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Electrical engineering

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BATTERY CELL MODELING FOR BATTERY MANAGEMENT SYSTEM

Lappeenranta 23.9.2012

ABSTRACT

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Battery Cell Modeling for Battery Management System

Master's thesis

2012

71 pages, 45 figures and 3 tables

Examiners: Juha Pyrhönen, Professor and Lasse Laurila, Associate professor

Keywords: Battery, battery management system, battery modeling

Usage of batteries as energy storage is emerging in automotive and mobile working machine applications in future. When battery systems become larger, battery management becomes an essential part of the application concerning fault situations of the battery and safety of the user. A properly designed battery management system extends one charge cycle of battery pack and the whole life time of the battery pack. In this thesis main objectives and principles of BMS are studied and first order Thevenin's model of the lithium-titanate battery cell is built based on laboratory measurements. The battery cell model is then verified by comparing the battery cell model and the actual battery cell and its suitability for use in BMS is studied.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto

Teknillinen tiedekunta

Sähkötekniikan osasto

Henri Aalto

Akkukennon mallinnus akunhallintajärjestelmään

Diplomityö

2012

71 sivua, 45 kuvaa ja 3 taulukkoa

Tarkastajat: Juha Pyrhönen, Professori ja Lasse Laurila, Tutkijaopettaja

Hakusanat: Akku, akunhallintajärjestelmä, akun mallintaminen

Akkujen käyttö energiavarastona kasvaa todennäköisesti merkittävästi mm. liikenneväline- ja työkonekäytöissä tulevaisuudessa. Suurissa akkujärjestelmissä tarvitaan akunhallintajärjestelmää akuston vikatilanteiden estämiseen ja käyttäjien turvallisuuden takaamiseen. Hyvin suunnitellulla akunhallintajärjestelmällä voidaan pidentää akuston yhden latauksen kestoa sekä akuston koko elinikää. Tässä työssä tutustutaan akunhallintajärjestelmien pääominaisuuksiin ja rakenteisiin, sekä tehdään laboratorio mittausten perusteella litium-titanaatti-akulle ensimmäisen kertaluvun Theveninin-malli, jonka soveltuvuutta akunhallintajärjestelmään tarkastellaan oikeaan akkuun verraten.

ACKNOWLEDGEMENTS

This master's thesis has been done for LUT Energy. I would like to thank my two instructors, Professor Juha Pyrhönen and Associate Professor Lasse Laurila, for giving me an opportunity to do this thesis, and I would also like to thank Kirill Murashko for helping me with this thesis.

I would also like to thank my family and friends who have supported me during my studies. Especially I would like to say thanks to my parents who have given me the strength to get through the hard times.

Lappeenranta, September 23, 2012

Henri Aalto

TABLE OF CONTENTS

DEFINITIONS AND ABBREVIATIONS

Ageing	Processes that decrease maximum available capacity of battery. [1]
Battery	"An assembly of any number of Li-ion or Li-ion polymer cells, associated electronics, battery packaging, and connector(s)." [1]
BMS	Battery Management System: "An integrated circuit that manages battery operation to prevent overvoltage, overcurrent, and stops battery operation at set high and low temperatures as well as at a set low-voltage cutoff."
C	Capacitance [F]
Cell	"Basic manufactured Li-ion or Li-ion polymer unit providing a source of electrical energy by direct conversion of chemical energy that consists of electrodes, separators, electrolyte, container, and terminals, and that is designed to be charged electrically." [1]
Cell Block	"One or more cells connected in parallel" [1], also module.
C-rate	Current rate at which battery is charged/discharged. 1C, for example, means in 50 Ah battery a 50 ampere current.
DOD	Depth-of-Discharge, amount of charge drawn from battery
Fault	"A defect in the cell/host/pack that causes the device to fail to perform normally." [1]
Host	"The device that is powered by a battery and/or charges the battery. Mobile computing devices and external chargers are examples of a host device." [1]
I	Current [A]
k	Peukert's coefficient
OCV	Open-circuit voltage. "The voltage at its terminals when no appreciable current is flowing." [2]
R	Resistance [Ω]
SOC	State-of-charge, amount of charge left compared to initial capacity
SOH	State-of-Health, capability of battery to provide power
t	Time [s]
τ	Time constant [s]
U	Voltage [V]

Z	Impedance [Ω]

1. INTRODUCTION

Increasing price and decreasing sources of fossil fuels and increasing CO_2-emissions are favoring alternative energy sources for automotive applications. Alternative energy sources include for example batteries and fuel cells. Batteries are chemical energy storages that convert chemical energy into electrical energy. In battery there are two electrodes and electrolyte between them. For example, the basic structure of Li-ion battery is presented in Fig. 1. Batteries are categorized to two categories: primary or secondary. Primary batteries are only dischargeable, meaning that it is not possible to recharge battery. Secondary batteries, which are used in EVs and most portable devices such as mobile phones, can be recharged. Secondary batteries (rechargeable batteries) are also known as accumulators, but in this thesis the term secondary battery is used to maintain simplicity.

Powering an electric device from a battery comes to consideration, when the application is portable such as a mobile phone, a laptop etc. or if fossil fuels are replaced (for example electrical vehicles (EVs) etc.) If misused a battery becomes easily damaged, which might affect its performance or lifetime. In use at EV for example, degrade of performance or sudden end of lifetime, might cause even life-threatening situations. To avoid such events, performance of batteries can be managed with proper design of battery management system (BMS). In this paper the focus is on secondary batteries (rechargeable batteries).

BMSs are used to avoid things such as overcharging/discharging, limiting charging or discharging currents and maintaining individual cells of the battery at balance. In an EV the BMS can tell the users how long the battery can be used before it needs to be recharged. Also showing health status of battery would be important. Batteries in electrical vehicle use are considered to be in need for renewing when State-of-Health of battery value reaches 80%, which means that maximum available capacity of battery has decreased to 80% of its initial capacity. This thesis mainly focuses on batteries based on Li-ion chemistries, but other chemistries are mentioned for comparison. Lithium-based batteries are good choices for energy storage because of their high power density. Lithium-based batteries also do not have a voltage depression effect (known as memory effect) like NiCd batteries have [3].

Battery has highly nonlinear dynamics and its operation parameters vary due to changes in State-of-Charge (*SOC*) and temperature. Usability of battery decreases due to battery ageing or with high discharge currents. Ageing, charge-discharge cycles and actual time, affect chemistry of battery in irreversible way that causes decreasing in its maximum available capacity (State-of-Health decreasing). Higher current in discharging causes capacity of battery to decrease faster when compared to normal values of current.

Tasks of this thesis are to describe what BMS is and what are its main principles and structures, and to build a simple first-order Thevenin's model for Li-Ti (lithium-titanate) battery. The battery model is built based on measurements with an actual Li-Ti battery cell. The built battery model is then compared to a battery model with two pairs of RC-branches from literature to define if the built battery model is suitable to be used in BMS. After the battery model is verified it is extended with current limiting to avoid overcharge/-discharge to model basic safety properties of BMS and the model is also used to model battery pack with multiple battery cells.

2. BATTERY AS AN ENERGY STORAGE

In this chapter power sources for portable devices are discussed. The most used power sources for portable devices and backup energy storages are batteries (primary or secondary batteries depending on the capacity requirement of the application), super capacitors and fuel cells. This thesis focuses mostly on rechargeable batteries, especially on Lithium-based secondary batteries, mainly used in traction vehicles or most portable devices.

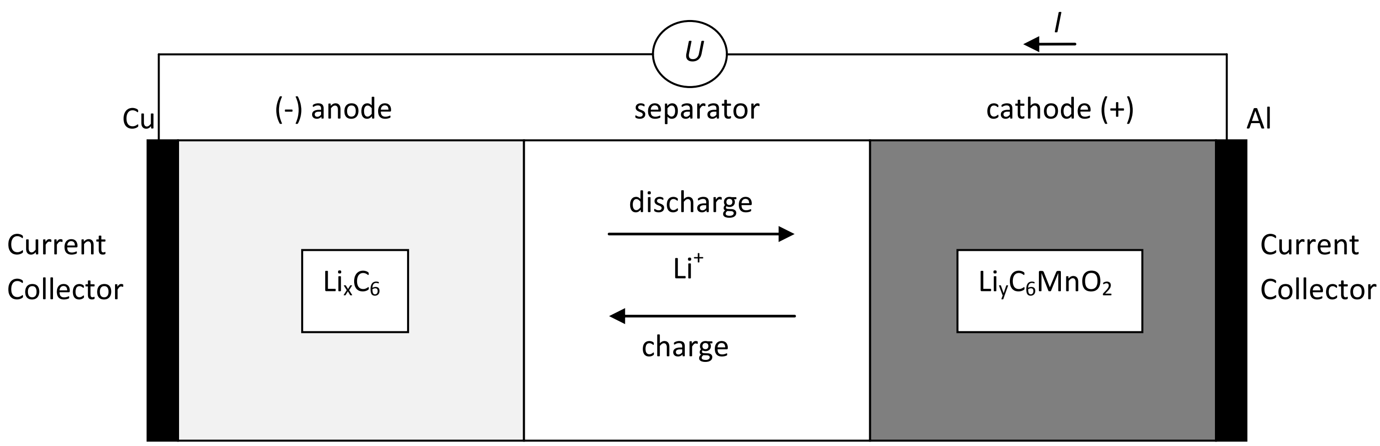

Figure 1. Schematic of Lithium-ion battery. Anode is Li_xC_6 material and cathode is $Li_yMn_2O_4$ material [4]

In Fig. 1 schematic of Li-ion battery is presented. Current is positive, when battery is discharged meaning current is drawn from battery. Current is negative when battery is charged, current is fed into battery.

2.1. Batteries

Usually the term “battery” is used when battery pack is discussed. Such a pack is a combination of battery cells in serial or parallel connection. The power requirements of application define the cell combination which is used. Basic structures how batteries can be connected are shown in Fig. 2.

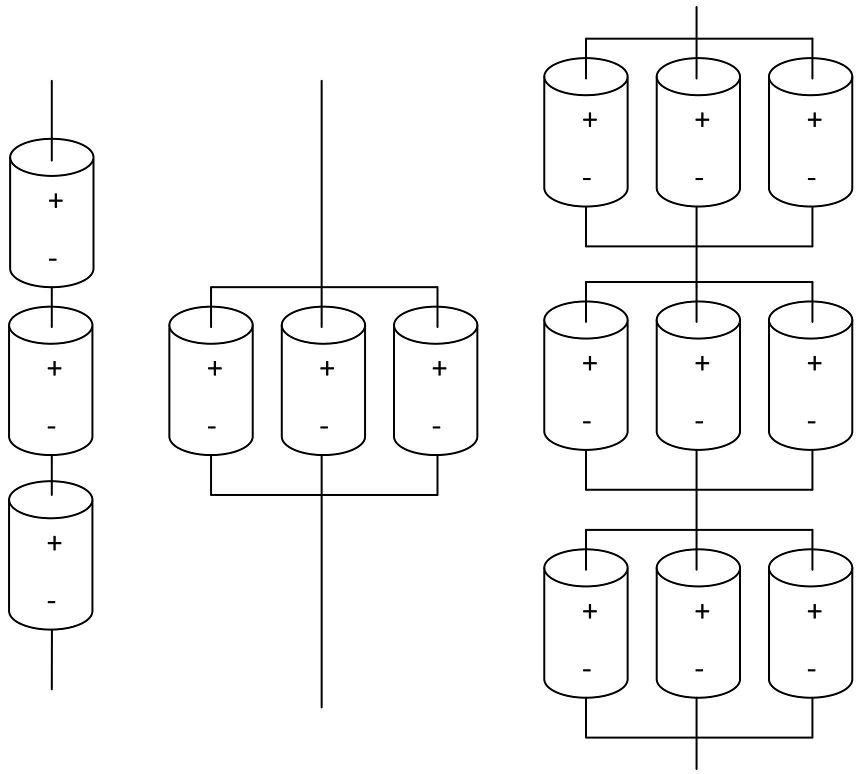

Figure 2. **Basic connections between individual battery cells. From left to right: serial, parallel, and serially connected parallel connections.**

With battery cells connected in series the battery voltage increases as a sum of battery cells leading to higher power without increasing current. Battery cells connected in parallel can be used with higher current to provide power without increasing battery voltage. Parallel connection also offers higher capacity if the same current as in series connection is used. Combination of such connection can provide both power and capacity. Calculation of *SOC* for each battery cell is the harder the more complicated connections are used.

For example EVs driving sequence can contain multiple uphill and downhill cycles, where current from or to battery varies whether driver is accelerating or braking. Chemistry of battery reacts to different kinds of currents, so it is important for the battery model to show good approximation for the end user.

Battery as an energy storage is usually a combination of individual battery cells. In an application, where the power consumption is small, the battery can consist of only one cell. In that kind of a system, battery management is quite simple, because there is no unbalance between cells or there is no need to consider which kind of serial or parallel combination to use to achieve power requirements. With system that needs energy for long period and there is a possibility for high peak current, advanced design of battery management is needed.

Li-ion battery (Fig. 1) belongs to the category of batteries having the highest energy density in category of rechargeable batteries thus making it the most advanced solution in automotive applications. With Li-ion batteries it is important to keep the load current under safety limits provided by manufacturers. Abuse of Li-ion batteries might cause thermal runaway, which is defined by IEEE standards as “The cell condition where the internal cell reactions generate more thermal heat than the cell can dissipate. The condition typically causes cell venting.” [1]. Thermal runaways can be caused by electric, mechanic or thermal abuse [5].

Comparison between different types of batteries for traction use is given in Table 1.

Table 1. Different properties of some battery types [6].

Battery Type	$LiCr_xMn_{2-x}O_4$ (EV)	NiMH	Lead-Acid (Traction)	Li-Ti[8]	Vanadium (VRB*)
Average cell voltage [V]	3.0-4.0	1.2-1.4	1.8-2.0	2.26	1.1-1.5
Specific energy [Wh/kg]	150	60-80	25-30	77	10-30
Energy density [Wh/L]	120-140	200-270	80	168	10-30
Specific power [W/kg]	440	150-300[7] (M to H)	200-400[7] (MH)	1333	M to H [6]
Temperature range [°C]	-20 - +50	-30 - +65	-20 - +40	-44 - +55	+10 - +50
Cycle life**	580	800-1200	1500	16000 @25°C	3000

*Vanadium redox-flow battery, ** Dependent on DOD, Moderate, High, Moderately High

From Table 1 it can be seen that Lithium-ion (LiCrxMn2-xO4 is used as an example) batteries have solid properties. Lead-Acid for example is a cheap choice but its energy capabilities are not as good as Lithium-ion batteries. Li-ion batteries are favored over other batteries in wide range of applications because of their much better energy-to-mass ratio. It can be also seen that specific energy and specific power of Li-ion (LiCrxMn2-xO4) battery are about double the amount in NiMH battery. Li-ion batteries have yet major setback, misusage of Li-ion battery could lead to explosion. Safety of Li-ion batteries can be provided with properly designed battery management system.

With normal battery cell, voltage across cell is ideally an accumulation of the electrolytic potential and electrode potential. However, internal resistance causes voltage drops to the generated voltage. Temperature safety range of Li-ion battery is set to -20 – +50 °C due to resistance varying with temperature. When the operating temperature rises above 45°C, internal resistance of battery cell starts rising [5]. Operation in higher temperature causes higher power losses and raises probability of thermal runaway.

Safety is an extremely important issue with batteries when charging as charging produces oxidizing and reduces compounds at both negative and positive electrodes. At some points charging might produce heat, which may lead to fire or even explosion caused due to a fast release of gases. The higher energy density of the battery is the larger amount of heat is released [9].

Ability of battery to provide power decreases when battery ages. When higher power is used, power retention of battery is higher. However, for some battery types, storage time also decreases power capabilities. Discharge power with Li-ion batteries also decreases when *DOD* increases. Regenerative power increases when *SOC* decreases [9].

3. BATTERY MANAGEMENT SYSTEM

In this section, the principles of battery management systems (BMS) are studied. Differences between battery management system design aspects of low power portable devices (such as cell phones, music players, PDAs, digital cameras, laptops and etc.) and high power systems (EVs etc.) are studied. To get some information about energy consumed from battery and capability of battery to provide power, well designed battery model is required.

3.1. BMS in portable and high power applications

Battery management systems are a little bit simpler in portable devices than in high power systems, such as electric vehicles (EV) and hybrid electric vehicle (HEV). For example in EVs BMS has to operate with number of other devices such as engine and air conditioner for example. BMS also needs to operate in situations where charge/discharge conditions change rapidly and there are also possibilities to have uncontrollable environmental changes. Regardless of power level of device, main objectives of BMS are:

- Optimization of operation of the battery to fit the needs of application powered by the battery
- State-of-Charge maintenance to keep operation range longer
- Prolonging battery life, for example monitoring State-of-Health
- Avoid damaging the battery and guarantee safety of user and device [10].
- Parameter, such as voltage and current, monitoring for each cell and whole battery pack
- Internal fault analysis
- Primary or secondary battery detection if needed

Battery management systems should be able to tell users information about State-of-Charge and State-of-Health of battery [11], so that user has knowledge when to recharge battery. Advanced BMSs can control charge and discharge current to prevent overcharging and overdischarging from occurring [10]. Overcharging (overvoltage) or overdischarging (undervoltage) causes decreasing in State-of-Health of the battery thus lowering life expectation of the battery. A complete BMS should take into account identification and history of usage of battery, measurements at current operation, information about capacity and remaining time before capacity runs out. Also some alarms about errors or misusing would be an asset [10]. Also, in the case if battery consists of multiple cells, cell balancing is required. Having a short circuit protection to limit maximum current would also be an asset [11]. Battery management system should keep *SOC* of the battery within proper limits. Higher limit of *SOC* would allow charging with regenerative braking [9]. When *SOC* is at maximum level, BMS should be able to stop charging to avoid overcharge. Overcharging the battery might even lead to an explosion or at least it can do some irreversible damage [9].

Determining state-of-charge of the battery is not a simple task. Parameter open-circuit voltage (*OCV*) of the battery drops when SOC decreases (Fig. 3).

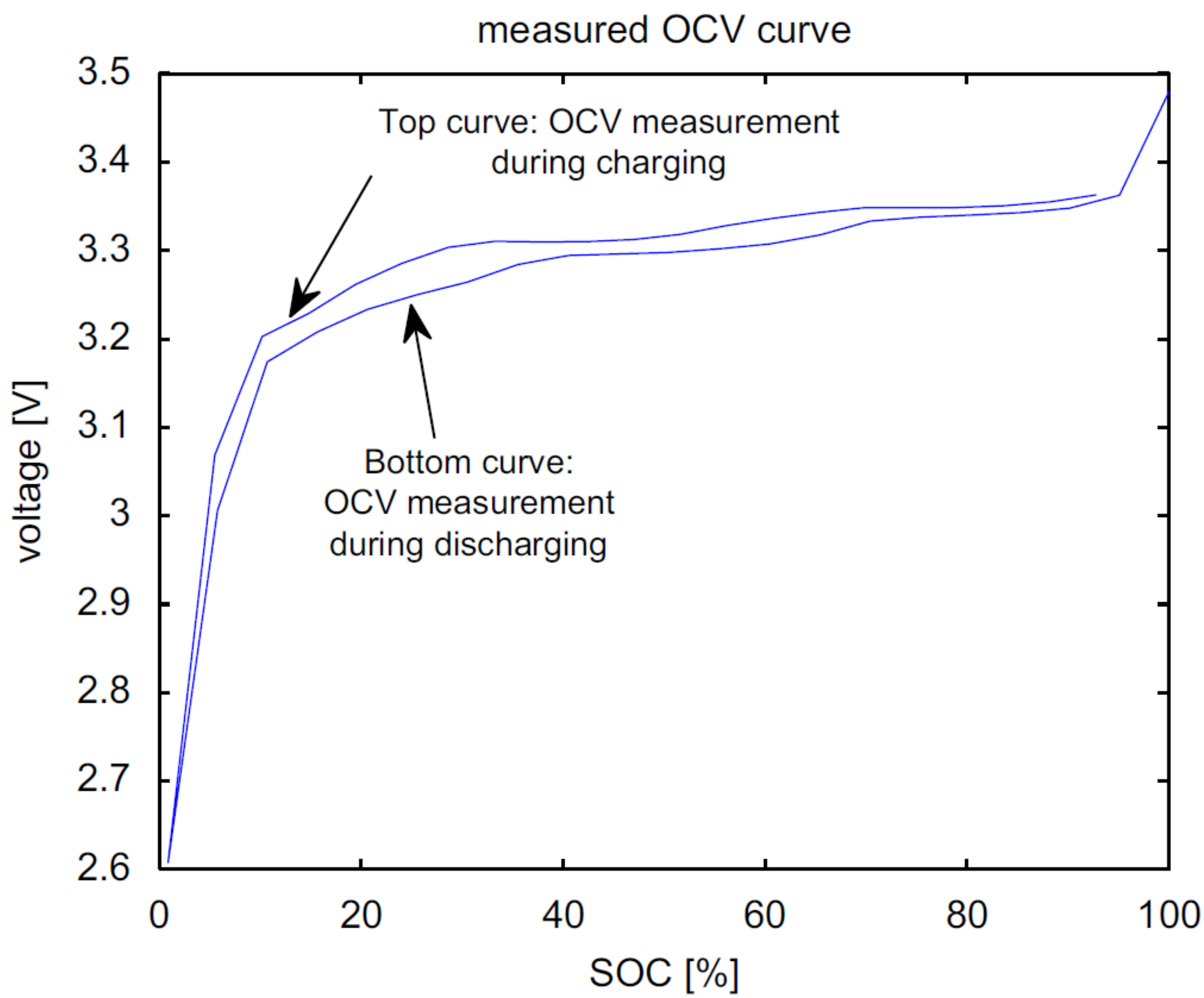

Figure 3. *OCV* of Li-ion battery during discharging and charging. Battery is allowed to rest for an hour before measuring *OCV* [12].

