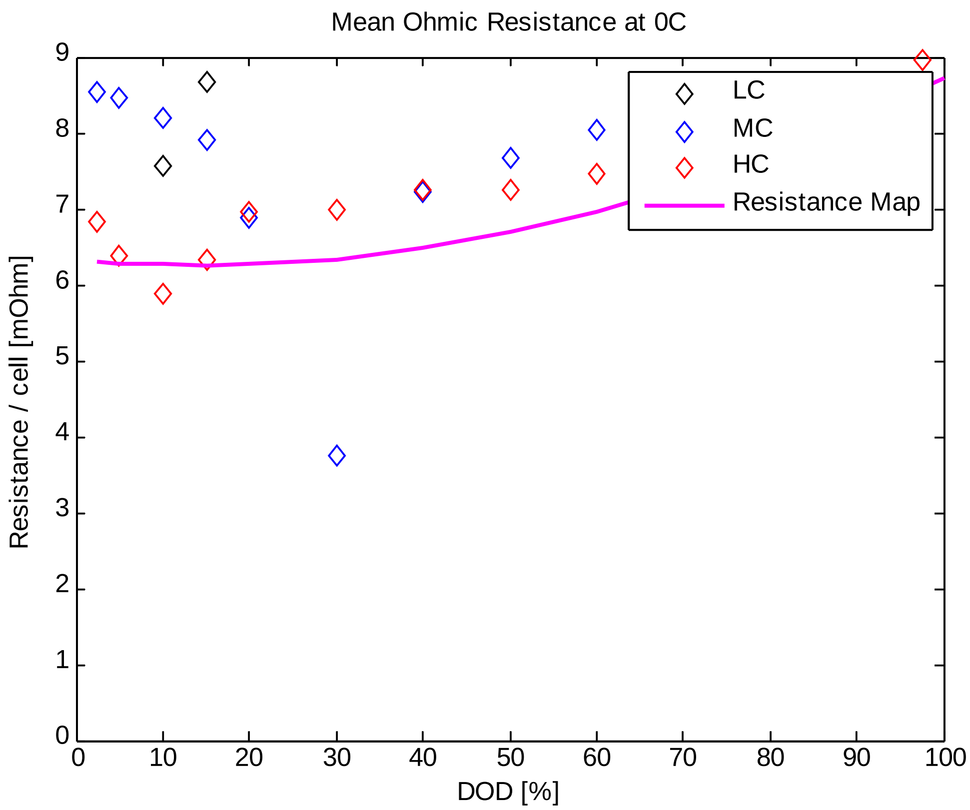

Open circuit voltage at 40◦C
Cell voltage [V]
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
0
20
40
60
80
100
DOD[%]
LC discharge
LC charge
MC discharge
MC charge
HC discharge
HC charge
Resulting discharge OCV
Resulting charge OCV

