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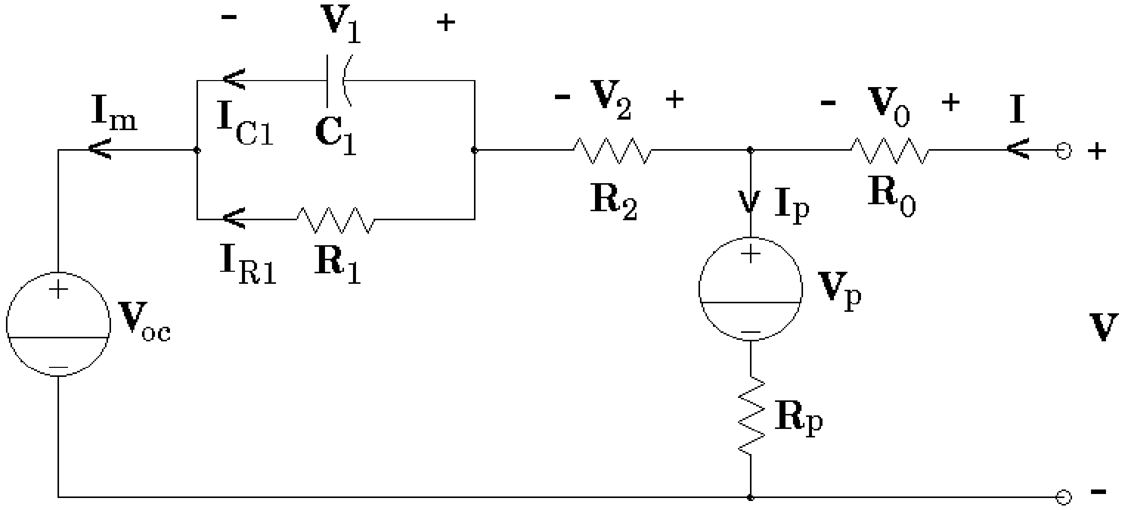

Modelling of a liquid lead-acid battery

Equivalent electrical circuit modelling

Master's thesis in Systems, Control and Mechatronics

Louisa Ahlenius & Natalie Ternevi Broberg

Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Abstract

Trucks are a large part of today's goods transportation, and in many cases the drivers spend a lot of time in the cab in between shifts. Therefore truck companies need to evaluate if the batteries will manage to supply enough energy to the cab while the engine is off, as well as make sure that there is enough energy left to be able to start the engine when the next shift starts. These kind of evaluations can be made by performing simulations of the energy consumption, where the battery is represented by a battery model for that specific battery.

This project has been performed at Volvo Group Trucks Technology, and the aim of the project was to create a more accurate battery model of the battery in question, than the model the company already had. The old model is referred to as the original Saber model. To model the battery, an equivalent electrical circuit was chosen to represent the behaviour of the battery. The circuit consist of a number of components with parameters that had to be identified. These parameters are dependent on the battery's state of charge as well as the electrolyte temperature, the temperature inside of the battery. To identify the parameters two different methods were tried; the least squares method and using a genetic algorithm. Results showed that the genetic algorithm found better results than the least squares and the genetic algorithm was therefore used.

The chosen circuit and the chosen parameter identification method was tried out by making a model based on the input and output data from the original Saber model. In this case the results were good and the model behaved as intended. Therefore the chosen method seemed to be appropriate. During the testing of the method, rig test of the real battery were specified and executed. The parameters were then identified based on the input and output data from the new tests which resulted in a model that did not behave as intended in some situations. To make the model work better, different circuits had to be used for discharging and charging the battery. In addition to this, the calculation of the state of charge could not be implemented as wanted due to insufficient knowledge in the simulation program, Saber. Furthermore, the open circuit voltage were, according to theory, supposed to only depend on state of charge. The results from the tests gave very different results of the open circuit voltage levels at the same state of charge during discharge and charge. They also showed different voltage levels at different temperatures. This indicates that some theory and/or some assumptions that were made are incorrect. However, there were indications that the test might not have been specified well enough to obtain useful outputs. One of these indications was that the pauses during charge and discharge were not long enough at some times, which resulted in the wrong open

circuit voltage at the corresponding state of charge.

The overall conclusions of the project was that the model that was used worked well under some conditions and could be sufficient for its purpose. However, some things need to be improved to achieve this. These things are mainly the SOC-calculation, properly specified and executed rig tests, and using the same circuit for charging and discharging.

Keywords: battery, lead-acid, modelling, equivalent circuit, equivalent electrical circuit, constant current charge, Saber, Synopsys.

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Louisa Ahlenius and Natalie Ternevi Broberg, Gothenburg, June 2018

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1 Introduction

This chapter presents a background of why this project was performed, the aim of the project along with its limitations. It also presents previous or similar work that has been done by others, as well as the structure of the report.

1.1 Background

Trucks are a large part of today's goods transportation. A comparison by Eurostat of transportation on road, railway and inland waterways [5] showed that 75% of the inland freight transport in Europe was on the road. The transports are measured in tonne-kilometres and one tonne-kilometre represents the transport of one tonne of goods over a distance of one kilometre [1].

With all these truck transports, truck companies spend a lot of time and money on making their trucks the best on the market. Transporting by truck often means long drives where the driver lives in the cab for a few days, or sometimes even weeks, during the hours when he or she is not driving. This means that truck companies want to make sure that the batteries installed in the trucks can supply enough energy so that the driver can live comfortably in the cab during the time in between the shifts. It is also necessary for the batteries to have enough remaining energy for the engine to be able to start when it is time for the driver to start the next shift.

To be able to know what kind or what amount of electrical components the driver can keep in his or her cab it is important to have a good model of the batteries. With a good model the truck companies can perform simulations to see how much energy the batteries can supply, given the climate the truck will be driven in and what kind of transports that will be made. It can for instance be important to know if the driver will be living in the cab or if there will be long breaks spent in the cab. The model can also be used if a driver wishes to add additional components to the truck, since an evaluation of the energy consumption can be made to see if the current batteries can deliver enough energy. If not it can be decided if, if possible, better batteries should be installed or if the new desired components should not be added.

There are two main approaches of modelling lead-acid batteries, which are to either make an electrochemical model or to make an equivalent electrical circuit model. The electrochemical model shows and describes the electrochemical process in the battery. The equivalent electrical circuit model on the other hand only describes the *behaviour* of the battery and not the chemical reactions that causes the behaviour.

The electrochemical models are the most accurate ones due to the fact that they model the chemical process in the battery. According to [10], the chemical reactions that occur in the battery can be modelled with great detail with the disadvantage that the simulation will be slow. More specifically it is stated that "... it may take hours to simulate a charge-discharge cycle of a detailed battery model if no model reduction approach is used to treat the battery equations.". In comparison to the chemical models the equivalent electrical circuit models are faster to simulate because they contain smaller equations.

In this project the equivalent electrical circuit approach was used to model the battery. The reason for modelling with an equivalent electrical circuit was partially to get a model that is more understandable to the company. Electrical circuits are also more familiar to the authors, in comparison to chemistry which is a more unfamiliar area. Furthermore, according to [8] it can be difficult to study an electrochemical process experimentally since it can be difficult to perform tests that give sufficient information about the chemical reactions. Normally the tests performed on a battery gives information about the current and voltage at the terminal. In this project it was important with a model where the parameters could be identified by using data from those types of tests since that was the type of data that was available from the company. It was also that type of data that was obtained from the new tests that were performed.

The usage for the battery model constructed in this project is to simulate mission profiles to obtain information about the available energy in the truck. Mission profiles are current profiles indicating how much current is drawn from the battery in different situations. The simulations where the battery model is used are executed offline using a computer. Given that it is mission profiles that are simulated and that the simulations are executed offline, it is suggested in [10] that a complex equivalent electrical circuit can be used to achieve accurate results like in the work of Cerealo [6], where the components of the electrical circuit depends on temperature and state of charge (SOC), and where the model also includes the charging of the battery. This makes the battery model more accurate over a wider span of conditions. Similar to the work of Cerealo [6], the components of the electrical circuit built in this project also depend on temperature and SOC, and includes the charging of the battery.

The battery that was modelled is a $12V$ liquid lead-acid battery. This is the battery generally used in the company's trucks today. However, to obtain a higher voltage, two of these batteries are used in series in the trucks. To replicate the setup in the trucks there are two battery models connected in series when the model is used in simulations.

1.2 Aim

The aim of this project was to model a $12V$ liquid lead-acid battery with 100% state of health (SOH), in the simulation program Saber. The model is of equivalent electrical circuit type and the parameters for the model were calculated for a battery with $225Ah$ capacity. The model output is the terminal voltage and the input to the model is the current drawn from the battery or fed into the battery. Furthermore the electrolyte temperature of the battery and the initial SOC need to be specified for each simulation. The goal was that the model would be more reliable than the original Saber model. Reliability for temperatures between $-20°C$ and $50°C$ is desired.

1.3 Limitations

A limitation in the project was that ageing of the battery as well as the battery's SOH was not taken into consideration when creating the model.

1.4 Previous/similar work done by others

There are many ways to model a lead-acid battery. Here, focus was on the equivalent electrical circuit modelling of a battery. However, also in this area of modelling techniques there are several different approaches. The most common one is to have an electrical circuit as in Figure 1.1 with an internal resistance R_0, an RC-block containing R_1 and C_1, and a voltage source, V_{oc}, that is the open circuit voltage (OCV) of the battery. However, the circuit in this figure is only used to model the discharge of the battery.

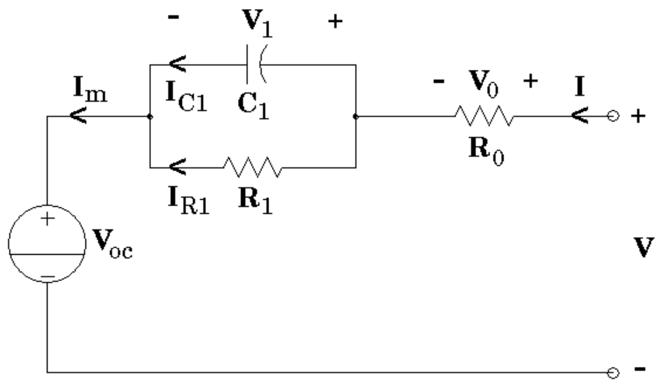

Figure 1.1: A first order equivalent electrical circuit used for modelling a lead-acid battery.

There are many different ways to obtain the parameters for the components of the circuit. One way is to use equations for the different components as in the work of Ceraolo [6]. He uses an equivalent circuit similar to the one in Figure 1.1 but has an additional branch added, to be able to model the charge of the battery as well as the discharge. This circuit can be seen in Section 2.2, Figure 2.1. Ceraolo then uses the results from many tests performed on lead-acid batteries to fit functions to how the components of the circuit varies with temperature and SOC. This is done to obtain an equivalent circuit that can be used in different SOC and temperatures when both charging and discharging the battery. The functions that were estimated by Ceraolo needs parameters that are obtained by doing different kinds of discharge and charge profiles and then take measures in the voltage output graph to calculate the parameters for the different functions. However, measuring in the graphs can be risky since it might not be clear exactly where to measure. In some cases, small measuring differences can have a large impact on the result. This is elaborated upon Section 2.3.

An alternative to measuring in the graphs is to use the least squares method on log data to obtain the parameters. This method is used in [7], among others. The least squares method is elaborated upon in Section 3.3.1.2.

In newer ways of parameter identification different approaches have been tested, and are tested continuously. In [11] a metaheuristic evolutionary algorithm is used to obtain the parameters of the components of the equivalent circuit for a certain SOC and temperature. In the article, the circuit equations are obtained by using Kirchoff's law to calculate the terminal voltage. The metaheuristic evolutionary algorithm called Bird Mating Optimizer showed excellent result when compared with the least squares method.

1.5 Thesis outline

The report is divided into different chapters; Introduction, Theory, Methods, Result, Discussion and Conclusion. Each of the coming chapters is described further below.

Theory

In the theory chapter necessary theory is provided to give the reader the knowledge to understand the work that has been done. The chapter includes a theory section regarding equivalent electrical circuit modelling where it is described what the circuit can look like, the parameters it contains and how the parameters depend on SOC and temperature. There is also a section about parameter identification, charge efficiency and the capacity of the battery.

Methods

In this chapter the different methods that have been used in the project are presented. It is for instance described how batteries can be tested on a rig and what the simulation environment looks like. Furthermore, it is presented how the new equivalent circuit model is made and how the new rig tests were constructed.

Result

In this chapter the results from the new rig tests are presented, as well as the results from simulations of the equivalent circuit model. Furthermore, a comparison and evaluations is made of the original Saber model, the equivalent circuit model and old rig tests.

Discussion

In this chapter the results are discussed and arguments and theories regarding why the these results were obtained are proposed.

Conclusion

Based on the results and the discussion regarding the results some conclusions are made about the chosen model, modelling method and parameter identification.

2
Theory

In this chapter the knowledge required to be able to follow the content of the report is provided. This includes theory regarding the SOC, the equivalent electrical circuit model, parameter identification, charging of the battery, the capacity of the battery and how cycling affects the battery.

2.1 State of Charge

The SOC is a measurement in percent of how charged the battery is. There are two different ways of expressing the SOC, the max SOC and the nominal SOC. The max SOC is the SOC relative to the condition that the battery is in at the present time. This means that if the battery is charged to the maximal capacity that it can reach in the present conditions, the SOC is 100%. If the battery is aged or cold, the capacity might be reduced, but 100% SOC means that the battery is as full as it can be in this specific condition.

The nominal SOC is the SOC relative to the nominal conditions, which is considered at $25°C$ and when the battery is new, i.e. when the SOH is at 100%. For the battery considered here the capacity is $225Ah$ in nominal conditions. Furthermore, when the temperature is higher than $25°C$ and the SOH is high, the capacity can be higher than $225Ah$, which means that the SOC can be above 100%. When the temperature is low or the SOH is low the SOC will never reach 100% since the maximal capacity that can be reached is less than $225Ah$. The max SOC is the same as the nominal SOC when the battery is at its nominal conditions.

2.2 Equivalent electrical circuit

A battery works due to the chemical reactions occurring inside and the external behaviour of the battery can be modelled with an equivalent electrical circuit. The electrical circuit consist of different components that are related to different reactions and processes in the battery. A literature review revealed that there is a general circuit of which different versions are normally used when modelling a battery, for both charge and discharge, and for different temperature and SOC. This circuit is presented in Figure 2.1.

In the circuit V is the terminal voltage and I is the current. A positive current is used to charge the battery and a negative current is used to discharge it. A negative

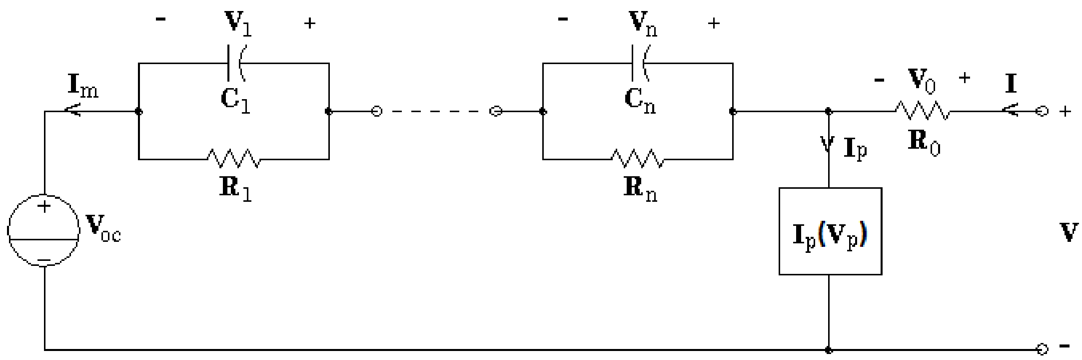

Figure 2.1: General equivalent electrical circuit for modelling a lead-acid battery.

current can also be referred to as a load current, since it represents that there is current drawn from the battery due to some load being applied. R_0 correspond to the internal resistance of the battery and V_{oc} is the OCV. R_i and C_i (i = 1,..,n) is a resistor and capacitor in parallel which is known as an RC-block. The number of RC-blocks needed depend on how accurate the model need to be and how the battery simluation will be used. Few RC-blocks gives a less accurate behaviour than more RC-blocks. Too many blocks however can give a too determined behaviour, causing the model to be less accurate if used in scenarios different than the ones used for parameter identification. Furthermore, the more RC-blocks, the more complex the model is and therefore the more complex the parameter identification is. The branch with the RC-blocks is called the main branch, and the branch in which the current I_p flows is called the parasitic branch. This branch is mainly used to be able to model the charging process, but in some cases it is also used to model the self-discharge of the battery.

2.2.1 The parameters

The components in the circuit vary with SOC and temperature. For instance, when the battery is exposed to cold temperatures the internal resistance increases. It also increases when the SOC is low due to sulfation in the battery [3]. When the temperature and/or SOC is high the internal resistance decreases again. The parameters in the RC-blocks are also dependent on SOC and temperature. The OCV dependency of temperature is very weak and is therefore assumed to be negligible. The model is therefore built as if the OCV only depends on SOC.

2.2.2 The parasitic branch

To understand how the parasitic branch works it is needed to know the concept of charge efficiency. The charge efficiency or charge acceptance, as it can be called, describes how well the battery accept the charge. It describes how much of the charging current actually goes to charging the battery. The charge efficiency is represented by a number between 0 and 1, where 1 represents that all of the current that goes into the battery is used for charging. 0 represents that none of the current that goes into the battery is used for charging. In some conditions large portions of the current can be transformed into heat, for example if the charge efficiency is low and a high current is put into the battery. The charge efficiency varies with SOC and temperature [4].

The parasitic branch is, as mentioned, mainly used to be able to model the battery behaviour in the charging process. How much the battery is charged depends on how much of the current goes through the main branch. The parasitic branch is used to regulate how much current that goes through the main branch and how much that goes through the parasitic branch. Once the battery is close to being fully charged, i.e. when the charge efficiency is close to 0, the battery should not be charged anymore and therefore very little or no current should go through the main branch. This means that all the current should go through the parasitic branch. When the battery has low SOC, i.e. when the charge efficiency is close to 1, all the current should instead go through the main branch and charge the battery and no current should go through the parasitic branch. In the circuit this is represented by the resistance in the main branch increasing when the battery is close to being fully charged. This leads to an increase in voltage over the parasitic branch, i.e. an increase in V_p, and a consequent increase in the current I_p. Less current will go through the main branch, hence the current that charges the battery is going towards zero as the SOC goes to 100%.

According to Ceraolo [6], the current that flows through the parasitic branch is not linearly dependent of SOC and temperature. It changes exponentially with the voltage over the branch and is therefore expressed as a box as in the figure, which could be represented with an equation. In some cases this branch is instead modelled as a branch with an impedance or a resistance, in series with a voltage source, which is how Ceraolo starts his work in [6]. This is also the way the circuit was modelled in this project.

2.3 Parameter identification

There are different ways to determine the parameter values for the different components in the circuit. One way is for instance to measure in graphs containing log data from battery tests, this will result in one set of parameters for every temperature and SOC. Another way is to find equations for each parameter and then determine the constants in those equations by looking in graphs from battery tests. The reason it is possible to look in the graphs to find parameters is that some behaviours in the data are related to the different parameters. For instance when there is a step in the current signal there is always an instant change in voltage which is directly related to the change in current, and the internal resistance R_0. The relationship is given by

$$\Delta V = R_0 \Delta I. \tag{2.1}$$

As can be understood from the equation a voltage and current graph with this kind of data can be used to identify R_0. An example of this voltage change can be seen in the plot in Figure 2.2, which displays a simulated scenario where the load current is increased from 0 to $11.3A$. The figure also contains an additional plot zoomed in on the voltage drop, and by observing the figure it seems like the instant voltage drop starts in point P_1 ends at point P_2. This gives an internal resistance of $R_0 = \Delta V/\Delta I = (13.45 - 13.11)/(0 - (-11.3)) = 0.03\Omega$.

