UPPSALA UNIVERSITET

UPTEC STS 15001
Examensarbete 30 hp
Februari 2015

Ensure the electric power system's durability through battery monitoring

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Abstract

Ensure the electric power system's durability through battery monitoring

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Battery monitoring is used to acquire information about battery conditions. It's a regular technology that most of us uses on daily bases. The charge gauge in a cellphone, consisting of bars which indicate the degree of charge left in the battery is an example. Battery monitoring gives the cellphone user information about the battery. The background to the thesis work is that this technology is requested for vehicles because empty or broken batteries are one of the most common causes for involuntary stops. One way to monitor battery conditions is with a battery sensor, which is a mechanical device that measures and calculates battery conditions.

This thesis' purpose is to develop evaluation criteria and evaluation methods to assess the possibility for battery sensors to deliver competent information in order to ensure functionality of electric systems. To enable generalized evaluations of battery sensors, their delivered information are delimited to three different and defined battery conditions which are State-Of-Charge (SOC), State-Of-Function (SOF) and State-Of-Health (SOH).

To be able to compare battery sensor calculations and actual battery conditions, a method to obtain the battery conditions was needed. To determine this method a literature review was performed and because of an accurate and continuous method was needed, Coulomb counting was selected. Coulomb counting is a book-keeping method which calculates the SOC accurate based on current integration.

To develop criteria that evaluate battery sensors possibilities to deliver competent information, tests about how vehicles starting affect batteries as well as tests about battery sensors performance in different scenarios have been investigated. The thesis work shows that the SOC has to be limited based on the degree of charge left in a battery, SOF has to be limited to batteries potential to deliver a certain voltage for a specific constant current and for SOH it is most important to maintain a continuous countdown.

The evaluation methods to evaluate battery sensors according to the criteria have been developed to test and ensure the battery sensors performance based on several test-cycles. The evaluation methods with certain conditions and test-cycles should be comparable to actual conditions for battery sensors installed on vehicles to ensure a continuous delivering of competent information.

To summary the thesis work has developed and partly verified evaluation criteria and evaluation methods to evaluate battery sensors possibility to deliver competent information about the battery conditions SOC, SOF and SOH. These criteria and methods make it possible to evaluate if a battery sensor, any battery sensor calculating these battery conditions based on similar parameters, could deliver enough competent information in order to ensure functionality of electric systems.

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ISSN: 1650-8319, UPTEC STS 15001

Populärvetenskaplig sammanfattning

De flesta av oss har varit med om att laddningen i mobiltelefonen börjar bli dålig, procentmätaren i hörnet går ner i botten och ger användaren en varning innan mobiltelefonen slocknar. Det är inte bara mobiltelefonerna som kräver elektricitet av batterier för att fungera i vår vardag utan det gör även bärbara datorer, surfplattor och bilar för att ta några exempel. Det är därför inte så förvånande att urladdade eller trasiga batterier är ett vanlig förekommande problem. För att minimera denna problematik använder flertalet batteridrivna föremål och även ovan nämnda produkter någon form av batteriövervakning.

Transportsektorn har elektrifieras, hybrid- och elbilar är en verklighet men trots allt så är fossildrivna fordonen fortfarande en övervägande majoritet. Det är däremot så att det även ställs högre krav på fossildrivna fordonens elkraftssystem på grund av både gamla funktioner som elektrifierats samt nya krävande systemfunktioner. Det är allt ifrån små basala funktioner som fönsterhissar och uppvärmbara säten till rena systemfunktioner som startmotorer och styrning. Det är även så att för kommersiella fordon är en av de vanligaste orsakerna till ofrivilliga stillestånd urladdade eller trasiga batterier. Det gör att batteriövervakning är efterfrågat i transportsektorn och med hjälp av batterisensorer kan visualiserande övervakning av batteriladdning ske likt mobilens procentmätare.

Batteriövervakning kan ske med hjälp av en batterisensor. Batterisensorer är ett område under utveckling med en stor potential och möjligheter att drastiskt minska dessa ofrivilliga stillestånd genom kontinuerlig övervakning. Det är mycket svårt att kontinuerligt övervaka batteriets prestanda på grund av batterikemins komplexhet vilket ställer höga krav på sensorerna för att ge tillförlitlig data.

Examensarbetet har utförts hos Scania som är en världsledande tillverkare av kommersiella fordon som lastbilar och bussar. Syftet med examensarbetet är att ta fram utvärderingskriterier och utvärderingsmetoder för att bedöma batterisensorers möjlighet till att leverara tillförlitligt underlag för att säkerställa elkraftsystemets funktionalitet. För att möjligöra generalisering har arbetet avgränsats till att utvärdera batterisensorernas beräkningar av batteritillstånden laddningsnivå, funktionalitet och hälsa. Funktionalitet med fordon i åtanke anses vara batteriernas möjlighet att leverera tillräckligt med kraft för att starta en motor. Det ska dock nämnas att resultatet endast kan generaliseras för batterisensorer som beräknar tillstånden på liknande sätt som undersökta batterisensorer.

För att utvärdera batterisensorernas beräkningar krävs en metod som är både noggrann och tillåter kontinuerliga beräkningar av batteriernas egentliga tillstånd. Litteraturstudien i arbetet tar upp flertalet metoder för att bestämma batteritillstånd och av dessa valdes Coulumb-räkning då den motsvarade efterfrågade krav. Coulomb-räkning är en bokförande metod som är baserad på integrering av strömmen.

Utvärderingskriterier för att säkerställa batterisensorernas möjlighet att leverera kompetent material skapades baserat på tester, både startbarhetstester där batteriernas möjlighet att starta motorer analyserades såväl som tester hur batterisensorerna presterade vid olika förhållanden. Det framkommer i arbetet att laddningsnivån begränsas med avseende på laddningsnivå kvar i batteriet, funktionaliteten begränsas i och med batteriernas möjlighet att leverera en förutbestämd nivå av spänning för en specifik ström och viktigast för batterisensorerna med avseende på batterihälsa är en kontinuerlig nedräkning.

Utvärderingsmetoderna formuleras för att utvärdera batterisensorerna med avseende på utvärderingskriterierna. Det tas fram testcykler och förutsättningar för att efterlikna verkliga förhållanden batterisensorerna kan utsättas för samtidigt som metoderna testar och säkerställer batterisensorernas möjlighet att leverera tillförlitligt material, både på kort och lång sikt, med avseende på kriterierna.

Examensarbetet har formulerat och delvis verifierat utvärderingskriterier och utvärderingmetoder för att bedöma batterisensorernas möjlighet att leverera tillförlitligt material om batteritillstånden laddningsnivå, hälsa och funktionalitet. Utvärderingskriterierna och utvärderingsmetoderna gör det möjligt att utvärdera ifall batterisensorer, som beräknar dessa tillstånd baserat på liknade parametrar, kan leverera tillräckligt tillförlitligt material för att säkerställa elkraftsystemets hållbarhet.

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1. Introduction

It's almost all of us that have experienced a cell phone with almost empty battery. The charge gauge consisting of bars indicating what degree the battery is charged has reached the bottom. In our daily life it's not only our cell phones that are dependent on batteries to work but also many other devices as laptops, tablets and cars. Therefore it's not surprising that discharged, empty or broken batteries are a regular problem in our lives. To minimise this problem a majority of our equipment use charge gauges similar the cell phones bars to continuous monitor the batteries charge and function. This is called battery online monitoring and the purpose is to give information about the batteries charge continuous to the user. Laptops visualize the battery online monitoring similar to cell phones and it's giving the user continuous information about remaining time or charge left which minimises the risk for a poorly charged or empty battery that could cause an involuntary shutdown.

Electrification of the vehicle market has increased the request for accurate battery online monitoring. Obviously electric vehicles need accurate battery charge measurement because electricity is the vehicles fuel but it is also requested for fossil driven vehicles, which are still a majority. This is because even in fossil driven vehicles the electric requirements are increasing, both due to older functions that are electrified and new functions that consuming a lot of power. There are all kind of functions, small basal functions as windows elevators and seat heating to pure system functions as starter and steering devices. It's because of all these functions that an accurate online battery monitoring is widely requested in the vehicle market and one solution could be to visualise the battery charge with battery sensors. Battery sensors make it possible to visualise the battery charge like the cell phones charge gauge.

1.1 Problem description

While driving a vehicle as a car or a truck, the alternator is generating electricity. This is to supply all electric equipment in the vehicle but also to charge the batteries, which are storing electricity that later can be used to start the vehicle. Engine starts requires energy, fuel, as well as certain electric power, current and voltage, delivered from a battery. To ensure that vehicles have enough fuel there are fuel gauges in the vehicles. However there's no gauge to ensure enough power output from the battery. If the battery doesn't deliver enough power, the engine wouldn't be able start irrespective of the fuel and this causes involuntary stops.

These involuntary stops create problems for all of us but it's an even larger problem for the commercial vehicles because this companies profit depends on that the vehicles are moving. Vehicles that involuntary are standing still don't generate any profits and unfortunately partly discharged, empty or broken batteries are one of the most common causes to involuntary stops (BS1 2014). It's especially common for vehicles driving short distances including a lot of start and stop but also for long haulage vehicles where the driver often sleeps in the vehicle. This is because the driver consumes electric power for entertainment, heating the cabin and cooking under the rest periods. During these longer breaks no electricity is produced. A further problem is that batteries are getting older and less effective as time goes. This causes that battery change has to be planned to minimise the involuntary stops. For transportation companies with many vehicles this is a great cost that results in economic loss however the battery is changed too early or too late (Kovacevic 2014).

This problem can be solved by battery online monitoring and one way to monitor batteries are with battery sensors. Battery sensors are an area under development with a great potential, especially to drastically reduce the involuntary stops caused from partly discharged or empty batteries. This is because both users and computers may obtain information to manage the electric power system, which could result in that the user turns off electric loads to reduce the discharge and avoid starting problems. Unfortunately, the battery chemistry is complex and everything from inner resistance, temperature, discharge and charge cycles are affecting the batteries performance. This causes problems to continuously monitor the performance of batteries and it’s also affecting the sensors accuracy. These issues complicate evaluation of battery sensors. It’s also because of that it’s hard to specify how accurate battery sensors have to be to accomplish their purpose, so that the users can trust them.

1.2 Purpose

The purpose of the thesis work is to produce evaluation criteria and evaluation methods to assess the possibility for battery sensors to deliver competent information in order to ensure functionality electric systems.

The produced evaluation criteria and methods should be applicable for as many battery sensors as possible. It’s difficult to determine generalized evaluation criteria and evaluation methods for battery sensors because there are many different models. These different sensor models use different measurement techniques, different equations to estimate their values but also differences in what they present as results. To allow generalizations for as many battery sensors as possible the criteria and methods of the thesis work are limited to the battery sensor ability to estimate State-of-Charge, SOC, State-of-Health, SOH and State-of-Function, SOF. The main aims for the thesis work are to produced evaluation criteria and methods for SOC and SOF.

2. Background

There are two basic types of batteries, primary and secondary. Both types store electric power to deliver voltage and current to connected loads. The difference between primary and secondary batteries are that primary batteries aren't rechargeable, while a secondary battery is a type of accumulator and therefore it can be used multiple times. Batteries aren't something new, their origin can be cited back to year 1800 and experiments performed by Alessandro Volta (Pavlov 2011,s 4-12 and Linden & Reddy 2001, s589-591).

2.1 Battery

Since Volta's days there have come a great number of different types of batteries. The users can choose between them depending on their required functions and capabilities so that the most suitable battery type can be selected.

Lead-Acid Batteries, LAB, are one of the most common and important battery types in the world and especially in the vehicles market. In fact there are direct correlation between number of motor vehicles registered and number of sold starting, lighting and ignition batteries in the world. LAB' sales correspond to around 40-45 percent of the sales value of all batteries in the world (Linden & Reddy 2001, s591-592). The main function of the battery is to provide the vehicle with electricity to start the engine and supply the electrical system when the engine is not running. The batteries store electricity when the vehicle is off and while the vehicle is driving the batteries gets recharge (Pavlov 2011, s21 and Linden & Reddy, s621-630). The development has increased the amount of electrical loads in vehicles both during driving and stops and therefore increased the requirements of the batteries.

LAB is an older battery type that partially has been replaced in newer hybrid and electric cars to give place for other electrochemical batteries. However, still a majority of all vehicles and almost every heavier vehicle, like trucks, use LAB. There are a lot of reasons why almost every heavy vehicle still use LAB and of course one is that the batteries' function and capacity are suitable, simultaneously as they are embedded in the system. To change such an embedded part in the system would affect a lot of functions in the electric power system of the vehicle and therefore changing type of batteries would be expensive (Linden & Reddy 2001, s591-592).

2.1.1 **Lead-acid batteries**

The first rechargeable battery was a LAB which was invented in 1859 by Gaston Planté. Since then a lot has happened but the principle is still the same. LAB is constructed of several serial and parallel linked identical cells that produce electric energy. These cells are also called galvanic cells. Each of these cells consists of two electronic conduction plates called electrodes, which are in contact with an ionic conducting phase, called electrolyte. On the market there are several models and types of LAB' with different capacity, voltage and size, but there are also differences in their cells. Regular lead-acid batteries are sometimes called flooded lead-acid batteries, FLA, because the electrolyte consisting of water and acid are flooded inside the batteries' cells (Linden & Reddy 2001, s587-592). Valve-Regulated Lead Acid, VRLA, batteries are another type of lead-acid batteries. VLRA batteries have unlike FLA batteries no fluid electrolyte; instead their electrolyte is Absorbed in a separator of Glass Mat, AGM-batteries, or bound in a Gel, Gel-batteries. In the thesis work the focus is on flooded lead-acid batteries and therefore, unless it's not mentioned lead-acid batteries are flooded lead-acid batteries. Basically FLA and VRLA are working similarly electrically and chemically (Pavlov 2011, s21 and Edström 2014).

FLA batteries works like follows. It's storing the electric energy in the electrolyte and to recharge or discharge, reactions are occurring on the plate's surface. These reactions mean that electrons are being exchanged between the electrodes and the ions in the electrolyte and that the charge flow is completed through an electric circuit between the electrodes (Linden & Reddy 2001, s592-602), see figure 1.

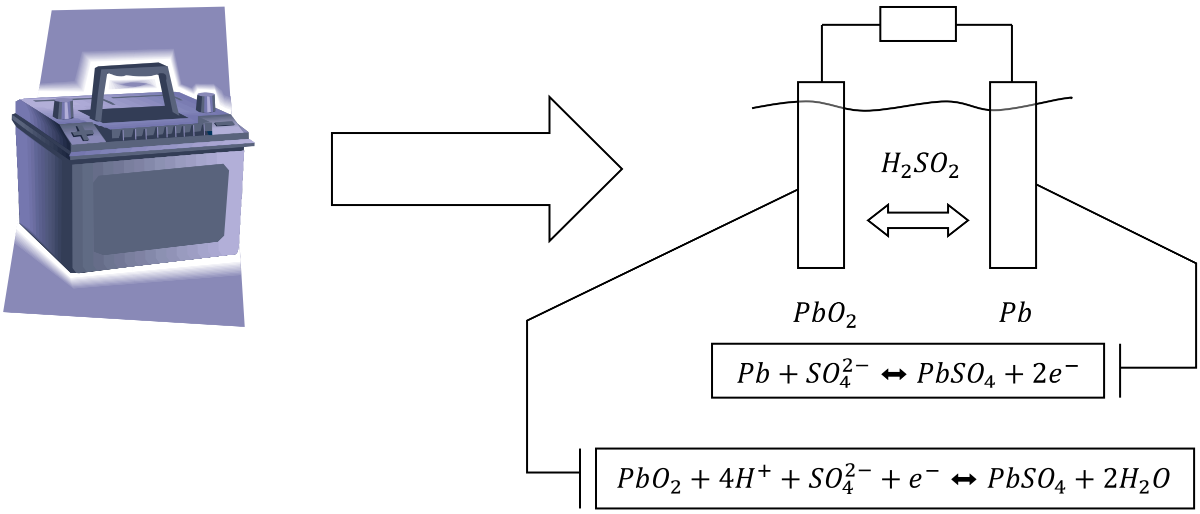


Figure 1: The chemical reactions inside a lead-acid battery.

Figure 1 explains what happens when charge or discharge a LAB. The figure shows total reaction; a fully charged LAB, where the positive electrode consists of dioxide (PbO2) and the negative electrode of metallic lead (Pb). The electrolyte consist of sulphuric acid (H2SO4) and water (around 35 % of the sulphuric concentration) (Linden & Reddy 2001, s592-602). The chemical reactions in a battery can be described as Equation 1 (Linden & Reddy 2001, s592-602).

$$PbO_2 + Pb + 2H_2SO_2 \Leftrightarrow 2PbSO_4 + 2H_2O \qquad (1)$$

It is evident from the formula that through discharge the electrolyte is replaced with more water and the active material is converting to lead sulphate, both the negative and positive plates are saturated. This process reduces the conductivity which leads to higher inner resistance and lower power output (Linden & Reddy 2001). Therefore the electrolyte density can give information about the battery's capacity. A fully charged battery has an electrolyte density around 1.28 g/cm^3 (Tudor 2014).

Battery capacity is rated and measured in terms of Ampere hour (Ah). The unit Ampere hour is the amount of amperes discharged multiplied with the time in hours. Battery capacity is depending on several parameters as discharge rate, depth of discharge and temperature. The batteries' inner resistance is increasing with a lower temperature and this gives an almost linear correlation between temperature and battery capacity. It can be described as for every degree Celsius the temperature is lowered, the capacity is decreased with one percent. This is applicable to a temperature range between -20 to 30 ° C (Edström 2013 and Kovacevic 2014).

2.1.2 **Lead-acid batteries function**

The electromotive force, EMF, is atom or molecule tendency to emit or receive electrons in relation to other materials. This is what converts chemical reactions to electric energy in batteries. Reactions in a lead-acid battery cell have a total standard potential at 2.03 V. The total standard potential is the potential of both the negative and the positive electrode reactions at equilibrium state, which is a solution with the concentration of 1 mole per kilogram and a temperature of 25 degrees Celsius. The difference between open circuit voltage and operating voltage can be described by these reactions and a voltage drop, polarisation, caused by inner resistance. Polarisation can be divided into three parts; Activation, Concentration and Resistance. The energy to overcome the resistance between electrodes and electrolytes, to start the reaction, is also known as activation polarisation. Concentration polarisation is the difference in concentration, in the amount of reactants meanwhile the reaction is occurring. Resistance polarisation is the ohmic resistance. The total polarisation, all three parts in together, is affecting the voltage changes and this is why the recharge voltage always has to be higher than the discharge voltage (Linden & Reddy 2001, s23-24 and 592-602).

2.1.3 **Problems with lead-acid batteries**

Of course LAB isn't perfect and therefore this subchapter mentions some of its problematics.

Sulphation

When using LAB, small sulphate crystals are being formed. These amorphous lead sulphates are frequent and not destructive. However, periods with low SOC and insufficient charge make the sulphates convert and deposit on the negative plates as stable crystalline, large crystals. Sulphation therefore reduce the batteries active materials and capacity. Furthermore it impairs the batteries charging function, as a result of high internal resistance (Linden & Reddy 2001, s592-602).

Corrosion

Corrosion is a problem of lead shedding that occurs in the grids of batteries, because the electrodes in a lead acid environment always are reactive. This problem can't be eliminated, only minimised through reducing the overcharge and operate at rational temperatures (Linden & Reddy 2001, s592-602).

Stratification

Stratification is when the electrolyte is stratified; the concentration of the acid is not equally distributed. A light acid concentration is formed in the top of the battery and a higher acid concentration is formed in the bottom. The light concentration results in a reduced battery performance whereas the higher concentration causes an overconfidence of the charge. In addition, this unequal charge is harmful for the batteries ability to crank engines and promotes corrosion (Pavlov 2011, s144). Figure 2 shows a normal battery (left) and a stratified battery (right). The acid concentration is equal for a normal battery while a stratified battery has layer of different acid concentration.

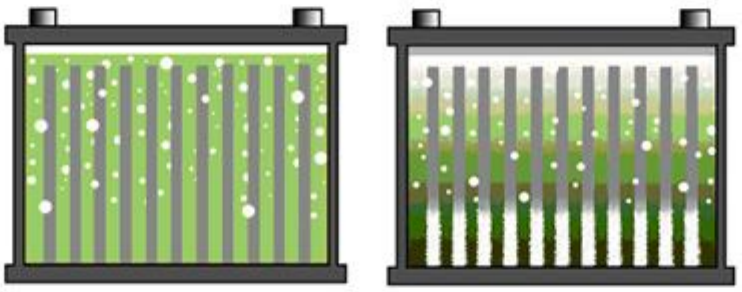


Figure 2: A normal and a stratified battery (Battery University A 2014)

Surface charge

Surface charge is a similar problem as stratification. It occurs when the battery won't convert lead sulphate to lead and lead dioxide fast enough. This leads to a higher charge, SOC value, on the outside plate's surface, then on the inner plate (Pavlov 2011, s144).

Vaporization

During use of batteries, especially when being overcharged, water evaporates to hydrogen and oxygen. This may result in water loss and eventually dehydration with reduced capacity as result (Pavlov 2011, s144).

Mismatched cell

Mismatched cell occurs when some of the battery cells are damaged or broken. The reason why this happens is because one cell is weaker than the other cells and consequently affects the whole battery. This reduces both the battery's performance and its lifetime (Linden & Reddy 2001, s592-602).

Capacity loss and internal resistance

LAB is aging and this is affecting their properties, especially the potential to store electrical energy. The batteries' storing potential can be separated into segments as; Refillable, Available and Unusable. Refillable can be described as the amount that is possible to recharge to the battery and available is the available amount of capacity that is stored in the battery. The unusable segment is a zone that no longer can or will store energy; it's mainly caused by age loss, sulphation and corrosion. A new battery should be able to store and deliver 100 percent of its capacity and shouldn't have any unusable segments (Pavlov 2011, s145).