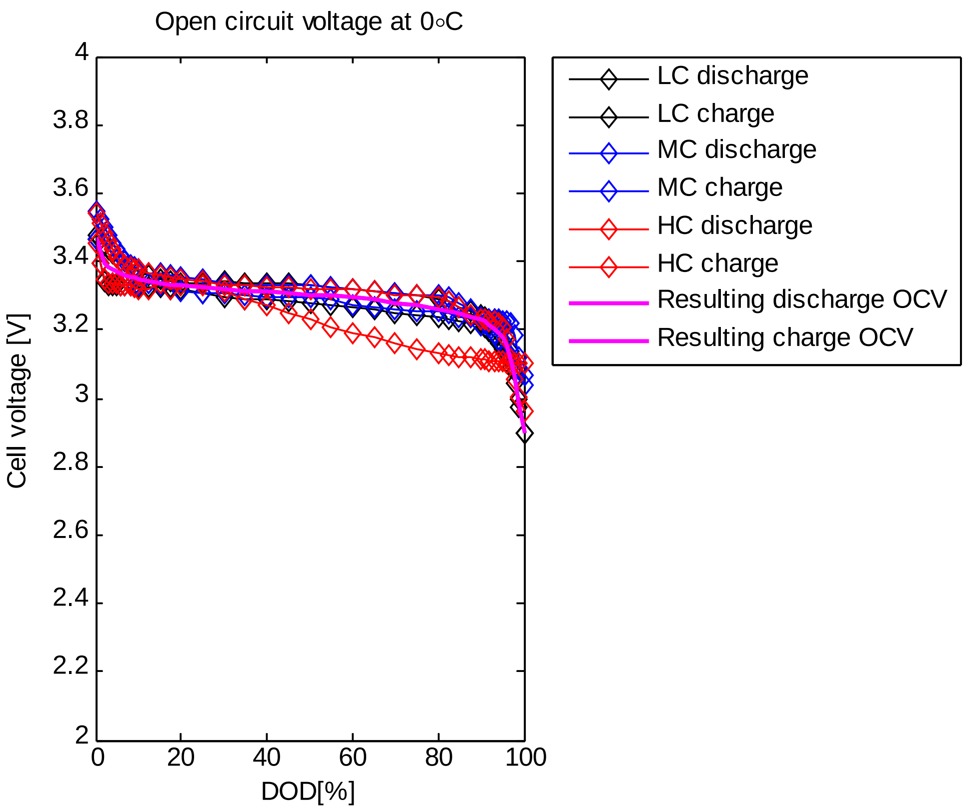

Saturation Resistance at 40◦C
Resistance / cell [mOhm]
140
120
100
80
60
40
20
0
0
20
40
60
80
100
DOD[%]
Discharge at LC
Charge at LC
Discharge at MC
Charge at MC
Discharge at HC
Charge at HC