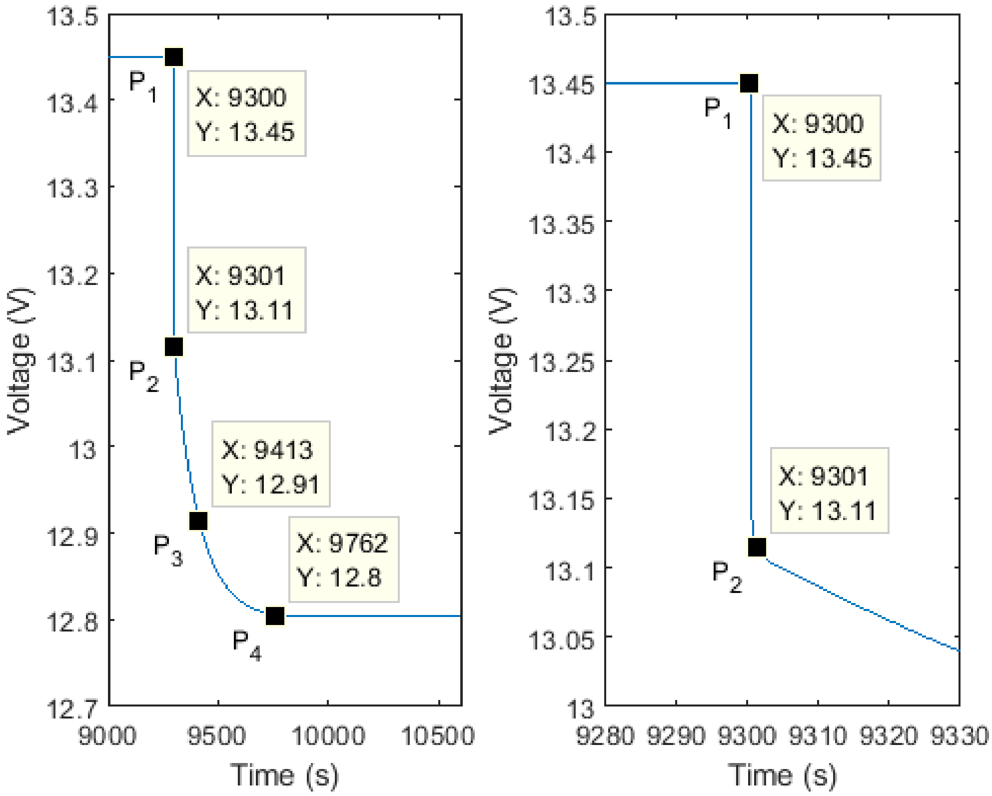

Figure 2.2: Simulated voltage of a scenario where the current starts at $0A$ and at time $9300s$ a constant current of $-11.3A$ is applied.

Furthermore, as can be seen in the figure, there is a transient after the instant voltage change. The start of the transient is at point P_2 and it ends when the voltage is stabilised, i.e. at point P_4. This transient effect is caused by the capacitors in the RC-blocks. The transient has a time constant and the time constant for an RC-block is normally known as τ. τ is related to R and C according to

$$\tau = RC. \tag{2.2}$$

The time constant for a first order equivalent circuit model represents the time it takes for the voltage to reach 63% of the voltage change between point P_2 and point P_4. 63% of that voltage change is reached at point P_3 in Figure 2.2, i.e. τ it the time it takes for the voltage to go from P_2 to P_3.

Additionally, when the current is $0A$ and the voltage is stable, the measured voltage is the OCV. This can be seen from the start until point $P1$, i.e from time $9000s$ to time $9300s$, in Figure 2.2. So in conclusion, parameters can be identified by measuring in the graphs. However, the data in the figure is obtained through a simulation and in some cases real log data can be hard to interpret correctly. When executing the same test as the one in Figure 2.2, on a rig, the obtained data can look like in Figure 2.3.

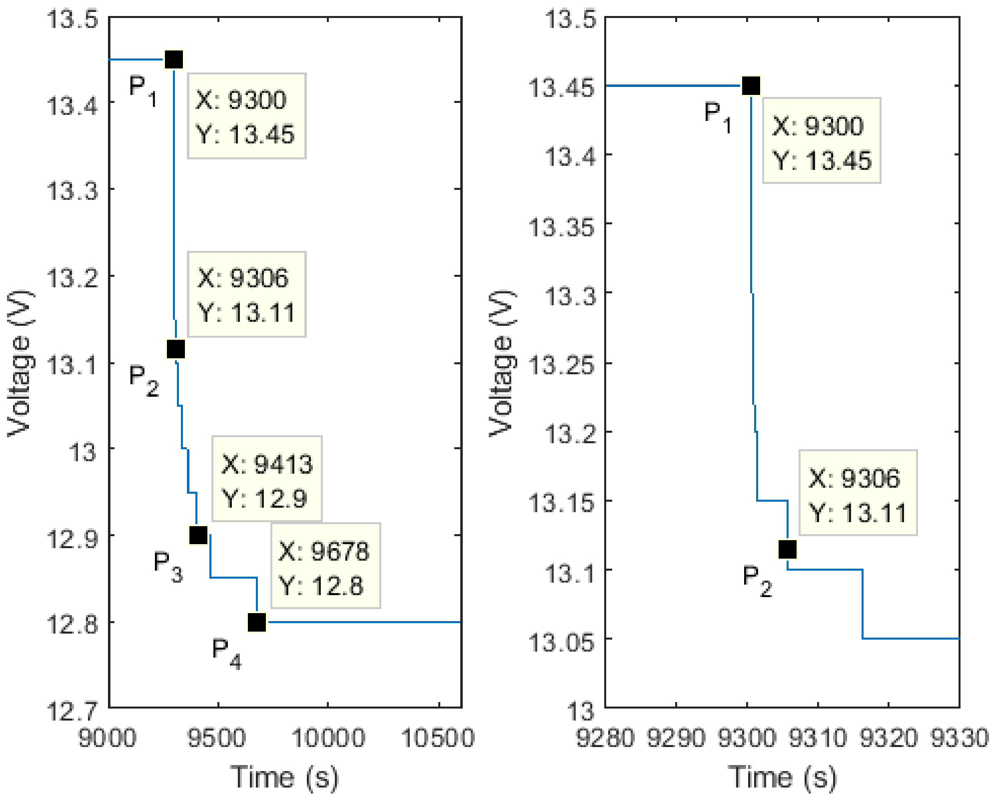

Figure 2.3: To the left: Log data of the voltage from a test with the same current as in Figure 2.2, i.e. the load current starts at $0A$, and at time $9300s$ a constant current of $-11.3A$ is applied. **To the right:** Zoomed version of the graph to the left.

As can be seen, the data in Figure 2.3 is not that accurate which makes it difficult to determine at what level the "instant" voltage drop occurs. In the graph to the right in the figure, point P_2 is placed at the same place as for the simulated scenario in Figure 2.2. By only looking at the zoomed version of the log data it can be seen that P_2 would most likely not have been placed as in this graph. Additionally, it is difficult to determine at what time the capacitor effect starts and ends, and therefore also what value τ has. As can be seen by comparing point P_4 in Figure 2.2 and 2.3 the voltage level is the same. However the time when the voltage reaches this level differs with $9762 - 9678 = 84s$ which would result in a difference in the values for the resistor and capacitor in an RC-block. Furthermore, something that applies to both figures is that if looking at a longer time period of this test, it would be seen that the voltage keeps decreasing after time $10500s$ since there is still a load applied. When this happens it is even more difficult to determine when the capacitor effect is gone, since it is can be a challenge to see when the voltage has stabilised and only keeps decreasing because of the load. The issue here is that small differences in the measurements can lead to large differences in the resulting parameters and therefore also differences in the result when using the model in simulations. To summarise, an approach where the parameter identification is to measure in the graphs is not ideal and sometimes not even a possibility, depending on how smooth the available data is.

The method mainly used in this project is theoretical due to low accuracy of the available data and due to the difficulties with an experimental approach as described above. The method is based on using Kirchhoff's laws to obtain equations that can be put together to form a transfer function. The transfer function is then discretized and written on regression form. After that the least squares method can be used to obtain the parameter values. This method requires data from tests that replicate common usage of the battery. Since the parameters depend on SOC and temperature the parameters will be calculated in different operation points, i.e. in conditions with different combinations of SOC and temperature. Interpolation is then used to obtain the values for each parameter for all SOC and temperatures. How this method is implemented is described further in Section 3.3.1.

There are also alternative ways to identify the parameters instead of using the least squares method. A particular approach, besides the least squares method, that was tested in this project was to use a genetic algorithm (GA) to determine the parameters. It was also investigated how or if the result differed from the results obtained with the least squares method. A genetic algorithm can be used in the same way as the least squares method, i.e. to determine the parameters in different operating points. The algorithm can also be used in very complex parameter identification situations where there for instance are a lot of parameters.

2.3.1 Genetic algorithm

There are many types of evolutionary algorithms and the genetic algorithm is one of them. The algorithm is used to stochastically find the maximum or minimum of a function, f, and to find the variables at this optimum. To understand how the algorithm works a few words that are used need to be introduced; generation, population, chromosome and gene.

To begin with, a population is initialised. This is done by creating a number of binary chromosomes of the same length, where each digit in the chromosome is a gene. The population size as well as the number of genes in each chromosome is determined by the user. The first population constitutes the first generation. The number of generations that will be evaluated is also determined by the user.

Once the first generation, i.e. population, is initialised each chromosome is decoded. This is done to assign each variable in the function a value in a range specified by the user. Each chromosome is decoded to represent values for all the unknown variables. Once each variable has a value the *fitness* of the chromosome can be evaluated. The fitness is a measurement of how good the chromosome is, which depends on how high or low the value of the function is. So for instance if the maximum of a function is searched for, the higher value of the function, the higher fitness. In a case like this the function value can be equal to the fitness. If the minimum is searched for instead, the lower function value, the higher fitness. Then a common way of assigning a fitness would be $fitness = 1/f$. In other words, to determine the fitness, the variable values are inserted in the function and the fitness is found. The chromosome with the highest fitness in a population is stored, as well as the corresponding fitness and variable values.

The next step is to start forming the next generation. In an evolutionary context the individuals, i.e. chromosomes, with the best genes are more likely to survive. The new generation will also consist of offspring from the individuals that survived. There will also be cases of mutation. In the algorithm, the start is to see who survives, which is done with a selection process. A common way of selection is to use tournament selection. This is done by randomly selecting a pair of chromosomes to tour. There is also a tournament selection parameter involved. This parameter is usually set to a value somewhere around 0.75. This means that there is a 75% chance that the chromosome with the highest fitness in the touring pair will be selected for the new generation. A random number between 0 and 1 is generated and if it is below the selection parameter, the chromosome with the highest fitness is selected. If the number is above the parameter value the chromosome with the lower fitness is selected. The selected chromosome is stored in the next generations population. Then a new pair is chosen from the current population and a new tournament is performed. This s done until the new population is of the same size as the current one. Furthermore, it should be mentioned that when a chromosome is chosen to tour, it is not removed from the current population, and can therefore be chosen to tour several times.

For every two chromosomes that are selected there is also the possibility of mating, which here is referred to as crossover. Here there is a crossover parameter involved, determining the chance of the two selected chromosomes mating. This parameter is usually set to a value somewhere around 0.8 but can, as every parameter, be adjusted to obtain a better result. In the same way as in the tournaments, a random number between 0 and 1 is drawn. If the number is below the crossover parameter the chromosomes will mate and otherwise they will remain the same. If they mate, the two chromosomes will be crossed with each other and the new resulting children will replace their parents in the new generation. There are different ways of performing the crossover but a common way is to decide a point in the chromosome where it will be cut of, and the second part of the chromosomes will be swapped with each other.

Once the selection and crossover are performed and a new population is obtained there is a chance that some of the chromosomes in the new population will have one or several mutated genes. Here there is a mutation parameter that is usually set to a value somewhere around $1/(number of genes)$. The mutation is done gene by gene, and for each gene in each chromosome a random number between 0 and 1 is drawn and if the value is smaller than the mutation parameter the gene will be mutated. Otherwise it will remain the same. Since the chromosomes are binary, a mutation of a gene means that a 0 will be a 1 and a 1 will be a 0.

Now the new generation is almost done, but to make sure that the best individual from the previous generation is included, elitism is sometimes used. This means that the previously stored best chromosome in the previous population will replace the first individual in the new generation.

Once the new generation is obtained, the whole process is repeated until the determined number of generations has been searched through to find the optima of the function. The initialisation of the population however is only done at the start and not for each new generation since that would mean that the creation of the new generation would be done for no reason. The parameters are also set at the start and do not change during the search. [12]

2.4 Charging

The most common way to charge a battery is to use a constant voltage. When this method is used, the current starts with a peak to boost the voltage to the applied voltage the battery is charged with. For the voltage to then remain constant at this level the current keeps decreasing towards zero as the SOC increases towards 100%.

Another way of charging a battery is by using a constant current. This can sometimes cause issues since the voltage can increase significantly in certain conditions, for example in cold temperatures. Normally when charging a battery with a constant current, the current that goes into the battery should decrease at the end of the charging to limit the risk of the voltage increasing to very high levels.

When the battery is fully charged and the charging continues the charging current will cause gassing. Gassing is when the battery produces excessive amounts of hydrogen gas. The hydrogen gas is poisonous, highly flammable and has a distinct smell. When the ambient temperature is higher than $20°C - 25°C$ the gassing will accelerate. [9]

2.5 Capacity

Even though the parameters in the equivalent circuit are assumed not to be dependent of the current, the current has an effect on the capacity of the battery. The capacity is also affected by the temperature.

2.5.1 Rated capacity - C20

The capacity that is stated by the battery supplier is the nominal or rated capacity which is usually the $C20$ capacity, at 25°C. $C20$ means that the battery lasts for 20 hours when discharging with the corresponding current, i.e. the $I20$ current. The Ixx current is defined as

$$\frac{\text{nominal capacity}}{\text{xx time}} \quad \Rightarrow \quad I20 = \frac{225Ah}{20h} = 11.25A. \tag{2.3}$$

For the battery in this project the $C20$ capacity is $225Ah$, hence $I20 = 11.25A$.

However, the nominal capacity is as stated nominal and will therefore differ between individual batteries. Some batteries have a slightly higher capacity and some slightly lower. Therefore, when doing tests on batteries, a $C20$-test is often performed in the beginning to see the actual $C20$ capacity for that specific battery. This is done by discharging the battery from 100% SOC until 0% SOC and then register the time it took. By knowing the time and the used discharge current, the actual capacity of the battery can be calculated with Equation 2.3.

Sometimes it can also be profitable to make other capacity tests, for example $C4$, $C10$, $C100$ and/or to perform the tests in different temperatures. A $C4$-test means that the battery should last for a four hour discharge, which gives the current $I4 = 225/4 = 56.25A$. These tests are performed due to the fact that the capacity differs with different applied currents and temperatures, which results in that a $C4$-test will usually not take exactly 4 hours. More about this can be read in the following sections.

2.5.2 Temperature dependency

As previously mentioned, the actual capacity of the battery is not always the rated capacity since it depends on temperature and current. When the temperature is lower than the nominal temperature, $25°C$, the internal resistance increases and the capacity is decreased. This causes the battery to last shorter when discharging with the $I20$ current compared to when discharging with the same current at $25°C$. For temperatures higher than $25°C$ the internal resistance decreases and the capacity increases, which results in a higher capacity and that the battery lasts longer when discharging with the same current.

2.5.3 Peukert effect

To be able to understand how a battery works it is good to keep in mind that there is something called the Peukert effect. The Peukert effect means that the capacity of the battery varies depending on which discharge current is used. The capacity is lower than the $C20$ capacity when a higher discharge current than the $I20$ is used. In the same way the capacity is higher when a lower discharge current is used. To find out what the capacity is when using a certain discharge current, Peukert's law can be used, i.e.

$$t = H\left(\frac{C}{IH}\right)^k \tag{2.4}$$

where t is the time it takes to discharge the battery given a certain discharge current, I. C is the rated/nominal capacity given by the battery supplier, which here is the $C20$ capacity, H is the number of hours it should take to discharge the battery given C and the corresponding current and k is the Peukert constant. Thus, if C is the $C20$ then H is 20 hours. [2]

The Peukert constant is sometimes given by the battery supplier, and other times it need to be calculated. This can be done by performing a few different tests where the battery is fully discharged with a constant current, starting as fully charged. The tests should be done for a few different currents. For instance it could be good to perform the following tests; $C4$, $C10$, $C20$ and $C100$. The result, i.e. the discharge time for each discharge current can then be put in a logarithmic plot which usually gives a fairly straight line. The slope of this line is the Peukert constant.

Although Peukert's law is a good way to find the capacity for a specific discharge current, there are a few things that are not considered, such as temperature, SOH or ageing of the battery.

2.5.4 Freezing temperature

Freezing temperature is also something that need to be kept in mind when working with batteries. The freezing temperatures vary depending on the type of battery as well as the SOC of the battery. For the liquid lead-acid batteries the freezing temperature increases with a decreasing SOC. This is due to the fact that when the SOC is close to zero, the electrolyte is close to water which gives a higher freezing temperature than when the electrolyte has a higher acid density. This means that in low temperatures the battery should not be discharged lower than to some certain value of SOC to avoid freezing the battery.

2.5.5 Cranking the engine

Calculating the SOC correctly is imperative. A reason for this is that the driver has to be able to crank the engine after spending time in the truck with the engine off. To crank/start the engine a certain amount of SOC is required. Therefore it is important to keep track of the SOC when the engine is off and the driver is living in the cab. If the SOC reaches some lower limit a warning is given that the engine need to be started to charge the battery, otherwise it will not be long until the engine will not be able to start. This is particularly important in cold temperatures since the battery does not last as long due to lower capacity. However, the SOC calculated in this project is not used in the actual trucks, but to be able to perform simulations that will give useful information regarding the energy the battery can provide without risking failure to crank the engine, it is still very important for the SOC calculation to be correct.

2.6 Cycling

To cycle a battery once means one discharge and one charge. The length of the discharge depends on how deep the battery should be cycled. A deep cycle is when the battery is discharged to 0% - 20% SOC and then recharged.

The lifetime of the battery depend on how deep the battery is cycled and how many times. Tests performed at the company has showed that when cycling a battery down to 0% it only lasts for 10 - 20 cycles. When only discharging the battery down to 90% SOC it can be cycled around 600 times. This means that cycling the battery deep should be avoided to obtain a lifetime that is as long as possible.

3 Methods

In this chapter different methods used in the project are presented. It is, for instance, described how battery rig tests are performed, what the simulation environment looks like, how the equivalent circuit was built and how new rig tests were specified.

3.1 Rig testing

There are times when information about different batteries is needed, for instance in order to find parameters for battery models, data collected when the batteries are used is needed. Data can be obtained by collecting it when the battery is used in a truck or by testing it on a rig. Either way the data is measured with a battery sensor that is attached to the battery. The advantage with rig testing is that the tests can be composed as desired, depending on what data that is required.