The batteries capacity is of limited use if the battery can't deliver the stored electrical energy. To deliver the stored energy the lead-acid batteries need a low internal resistance, this is because high resistance causes voltage drops which can lead to shutdown of electrical equipment. Lead-acid batteries have a low internal resistance and respond well to high current for a few seconds. High current for a few seconds is what a vehicle requires to start the engine and this is one reason why lead-acid batteries are suitable for starting of motor vehicles (Linden & Reddy 2001, s73-96) .

2.2 Battery sensor

A battery sensor is a device used for continuously monitoring parameters of a battery. The device is mounted on the battery to estimate the battery's characteristics. This chapter describes what the battery sensors are estimating and why.

2.2.1 State-of-Charge, SOC

State-of-Charge is an indicator of the charge level in the battery, the amount of ampere hours which are available for discharge. This value is often presented in percent, as the remaining capacity with the respect to the nominal value. However in the thesis work SOC levels will be presented as remaining ampere hours. The definition of SOC as the available amount of ampere hours for discharge is differ based on how it is presented, if it presented in percent or in ampere hour. If SOC is given in percent it differs if it's associated to the nominal capacity or the net amount of charge, which is the ampere hour discharged from the battery since the last full SOC. The nominal capacity and net amount of charge can differ because of ageing and the batteries SOH. (Piller, Perrin & Jossen 2001).This is why the thesis work presents the SOC in ampere hour.

The SOC value is affected by many parameters. Temperature, depth of discharge and ageing are well discussed in literature (Pop et al 2008, s1-30).

2.2.2 State-of-Health, SOH

State-of-Health is a parameter of the battery condition, its health. The SOH value is indicate how well the battery can be recharged and keep the charge. For example a low SOH value indicates that the battery cannot be recharged in near of nominal capacity and to keep the charge as good as before. This fact points towards that the battery approaching or has reach its end of life, it cannot ensure the consumers their requested electric output from the battery. The battery health is a complex expression and it is influenced by several parameters in a long term condition such as aging, self-discharge, inner resistance, number of charge-discharge cycles and its depth. It’s because of that the SOH is hard to monitor and estimate and it’s even harder because all parameters has to be weigh against each other to decide how much they affect the battery health (Coleman et al 2006).

In summary SOH is a value of ageing and capacity loss but also a measurement of the battery performance compared to its original properties. SOH is a comparison between present values and the values the battery had when it was new, this is why the SOH value is presented in percent (Coleman et al 2006).

2.2.3 State-of-Function, SOF

State-of-Function is an expression that directly depends on the statements above, SOC and SOH. The purpose of SOF is to objectify the preparedness of the battery, which means what power the battery can deliver at a specific time. SOF includes parameters as capacity, internal resistance and amount of charge (Meissner & Richter 2003).

The definition of SOF is how well the battery works, if it is good enough to meet the given requirements. The batteries function in a vehicle is as mentioned earlier to store the charge, recharge when driving and to deliver enough capacity to start the engine. SOH includes how well the battery stores the charge and how well it can be recharged while SOC gives how much capacity there is left. SOF is depending on SOH and SOC to ensure the battery’s functionality. Therefore in the vehicle industry SOF is a measurement of whether the battery is good enough to perform an engine start or not. This is not an easy task because ensuring that the battery has and can deliver enough power to start an engine also includes knowledge of the mechanical functions of the engine. For instance the temperature affects both the battery conditions and the mechanical functions in the engine (Meissner & Richter 2003).

How different battery sensors calculate SOF varies but none of them uses engine properties. The calculations are based on delivered current and voltage. This can be done during a Cold Cranking Ampere test, CCA test. CCA test is Swedish standard to ensure a battery’s performance, its crank-ability. The test is based on two discharges within a cold temperature, -18 degrees Celsius. The test procedure is starting with a discharge for 10 seconds with a specific current, I_{cc}, and during the discharge the voltage shouldn't be less than 7.5 V. I_{cc} should be specify by the manufacturer and is determined as the current a battery could deliver in -18 degrees Celsius for 10 seconds without reaching a certain voltage, 7.5 V. The test is continuing with a rest period for 10 seconds, before the second discharge. The current in the second discharge should be 0.6 I_{cc} and it should continue to the battery voltage reach 6 V. The discharge time should be record in seconds because based on the battery area of use it should fulfil decent limitations (SEK 2006). The CCA value is also an indicator of the battery health, therefore the CCA value is often equated with SOF (Millinger 2009).

2.2.4 **Battery sensor presentation**

How a battery sensor performs its result differs between different manufactories. The SOC is often presented as charge level left given in ampere hour, percent or remaining time. The SOH is sometimes presented in percent but more often as a warning signal, which indicates if the battery approaches end of life and consequently recommends the user to replace it. The SOF is not commonly used. When presented it's often integrated with the SOC, as a warning for the lowest possible level for engine start or the remaining time for guaranteed engine start (Pop et al 2008, s1-30).

A large competing manufacturer to Scania, Company 1, visualizes the battery sensor information in their trucks as in figure 3. The left picture shows the battery sensor warning, that the batteries are almost empty and the right picture represents the battery gauge, where the degree of charge left in the batteries is presented as stacks of charge left (Scania inline document 1).

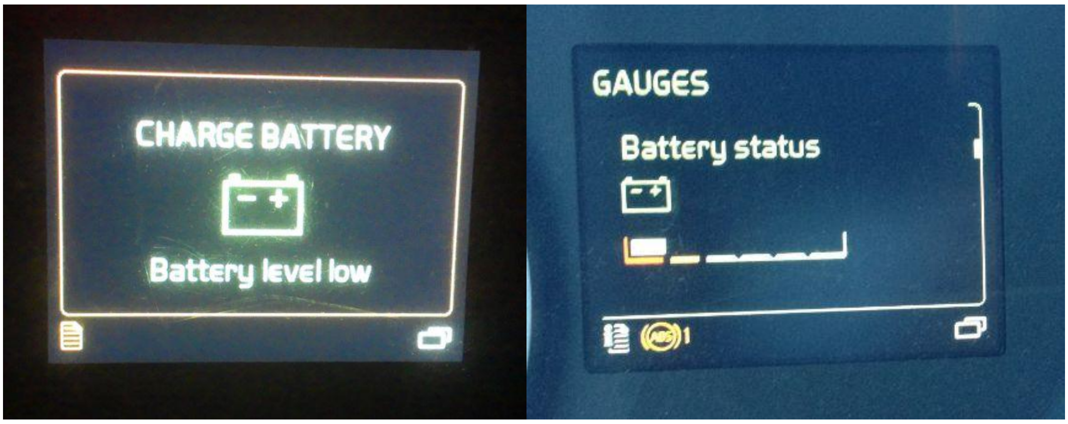


Figure 3: Company 1's digital battery status display (Scania inline document 2)

Company 1 has also integrated the battery sensor in the electrical system to manage other functions in the vehicle. This means that their trucks use data from the battery sensor for electric management, to example shutoff large discharging loads as cabin heating (Scania inline document 1).

Another competing manufacturer, Company 2, has a battery sensor from Kromberg & Schubert. Company 2 visualize the battery sensor information to the driver according to figure 4. The left picture is a warning sign, a last one that encourages the driver to start the engine. The right is an enlarged picture of the battery gauge that usually is presented in the same display as the warning sign. The enlarged picture of the battery gauge in figure 4 visualizes the amount of charge left (white) and the discharged amount (black) but also if the batteries are charge or discharge with an arrow. It has also a red line that indicates the minimal capacity to start the engine. In this case the red line is a bit lower than a third of a fully charge battery pack, which for vehicle with 225 Ah batteries are around 65 Ah (Ledfelt 2011).

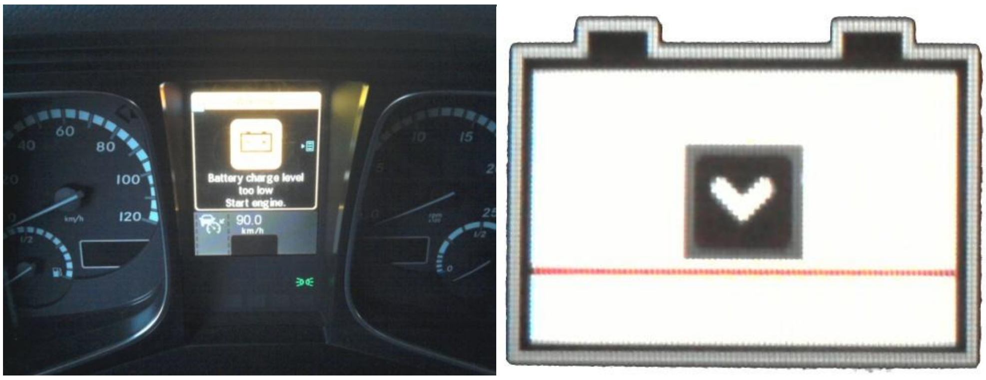


Figure 4: Company 2, a digital warning sign and an exaggerate picture of the battery gauges (Scania inline document 3).

Company 2’s battery sensor has also electric management functions and is integrated in the vehicle’s electric system.

Scania has performed tests on this two manufacturers’ battery sensors to benchmark the product. The test indicated on inaccurate measurement for SOC. This also has a negative impact on the electric management because inaccurate SOC results in false shutoff. This means that the customer benefits with electric management from battery sensor are revoked (Scania inline document 3 and Scania inline document 1).

3. Theory

The theory chapter is divided in five parts. The first part begins to introduce techniques to obtain batteries capabilities and ends with a summary and conclusion of them. The next three parts are about methods based on these techniques to battery monitor SOC, SOF and SOH. The last part introduces the theoretical framework for the thesis work with models based on the earlier parts.

3.1 Techniques to obtain batteries capabilities

The battery sensor uses several different techniques and methods to calculate their results (SOC, SOH and SOF). There are also various ways to obtain the actual values for these parameters, the actual batteries capabilities. Therefore some of these methods are used both in the battery sensors estimation and to calculate the actual values. To preserve the clarity in this subchapter these different techniques are divided in following categories: instant measurements, book-keeping systems and adaptive systems and summarized in Table 1 in 3.1.3.

3.1.1 **Three categories**

Instant measurement

Instant measurements are techniques that measure all kinds of variables of a battery. It could be voltage, current and in some cases impedance but it's not what are measured that categorizes them together. It's how the technique measured these variables. That it's measured directly from the battery and based on these measurements something about the batteries capabilities could be deduced. Some examples of instant measurement techniques are EMF and impedance methods, such as Electrochemical Impedance Spectroscopy, EIS, which relies on measurements of the batteries complex impedance over a wide range of frequencies (Pop et al 2008, s23-42). It also worth mentioning that measurement of the electrolytes physical properties can be categorised in this category. This method is based on linear relationship between change of acid density and SOC (Piller, Perrin & Jossen 2001).

Book-keeping system

Book-keeping systems are techniques that count, accumulate and book-keep information to calculate battery capabilities. Coulomb counting (or Ampere hour counting) is an example of this category. Coulomb counting is based on current integration. It's current measurement but the difference from instant measurement techniques is that Coulomb counting integrates the current to determined charge and discharge from a battery to obtain the degree of charge left. To obtain a more accurate SOC value the technique could add other parameters, such as temperature, charge and discharge-effect as losses and self-discharge (Pop et al 2008, s23-42).

Adaptive system

To the category adaptive system belong methods like Artificial Neural Network, ANN, Fuzzy Logic and Kalman filter. It's techniques that adapt parameters and changing the calculation equations based on memorisation. Therefore these methods gets more accurate after longer cycling and are good when batteries ages and their characteristics changes. It's also depending on other techniques to obtain input data, measurement techniques to receive data. The disadvantages of these methods are that they are very complex and difficult to implement (Pop et al 2008, s23-42).

3.1.2 Specific information for different techniques

In this subchapter several interesting techniques will get a short description.

Open Circuit Voltage, OCV is the terminal voltage without any load. It could be measured to determine a battery's SOC because of linear relationship between a battery's OCV and its SOC, as figure 5 shows. The problem with this technique is that it needs long rest periods; otherwise resent charge and discharge will affect the measurement. Since commercial vehicles rarely have longer rest periods this method is often combined with other techniques. Just like for many other methods the monitoring accuracy is affected by acid concentration and acid stratification (Piller, Perrin & Jossen 2001).

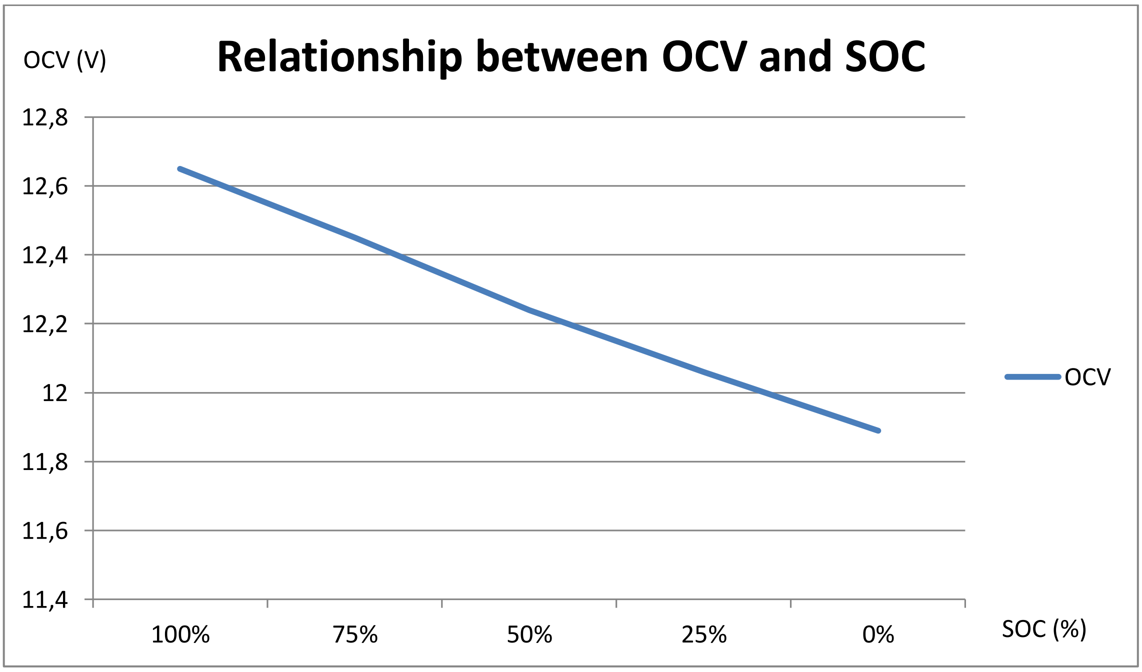


Figure 5: Linear relationship between OCV and SOC for a flooded LAB, 50 Ah, at 26° C and with 24 h rest after charge or discharge (Battery University 2014).

EMF is the batteries internal driving force independent of the batteries inner resistance. EMF can be obtained by thermodynamic data, by methods as linear interpolation or by voltage relaxation, because a battery will relax to EMF after a time with quiescent or no current. EMF is similar to OCV and can be assimilated when there is no load, current, in the circuit. It can be assimilated because without current the voltage wouldn't drop over the inner resistance. To set up a SOC algorithm on EMF requires an accurate method, such as a Look-up table describing relationship between EMF and SOC, or a Pricewise linear function, where EMF values can be linked to SOC values (Pop et al 2008, s63-70).

EIS is a common measurement technique for investigating electrochemical processes. It measures the impedance of a system over a range of frequencies and therefore the frequency response, including the energy storage and dissipation properties (Piller, Perrin & Jossen 2001). EIS is temperature sensitive and cost intensive, and is therefore more suitable for a controlled environment than field testing or rough environment such as the vehicle field (Pop et al 2008, s23-42).

Internal resistance is a simplification of EIS, where the voltage drop is divided by the current change during the same time interval. This method is highly depending on small time intervals. To get Ohmic effects only requires shorter time intervals, shorter than 10 milliseconds. Extended intervals are more complex because of transfer reactions or acid diffusion, when measuring these it's better to use impedance spectroscopy (Piller, Perrin & Jossen 2001).

Discharge test is a technique to find out how much charge that is left in a battery. The technique is simple, to obtain the SOC, the amount of charge left in a battery. Calculate the amount of charge possible to withdrawal, discharge from the battery. This is not a practical technique because it's time consuming, it can't be done continuous and it abrades the battery (Piller, Perrin & Jossen 2001).

Electrolytes physical properties can be obtain by electrolyte (or acid density) measurement and is one of the most accurate techniques. This is because it exist a direct relationship between acid density and the degree of charge in a battery, SOC (Pop et al 2008, s23-42). The reason to the direct relationship is that the electrolyte is the active material in a lead-acid battery (Persson 2012). The problem with this technique is that it requires access to the acid in the batteries, which not is suitable for continuous measurements and impossible for VRLA batteries (Pop et al 2008, s23-42). This is because the electrolyte, as mentioned earlier, is bounded in other materials. Other difficulties are acid stratification, water loss and stability of sensors if continuous measurement is required (Piller, Perrin & Jossen 2001).

The Coup de fouet method is based on the phenomenon "coup de fouet", which is a short voltage drop in the beginning of discharge following a full charge of a LAB. Two parameters with linear relationship to the capacity are considered which can be seen in Figure 6. The first is the through voltage, the minimum voltage during the occurrence of a "coup de fouet". The second is the plateau voltage, the maximum voltage reached during voltage recovery at the end of a "coup de fouet" (Piller, Perrin & Jossen 2001).

The method requires a fully charged battery and a test about the linearity because it’s not sure that the correlation always is linear (Bose & Laman 2000).

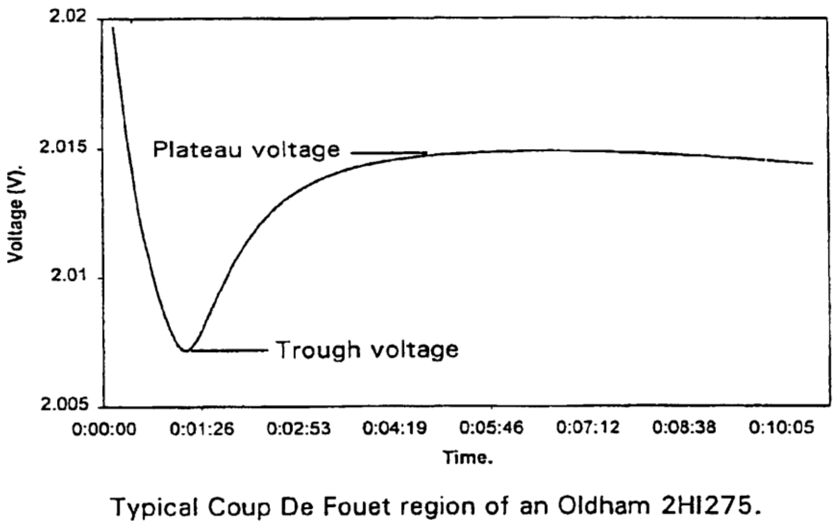


Figure 6: Typical Coup de Fouet (Google Patent 2012)

Coulomb counting (ampere hour counting) is as mention a technique based on current integration. It count and accumulate the charge to and discharge from the observed battery. Together with other parameters such as temperature, charge and discharge-effects as losses and self-discharge the battery’s SOC can be calculated. The difficult with these parameters is how it should be weighed against each other and their effect on the SOC. In a lab environment, with similar test condition, most of them can be neglected while others, such as self-discharge and a model for losses, affected most in a longer perspective. Due to losses higher voltage than a battery’s voltage is needed to charge a battery. It’s also a lot more that affect a charge, some examples is temperature, current and battery type but a factor is approximately between 1.05 and 1.2 because of all losses (Piller, Perrin & Jossen 2001). Coulomb counting has also problem due to the integration. The technique needs an initial value because an integration method needs a value to start calculate from and it also needs re-calibrations points, to calibrate if the integration has been wrong.

Fuzzy Logic is a form of many-valued logic and compared with other techniques this technique handles a truth value in a range, not as right or wrong. Figure 7 shows an example of this; instead of real numbers such as -5 degrees Celsius this technique uses categorised value as Cold, which could be -5 degrees Celsius as well as 8 degrees Celsius. This mathematic is used to analyse data which are categorised in crisp or fuzzy sets that as mention are categorised in uncertainties such as cold temperature or low SOC. Data is then defined by its membership function, degree of membership to these fuzzy sets. Figure 7 shows three fuzzy sets and the temperatures degrees of membership. Fuzzy Logic is requires a large working memory to process all data (Pop et al 2008, s23-42).

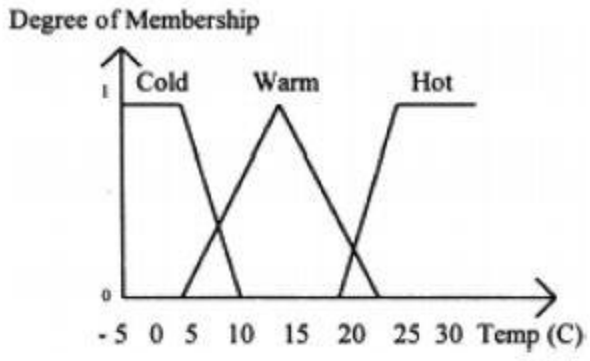


Figure 7: Membership function for temperature (Pop et al 2008, s37).

ANN methods are based on the relationship between input and output data of any kind. These techniques have been adopted to determine both SOC and SOH with varying results. Still this is a technique depending on some other techniques, measurements to receive input data. Example Anand and Mathur (2013) introduce an ANN model to estimate SOC. The network model uses several parameters as figure 8 shows, such as terminal voltage, current flow or discharge rate, Coulomb counting, temperature and specific gravity of the sulphuric acid electrolyte in the battery. Their model is a kind of ANN; an adaptive neuro fuzzy inference system (ANFIS) based on Takagi-Sugeno fuzzy inference system. It's classified both as a neural network and a fuzzy logic; therefore it has potential benefits of both in a single framework. The authors conclude that the specific gravity improves the results but only during discharge. The error of this technique is still depending on how well data is trained before use and the training method (Piller, Perrin & Jossen 2001).