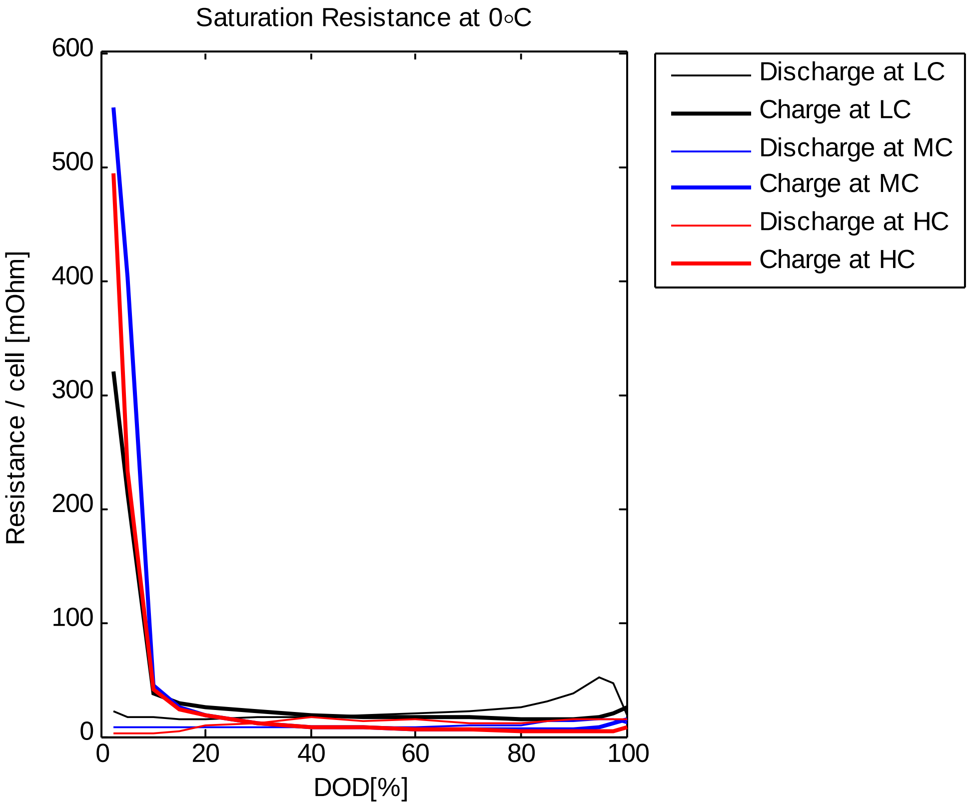


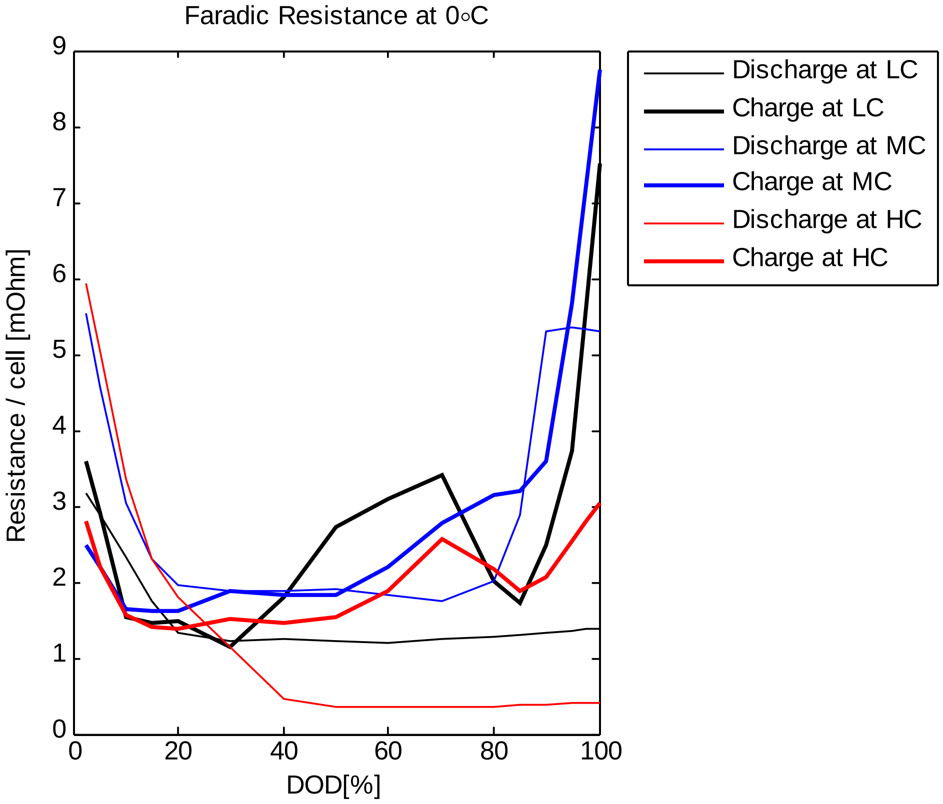


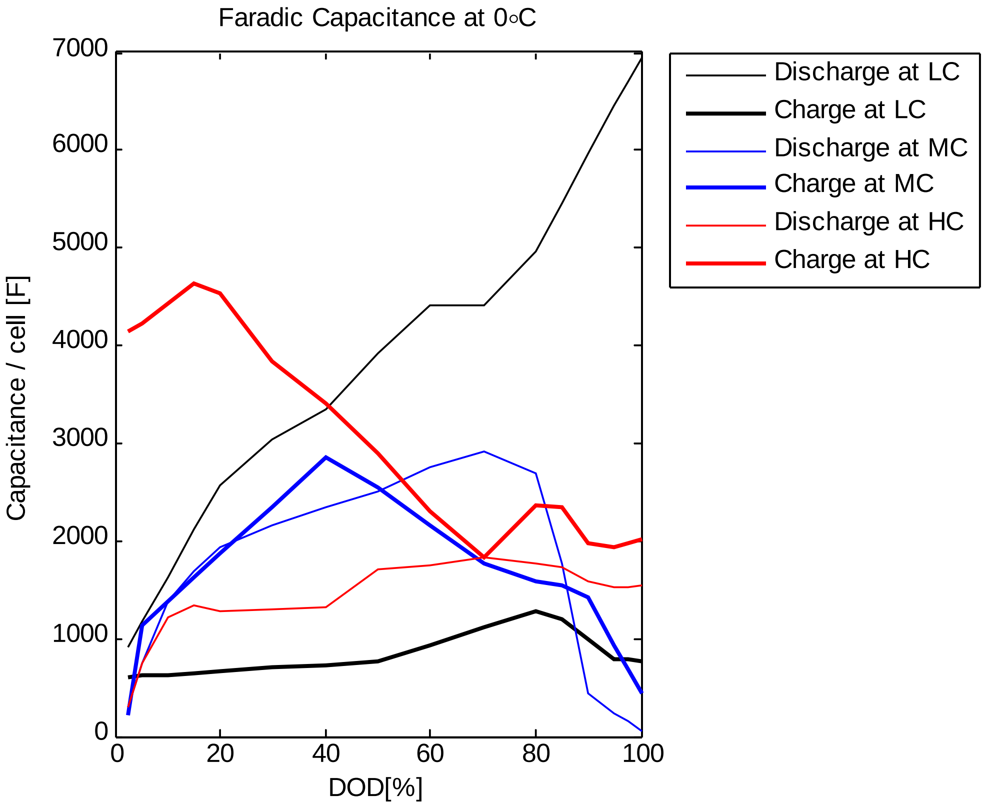
Parameters for 0 degrees Celsius


Mean Ohmic Resistance at 0C
Resistance / cell [mOhm]
DOD [%]
LC
MC
HC
Resistance Map