3.1.1 Rig test setup

The tests performed on the rig were conducted with several different components. Old tests regarding the battery in this project that are available were performed with a climate chamber, a battery test bench and an alternator test bench, where in this case two $12V$ batteries were connected in series and placed in the climate chamber. The setup on the rig can be seen in Figure 3.1. The climate chamber is used to be able to perform tests in different temperatures. The batteries are also connected to the battery test bench and the alternator test bench. The alternator test bench, the battery test bench and the batteries are all connected in parallel. The alternator test bench consists of an electrical motor and an alternator. The electrical motor is used to run the alternator to replicate the behaviour of when the truck engine is running, which means that the battery is being charged. The battery can also be charged with a constant current by using a Digatron machine.

The battery test bench is used to control the load, i.e. the current drawn from the battery by a load at any time. The load can be adjusted to resemble different mission profiles that have been observed when logging information from trucks in use. These mission profiles usually consist of a certain current drawn during a certain period of time. For instance, the currents that are normally drawn during the hours when the driver is sleeping might be in a certain span. The currents drawn when the driver is not working nor sleeping is in another span, i.e. the current drawn when he or she might be watching TV and charging the phone etc. The average of these spans are then used to create mission profiles that correspond to common drive cycles for different types of trucks. A drive cycle is how a certain type of truck is regularly used. The drive cycles are different depending on what the truck is used for, for instance if it is used for long transports or if it is used for distribution jobs in a city environment etc.

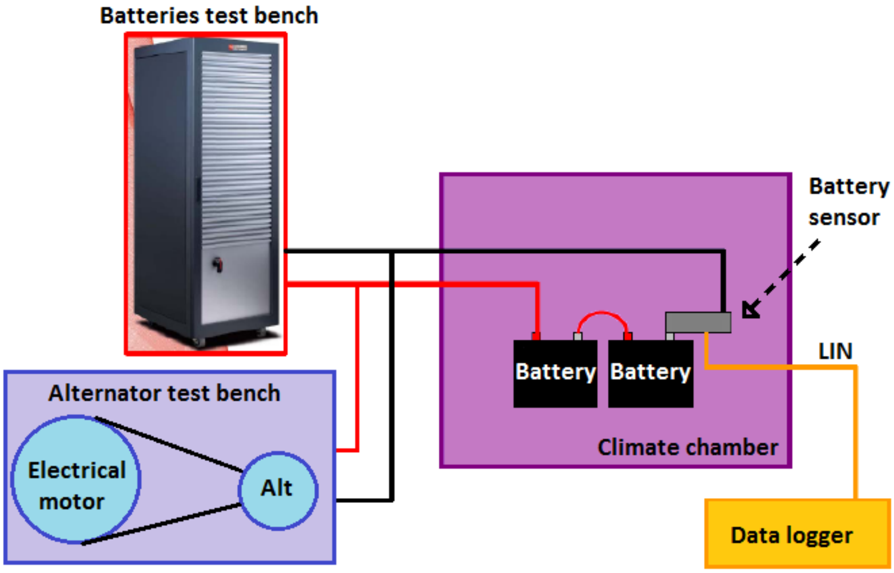

Figure 3.1: Rig setup with batteries test bench, alternator test bench, climate chamber, batteries and battery sensor.

3.1.2 Battery sensor

The data from the rig tests is measured by a battery sensor that is attached to a terminal on one of the batteries. The measurements from the sensor is sent through the Local Interconnect Network (LIN) to a computer, where the data is stored. The sensor measures, among other things, voltage, current, nominal SOC, SOH and temperature. However, the accuracy and reliability of the sensor varies depending on the measured quantity. The SOC for instance, can be unreliable in tests that were performed some years ago, since the sensor was not that well performing at that time. This is the case for some of the tests presented in Section 4.8. The reason for using the old data for comparisons is due to lack of better data. On the measurements from the sensor, the voltage changes with a step of $0.5V$ and the current changes with a step of $0.1A$.

3.2 Saber simulation environment

A common environment in which the battery model is used is presented in Figure 3.2. As can be seen in the figure, the batteries are connected in series, and are also connected to the mission profile block/load current and the alternator, all in parallel as on the test rig. The mission profile block only represent load currents and can therefore only draw current from the battery. To charge the batteries the alternator is needed. There is also an additional block, connected to the battery to the left, which takes the max SOC and temperature as input and gives the nominal SOC as output.

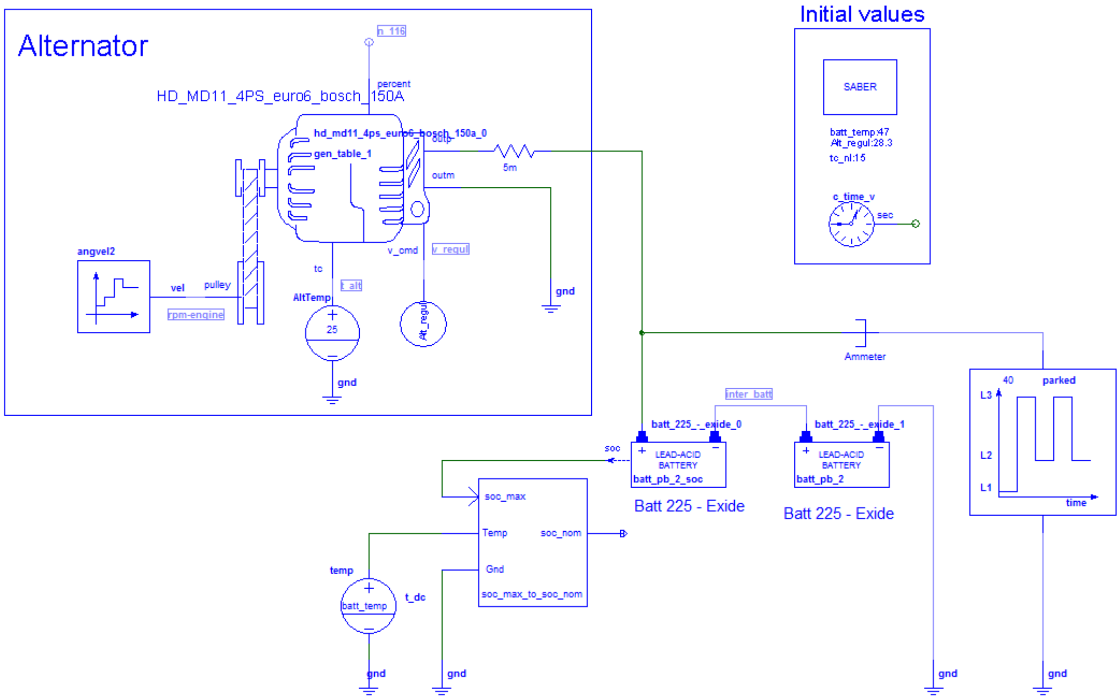

Figure 3.2: Saber simulation setup with alternator and load.

When recreating some of the tests performed on the rig shown in Section 4.8 in simulation, the input signal data, i.e. the current, needed to be as similar to the rig current as possible, to be able to evaluate the model performance. By looking at test reports as well as actual log data, the input data could be somewhat correctly recreated by using the alternator and the mission profile. This however resulted in that the recreated input, i.e. the Saber input data, occasionally differed from the input data used on the rig-test. When comparing the results these differences had to be taken into consideration since that could be the reason for differences in the output. To avoid getting differences in the output data that depends on differences in the input data, the input data set was instead collected from the rig-tests and put directly into a current-source in Saber. Since the current source can represent both charging and discharging it could replace the mission profile block, and the alternator could be removed. The new setup can be seen in Figure 3.3. The fewer components used in the simulation in addition to the battery model, the better. With only the current source and the battery model, the parts that differ in the comparison of the output data can be directly traced back to the battery model.

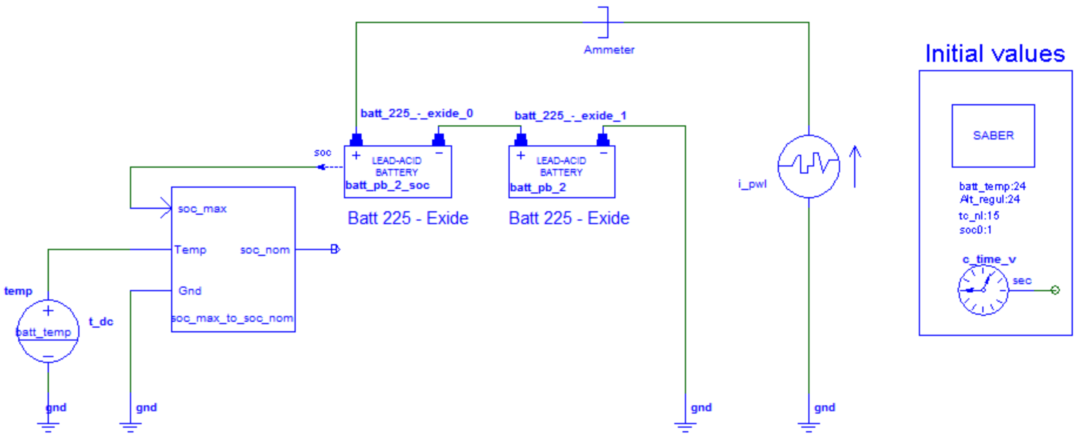

Figure 3.3: Saber simulation setup where alternator and load are replaced by a current source.

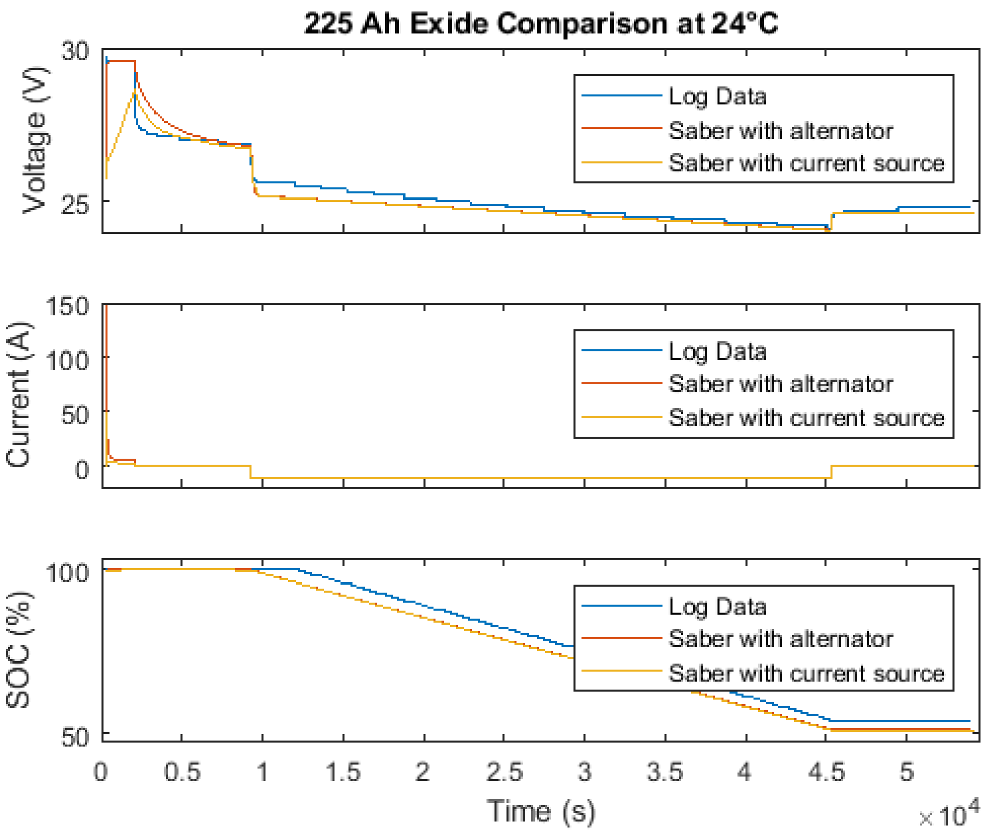

Figure 3.4: Test result comparison between log data, Saber simulation setup with alternator and load and Saber simulation setup with current source.

The different data sets that were obtained with the different simulation setups, when recreating the same test from the rig, are demonstrated in Figure 3.4. The shape of the input data, i.e. the current, that is seen between time 0s and approximately time 2000s indicates that the alternator is used. It is started when the current peak appears and turned off when the current starts being constant. As can be seen the Saber model voltage corresponds well to the log data in the beginning, when using the model setup with the alternator, contrary to when using the model setup with the current source. However, when using the setup with the alternator the current does not correspond to the log data; the current in the model is $150A$ while the current from the log data is $50A$. When using the log current as input in the current source in the model setup without the alternator, the voltage does not correspond well. This, however, means that the battery model does not give the same voltage response as the rig, when using the same input. By using the model setup without the alternator the errors in the voltage signal can be directly connected to the battery model. When using the model setup with the alternator, it is difficult recreating the same input signal as on the rig and therefore the behaviour of the battery model cannot be evaluated for the correct input signal. This is the reason for using the setup without the alternator for the remainder of the project.

3.3 New model

In this section the steps in creating the model are presented.

3.3.1 First step in building a new model - Equivalent electrical circuit

The model that was first considered was a simple version of the general electrical circuit shown in Section 2.2, Figure 2.1, and is presented in Figure 3.5. This circuit does not have the parasitic branch and can therefore not model the charging process in a good way. Although it cannot model the charging process, it was of interest to start with a simple model to investigate how well it can model the discharge process with one RC-block.

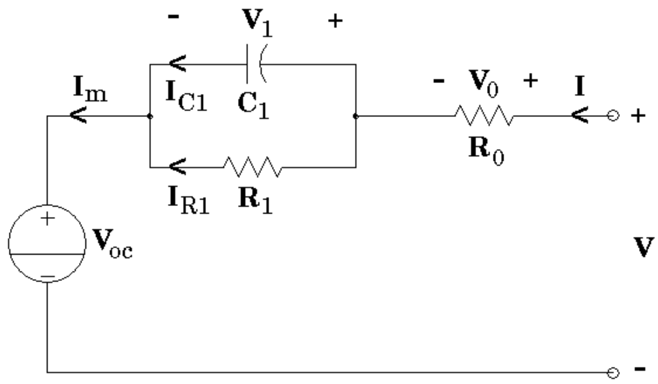

Figure 3.5: Equivalent electrical circuit for modelling discharge of the battery.

In Figure 3.5 R_0 is the internal resistance, R_1 and C_1 is an RC-block with a resistor and a capacitor connected in parallel, V_{oc} is the OCV, V is the terminal voltage and I is the current.

In order to obtain the parameters in the circuit a transfer function for the model was derived by using Kirchhoff's voltage and current law. With this approach the parameters need to be calculated in different operating points, i.e. for different SOC and temperatures. The values for the parameters for each operating point would then need to be interpolated to get the full behaviour of the model. In the following sections a deeper explanation of how the parameters in the equivalent electrical circuit were identified in an operating point is presented.

3.3.1.1 Continuous and discrete transfer function of the electrical circuit

By using Kirchhoff's voltage law, Kirchhoff's current law and the capacitor equation in the electrical circuit in Figure 3.5, the following equations were obtained:

$$v = R_0 i + v_1 + v_{oc} \tag{3.1}$$

$$i = i_{C_1} + i_{R_1} \tag{3.2}$$

$$i_{C_1} = C_1 \dot{v}_1 \tag{3.3}$$

A combination of Equation 3.1, 3.2 and 3.3 resulted in

$$v = (R_0 + R_1)i - R_1 C_1 \dot{v}_1 + v_{oc}. \tag{3.4}$$

Differentiating Equation 3.1 results in the following equation:

$$\dot{v} = R_0 \dot{i} + \dot{v}_1 + \dot{v}_{oc}. \tag{3.5}$$

By inserting Equation 3.5 in Equation 3.4, we obtain

$$v - v_{oc} + R_1 C_1 (\dot{v} - \dot{v}_{oc}) = (R_0 + R_1)i + R_0 R_1 C_1 \dot{i}, \tag{3.6}$$

where all terms were multiplied with $V - V_{oc}$, I or its derivatives. By using Laplace transformation the time-dependent Equation 3.6 becomes the following frequency-dependent equation:

$$(1 + sR_1C_1)(V - V_{oc}) = (R_0 + R_1 + sR_0R_1C_1)I. \tag{3.7}$$

The resulting transfer function can then be written as

$$H(s) = \frac{V(s) - V_{oc}(s)}{I(s)} = \frac{R_0 + R_1 + sR_0R_1C_1}{1 + sR_1C_1} = R_0 + \frac{R_1}{1 + sR_1C_1}. \tag{3.8}$$

This transfer function is in continuous time and to be able to use the data collected from the rig to determine the parameters, the transfer function needs to be discretized. This is due to the fact that the data from the rig tests is discrete and also that there are no measurements of the derivatives of the current or voltage.

The transfer function was discretized using the following zero-order hold equivalent

$$H(z) = (1 - z^{-1})Z\left\{\frac{H(s)}{s}\right\}, \tag{3.9}$$

where Z is the Z-transform. This results in a discretized transfer function

$$H(z) = \frac{V(z) - V_{oc}(z)}{I(z)} = R_0 + \frac{R_1(1 - e^{-\frac{T_s}{R_1C_1}})}{z - e^{-\frac{T_s}{R_1C_1}}}, \tag{3.10}$$

where T_s is the sampling time.

A general form of a discrete transfer function is

$$H(z) = \frac{b_0 + b_1z^{-1} + ... + b_mz^{-m}}{a_0 + a_1z^{-1} + ... + a_nz^{-n}}. \tag{3.11}$$

By writing Equation 3.10 on the general form, the following is obtained:

$$H(z) = \frac{R_0 + \left(R_1 - (R_0 + R_1)e^{-\frac{T_s}{R_1C_1}}\right)z^{-1}}{1 - e^{-\frac{T_s}{R_1C_1}}z^{-1}}. \tag{3.12}$$

This gives

$$\begin{aligned} a_0 &= 1 & b_0 &= R_0 \\ a_1 &= -e^{-\frac{T_s}{R_1C_1}} & b_1 &= R_1 - (R_0 + R_1)e^{-\frac{T_s}{R_1C_1}} \end{aligned} \tag{3.13}$$

3.3.1.2 Regression form and least squares method

The discrete transfer function can be written on the regression form

$$y_d(k) = \varphi_d(k)\theta_d, \tag{3.14}$$

where y_d is the output, φ_d is the regressor vector and θ_d is the parameter vector. The regressor vector contains log data, and the parameter vector contains the unknown parameters. To know how to build the regressor and parameter vector the discrete transfer function in Equation 3.12 can be rewritten as

$$\frac{y_d(k)}{u_d(k)} = \frac{b_0 + b_1z^{-1}}{a_0 + a_1z^{-1}} \tag{3.15}$$

where $u_d(k)$ is the input current. This leads to

$$y_d(k)(a_0 + a_1z^{-1}) = (b_0 - b_1z^{-1})u_d(k) \tag{3.16}$$

which can be rewritten as

$$y_d(k) = -\frac{a_1}{a_0}y_d(k-1) + \frac{b_0}{a_0}u_d(k) + \frac{b_1}{a_0}u_d(k-1). \tag{3.17}$$

Since a_1/a_0, b_0/a_0 and b_1/a_0 contain the unknown parameters these will form the parameter vector. Hence, the regressor vector is

$$\varphi_d(k) = \begin{bmatrix} y_d(k-1) & u_d(k) & u_d(k-1) \end{bmatrix} \tag{3.18}$$

and the parameter vector is

$$\theta_d = \begin{bmatrix} -\frac{a_1}{a_0} & -\frac{b_0}{a_0} & -\frac{b_1}{a_0} \end{bmatrix}^T \Rightarrow \{a_0 = 1\} \Rightarrow \begin{bmatrix} -a_1 & b_0 & b_1 \end{bmatrix}^T. \tag{3.19}$$

For the discrete transfer function

$$y_d(k) = v(k) - v_{oc}(k) \quad \text{and} \quad u_d(k) = i(k), \tag{3.20}$$

which gives the regressor vector

$$\varphi_d(k) = \begin{bmatrix} v(k-1) - v_{oc}(k-1) & i(k) & i(k-1) \end{bmatrix} \tag{3.21}$$

and the parameter vector

$$\theta_d = \begin{bmatrix} e^{-\frac{T_s}{R_1 C_1}} & R_0 & R_1 - (R_0 + R_1)e^{-\frac{T_s}{R_1 C_1}} \end{bmatrix}^T. \tag{3.22}$$

In Equation 3.21 v and i are log data from rig tests. v_{oc} is a constant value, since this method is used in each operating point, and in one operating point the SOC is constant. In Equation 3.22 T_s is the sample time for the log data and R_0, R_1 and C_1 are parameters to be calculated. To calculate the parameters the least squares method was used, i.e.

$$\hat{\theta}_d = \left[\sum_{i=1}^{N} \varphi_d^T(k_i)\varphi_d(k_i)\right]^{-1} \sum_{i=1}^{N} \varphi_d^T(k_i)\left(v(k_i) - v_{oc}(k_i)\right), \tag{3.23}$$

where $\hat{\theta}_d$ is the estimated parameter vector. Since there are three unknowns and three equations, R_0, R_1 and C_1 could be calculated.