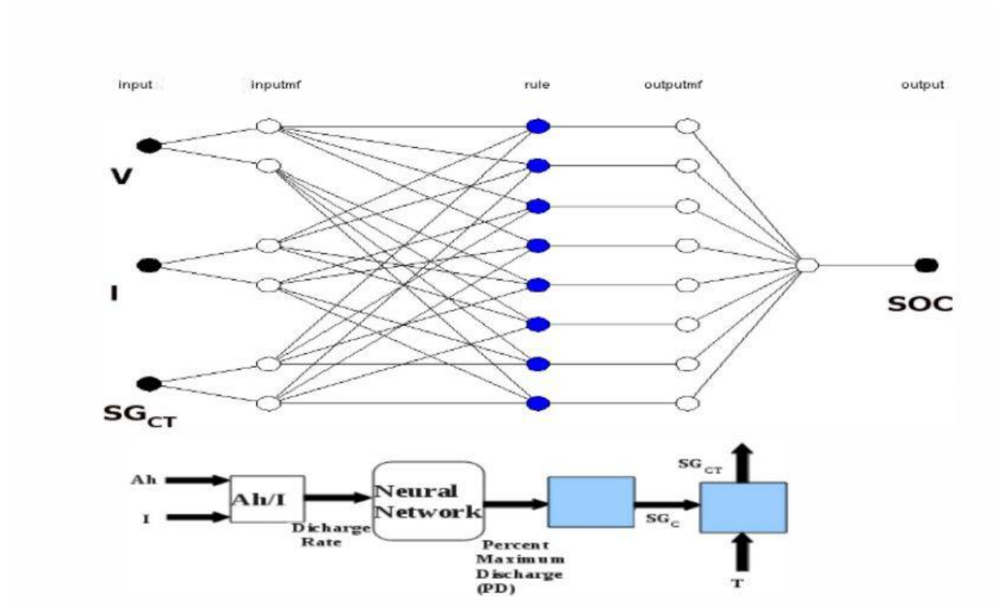


Figure 8: Anand and Mathur (2013) proposed topology for SOC Estimation using ANFIS.

Kalman filter states can be estimated in a dynamic system from noisy measurements. It can be described as an algorithm to estimate the inner state of any dynamic system. It's a technique that can reduce the estimation error when working with unknown processes and measurement noise covariance values (Han, Kim & Sunwoo, 2009). Estimation about battery capabilities is based on a model of the dynamic system, the battery, where one of the inner states is the SOC (Piller, Perrin & Jossen 2001). This technique is similar to the other adaptive systems based on direct measurement, book-keeping or a combination of these two (Pop et al 2008, s23-42). Example Zhang and Xia (2011) have adapted a combination of EMF and Coulomb Counting and presented a Kalman Filter theory with a comprehensive battery model to estimate SOC. Kalman-filter is also difficult to implement if the algorithm takes non-linear factors in account (Pop et al 2008, s23-42).

3.1.3 Summary

Table 1 is a summary of earlier described techniques. It also includes the techniques advantages and disadvantages. To clarify, an online technique is a technique that continuous could monitor battery capabilities.

Table 1: Summary of techniques to estimate SOC, SOH and SOF

Technique	Advantages	Disadvantages	Category
OCV	Online, fast and simple.	Long rest time. Problem with acid stratification.	Instant measurement
EMF	Online, fast and simple.	Long rest time. Problem with acid stratification.	Instant measurement
EIS	Online and good indicator for SOH.	Temperature sensitive, need a controlled environment and special equipment.	Instant measurement
Internal resistance	Easy and good indicator of SOH.	Offline and poor accuracy for high SOC values.	Instant measurement
Discharge test	Easy and accurate.	Offline, time consuming and a negative impact on batteries.	Instant measurement
Electrolytes physical properties	Easy and one of the most accurate.	Temperature sensitive, problem with acid stratification, water loss and to be online.	Instant measurement
Table1 continues on next page.			

Coup de fouet	Online.	Require test of linearity as reference data. Only appears within fully charge batteries.	Instant measurement
Coulomb counting	Online, easy and accurate.	Require re-calibration points, model for losses and has initial problems.	Book-keeping system
ANN	Online, good for complex calculations and as predictor.	Require data from similar battery to train network and often need other techniques as well.	Adaptive system
Fuzzy Logic	Online and good for complex calculations.	Require a lot of working memory and categorizes with affect the accuracy.	Adaptive system
Kalman filter	Online.	Require large computing capacity and suitable battery model. Problem with nonlinearities.	Adaptive system

Source: (Piller, Perrin & Jossen 2001) and (Pop et al 2008, s38).

To obtain actual battery parameter values, that could be compared with estimated values the thesis work needs an online and accurate technique. It could be deduced from Table 1 that internal resistance, discharge test and electrolytes physical properties aren't suitable because these techniques are offline. Electrolytes physical properties could be online but it requires a stable measurement method in the electrolyte and couldn't be applied for VRLA batteries and is therefore not suitable. Neither is OCV and EMF online and accurate. These methods needs long rest periods after charge or discharge to be accurate. Therefore it's not possible for these techniques to be both online and accurate. Similar to these techniques the instant measurement technique Coup de fouet isn't suitable to preform generalized evaluations. It requires fully charge batteries and to ensure a linear relationship to SOC, a test for every battery has to be performed. The techniques remaining in Table 1 is now EIS, Coulomb counting, ANN, Fuzzy Logic and Kalman filter. It's several of these techniques that are complex and good to obtain but also to predict multifaceted problems. Due to the thesis work's purpose it's not reasonable to choose a too complex technique. The main aim is on SOC and SOF and these techniques are more suitable to calculated SOH. ANN, Fuzzy Logic and Kalman filter aren't chosen because of this but also because their needs of other techniques. EIS is also a complex technique that needs a controlled environment and special equipment. It is not a problem that the technique needs a controlled environment when testing in a laboratory but it's a limitation, the evaluation methods couldn't be adapted to actual vehicle if it’s wanted. The only technique left in Table 1, Coulomb counting is also easier than EIS but still online and accurate and is therefore chosen. The technique’s disadvantages could also partial be neglected or removed because recalibrations are most needed in a longer time perspective and initial problems could be solved by either a completely charge or discharge to determined a starting or ending point. It’s similar for the problematic with a model for losses, a low current gives smaller losses but at the same time this is something that affects the results and it should therefore be kept in mind. It’s also a benefit, not a require, that Coulomb counting only uses voltage, current and temperature to determine the actual values because it enable the thesis work to use earlier preformed battery sensor tests at Scania.

A literature search confirms this choice of technique. Zhang and Xia (2011) describe several common techniques for SOC estimation; methods such as OCV, EIS and ANN. Zhang and Xia (2011) concludes that the most suitable technique for SOC estimation is coulomb counting based on current integration. It’s according to them the most direct and transparent technique that is easily implemented with an accurate result, especially for SOC in a low and medium range. Yang, Jiang and Wu (2013) summarize SOC estimation techniques and confirm Zhang and Xia (2011)’s statement. Yang, Jiang and Wu (2013) also mention internal resistance methods and electric liquid density as good methods but clarify that their generally are very difficult to apply.

Due to the literature search and the deduced from Table 1 the thesis work chose the Coulomb counting technique to obtain actual battery values. In the next subchapter Coulomb counting is explained more.

3.2 Battery monitoring – SOC

Coulomb counting is as mention a book-keeping technique, a technique based on current integration. It count and accumulate the charge and discharge based on the current. This subchapter should explain how Coulomb counting calculates SOC.

3.2.1 **Coulomb counting**

Coleman et al (2006) and Becherif et al (2012) both present equations to determine the SOC of a battery based on current integration. The equations are very similar; therefore they have been summarized and written as one equation, Equation 2. SOC_0 represent the nominal SOC, C_N the rated capacity, $\eta_{(I)}$ the current loss coefficient and i_{batt} the current.

$$SOC = SOC_0 - \frac{1}{C_N}\int_{t_0}^{t} \eta_{(I)} i_{batt}\, dt \tag{2}$$

Equation 2 uses Coulomb counting, the integration, and because of the rated capacity the answer, SOC, will be in percent. The earlier mention disadvantages with Coulomb counting are also in the equation; the initial problem is to obtain the nominal SOC and the model for losses is of course the current loss coefficient.

3.2.2 **Problem with initial SOC estimation**

Both literature, for instance M.Becherif et al (2012) and earlier tests performed at Scania, e.g. Millinger (2009), indicate that the estimation based on Coulomb counting is highly dependent on the initial SOC value. If the initial SOC estimation is poor it will affect the entire estimation. It's usual that the initial error follow the estimation and create a gap between the actual and the measured SOC value, see Figure 33. To solve this issue several methods which use combinations of Coulomb counting and other techniques have been published. An example is Zhu, Coleman and Hurley (2004) that proposed a method based on current integration and terminal voltage without any load. The method is based on that the Coulomb counting is good at quick charging and discharging cycles meanwhile EMF is better at initial value of SOC and can be calibrated for accumulative errors. Problems related to this method are the same as for the techniques separately but the most difficult problem is the EMF's need of a time with only quiescent current to stabilise without influence of earlier charge or discharge.

Another method that uses a combination of Coulomb counting and other techniques is Becherif et al (2012). The authors present a method to determine SOC and, what's more interesting, a more accurate method to determine the initial SOC. It's based on an adaptive initial SOC test with measurements of the battery impedance, the current being discharged and the battery voltage. The temperature is not considered in this phase but the authors will consider it in a future work because of the fact that the temperature influences the impedance of the battery.

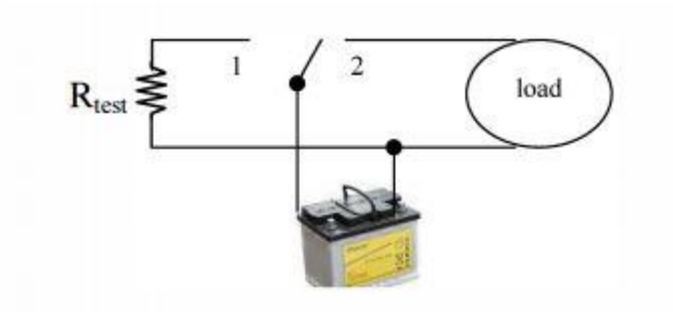


Figure 9: Becherif et al (2012) initial SOC determination test

Figure 9 shows a battery connected to a switch with two positions and in figure 9 the switch is in position 2 which connect the battery to a load. Position 1 disconnect the load from the battery and connect it to a resistance. Due to the switch and Position 1 it's possible to determine the initial SOC by an impedance measurement with defined test resistance and constant discharge current. Through this test the initial SOC of the battery can be determined. The benefit is that this test easily can be done in real application, with a switch device and test resistance, to improve the initial estimation. It's not a problem if the nominal SOC is determined but it's still important to know solutions for the initial problem because the battery sensors have to manage it.

3.3 Battery monitoring – SOH

Coleman et al (2006) present different methods developed to determine SOH value. To summarise there are three tests; Full Discharge Test, Internal Resistance Test and Conductance or Impedance Method. Full Discharge Test measures the difference between the batteries actual amount of charge and the amount it had when it was new. This is determined by the amount discharge to empty. Internal Resistance Test involves applying a load to measure the change in voltage and current and therefore be able to determine the internal resistance of the battery with ohms law. This works because the internal resistance increases with the batteries age. Conductance or Impedance Method involves applying an AC current or voltage signal across the terminals and measuring the voltage or current response. The conductance decreases and the impedance increases as the SOH decreases. It’s possible to adapt these measurements as input to adaptive systems such as an ANN to predict and estimate batteries SOH.

3.3.1 **Determined SOH**

Yatsui et al (2012) establish a SOH model as depending on many factors, a very complex view that includes battery chemistry, number of cells, temperature et cetera. However most of these factors are negligible in laboratory tests because each battery is under equal ambient condition and SOC. Yatsui et al (2012) therefore determined the remaining factors for SOH comparison as current internal resistances, current capacity, original internal resistance and original capacity, since all batteries undergo capacity fading through cycles. Capacity is the measurement of maximum amount of charge stored within the battery, whose fade is considered as the resultant effect of ageing and damage. A mathematical expression for SOH of each battery is formed as the Equation 3.

$$SOH(R_a, Q_a) = 50\% \left(\frac{R_0}{R_a}\right) + 50\%(\frac{Q_a}{Q_0}) \qquad (3)$$

Ra, Qa, Ro, and Qo represent the present internal resistance, present capacity, original internal resistance and original capacity. 50 percent is the weight that Yatsui et al (2012) assigned since they thought that capacity and internal resistance are equally important.

3.4 Battery monitoring – SOF

Ensure a functional battery is important in modern vehicles but this is a complex and difficult process because functionality is involved in the vehicles cranking ability. Bohlen et al (2004) proposed a method to predict the battery voltage response for a given pulse load at a certain time. The pulse load is based on a worst-case scenario and essential information of the voltage response is the lowest battery voltage during the pulse current. So if the voltage drops below a predefined voltage threshold the SOF for the application is zero, the applications demands will not be satisfied and the operation will fail. Otherwise the SOF can be defined as Equation 4.

$$SOF = \min(V_{pulse\ load}) - V_{lim} \quad (4)$$

$\min(V_{pulse\ load})$ is the lowest battery voltage under the pulse current and V_{lim} is the predefined voltage threshold. The equation results in SOF as the voltage reserve to a successful functionality, for vehicles the crank ability. The voltage response is predicted in 50 milliseconds, one respective five seconds after the start of the current pulse. The reason to predict these time points are to predict the lowest voltage and two more time points because it's important times for an engine start, se figure 10.

The voltage response and batteries cranking potential is according to Sabatier et al (2010) depending on the batteries resistance, which in turn is depending on the batteries available capacity. So the voltage drop over a crank is depending on the available capacity as figure 10 shows.

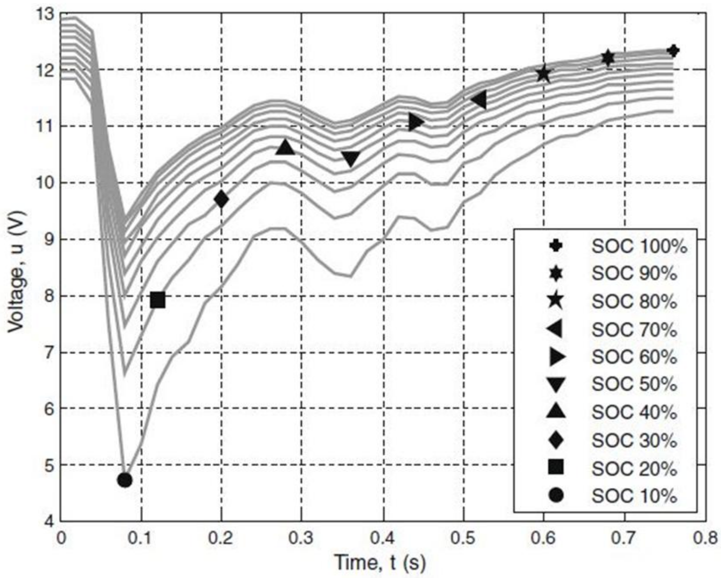


Figure 10: Battery voltage at engine start for new batteries with same cranking current (Sabatier et al 2010).

Sabatier et al (2010) also determined that the cranking function is ensured if the current, proportional to the starter torque, is higher than the stationary engine resistant torque and if the voltage, proportional to the starter speed, is higher than the reset threshold of the engine's micro controller. Sabatier et al (2010) analyzed Figure 10 and determined that the battery resistance is constant for all SOC higher than 50 percent but they also stated that the resistance increases with decreasing temperature, SOC and SOH. The main drawback of these statements is that each cranking is unique and a cranking process is a non-repeatable process.

Cugnet et al (2010) continues this argumentation, that the batteries cranking potential depends on available power. They furthermore establish a crankability-indicator based on resistance, because the available power can be estimated from its resistance. This is a promising method because the resistance varies with age and temperature, so in the future it can be used for lifetime diagnoses such as SOH and not only for determination of battery cranking potential.

3.5 Theoretical framework

To summarize this theoretical chapter and create a theoretical framework for the thesis work models of SOC, SOH and SOF follow.

3.5.1 **SOC model**

The Coulomb counting technique has been chosen based on earlier information and the reasons can be deduced from Table 1 and 3.1.3. The thesis work is searching for a technique that is both continuous (online) and accurate to evaluate battery sensors. It should be applicable in a lab environment and Coulomb counting meets these requirements. M.Becherif et al (2012) and Coleman et al (2006) recommend Coulomb counting for short and medium long calculations of SOC and due to that no longer calculations should be done, this technique is to prefer. Furthermore, in the literature search, different methods often are compared with Coulomb counting for determination of actual SOC.

In a laboratory environment the most disadvantages with Coulomb counting can be neglected but a deficiency is the current loss coefficient, that's discussed later in subchapter 6.4.4. To determine the actual SOC, Equation 5 could be used which is a modifications of Equation 2 without the initial SOC as well as without the current loss coefficient.

$$SOC = \int_{t_0}^{t} i_{batt}\, dt \tag{5}$$

Figure 11 shows to graphs, a current and SOC graph. To the left is the current graph which in the end shows a large positive current followed by a negative current. This could with Coulomb counting and Equation 5 calculate the graph to the right. Due to backward integration with the initial start in zero, the negative current could be calculated as a discharge, current multiplied with time to ampere hour. The positive current could then be calculated similar as a charge and by this the battery SOC graph could be determined.

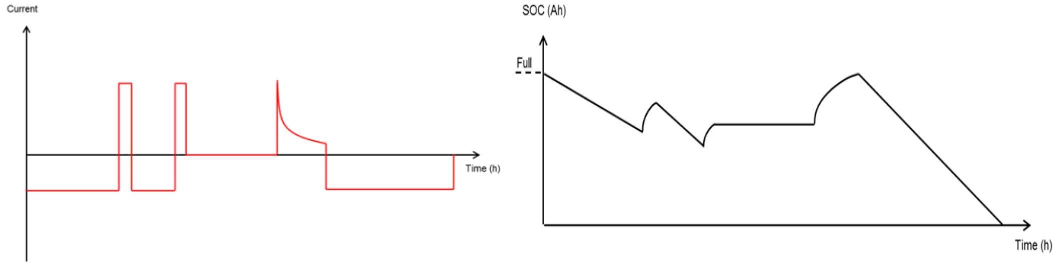


Figure 11: Current and SOC graphs

It’s also beneficial to use the Coulomb counting method because both the battery sensors and other measurement equipment could measure the current accurate which minimize the measurements error.

3.5.2 **SOF model**

A framework to evaluate cranking ability has been formulated by Bohlen et al (2004) method. It’s based on the assumption that a pulse load, a constant current load, can determine if the battery can deliver enough power to support an engine start. This model is chosen because if a battery can deliver enough voltage, higher than a voltage threshold for a constant current, it should manage a cranking current within a real engine cranking. It might also have been beneficial to look at the resistance, as Sabatier et al (2010). However it’s unnecessary to examine the resistance because the resistance is affecting the voltage drop and therefore the voltage response should give a sufficiently indicator if the battery delivers enough power to support an engine start. The voltage response model is also to prefer because of that the battery sensors measure the voltage continuously and accurate while not all sensors measure the battery resistance.

Figure 12 shows a voltage drop cause by a constant current load and the SOF model could be explained by this figure. The SOF is fulfilled if the lowest voltage cause by a pulse load is over the threshold voltage, $V_{lim}(2)$, but if the threshold instead is $V_{lim}(1)$, the SOF isn’t fulfilled. This model should be adapted for two time segments instead of three time points as in 3.4. This is because to know if an engine start, both the lowest voltage as well as voltage over time to crank the engine is required. In subchapter 5.2.2 this segments time is determined. Bohlen et al (2004) predicted the voltage response at 50 milliseconds, one respective five seconds after the start of the current pulse.

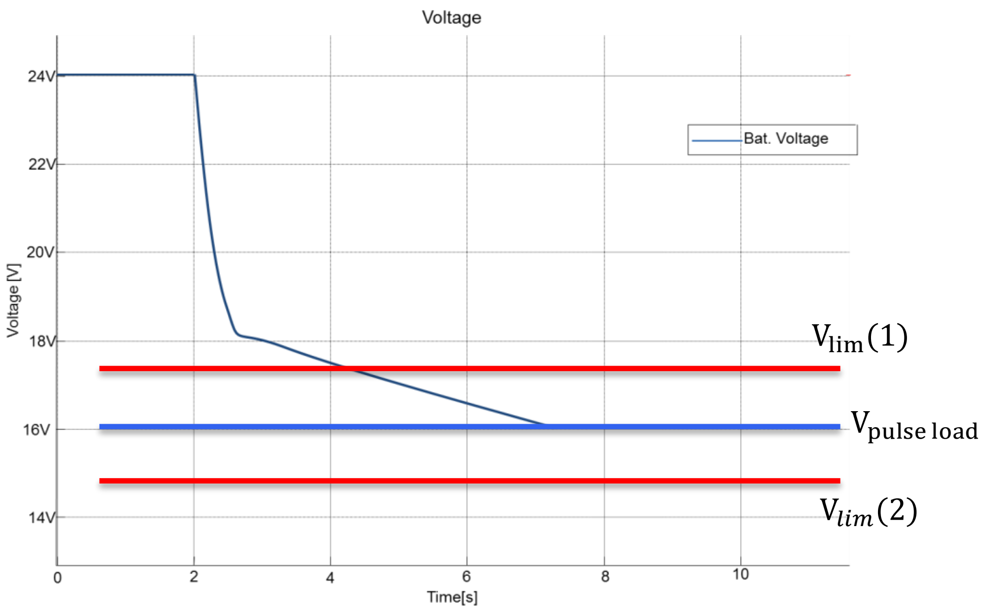


Figure 12: Voltage response for a constant current.

3.5.3 **SOH model**

The SOH model doesn't have to be as accurate as SOC and SOF. It's because the decision making according to SOH, change battery or not, has a longer time perspective than the SOC and SOF. It's more important that SOH is following the slowly changes caused by ageing and use of the batteries. This is enough because the prime use is to enable predictions and plans for battery changes.