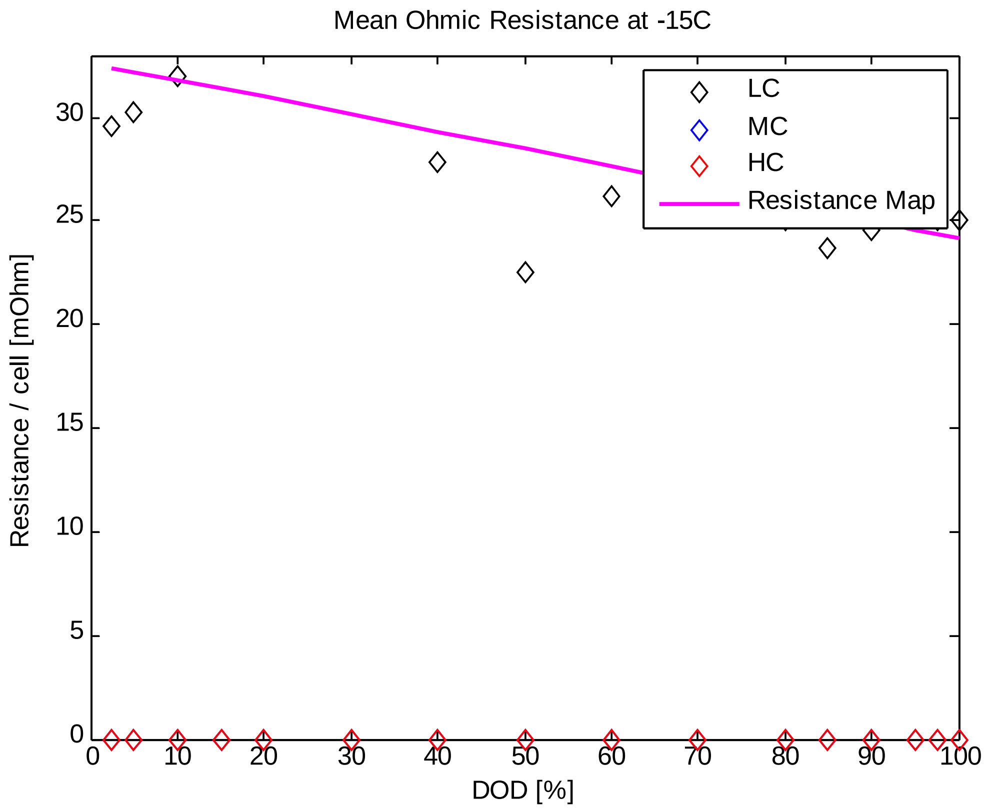

Open circuit voltage at 0◦C
Cell voltage [V]
DOD[%]
LC discharge
LC charge
MC discharge
MC charge
HC discharge
HC charge
Resulting discharge OCV
Resulting charge OCV

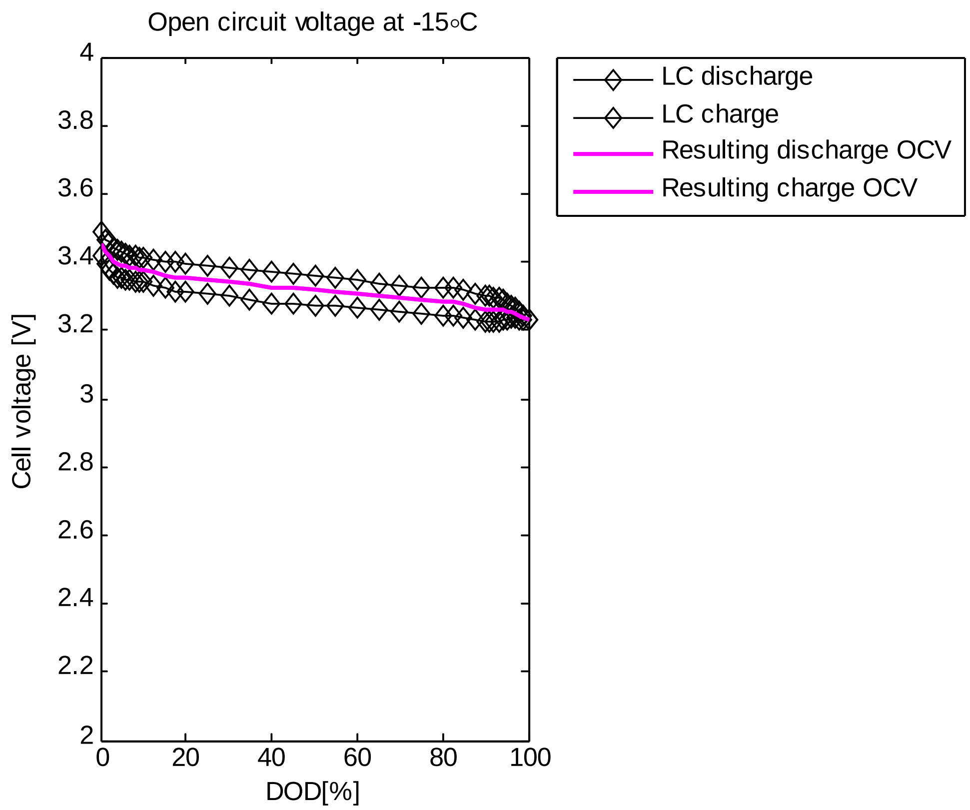

Saturation Resistance at 0◦C
Resistance / cell [mOhm]
600
500
400
300
200
100
0
0
20
40
60
80
100
DOD[%]
Discharge at LC
Charge at LC
Discharge at MC
Charge at MC
Discharge at HC
Charge at HC