One way to calculate *SOC* would be using *OCV* (or capacity). But there are many other factors too, which affect *SOC*. Temperature, ageing and self-discharge have a major effect on *SOC*. Using only *OCV* to calculate State-of-Charge might cause very large errors in calculation if battery is very old, or operation temperature changes at wide range. Battery management should measure and monitor parameter changes in battery pack or module. More about *SOC* calculation is discussed at chapter 3.3.

[10] reports comparison between BMS for portable electronics and electric vehicle use. For portable electronics (PE), there are usually not very high current rates, at least not continuously. Estimation of *SOC* in PE does not have to be as accurate as in EV or HEV use. State-of-Health calculation is not needed in PE, because decrease of *SOH* is not as potentially hazardous as it is in EV/HEV. Cell balancing in EV/HEV is needed for both charge and discharge operation. This ensures good performance and does not lead to unwanted situations where unbalanced cells can cause malfunction of the whole battery pack. In PE cell balancing is only needed for charging to avoid overcharge of an individual cell. In PE *SOC* of the battery is used in wider range compared to EV/HEV.

When designing a battery management system for high power systems starting currents should be taken into account [9]. Some battery types are not able to deliver high peak current for long periods of time. Operation temperature also weakens ability for high current peaks. Power levels for different kinds of applications, where proper BMS are needed, are shown in table 2.

Table 2. Typical BMS applications for industrial applications at different voltage ranges [9].

Voltage range [V]	Applications	Example BMS used in apps.
0-60	Microhybrid, light electric vehicles, industrial veh.	bq77pl900 (Texas Instruments) [9]
60-500	Full hybrid, electric vehicles, plug-in hybrid	LTC6802 (Linear Technology Corporation) [9]
500-1200	Electric buses, electric carriers etc.	

Battery management systems for traction vehicles have few important differences from traditional BMS applications such as consumer/industrial products, laptops and cell phones, power tools etc. There are same principals, considering *SOC* calculation and user interfaces in most applications. Battery management in traction vehicles has to be more critical however, because sudden power cutouts can lead to life-threatening events. Also batteries in traction vehicle applications have bigger size, power and end-usage of batteries needs to be designed so average end-user can use battery in everyday use [9].

3.2. Structure and interfaces

Battery management system manages critical parameters of battery, such as charge/discharge currents. Battery management system consists of few basic blocks. Advanced battery powered system usually has battery as a power source, a battery management system, a load that can in some applications be a generator, and a communication from BMS to host device/user. With secondary batteries, charging can happen with an external device. Basic ideal battery powered system with BMS is presented in (Fig. 4).

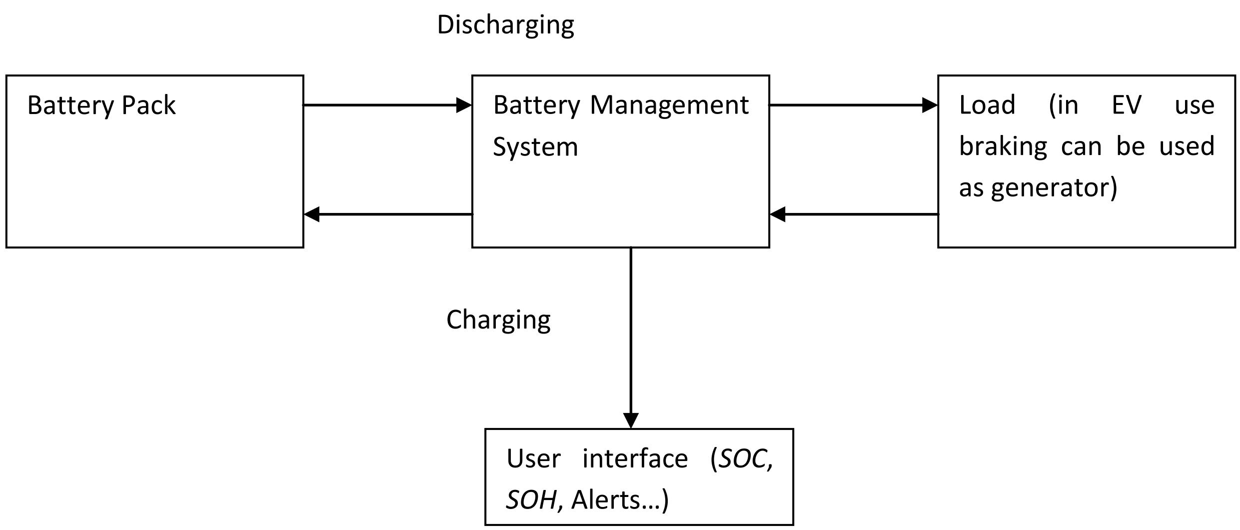

Figure 4. Block diagram of an ideal battery powered system with BMS.

Battery management system should be able to perform with any sort of battery chemicals, or combination of connections of battery cells. Batteries can be connected to each other in parallel, series or combinations of both to gather power level needed for application. Charging sequence is only applicable when there is secondary battery.

BMS keeps voltages of individual cells under control, meaning that over/under voltages should be avoided. This can be done by either passive or active cell balancing. Cell balancing is discussed in chapter 2.3. BMS should also keep user informed on state of the battery. *SOC* (chapter 3.1) and *SOH* (chapter 3.2) indicators are usually built within BMS of electric traction vehicle [10]. *SOH* indicator requires knowledge of the initial state and usage history. *SOC* calculation can be done on-line with measurements of parameters such as voltage and temperature.

Conceptual diagram between user and a mobile computing device is shown in Fig. 5.

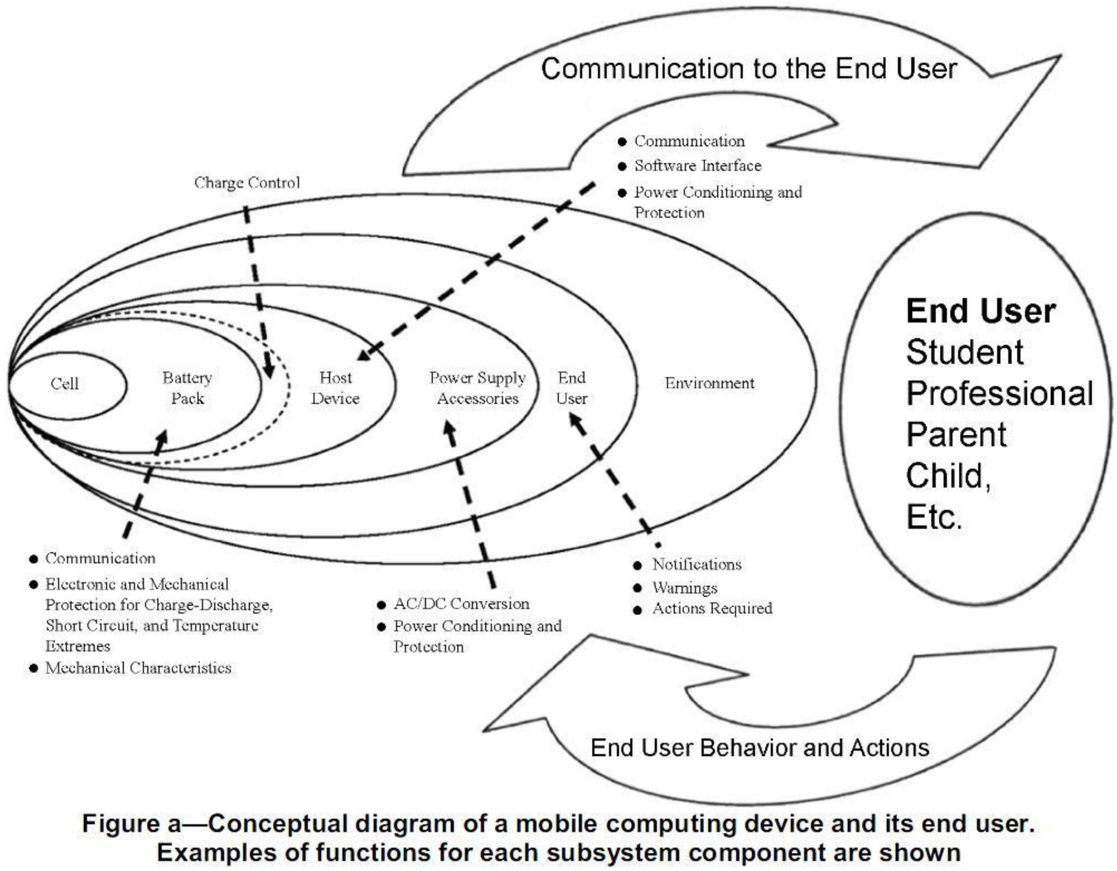

Figure 5. Communication between subsystems of mobile computing device and end user [1].

Communication between different parts of BMS is important to maintain fast and accurate operation. Ideal block diagram of BMS is presented in figure 6. Data buses between BMS and main computer of device can be for example CAN bus.

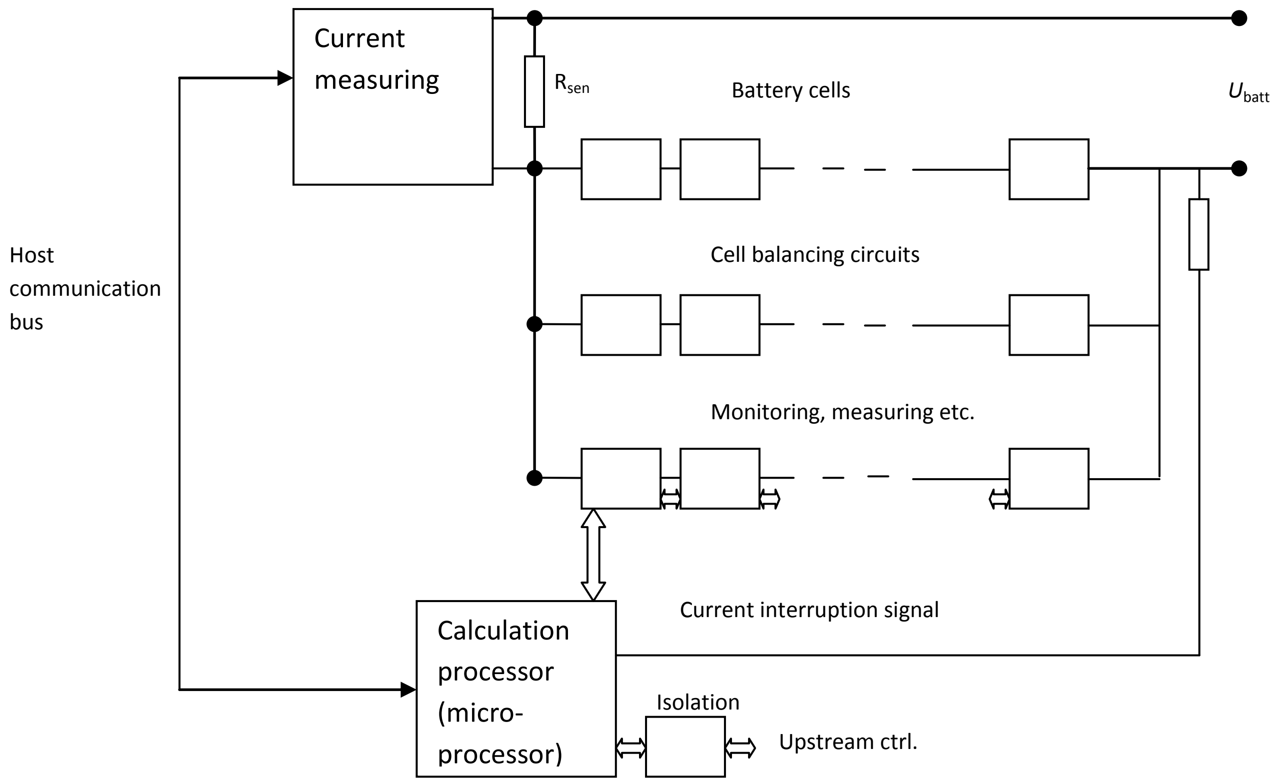

Figure 6. **BMS example for battery with multiple cells [9], [13].**

In the figure above, a typical BMS structure is presented. In advanced BMS applications, like EV, user interface is required to keep user informed about status of the battery. BMS placement can be either centralized (all function at same place) or distributed (measuring is done by different modules) [9].

Data exchange between controllers and measurements instruments in vehicle is important to gain information about functional state of car. For example, collecting information about the state of energy storage of the vehicle is important as well as the speed of rotation [rpm] of the engine. In automotive electronics such information can be collected via CAN bus for example [14].

CAN bus uses serial data communication (Fig. 7) protocol, which is widely used in automotive industry. It was invented to receive data exchange between controllers and measurement instruments. Communication medium can be double stranded wire, coaxial cable or optical fiber. CAN bus network on EV includes a master node and slave nodes. The master node sends messages to the slave nodes which then send messages back to the master node [15]. CAN bus provides high reliability and good real-time performance with very low cost and it is used in wide range of applications such as in-vehicle communication, automotive manufacturing and distributed process control environment. CAN bus uses CSMA+AMP mechanism (Carrier Sense

Multiple Access With collision detection and Arbitration on Message) which makes it flexible [16].

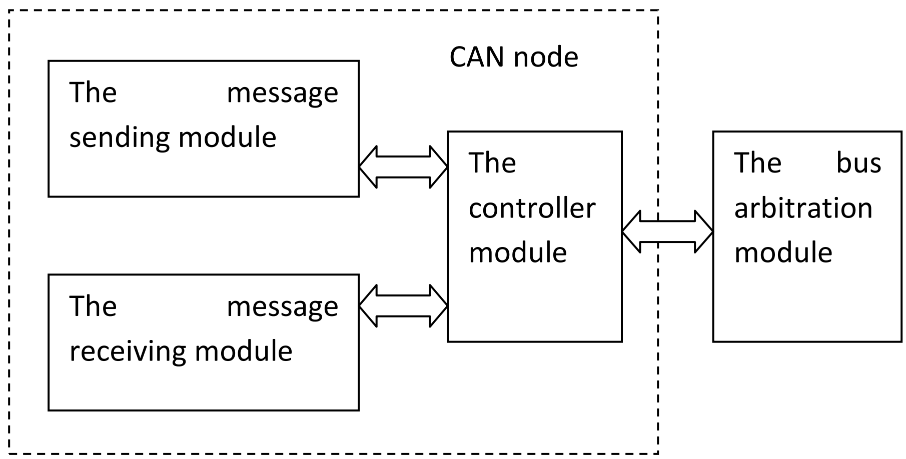

Figure 7. Basic CAN bus communication system [16].

Calculation processor, Fig. 6, communicates with current measuring block via host communication bus. Calculation processor also gathers data from each monitoring device of the battery system. In advanced system, each cell is accompanied with monitoring device that measures *SOC* of cell for example. If there are notable differences between cell capacities, the calculation processor can give enable signal for the divergent cell to balance capacity. In high power systems, the processing unit can start cooling the cells if they are heated to the maximum temperature level allowed.

Centralized BMS is simpler than distributed BMS and has lower costs. It has all its parts in the same circuit. There is no need for signal cable between parameter measuring, voltage and current for example, and BMS [9]. Centralized BMS has often advantages such as smaller size. Disadvantages compared to distributed structure are that centralized BMS is harder to implement with large battery packs which make it less desirable for EV use.

Distributed BMS can be used in larger systems. It is more desirable for battery systems, where multiple cells are used. Measurement of parameters is done separately for each parameter such as voltage and temperature [9].

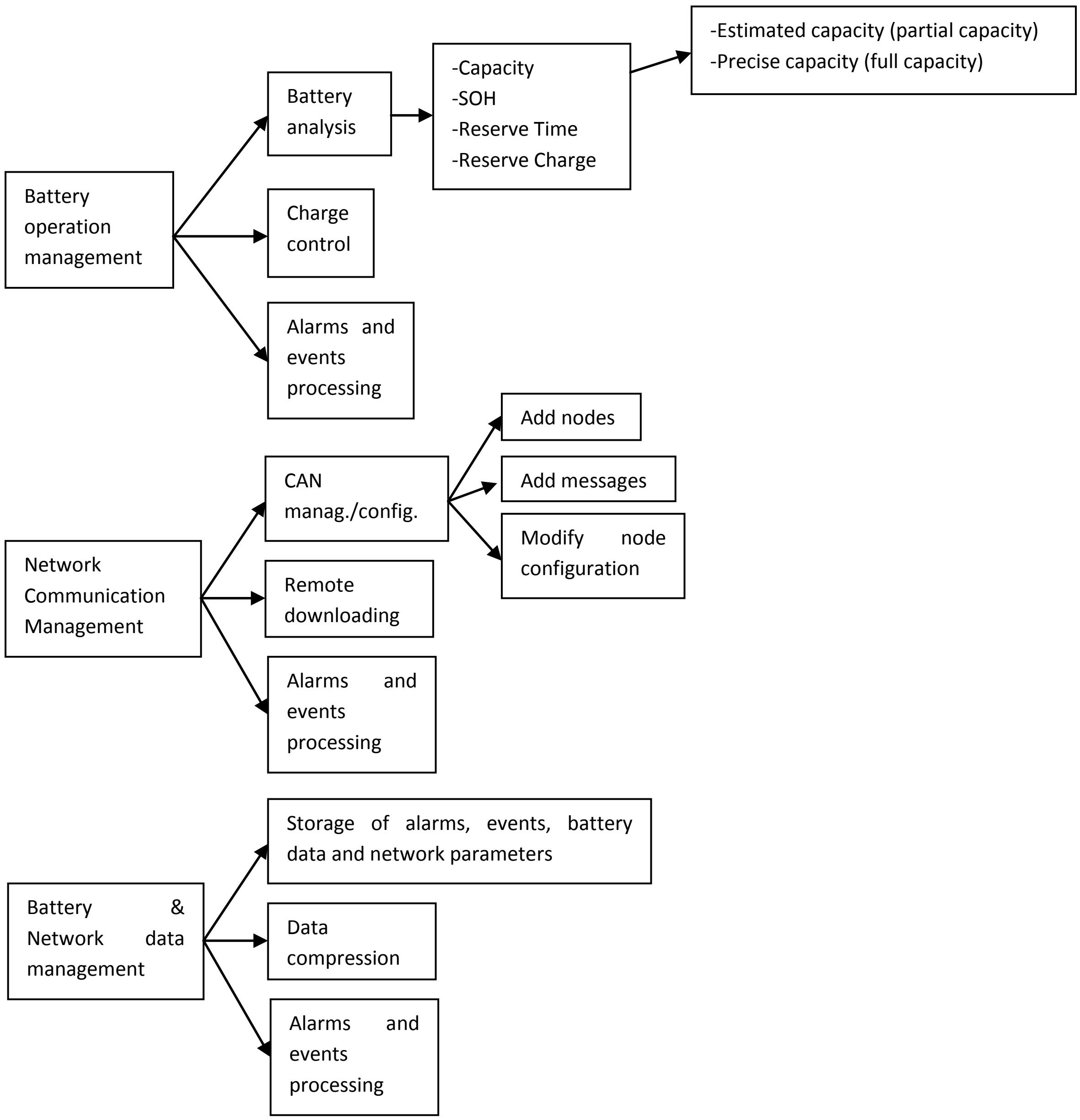

Figure 8. **Typical BMS task organisation. In the first level there is battery level management, second is network level management and the lowest is data management from whole system [17].**

For example, battery level operation management has many distributed management tasks, where measurements are collected for battery analysis. Battery analysis is done with processing unit of BMS that calculates total *SOC* based on *SOC*s of all battery cells. Battery level also includes charge control. BMS in EVs gives information to user via CAN bus for example [7]. User is kept acknowledged about state of the battery all the time. Information about runtime is the most important in EV use. Also knowledge about *SOH* should be provided so that user may change the whole battery pack, or at least most worn out cells/modules.

3.3. Battery modeling

To design a proper battery management system, a proper model for the battery is required. The first task in modeling the performance of the battery is to define an equivalent circuit for the battery. Each component should have predictable behavior [18]. In this work electrical equivalent circuit of battery is selected for modeling. Basic equivalent circuits of battery are shown in figures 9-11. Battery as a component is highly nonlinear and dynamic system because of chemical reactions [19]. A battery model is required for getting useful information about status of the battery, for example State-of-Charge and State-of-Health of the battery. Good model also tells user how changes in load affect performance of the battery. Battery designed without proper modeling might cause that battery is inefficiently supplying power and controlling load devices [19].

Modeling of the battery is a difficult task, since there are many variables that have an effect on capability of the battery. Usually those are measurable parameters such as temperature and performance characteristics such as voltage. But battery gets affected also by few other not so easily measured factors such as ageing and usage history. And when a battery consists of many cells, variations between parameters of each cell are needed to be taken into account [18]. Internal characteristics of the battery and circuit parameters vary as a function of *SOC* and temperature.

Battery model should be able to follow parameters of the battery at varying conditions. Mainly battery models are based on open circuit voltage to make an approximation of State-of-Charge of the battery. This paper uses modified Thevenin's electrical equivalent circuit of the battery (see fig. 1). To obtain a good model, it is important to measure *OCV* of the battery at wide range of *SOC*.