As mentioned previously the method described above holds for a constant SOC and temperature. Therefore it needed to be used in different operating points and then be interpolated to get values for each parameter in the entire operating window. The available log data, however, did not contain a sufficient amount of operating points. Since this circuit is only a very simple model, a comparison with the log data was made in only one operating point, before continuing the work with a more advanced model. Additionally, new rig tests needed to be specified in order to get high quality log data in all operating points, which is discussed further in Section 3.4.

3.3.1.3 Simple evaluation of the new model in one operating point

The parameters were calculated in the operating point where the SOC and temperature was 100% and 24°C, respectively. A simulation with the obtained parameters was made, and the result can be seen in Figure 3.6, along with the log data. As can be seen the result is not very good, since the voltage from the least squares method does not follow the transient, and then levels out on another voltage level than the log data. This lead to trying another method, which was to identify the parameters with the genetic algorithm described in Section 2.3.1. The result from identifying the parameters with the genetic algorithm can also be seen in Figure 3.6, along with the result from the least squares method. It is clear from the figure that the genetic algorithm generated a better result since the voltage curve follows the log data well, both in the transient and once the voltage levels out.

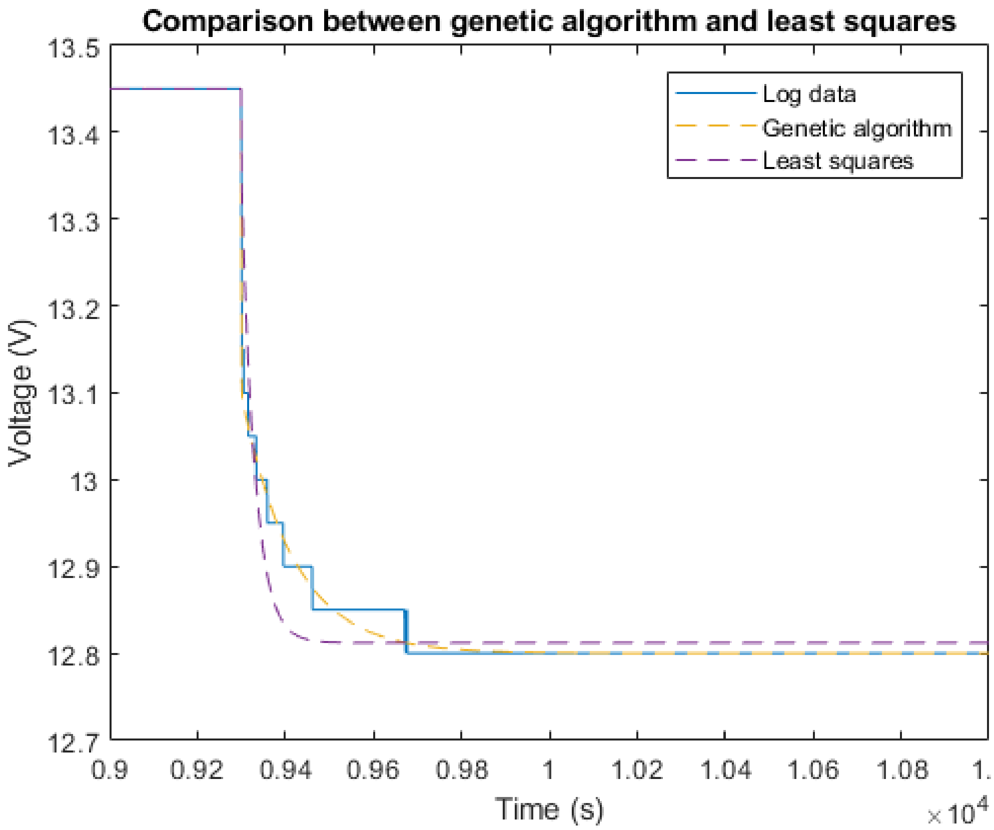

Figure 3.6: Comparison between log data, equivalent circuit model when identifying the parameters with least squares and equivalent circuit model when identifying the parameters with the genetic algorithm.

The quadratic error was calculated for both methods as in the equation below, and the errors can be seen in Table 3.1.

$$\text{Quadratic error} = \frac{1}{N}\sum_{i=1}^{N}(V_{log}(i) - V_{calc}(i))^2. \tag{3.24}$$

In the equation, N is the number of samples, V_{log} is the log data voltage and V_{calc} is the voltage that was calculated with the estimated parameters.

Method	Quadratic error
Least squares	$8.0307 * 10^{-4}$
Genetic algorithm	$9.9047 * 10^{-5}$

Table 3.1: Quadratic error for least squares result and result from genetic algorithm.

In the table it is seen that the quadratic error is smaller when the parameters were estimated with the genetic algorithm than when they were estimated with the least squares method. This should not be possible since the least squares method should find the solution with the least squared error, which is an indication that the least squares methods might not have been performed correctly. However, no faults were found in the calculations and therefore the genetic algorithm was chosen as method to identify the parameters for the equivalent circuit.

3.3.2 Second step - equivalent electrical circuit with parasitic branch and R2

Once it was possible to determine the parameters for the simpler model, a more complex model was made. This model can be seen in Figure 3.7. In this model the parasitic branch has been added to be able to model discharge. Since all the current is supposed to go through this branch at the end of charging when close to 100% SOC, another resistance, R_2 was added. R_2 could then be increased as SOC goes to 100%, to push the current through the parasitic branch.

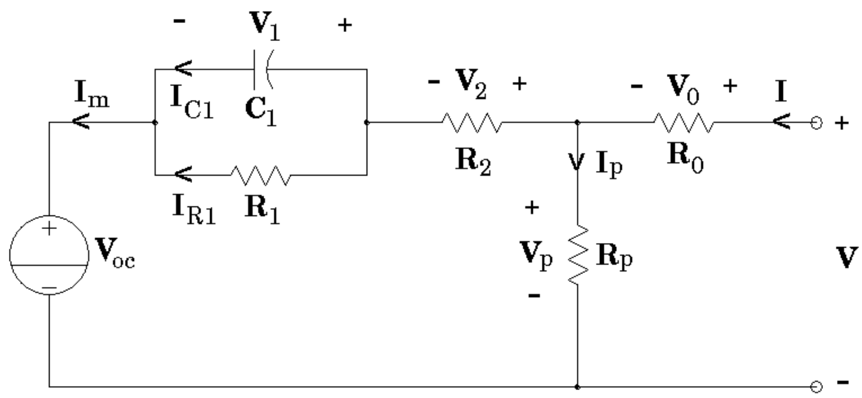

Figure 3.7: Model for both charge and discharge, with the parasitic branch consisting of a resistance.

As can be seen in the figure, the parasitic branch only consists of a resistance in this model, which was an attempt to lower the complexity. At this point, data for R_0 was received from the battery supplier between 50% SOC and 100% SOC. The data below 50% SOC was obtained through interpolation. This leaves four unknown parameters in the new circuit; R_1, C_1, R_2 and R_p. When the same steps as in Section 3.3.1 were followed in order to find the transfer function, there were only three equations and four unknown parameters, since the regressor vector remained the same as in Equation 3.21. Therefore the parasitic branch was removed again to determine the parameters R_1, C_1 and R_2 while discharging. Since these parameters are assumed to only be dependent on SOC and temperature, and not current, they are assumed to be the same at a specific SOC and temperature regardless what the current is, i.e. regardless if the battery is being charged or discharged. Therefore, once these parameters are determined, R_p can be identified by performing a test where the battery is charged.

By disregarding the parasitic branch and following the same steps as in Section 3.3.1 the transfer function that follows was obtained:

$$H(z) = \frac{(R_0 + R_2) + \left(R_1 - (R_0 + R_1 + R_2)e^{-\frac{T_s}{R_1C_1}}\right) z^{-1}}{1 - e^{-\frac{T_s}{R_1C_1}} z^{-1}}. \tag{3.25}$$

Again, this transfer function is for discharging only. By considering the general form in Equation 3.11, Equation 3.25 gives

$$\begin{aligned} a_0 &= 1 & b_0 &= R_0 + R_2 \\ a_1 &= -e^{-\frac{T_s}{R_1C_1}} & b_1 &= R_1 - (R_0 + R_1 + R_2)e^{-\frac{T_s}{R_1C_1}} \end{aligned} \tag{3.26}$$

This gives the following regressor vector and parameter vector:

$$\varphi_d(k) = \begin{bmatrix} v(k-1) - v_{oc}(k-1) & i(k) & i(k-1) \end{bmatrix} \tag{3.27}$$

$$\theta_d = \begin{bmatrix} e^{-\frac{T_s}{R_1C_1}} & (R_0 + R_2) & R_1 - (R_0 + R_1 + R_2)e^{-\frac{T_s}{R_1C_1}} \end{bmatrix}^T. \tag{3.28}$$

3.4 New rig tests

To be able to identify the parameters in the circuit, new rig tests were needed. The available data was not sufficient since data was not available for all the operating points, which is necessary in order to identify the parameters correctly. A suitable test for this purpose contains operating points where the instant voltage change and the transient effect is included.

The tests were done by charging and discharging the battery in different temperatures with the $I20$ current, $11.25A$, and doing pauses, in which the current is $0A$. This was done to obtain the "instant" voltage change and the transient, which is necessary for calculating the capacitance C_1 and the resistances R_1 and R_2. The length of the pause had to be long enough for the voltage to stabilise and reach the OCV. The length of the pauses were chosen by looking at data from the supplier of the battery where it could be seen approximately how long it would take for the battery voltage to stabilise in different temperatures.

The operating points were chosen by looking at charging and discharging curves that has been made by the battery supplier. In the linear parts of the curves the operating points could be few and where the curves changed in a non-linear way, more operating points were needed.

It was not sure whether or not the parameters changed in a linear way where the discharge curve did. Therefore, a test was made by training the model on data from the original Saber model, it could be seen that a good result was obtained by using this hypotheses. The result from the test can be seen in Figure 4.1.

Between the different temperatures the battery needed a boost charge in order to assure that the battery was fully charged. This is important since the capacity of the battery changes in different temperatures as explained in Section 2.5.2. Furthermore, the boost was needed because it was not certain if the SOC would actually be at 100% after the charging process in the test, due to that no time preferences on constant current charge on the battery could be found.

According to the battery supplier it takes 1-20 days for the battery to reach its OCV after being charged to 100% SOC. Since the time to perform these tests was limited, a method that have been used at the company to remove the voltage bias corresponding to the relaxation. The method used was to discharge the battery with $5A$ for four minutes, which corresponds to turning on the headlamps for four minutes. This was done after the boost charge of the battery in order to reach the OCV.

These tests are very tough on the battery since it is discharged down to 0% SOC in both very hot and very cold temperature conditions. The battery will only last for 10-20 cycles when discharging down to 0% SOC. When the cycling is done in extreme conditions, the battery's lifetime is even shorter. This means that the health of the battery will decrease during these tests. When the health of the battery decreases the capacity decrease as well. This means that the battery that was tested had a specific capacity at 100% SOC when the tests were started and the battery was new, but when the tests were done the battery had been cycled a couple of times in different temperatures and, therefore, the capacity was not the same at 100% SOC.

The difference in the health of a battery in the beginning of a tests and in the end can be estimated by doing a $C20$-test before the actual test starts and then a $C20$-test again after the tests has been performed. Then the capacity of the battery before and after can be compared to get an approximation of the SOH of the battery. This was implemented in the specification of the new rig tests.

There were some uncertainties about the new rig tests as well. One was that, as stated in Section 2.5.4, the battery could freeze when it reaches low temperatures, especially when the SOC of the battery is low. By charging the battery immediately after the discharge and by that, not leaving the battery at low SOC in low temperature for a long time, the risk of the battery freezing or being damaged from staying frozen during a long time was limited.

Another uncertainty was that when over-charging the battery it can produce hydrogen gas as stated in Section 2.2.2. The charging time of the battery could not be calculated exactly due to the fact that individual batteries differ from each other and no tests with a constant current charge in different temperatures could be found. This meant that some over-charging could occur. The concern was mostly for the test in $50°C$ where the gassing is accelerated due to the higher temperature. The hydrogen gas is highly flammable and can result in an explosion if it is not handled with care. Since the hydrogen gas has a distinct smell this concern was dealt with by not leaving the test without supervision for long periods of time.

3.4.1 Discharge

By looking at the voltage curve from a regular $C20$-test, which is presented in Figure 3.8, it can be seen that the curve is fairly linear from around 90% SOC to until around 20% SOC. Therefore it is not necessary with many operating points between these SOC, instead it is better to pick operating points closer together for high, and in particular low values of SOC.

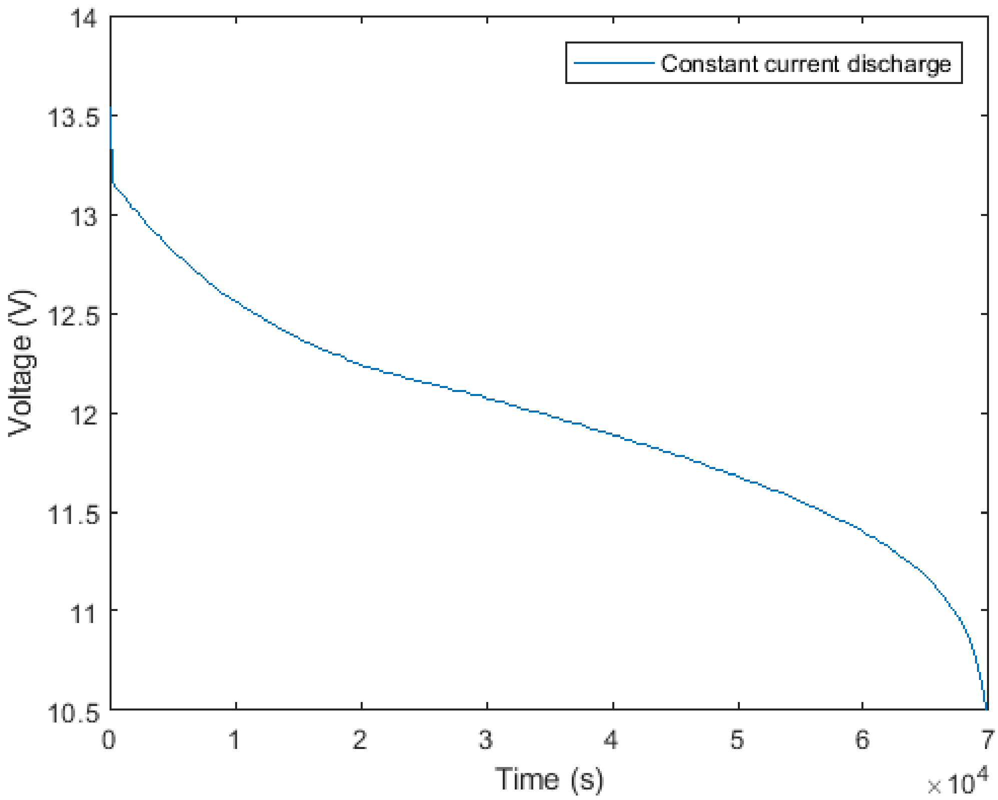

Figure 3.8: The voltage curve for a $C20$-test. The load current is $11.25A$.

The operating points also need to include temperature, and therefore the same test was performed several times, at different temperatures using the climate chamber on the test rig. The temperatures that the tests were performed in were $50°C$, $25°C$, $0°C$ and $-20°C$. The discharge test that was performed in each temperature can be seen in Figure 3.9.

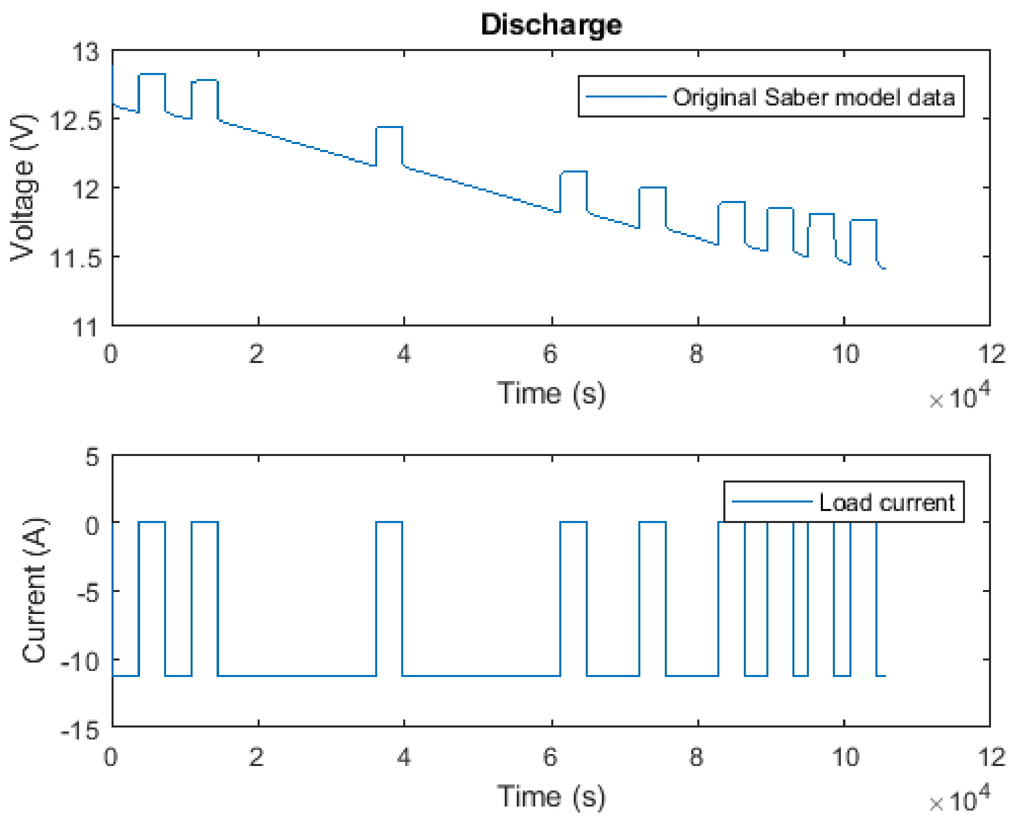

Figure 3.9: Test procedure for discharging the battery.

3.4.2 Charge

The operating points in the charging part of the tests were chosen in the same way as for the discharge part. Few operating points were chosen where the curve was linear and many operating points where it was not. However, as can be seen in Figure 3.10, the constant current charging curve does not look the same as the constant current discharging curve in Figure 3.8. Therefore the operating points will not be at the same SOC for charge and discharge.