Faradic Resistance at 0◦C
Resistance / cell [mOhm]
9
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
DOD[%]
Discharge at LC
Charge at LC
Discharge at MC
Charge at MC
Discharge at HC
Charge at HC

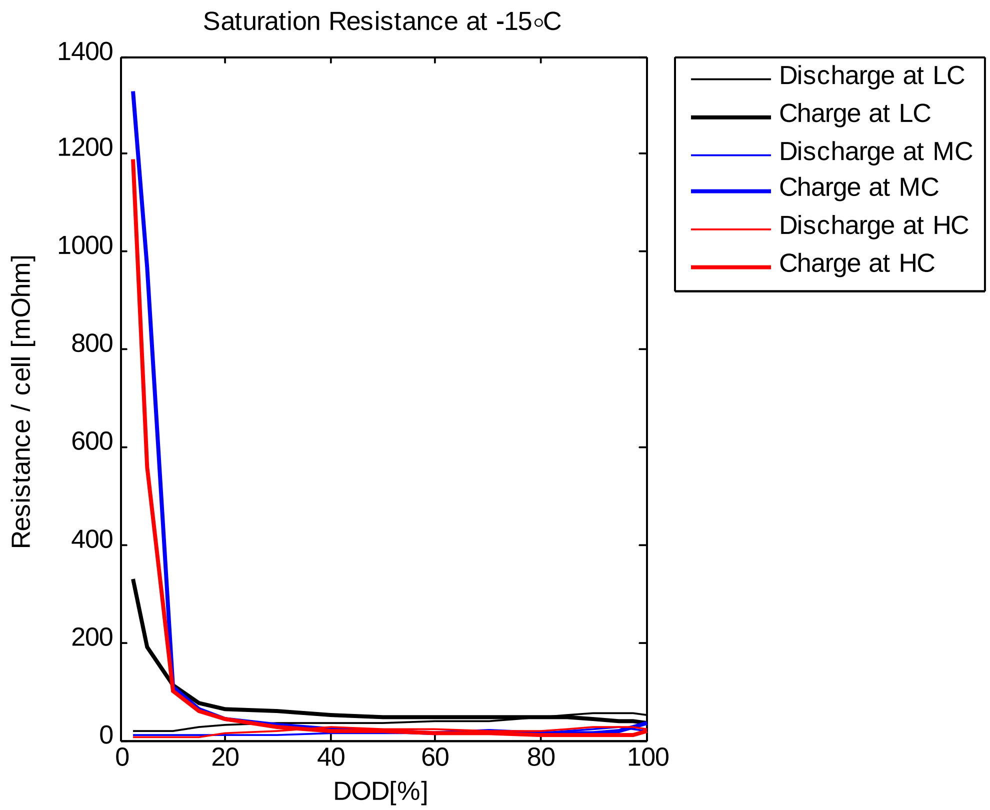


Parameters for -15 degrees Celsius

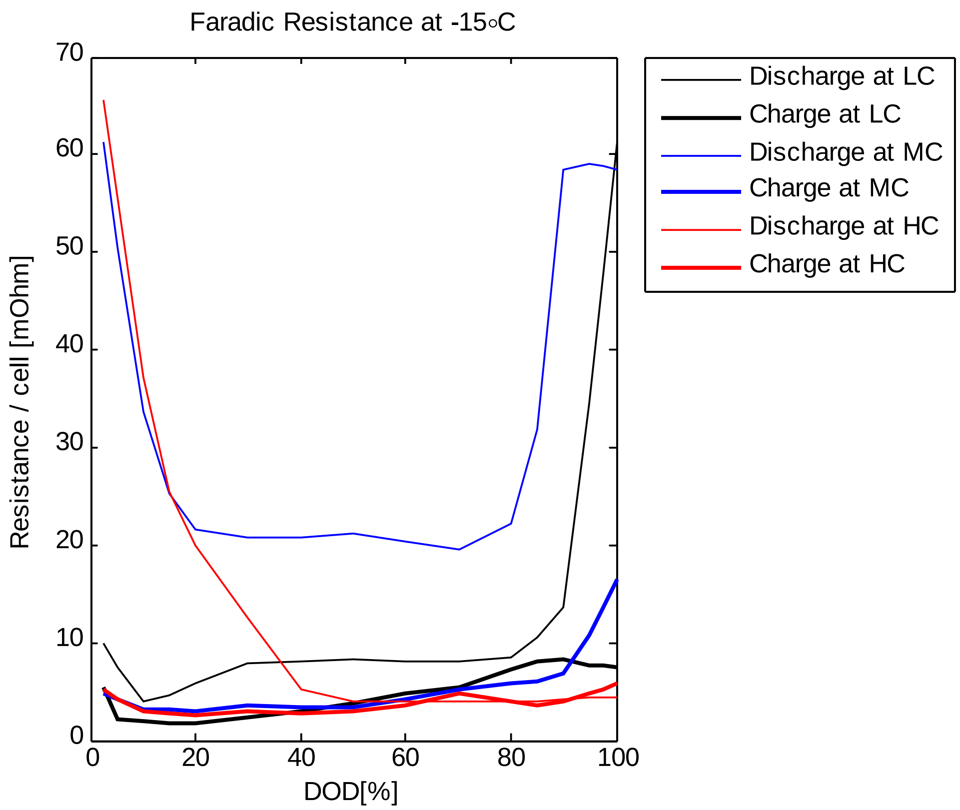


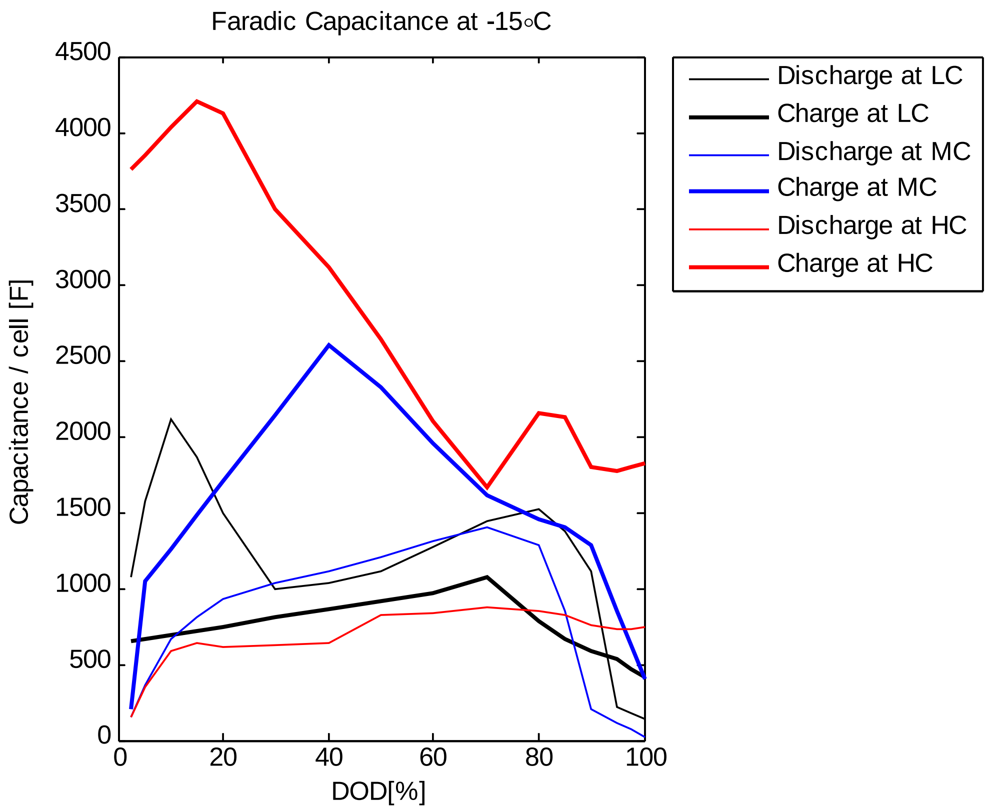


Open circuit voltage at -15◦C
Cell voltage [V]
DOD[%]
LC discharge
LC charge
Resulting discharge OCV
Resulting charge OCV



Saturation Resistance at -15◦C
Resistance / cell [mOhm]
DOD[%]
Discharge at LC
Charge at LC
Discharge at MC
Charge at MC
Discharge at HC
Charge at HC


Faradic Resistance at -15◦C
Resistance / cell [mOhm]
DOD[%]
0
10
20
30
40
50
60
70
0
20
40
60
80
100
Discharge at LC
Charge at LC
Discharge at MC
Charge at MC
Discharge at HC
Charge at HC


Faradic Capacitance at -15◦C
Capacitance / cell [F]
DOD[%]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
20
40
60
80
100
Discharge at LC
Charge at LC
Discharge at MC
Charge at MC
Discharge at HC
Charge at HC

APPENDIX B

LiFePO4 based Product

ePLB F

Technology	Feature
• Lithium Ion Polymer Battery • LiFePO4-based Cathode • Carbon-based Anode	• High Structural Stability • Long Life Cycle • Minimum Self-Discharge • Wide Temperature Range

Product General Specification

Mechanical Characteristics

Model	F014	F010
Length	216 ± 1 mm (without terminal)	216 ± 1 mm (without terminal)
Width	130 ± 1 mm	90 ± 1 mm
Thickness	7.1 ± 0.2 mm	6.9 ± 0.2 mm
Weight	approx. 400 g	approx. 270g