To keep operation of the battery at good performance, a safe *SOC* range is needed to define. It is found that the safe range of *SOC* is roughly between 10% and 90% so that at the lower limit overdischarge of battery is being prevented and at higher limit risk to overcharge the battery is lowered. Limiting high values of *SOC* also allows sudden charges with regenerative energy [10]. Such events may occur for example in EV use when battery pack is fully charged (to 90%) and driving sequence consists mostly of downhill.

Challenge about modeling batteries is how to define values for the parameters of the equivalent circuit [20]. Model-based methods require accurate modeling of the behavior of cell through whole battery life and for all conditions [21]. Few equivalent circuits are presented in figures 8-12.

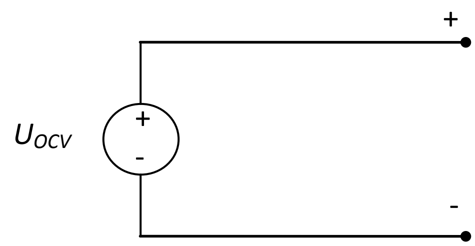

Figure 9. Ideal model of the battery [11].

Ideal model (Fig. 9) is the simplest, and thus it is not very suitable for any real use as a battery model. Ideal model describes battery as a constant voltage source, thus ignoring all parameters of the battery, which are important for understanding dynamics of the battery.

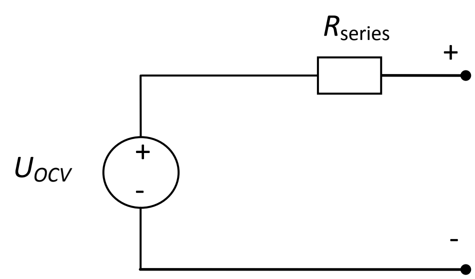

Figure 10. Linear model of the battery [11].

Linear model (Fig. 10) takes into account internal resistance of the battery, thus making it a slightly more educated model than the linear model, but it does not consider the internal impedance of the battery, which is an important part of *SOC* calculation. Linear model can be used when current profile of load is simple, meaning that there is no varying. Linear model might be suitable for low frequency modeling.

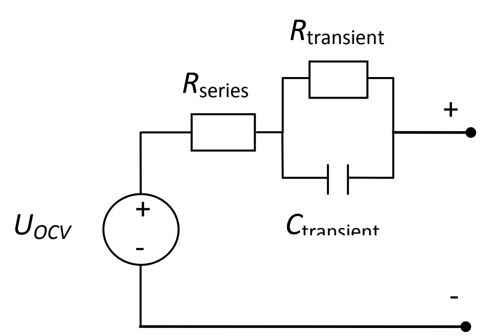

Figure 11. Thevenin's model of the battery [11].

The most advanced model of the simple models above is Thevenin's model (Fig. 11), which includes both internal resistance and impedance. In Thevenin's model the resistance $R_{transient}$ depicts nonlinear resistance between plate and electrolyte and capacitance, $C_{transient}$, depicts capacitance between parallel plates [11]. R_{series} depicts internal resistance of the battery. Still even Thevenin's model has its flaws due to the constant values of model, because actual values of components vary due to the condition and state of the battery. However, this model can be improved by adding an extra RC-branch to it [22].

3.3.1. Analysis of different battery models

Batteries can be modeled by different methods. Three most used battery models are electrochemical models, mathematical models and electrical models [23]. Battery models vary in complexity. Simple models can be used if load currents are low and there is not any large difference in current profile. When there are high dynamics and high currents, more advanced model should be used to get accurate prediction [24].

Electrochemical models are complex and time consuming because they need partial differential equations and detailed battery information that is hard to obtain. However, their accurate modeling of physical aspects of battery makes them an accurate modeling tool. Mathematical models are simpler than electrochemical models. Mathematical models are good for predicting such values as battery runtime, efficiency and capacity. Mathematical models cannot offer current-voltage information that is important for simulation and optimization. Also accuracy of mathematical models is rather low (5-20%) and they are usually designed for specific applications [23].

Electrical models are most used battery modeling tool for electrical engineers and in that case it is selected for the modeling tool in this paper. The accuracy of the electrical models of the battery (1-5% error) is quite good, somewhere between electrochemical and mathematical models. Electrical model consists of voltage sources, resistors and capacitors. Electrical models can be classified under three categories: Thevenin-, runtime- and impedance-based models [23]. There are several drawbacks with electrical models with coverage of the broad operation range of automotive application. Parameter varying with temperature, *SOC*, current and ageing of the battery makes challenges when using electrical model [21]. Ageing for example, decreases maximum available capacity and also increases internal resistance [21] which affects capability of the battery to provide high discharge currents due higher power losses.

Thevenin-based model (Fig. 11) models battery with voltage source, internal resistance and RC-branches. With simple Thevenin-based model, components predict response of the battery to load.

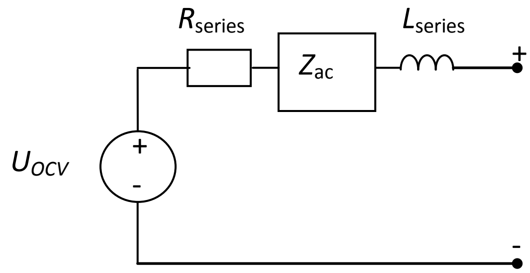

Figure 12. Impedance-model of the battery [23].

Impedance model (Fig. 12) uses electrochemical impedance spectroscopy to obtain ac-equivalent impedance model for impedance characteristics of the battery. Impedance-model itself cannot provide information about capacity [19], thus it is difficult and complex procedure and impedance models work usually for fixed *SOC* and temperature, hence making runtime analysis harder [23]. Inductance L_{series} is needed in battery models when there are high frequencies. Using impedance magnitude and phase delay for calculating relationship between voltage and current, impedance method is acceptable choice. However, it has few drawbacks as charge and discharge characteristics and *SOC* have to be defined from charge/discharge curves [19].

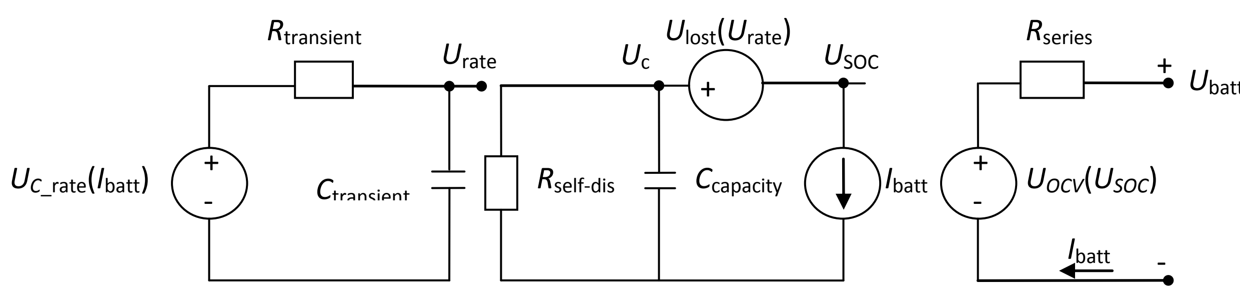

Figure 13. Runtime-based model of the battery [23].

Runtime-based models use complex circuit network to simulate battery runtime and dc response. Runtime-based model can be implemented either with continuous- or discontinuous time. Setback for runtime-model is that it cannot predict runtime or voltage response if load varies [23].

All models are individually suitable for some part of modeling. Yet there are still some parameters that the models presented above cannot take into account accurately [23] so there is a need to design a model that combines suitable properties.

3.3.2. Calculation of State-of-Charge of battery

Estimation of the State-of-Charge is an essential part of BMS. *SOC* provides information about how much charge of battery is left compared to its maximum capacity at current cycle and given C-rate. State-of-Charge can simply be determined ideally for every battery type independently of all chemistries as [11]

$$SOC = \frac{\text{Actual amount of capacity left}}{\text{Maximum available capacity at given C-rate}}. \quad (1)$$

Easy way to determine *SOC* is method called Coulomb counting. It can be used in low power applications, such as portable devices. It is very sensitive to temperature effects, making it less accurate for high power applications. For high power applications *SOC* calculations are presented in chapter 3.3.6. Equation (1) can be expressed more accurately with current integration as follows [22]

$$SOC = SOC_{\mathrm{ini}} - \frac{\int \eta i_{\mathrm{L}} dt}{C_{\mathrm{N}}}, \quad (2)$$

where SOC_{ini} is the initial value of *SOC*, η is the Coulombic efficiency and C_{N} is the nominal capacity. Equation (2) can be transformed to a discrete form [22]

$$s_{\mathrm{k}} = s_{\mathrm{k-1}} - \frac{\eta i_{\mathrm{L,k-1}} \Delta t}{C_{\mathrm{N}}}. \quad (3)$$

Where s_{k} and $s_{\mathrm{k-1}}$ are values of *SOC* at steps k and k-1 respectively. Δt is the time step used.

There are also few problems with measuring the amount of capacity. Maximum available capacity of battery decreases due to ageing of the battery, operation temperature and current. Maximum available capacity can be expressed as State-of-Health. There are many ways of determining *SOC*. The easiest way to determine *SOC* would be measuring open circuit voltage (*OCV*), and compare value to a lookup table. Calculation of *SOC* with *OCV* might cause some error because *OCV* might differ when load varies [11]. However, *OCV* is found to change as a function of *SOC* [12]. Therefore, using extended Thevenin's model (see Fig. 11), we can calculate voltage of the battery by equation (chap 3.3.6)

Other way to determine *SOC* would be to use electromotive force (*EMF*) of the battery. *EMF* is internal force of the battery that figures capability of the battery to provide energy to load [25]. Relation between *SOC* and parameters *EMF* and internal resistance can be found easily. Determination of *EMF* and internal resistance gives possibilities to calculate *SOC* versus voltage of the battery at different charging or discharging currents [26]. *EMF* can be determined by calculating voltage average from consecutive charge and discharge voltages using same currents at same temperatures. Measuring *EMF* is a good way to measure *SOC* for Li-ion battery because the relation between *SOC* and *EMF* does not chance during cycling of the battery [25]. From above, it is seen that *EMF* is related to *OCV*.

Charge of the battery is discharged relatively quicker from battery if current is high. Meaning that, for simplified example, if full discharging of the battery at 1 A current takes 10 h, full discharge at 10 A current takes less than 1 h. This phenomenon is very important to take into consideration in EVs, because current varies greatly during a driving session, hence this might lead to a miscalculated remaining capacity calculation, which may result in reaching the end of useful capacity sooner than calculated [18]. Defining *OCV* is also easier if depth of discharge is known. To model behavior of the battery with varying currents Peukert's equation can be used

$$C_{\mathrm{p}} = I^{k}T. \qquad (4)$$

Where C_{p} is Peukert's capacity, *k* is Peukert's coefficient (varies with different battery chemicals and battery ageing), *I* is a constant discharge current and *T* is time in hours [18]. Peukert's coefficient, *k*, can be calculated when two different discharge current, I_1 and I_2 and, times T_1 and T_2 are known. Hence we get

$$I_1^k T_1 = I_2^k T_2, \qquad (5)$$

by arranging currents to left, and times to right side of the function, and taking a logarithm, we can get

$$k = \frac{(\log T_2 - \log T_1)}{(\log I_1 - \log I_2)}. \qquad (6)$$

Calculations for *k* can be done for any battery chemicals. It can be seen that, the lower the value of *k* is, the better capacity of the battery at higher current is [18]. However, it is known from literature that with Li-ion batteries Peukert's coefficient value is typically near 1. Hence capacity of Li-ion batteries will not drop depending on the discharge current rate [27].

As discussed earlier, determination of internal resistance and open-circuit voltage of the battery, gives a good tool for *SOC* calculation. However, both *OCV* and internal resistance vary with temperature changes. Internal resistance is also different with different current directions. When battery is discharged the internal resistance is little higher than in the charging mode. Internal resistance also varies as a function of *SOC*, as mentioned earlier. At really low and high value of *SOC*, the internal resistance rises greatly. From 10% to 90% *SOC* region the internal resistance is almost constant, only small difference appears. Temperature also affects the internal resistance. At higher temperature, internal resistance is lower than at low temperatures. This can be explained by chemical properties of battery [28].

Calculation of *SOC* for each cell in the battery pack requires measuring of parameters of an individual cell. If BMS has an advanced active battery balancing system those required parameters needed to calculate *SOC* can be measured. If measuring of data is out of options an approximation can be done for each cell based on information gained from battery pack. In that case battery packs cell combination must be known.

3.3.3. Calculation of State-of-Health of battery

State-of-health (*SOH*) is an important value that measures ability of battery to store energy, source and sink high currents and ability to maintain charge compared to initial capability of battery. *SOH* decreases with battery ageing, which causes decreasing in maximum available current [11]. *SOH* can be determined by comparing maximum available capacity to rated capacity of battery. *SOH* is a good indicator whether condition of battery is good, or if it is reaching end of its lifetime. State-Of-Health can be simply determined as follows [29]

$$SOH = \frac{\text{nominal capacity} - \text{capacity fade}}{\text{nominal capacity}}. \qquad (7)$$

It is known from literature, that when *SOH* drops below 80%, the battery is considered to be at end of its life [6]. End of life when at 80% *SOH* results from decrease in peak performance and shortening of cycle time of battery, thus crucially affecting operation of device. *SOH* of $LiFePO_4$ battery decreases to 80% about in 1000 (100% *DOD*) discharge-charge cycles [29]. For example, with an average lithium-titanate battery cell (used in this thesis) 80% *SOH* is reached after 16000 full discharge-charge cycles [8].

3.3.4. Temperature effects to battery

When using to supply power to a load, battery usually starts to heat due to power losses in internal resistance. Also the initial operating temperature has some effect on performance of battery. Electromotive force and *OCV* of battery vary as functions of temperature [26]. Capability of battery to provide high current rates (for example 3C) drops significantly at very low temperature like -10°C or lower. If high currents are drawn from batteries at low temperature, battery reaches critically low *SOC* faster, and this affects usage time.

Thermal management is an important part of BMS in EV/HEV use. Battery temperature has influences on available power, for example in cold temperature, like -20C, capability of battery to provide power for startup/acceleration is not as easy as in desired temperature [10]. This can be explained by reasons mentioned above. Temperature affects also the ability to charge when in regenerative driving [10]. Misbalanced temperature between cells causes misbalance to *SOC* of the battery cells and uneven power distribution [9]. Taking these effects into consideration, it is a vital part of BMS to keep operation temperature mainly at desired range.

As a conclusion it can be said that battery, or battery packs, require temperature control. Whether it is cooling or heating, operating temperature of battery needs to be at desired range. Internal temperature of battery rises when high current rates are used. Optimal operating temperature range of battery is about from -10°C to +50°C [30]. Though for, for example, lead-acid batteries, an optimal operation temperature range is said to be between +25°C to +45°C. Temperature range for HEV/EV could be set to from -30°C to +60°C [10]. Li-ion batteries are better at higher temperature compared to aqueous batteries such as NiCd- and NiMH-batteries [9].

In this paper temperature effects to performance of the batteries are only discussed because measurements were done in just one temperature. Parameters of battery were measured at room temperature.

3.3.5. Errors caused by operation history of battery

Battery ageing occurs after every discharge-charge cycle. Some chemistries also age with actual time, but for example with Li-ion ageing with time is minor compared to lead-acid for example. In Table 1 are presented some cycle lives for few battery chemistries. Cycle life in EV use is defined so that *SOH* of the battery pack is decreased to 80% of the initial capacity. Amount of cycles before this limit is exceeded varies with different battery materials. Ageing of battery affects chemistry of battery, hence parameters of the battery such as internal resistance also changes when ageing occurs [9].

Modeling of the ageing of the battery is hard task to implement in BMS. For modeling of the ageing process it is needed to take measurements with the ageing of the battery to define *SOH* after each cycle. This way BMS could calculate new *SOH* after each cycle. Also varying of the parameter values during cycle life should be taken into account when designing BMS.

3.3.6. Parameters of battery modeling

Battery model used in estimation is presented in figure 10. Typical dc resistance, for example $LiFePO_4$-battery, is 0,017 Ω at linear *SOC* interval [24]. Parameter R_{tot} of model, which corresponds to total resistance, can be calculated for both charging and discharging by measuring direct voltage drop after a current is drawn into or from battery by simply using Ohm's law [22].

$$R_{\mathrm{tot}} = \frac{\Delta U}{\Delta I} \tag{8}$$

Value of R_{tot} is different for charging and discharging. R_{tot} also varies as a function of *SOC* and temperature. Values of R_{tot} are measured under various values of *SOC*. Varying temperature also changes values of R_{tot}, in this thesis however temperature effects to the battery are left out because model of the battery is kept simple. R_{tot} includes both internal resistance R_{i} (R_{series}) and resistance of RC-branch R_1 ($R_{\mathrm{transient}}$). R_{i} can be calculated based on immediate voltage drop/rise after current is drawn from/into battery.

RC-branch of battery model can be measured and used in calculation of *OCV*. Capacitance value of the RC-branch can be defined by determining rise time of voltage curve. Voltage across RC-branch can be defined as follows [31]

$$\frac{dU_{\mathrm{n}}}{dt} = \frac{1}{R_{\mathrm{n}}C_{\mathrm{n}}}U_{\mathrm{n}} + \frac{1}{C}I \tag{9}$$

where n is ith RC-branch and *I* is current. RC-branch simulates transient response of the battery, when current is drawn of fed into the battery. Capacitance of RC-branch can be defined approximately from discharge/charge pulses [23]. The higher order of the model is used, the more difficult it is to calculate different capacitance values. Calculation of capacitance requires approximation of time-constant. Time-constant is the time needed for RC-circuits capacitor to charge to approximately 63.2 % of its initial capacity [32]. For discharging it is time to reach 36.8 % capacity. Voltage of RC-branch can be calculated by distracting internal resistance from total resistance.

OCV depends on *SOC* and temperature. *OCV* dependence on *SOC* is small with Li-ion batteries, so *OCV* needs to be measured accurately [21]. In this paper, U_{OCV} and other parameters are modeled as nth degree polynomial functions of *SOC*. For example, polynomial function of U_{OCV} is as follows

$$U_{OCV} = a_3 z^3 + a_2 z^2 + a_1 z + a_0 \tag{10}$$

where z is *SOC* as decimal [0,1] and $a_{0\text{-}3}$ are tunable coefficients, which can be defined by curve fitting techniques. In this paper, *OCV* is modeled as a polynomial function of *SOC*.

Defining of *SOC* and capacity is an important part of batter model. It is known that when battery is fully charged, it takes one hour to discharge it completely with 1C current rate. *SOC* of the battery can be defined as [31]

$$\dot{z} = -\frac{1}{3600 C_\mathrm{n}} I, \tag{11}$$

where C_n is nominal capacity and I is current used either charge or discharge the battery. Usable capacity decreases as cycle number, discharge current rate and storage time increase. Temperature below optimum temperature affects usable capacity decreasingly due to increase of both charging and discharging internal resistance [31]. Capacity can be expressed as [23]

$$C_\mathrm{capacity} = 3600 \times Capacity \times f_1(cycle) \times f_2(temp), \tag{12}$$

where *capacity* is the nominal capacity of the battery, f_1 is amount of full discharge cycles and f_2 is operation temperature. In this thesis however, capacity of the battery will be the same regardless of cycles and temperature.

Terminal voltage, U_{batt}, of the battery pack is calculated by using *OCV* and internal parameters. *OCV* curve is nonlinear as a function of *SOC*.

$$U_{\text{batt}} = U_{OCV} - R_{\text{i}}I - R_1(1 - e^{-\frac{t}{\tau}}) \tag{13}$$

Where U_{batt} is terminal voltage of the battery, U_{OCV} is open circuit voltage, which is a function of *SOC*, R_{i} is internal resistance, R_1 is resistance of RC-branch, t is time and τ is time constant. Technically U_{OCV} has some effects with temperature changes, but in this paper it is neglected due two reasons: temperature effects on *OCV* curve could not be measured with used laboratory equipments and it is known from literature [31] that the difference is negligible. In [12] battery model parameters are calculated with linear parameter varying method. In this thesis the parameters are fitted to measured data.

For validation of presented model (chapter 4), real *OCV* curve of the modeled battery is measured. Measurements are done with several values of *SOC*. Before the value is measured, battery is allowed to have a little relaxing time so that voltage of the battery increases/decreases to its equilibrium. After measurement of the *OCV* curve it is compared to modeled *OCV* curve.

3.4. Cell balancing

Maintaining cell voltages of battery pack at equilibrium is called cell balancing, which is an important part of the battery management system. Power demanding applications like EV/HEV have battery packs that consist of multiple batteries connected via series and parallel connections to reach power level required. High power applications such as EVs require high currents and high capacities. In high power applications, battery as a complete energy storage is studied usually as a battery pack, which consists of battery modules. Larger battery packs are built using battery modules which are combination of battery cells. However, because of manufacturing tolerances, individual cells of a battery pack are not identical when compared to each other. For example, there might be notable differences between capacities of cells. Cell voltage of one lithium ion cell varies between 3.0 and 4.0 V [33]. Li-ion also limits how balancing can be done [9]. Differences between cells must be balanced to keep the performance steady. Therefore cell balancing is required in multiple cell battery applications. Cell balancing principal is to equalize cells by transferring charge from higher voltage cells to lower voltage cell.