Yatsui et al (2012) propose a method to estimate SOH, Equation 3, which is based on differences in capacity and inner resistance. They weigh the importance of capacity and resistance to fifty-fifty, similar important to calculate the SOH. The thesis work SOH model only take one of these parameters into consideration, the difference in capacity. It's due to that SOC and SOF has been the main aim as well as the fact that none of the battery sensors in the thesis work used resistance to determine SOH. The battery resistance is not even measured by both battery sensors and Sabatier et al (2010) consider the capacity and resistance as interdependent. The simplified Yatsui et al (2012) equation is therefore only formed as difference in capacity, the present maximal SOC divided by the nominal SOC which Equation 6 shows.

$$SOH = \frac{SOC_{present\ maximal}}{SOC_{nom}} \tag{6}$$

4. Method

To be able to answer the purpose of the thesis work literature search in the field has been examined as well as experiments have been performed and analysed. To obtain information about battery sensors both competing firms and suppliers have been studied. Literature has included a review of the field as well as input to evaluation methods and examination of different methods. It has helped to formulation of evaluation criteria that have been parameterized and examined by iterative tests. To ensure that these criteria and methods are possible, feasible and good enough to fulfil their purpose, their connection to both customers and suppliers have been examined.

The underlying information to formulate criteria and methods are as mention literature, tests as well as interviews. To obtain reliable information about the requirements for battery sensor performance qualitative interviews with both Scania's customers and suppliers have been done. This provided the thesis work with information about what is requested and how these requirements are assessed and calculated by battery sensors. Machine-related specifications, such as motor starting characteristics, have also been reviewed at Scania to ensure more actual requirements which means what the vehicle and its components require. The material has been supplemented with both previously executed test and newly made ones. This information provided a solid basis for developing evaluation criteria for battery sensors. Then the criteria and literature formed the basis for the evaluating method.

4.1 Interview

The interview method has a great advantage in its flexibility. It's easy to follow up ideas and to get deeper answers but also to obtain information by observing the respondent, how he or she uses pauses and expressions. The disadvantage could be a risk of certain skewed results because the respondent is affected by the circumstances. To avoid that this happens the interviewer should be careful and prevent leading questions and unspoken assumptions. Also it takes a long time to prepare the interview, to perform it and to analyse the answers, compared to other methods (Bell 2000, 199-123).

There are different ways to set up an interview. The interview's structure gives different answers and possibilities. An interview can be structured as a poll with clear questions and limited answers. It can also have a more free structure, where the questions is open and therefore gives the respondent possibilities to talk about the subject (Bell 2000, 199-123). The thesis work has used a combination of these two methods, a semi-structured way, because this gives opportunity to receive clear answers on questions as well as deeper answers and discussions.

4.1.1 **Selection of interviewee**

The interviewees were selected by their competence with help from my supervisor at Scania, Igor Kovacevic. Suppliers and customers were chosen for their availability and experience in the field. Michael Beba and Krystian Hirsch have been interviewed, which both represented battery sensor manufacturer. From Uppsala University Kristina Edström was interviewed, it was because of her knowledge about batteries but also because of she was supervisor to Mattias Millinger that earlier thesis work at Scania in a similar field. Robin Andersson working for Björkmans Transport as driver was selected to give this thesis a customer perspective. Other employees at Scania that have been interviewed or have been helping are Tomas Claesson and Gunnar Ledfelt. Thomas Claesson knowledge about the program IPEmotion and experience in testing battery sensor has been to great use.

4.2 Test presentation

The experiments that has been performed or analysed are starting characteristics and battery sensor tests. The battery sensor tests has both been performed and analysed while the starting characteristics only been analysed in the thesis work. It should also be mention that all tests and analyses in the thesis work has used and is determined for 12V (Varta C-type) 225 Ah LAB, often seen as a serial battery pack at 24 V as in vehicles.

4.2.1 **Starting characteristics tests**

The starting characteristics tests examine the starting characteristics for different engines in several temperatures. For all temperature and engines the test started with a fully charge 225 Ah LAB. The test process was repeated engine starts and discharges, to the batteries couldn't start the engine. Figure 13 shows the test process, starting with an engine start. If the battery perform a successfully engine start, an discharge at around 10 Ah was follow and then the battery fail to start the engine the test was ended. The conclusions from these tests can be read in chapter 5.2.

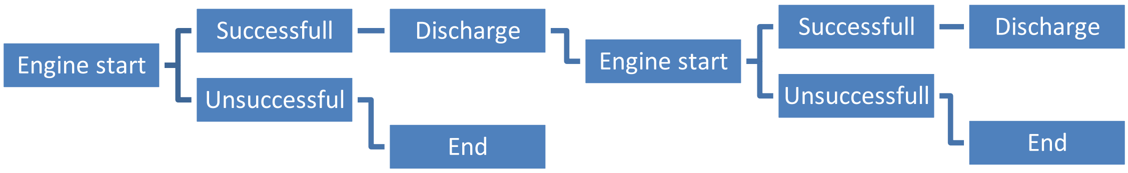


Figure 13: Describe the test process – repeated engine starts and discharges until engine starts fails.

4.2.2 **Battery sensor tests**

To test battery sensors a test bench has been setup in Scania's battery laboratory. The test bench layout enable two independence battery sensor tests at the same time. Figure 14 shows the test bench circuit diagram that includes the two independent test positions, A and B.

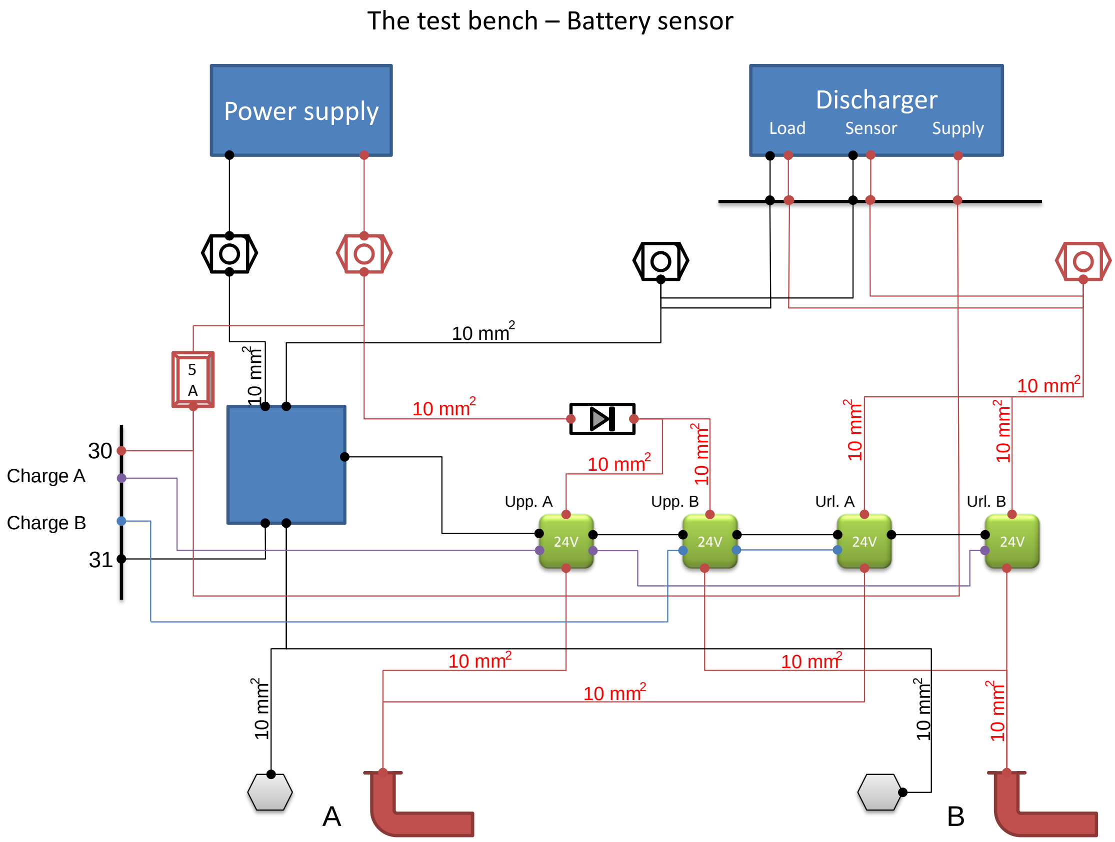


Figure 14: The test bench circuit diagram that includes two independent test positions, A and B.

To perform a battery sensor test the selected battery sensor should be connected to a battery pack that is connected to the test bench on either position A or B. See Figure 16 in subchapter 5.1.1 Battery sensor 1 for a more detailed picture of how a battery sensor is installed on a battery pack. Due to the test's setup, formation of charge and discharge, the loads (discharger) and power supply (24 V) should be set after requested settings and then the last thing is to connected the plugs (Charge A, Charge B, 30 and or 31). This setup enables constant current discharges to a specific minimum voltage as well as constant voltage charges. The blue nameless bow in the middle is a terminal block, the ground.

This test bench is designed to be safe and reliable and it should also manage to run two independent tests at its own. This is possible due to the plugs and a white device that could be seen in Figure 15, between the laptop and the test bench. It's a microcontroller that is time dependent. This device could be program with different time cycles and based on the programing, it connects different plugs at the test bench with result in varied charges and discharges. Example if the plug 30 and charge A are connected, position A charges and position B discharges.

Figure 15: The entire test bench, with batteries, power supply, loads and computer to log the data.

Figure 15 shows the entire laboratory that includes the test bench, a laptop, two battery packs, battery sensors, two electric loads and a power supply. To log information from the battery sensor a communication cable is used. The LIN-interface (see subchapter 5.1.4) is connected to a computer that registers the sensors output. The software IPEmotion is used to log data.

Test cycles

To introduce and explain tests that have been performed in Scania's laboratory a short overview of test cycles and settings is present below. It's overall information which means that it isn't sure that all tests are exactly identical with these explanations. The following four test cycles has been run in the thesis work:

- Charge-Discharge cycle
- Repeated Charge-Discharge cycle
- Mixed Charge-Discharge cycle
- Extended Mixed Charge-Discharge cycle

The Charge-Discharge cycle is the easiest; it only includes a charge to fully charge and a discharge to empty. It examines the BS for longer discharge to empty, which for instance could happen the lights is forgotten on. The Repeated Charge-Discharge cycle is repeated charges and discharges. The charge and discharge time is generally equal. This cycle examines if the BS manage to follow repeated charge and discharge because it's the LAB normality in a vehicle. Mixed Charge-Discharge cycle is a specific cycle designed by Scania to evaluate BS. The charge and discharge is in order and time: 12 hours discharge, 2 hours charge, 6 hours discharge, 6 hours charge and finally a total discharge to empty batteries. It's designed as this to approach the actual situation in a vehicle. Extended Mixed Charge-Discharge cycle is almost equal the Mixed Charge-Discharge cycle, with the addition of a longer rest period. It's to approach the actual situation in a vehicle even more but also to give the BS time to recalibrate.

The discharge is for all cycles defined as a constant current at 11.25 A (I_{C20}). It's calculated as a twentieth of the battery's rated (nominal) capacity, for 225 Ah LAB it's 11.25 A. The charge has for all cycles defined as a constant voltage between 28 and 29 V. It's to emulate the vehicles charge. Finally all tested cycles ends with a total discharge to empty, it's to obtain an initial value for the Coulomb counting, see subchapter 3.1.3. SEK (2006) defined a total discharge to empty as a discharge to the battery voltage is 10.5 V, which for a battery pack's (24V) is 21 V.

5. Empiricism

This chapter is going to present more information about battery sensors but also what the starting characteristics tests and customers requires of the battery sensors.

5.1 Scania battery sensors

The thesis work investigates two battery sensors, BS, more closely to understand their construction and technology. It’s to get information about how the BS work but also to observe from which parameters BS performance could be evaluated. The two BS that are considered in the thesis work are Battery sensor 1 and Battery sensor 2. The different BS calculated as well as display different parameters but three regular characteristics and parameters the thesis work investigates are SOC, SOF and SOH.

5.1.1 **Battery Sensor 1 – BS1**

The BS1 is used to record measured values and for preliminary process of power management. Mechanically the consists of a battery clamp with an embedded shunt, insulators, fastening elements and a thread bolt, as Figure 16 shows.

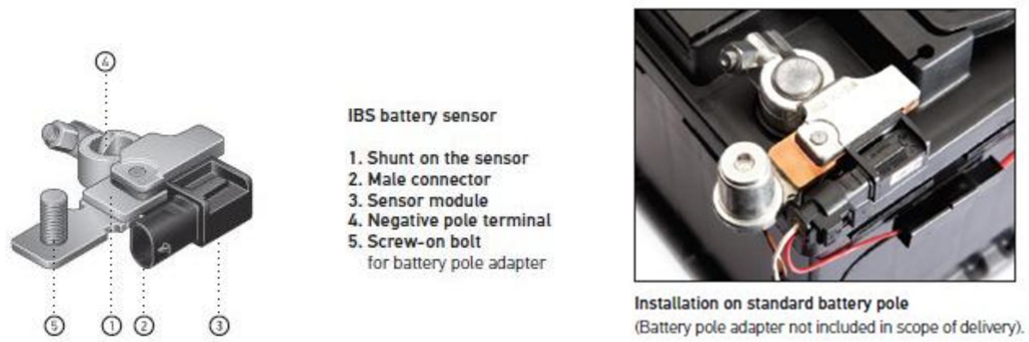


Figure 16: Design and function of Battery Sensor 1 (BS1 2014)

Figure 16 is also describing how to install BS1. It is installed on the negative pole terminal and connected parallel to the batteries, 12 and 24 V. For an overview of how a battery sensor is connected in tests, read subchapter 4.2.

BS1’ battery monitoring software, BMS, contains several different functions of which some are depending on each other. A description of which functions BS1 contains and how BMS calculate these functions is done below. BS1 is communicating via LIN-bus, see subchapter 5.1.4 (BS1 2013).

SOC

The BS1 measures current, voltage and temperature from the battery pole. The temperature is measured at the pole clamp but the BMS requires the battery's acid temperature, which causes a deviation between measured and actal battery temperature. This is solved by a thermal model that minimizes the temperature error (BS1 2013).

These parameters are then implemented in algorithms and the BMS calculate SOC, SOH and SOF. BMS calculate the SOC value through two main calculations, Ampere hour counting and recalibrations, which are Equation 7 shows.

$$SOC = SOC_{OCV} + \frac{1}{C_{Nom}} \int i \, dt \qquad (7)$$

SOC_{OCV} is the initial and recalibrated value of the SOC by OCV, C_{Nom} is the nominal capacity of the battery and i is the flowing current (BS1 2013).

The second part of the Equation 7 is ampere hour counting. This is the same as Coulomb counting, a calculation of the throughput ampere hours, charge and discharge. The first part of the equation is, as mentioned earlier, the OCV calibrations and it's to this value the Coulomb counting is added. It's measured by OCV of the battery; see the linear relationship between OCV and SOC in figure 5. Due to polarization effects OCV measurement shouldn't be performed the first three hours after charge, which is defined as higher current than quiescent, 250mA. If the recalibration has to be done within three hours after charge the OCV measurement cannot be done. Instead a more advanced high load OCV is adapted, though this method has poorer accuracy than normal OCV recalibrations (BS1 2013). SOC_{OCV} is initial after a restart, before any recalibration, 80 percent of the parameterized value, the batteries nominal capacity. It's also only possible to recalibrate to a lower SOC value for 0-3 hours after a restart (Beba 2014)

One thing that should be mentioned about Equation 7 is that C_{Nom} is the nominal capacity and not the maximal available capacity, therefore BS1 calculate the SOC without consideration of capacity loss.

SOH

To track the ageing effects on a battery the BS calculates SOH through Equation 8, where $C_{LossBottom}$ is considering two ageing effects, ageing over time and ageing caused by the throughput ampere hour.

$$SOH = \frac{C_{Nom} - C_{LossBottom}}{C_{Nom}} \qquad (8)$$

The BS indicates a battery as defect if the internal resistance increases more than 50 percent or if a voltage at constant discharge current of more than 2 V is detected. It's calculates $C_{LossTop}$, that is the maximum reached SOC during the last driving cycles or a detected full charge. This is used to flag for sulphation (BS1 2013 and Beba 2014).

SOF

The BS measures the cranking ability, SOF, of the battery that is quantified with the expected minimal start voltage. To predict the start voltage the OCV, $U_{0,}$, impedance of the battery , R_i, and the resistance of the starter motor, $R_{starter}$, are used. Calculation is done to predict both expected start current and expected start voltage as Equation 9 shows (BS1 2013).

$$SOF = U_{pred} = U_0 - I_{pred}R_i \ \ with \ \ I_{pred} = \frac{U_0}{R_i + R_{starter}} \tag{9}$$

A start detection module extracts and store characteristic points during cranking. It extracts and stores points, such as 100ms after the minimal start voltage, 1st maximum and 2nd minimum. For this BS SOF represents the cranking ability of the battery and it's presented in an expected minimal starting voltage (BS1 2013).

5.1.2 **Battery Sensor 2 – BS2**

BS2 measures a battery's current, voltage and temperature. It estimates SOC and SOH through specialized software algorithms (BS2 2013).

BS2 uses the coulomb counting technique to estimate the batteries SOC value. It's similar to BS1 but performing different recalibrations. The calibrations is done with an OCV method after an 24 hours quiescent current but the sensor also recalibrates through flowing current and voltage drop caused by a starting current (BS2 2009). Unfortunately 24 hours with quiescent current is a situation that rarely happens for commercial vehicles.

BS2 communicates through LIN or CAN interfaces, see subchapter 5.1.4. BS2 has accuracy at +/- 2 ° Celsius (BS2 2008).

SOC

BS2 calculates SOC through a method based on available capacity (C_{nom}). C_{nom} is decreasing with temperature and age. BS2's method is formed as Equation 10, where C_{max} is maximal capacity, actual capacity based on age but at nominal temperature (20 ° C). $C_{max@T}$ is the maximal capacity at present temperature and Q_{stored} is the currently stored amount of coulombs, ampere hour (BS2 2011).

$$SOC_{nom} = SOC_{max} * SOH * \frac{C_{max@T}}{C_{max}} \ \text{ with } \ SOC_{max} = \frac{Q_{stored}}{C_{max}} \tag{10}$$

The SOC calculation in Equation 10 is then recalibrated with End of Charge (EOC), OCV and End of Discharge (EOD) (BS2 BMD 2011). This applies regardless of the Coulomb counting and adjusts the SOC calculations. It can also be used to avoid overcharging (BS2 2011).

BS2 also sends warnings to the users. If SOC is below 60 percent it’s sending a warning signal and below 50 percent it’s sending an alarm signal (BS2 2009).

SOH

BS2 doesn’t calculate a minimum starting value or some other parameters of the batteries functionality, SOF. However BS2 calculates SOH by three definitions.

Definition 1 is coulomb counting until EOD and it’s calculated through the Equation 11, where the units are the same as above (BS2 2008 and BS2 BMS 2011).

$$SOH = \frac{C_{max}}{C_{nom}} \tag{11}$$

Definition 2 is based on weighted Ah throughput. This definition has no direct relationship to C_{max} and continuous determines SOH. Definition 3 is a calibration of SOH based on progression of battery voltage during 60 Ah discharges. The thesis work does not have any detailed description of how these are combined to obtain a SOH value. It’s only described as high discharge rates cause reliable capacity calculations and if only low discharge rates are available the rated Ah method gives an indication when to exchange the batteries (BS2 2008).

5.1.3 Other Battery Sensors

Kromberg & Schubert’s (2011) indicate that their battery sensor gives a SOC value that has a good accuracy after 15 minutes rest after installation. To obtain a decent value for the battery temperature it’s instead needs 30 minutes rest. It’s also mentioned that their BS needs at least 5 cranks to give an accurate SOH estimation but that this result isn’t totally reliable because sometimes other events also are needed, such as longer charging periods.

5.1.4 Communication

A BS uses digital communication. It’s offering two different interfaces, Local Interconnect Network (LIN) or Controller Area Network (CAN). Both LIN and CAN are developed for the vehicle industry (Millinger 2009).

LIN is single master broadcast serial communication system. A LIN system is consisting of one master that is able to send out information and control up to 16 slaves. No collisions are occurring in a LIN system because all messages are initiated by the master and sent one bit at a time. The recipients are all other devices in the network and the responses are done by the requested slaves.

CAN is a more complex communication interface. This is because CAN is a multi-master broadcast serial bus. The difference between LIN and CAN is that every node in CAN is like a master in LIN. Every node is able to both receive and send messages. CAN is both an ISO-standard computer network protocol and a bus standard.

5.2 Requirement from the vehicles

The starter requires at least 18 V to activate the solenoid; furthermore it has to be able to crank enough to start the engine (Scania inline document 4). It's hard to determine the requirements for a successful engine start because it depends on several parameters such as current, voltage, temperature and the torque of the engine. The problem is increasing because of the complexity of how these parameters are related to each other. However some generalisations for three of Scania's engines have been formulated in this chapter.

According to Scania is defined that the degree of charge in a battery shouldn't be less than 40-50 percent of their full capacity. This definition is based on battery chemistry, which states that it's more likely that the batteries are damaged by example sulphation for higher discharges. To convert this amount of charge from percent into ampere hour it's recommended not to discharge more than 90 Ah for 225 Ah LAB. It's also important to take in consideration that the pole voltage of a battery is clearly affected if the battery has been charged or not. To receive right value a resting time is recommended before measurements (Scania inline document 5).

5.2.1 **Amount of charge require to start different Scania engines**

This is a summary of tests performed at Scania to examine the starting characteristics for different engines. The focus of this subchapter is to investigate the required amount of battery charge to start different engines. For test presentation see 4.2.1.

For these tests several parameters become recorded, such as the amount of charge at last engine start, current and voltage under start and engine's rotational speed during start. The temperature range for the experiments were between -20° C and 25° C, with two exceptions, -21° and 30° C. Scania's vehicles operate in both warmer and colder temperatures but this temperature range, is assumed to be representing a majority of all operation temperatures for vehicles in Sweden. This assumption is based on that Sweden's mean temperature is around 2-3° C (SMHI 2012) and it's why the range is almost equilateral. The endpoints are determined by a mean temperature of Sweden's highest and lowest temperature of all months (SMHI 2011). Perhaps the lowest test temperature should be lower but at the same time an engine start in colder temperature than -25° C can fail even if the batteries are delivering enough power for an engine start. Therefore it's not so useful to analyse lower temperatures in the thesis work.