Electrical Characteristics

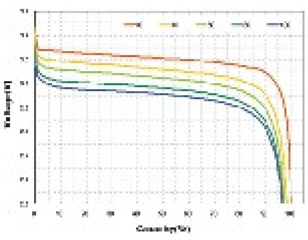
Nominal Voltage	3.2 V	3.2 V
Nominal Capacity	14.5 Ah	10.0 Ah
AC Impedance (1 KHz)	< 5 mΩ	< 10 mΩ
Specific Energy	100 Wh/Kg	120 Wh/Kg
Energy Density	220 Wh/l	240 Wh/l

Operating Conditions

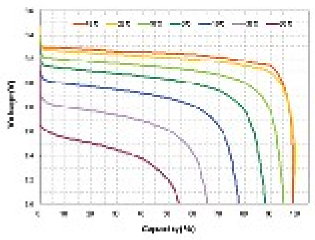
Charge Conditions :		
Recommended Charge Method	CC/ CV	CC/ CV
Maximum Charge Voltage	3.65 V	3.65 V
Recommended Charge Current	0.5 C Current	0.5 C Current
Maximum Charge Current	1.0 C Current	1.0 C Current
Discharge Conditions :		
Recommended Voltage Limit for Discharge	2.4 V	2.4 V
Lower Voltage Limit for Discharge	2.0 V	2.0 V
Recommended Discharge Current	up to 5 C Current	up to 3 C Current
Maximum Discharge Current (Continuous)	10 C Current	5 C Current
Maximum Discharge Current (Peak < 10 sec)	15 C Current	10 C Current
Operating Temperature :	-30 °C / + 50 °C	-30 °C / + 50 °C
Recommended Charge Temperature	0 °C / + 40 °C	0 °C / + 40 °C
Storage Temperature	-30 °C / + 50 °C	-30 °C / + 50 °C
Cycle Life at 25 °C (1C Charge / 1C Discharge DOD100%)	2000 Cycles to 80% Nominal Capacity	2000 Cycles to 80% Nominal Capacity

ePLB F014 Performance

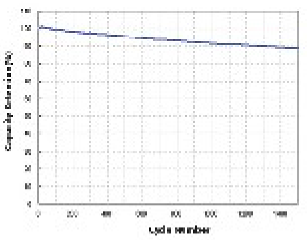
Discharge Rate Characteristics



Temperature Characteristics



Cycle Life



All specifications are subjected to change without notice.
For your system requirements, please contact info@eigbattery.com

High Energy Product

ePLB C

Technology	Feature
• Lithium Ion Polymer Battery • Li[NiCoMn]O₂-based Cathode • Carbon-based Anode	• High Energy Density • Long Life Cycle • Minimal Self-Discharge • Balanced Energy to Power Ratio

Product General Specification

Mechanical Characteristics

Model	C008	C020
Length	115 ± 1 mm (without terminal)	216 ± 1 mm (without terminal)
Width	102 ± 1 mm	130 ± 1 mm
Thickness	7.8 ± 0.2 mm	7.2 ± 0.2 mm
Weight	approx 175 g	approx. 410 g

Electrical Characteristics

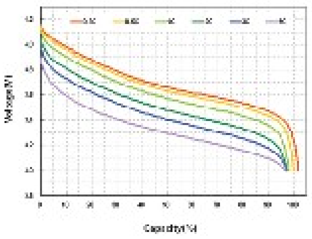
Nominal Voltage	3.6 V	3.6 V
Nominal Capacity	8.0 Ah	20.0 Ah
AC Impedance (1 KHz)	< 5 mΩ	< 3 mΩ
Specific Energy	165 Wh/Kg	180 Wh/Kg
Energy Density	315 Wh/L	365 Wh/L
Specific Power (DOD50, 10sec)	1400 Wh/Kg	1400 Wh/Kg
Energy Density (DOD50, 10sec)	2800 W/L	2800 W/L

Operating Conditions

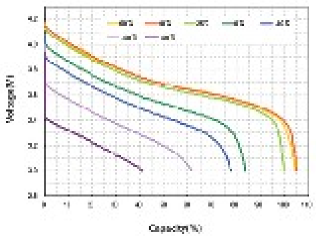
Charge Conditions :		
Recommended Charge Method	CC/CV	CC/CV
Maximum Charge Voltage	4.2 V	4.2 V
Recommended Charge Current	0.5 C Current	0.5 C Current
Maximum Charge Current	1.0 C Current	1.0 C Current
Discharge Conditions :		
Recommended Voltage Limit for Discharge	3.0 V	3.0 V
Lower Voltage Limit for Discharge	2.5 V	2.5 V
Recommended Discharge Current	up to 3 C Current	up to 3 C Current
Maximum Discharge Current (Continuous)	5 C Current	5 C Current
Maximum Discharge Current (Peak < 10 sec)	10 C Current	10 C Current
Operating Temperature :	-30 °C / + 50 °C	-30 °C / + 50 °C
Recommended Charge Temperature	0 °C / + 40 °C	0 °C / + 40 °C
Storage Temperature	-30 °C / + 50 °C	-30 °C / + 50 °C
Cycle Life at 25 °C (1C Charge / 1C Discharge DOD 100%)	1000 Cycles to 80% Nominal Capacity	1000 Cycles to 80% Nominal Capacity