Variations of cell voltages in battery pack are caused by differences in operation temperatures between cells or manufacturing differences. Internal resistance varies also with temperature, so when connected to load, battery packs cells are discharged unequally. This causes imbalance in *SOC*s of cells, which leads to a need for balancing to keep cycle of battery pack longer. Balancing is not required for all types of chemistries, for example NiMH, or for every types of electric traction vehicle [9]. Example of how capacity may be drawn differently from different battery cells in same battery series connected string is shown in Fig. 14.

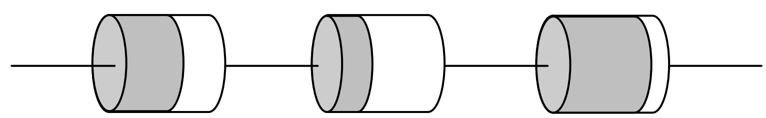

Figure 14. Capacity or charge differences between three cells in serial connected string. Gray area presents the amount of capacity left in the cell.

The most frequently used cell balancing methods are active or passive cell balancing. Passive cell balancing (Fig. 15) is cheaper and easier to use compared to active, because it only uses resistive components to discharge cells with higher capacity, hence making it more widely used in most battery packs [33]. Despite its easy design and usability, the passive balancing method has a few disadvantages. When using resistor to balance overcapacity of cells, the resistor produces heat and so rises temperature, causing that overheat needs to be cooled. Other major disadvantage is low energy efficiency of this method. Passive balancing is usually only used when charging [33].

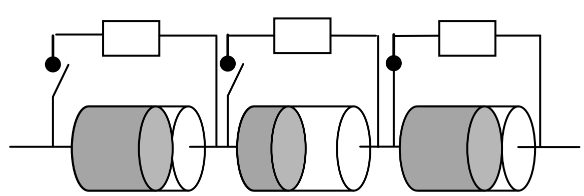

Figure 15. Passive cell balancing. Overcharging of cells with lower maximum capacity is avoided with resistors. This method can be only used when charging.

Active balancing (Fig. 16) method usually has a microcontroller based system that controls voltages over individual cells. Each cell in its string has its own converter, which drives current to cells that have smaller capacity via share bus [34]. With active cell balancing it is possible to balance capacity between different cell strings [33]. Balancing on cell-to-cell level in one cell string in high power applications might be inefficient due to power losses in power switches [21].

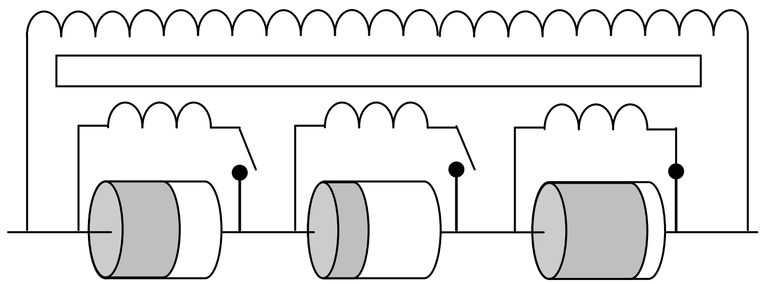

Figure 16. Active cell balancing with flyback converter [33]. Cells with much higher capacity load their capacity to transformer which then charges cells with smaller capacity.

Passive balancing is suitable, if there is not a need for an efficient method. It is much easier and cheaper to implement than active balancing. For example, using passive balancing method in applications where energy optimization of battery is not advanced (for example HEV) is more usable option than active cell balancing [9]. HEVs have an internal combustion engine (ICE) drive generator as an alternative electric energy source, so energy efficient balancing system for battery pack is not necessarily a primary object. However, electric energy produced by an ICE aggregate is very expensive that, on the contrary, suggests as efficient use of the generated electricity as possible. Overcharged cells are, however, often balanced with resistors when battery pack is charged.

Devices that mainly use electrical energy, or where ICE is a backup generator when *SOC* of battery pack is at low level, have more need for active battery balancing. For example, such a device could be pure electric vehicle (PEV). PEVs mainly energy storage is battery pack, so there is a need for energy efficient design. With proper design of balancing system cycle range of battery pack can be lengthened.

In [35] passive and active cell balancing methods are compared. Passive cell balancing is done with resistors, and active cell balancing is done using flyback converter. By using active cell balancing lower power dissipation can be achieved compared to passive cell balancing. Active cell balancing can reduce energy losses from 2.3 % to 0.84 % when compared to passive cell balancing [35]. Due to higher power dissipations using the passive cell balancing might lead to a need of a cooling system. Also length of discharge period extends when using active cell balancing compared to no balancing, because the cell with lowest voltage does not reach cut-off voltage so quickly.

3.5. Charge and discharge current management

Charging control for the battery has to be taken into consideration. Batteries with different chemistries react differently with overcharge and undercharge situations. Li-ion batteries are typically charged with constant current-constant voltage (CCCV) method (Fig. 17) [5], [9]. First battery is charged with constant current rate, for example 1C, to level where voltage reaches maximum level. However, reaching of this maximum voltage does not mean that the battery is fully charged, so there is still some capacity left to fill. Remaining capacity can be restored by charging battery with constant voltage. Current charging the battery starts slowly to decrease after constant voltage charging is initialized. End of charging sequence should be defined so that charge of the battery will not exceed its maximum capacity. This can be achieved by setting low current switch-off for constant voltage sequence [5], [36].

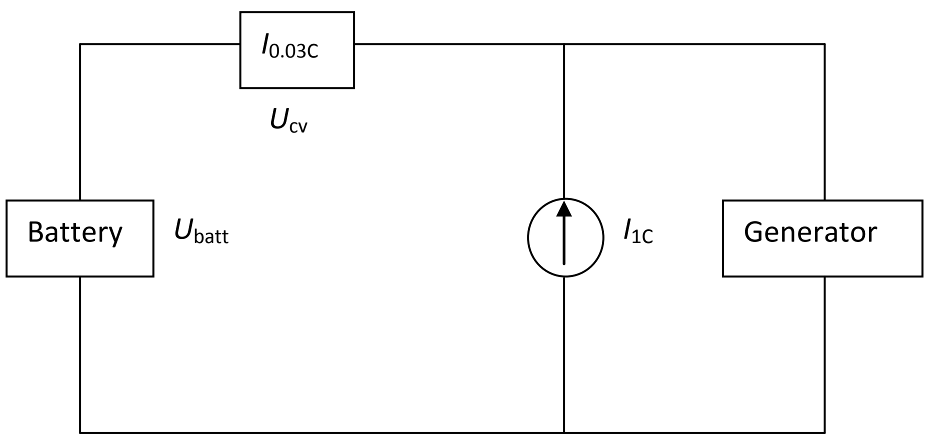

Figure 17. Battery charging with CCCV-method [5]. I_{1C} is current at constant current charging sequence, when U_{batt} is reached, constant voltage sequence is initiated. Voltage is kept at U_{cv} and charging is ended when current reaches 0.03C

Battery management system should limit charging current for rechargeable batteries. Limiting discharge current is needed to avoid damaging the battery [6].

Battery type detection is important if the application can be powered by primary or secondary batteries. If both battery types are used, it is very important to avoid charging currents when primary batteries are used. Primary batteries, as mentioned earlier, are a type of battery that cannot be recharged. In fact, even a short charging current can cause permanent damage to battery. Hence, primary batteries are disposable batteries. If there is a possibility in application that primary batteries are used instead of secondary batteries, an identification method for battery type should be present [37].

For example, such method is presented by Maxim-IC [37]. In this method, an impedance test is performed when batteries are imported to application. As primary batteries have higher internal impedance compared to secondary batteries, primary batteries can be detected by such test. Impedance of the battery can be calculated by discharging some current from the battery. In [37] there is a list of impedances of different battery types.

Too high charging current causes irreversible damage to battery as battery overheats. Overcharging, as well as overdischarging causes irreversible damages when using lithium-based batteries. Irreversible damages are damages that weaken capability of the battery to provide high load currents and decreases *SOH* of the battery.

The battery type used in the tests of this thesis, lithium-titanate, is slightly different for charging sequence. It can be charged with higher current for longer time. For continuous charging even 6C currents can be used and 10C current can be used for 10 seconds [8]. Higher charging and discharging current can be explained by structure of lithium-titanate batteries. Carbon at anodes in normal Li-ion batteries is replaced with nanostructure lithium-titanate [38]. This increases surface of the anode material allowing faster movement of electrons.

4. EXPERIMENTAL TESTS AND VERIFICATION

Battery management system is modeled in this thesis using Matlab Simulink. BMS model includes presented battery model. Charge/discharge current control is made with estimation so that high currents are regulated at high/low *SOC*. In real BMS it is done with software controlled switches and in the model built in this thesis is done with ‘blocks’ that models such switches. In real BMS there are also alerts of critical conditions which are done with software based calculations using measured information. Calculation of parameters and hence modeling of the battery is done based on [23], [31] and [39].

Battery model in this thesis is built based on Thevenin’s circuit model (Fig. 11). Simplified model of the battery powered system in Simulink is shown in figure 18. *SOC* is calculated by current integration.

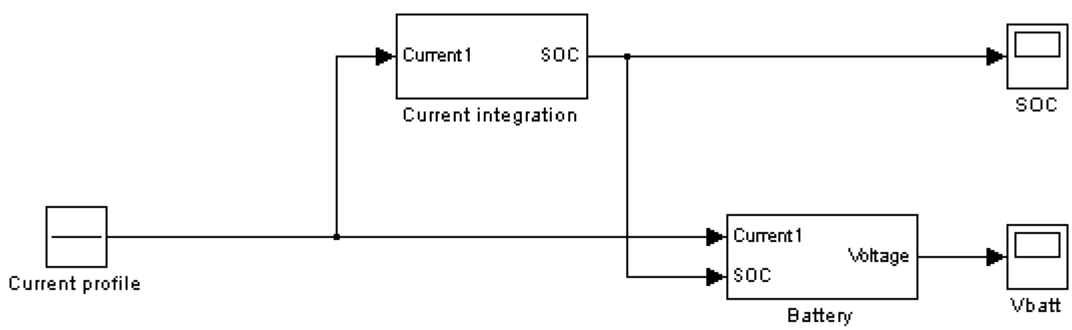

Figure 18. Simulation system of BMS built in Matlab/Simulink

Current limiting is later added to modeled system. Current is limited whether *SOC* of the battery is too high or too low.

4.1. Laboratory equipment and measurements

Parameters for battery modeling were defined after measuring several *OCV* values at different *SOC* values. Laboratory equipment diagram is shown in Fig. 19. Battery cell used in measurements is Altairnano’s 60 Ah lithium-titanate battery cell [8]. Picture of measurement equipment is shown in Fig. 20.

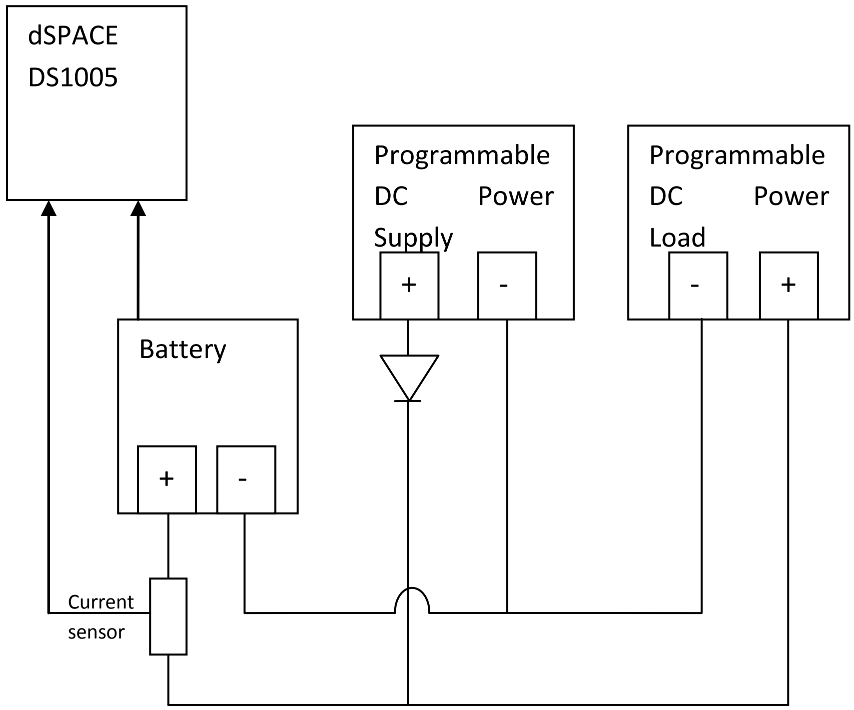

Figure 19. Laboratory equipment used in the measurement.

At first, one lithium-titanate battery cell was charged with constant current constant voltage method. After the battery cell reached terminal voltage of 2,7 V it was charged with lower current. Then the battery cell was considered to be fully charged at 100 % *SOC*. The battery cell was not charged to its ideal maximum charge level due to safety reasons.

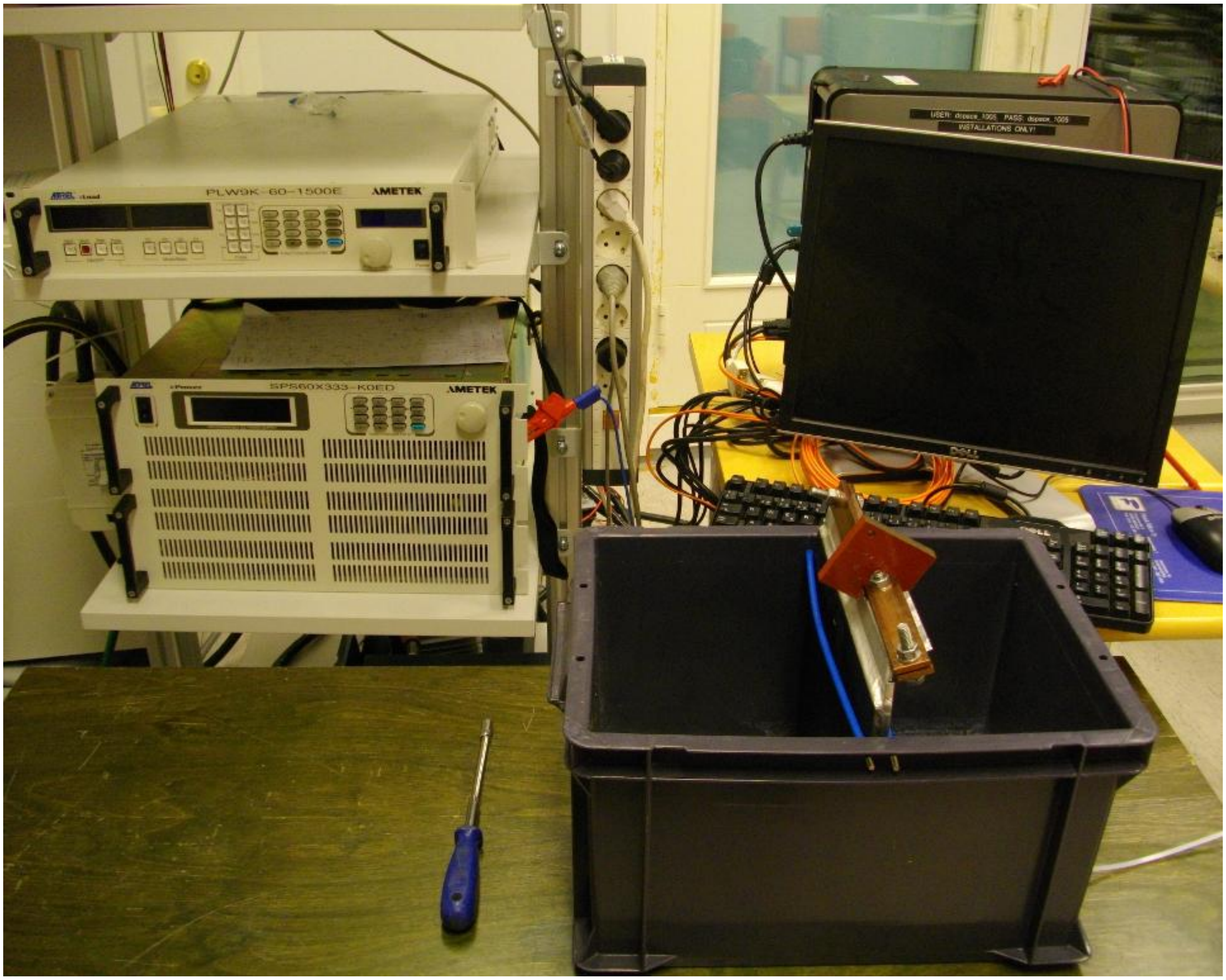

Figure 20. Photo of measurement equipment. The battery cell is located in front, the programmable dc power load is upper left and under it is the programmable dc power supply. dSPACE DS1005 is located under the power supply. dSPACE is connected to pc where data is collected.

In Fig. 20 photo of measurement equipment is presented. If current used in the test is positive the battery cell is discharged to the power load and if the current is negative battery is charged from the power supply. dSPACE DS1005 collects data from sensors and sends the data to PC. The battery cell was not connected to power load/supply when the photo was taken.

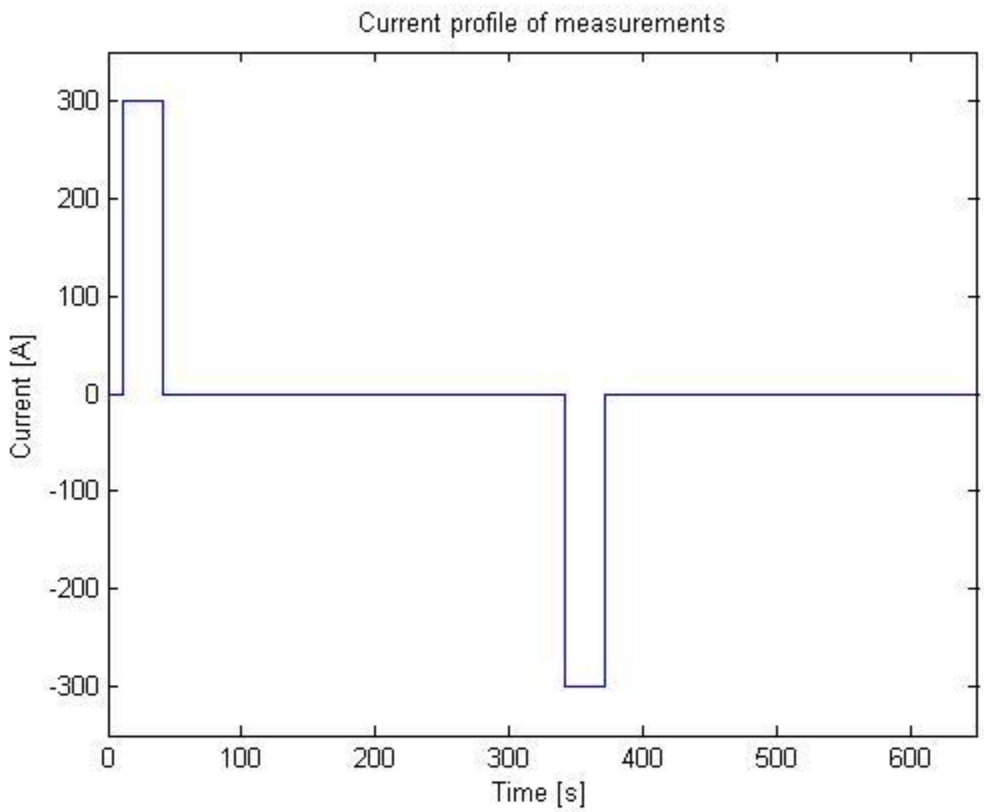

Figure 21. Current profile used in measuring for parameter definition.

Current profile of charge-discharge used in measurements is shown in Fig. 21. Current is set to 300 A, which is 5C current rate for the battery cell used in test. Nominal capacity of fresh battery cell is 60 Ah. However, the battery cell has been used in few experiments, thus *SOH* has been decreased. Charge-discharge cycle is designed so, that first the battery cell is discharged 30 seconds with 300 A current and then cell is allowed to rest. After a short resting period cell is then charged for 30 second with 300 A current and again cell is allowed to rest. Again after short resting period, cell is discharged with same 5C current for 60 seconds. After discharge, charge-discharge sequence was repeated. This whole measurement sequence was repeated nine times. Values of *OCV* were measured for wide range of *SOC* from 100 % to 8 %. Determining of parameters for charging is however done only in *SOC* range of 10 % to 90 %. For the measured battery, the voltage curve as a function of *SOC* is shown in Fig. 22.