To obtain charge requirements for engine starts, the minimum amount of ampere hours required for engine start several tests to investigate the charge requirements for engine start for three different engines, Engine 1, Engine 2 and Engine 3, was analysed. Considering the last successful start for each temperature and engine the minimum amount of ampere hours for each temperature and engine could be obtained. The minimum amount of ampere hours for all investigated temperatures and engines indicates that all studied engines started with a charge of around 25 ampere hours for the temperature range between -20° to 25° C. Lower temperatures were examine but it didn't result in any successful start. The conclusion of these tests is that there is hard to generalize required amount of ampere hour for engine starts because it's depending the engine type. However for these three engines, new batteries with 25 Ah charge left should be enough for engine start within the determined temperature range.

It should also be mention that it's a small margin between the first failed and the minimum capacity for engine start, the first failed is only around 5-10 ampere hour lower than the minimum capacity for engine start. The discharge times between last successful and first failed engine start are affect these results. Still the conclusion from these tests are that even a smaller amount of charge, as 5-10 Ah, can be devastating for the drivers decision making to ensure start.

It is worth to mention that these tests were performed with new LAB, so usages and ageing properties can be disregarded. It should therefore be taken into consideration that vehicles in field could have worn LAB. Due to this the amount of charge for engine start probably are a lot higher than what these tests shows. To obtain a comparable value for worn LAB, these tests conclusion 25 Ah should be multiplied with some factor for both the batteries and vehicles years in field. It isn't possible to develop this factor in the thesis work but an assumption could be that some worn LAB are twice and some are thrice as weak as new LAB. Therefore the assumption should be a value between 50 and 75 Ah. The thesis work has chosen 60 Ah but this value is an assumption and isn't verified in any other way. It's not particular important to verify because it shouldn't affect the evaluation of the BS. If a BS could estimate the SOC for new LAB accurate, it should manage worn LAB as well.

5.2.2 Voltage and Current

It requires more than charge left to ensure an engine start in a battery perspective because the battery also has to deliver a specific amount of current and voltage fast enough to crank the engine. A worn and aged battery has higher inner resistance, which has a negative impact on its ability to response at high current. It's therefore important to investigate start currents and voltages for the three engines in different temperatures (Kovacevic 2014). This subchapter summarize several tests of these aspects.

Figure 17 shows two typical successful engines start. It shows how the voltage is affected by the starting process and it also indicates that a start contains several cranks before the engine is started. Figure 17 is the first and last successful start at +25° C for Engine 2. The initial voltage as well as the lowest voltage during the start is higher for the first successful start then at the last. It's due to the lower charge in the LAB, the first successful start is fully charged (225 Ah) while the last successful start only is around 12 Ah according to tests in subchapter 5.2.1.

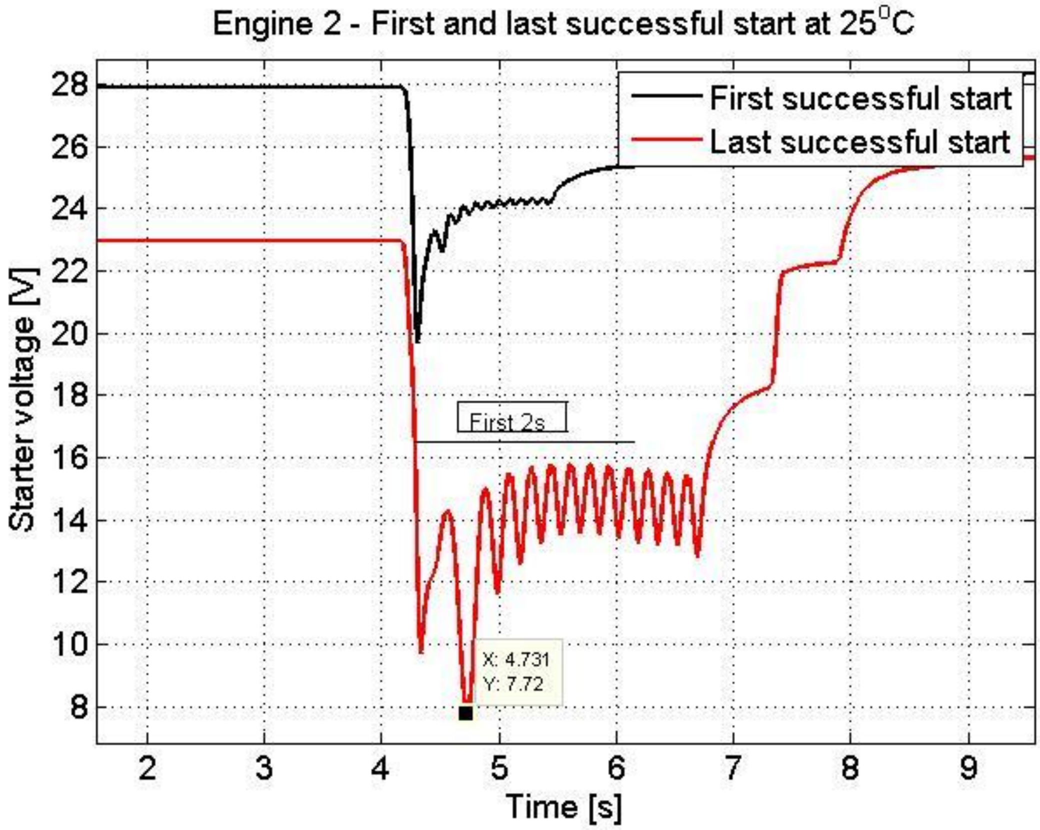


Figure 17: Starter voltage and time - First and last successful start for Engine 2 at +25° C.

Figure 17 is also indicates the first two seconds of the start as well as the lowest voltage. It's due to that the lowest voltage often appears in this first part of an engine start. It's often the first crank that is results in the lowest voltage. This is because the starting current is largest in the beginning which creates a larger voltage drop. The first crank facilitates the cranking and therefore the current that is needed to crank the engine is lower and lower until the engine starts, it's also influences the voltage as earlier mention which Figure 17 shows (Kovacevic 2014).

To analyse engines starting process low voltages as well as starting times has been investigated. The starting process has been divided into segments to obtain critical points. Figure 18 indicate and explain how these critical points, lowest voltages, in each segments have been deduced.

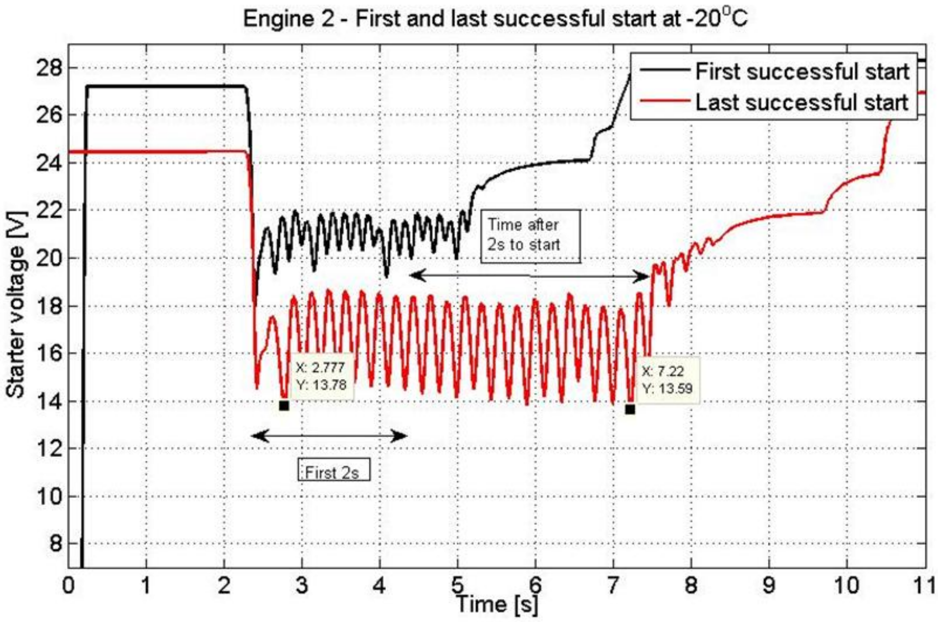


Figure 18: Starter voltage and time - Engine 2, first and last successful start at -20° C, with segment (1), first two seconds, and segment (2), between 2 and 5 seconds.

Figure 18 shows two of the segments that all engine starts has be divided in. These segments are the first two seconds during a start (First 2s) and between two and five seconds (Time after 2s to start). The lowest voltage in each segment and the lowest voltage for the whole starting process can be deduced and analysed. Figure 18 indicates that the lowest voltage and the lowest voltage within two seconds of the start is the same voltage.

The engine start process is divided in three segments and the reason why Figure 18 only has two segments is that the engine almost starts before the last segment, it's only 0.54 seconds. However, the start process is divided in the three segments, the first two seconds (1), the next 3 seconds (2) and the rest of the starting (3). The backgrounds to the decision to analyse and extract lowest voltage of these segments are both because the BS1's operation method, Bohlen et al (2004) in subchapter 3.4 as well as it according to the starting tests could facilitate the analyses. To clearly visualize, a summary of lowest voltage in each segments for all engine and all temperature is presented in Table 2. Table 2 is also includes average starting current for the engines. It's deduced from the relationship between average starting current and temperature. Figure 19 shows this relationship for Engine 1 in a temperature range between -20° and +32°.

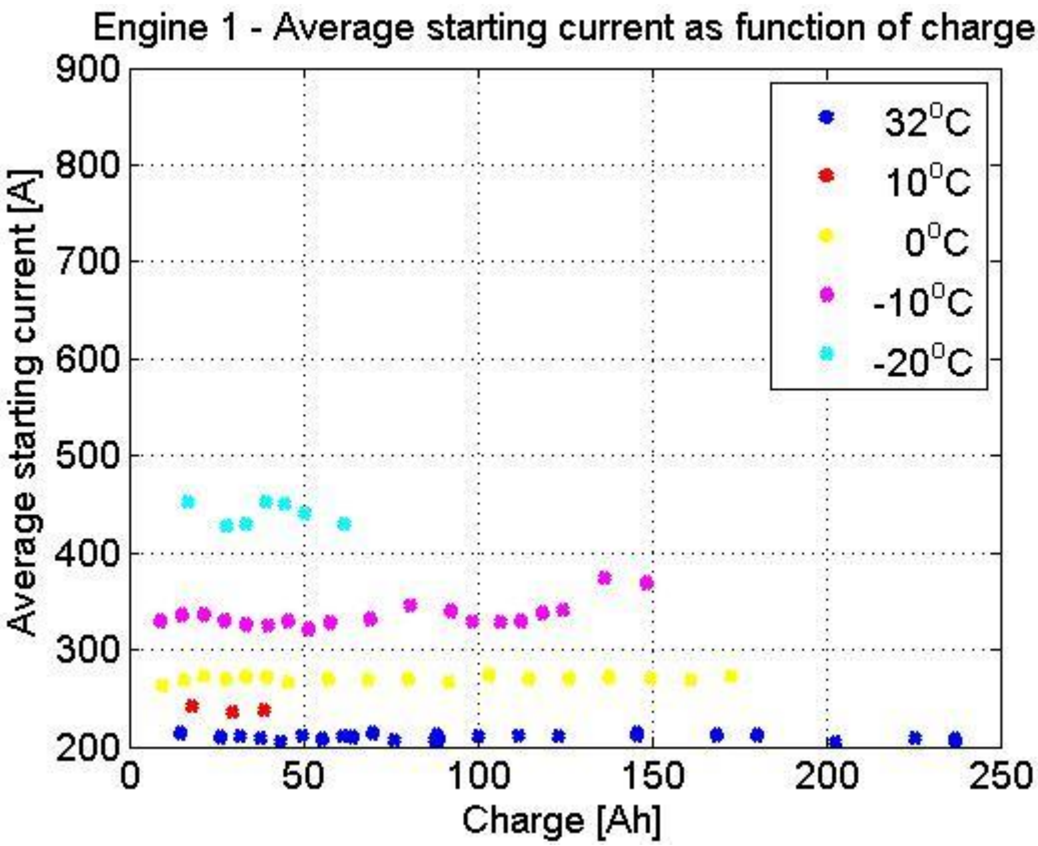


Figure 19: Average starting current and charge - Engine 1 for different temperatures.

Figure 19 indicates that the average starting current is independent from the amount of charge left in the batteries. It's instead varies with the temperatures. Due to this it's easy to deduce average starting currents for a specific temperature and engine. Figure 19 shows that the average starting current for Engine 1 in -20° C is around 450 A. The average starting current for the other engines and temperatures can be seen in Table 2.

Table 2 summarize the voltages and currents analysis from the starting characterises tests. It should be mention that Engine 1 has been tested at 32° C instead of 25° C but at such high temperature the difference should not be as high so it affects the comparison. Table 2 only includes the highest and lowest temperatures, -20° respectively 25° C as well as the highest and lowest average starting current for the engines. It's due to that all engines with some exceptions require higher voltage to start a engine the colder it gets.

Here follow some explanations to clarify Table 2. L.V is the lowest voltage for the whole start process and the segments are shortened as L.V1 (1) and L.V2 (2) with means lowest voltage within 2 seconds (1) and lowest voltage between 2 and 5 seconds (2). The last segment, lowest voltage after 5 seconds, is not included in Table 2. Current High is the highest current, the average starting current for -20° C (I_{-20}) and Current Low is the average starting current for +25° C (I_{+25}). Temp. is an shortening for temperature.

Table 2: Summary of the analysis of starting characterises test at Scania

	Engine 1			Engine 2			Engine 3		
Current High	450 A			550 A			700 A		
Current Low	200 A			250 A			300 A		
	L.V	L.V1	L.V2	L.V	L.V1	L.V2	L.V	L.V1	L.V2
Temp. 25°C	8,8 *	8,8 *	13,7	7,7	7,7	12,8	7,5 V	7,5 V	12,4
Temp. -20°C	14,2	14,2	15,1	13,6	13,8	13,6	11,2 **	11,2 **	12,5

*different temperature, 32 °C, **different temperature, -21 °C

The time to start is increasing with lower temperature for all engines. Engine 1 indicates on an almost linear growth for the starting time; the last start at +25° C takes less than 3 seconds, the last at 0° C takes nearly 5 seconds while at -20° C the last start takes around 10 seconds. Engine 2 and 3 don't show the same relationship but the starting time is still increasing with decreasing temperature (Scania inline document 6). The time to start for the same starts as in Table 2 is showed in Table 3, with more information, such as number of compressions and initial voltage.

Table 3: Staring times, initial voltage and number of compressions for starting characteristics tests

	Engine 1		Engine 2		Engine 3	
	Temp. 32°C	Temp. -20°C	Temp. 25°C	Temp. -20°C	Temp. 25°C	Temp. -21°C
Starting time	2,45s	10,20s	2,40s	5,54s	2,95s	3,10s
Initial voltage	23,0 V	25,1 V	23,0 V	24,5 V	23,1 V	24,1
Number of compressions	13	39	12	26	17	16

Table 3 indicates that it's only Engine 1 that has significant longer starting time than 5 seconds at -20° C. Engine 2 has also a starting time longer than 5 seconds but its only 0.54 seconds longer.

The lowest voltages, starting times and more have been analysed but it's also possible to distinguish an average voltage for the three earlier defined segments in a starting process. The average voltage is calculated from the lowest voltage for every compression, Figure 20 shows the lowest voltage for all 16 compressions that Engine 3 cranked before it started at -21° C. The average voltage is due to the calculation not the average voltage but rather the lowest average voltage. It's calculate an average value of the lowest voltages and the answer is therefore a lowest average voltage to ensure start.

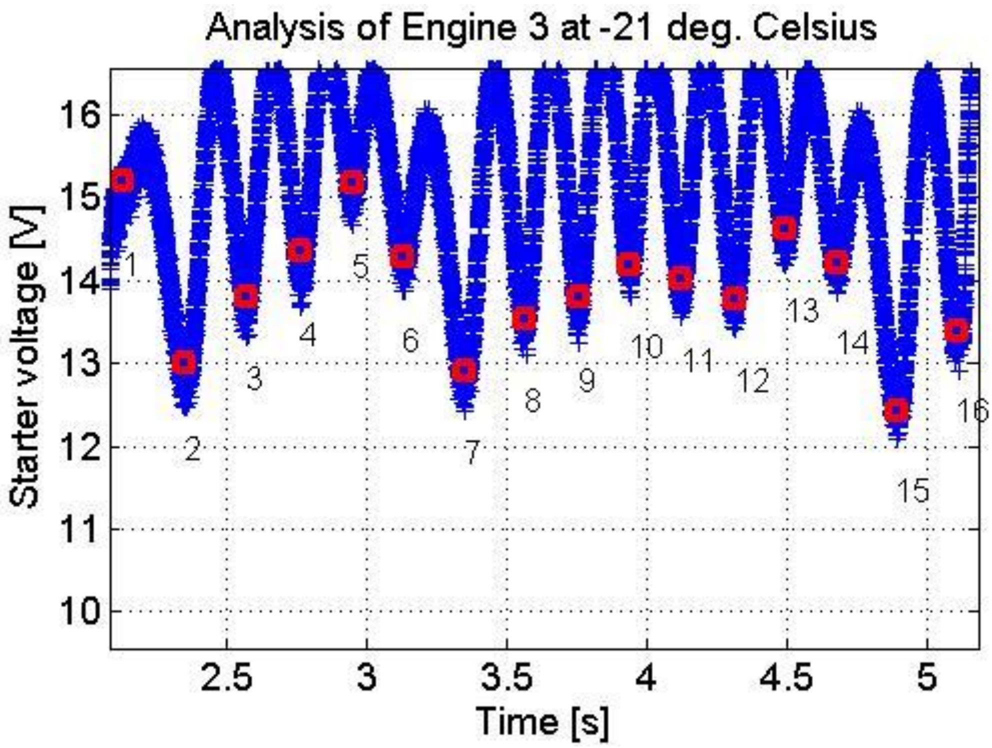


Figure 20: Starting voltage and time – Compressions analysis of Engine 3 at 21° C.

The lowest average voltage calculations for the same starts as for Table 2 and 3 are sum in Table 4. The lowest average voltage is separated in; lowest average voltage within 2 seconds representing segment (1), lowest average voltage between 2 and 5 seconds representing segment (2) and lowest average voltage after 5 seconds representing segment (3). A.V is a shortening for lowest average voltage. The term "compressions to above" establish which compressions the lowest average voltage above is calculated from in Table 4. Example Table 3 and Figure 20 show that Engine 3 at -21° C has 16 compressions in the whole starting process. Table 4 indicates which of these 16 compressions that is used to calculate the different segments lowest average voltage. It could therefore be deduce from Table 4 that compression 1-11 is used to calculate the lowest average voltage within two seconds, 14.0 V, for Engine 3 at -21° C. It could be confirmed by Figure 20, if the lowest voltages for compression 1 to 11 are added together and then divided by 11, the sum should be the lowest average voltage within two seconds for Engine 3 at -21° C, 14.0 V.

Table 4: Continued on Table 2 and 4, more analysis of starting test at Scania

	Engine 1		Engine 2		Engine 3	
	Temp. 32°C	Temp. -20°C	Temp. 25°C	Temp. -20°C	Temp. 25°C	Temp. -21°C
A.V within 2s	**13,4 V**	**16,3 V**	**12,5 V**	**13,5 V**	**12,1 V**	**14,0 V**
Compressions to above	1-10	1-9	1-9	1-9	1-13	1-11
A.V between 2 and 5s	**14,6 V**	**17,0 V**	**12,2 V**	**13,6 V**	**12,7 V**	**13,7 V**
Compressions to above	11-13	10-32	10-12	10-23	14-17	12-16
A.V after 5 seconds	**-**	**19,5 V**	**-**	**14,5 V**	**-**	**-**
Compressions to above	-	33-39	-	24-26	-	-
Number of compressions	13pcs	39pcs	12pcs	26pcs	17pcs	16pcs

The conclusion of Table 4 is that it's very hard to generalize anything for different engines. The engines different properties affect the results which not is surprising because there are completely different engines with various forms and numbers of cylinders that are examined. Still it's possible to sum that for the temperature +25° C (and +32° C) these three Scania engines normally should start if the average voltage delivered within 2 seconds is over 13,4 V and after 2 seconds is over 14,6 V. It's due to that these values are the highest values for all engines at the specific temperature. The corresponding value to start all engines at -20°C (and -21°C) should according to Table 4 be 16,3 V within 2 seconds, 17,0 V between 2 and 5 seconds and 19,5 V after 5 seconds up to 10 seconds. These lowest average voltages are of course depending on a cranking current, a current that cranks during a starting process which differs from the average current showed in Table 2.

5.3 Customer benefits with battery sensors

The benefit with BS is that it can deliver information about the batteries conditions to both driver and the electrical management system. The BS's delivered information could then be decision basis for both the driver and the electrical management system. Therefore it's important that the information is reliable so that decisions not based on inaccurate information.

An analysis of Scania's competing firms has showed that larger errors in data from battery sensor causes reduced trust for the vehicle's equipment and this is confirmed by Andersson (2014). This isn't good because it can also affect the firm's trademark and Scania especially is built on ideas as customers first, respect of the individual and quality (Scania 2014). To fulfil these visions it's important that customers associate Scania with trust and quality; therefore the battery sensors have to deliver reliable information. Incorrect SOC and SOH calculations together with an electrical management system can cause unnecessary shutdowns and it also could mislead the driver to example unnecessarily battery changes. This deficiencies or even smaller errors could lower the trust for the equipment and it could eventually also affect the firm's brand.