In Figure 3.11 it can be seen what the test procedure looked like when performing it on the original Saber model.

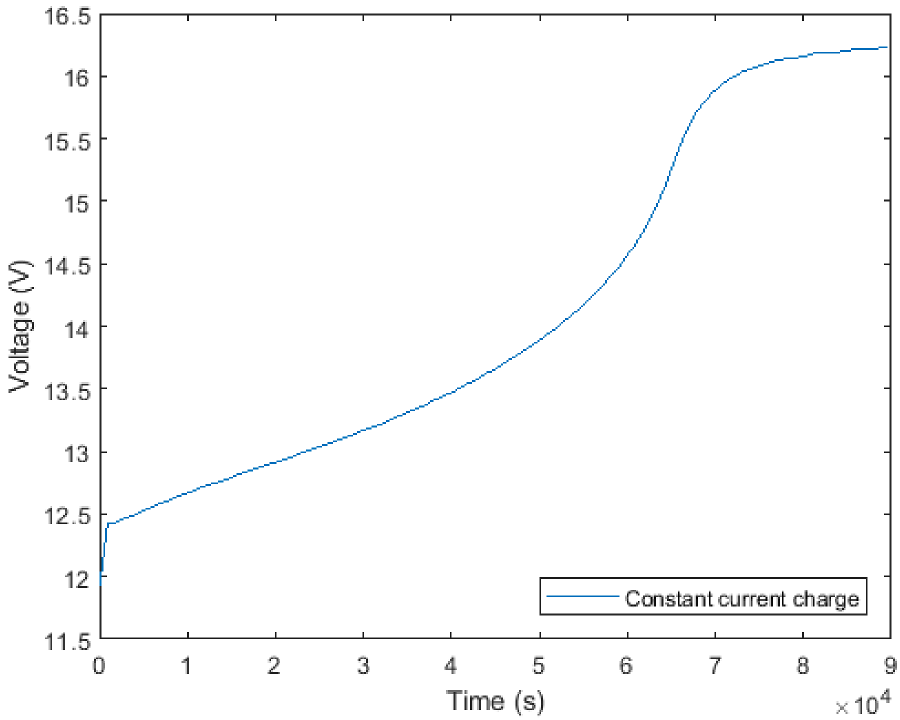

Figure 3.10: The voltage curve for a constant current charge. The charge current is $11.25A$.

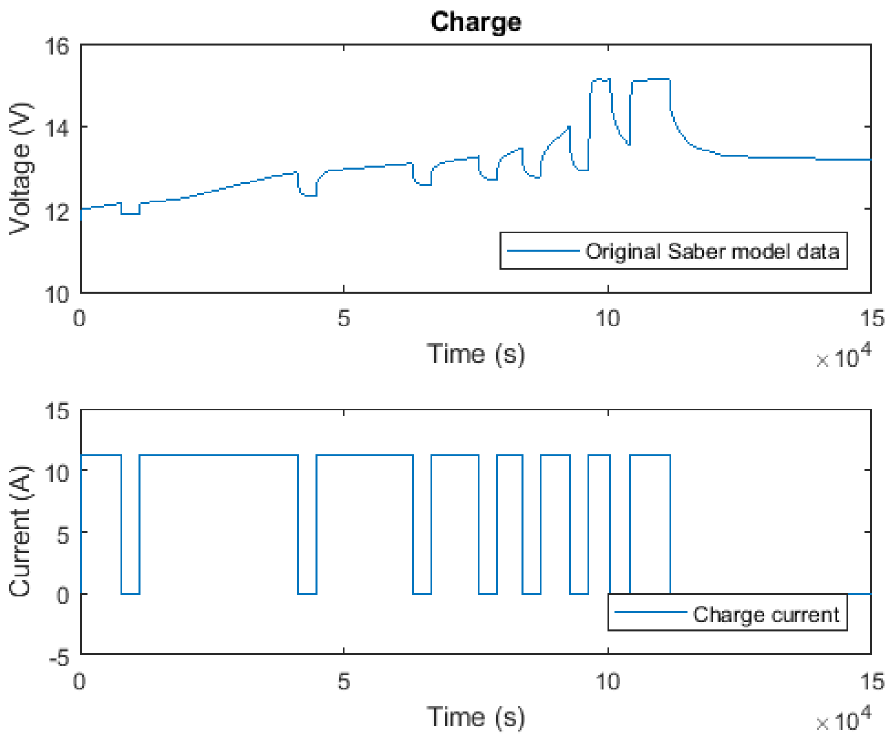

Figure 3.11: Test procedure for charging the battery.

3.5 State Of Charge

When charging the battery, all current that is fed into the battery will not be utilised to charge it. This is represented by the parasitic branch in the equivalent circuit model. Therefore, when calculating the SOC of the battery, the idea was to use the current through the main branch, I_p in Figure 3.7, to calculate how much capacity $[Ah]$ that goes into the battery.

Since the capacity of the battery depends on the current and temperature this must be included in the calculation of the SOC. This resulted in the following equations:

$$SOC(0) = SOC0 \tag{3.29}$$

$$SOC(k) = SOC(k-1) + \frac{i_m(k) * Ts}{Q_{max}(i(k), temp(k))} \tag{3.30}$$

where $i_m(k)$, is the current through the main branch at that time step, Ts is the step time in hours, $temp(k)$ is the temperature at that time step and $Q_{max}(i(k), temp(k))$ is the max capacity the battery has for a specific current and temperature. $SOC0$ is the SOC the battery has in the start of the simulation.

The max capacity for the battery for different currents and temperatures was obtained from old tests made at the company. In those tests different constant currents were drawn at different temperatures to obtain the capacity. To be able to use the results from the tests in the model, interpolation was made between the different currents and temperatures to get the max capacity for different conditions.

However, the knowledge in the programming language used by Saber, MAST, was limited, which resulted in that only the predefined blocks in Saber could be used. When using those blocks it was not possible to make a feedback loop to obtain $SOC(k-1)$ in the next iteration. This resulted in an implementations that was not correct but might be good enough.

The equation for the solution is

$$SOC(k) = SOC0 + \frac{Ts \sum_{j=0}^{k} i_m(j)}{Q_{max}(i(k), temp(k))}. \tag{3.31}$$

This equation was implemented as in Figure 3.12.

The problem with this calculation is that it always uses the integrated current signal from time 0 but divides it with the capacity for the currently used current and temperature. This results in that the capacity extracted from the battery will be divided with the max capacity for the currently used current regardless of what current was used previously, in comparison to the preferred calculation method in Equation 3.30, where the capacity extracted in each time step is divided with the max capacity for the current used in that time step. This results in incorrect SOC

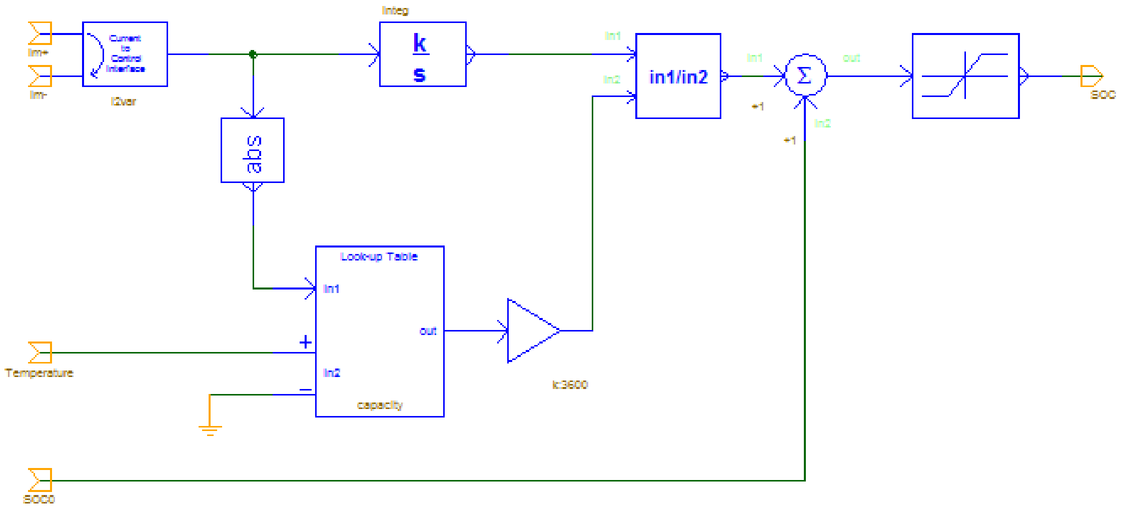

Figure 3.12: SOC calculation in Saber.

calculation when different currents are used.

Also if the battery is charged even though the SOC is at 100% the integrated current will keep increasing and will result in that the SOC will stay at 100% when the battery is being discharged and the SOC should start to decrease.

4

Results

In this chapter the resulting modelling method is presented as well as the resulting equivalent circuit model. The results from the equivalent circuit model with the identified parameters that were based on the performed rig tests are also presented. The results are discussed in Section 5.

The new rig tests that were performed were done in the temperatures $25°C$, $50°C$, $0°C$ and $-20°C$. Due to delays in the performance of the rig test and time limitations, the data was only processed for the first two tests, i.e. $25°C$ and $50°C$.

4.1 Modelling method

In order to see if the modelling method that was chosen was sufficient to model a lead acid battery, the rig test were done on the original Saber model and then a new model was built on that data. In other words, a model was made based on data from another model. This is not an acceptable way of making a model, but was only used to test the modelling method while the real rig tests were executed.

In Figure 4.1 it can be seen that by using the proposed method to identify the parameters the new model can resemble the original Saber model well when using the same input current. In this state of the process the SOC was taken from the original Saber model and used as an input to the equivalent circuit.

In the figure it can also be seen that the theory that the parameters changes linearly where the voltage is linear, seems to be relatively correct when comparing with the original Saber model. Therefore, the same operating points as planned were used in the new rig tests.

In Figure 4.2 it can be seen that the equivalent circuit model follows well except when discharging with a current of $16A$. When discharging with $16A$ the voltage drop for the new model did not correspond to the voltage drop for the original Saber model.

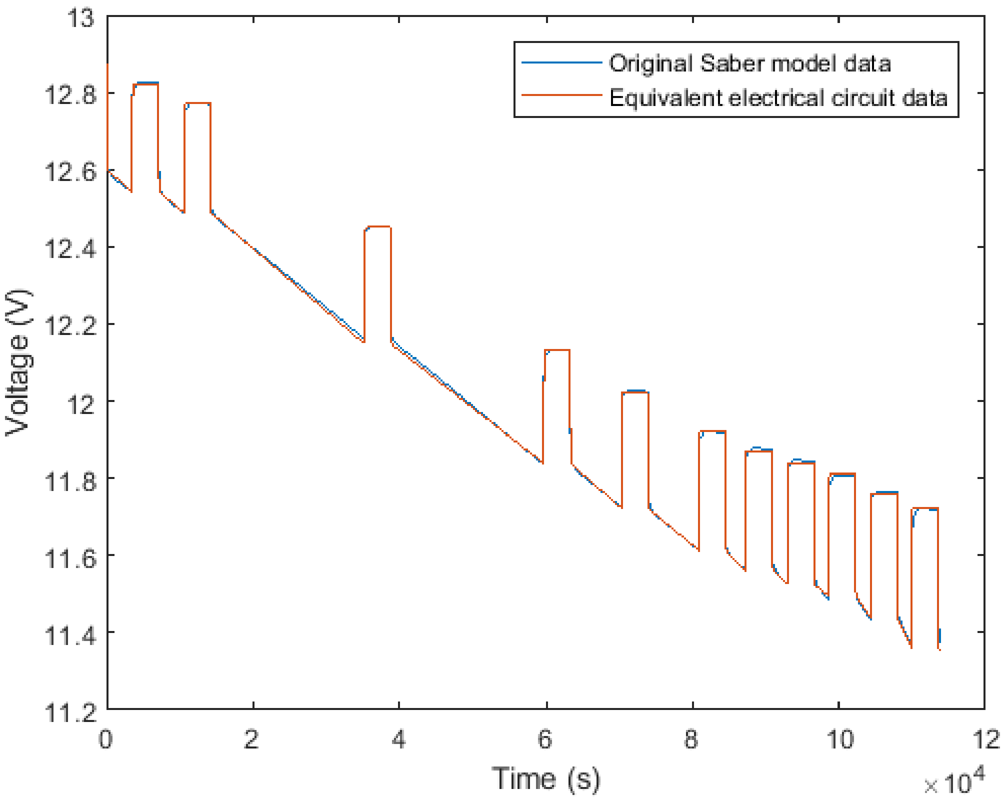

Figure 4.1: Test data constructed with the original Saber model compared with the new model trained with that data.

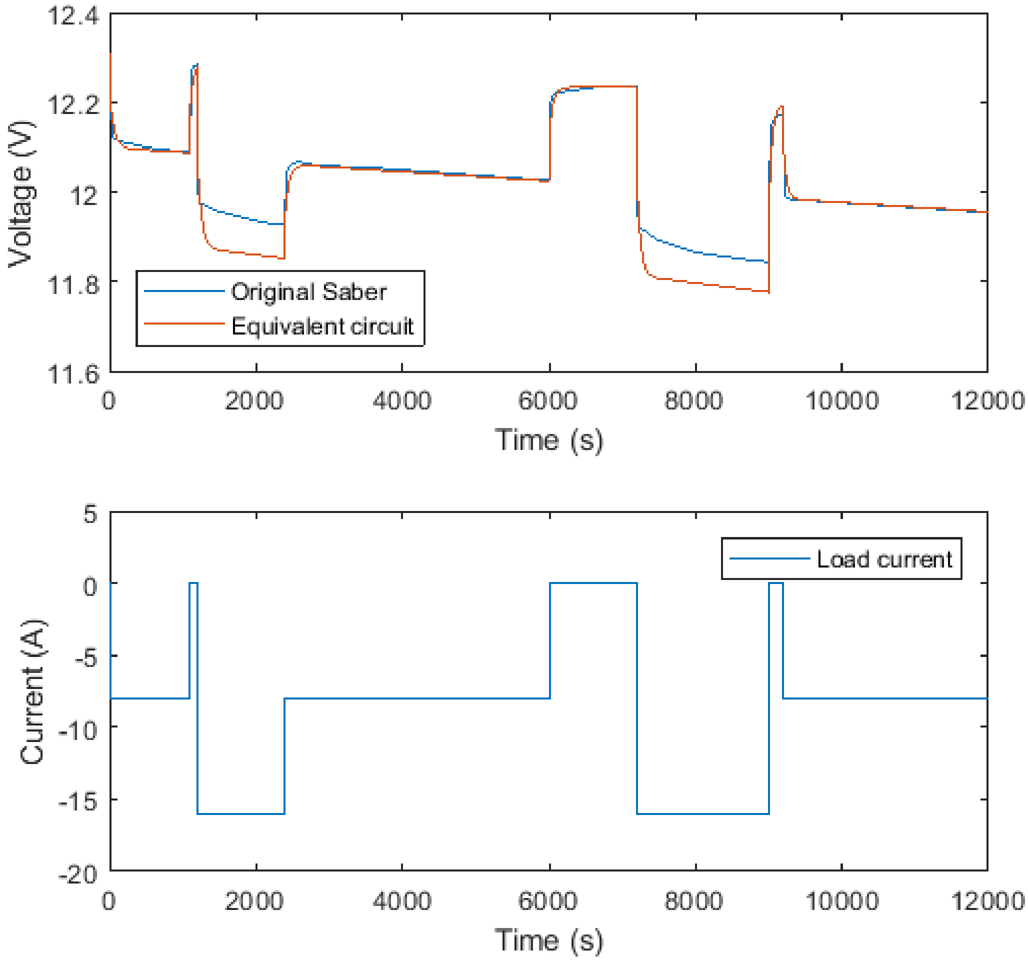

Figure 4.2: Original Saber model compared with the new model, trained with data from the original Saber model.

4.2 Equivalent electrical circuit model

The model was made with one circuit for discharge and one circuit for charge, as can be seen in Figure 4.3. All the resistors, capacitors and voltage sources are implemented as look-up tables with SOC and temperature as input. The SOC-calculation that is located in the bottom middle of the figure also has temperature as input but also SOC0, the initial SOC for the simulation. In the upper right corner is a controller that can take a SOC-curve over time as input and then feed it to the different components, instead of using the SOC-calculation. Below the controller is the temperature source where the temperature for the simulation can be chosen. Below the temperature source is a logical circuit that decides if the discharge or charge circuit is going to be used depending on if the current at the terminals is positive or negative. The terminals to the battery are located in the bottom right corner where a current source is connected in order to charge or discharge the battery.

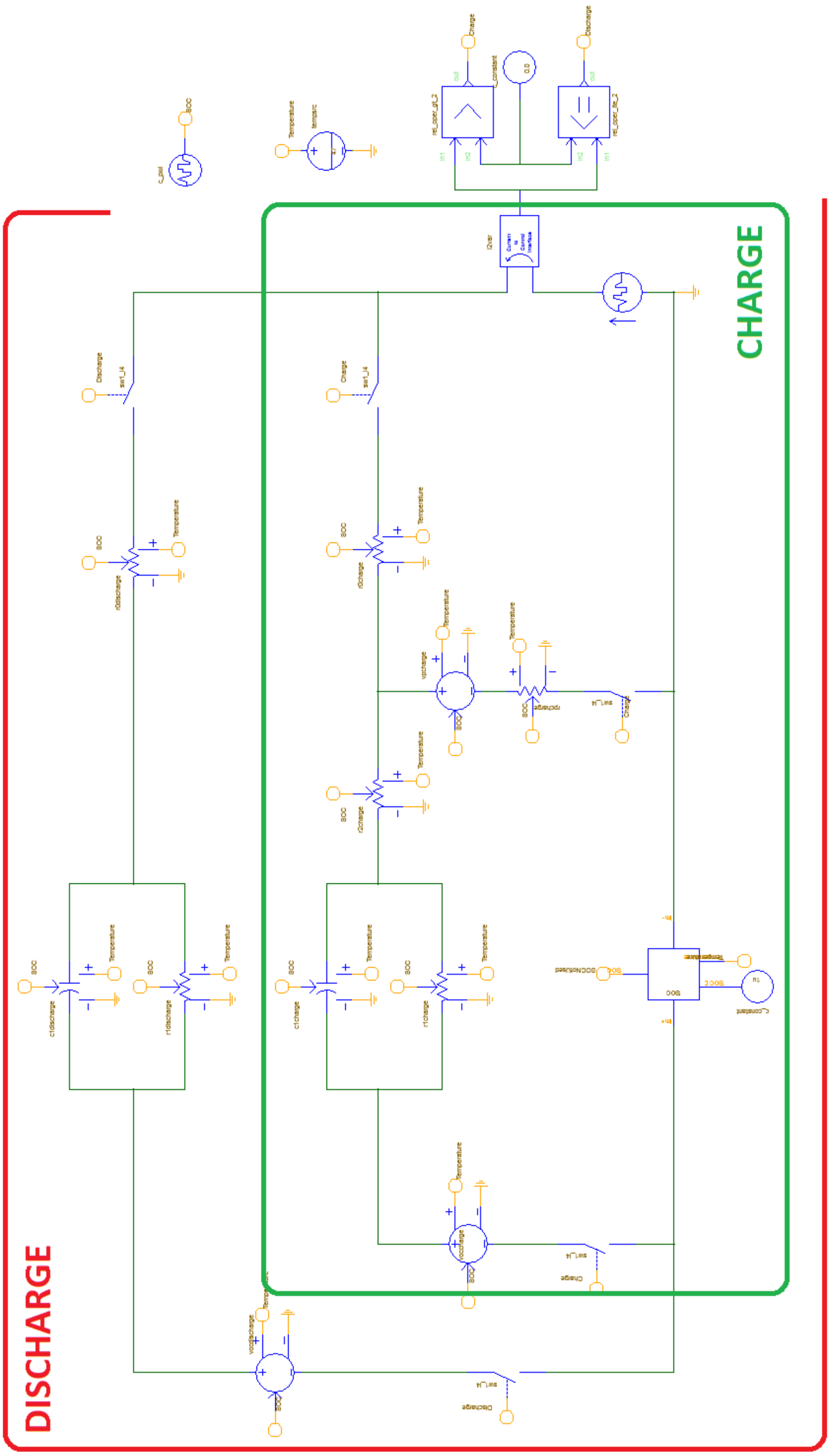

Figure 4.3: Equivalent circuit model in Saber.