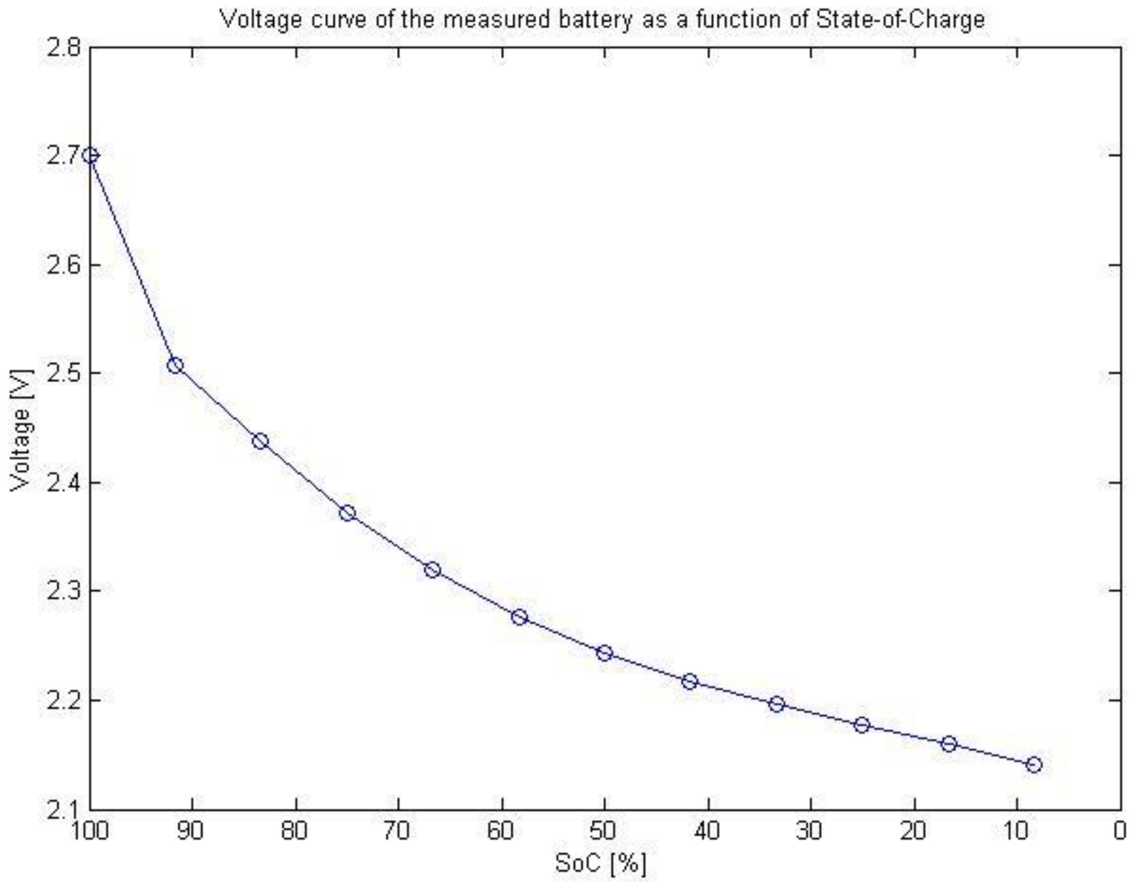

Figure 22. Voltage curve as a function of State-of-Charge for the measured battery during discharge.

State-of-Charge of the battery cell during the measurement test was calculated by using current integration (equation 2). As earlier mentioned, a decision was made that 2,7 V indicates maximum *SOC* of the battery for safety reasons. Same principles apply for the lower limit. Measurement points in Fig. 22 are indicated with round circles. All of the calculations for following parameters are calculated at same points.

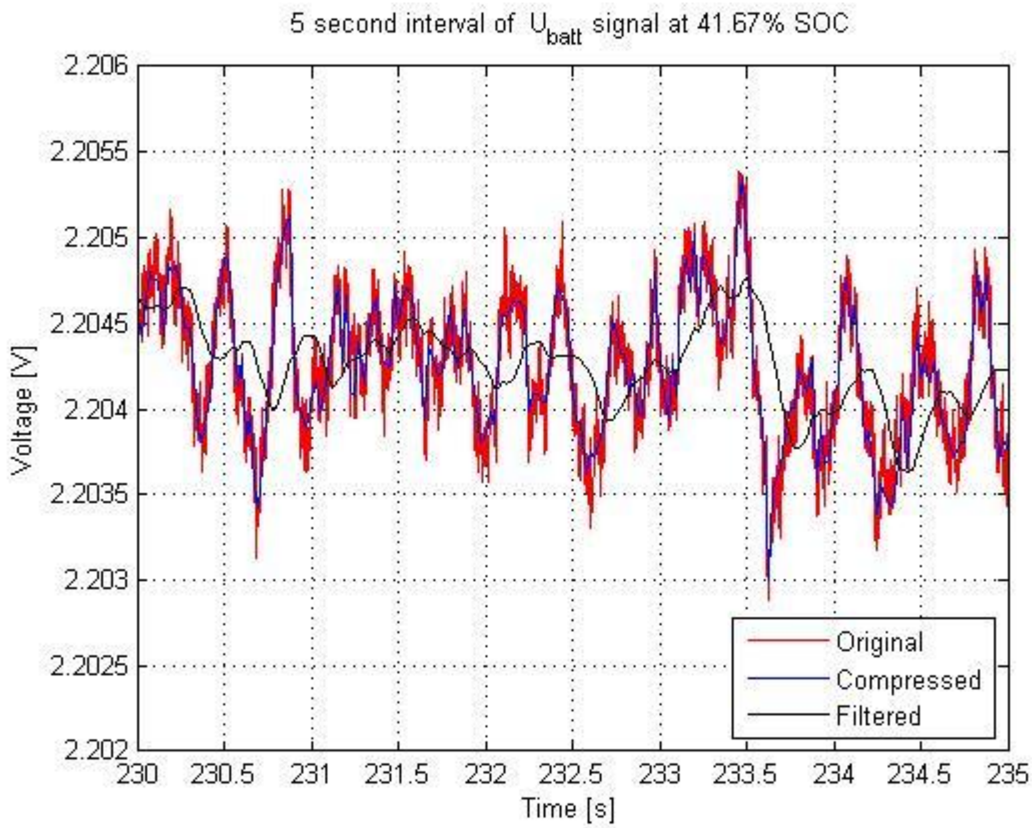

Figure 23. 5 second interval of measured data. Original measured data is red line, compressed data is blue line, and filtered and compressed data is black line.

The length of the measurement is 650 seconds during which data were measured for 2600001 data points (4000 data points / second). Data is imported in Matlab-program where it is compressed and filtered so that it is easier to analyze. Compression and filtering causes a little error compared to original measuring, but it can be neglected because there are also errors from measurement environment. Errors from environment cause voltage varying.

Example of data manipulation is shown in figure 23. Errors between compressed and original data seem to be acceptable. At given time interval in Fig 23. error between original and compressed data is about 0.0005 V (about 0.02 %). Little delay is added to the signal due to filtering. Filtering is done using Matlab's *filter*-function with length of 10. Error between compressed and filtered signal at given interval is about 0.001 V (about 0.05 %) at most. Whole compressed and filtered signal at same *SOC* is shown in Fig. 24.

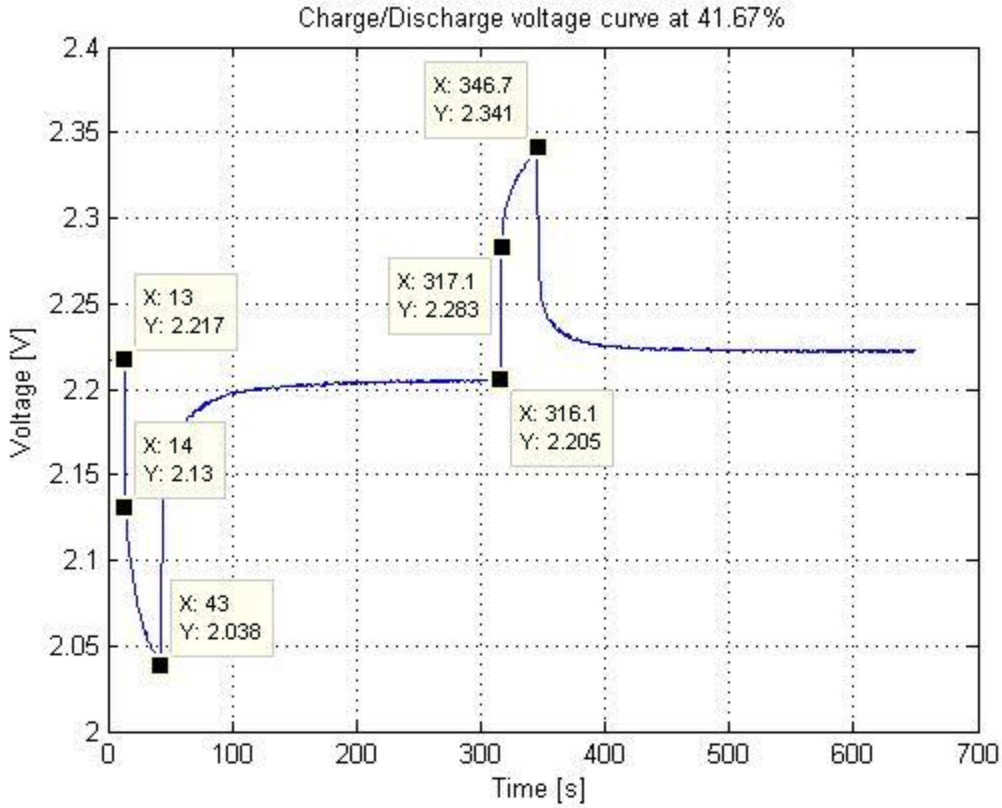

Figure 24. Measured voltage at 41.67% SOC.

As mentioned earlier, internal resistance R_i can be calculated from charge/discharge curves. Figure 24 presents one discharge/charge pulse at approximately 41.67 % *SOC*. R_i for discharge is calculated with equation 8 from linear voltage drop from discharge pulse between points a (X=13) and b (X=14).

Total resistance R_{tot}, combining both internal resistance and resistance of RC-branch, R_1, is from voltage drop between points a and c (X=13 and 43 respectively) [39]. Resistance values for charge pulse can be calculated using same approach. Parameters for both charge and discharge are calculated for all measured *SOC* points. At 100 % *SOC* only discharge parameters are calculated.

Points, which are used for parameter calculations are manually selected. That affects accuracy of the model parameters and calculations naturally.

Capacitance of equivalent circuit can be calculated for discharge and charge from discharge/charge pulses [23], [31]. Capacitance is calculated only with long time constant. Using model including only one capacitor makes it only a rough approximation. Using two RC-branches with short and long time constants makes model a little more accurate. Method for defining parameters is based on [23] and [39].

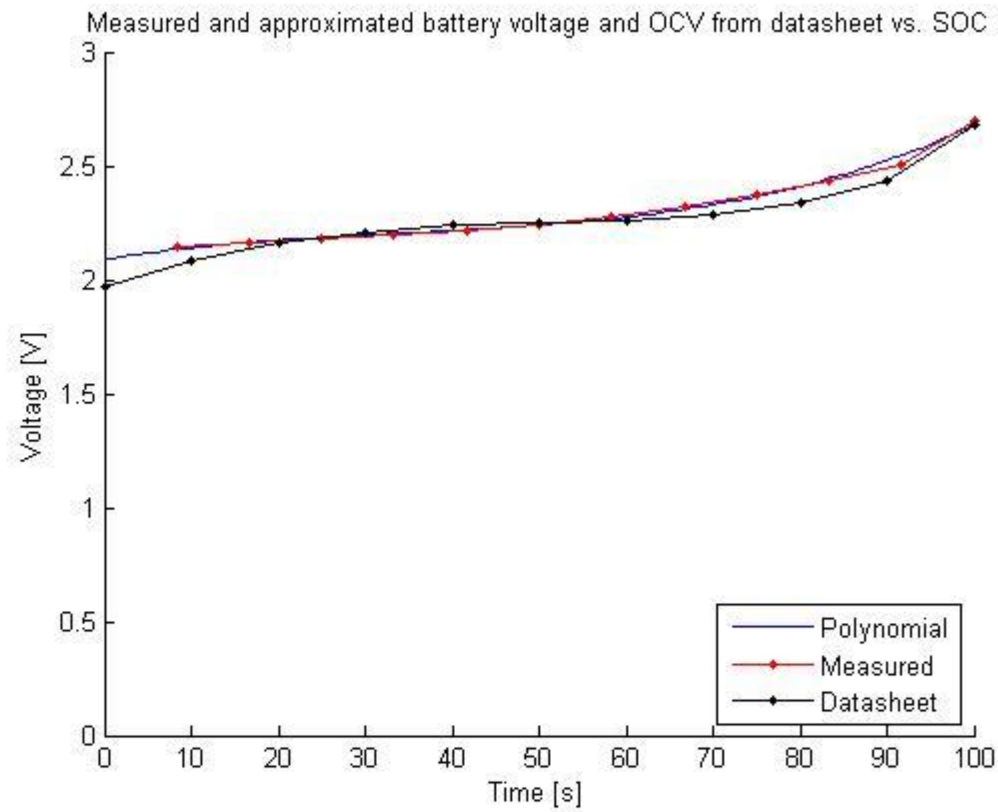

Figure 25. Open-circuit voltage comparison between measured and datasheet values as a function of *SOC*

From the figure above, it can be seen that measured values are approximately close to values of datasheet curves. There are minor differences between values at *SOC*s from 70 % to 85 % and at 8 %. This can be explained by age of battery and errors during measuring. During measurements, voltage values from 8.33 % to 0 % *SOC* were not measured, so for the model voltage curve at that interval is approximated based on modeled *OCV*-function.

Measured *OCV* curve is found to seem similar to third degree polynomial function. Voltage data points as function of *SOC* are fitted to third degree function with Matlab's *polyfit*-function. Following polynomial fit function was found for *Uocv*

$$U_{OCV} = 1.1982z^3 - 1.226z^2 + 0.61348z + 2.0898, \tag{14}$$

where *z* is *SOC* as decimal between 0 and 1. Coefficients for all of the parameters of the model are given in Table 3. It is needed to be taken into account that *OCV* measurement is done during discharging of the battery cell.

Measurement data was used to calculate parameter values for the battery model. First discharge resistance parameters (figures 26-28) are defined and fitting curves are built based on measurements for each parameter. Then same procedure is repeated for charge resistances (figures 28-30) and finally for both discharge and charge time constants (figure 32) which are used to calculate capacitance (figures 33-34) for both discharge and charge. For simplicity, for internal resistance, R_i is used as instead of R_{series} and for resistance of RC-branch, R_1 is used as instead of $R_{transient}$. For capacitance, C_1 is used as instead of $C_{transient}$.

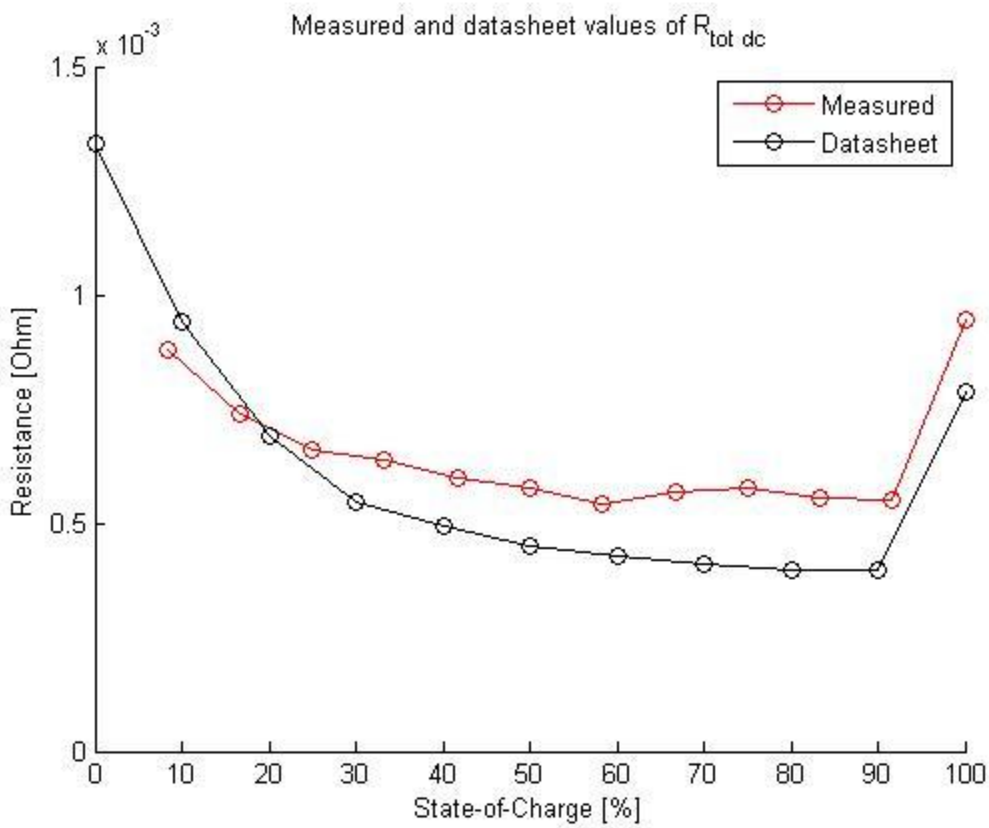

Figure 26. Measured total discharge resistance compared to datasheet resistance as a function of *SOC*. Red line is measured resistance and black line is resistance from datasheet.

Total discharge resistance, $R_{tot\_dc,}$ is presented in Fig. 26. There are differences between measurement (red line) and datasheet value (black line). Differences at values from 0 % to 20 % *SOC* can be explained by measuring and data filtering errors. Differences at 20 % to 100 % *SOC* come from battery ageing and the same errors described earlier. However, nature of measuring curve is slightly same as in datasheet curve, so some kind of approximation can be done.

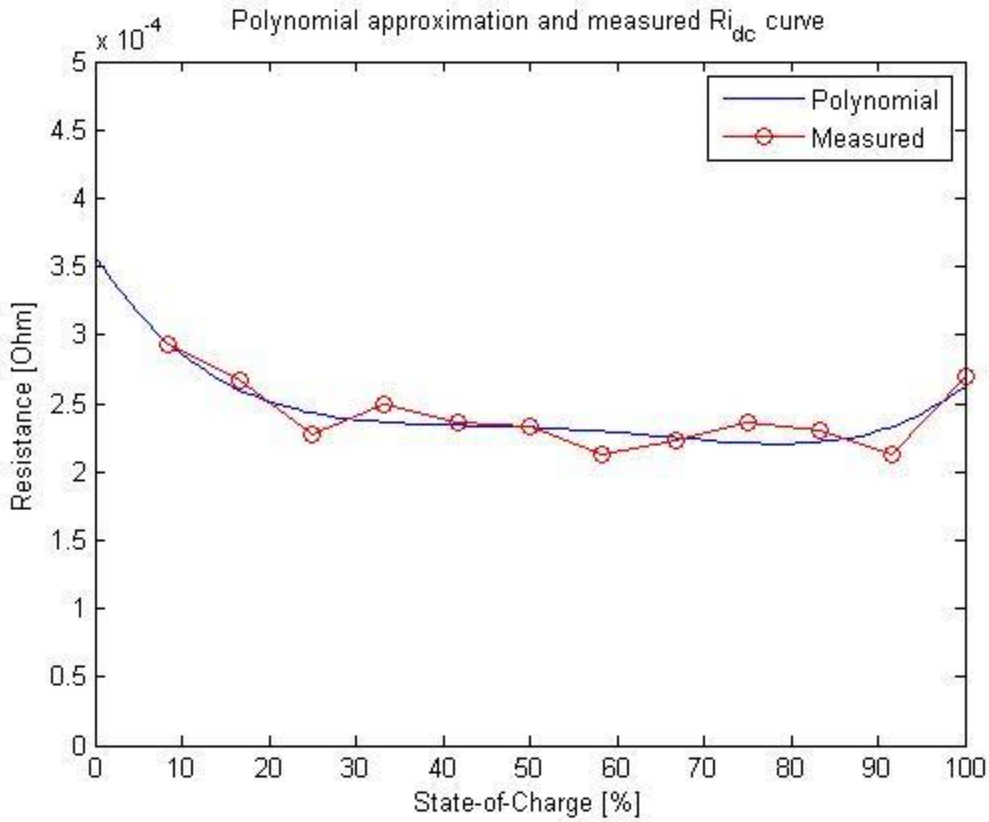

Figure 27. Internal discharge resistance of the battery as a function of *SOC*. Red line is resistance calculated from measured data and blue line is polynomial resistance approximation curve.

Internal discharge resistance, R_{i_dc} is presented. Red line is resistance value calculated from measurements. There are small errors between measurements and polynomial estimation curve but average seems to be close so it can be concluded that polynomial estimation built for model is a good approximation for actual internal discharge resistance.

Polynomial estimation curve is a fourth degree polynomial. Coefficients of the polynomial function are given in Table 3.