To maintain the customer's benefit with the product and at the same time not affect Scania's trademark negative, it's of great important that the battery sensor delivers reliable information. The information should be as reliable as any other equipment in the vehicles. How reliable and accurate the information has to be is also influenced by how the information is visualised for the users (Andersson 2014). Example if the SOC is visualized as a remaining time with a warning to ensure engine start, the time has to be very accurate to not mislead the drivers. It's not reliable if the remaining time leaps as well as it shouldn't be sending the warning to early. If the SOC instead is visualized as a fuel gauge, it shouldn't have to be as accurate as for remaining time because then it's up to the drivers to make decision about when to start the vehicles. It's due to that a fuel gauge or "battery gauge" could divide the information in categories, sets such as critical low SOC, low SOC and good SOC. It reduces the customer benefit with the product a bit, no deadline warning, but at the same time it's better than that the trademark is affect negatively. SOF could improve SOC calculation with this aspect but SOF has not the potential to ensure an engine start, it can only ensure that the batteries characteristics are enough for an engine start. It's also requested to know the batteries health, to minimize unwanted stops and especially to help the firms to plan battery changes. To manage that, a warning or at least a countdown to inform the driver about the battery's health is needed (Andersson 2014).

5.3.1 How to visualize the battery sensor information

To take advantages of the battery sensor it's important that the information is visualized in a perspective that favours the customers. To maintain the benefits with a BS it could be visualizes as some type of battery gauge, that indicate the amount of charge left. This could be solved in different ways, either as competing firm's visual battery, time left, a percent counter or a regular gauge, similar the fuel gauge. To clarify and improve this information it could be set in parity with SOF information, start or not. There is no need for more information about SOF, functionality or not is what is important to know because SOH indicates when the batteries are beginning to be dysfunctional because of wear and ageing. SOH is a complicated value that is hard to verify but one thing is sure, the value should only be lowered by the time. The batteries' health shouldn't improve because ageing affect them negative. Temperature affects the batteries' capacity, the discharge and recharge level is decreased by a lower temperature but it shouldn't affect the actual health. The SOH value shouldn't jump up and down because the customer benefit of this value is to help the driver to decide when to change the batteries. To maintain this benefit the SOH value should be visualised as a countdown, that is following the SOH changes to inform the driver when the batteries' health no longer is good enough.

To ensure that the driver is aware of the BS information it should be visualised on the dashboard. It's possible to add warning signals if the information is accurate enough. This could then be a safety guarantee to ensure engine starts for example drivers that are sleeping in the vehicles. The electrical managing system could by BS information turn off loads, larger consumers automatically in critical situation. Even more exclusive system could visualize the SOC on the driver's phone, watch or key. This makes it possible for the driver to know the SOC and SOF even outside the vehicle.

6. Results and Discussions

This chapter present the evaluation criteria and evaluation methods for SOC, SOF and SOH. It starts with all evaluation criteria, then corresponding evaluation methods is present. The chapter ends with a subchapter about the evaluation methods applicability.

6.1 Evaluation criterion for SOC

This chapter is divided in four subchapters to make it easier for the reader to follow. The first two subchapters are reviews and analysis to formulate an equation that in the third subchapter summarizes and defines as the evaluation criterion. The last subchapter is about that the evaluation criterion for SOC also affects SOF and SOH.

6.1.1 **Formulate equation to evaluation criterion for SOC**

There are, as mentioned earlier, several advantages with battery sensors but with inaccuracy in the estimations these advantages could disappear. To maintain these advantages it’s important in a functional view that the BS estimates an as correct value as possible. This chapter discusses how good a BS should estimate the SOC value to not compromise these advantages and it’s also begins to formulate an evaluation criterion for BS SOC estimations.

To formulate this criterion the estimated SOC needs to be verified against a correct value. The correct value, the actual SOC is calculated with Coulomb counting. In chapter 3 other techniques are discussed but Coulomb counting was chosen as the technique to obtain the actual value in the thesis work, see subchapter 3.1.3. Coulomb counting as SOC model is describes in subchapter 3.5.2 but shortly it’s a technique based on current integration. It’s therefore sometimes also called Cumulated Current, which it could be mention as in some figures. Coulomb counting could find the ampere hour at each time point with Equation 5, which can be compared with the BS estimated SOC.

Scania has earlier specified a requirement specification about the accuracy for BS’s estimation and it was formulated as a maximum error at 5 percent for SOC and at 10 percent regarding to SOH. The requirement specification hasn’t been verified so therefore this thesis work should begin with this value for SOC as initial value in an iterative process to formulate an evaluation criterion for BS.

Scania’s requirement specification for SOC is kind of unclear. Is it referring to the LAB capacity or the present charge? Is the maximum error a total maximal error or is it a constant error limit, that the error should be smaller than 5 percent at all time? Due to how it formulate an assumption could be that it’s considered as 5 percent of the nominal capacity and as a constant error limit. It’s therefore this iterative process initial value, a constant limit at 5 percent of the nominal capacity, which Figure 21 shows.

To ensure that both overestimated and underestimated errors are considered in the limitation, the criterion should have both high and low boundaries. The boundaries are calculated as 5 percent of nominal capacity, 0.05 multiplied with 225 Ah and then it's both added to and subtracted from the coulomb counting to create both high and low boundaries to the actual SOC for each time point. Figure 21 shows the boundaries (Evaluation criterion) in the third subplot as the red-dots lines.

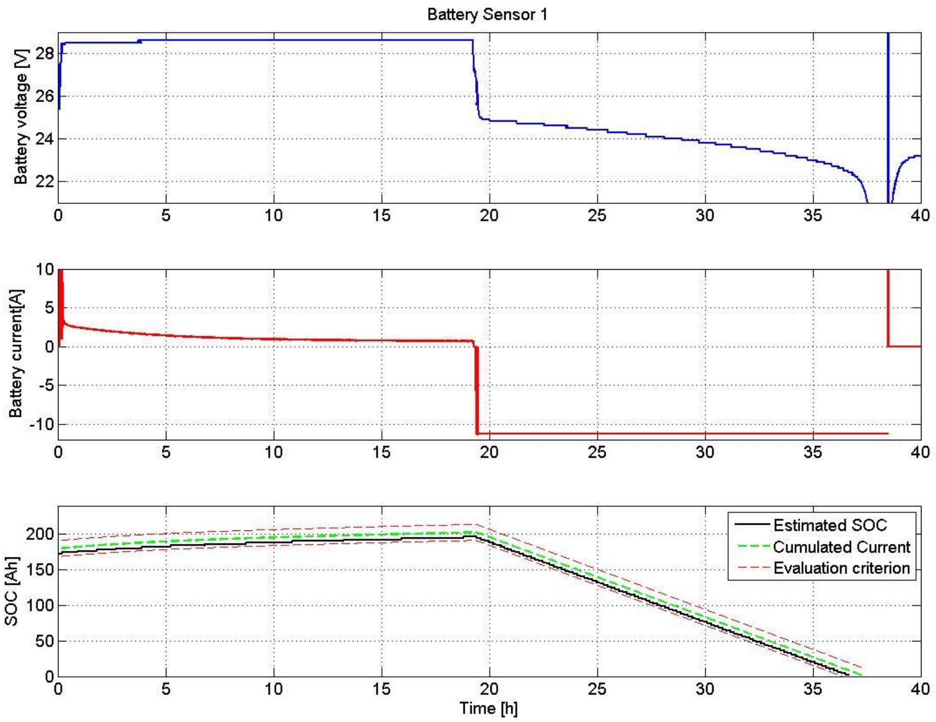


Figure 21: Charge-discharge cycle - BS1. It's a subplot from above with voltage, current and SOC. Limitation in the last subplot, at maximum 5 percent error of nominal capacity added to present SOC.

Figure 21 is a subplot of output values from the tested BS that is BS1. The first subplot, at the top, is the current over the 24 V battery pack and the second subplot, in the middle, is the corresponding voltage for the cycle. These two plots show a positive current and a voltage over 24 V in around 20 hours which indicates that the battery back, the LAB are charge. Then the current gets negative and the voltage slowly decreases down to 21 V which indicates empty LAB. The leaps in the end, after 38 hours, can be neglect because the cycle is over when the battery pack is empty. The third subplot is what should be analysed. It shows both the estimated BS SOC value (Estimated SOC) and the actual SOC value (Cumulated Current) calculated by Coulomb counting. These parameters follows the two first subplots, the SOC value in ampere hour is increasing to around 20 hours and then it's decreasing to empty. For an overview about which cycles the BS and LAB has been subject to read chapter 4.2.1.

Figure 21 show that the tested BS's estimated SOC is inside the boundaries during the whole cycle. It indicates an accurate SOC estimation according to Scania's earlier requirement specification. However this thesis work has concluded that it isn't reasonable to evaluation a BS based on constant limitations because when the SOC is higher, the error could be larger without lower the equipment's trust. In contrast the error must be small for a lower amount of ampere hours left because otherwise the BS could mislead the customer. Therefore a limitation according to the present SOC is tried instead of the constant 5 percent limit based on nominal capacity. Figure 22 shows this limitation, which keep the 5 percent limit but is calculated based on the present SOC instead of the nominal capacity. To calculate the limitation, the present SOC is multiplied with 0.95 for the lower boundary and 1.05 for upper boundary.

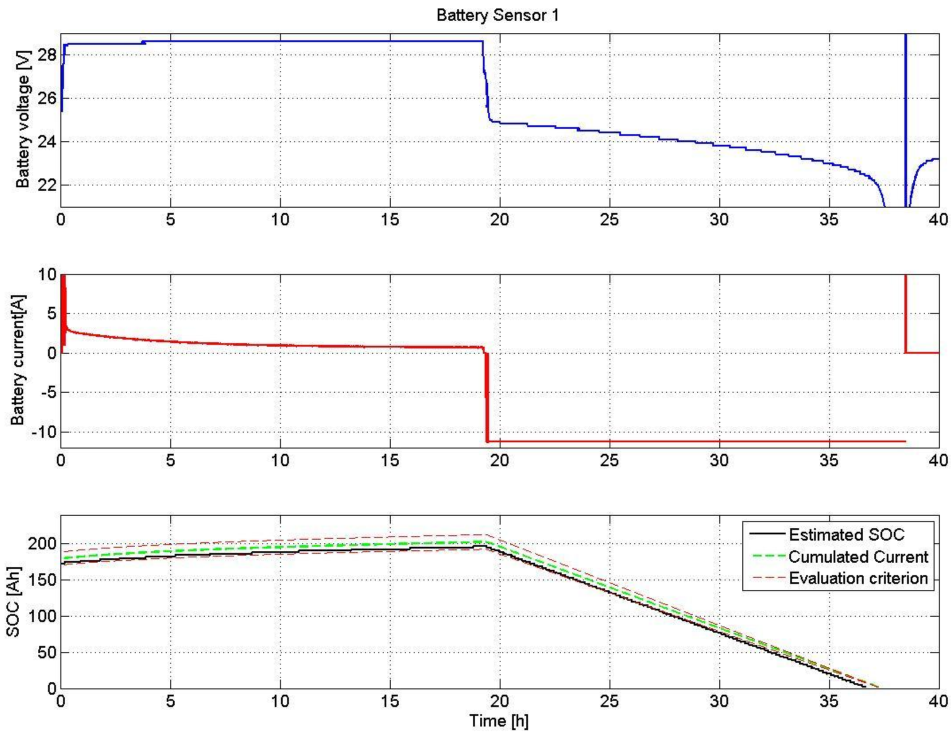


Figure 22: Charge-discharge cycle - BS1. The BS limitation in the last subplot has boundaries at 5 percent of present SOC.

The limitation in Figure 22 takes the customer benefit into account, that the estimation must be more accurate at low SOC than for higher. The BS's estimation of SOC is still inside the boundaries in the beginning but when the boundaries are tightening, it slips out. Due to that this SOC estimation seems rather accurate, only some ampere hour in a constant error according to the actual SOC, it was conclude that this limitation not was an optimal arrangement. It was not realistic that the estimation should be so accurate at small amounts and exactly right with no ampere hours left. To confirm this conclusion Figure 23 shows a different longer cycle, Repeated Charge-Discharge cycle, with same limitation.

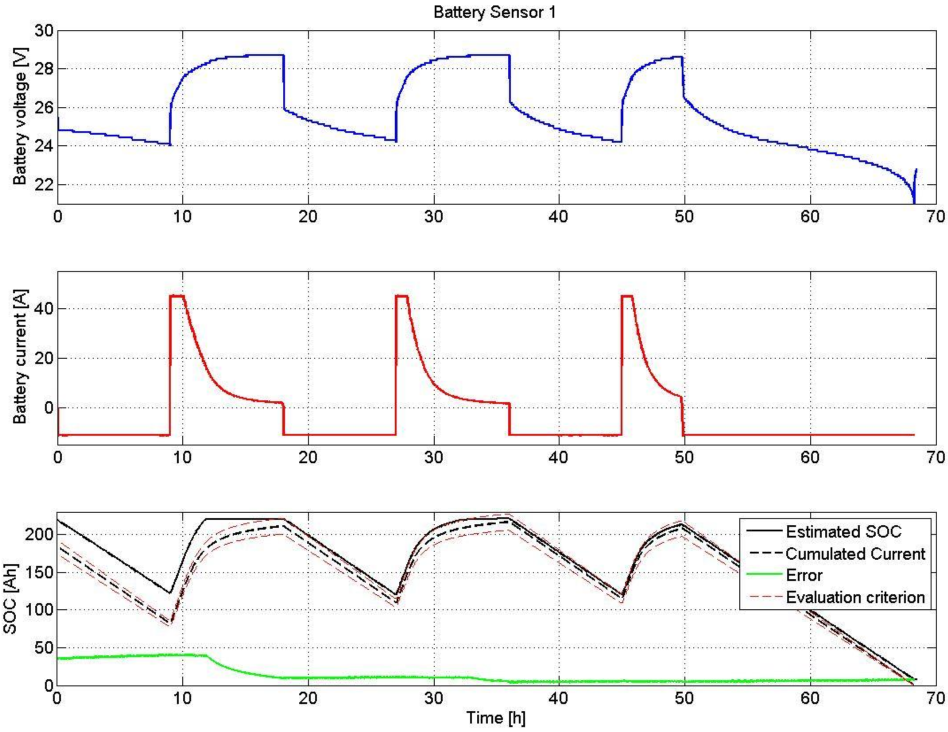


Figure 23: Repeated Charge-Discharge cycle –BS1. Limitation at 5 percent of present SOC and is also includes error calculations.

Figure 23 confirms the earlier conclusion that it isn't realistic to require a so exact SOC estimation. Figure 23 indicates that the BS has problem both in the beginning and the end of the test to manage the limitation. In the third subplot a green line (Error) is showed. It's a calculation between estimated SOC and actual SOC, the error between these two. This line indicates on a better and better estimation over time but still it clearly outside the boundaries in the end. The vehicles' requirements do not demand such accurate SOC estimation. The minimum starting capacity for new batteries is around 25 ampere hours, see subchapter 5.2.1, and therefore it's more important with good accurate at this point then exactly right at empty batteries. Equation 12 could be used to calculate the final error. The BS's estimation could be accurate although the Equation 12's result isn't zero.

$$SOC_{final\,error} = SOC_{ref}(t_{end}) - SOC_{est}(t_{end}) \qquad (12)$$

In equation 12, SOC_{est} is the BS estimated SOC, SOC_{ref} is the actual SOC and t is the time. Equation 13 could be used to calculate the maximal error; the same parameters as Equation 12 is used but instead of calculated the final error at t_{end} it should go through all time point and extract the largest.

$$SOC_{\max\,error} = max|SOC_{ref} - SOC_{est}| \qquad (13)$$

As mention subchapter 5.2.1 concludes that it requires around 25 Ah to ensure that a new battery pack can start all investigated engines. It's also a small difference, only 5-10 Ah, between a successful or failed engine start. Due to this information the maximum error, which can be calculated by the Equation 13, should be around 5-10 Ah for low SOC (0-100 Ah) while it could be larger, 10-20 Ah, for higher SOC values (101-225 Ah) without mislead the users and reduce the customer benefits. A mathematical overview of this statement is showed below.

$$\begin{cases} 5 \leq SOC_{\max error}(0 \ \rightarrow 100Ah) \leq 10 \\ 10 \leq SOC_{max\,error}(101 \ \rightarrow 225Ah) \leq 20 \end{cases}$$

The statement above is of course depending on size of batteries but in this thesis work, only 225 Ah LAB' are considered. It also confirms the earlier tried limit based on present SOC instead of a constant limit. Therefore an evaluation criterion based on the $SOC_{\max error}$ statement and that it should vary with the SOC values is formed. The result is Equation 14, where $SOC_{\max error}$ is a number which varies based on present SOC due to $\frac{SOC_{ref}}{SOC_{nom}}$.

$$SOC_{limitation} = SOC_{\max error} \ \frac{SOC_{ref}}{SOC_{nom}} \tag{14}$$

Equation 14 uses the same parameters as Equation 12, SOC_{est} and SOC_{ref}. To investigate how the criterion would be with Equation 14 and the maximal $SOC_{\max error}$ statement some calculations has been done which are summarized in Table 5. The maximal $SOC_{\max error}$ statement is that $SOC_{\max error}$ in Equation 14 is 10 Ah for SOC between 0 and 100 Ah and 20 Ah for SOC values between 101-225 Ah.

Table 5: Maximum error (MaxError) for different SOC values (Actual SOC) – for limitation based on Equation 14 and the $SOC_{max\,error}$ statement

Actual SOC (Ah)	225	200	175	150	125	100	75	50	25	0
MaxError (Ah)	20	17,8	15,6	13,3	11,1	4,4	3,3	2,2	1,1	0

Table 5 indicates that low SOC are limited rather hard, almost too much because it's limited twice, both by the statement (10 Ah instead of 20 Ah) but also by the varying $\frac{SOC_{ref}}{SOC_{nom}}$ part in Equation 14. To not limit the estimation twice, Equation 14 with a constant $SOC_{\max error}$ at 10 Ah and 20 Ah for all SOC values was tested and the result of error calculation could be seen in Table 6.

Table 6: Maximum error (MaxError) for different SOC values (Actual SOC) – for limitation based on Equation 14 and constant $SOC_{max\,error}$ values, 10 and 20 Ah.

Actual SOC (Ah)	225	200	175	150	125	100	75	50	25	0
MaxError(Const.10) (Ah)	10	8,9	7,8	6,7	5,6	4,4	3,3	2,2	1,1	0
MaxError(Const.20) (Ah)	20	17,8	15,6	13,3	11,1	8,9	6,7	4,4	2,2	0

Table 6 indicates that it's probably enough to use $\frac{\mathrm{SOC_{ref}}}{\mathrm{SOC_{nom}}}$ to claim a more accurate estimation at lower SOC values, because Table 6 shows that the maximal error (MaxError) decreases rather fast despite the constant $SOC_{\max error}$. The maximal error decreases according to the present SOC and reduce the allowed area between the boundaries. Therefore a final evaluation criterion is defined as Equation 15.

$$\pm XX\ Ah\ (\frac{SOC_{ref}}{SOC_{nom}}) \tag{15}$$

Equation 15 includes a XX, it's the tolerance amplitude and should be parameterizes between 5 and 20 Ah based on the $SOC_{\max error}$ statement. Due to that it isn't reasonable to require no error at all for empty batteries a final modified evaluation criterion is defined as the Equation 16.

$$\pm XX\ Ah * (1 + \frac{SOC_{ref}}{SOC_{nom}}) \tag{16}$$

SOC_{ref} is still the actual Coulomb counted SOC, the actual present SOC in every time point and SOC_{nom} is the nominal SOC value for the LAB in ampere hour.

To show the differences between this two equations table 7 contains both Equation 16 with tolerance amplitude at 10 Ah and Equation 15 with tolerance amplitude at 20 Ah. The difference is rather small for high SOC value but Equation 16 gives much larger margin for the estimation for smaller amounts of ampere hours. To decide which equation and what tolerance amplitude that is reasonable to use to evaluate BS, the two BS in the thesis work have been examined for several different tolerance amplitudes, between 5 and 20 Ah.

Table 7: Limitations for Equation 15 and 16 according to specific SOC values

Actual SOC (Ah)	225	200	175	150	125	100	75	50	25	0
Eq. 16, 10 Ah	20	18,9	17,8	16,7	15,6	14,4	13,3	12,2	11,1	10
Eq. 15, 20 Ah	20	17,8	15,6	13,3	11,1	8,9	6,7	4,4	2,2	0

Table 7 indicates as mention that Equation 16 with tolerance amplitude at 10 Ah has rather large margins to limit the estimation with, which could lead to failed starts. For 25 Ah SOC left it allows 11 Ah in error, which could result in an estimated value at 25 Ah while the actual value only is 14 Ah. This isn't good but with a low SOC warning at for instance 60 Ah as the assumption about worn batteries in subchapter 5.2.1. There's still margin to start because for 60 Ah SOC Equation 16 with tolerance amplitude at 10 Ah allows error at 12,6 Ah, which means that the lowest accepted value at this point is 43,3 Ah.

Equation 15 and 16 allow the BS estimation to vary as long as the estimation is inside the boundaries. This is a presumption for the BS' possibilities to recalibrate. Figure 28 in subchapter 6.1.2 shows a recalibration leap that increases the estimation's accuracy. However, to be reliable information for decision making the BS estimation shouldn't leap up and down. These leaps will lower the BS credibility and also reduce the customer benefits with it. Therefore the formulated evaluation criterion has to limit these recalibration leaps, of course the BS still must be allowed to calibration to improve the estimation but not with to large leaps. Equation 15 and 16 limit this recalibration leaps rather well as it is with their boundaries but the area between the boundaries are also dependent on the tolerance amplitude and this should be keep in mind.

6.1.2 Parameterized the equation to evaluation criterion

This subchapter should chose which elaborated criterion that should be used. It should also parametrizes the tolerance amplitude in the selected criterion. To do this an iterative test process has been done, which included the both BS, BS1 and BS2, as well as several tests to till if the criterion is reasonable according to requirements for both the customer and the vehicles.

The iterative test process includes five tests. The first two, Test 1 and 2 are easier tests based on a Charge-Discharge cycle. Test 3 is based on a Repeated Charge-Discharge cycle while Test 4 is based on a Mixed Charge-Discharge cycle. The last test, Test 5 is closes to the actual situation in a vehicle and is based on an Extended Mixed Charge-Discharge cycle. For an overview about which cycles the BS and LAB has been subject to read chapter 4.2.1.