4.3 Open circuit voltage

The OCV was said to only be dependent on SOC and not on temperature. The results from the new rig tests gave a different result, where it was seen that the OCV was different for different temperatures, as well as for the charge and discharge procedure. This can be seen in Figure 4.4 where the OCVs from the new rig tests are plotted against the SOC measured by the battery sensor. The OCV for the original Saber model is also shown in the figure and it can be seen that it is quite linear. It is also the same for different temperatures and for discharge and charge in contrary to what the rig test results showed.

The OCV from the new rig tests was identified by checking the voltage level at the flat parts of the log data voltage, in the end of each pause. Those values were chosen as the OCV for the corresponding SOC for each pause.

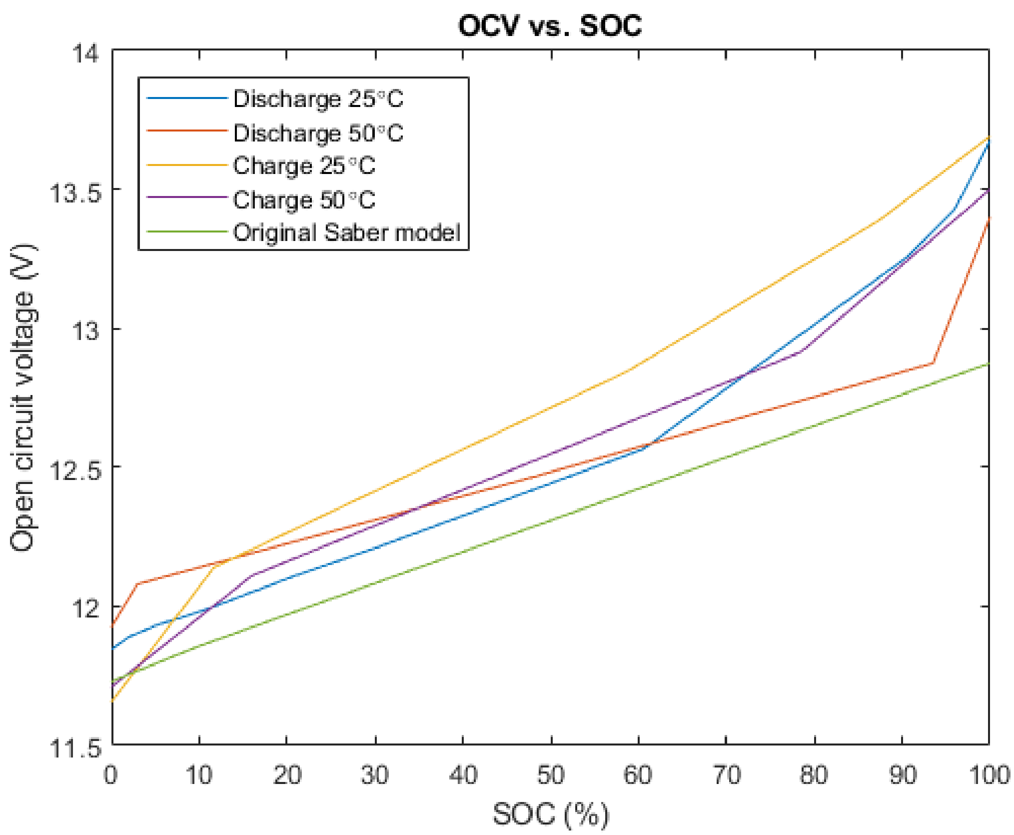

Figure 4.4: OCV with respect to the SOC according to the new rig tests, the original Saber model and the battery supplier.

4.4 Parameter identification

Once the new rig tests were performed, the data was processed and the parameters were estimated. In this section the result from estimating the parameters are presented and compared with the data from the rig tests, as well as the result from performing the same test in the original Saber model. In all the figures, the log data is represented with a blue line, the original Saber data with a red line and the equivalent circuit data with a yellow line. For the equivalent circuit the current input was retrieved from the log data. The same type of test was previously performed in the original Saber model and any differences in current can be seen in each figure. Furthermore, the SOC that is displayed in the figures is the nominal SOC.

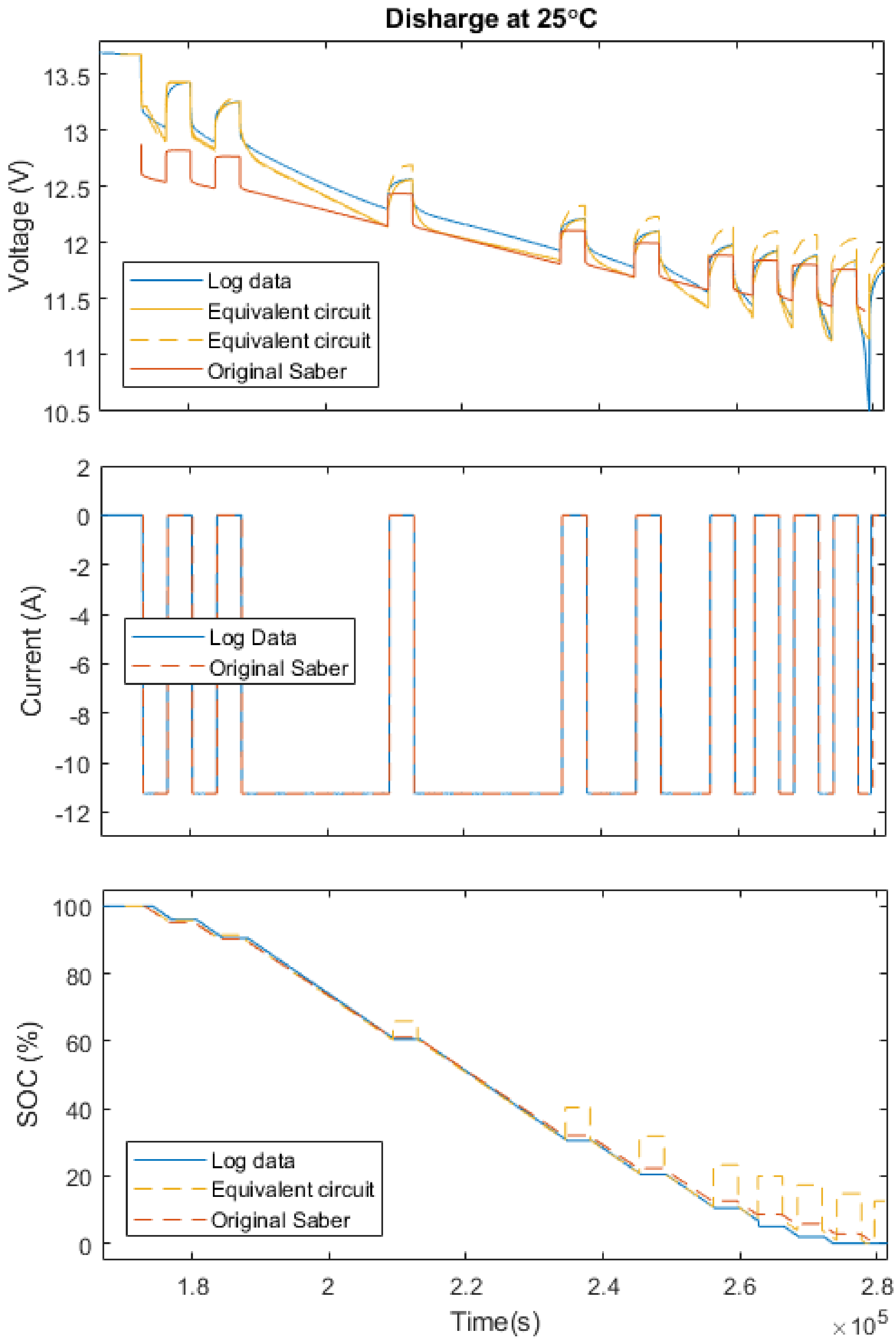

Figure 4.5: Discharge test at $25°C$.

In Figure 4.5 the result from discharging in 25°C is presented. There are two yellow lines, one solid and one dashed line that represents the equivalent circuit. The dashed line is the result when calculating the SOC based on the current that is drawn from or put into the battery. The solid yellow line represents the equivalent circuit when the SOC data from the rig tests has been taken as an input instead of calculating it. As can be seen in the SOC graph, the calculated SOC (yellow dashed line) corresponds very well to the SOC measured in the rig tests, except for when the current is equal to $0A$, i.e. in the pauses of the discharge. During the pauses the SOC jumps to a higher level. Since all the parameters are dependent of SOC, an incorrect value of SOC will yield incorrect values of the other parameters. This is especially clear when it comes to the OCV. When the SOC jumps to a higher level during the pauses the OCV will also be incorrect during each pause. This can be seen clearly in the voltage graph, where the dashed yellow line has an incorrect voltage level in the pauses, but during discharge it is the same as the solid yellow line. Because of a limited amount of time to correct the issue with the SOC calculation, the other comparisons have only been made where the equivalent circuit takes the rig data SOC as input, just as the solid yellow line in the voltage graph in Figure 4.5.

In the figure it is clear that the voltage from the original Saber model is at a lower level for high values of SOC. In the middle part however it corresponds quite well with the equivalent circuit but neither of the models are at the same level as the log data voltage. Furthermore the log data voltage drops in the end of the test which is not the case for the models. This drop occurs after the SOC reaches 0% and is therefore not interesting. How well the voltage from the different models correspond to the log data in each pause is better presented in Figure 4.6 where two of the pauses are zoomed in on. In the graph it is clear that both the original Saber model and the equivalent circuit has a lower voltage during discharge, but in the pauses the equivalent circuit reaches the same OCV as the log data. The original Saber model does not reach the same OCV, and it does not have the same transient behaviour. The original Saber model has a sharper curve form compared to the equivalent circuit that has a similar shape as the log data.

In Figure 4.7 the charge test in 25°C is displayed. In the voltage graph the equivalent circuit corresponds very well to the log data for most part of the test. At time $360000s$ however, the voltage starts to differ and then stops at a certain voltage level, since the SOC is constant from that point. The original Saber model is again too low compared to the log data. The transients however seem to have a more similar shape to the log data than in the discharging test in 25°C. The SOC for the original Saber model and the log data are quite similar although according to the log data the battery never reaches 100% SOC. It stops at around 90%, in contrast to the original Saber model that keep increasing until it reaches 100% SOC.

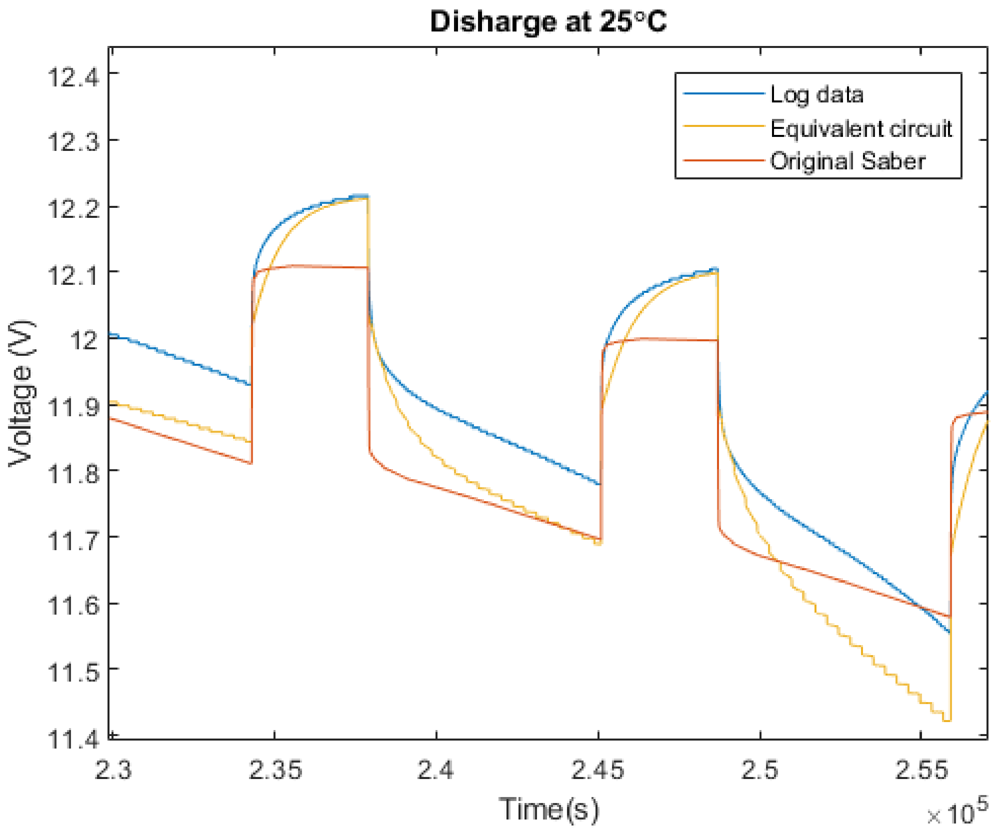

Figure 4.6: Zoom of the discharge test at 25°C.

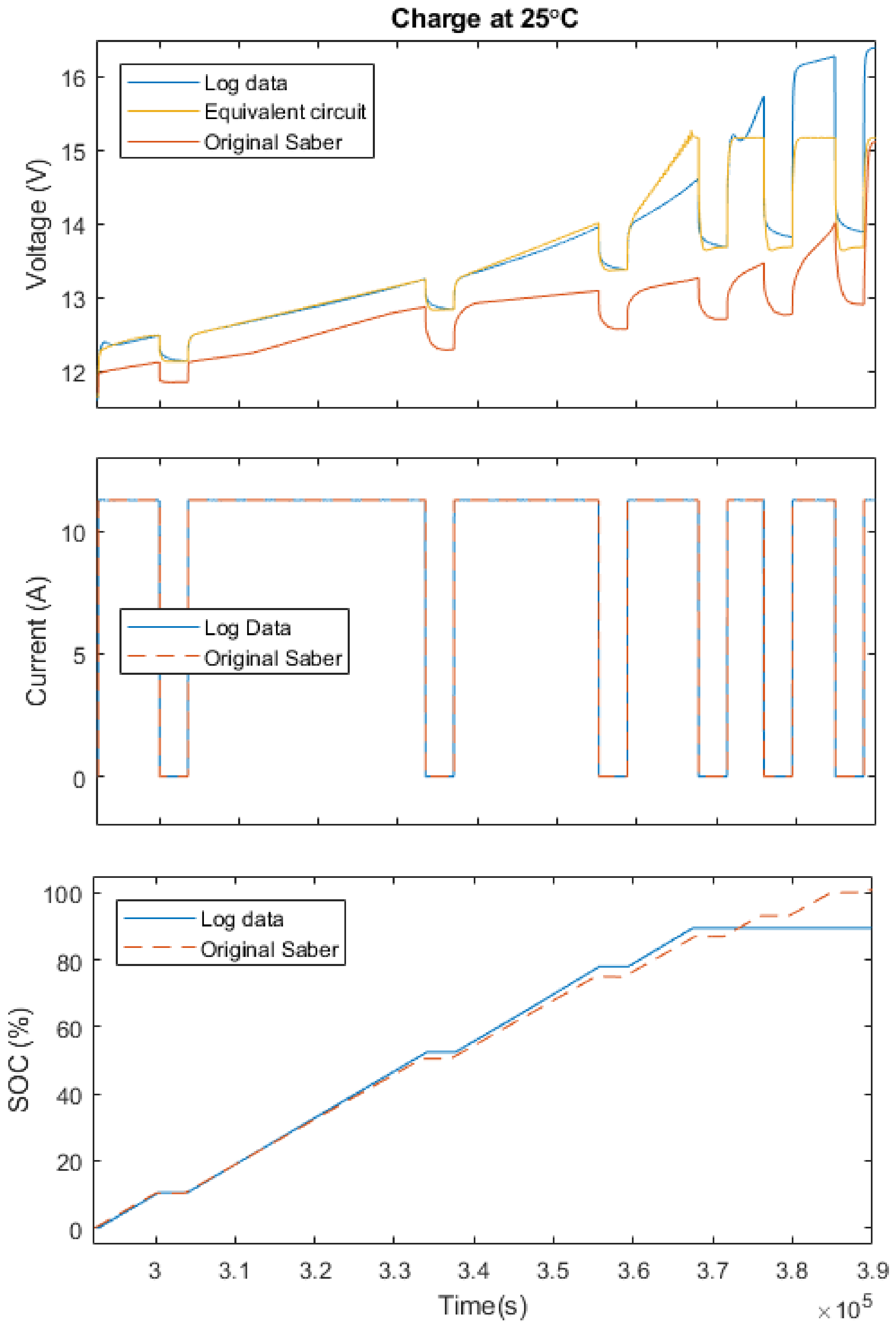

Figure 4.7: Charge test at 25°C.

The discharge test in 50°C is presented in Figure 4.8. In this test the original Saber model behaves as in the discharge test for 25°C. It starts at a lower OCV than the log data, and stays at a lower level for the majority of the test. However, from time 60000s and forward the OCV seem to match in the pauses. The SOC differ quite a bit in these pauses though, which means that the OCVs does not match in relation to the SOC. The shape of the transients is not quite as smooth as the log data. In the end the voltage differs significantly from the log data, but again, since the SOC has already reached 0% this part of the behaviour is not of interest. The equivalent circuit matches the log data poorly in the first pause, which is a consequence of that the SOC does not start to decrease until after the first pause. After the first pause however, the model matches the log data well until approximately time 90000s. At this time it starts to differ from the log data voltage, especially once the SOC reaches 0%.

There is also a significant difference in the SOC between the log data and the original Saber model, which has not been the case in the previous tests. According to the log data SOC the battery is empty much sooner than the original Saber model indicates.

In Figure 4.9 the result from the charging test is presented. Like in the previous tests the original Saber model voltage is too low compared to the log data. The voltage from the equivalent circuit is similar to the log data until the SOC reaches 100%. From this point forward the equivalent circuit voltage is constant during charging since the SOC is constant. The original Saber data voltage has the same behaviour once that models SOC reaches 100%. This is not the case for the log data, since the log data voltage keep increasing after the SOC indicates that the battery is fully charged.

Furthermore, here as well as for the discharging test at 50°C, the log data SOC is very different from the SOC in the original Saber model. The log data SOC indicates that the battery is fully charged much sooner than the original Saber model indicates.