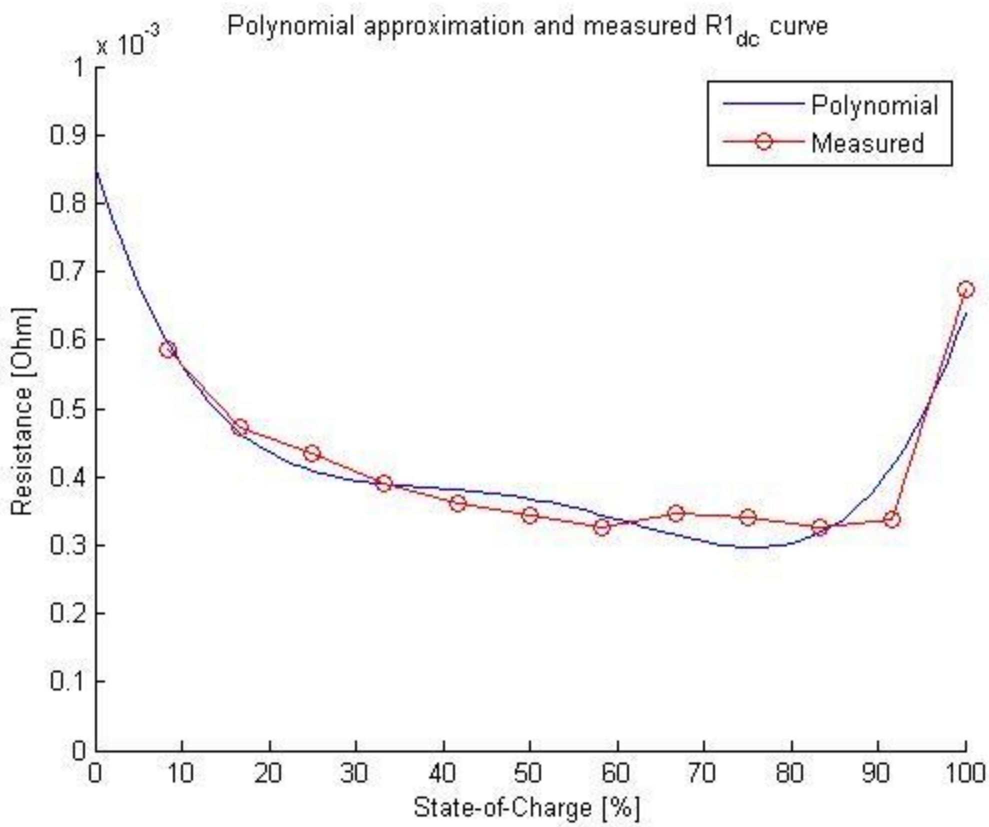

Figure 28. Discharge RC-branch resistance of the battery cell as a function of *SOC*. Red line is measured resistance and blue line is polynomial fitted approximation curve

In Fig. 28 discharge resistance of RC-branch is presented. Resistance R_{1_dc} can be calculated as described in chapter 3.3.6.

A fourth degree polynomial fit is built for R_{1_dc} based on measured values. Polynomial approximation curve seems to follow nature of the measurement curve. However, there are errors at *SOC* interval 65-80 % and at 85-95 %.

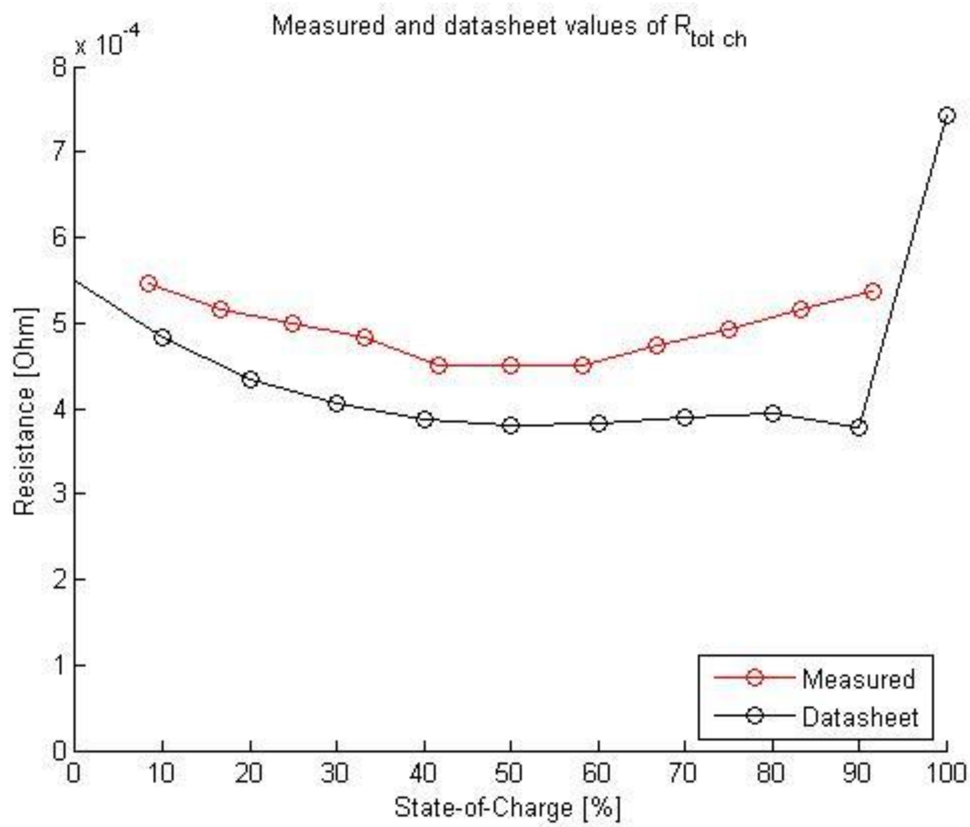

Figure 29. Measured total charge resistance compared to datasheet resistance as a function of *SOC*. Red line is measured resistance and black line is resistance from datasheet.

In Fig. 29 total charge resistance, R_{tot_ch}, is presented. Red line presents measured values which are calculated from measurements same way as total discharge resistance. Black line is resistance from datasheet of the battery. Measured values are higher than datasheet values at all values of *SOC*. This can be explained by ageing of cell and errors caused by measuring and data filtering. Rapid change of datasheet resistance curve at 90 % *SOC* is due to data points used to draw the curve. Curve is drawn using 11 data points (10 % increases) between 0-100 % *SOC*. Increase of resistance from 90 % to 100 % *SOC* can be explained by battery chemistry.

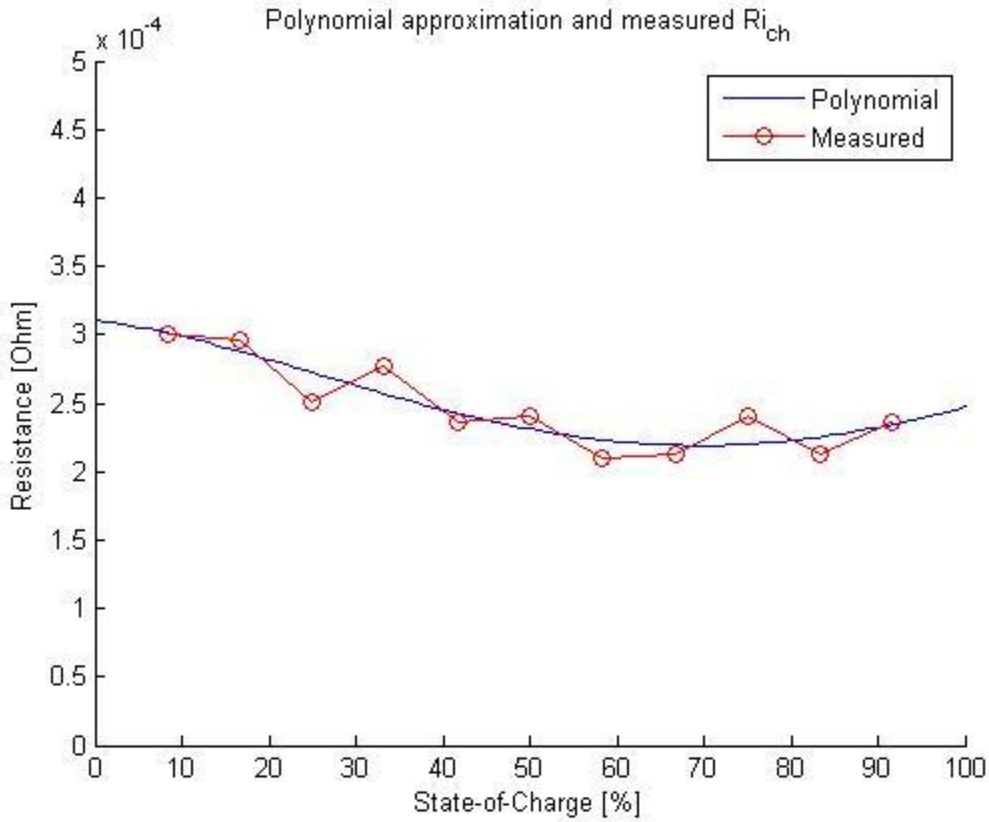

Figure 30. Internal charge resistance of the battery cell as a function of *SOC*. Red line is resistance calculated from measured data and blue line is polynomial resistance approximation curve.

In Fig. 30 internal resistance, R_{i_ch} of the battery cell for charging is presented. Resistance is calculated from measurements. It is calculated same way as internal discharge resistance but when the battery cell is charged.

A fourth degree polynomial fit function is built based on measured resistance values. Built function seems to nicely follow the measured values.

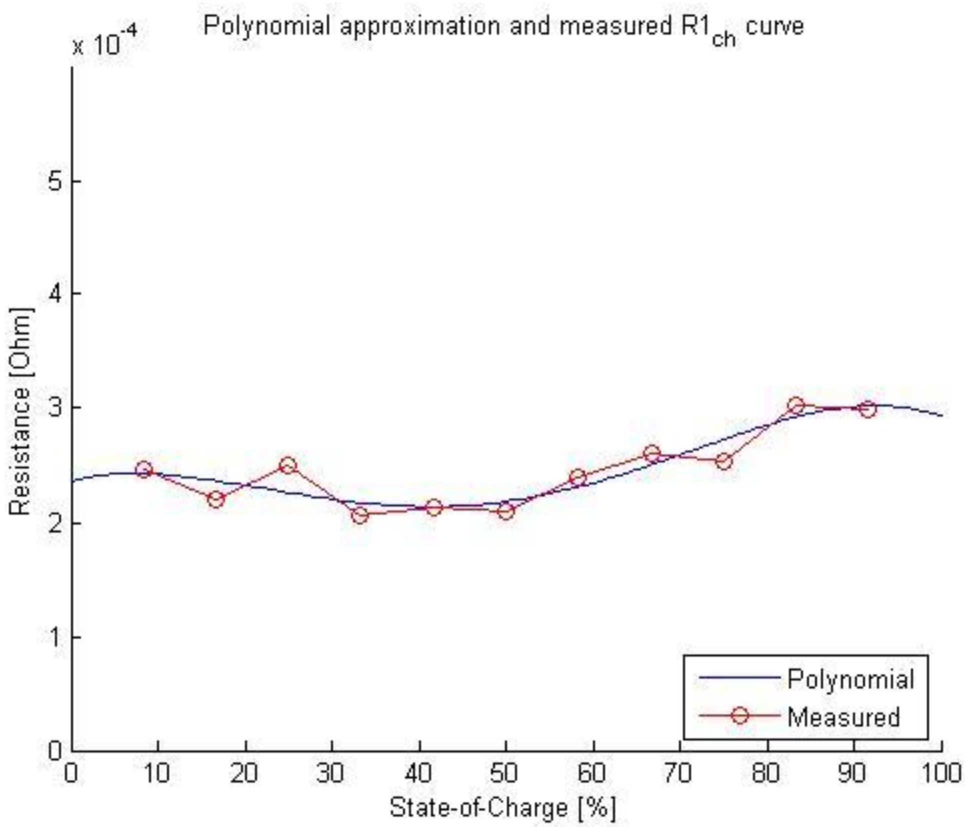

Figure 31. Charge RC-branch resistance of the battery cell as a function of SOC. Red line is resistance calculated from measured data and blue line is polynomial resistance approximation curve.

In Fig. 31 RC-branch resistance, R_{1_ch}, for charging is presented. It is calculated in way corresponding to discharge R_{1_dc} resistance.

A fourth degree polynomial fit function is built for R_{1_ch} in same way as R_{1_dc}. Polynomial estimation seems to follow nature of R_{1_ch} quite nicely, so it is a good approximation.

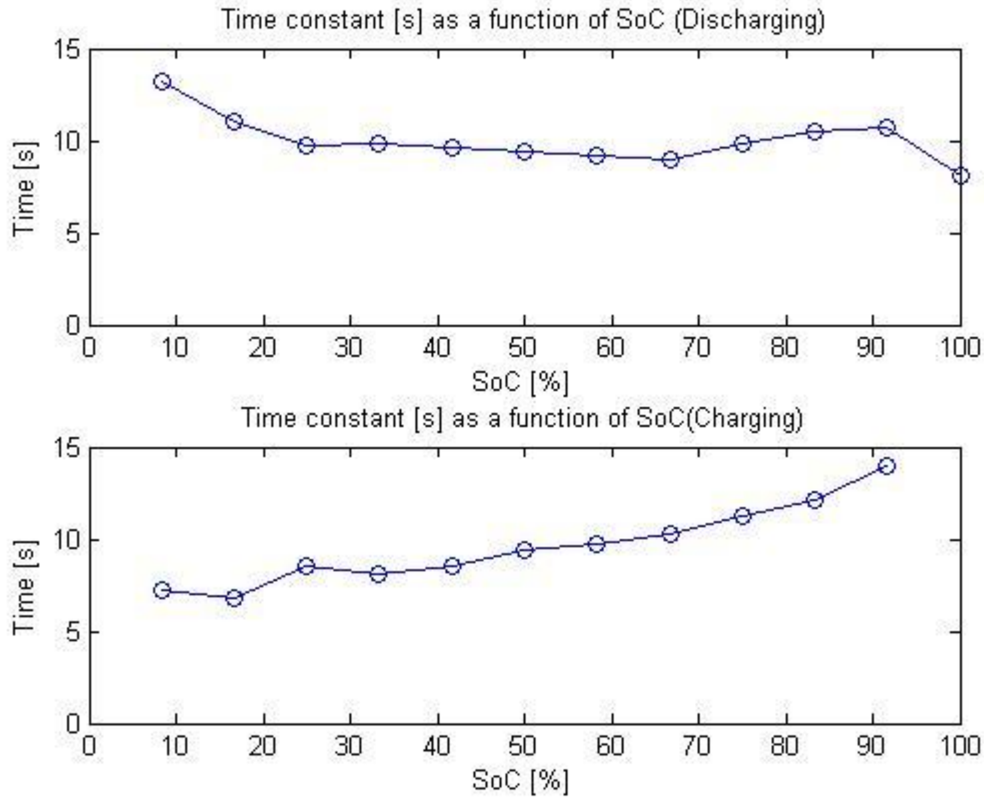

Figure 32. Time constants for discharging (upper) and charging (lower).

Time constants for both discharging and charging are presented in Fig. 32. Values are calculated with the method mentioned in chapter 3.3.6. Time constants are used to calculate capacitance values. Also resistance of RC-branch, R_1, is needed for calculations. Measured capacitance values for both discharge and charge are shown in following figures (30-31).

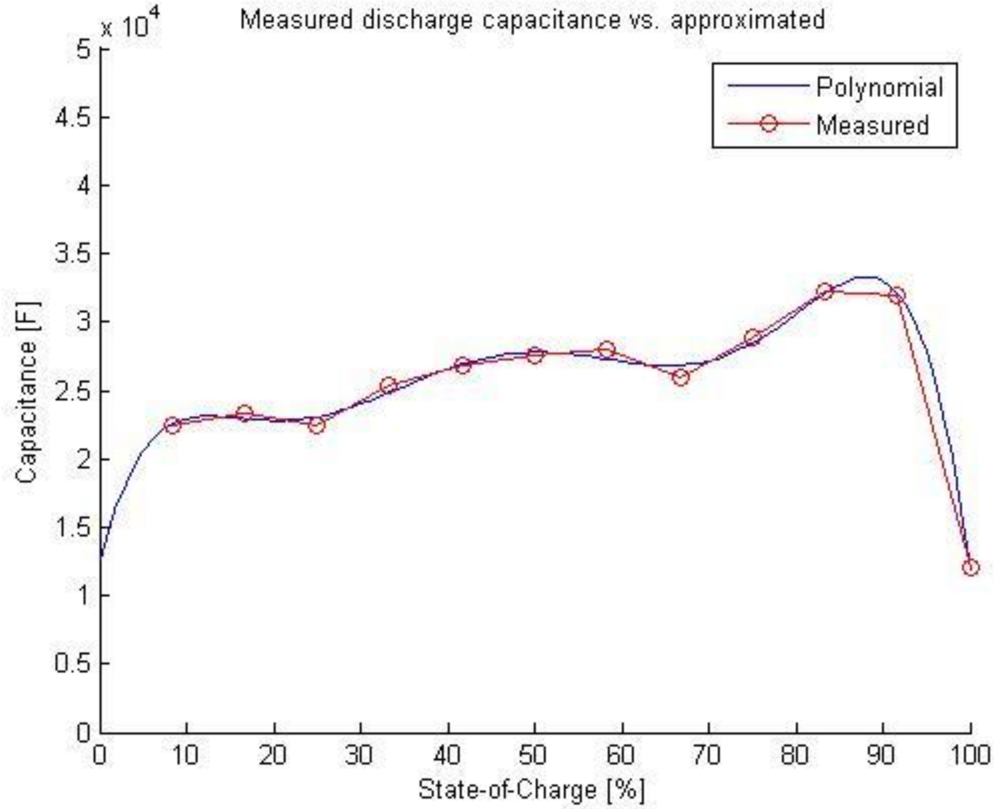

Figure 33. Equivalent capacitance of RC-branch when discharging. Capacitance calculated from measured data is red line and polynomial fit is blue line.

In Fig. 33 discharge capacitance C_{1_dc} value is presented. Red line is C_{1_dc} based on calculations with measured values of R_{1_dc} and discharge time constant. Blue line is approximation value that is calculated from measured values.

Sixth degree polynomial fit for discharge capacitance is calculated based on measured values. Shown polynomial function seems to follow measured capacitance value from measured time constant and R_1 quite accurately, and end-of-discharge (from 10 % to 0 %) seems to be same as in literature [23].

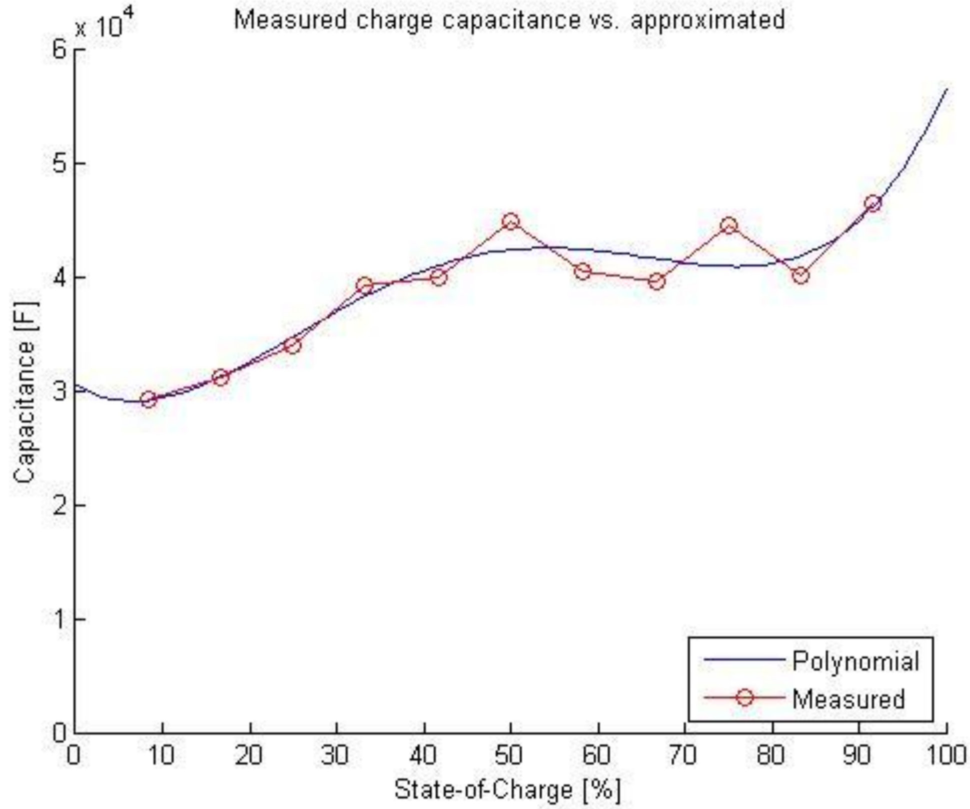

Figure 34. Equivalent capacitance of RC-branch when charging. Capacitance calculated from measured data is red line and polynomial fit is blue line.

Fig. 34 presents capacitance of RC-branch, C_1, for charging. Calculated capacitance value with measurement values of R_{1_ch} and charge time constant is red line. A fourth degree polynomial fit function for charge capacitance, C_{1_ch}, is blue line.

The fact that all measured values are limited to 8.33-100 % *SOC* for discharging and to 8.33-91.67 % *SOC* for charging has to be taken account when modeling the battery. Modeling results that are beyond those *SOC* limits cannot be compared to measurement results.

Coefficients of fitted curves are presented in Table 3. Coefficients are used in the battery model to be able to model performance of the battery cell at different *SOC*s. There are some errors when fitted curves are compared to measured curves. This must be taken into account when analyzing results with the modeled battery cell.

Table 3. Coefficients for polynomial functions used in battery model. Coefficients can be used with the same principles as with U_{OCV} in equation 14.

Value\CF (degree)	a6	a5	a4	a3	a2	a1	a0
U_{OCV}	-	-	-	1.1982	-1.226	0.61348	2.0898
R_{i_dc}	-	-	0.00171	-0.00369	0.00285	-0.00097	0.00036
R_{1_dc}	-	-	0.00935	-0.01866	0.01314	-0.00405	0.00085
R_{i_ch} (*10^-3)	-	-	-0.2627	0.7436	-0.4643	-0.0799	0.3106
R_{1_ch}	-	-	0.00482	-0.00899	0.00585	-0.0015	0.00034
C_{1_dc}	-5605200	15940000	-17238000	8852300	-2202100	252300	12446
C_{1_ch}	-	-	411090	-749740	409700	-45064	30450

4.2. Verification of the presented battery model

Measured data from battery is compared to modeled values. This way parameters of the battery model can be verified to be in good relation to actual battery. Simulink battery model used in this paper is shown in Fig. 35. Verification is done with 50 % and 75 % *SOC* values.