Test 1: Charge-Discharge Test – first part, BS1

Test 1 is divided in two parts, the first for BS1 and the second for BS2. Figure 24 shows a charge-discharge test for BS1. The subplot in the top shows the voltage during the test and the middle subplot shows current as in earlier figures. These graphs indicates that the test start with a charge at 28.3 V. It's due to that Scania's vehicle's alternator usually charges with this value at ordinary temperature (20° C). The charge is approach a fully charged LAB around 20 hours in the test, the charge is at that time changed to a discharge with constant current, (I_{C20}) as for 225 Ah LAB is 11.25 A. The LAB is discharged to 21 V which indicate empty LAB. The leaps in the end of the current and voltage subplots are measurement errors that don't affect the results of the SOC subplot in the bottom. These errors probably occur because the discharging doesn't shut down as it should, at 21 V.

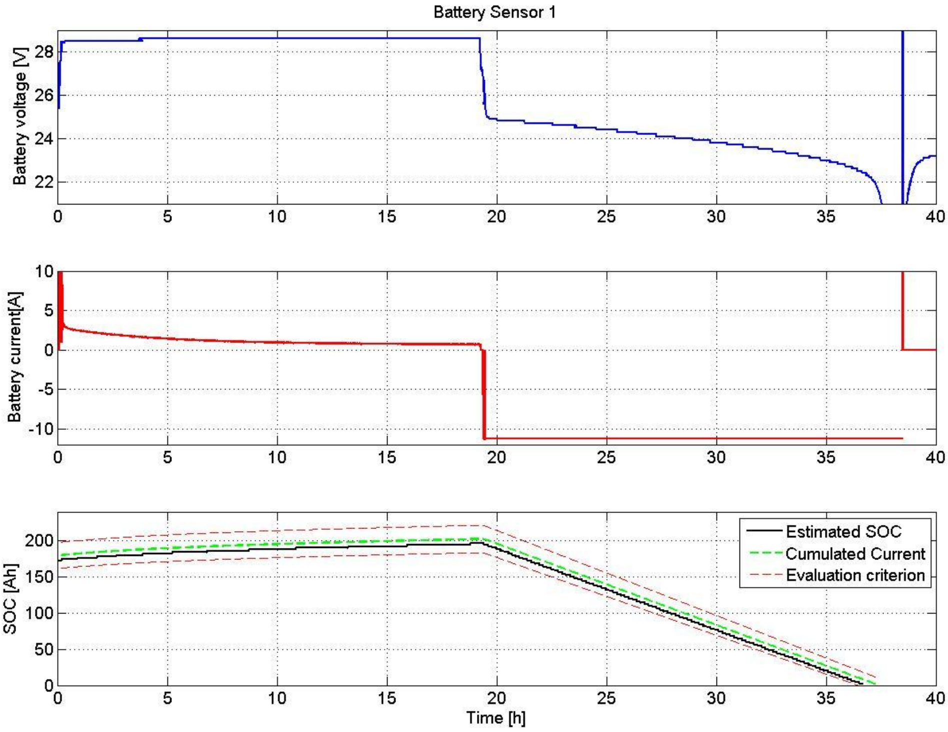


Figure 24: Charge-discharge cycle- BS1. Current, Voltage and SOC. Evaluation criterion based on Equation 16 - tolerance amplitude at 10 Ah.

The bottom subplot in Figure 24 is the one of interest. This subplot shows the BS1 estimated SOC (Estimated SOC), the Coulomb counting and an evaluation criterion including both upper and lower boundaries (Evaluation criterion). The evaluation criterion is the previous proposed Equation 16, with tolerance amplitude at 10 Ah. Figure 24 indicates that the BS1 is underestimating the SOC but still the value is between the boundaries. It's a good result because BS1's estimation is only around 5 Ah from the actual SOC. Figure 25 shows the same test as in Figure 24 but with a different evaluation criterion. It's still Equation 16 but instead of 10 Ah the tolerance amplitude is 5 Ah.

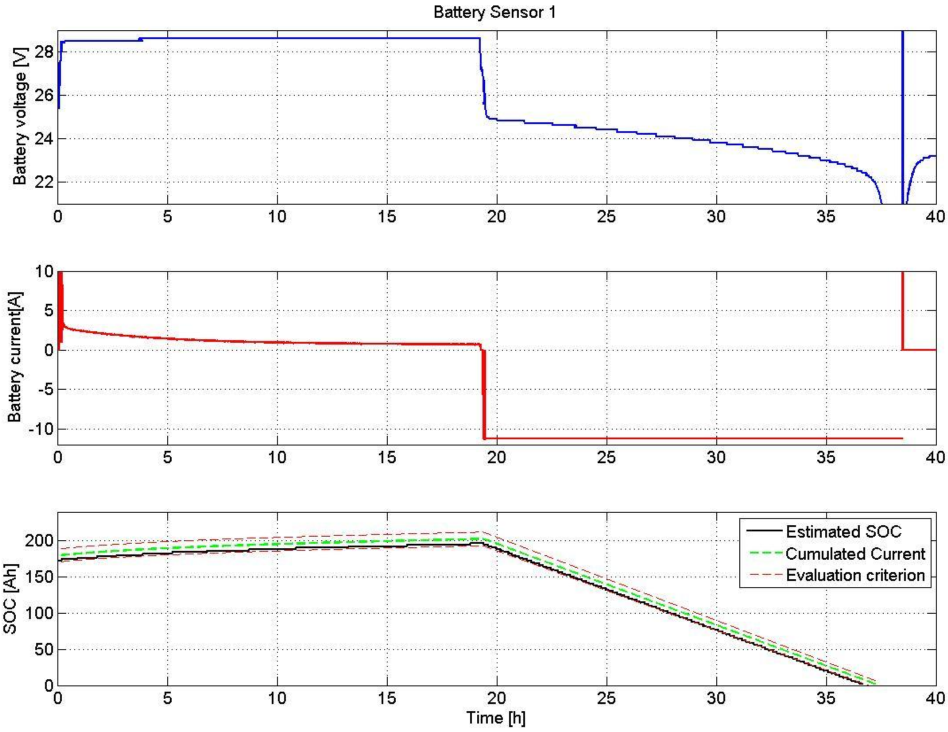


Figure 25: Charge-discharge cycle- BS1. Current, Voltage and SOC. Evaluation criterion based on Equation 16 - tolerance amplitude at 5 Ah.

The lower tolerance amplitude does it more difficult for the BS to manage the criterion. Figure 25 show that BS1 still almost managed the criterion. As mention in subchapter 6.1.1 this criterion allows larger error at higher SOC and vice versa. The BS estimation error for this test is constant, which result in that the estimation is between the boundaries until around 30 hours and is then slips out. This test indicates at problems with the initial value, that the initial error follows the whole test. Millinger (2009) mentions it as regular problem for BS. The BS estimation in Figure 25 would be much better if this problem could be solved because the estimation follows the actual value but with a gap that the initial error creates.

Table 8 summarizes the estimation's error according to criterion, not actual SOC, for BS1's Charge-Discharge tests. It includes Figure 24 and 25 as well as criteria based on Equation 15 with tolerance amplitude at 10 and 20 Ah, which could be seen in Appendix A. The criteria based on Equation 15 show similar result as Figure 25, that the estimation slips out at around 30 hours. It could be conclude from these criteria and Table 8 that larger tolerance amplitude doesn't affect this problem. Irrespective of tolerance amplitude the estimation not could accomplish these criteria for low SOC values because criteria based on Equation 15, requires very exactly estimation for low SOC. Table 8 describe this problematic mathematical, all criteria based on Equation 15 has large error (average error is around 3 Ah) and a higher tolerance amplitude didn't solve this, it's due to this problematic at low SOC. The calculations has been done in

MATLAB and Table 8 includes number of errors (sampling points), final error (Equation 12, in Ah), average error (i.e. total error divided with number of errors, in Ah) and total error (in Ah) for different equation and tolerance amplitudes.

Table 8: Summary of Charge-Discharge test for BS1

Equation and tolerance amplitude	Number of errors	Final error	Average error	Total error
5 percent of the nominal SOC	0	-	-	-
5 percent of present SOC	**42468**	**5,5690**	**3,3419**	**1,4192e+5**
Eq 15, tolerance amplitude 10 Ah	**48262**	**5,6133**	**3,3525**	**1,6180e+5**
Eq 15, tolerance amplitude 15 Ah	31191	5,4362	3,2780	1,0224e+5
Eq 15, tolerance amplitude 20 Ah	22789	5,2592	3,1821	7,2545e+4
Eq 16, tolerance amplitude 5 Ah	**26780**	**0,7903**	**1,0162**	**2,7213e+4**
Eq 16, tolerance amplitude 6 Ah	9998	0,0013	0,5976	5,9752e+3
Eq 16, tolerance amplitude 7 Ah	1496	7,8642e-7	0,2581	386,1534
Eq 16, tolerance amplitude 8 Ah	0	-	-	-
Eq 16, tolerance amplitude 10 Ah	***0***	**-**	**-**	**-**

Table 8 shows that criteria based on Equation 15 are quite similar to a 5 percent of present SOC criterion (bold type atop). It's due to the problematic mention earlier, that both require very exactly estimations for low SOC. Table 8 also confirm Figure 24 and 25, that the estimation is inside the limitation all time for Equation 16 with tolerance amplitude at 10 Ah while it is a larger errors for a tolerance amplitude at 5 Ah (bold type in middle and at bottom)

Test 1: Charge-Discharge Test – second part, BS2

It's an equal test procedure as for first part. Figure A's third subplot in Figure 26 shows BS2's estimation as well as the actual SOC and criterion based on Equation 16 with tolerance amplitude at 10 Ah. BS1 estimation manage this criterion without any error while Figure A in Figure 26 show that BS2's estimation is worse, it's not even close to manage the criterion. BS2 misses the charge which makes the estimation rather bad but instead it recalibration at the end and find, leaps to a value close to the actual SOC. The reason to BS2's bad estimation was investigated and it could be due to the conversion because unlike BS1, BS2 presents the estimated SOC in percentage. To convert percent into ampere hour, the percent from BS2 was divided with 100 and then multiplied with the SOH and the nominal batteries capacity, 225 Ah. BS2's SOC estimations therefore depend of the SOH value. Due to this, changes in SOH also influence the SOC value specified in ampere hour. To investigate the conversion impact on BS2's rather bad estimation a correction was made. Instead of multiplying every sample of SOC with the same sample of SOH, the last SOH value was multiplied to every SOC value. It was due to that the last SOH value was better than all other, it was the highest and the LAB' were almost new so their health and condition should be rather good. Figure B in Figure

26 shows same test but with this correction as well as a new tolerance amplitude at 20 Ah. Figure A and B in Figure 26 could be seen in full scale in Appendix B, B1 and B2.

Figure A (B1)

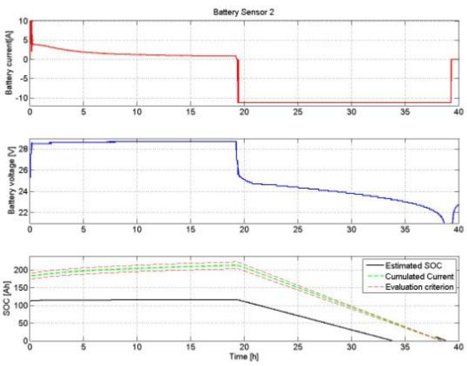


Figure B (B2)

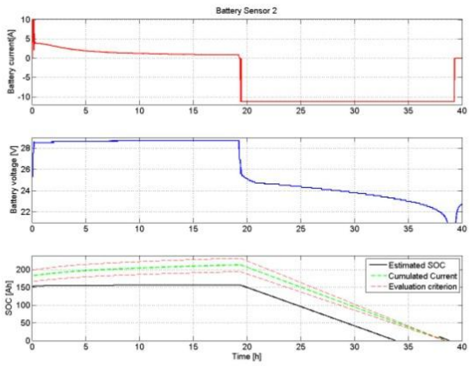


Figure 26: Charge-discharge cycles – BS2. Current, Voltage and SOC. Figure A - criterion from Equation 15, tolerance amplitude 10 Ah. Figure B with calculation correction - criterion from Equation 15, tolerance amplitude 20 Ah

Figure B in Figure 26 indicates on a better estimation after the correction but still it's rather bad. It couldn't manage a criterion based on Equation 15 with tolerance amplitude at 20 Ah, not even for high SOC there this criterion is rather kind. Both figures in Figure 26 indicates inaccurate initial estimation that affects the rest of the estimation, expect the last hour of the cycle. If this has been visualized as remaining time, the recalibration at the last hour wouldn't make any difference because the driver should have been told to start the engine around five hours earlier.

Test 2: Charge-Discharge Test - BS2

Previous tests of BS2 at Scania indicate much better estimations compared to Test 1. Due to this the Charge-Discharge for BS2 was redone. This test had longer duration because the LAB' were empty initial. The recharge therefore was longer and it also was close down before the LAB' were completely full charge. It was done because the current was close to zero, as the top graph in Figure 27 indicates. Figure 27 uses the previous discussed correction for conversion to ampere hour and it improves the estimation. Appendix C includes same figure without the correction but otherwise the correction is used for all other BS2 tests in this thesis work.

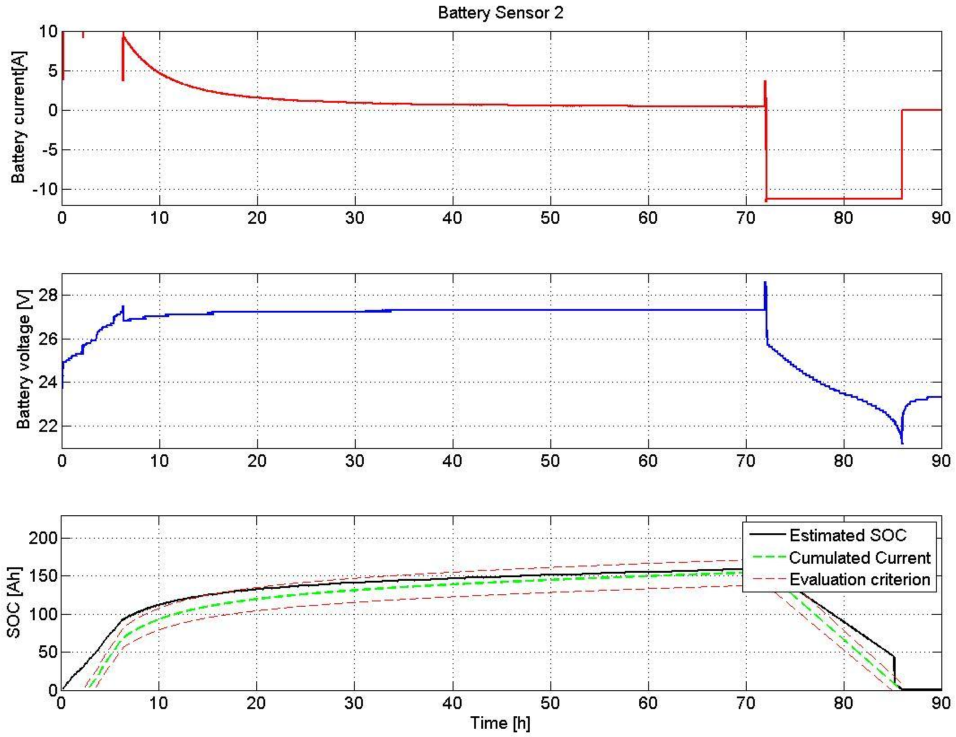


Figure 27: Charge-discharge cycle - BS2 with calculation correction. Current, Voltage and SOC. Evaluation criterion based on Equation 16 - tolerance amplitude at 10 Ah.

This redone Charge-Discharge test gives BS2 two reference points, zero amount of charge initial and at the end, which would help the BS to estimation better according to subchapter 5.1. Figure 27 indicates a much better estimation by BS2. It almost manages the criterion, except that it underestimated both the slope to the charge and the discharge which impairs the result. Once again it finds and leaps to the end point. The leap is almost 40 Ah, as Figure 28 shows, which is quite much. That size of leaps is not acceptable because it will mislead users. The leaps are recalibrations, probably consider to the voltage (see subchapter 5.1.2, EOD). The assumption is done because BS2 finds the end point at 21 V. If other BS manufacturer also would do this recalibration it might be possible to require higher limitations at almost empty batteries.

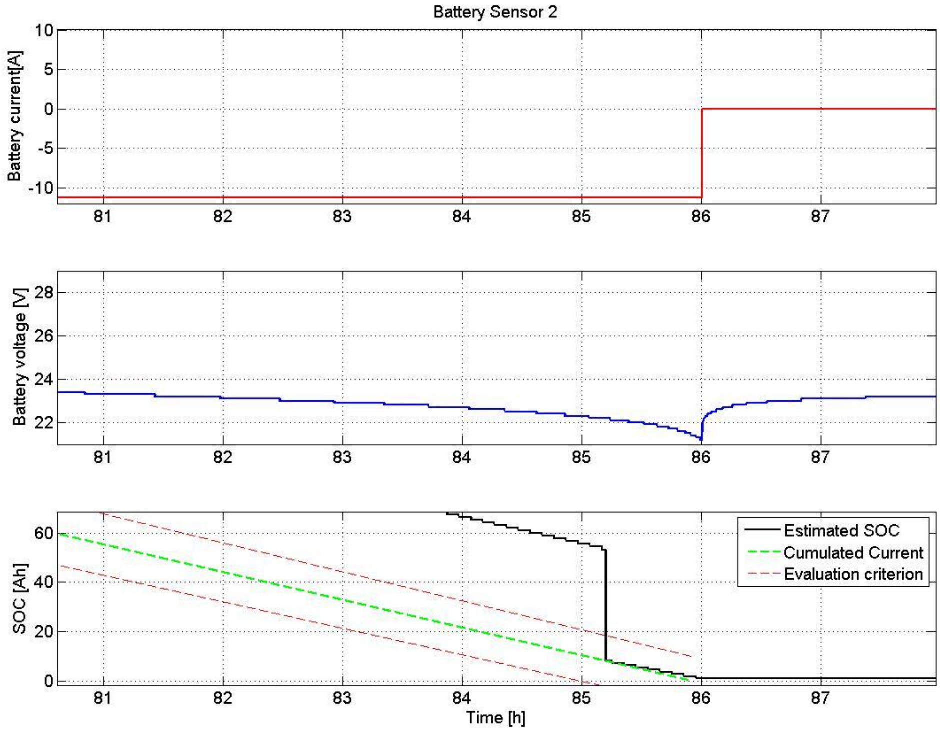


Figure 28: Charge-discharge cycle- BS2. The last hour in Figure 27 is zoomed to visualize the leap.

Test 1 and 2 indicates that BS1 estimate better than BS2 and according to these tests, it's reasonable to require criterion based on Equation 16 with tolerance amplitude at 10 Ah or less.

Test 3: Repeated Charge-Discharge Test – first part, B2

Test 3 examine if a BS manage to follow repeated charges and discharges. Test 3 is divided in two parts, the first part includes BS2 and the second part includes BS1. These test cycles were not entire equal, for BS2 the test cycle was in order and time as follow: 9 hours discharge, 9 hours charge, 9 hours discharge, 9 hours charge, 9 hours discharge followed by a 5 hours charge and finally a total discharge to empty. Figure 29 includes same subplots and labels as for Test 1 and 2 but with the minor difference that the first subplot is voltage and the second is current. The third subplot is similar to earlier figures but it also includes an error calculation (green line – Error). It's the difference between the estimated SOC and the actual SOC in ampere hour.

Figure 29 and 30 shows the BS2's estimation for the test cycle. Figure 29 shows that the estimation improves with the time due to recalibrations. The estimation is gradually better and after around 20 hours the estimation is within the boundaries, based on Equation 16 and tolerance amplitude at 5 Ah. The error calculation (green line) also indicates this, the estimation error decreases with time. It's a reasonable to assume that with a better initial estimation BS2 should manage this or at least a limitation with slightly higher tolerance amplitude.

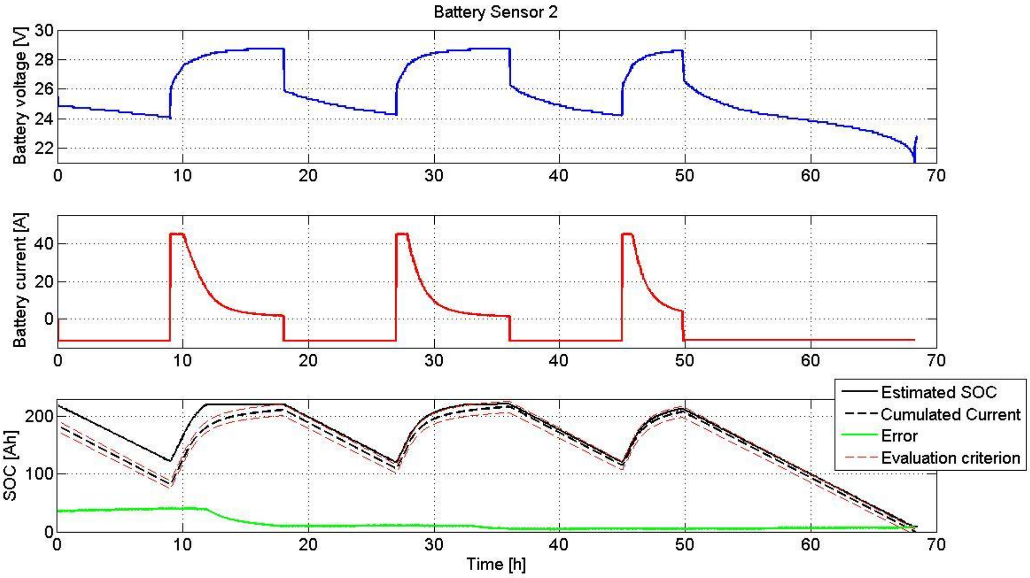


Figure 29: Repeated Charge-Discharge cycle- BS2. Voltage, Current and SOC. Evaluation criterion based on Equation 16 - tolerance amplitude at 5 Ah.