ePLB C020 Performance

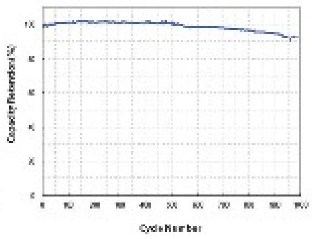
Discharge Rate Characteristics



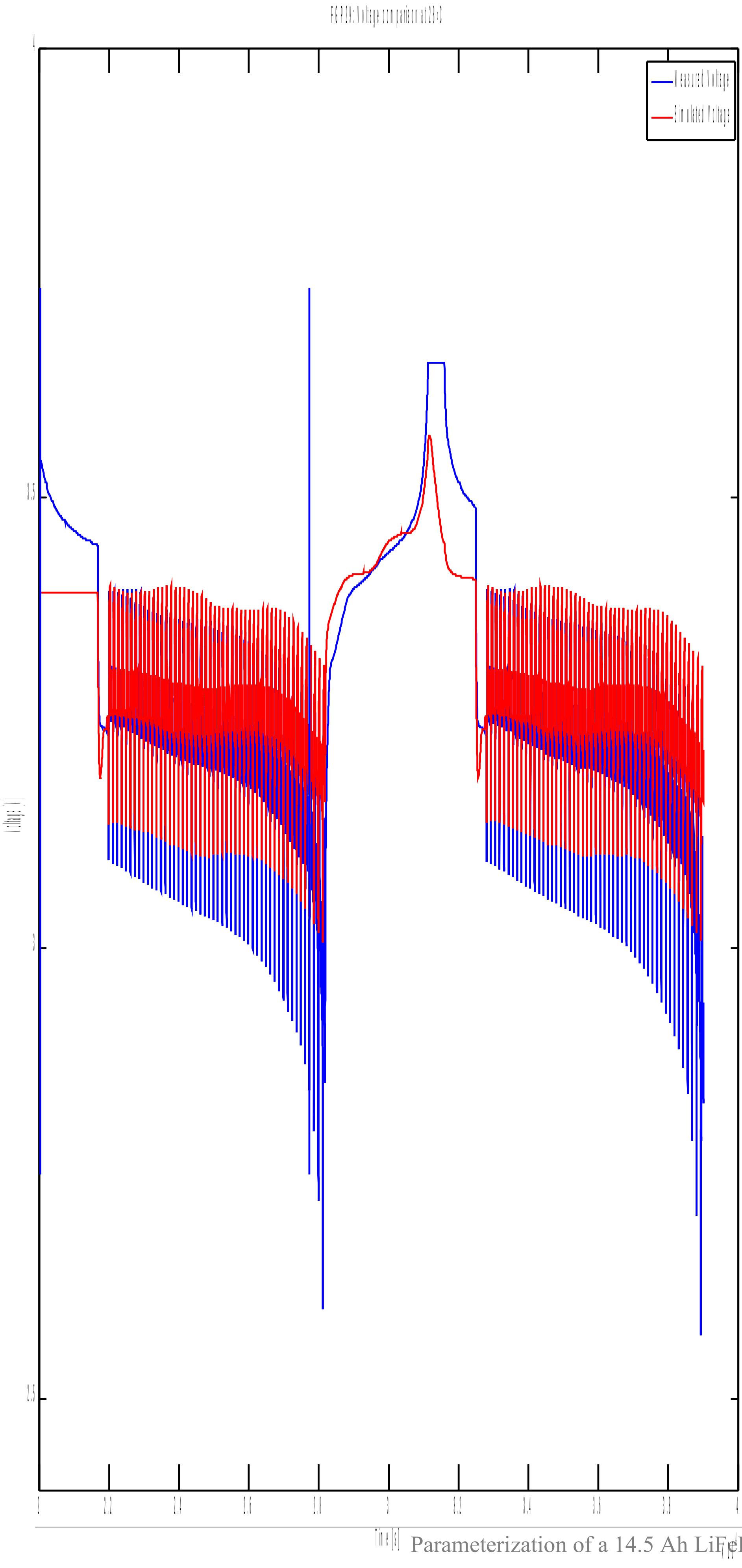
Temperature Characteristics



Cycle Life



All specifications are subject to change without notice.
For your system requirements, please contact info@eigbattery.com


F G P 29: Voltage comparison at 28 °C
Measured Voltage
Simulated Voltage
Voltage [V]
Time [s]