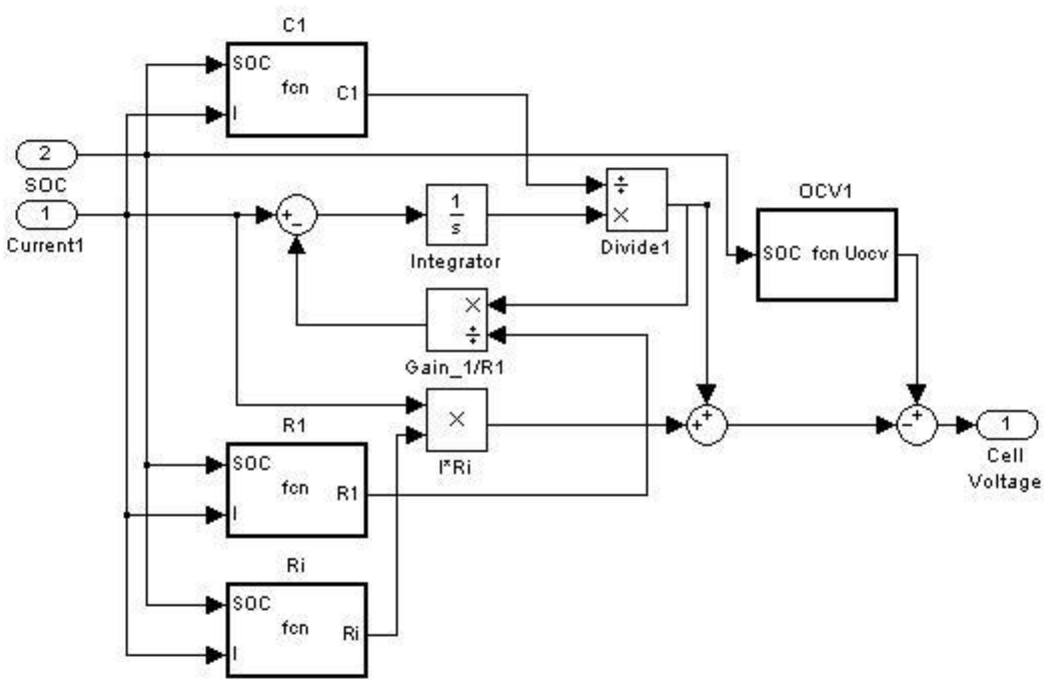

Figure 35. Simulink-model of the battery cell. Blocks C1, Ri and R1 contains built polynomial functions.

In Fig. 35 cell model built in Simulink is presented. There are two inputs: current and *SOC*, and one output: cell voltage, U_{batt}. Current input is used to detect whether cell is discharged (I>0 A) or charged (I<0 A). Cell model parameters, R_{i}, R_1 and C_1 are calculated with polynomial functions given earlier. Value of each parameter depends on *SOC* and current direction. Sums of voltage losses at different parts of the cell are calculated with sum-blocks. Finally, total voltage loss is extracted from U_{OCV} and as a result, U_{batt} is got.

The battery model is verified by comparing measured voltage curve to voltage curve of cell model at different *SOC*. First, initial *SOC* is set to be 50 % and then current used in measurements (Fig. 21) is used as an input to system. Given voltage curve is then compared to measured voltage curve at same *SOC*.

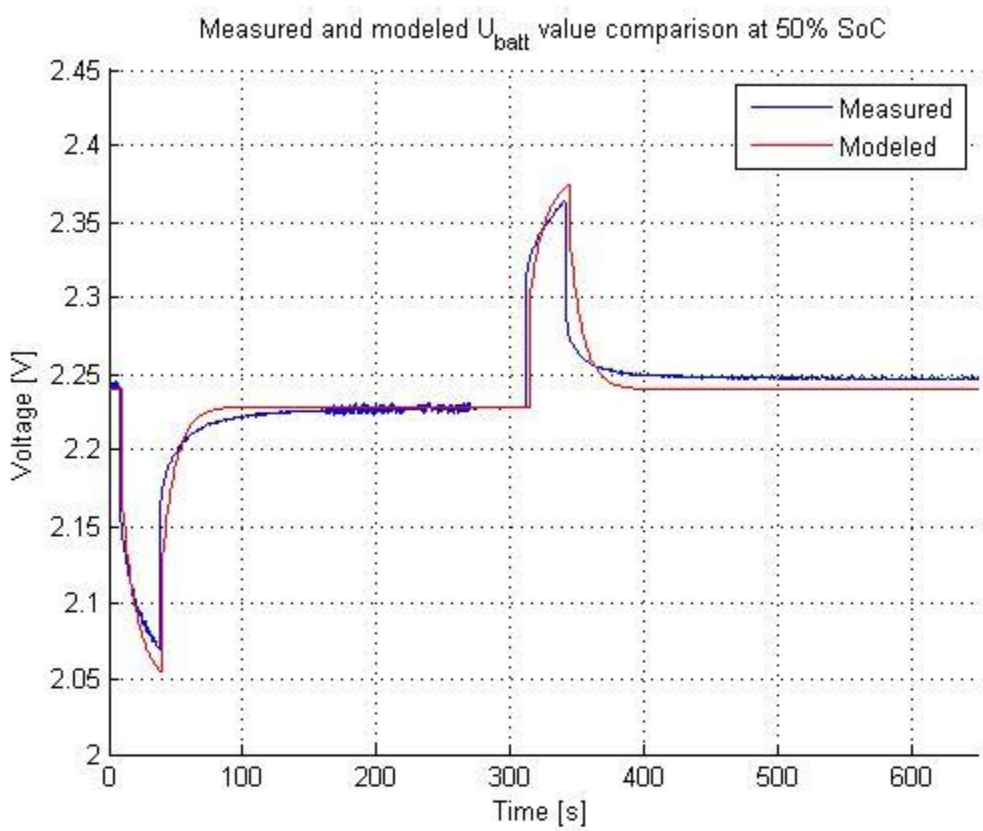

Figure 36. Comparison of measured and modelled battery voltage, U_{batt}, as a function of time. Measured U_{batt} is blue line and modelled battery voltage is red line.

Voltage of the modeled battery cell is quite as expected. In the model there is only one RC-branch used, which can be seen from discharge and charge slopes. More accurate curve could be achieved if at least two RC-branches were used. In this paper only one RC-branch is used, which leads to only one time constant to be used. Using of two time constants allows describing of short and long transients. With short transients time constant beginning of slope would be faster, and with long transient time constant end of slope would be slower.

However, by using only one RC-branch it seems that the voltage curve is quite close to the wanted curve. Peak voltage loss is higher for both discharge and charge sequence which can be explained by an error from approximation of R_1. Voltage error at the end of pulse is caused by measurement errors. It seems that voltage at the end of testing pulse is higher than at the beginning of such test pulse. This might have been caused by either longer charging sequence or higher charging current.

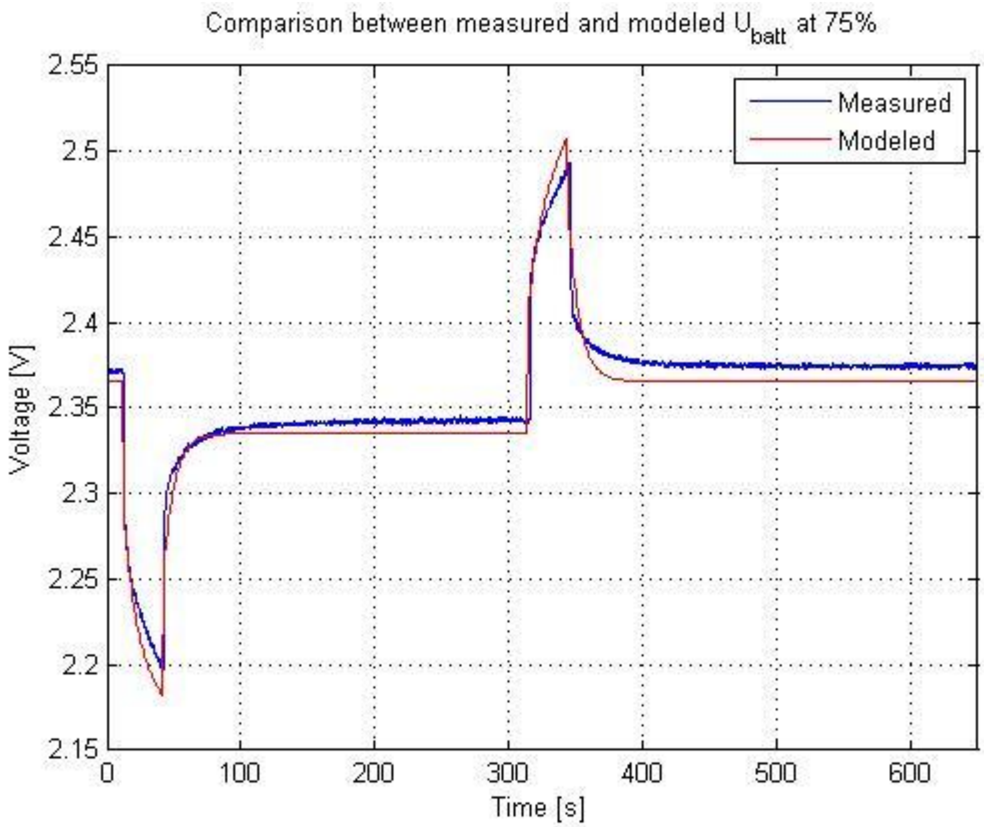

Figure 37. Measured battery voltage as a function of time at 75% *SOC* compared to simulated battery voltage as a function of time. Measured battery voltage is blue line and simulated battery voltage is red line.

Same comparison that is made at 50 % *SOC* is done also at 75 % *SOC* (Fig. 37). There are small differences between measured and simulated battery voltages at relaxing period voltage. However, this error is about 0.01 V at maximum, which equals to about 0.5 %. Measured battery voltage at the end of test is higher than at the beginning the same way as at 50 % *SOC* test meaning that error at the end of test is higher than it should be. Voltage curve when charging/discharging the battery is acceptable, but again using only one RC-branch causes change of voltage drop/rise to be slow at beginning of the current pulse and faster at end of the current pulse. Voltage curve peak values are also higher at simulated curves compared to measured values. That is caused because only one RC-branch is used. The resistance value of RC-branch is higher with used method than resistance of first RC-branch when multiple RC-branches are used.

After verification, more complicated current profile is generated and it is used as input to battery model. Battery voltage errors of the model compared to actual battery should be taken into account when results are studied. The battery in this case consists of only one battery cell.

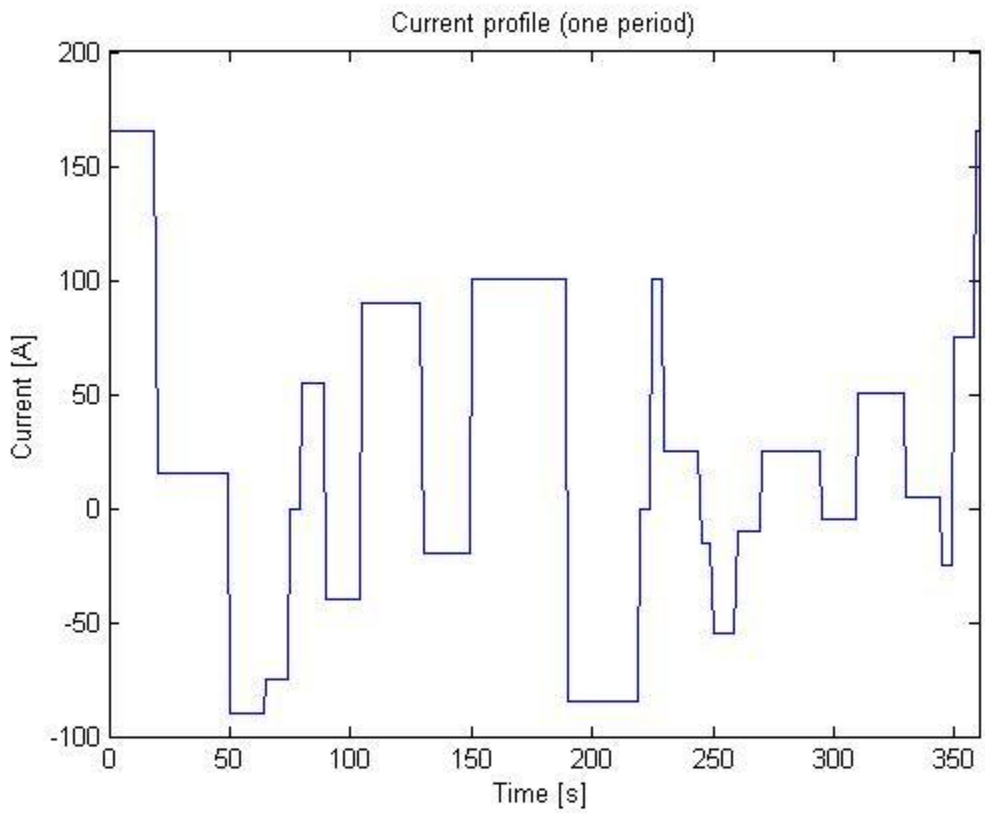

Figure 38. Generated current profile for simulation of battery model.

In Fig. 38 one period of test current is shown. Current signal is built so that it would have little varying, short and long current peaks. The length of one simulated period is 360 s. The length of the whole simulation is one hour and consists of totally ten periods. When the current is positive, it means that current is drawn from battery, which can be presumed in EV use to be accelerating, driving uphill etc. Negative current is regenerative current (braking, downhill etc.) which charges the battery.

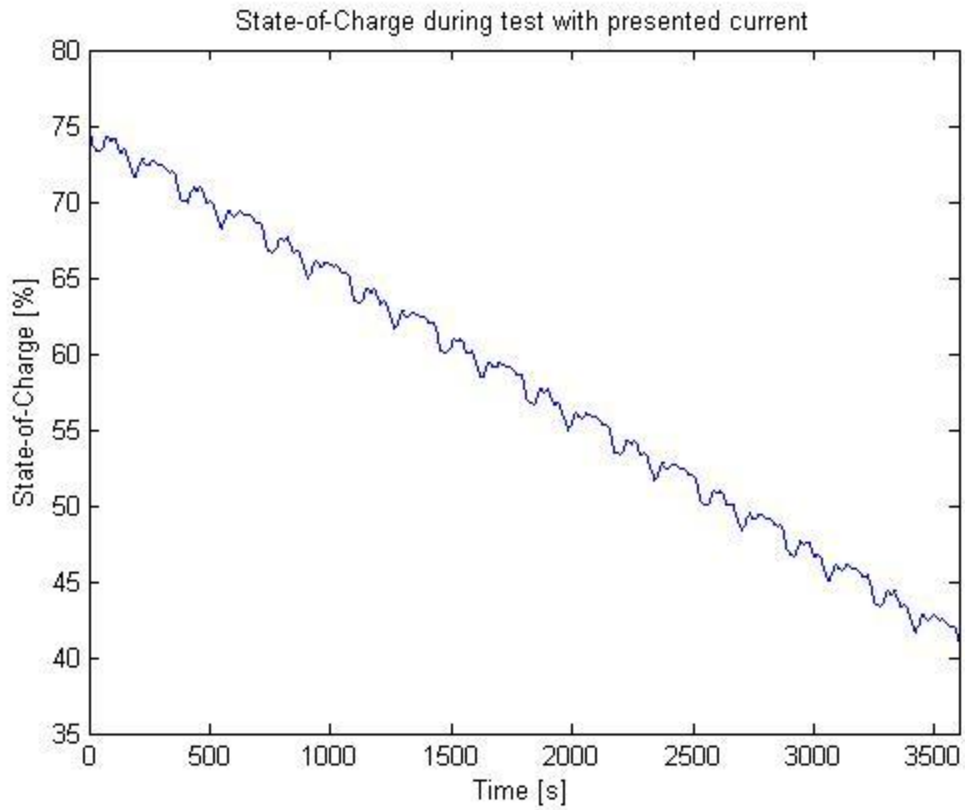

Figure 39. **State-of-Charge of the battery during simulation with the generated current profile.**

State-of-Charge of the battery during simulation is shown in Fig. 39. State-of-Charge is set to 75 % before the simulation is started. *SOC* is calculated with current integration. At the end of simulation *SOC* is at 41 %.

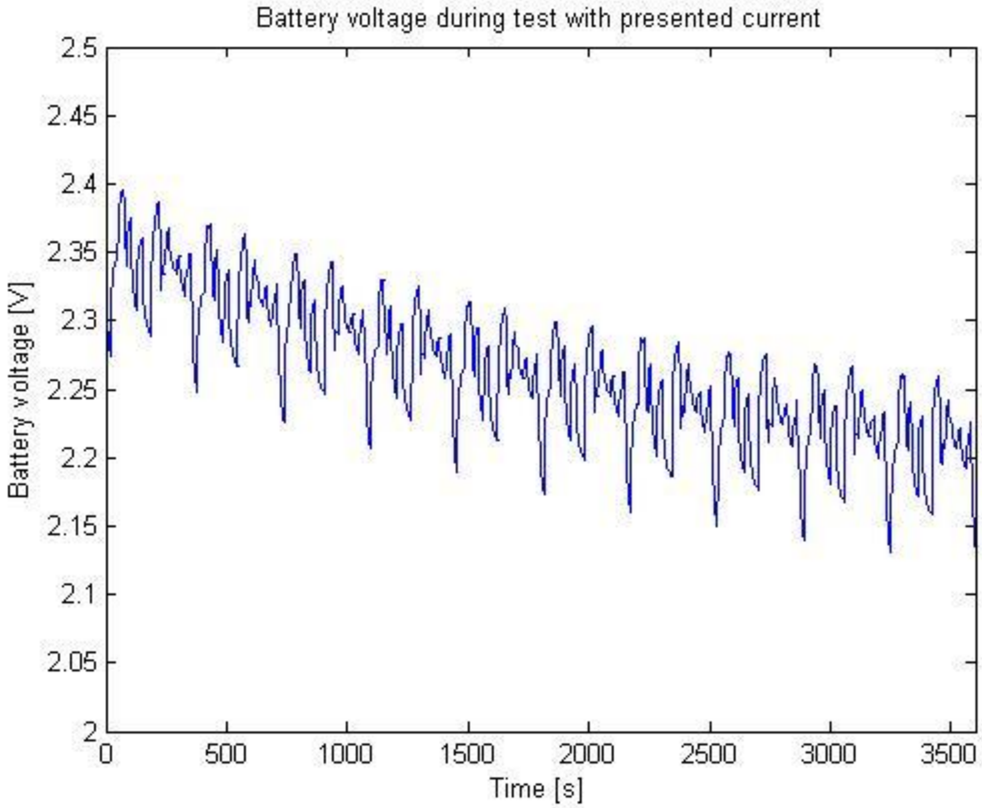

Figure 40. **Battery voltage, U_{batt}, with generated current profile.**

In Fig. 40 battery voltage, U_{batt}, during simulation with generated current profile is shown. Average voltage drop seems to be decreasing slower during the test. This is resulted by resistance parameters being almost constant during test *SOC* range. Voltage peaks during the test differ a little, so the presented model works well considering the fact that the model consists of only one RC-branch.

5. EXTENSIONS OF THE BATTERY MODEL

As mentioned earlier, a battery model with only one RC-branch does not give very accurate results. This is due to a fact, that given time constant of one RC-branch is somewhat an average of high and low transients [23]. Voltage curve at capacitive parts of slope with one RC-branch is somewhat an average when compared to higher order models.

5.1. Modeling of battery management system

The battery model is made more advanced by adding a current limiting element to the model. The limiter follows the *SOC* of the battery cell and limits current to ±5 A when *SOC* is too high (95 %) or too low (5 %) to model safety concerning overcharge and overdischarge. With this block actual overcharge/-discharge management of BMS is modeled simply. For example, *DOD* of one load cycle of EV could be 80 % [10] and in HEV use charge limits are typically set between 40-80 % [10]. This way the battery voltage cannot reach values that are too high or too low which could harm battery pack. The method used in this thesis will not deny chances to fully charge (or discharge) the battery.

Such method in real BMS could be done by using alerts in user-interface. Risk of overcharge could be avoided by using brake resistor, instead of charging the battery energy is consumed in brake resistor. Risk of overdischarge could be avoided, for example in automotive applications, by using alerts of low SOC.