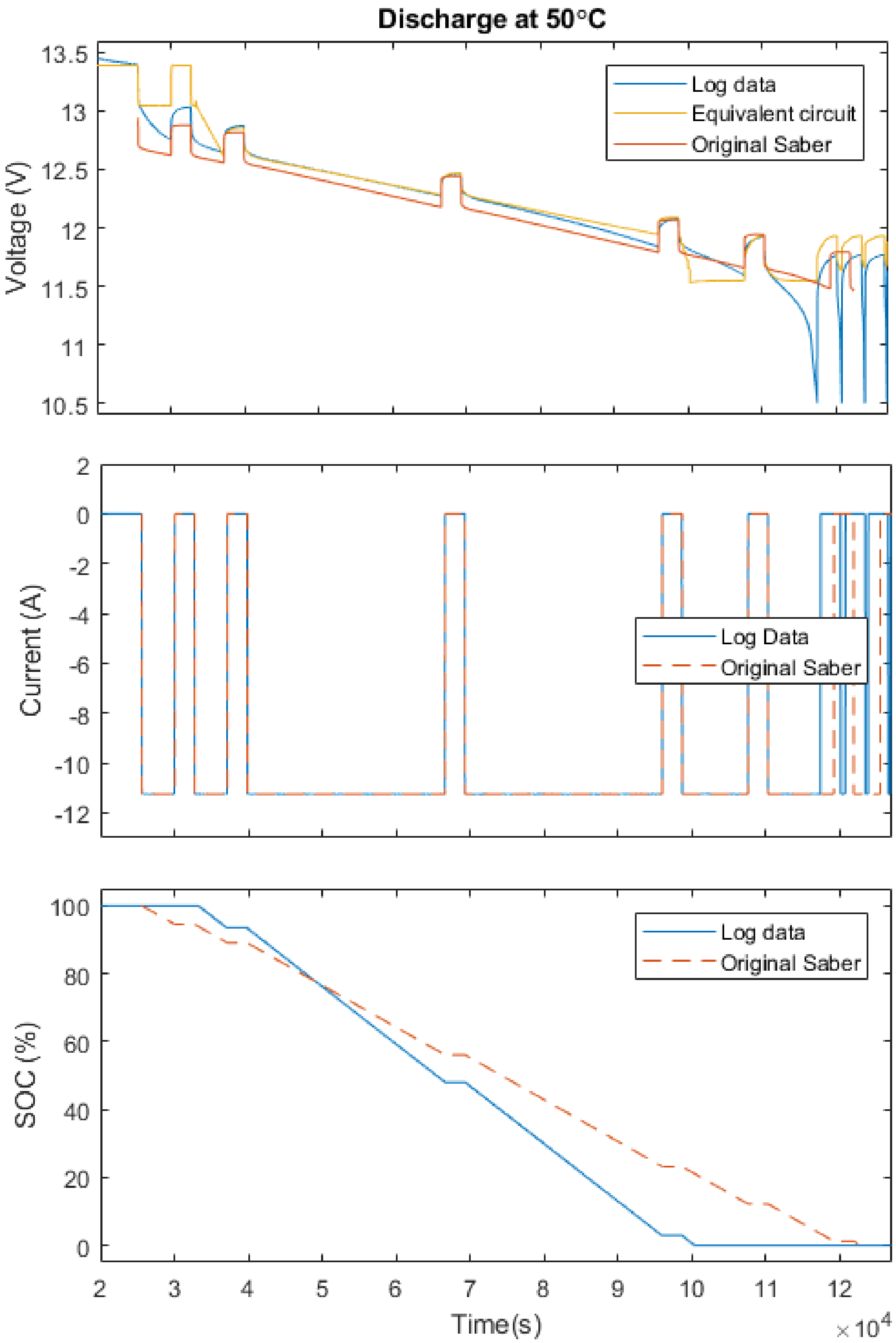

Figure 4.8: Discharge test at $50°C$.

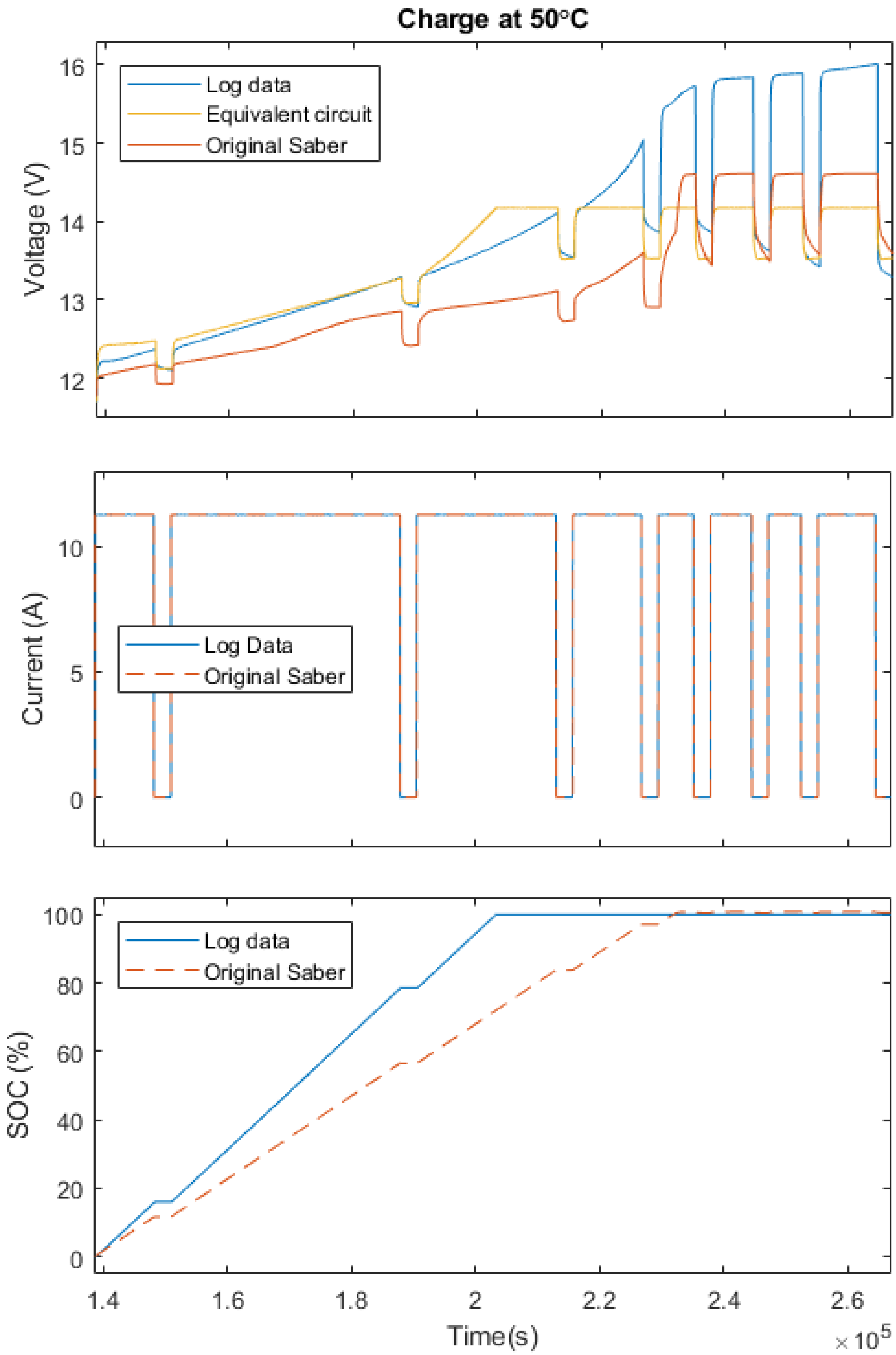

Figure 4.9: Charge test at $50°C$.

4.5 Transients

When deciding what model to use it was assumed that the transients that occur when going from discharging the battery and pausing would be the same as when pausing and then starting to discharge the battery again. It was discovered that this assumption was not correct, which can be seen by closely reviewing Figure 4.6.

In Figure 4.9 it can be seen that with higher SOC it takes longer time for the transient effect to end and reach the OCV value. At lower SOC the voltage levels out quite well during the pauses, and at higher SOC it can be seen that the voltage is not as close to stabilising at a constant level before the pauses are ended and the charging is started again. The reversed behaviour can be seen for the discharging in Figure 4.8, i.e. that the voltage in the pauses at low SOC does not level out as well as at higher SOC.

4.6 Capacity and state of health

The times to discharge and charge the battery during the tests were calculated from similar tests made at the company. The calculated times did not correspond to the actual times it took to discharge and charge the battery in the new rig tests. In Table 4.1 the calculated capacity and the battery's actual capacity can be seen. The capacity that the battery actually had was calculated by subtracting the time for the pauses in the discharging tests. That way the total discharging time is obtained and since the current is known the capacity can be calculated as in Equation 2.3.

	New rig tests	Calculated from old rig tests
$25°C$	$222Ah$	$225Ah$
$50°C$	$200Ah$	$279Ah$

Table 4.1: Comparison of the capacity in the new rig tests and the calculated capacity from rig tests made at the company.

As stated in the theory the battery takes damage when cycling it and using it in cold and hot temperatures. A $C20$-test was made before the new rig tests were made in order to obtain the capacity for this specific battery. Unfortunately a mistake was made on the $C20$-test that resulted in that a current of $11.25A$ was drawn for 20 hours instead of until the battery was completely empty. Because of this the capacity of the battery could not be calculated from the initial $C20$-test. However, since the battery lasted for 20 hours it is known that the capacity should be at least $225Ah$.

Because of the cycling the battery was damaged and its capacity decreased. The model was supposed to represent a new battery with 100% SOH but these tests cannot represent a battery with 100% SOH since the tests damage the battery. How much the battery was damaged was approximated by a sensor that measured the SOH. The SOH before and after each test can be seen in Table 4.2.

Temperature	Type of test	SOH before	SOH after
$25°C$	Discharge	100%	89%
$25°C$	Charge	89%	89%
$50°C$	Discharge	89%	89%
$50°C$	Charge	89%	89%

Table 4.2: The SOH before and after each test.

As can be seen in the table the SOH is drastically decreasing during the $25°C$ discharge test. For the rest of the tests the SOH is constant at 89%.

4.7 State of charge

It was known beforehand that the SOC-calculation in Saber would not be perfect. It was not known however, whether it would be usable or not. When looking at the results from the comparisons between the original Saber model, the new log data and the new equivalent circuit model, in Figure 4.5, it can be seen that it is only in specific conditions the SOC calculation matches the SOC from the original Saber model and the log data. Those conditions are when a constant current is used to discharge or charge the battery without pauses.

When discharging or charging with a constant current and then doing a pause the SOC jumps to a higher or lower value respectively. This is because the SOC calculation is using the whole integrated current from the start of the test but dividing with the max capacity for the currently used current and temperature. This results in that the SOC will appear higher than it really is when doing a pause in a discharge process and lower than it really is when doing a pause in a charge process. The same thing is applicable when using different currents in the same simulation. If discharging with a high current and then a low current the SOC will be higher than it should and the other way around when charging.

The max capacity used in the calculation of the SOC was taken from tests made at the company and it cannot be certain how accurate these tests are. Furthermore, the values from those tests were only based on tests made on a single battery. Every time the battery is cycled it also looses SOH. This makes the capacity lower. Since it is unknown what the SOH was for the battery that the company tests were made on, the max capacity from those tests might not correspond to the max capacity for the battery used in the new tests. This could contribute to an incorrect calculation of the SOC.

4.8 Comparison between old rig tests, original Saber model and equivalent circuit model

The equivalent circuit was compared with old rig tests and the original Saber model. The log current from the old rig tests were used as input to the original Saber model and to the equivalent circuit model. The SOC from the log data was also used as input to the equivalent circuit. These rig tests however, are from some years ago, which means that the battery sensor is not very reliable when it comes to the SOC.

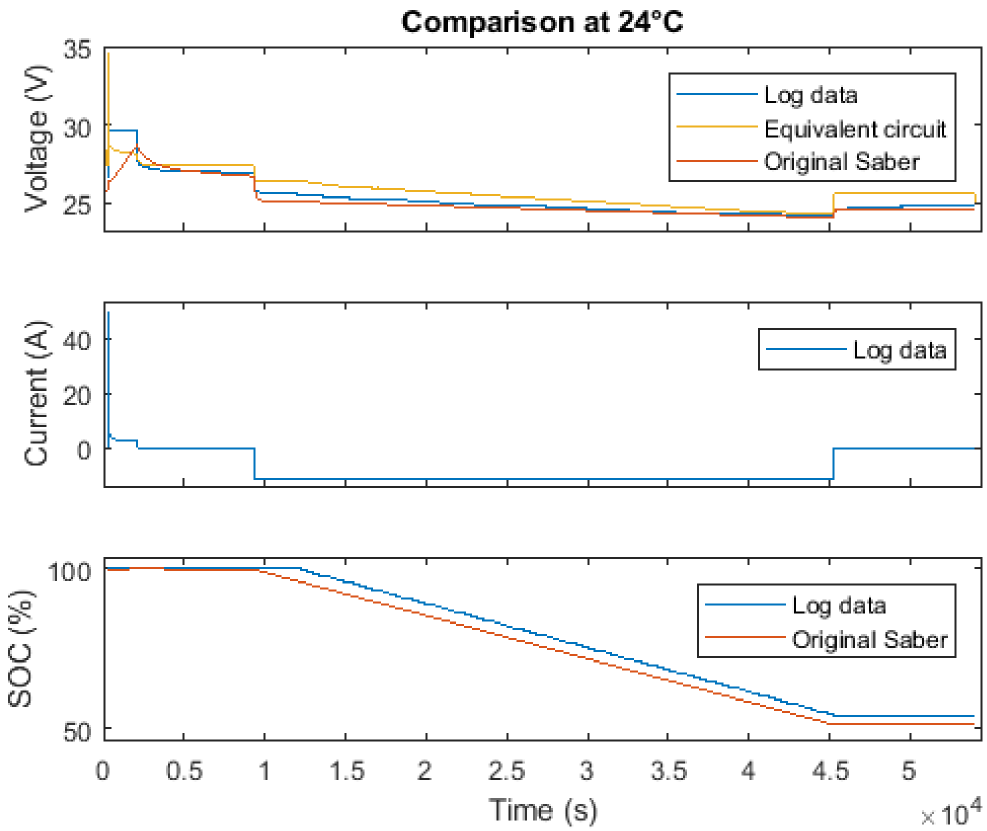

Figure 4.10: Comparison between the old log data, original Saber model and the Equivalent electrical model at $24°C$.

In Figure 4.10 the voltage curves are fairly similar. However, the Saber model voltage tend to be a bit lower than the log data voltage. It is also obvious that the Saber model cannot charge the battery with the type of current signal that is used in the initial phase, i.e. it cannot handle charging the battery that fast. The voltage also drops slower than the log data when the charging stops, and faster when a load is applied.

In Figure 4.10, 4.11 and 4.12 it can be seen that the level the voltage from the equivalent circuit converges to when the current is at $0A$ does not match neither the original Saber model, nor the old rig tests. The equivalent circuit starts and ends at higher voltage levels than the log data and the original Saber model. This is because the equivalent circuit model has higher values of the OCV.

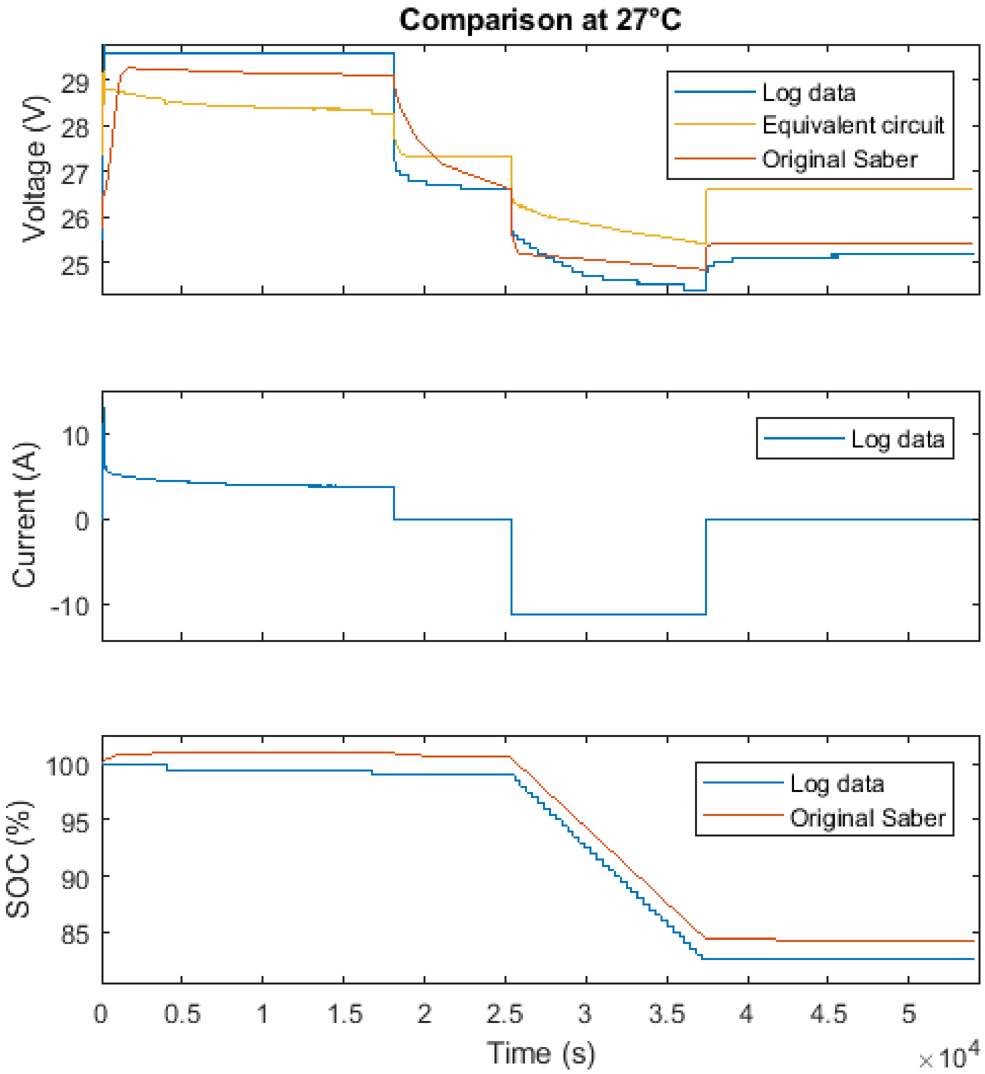

Figure 4.11: Comparison between the old log data, original Saber model and the Equivalent electrical model at $27°C$.

As can be seen in Figure 4.11 the peak in the current signal at time zero does not generate as high battery voltage in the Saber model as on the battery on the rig. This means that when charging with the alternator the model does not give the correct voltage. The Saber model response is also slower than the log data in the initial phase and when the charge process is ended and no load is applied. When a load is applied at time $25000s$ the voltage in the original Saber model decreases too fast and levels out at a too high voltage. As a consequence of levelling out on a too high voltage, the voltage is too high in the following phase as well, i.e. the phase when the load is removed. Even though the log data curves are not very smooth, it can be seen that the Saber model does not correspond that well. If making a change in the current signal at time $20000s$ for instance, the voltage level will start changing from very different voltage levels which could result in a large error between the model and the log data. The SOC is mainly displayed to get a sense of approximately what the SOC level is. The reliability of the battery sensor when it comes to the SOC, however, is not very good, as explained in Section 3.1.2.

In Figure 4.10, 4.11, 4.12 and 4.13 it can be seen that when doing a constant voltage charge in the log data, the voltage for the equivalent circuit get the same shape as the current instead of a constant voltage as in the log data. The same thing can be seen for the original Saber model when doing a constant voltage charge in high temperatures, such as in Figure 4.13.