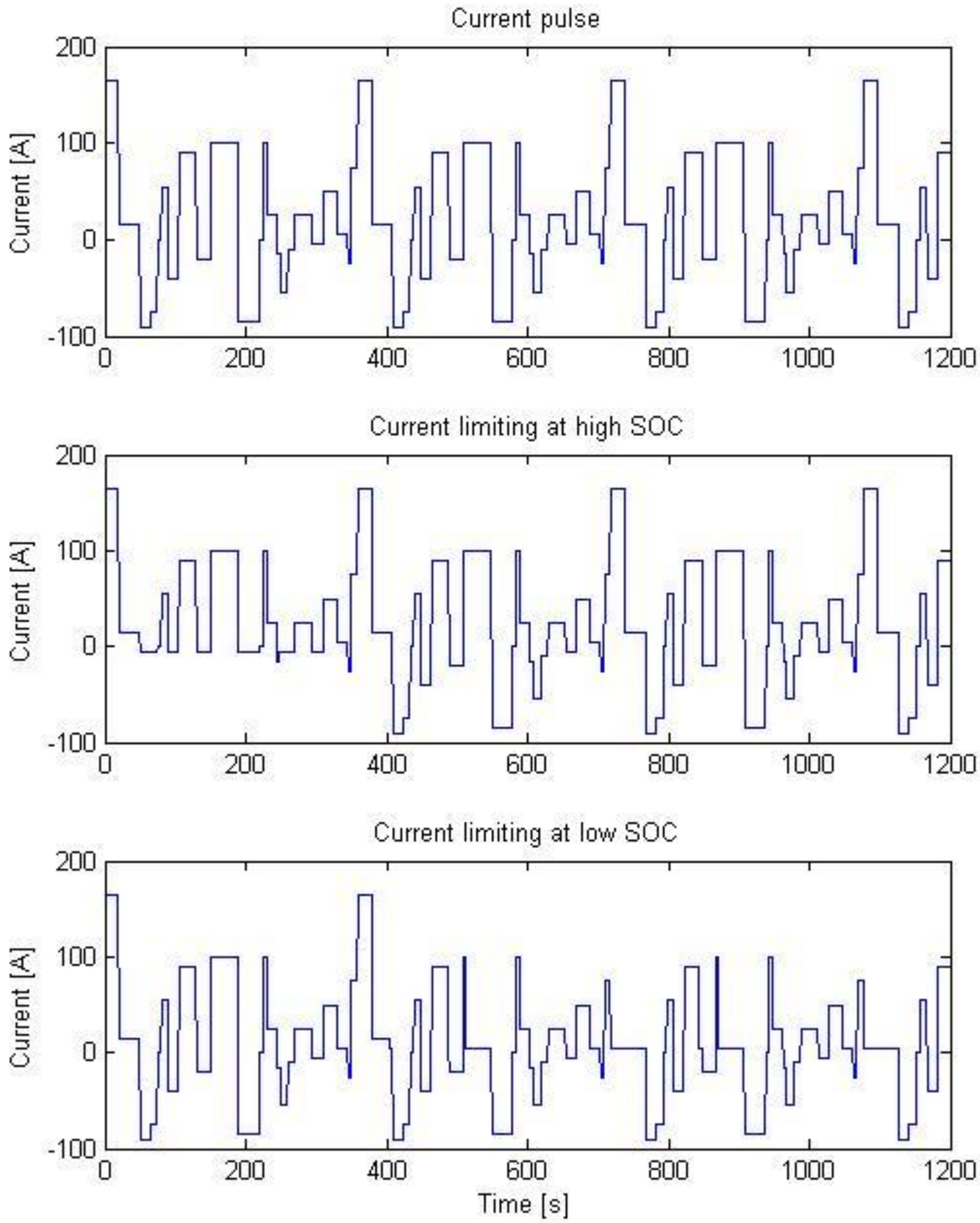

Figure 41. Current pulse (upper) used during current limiter simulation. Middle picture is current when *SOC* is at higher level and the lowest picture is current when *SOC* is at lower level. When reaching used safety limits of *SOC* (95% for high *SOC* and 5% for low *SOC*) battery is not allowed to charge or discharge with high currents.

In Fig. 41 current pulse of the current limit simulation, current at high *SOC* and current at low *SOC* are presented. From current at high *SOC* can be seen that current is limited to -5 A if *SOC* is higher than 95%. Current at low *SOC* is limited to 5 A if *SOC* is lower than 5%. Such limits are used to simulate the situation where BMS should inform user that battery is fully charged or discharged. However in this case, battery can be charged or discharged with small currents. Effect of the safety limits can be seen when limited current is compared to original current pulse after about 400 seconds. In real life applications however, the low and the high *SOC* limits should be more absolute limits that the battery cannot be damaged. Users of such applications must be warned for reaching low or high limits of *SOC.*

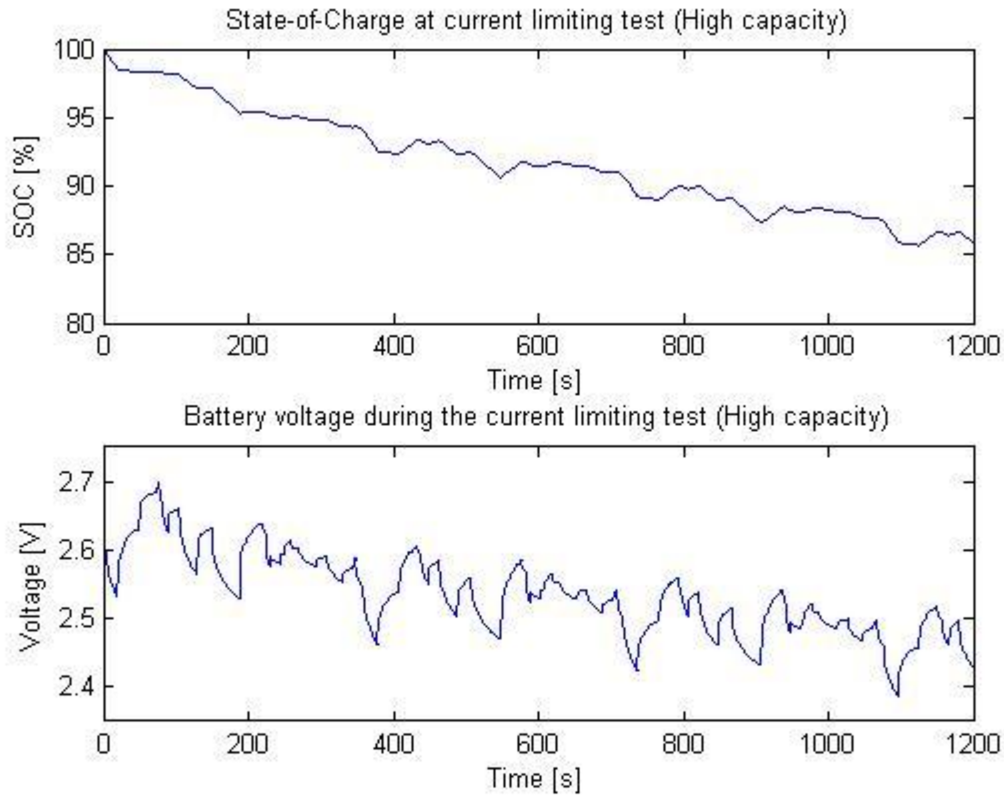

Figure 42. *SOC* (upper) and U_{batt} (lower) during current limiting test at high *SOC*.

In Fig. 42 *SOC* and battery voltage, U_{batt}, during current limiting simulation at high *SOC* are presented. As it is shown in upper picture, which *SOC* curve is presented, *SOC* does not increase greatly during first 400 seconds because of charge current limiting to 5 A. After *SOC* drops below 95% current limit is set off are again accepted and battery can be charged with higher currents.

In lower picture battery voltage, U_{batt}, is presented. Only minor changes are caused by current limiting to voltage curve, this can be seen when comparing voltage curve at 0-360 seconds to, for example, curve at time interval 720-1080.

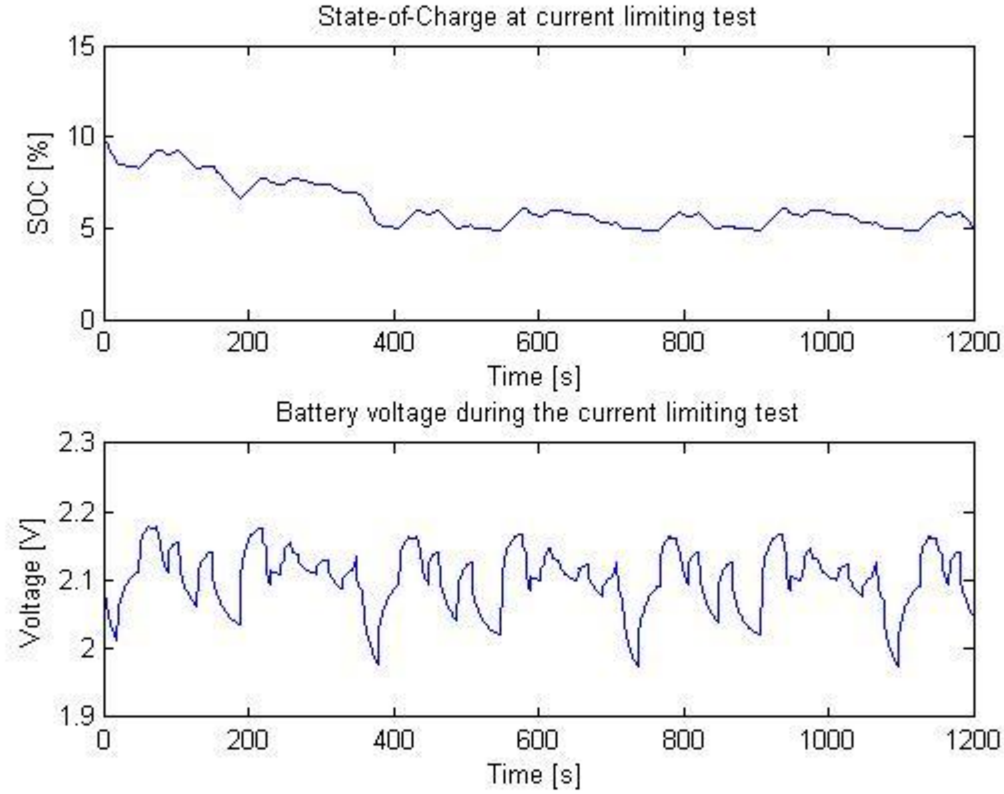

Figure 43. ***SOC*** **(upper) and battery voltage,** U_{batt}**, (lower) during current limiting simulation at low** ***SOC*****.**

In Fig. 43 *SOC* and battery voltage, U_{batt}, during current limiting test at low *SOC* are presented. At the beginning of test initial *SOC* is set to 10% of maximum capacity. Current limiting starts at about 400 seconds after beginning. It is shown in upper picture that *SOC* will not decrease below 5%. Again, there are no any notable differences at U_{batt} curve at different time intervals.

5.2. Modeling of multiple battery cells

Earlier tests in this thesis are modeled with only one battery cell. However, in high power applications power and capacity requirements are much higher than only one cell. For example, the battery pack used in Mitsubishi's i-MiEV has nominal voltage of 330V [9]. With the battery cell used in this thesis, for such nominal voltage, at least 122 battery cells are required to be connected in series. In this thesis battery pack is only simulated. For the test, 4 battery strings are connected parallel, hence combining total of 64 kWh energy and 488 battery cells. In this thesis, modeling of the battery pack is simplified by only multiplying battery voltage of single cell by the number of cells connected in series and multiplying initial maximum capacity by the number of cells connected parallel. Hence, voltage losses of the whole battery pack are assumed to be a sum of individual cells connected in series. Also, battery cells are presumed to be ideal, so there are no differences between capacities of individual cells. Voltage losses of connectors and cables between have been neglected.

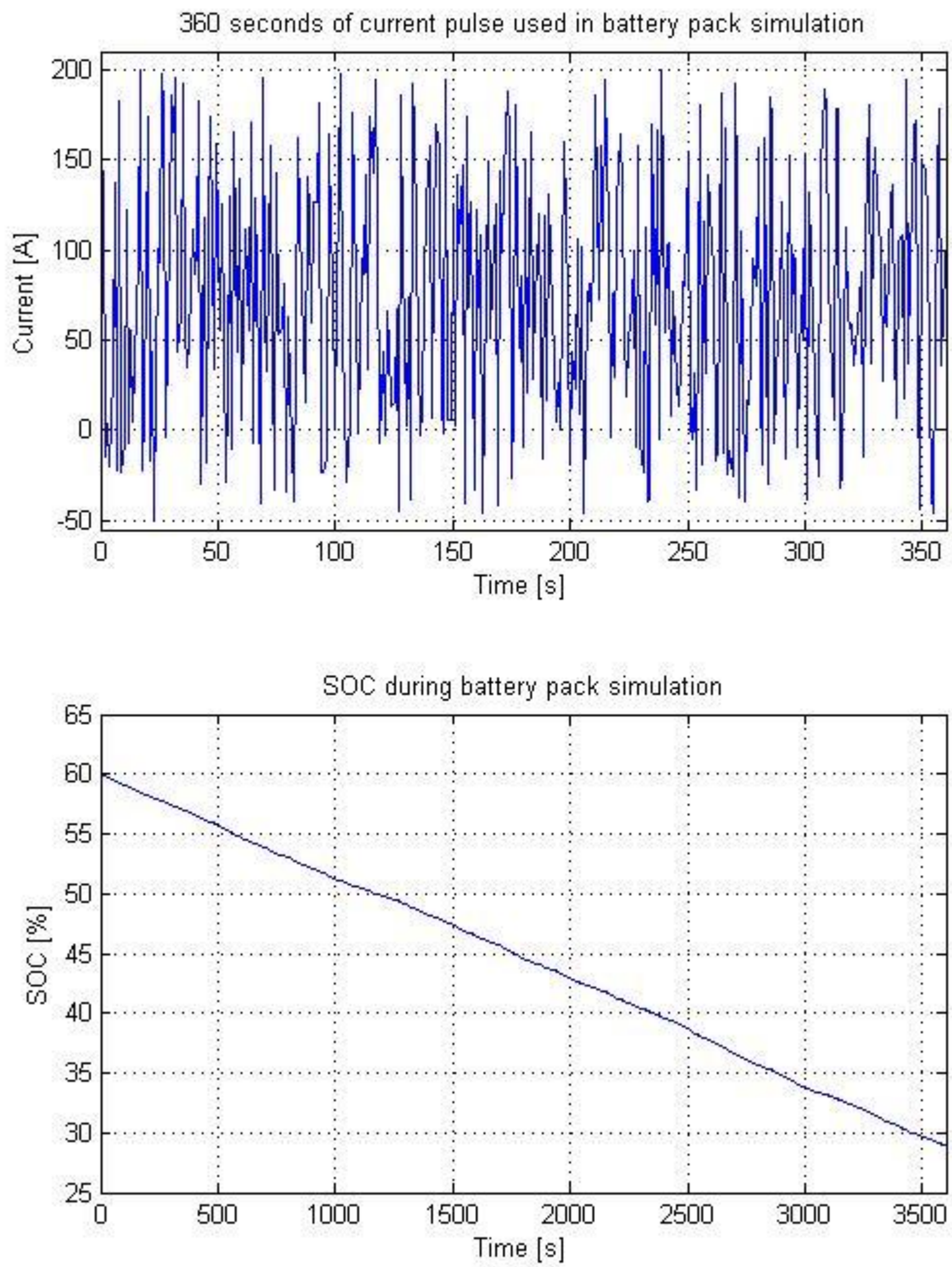

Figure 44. One period of current pulse and *SOC* during battery pack simulation

In Fig. 44, one 360 s period of current pulse of pack simulation is presented. Average current of the pulse is 74.7 A. Current pulse is randomly generated so, that maximum value of the current is 200 A and minimum value is -50 A. Total length of the battery pack simulation is 3600 seconds. *SOC* is set to 60% at the beginning of simulation and it decreases almost linearly during simulation to circa 29 %.

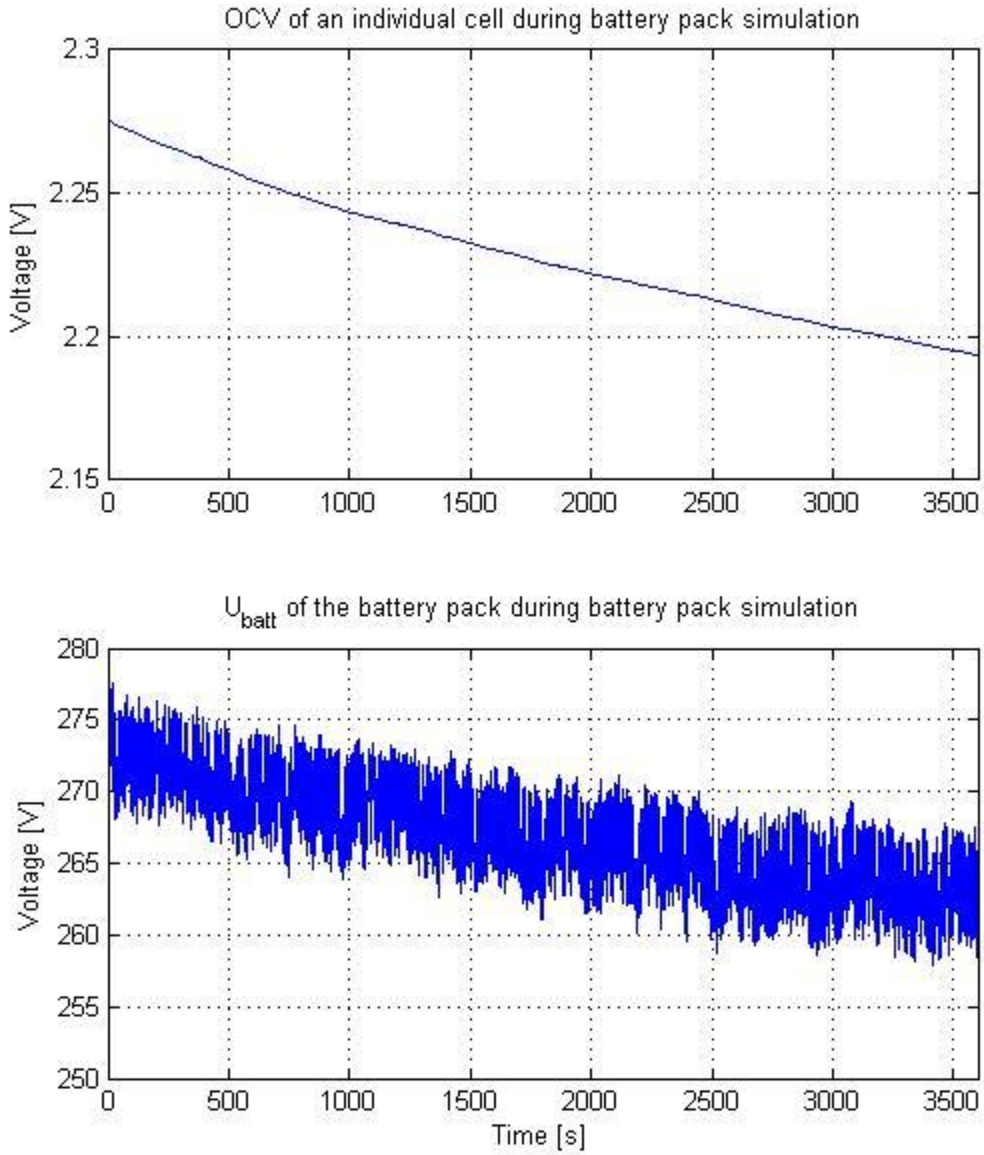

Figure 45. U_{OCV} and U_{batt} during battery pack simulation

In Fig. 45 *OCV* of an individual battery cell and battery voltage of the whole battery pack are presented. *OCV* decreases with *SOC* decreasing. There is a lot of varying in U_{batt} curve due to changes in current pulse. However, it is needed to be taken into account that impedance of the battery pack is kept as a sum of series connected battery cells. In real life battery packs impedances of individual battery cells are not equal and there are also some resistances from wires used in the battery system.

6. CONCLUSION

Battery becomes a crucial part of automotive vehicle when internal combustion engine is replaced with electrical engine. Electrical vehicle requires lots of energy which means that multiple battery modules are found in a battery pack. In order to receive better performance and improved safety of operation, a battery management system is required. The battery management system controls discharging and charging of the battery pack. Overcharging and overdischarging may cause irreversible damages to the battery, affecting performance of battery such as capability of providing higher output current. Abusing of battery might even lead to life threatening situations such as explosions. Important task of BMS is also to extend battery packs usable time by evening charge misbalances between battery cells.

In this thesis, principles and main objectives of battery management systems were studied and a simple battery model for battery management system was built. Parameters of the model were acquired from measurements with an actual battery cell, and then functions of *SOC* were built for each parameter for both charging and discharging. The battery model was built in Matlab/Simulink and few simulations were run. The first order battery model with one RC-branch was found to be a rough approximation of the real battery because there were notable differences. However, results with the battery model were still acceptable. However, better modeling results can be achieved if a model with more RC-branches is used.

The presented battery model was then improved by adding a current limiter to a model to describe some important functions of an actual BMS. Current limiter follows *SOC* of the battery, and if *SOC* reaches too high or low level, current limiter actives. Current is limited to ±5 A in 60 Ah cell depending on if *SOC* is high or low to prevent damaging the battery. Battery model is also improved to model large battery pack by simply multiplying voltage of one battery cell by the number of cells connected in series and multiplying maximum capacity by number of serial strings connected in parallel.

The first order battery model built in this thesis is not the best choice for applications that require higher level of accuracy. Applications in which the built model could be applied might be small power portable applications in which lack of accuracy is not a problem. Also simplicity of the model makes it suitable for such applications. The built model does not require an advanced calculation processor. For automotive applications more accurate battery model would be more suitable.

In research projects of LUT Energy main objectives are to improve energy efficiency and to reduce CO_2- and other emissions of different applications, such as electric vehicles and mobile working machines. Changing fossil fuels to regenerative energy storages, like batteries, reduces CO_2-emissions. Energy efficiency of such applications could be improved by designing proper battery management system. The battery modeling method presented in this thesis could be applied in such design. In advanced systems more complex battery modeling (2^{nd} or higher order) could be recommended. Temperature effects to the battery could be also included in the battery model. In future projects energy efficient cell balancing of the battery pack could be studied and possibilities to build some kind of adaptive BMS that could take into account ageing process of the battery and different battery chemicals.

7. REFERENCES

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