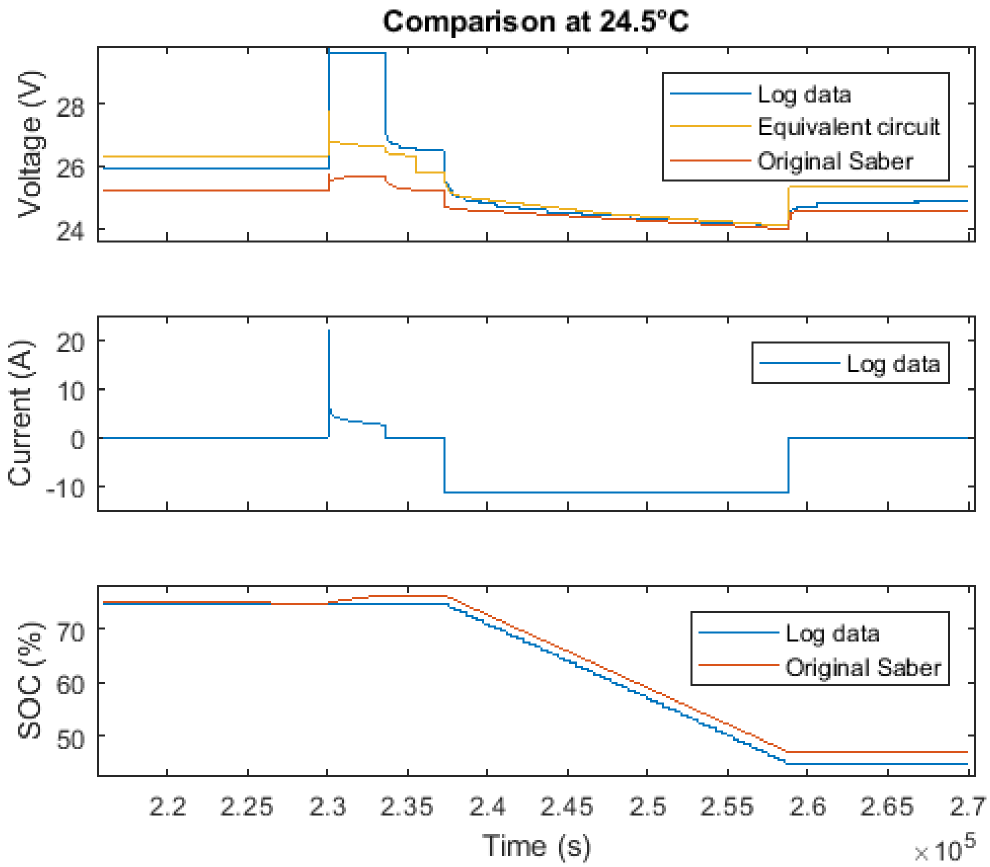

Figure 4.12: Comparison between the old log data, original Saber model and the Equivalent electrical model at 24.5°C.

In Figure 4.12 there is an error between the voltage curves at time 215000s. Since there is no load applied and there is no charging of the battery the voltage in the first phase of the plot should represent the OCV of the battery at 75% SOC. The OCV depends on the SOC and the difference in the voltage between the log data and the Saber model indicates that either the OCV in the model is wrong or the battery have not rested enough to reach OCV. However, since the log data voltage does not decrease during the first four hours it seems to be at the OCV. Another possibility is that the log data SOC is wrong and therefore when starting at that SOC in the simulation, the OCVs does not match.

In Figure 4.10, 4.11 and 4.13 it can be seen that when going from a charge to a pause, $I = 0A$, the voltage transients that occur in the equivalent circuit follows the log data voltage pretty well compared to the original Saber model. Also the decrease in voltage that occurs when doing a constant discharge as in Figure 4.12 is similar in the shape between the old log data and the equivalent circuit.

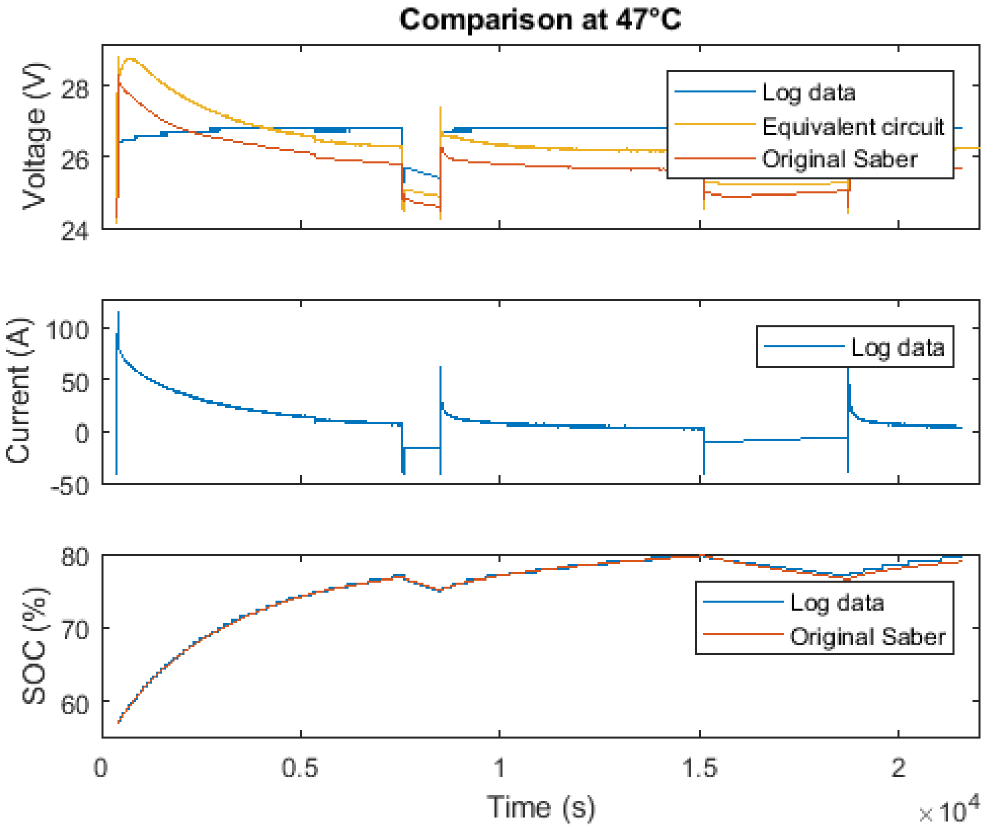

Figure 4.13: Comparison between the old log data, original Saber model and the Equivalent electrical model at $47°C$.

In Figure 4.13 the voltage from the Saber model increases too much from the peak in the input data. Instead of that the current inputs to the original Saber model results in a constant voltage charge, the voltage follows the same patterns as the input current. This behaviour is discussed in Section 5.2.

In Figure 4.14 it can be seen that when doing a constant current discharge and then a constant current charge the original Saber model nor the equivalent circuit can match the voltage from the log data neither at low nor at high SOC.

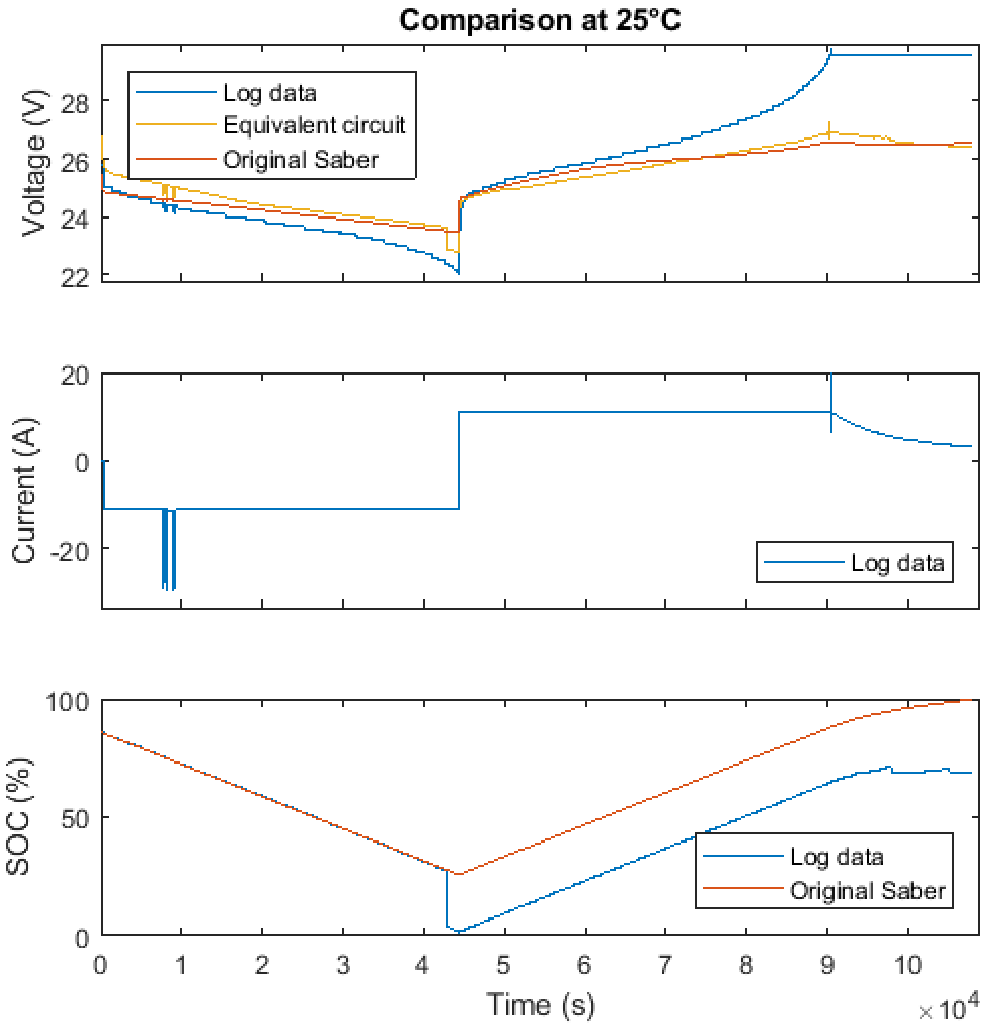

Figure 4.14: Comparison between the old log data, original Saber model and the Equivalent electrical model at 25°C.

In Figure 4.14 comparisons made for 25°C are presented. As can be seen in the current-graph there is a constant load applied for around 45000s and then the battery is charged with a constant current until approximately time 90000s when the battery is instead charged with the alternator. When the constant load is applied, the Saber model voltage does not decrease as much as the log data, but when starting to charge, it rises to the same level. After some time of constant charging the log data increases exponentially which is not the case for the model. When starting to charge with the alternator both voltage curves stay fairly constant but at different levels. This could be expected since they are at different levels when the charging with the alternator starts.

In Figure 4.10, 4.11 and 4.12 it can be seen that when going from a discharge to a pause there is no transient effect in the equivalent circuit voltage.
A summary of the behaviour of the original Saber model from all the above com-

parisons, is that when charging with the alternator the Saber model does not reach as high voltage as the battery in the rig test does. Furthermore, the Saber model voltage seem to change faster than the log data when applying or removing a load. However, when ending a charge session with the alternator the Saber model voltage often decreases slower that the log data. From the tests it can also be seen that the Saber model voltage seem to level out at the same level as the log data after some time, when using constant currents for long periods of time and not applying too large changes. Since it is at the transients the voltage curves differ most, large and/or frequent changes in current will cause the Saber model voltage to start changing before it levels out. This means that it will start changing from a different level than the log data and hence, it will reach a different level after the change as well.

5
Discussion

In this chapter the methods that have been used as well as the results presented in Chapter 4 are discussed.

5.1 Modelling method

When making a model of a model, such as identifying the parameters for the equivalent circuit model based on data from the original Saber model, there are many things that differ from the normal case when making a model based on data from tests made on real batteries. For instance, the output from the original Saber model will be theoretically correct and consistent since it is generated from equations and calculations. That makes it easier to make a model that will give the same output, compared to making a model of test data from a real battery test. This could be a reason for why the parameter identification from the original Saber model data went so well.

As could be seen in Figure 4.2 the voltage for the equivalent circuit did not have the same drop as the original Saber model. According to Ohm's law the behaviour of the equivalent circuit model is correct. If the resistance of the circuit is the same, a doubled current change will result in a doubled voltage change. In the figure, the voltage drop is doubled for the equivalent circuit model but not for the original Saber model. The difference in drop between the models could be explained by that the resistance, R_0, in the original Saber model might be dependent of the current.

5.2 Equivalent circuit model and comparison between old rig tests, original Saber model and equivalent circuit model

The SOC-calculation made in the equivalent circuit model did not work well enough to be trusted. Therefore the equivalent circuit model cannot be used to see under what conditions the truck can be used in order to still be able to crank the engine. Fixing this calculation could change some of the obtained results, especially where the log data SOC did not behave as it should. An example of this is in Figure 4.8, where the SOC should start to decrease as soon as there is a load applied, but it does not. The calculated SOC would have decreased, like the SOC from the original Saber model, which would have lead to a better behaviour of the voltage at this time.

Furthermore, the equivalent circuit model did not work as intended. As stated in Section 4.8 there is no transient when going from a discharge to a pause. This is probably because when doing a discharge the equivalent circuit uses the discharge circuit and when doing a pause, which is defined as 1 micro Ampere in simulation, it uses the charge circuit. When switching from the discharge circuit to the charge circuit, the capacitor in the charge circuit is empty. Since the current is close to zero no current will be used to charge the capacitor which causes the transient to be absent.

In Section 4.8 it could also be seen that when doing a constant voltage charge the voltage of the equivalent circuit had the same shape as the current instead of being nearly constant. When this occurs it means that the circuit only consists of resistors, there is no current flowing through the capacitor. This might be explained with that when doing a pause the current is set to 1 micro Ampere. The pauses are very long and the small current flowing through the circuit might result in that the capacitor of the circuit is reaching steady-state and is fully loaded. When this happens all current will go through the resistor instead of the capacitor. If then changing the current to a charge it will still be fully loaded and all current will go through the resistors and give the results as in the figures in Section 4.8.

5.3 Open circuit voltage, parameter identification and transients

The OCV for the new rig tests differs between different temperatures and also between discharge and charge. This should not be the case. One issue is that once the battery has been charged to a high voltage, as it is for example every time the battery is top charged between each test, is that it can take 1-20 days for the OCV to decrease and stabilise at its correct OCV level, according to the battery supplier. To be able to finish some of the tests in time, this kind of waiting before each test was not possible and therefore an alternative method was tried out, where a small discharge of $5A$ during 4 minutes was made. This corresponds to turning on the headlights on the truck. This method had not been verified but was sometimes used on other tests at the company. It is likely that this small discharge was not enough to quickly reach the true OCV, which is why the OCV in the new rig test was quite high. This could also be a reason why the OCV differs between charge and discharge at high SOC. However, at low SOC the OCV should have been the same for charge and discharge.

Additionally, incorrect behaviour in the log data SOC from the battery sensor could affect the OCV-SOC relation. If the sensor does not show the correct SOC value in each pause the OCV value in each pause will correspond to the wrong SOC.

Too short pauses is another thing that could affect how correct the obtained OCV values are. As can be seen in Figure 4.9 the voltage seem to level out fairly well at low SOC, but at high SOC it is not stabilised before the charging starts again. That means that the voltage reached at the end of the pause is probably not the correct OCV.

Too short pauses could also cause the other parameters to be incorrectly estimated. For instance, if the voltage does not reach OCV during a pause, the instant voltage change after the pause might be smaller than it normally should be. This would lead to a too low estimated value on the internal resistance. It also makes it more difficult to estimate parameter R_1 and C_1 correctly, since the full transient is not visible. Furthermore, starting at a too high OCV at 100% SOC could also lead to incorrectly estimated parameters, which could make the model start at the wrong level and then show the wrong behaviour if used in another scenario.

It is also difficult to determine how well the parameters were estimated since there are no other tests performed on the battery that could be used as verification. Ideally when making a model there is one set of data used for making the model, one set of data for choosing the best model and one set of data for making the final verification of how accurate the model is.

Additionally, it could be problematic to use a genetic algorithm to estimate the parameters. Since the algorithm uses a stochastic search to find good parameters there could be several different values for the parameters that will give approximately the same result. This also means that when identifying the parameters in each operating point separately, they might not follow a pattern which they normally do.

Finally, the issue with the transients being different in the start and end of a pause would most likely need to be handled by using a more complex equivalent circuit model with more RC-blocks.

5.4 Capacity, state of health and state of charge

As can be seen in Table 4.1 the capacity for the first test, i.e. the $25°C$ discharging test, the capacity was $222Ah$. However based on the result from the $C20$-test, the capacity should have been at least $225Ah$. The reason for this difference could be that the battery lost some capacity during the charging after the $C20$-test, although this should not happen.

The battery model was supposed to be made for a battery with 100% SOH which is very difficult since the tests that were made decrease the SOH during the test procedures. Most batteries do not have 100% SOH for a very long time which also makes it unrealistic to make a model for that kind of battery. That will give a model that is more optimistic than most real batteries, which is usually not desirable.

As can be seen in Table 4.2 the SOH decreases after the first discharge test and then remains constant. This is not a very likely scenario which indicates that the

SOH measurement might not be completely correct. However, it is normal that the SOH does decrease after discharging a battery to 0% SOC, which could be a reason for the SOC not being able to reach 100% when charging the battery again, as in Figure 4.7. This is reasonable since the SOC that is shown in the figures presenting the results from the new rig tests is the nominal SOC, i.e. if the SOH is decreased the SOC cannot reach 100%.

Although the decreasing SOH could be an explanation to why the nominal SOC does not reach 100% when charging the battery in $25°C$, it does not explain how the SOC is at 100% once the test at $50°C$ is started. One explanation for this could be that the SOC is not correctly measured, or that the measurement temporarily is not functioning well at the end of the $25°C$ charging process.

In both the charging and the discharging test for $50°C$ the log data shows that the real battery is discharged/charged faster than the original Saber model. This is most likely due to the fact that the battery sensor is incorrect. Another reason could be that the SOH was not 100% for the real battery which means that it had less capacity. The original Saber model is based on a battery with 100% SOH and therefore expects the battery to have more capacity. However, if the battery had less SOH than 100%, the SOC should not have been able to be 100% which it is at some point during both tests.

Regarding the incorrect calculation of the SOC, the issues that it caused, such as having to rely on the battery sensor for the SOC, could have been solved with better knowledge in Saber. Then the calculation could have been implemented as intended.

6
Conclusion

In order to make the model functional the SOC-calculation needs to be implemented in the Saber program such as in Equation 3.30. Additionally, the issues discussed in Section 5.2 with the capacitor in the equivalent circuit being in steady-state causing an absence of transients needs to be solved.

Furthermore, a more complex model could solve some issues, such as modelling the different transients in the start and end of a pause and modelling the behaviour of the battery in the end of the charging process once it reaches 100% SOC.

In order to get a reliable model the data that is used to make the model needs to be reliable. This is not the case for the data that was obtained from the rig tests. In Section 5.3 the issues with the log data from the new rig tests are discussed. More tests need to be done where these issues are taken into consideration, such as making sure the OCV is at the correct level at the start of the tests. It would also be beneficial to perform the tests on a set of batteries in order to see how the batteries differ from each other. Different tests would also be preferable, to get one set of data that can be used for modelling and at least one set that can be used for verification.

Making the tests, however, is a very time consuming process and it could therefore be good to investigate if there are alternative methods that are simpler to perform.

Another conclusion is that the battery sensor used to calculate the SOC and SOH of the battery does not seem to work perfectly. More investigations have to be made in order to find what the cause of these errors is.

To summarise, the model that was used worked well under some conditions and could probably work well enough for its purpose. However, some things need to be fixed and improved. These things are mainly the SOC-calculation, new rig tests and having the same circuit for discharge and charge.

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