Figure 30 is similar as Figure 29 but with the difference that the limitation is based on Equation 15 with a tolerance amplitude at 20 Ah. Figure 34 shows similar results, problem at low SOC, as earlier tests, see Table 8 or Appendix A. Figure 30 indicates that the SOC estimation is clearly outside the boundaries to around 15 hours. It's then close to or inside the boundaries until it slips out at the end (hour 55) of the test. It's due to that the boundaries are reduced fast for lower SOC because the estimation is as mention become more accurate with the time. The fast reduction of the boundaries isn't solved by higher tolerance amplitude. It expands the boundaries but not as much as for high SOC, which makes it ineffective. Due to Equation 15's deficiency, BS' hereafter only will be examined by criteria based on Equation 16 with different tolerance amplitudes.

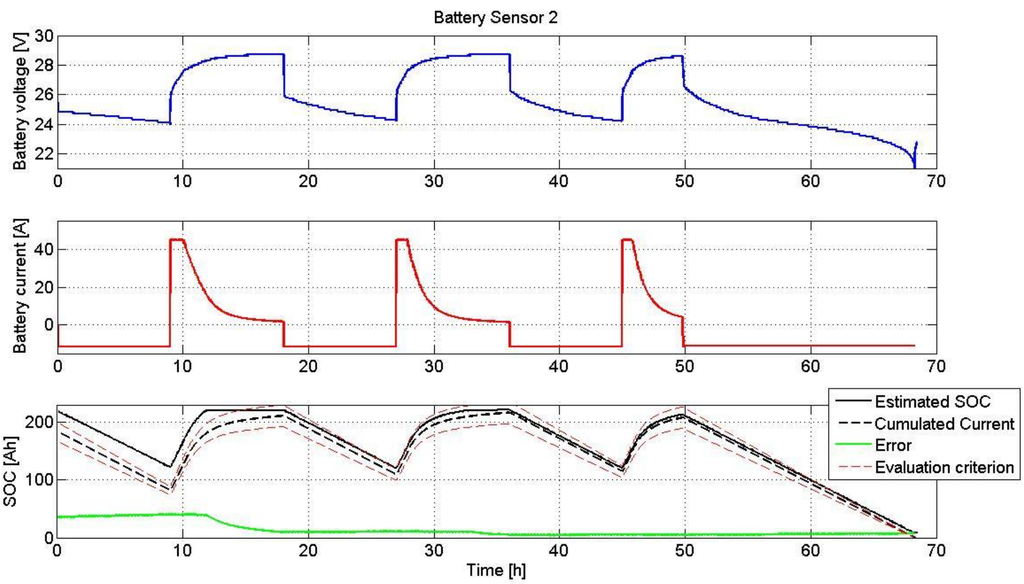


Figure 30: Repeated Charge-Discharge cycle- BS2. Voltage, Current and SOC. Evaluation criterion based on Equation 15 - tolerance amplitude at 20 Ah.

Test 3: Repeating Charge-Discharge Cycle – second part, BS1

Test 3 continues with BS1 and BS1's test cycle was in order and time as follow: 9 hours charge, 9 hours discharge, 9 hours charge, 9 hours discharge, 9 hours charge and then a total discharge to empty. The difference against BS2's cycle is that this cycle starting with a charge instead of a discharge, and it's because the batteries had a lower SOC initial.

Figure 31 shows same three subplots as before but the third subplot includes two criteria, both based on Equation 16 but one with tolerance amplitude at 5 Ah (1) and the other at 10 Ah (2). Figure 31 show that the estimation not could manage the criterion (1) but that it's at the upper boundaries for criterion (2). Similar to BS2, this estimation is affected negative by its initial estimation. The result would be more accurate with a better initial estimation. However it also overestimated the slope of charge and due to this the estimation doesn't become more accurate with the time, instead the error is almost constant except at the start. It could be deduce by the error calculation in the third subplot (green line – Error).

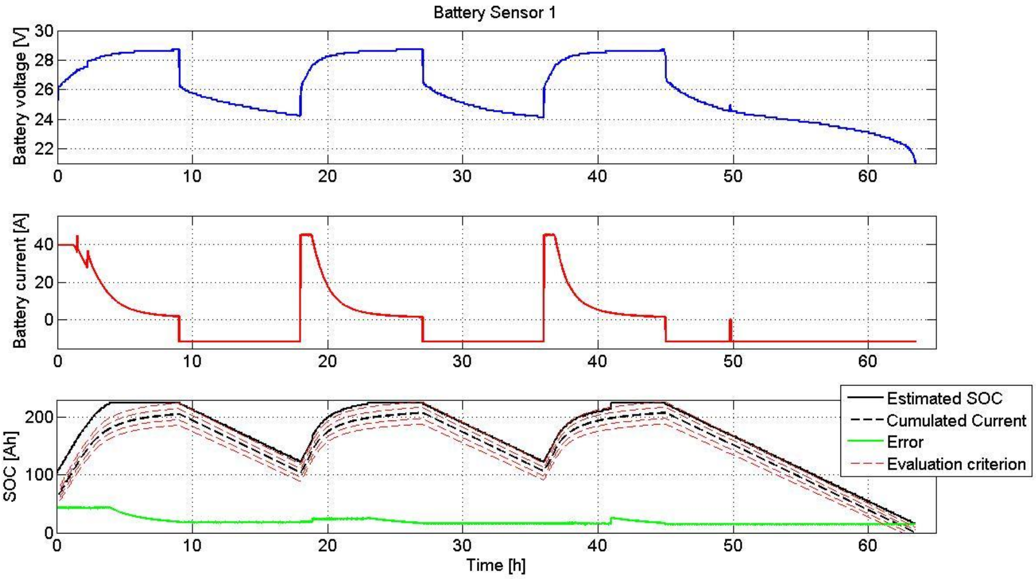


Figure 31: Repeated Charge-Discharge cycle- BS1. Voltage, Current and SOC. Evaluation criterion based on Equation 16 - tolerance amplitude at 5 and 10 Ah.

Test 4: Mixed Charge-Discharge - BS1

Test 4 is designed by Scania to evaluate if a BS manage repeated charges and discharges of varying duration. It's designed to be closer to an actual situation in a vehicle than the Repeated Charge-Discharge cycle. The Mixed Charge-Discharge cycle is in order and time as follow: 12 hours discharge, 2 hours charge, 6 hours discharge, 6 hours charge and then a total discharge to empty. It's. Figure 32 shows BS1's estimation for this test cycle. The error calculation in Figure 32 is constant and has a mean value of 19.85 Ah, almost 20 Ah. Therefore it could be conclude that the estimation is inside the boundaries only at 225 Ah, due to that the allowed error for this SOC is 20 Ah according to Table 7. The estimation is close to the boundaries all time but still it could be more accurate if the initial value had been better estimated. This problem has been recurring in almost all tests for BS1, a bad initial estimation and an almost constant error. The BS manufacturer argue that the tests should be closer to actual situation in a vehicle and that the BS would be more accurate if the test cycle includes a rest in the charge episode (BS1 2014 and Claesson 2014). Due to this information a last cycle was designed. The reason to that a BS could give a more accurate result if the cycle includes a rest can be seen in chapter 5.1.

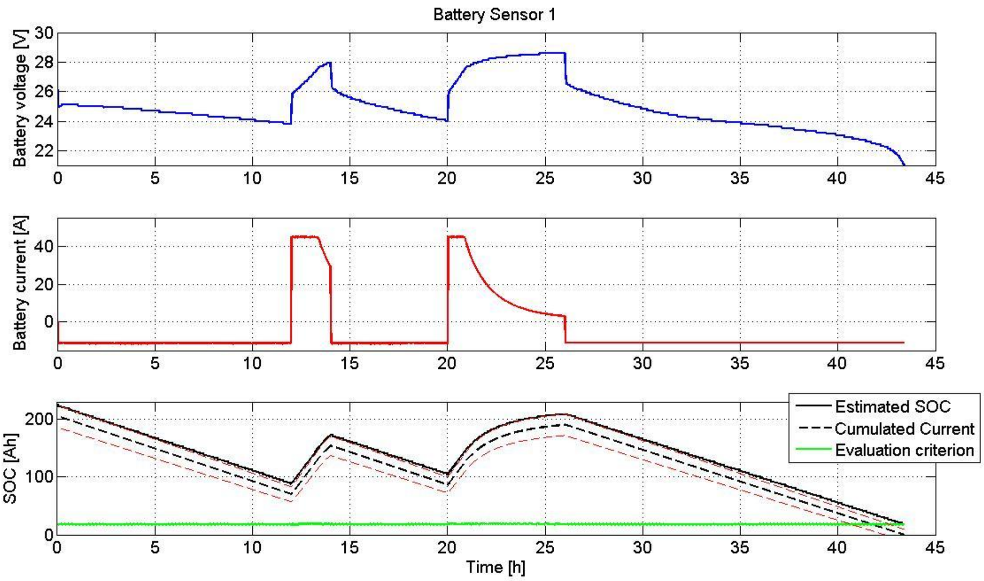


Figure 32: Mixed Charge-Discharge cycle – BS1. Voltage, Current and SOC. Evaluation criterion based on Equation 16 - tolerance amplitude at 10 Ah.

Test 5: Extended Mixed Charge-Discharge Test – BS1

Test 5's test cycle, Extended Mixed Charge-Discharge cycle is as mention equal to the Mixed Charge-Discharge but with the addition of a longer rest in a charge. The cycle is designed as follows: 12 hours discharge, 2 hours charge, 6 hours discharge, 1 hours charge and then a longer rest for 12 hours, followed by a charge in 5 hour and finally a total discharge to empty. Figure 33 shows BS1's estimation for this cycle but it didn't become as the BS manufacturer believed. Figure 33 shows that BS1's estimation has a constant error at around 50 Ah and due to this no evaluation criterion was added. BS1 recalibrated under the rest but not to the better, the estimation instead become worse. Still it could be an accurate estimation if the earlier mention problem for BS1 with the initial estimation is solved.

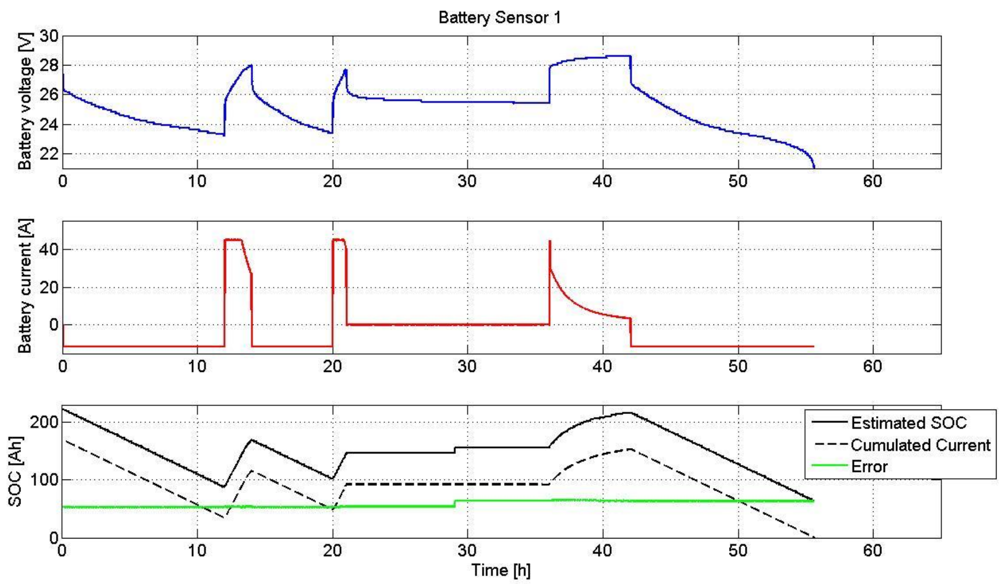


Figure 33: Extended Mixed Charge-Discharge cycle – BS1. Voltage, Current and SOC.

Test 5: Extended Mixed Charge-Discharge Test – BS2

Figure 34 shows the Extended Mixed Charge-Discharge cycle with BS2's SOC estimation. BS2's estimation is much more promising than BS1 for this cycle but it's still clearly outside the boundaries most of the time. BS2 is even for this cycle approaches and finds the point when the batteries are empty. Remember that the third subplot in Figure 34 has an x-axis that goes below zero because the BS underestimated the SOC. It underestimated the SOC 27 Ah at most. This test's estimation is an exception from the other estimations. Initial as well as in the end this estimation is quite accurate but because of recalibration and poor ampere hour counting it gets worse. It's often the opposite, the initial and recalibration is poor while the coulomb counting is accurate. That's reason why the estimations often follow the actual SOC well but with a constant error.

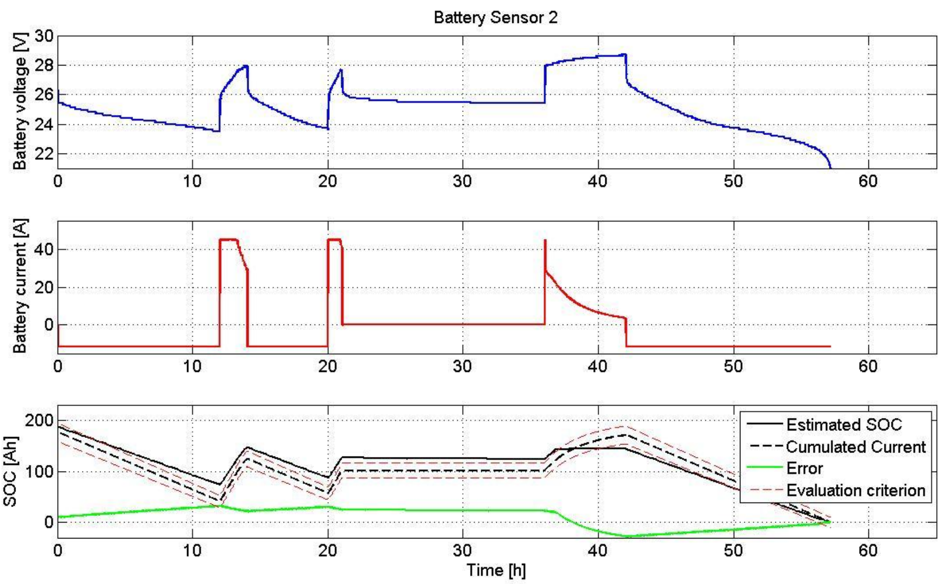


Figure 34: Extended Mixed Charge-Discharge cycle – BS2. Voltage, Current and SOC. Evaluation criterion based on Equation 16 - tolerance amplitude at 10 Ah.

6.1.3 **Summarize and defined the final evaluation criterion for SOC**

This chapter go through tests to define the final evaluation criterion for SOC. For Equation 16 Test 1 to 3 showed a scattered result for the quested parameter, the tolerance amplitude. In Test 1 the BS1 indicated that the parameter should be between 5-7 Ah to be reasonable and still challenging for the manufacturer. For same test BS2's estimation was extremely bad compared to BS1. BS2' estimation was not even close to manage a criterion with tolerance amplitude at 20 Ah. To observe if this bad estimation was an exception Test 2 was performed. Test 2 indicated a better result for BS2 but still it wasn't close to manage tolerance amplitudes at 5-7 Ah such as BS1. Instead it almost managed a criterion with tolerance amplitude at 10 Ah. Test 3 indicated that the results from Test 2, tolerance amplitude around 10 Ah, were more likely than the result from Test 1, tolerance amplitude at 5-7 Ah. To be inside the boundaries larger tolerance amplitude than 10 Ah often was required. This was because of that both BS had problem to determine the initial value. However this indicates that the BS's could, has potential to, manage smaller tolerance amplitudes. Test 3 also showed this because BS2 would with a better initial value even manage Equation 16 with tolerance amplitude at 5 Ah. Contrariwise BS2 couldn't manage Equation 15 because of the fast tightening of the boundaries in the end, which the tolerance amplitude almost not influences on. BS1 had the same problem with the initial value as BS2 and was also show worse results for Test 3 compared to Test 1. It indicated on an almost constant error and wasn't close to be within a criterion based on Equation 16 with tolerance amplitudes at 5-7 Ah as earlier test. Instead it required tolerance amplitude at 15 Ah to barely manage this test. Therefore Equation 15, which is harder, not was evaluated.

The tests Test 1 to 3 were also indicating that Equation 15 with 10 Ah tolerance amplitude were similar to 5 percent of the present SOC, which also can be read out from Table 8. Criteria based on 5 percent of present SOC and Equation 15 was tightening the boundaries too fast, which wasn't reasonable or required. The tolerance amplitude couldn't slow down this fast tightening for Equation 15. It's not bad that Equation 15 limits the estimation to a very small error for a low SOC and exactly right when the amount is zero. However according to the BS use as decision support it's not requested with that accurate and precise estimations. Therefore only Equation 16 was tested in more reality-based cycles.

Test 4 and 5 indicated on worse estimations compared with Test 1 to 3. Test 4 indicated that BS1 had problems to determine the initial value which lead to a constant error at 20 Ah. Therefore it couldn't manage tolerance amplitude at 10 Ah, which also can be read out from Table 7. On advice Test 4 was modified, so that the BS could recalibrate. This should benefit the BS but in Test 5 BS1's estimation was worse. It had a worse initial value according to the actual SOC and a larger constant error, around 50 Ah. BS2's estimation were better than BS1 and it also had a better initial value, but still it couldn't manage Equation 16 with tolerance amplitude at 10 Ah. Test 4 and 5 indicated that estimation of the initial value is important and that this is the part that has to be developed to achieve better estimations. It also showed that Equation 16 with tolerance amplitude as low as 5-7 Ah almost was impossible for the BS' to manage, a more reasonable and challenging tolerance amplitude should according to the two tested BS's performance be 10 Ah.

Equation 16 with tolerance amplitude at 10 Ah, gives an accurate estimation and challenging the manufacturer. Several tests and especially Figure 32 and 34 indicated that it's hard for the manufacturer to deliver a BS that can manage this criterion all the time. Still it shouldn't be impossible because the largest error was often cause by bad initial estimations. If this problem could be solved it would result in a lot better estimations and it would also be possible to require more accurate estimation because many estimations followed the actual SOC but with a gap that the initial error had created. This can be seen in Figure 24 and 33. Therefore the evaluation criterion to evaluation SOC estimation is determined as Equation 16 with tolerance amplitude at 10 Ah, which is showed in Criterion 1 below.

$$-10\left(1+\frac{SOC_{ref}}{SOC_{nom}}\right) < SOC_{est} < +10(1+\frac{SOC_{ref}}{SOC_{nom}})$$

The estimated SOC should be inside the evaluation criterion and due to that the rather small tolerance amplitude, not exceed 10 Ah, limits the leaps it's not necessary to limited any more than the regular boundaries. Still Criterion 1 allows large error at low SOC, which could cause problem to start but this problem could also be eliminated. If Criterion 1 is combined with a margin at 60 Ah, the criterion accepting errors at 12.6 Ah negative or positive at 60 Ah. This means that with new batteries according to 5.3.1, Scania vehicles engines should start. Therefore Criterion 1 is reasonable and corresponding to the requirements from the vehicles, customers and manufacturer on the BS.

6.1.4 **Evaluation of SOC also include SOF and SOH**

In some aspects the evaluation criterion for SOC also includes evaluation of SOF and SOH. To formulate and parameterize the SOC criterion the minimum capacity to start an engine has been taken into consideration, which links the SOC criterion to SOF. Contrariwise it isn't enough to only consider the minimum capacity to ensure an engine start. SOH is also validated through the SOC criterion because of the BS calculation methods to determine SOH. SOC is used to determine SOH so if the SOC is closer to the actual SOC, the SOH estimation should be better. Therefore SOC partially evaluate both SOF and SOH but neither it's enough to evaluate SOF or SOH completely.

6.2 Evaluation criterion for SOF – a minimum battery performance to start

A lot of parameters impact an engine's ability to start but the thesis work only examines the minimum needed performance from LAB' to create a successful engine start. As earlier mentioned an amount of 25 Ah for new batteries would be enough to start according to the SOC. However an engine start doesn't depend on the LAB's SOC only, it also depends on how much energy the batteries can deliver and how fast. Therefore a minimum cranking level based on capacity is deficient. To ensure engine starts a different approach based on voltage and current is required.

Based on information from subchapter 5.3.2, a minimum battery performance for engine start can be determined. The underlying tests are indicating that Scania trucks require a certain average current that only depends on the temperature and the engine type. Table 2 gives the highest average current, 300A in +25°C, which is caused by Engine 3. The same engine causes the highest average current in -20°C, which is 700A. Table 2 and 4 indicate that an average starting time in +25°C is around 2.6 seconds meanwhile in -20°C it's 6.28 seconds, which gives an overall average time of 4.4 seconds to start an engine. Due to this and based on the background to the segments distribution in subchapter 5.2.1, the evaluation criterion for SOF is divided in two segments, the first two seconds (within 2 seconds) and next three seconds (between 2 and 5 seconds) after the constant current is applied.

It's therefore possible to determine an average lowest voltage to start all engines and a lowest voltage for all engines in each segment, within 2 seconds and between 2 and 5 seconds. Table 4 indicated that the average lowest voltage to start all engines in -20°C within 2 seconds is 16.3 V. Table 3 specified that the lowest voltage to start all engines in the same temperature is 14.2V within 2 seconds and the next three seconds it's 15.1 V. Similarly the average lowest voltage to start all engines in +25°C is 13.4 V, the lowest voltage to start all engines within 2 seconds is 8,8 V and the next three seconds it's 13,7 V. These values should represent and ensure start of all the tested engines within the tested temperature range. So this could represent a minimum battery performance to start all tested engines.

To evaluate SOF the BS should evaluate the batteries' cranking potential, because if the batteries are able to deliver this voltage and current all Scania's tested engines should start according to subchapter 5.3.2 and the underlying tests. To summarize a battery pack should be able to deliver at least 17 V (16,3) within 2 seconds in -20°C for a constant current of 700 A and should also within the next three seconds be able to deliver at least 15 V (15,1). In +25°C for a constant current at 300 A, a battery pack should be able to deliver a least 14 V (13,4) within 2 seconds and within the next three seconds deliver at least 14 V (13,7), or more comprehensible it should be able to deliver a least 14 V during 5 seconds.

The battery sensor should therefore be able to identify if the LAB could deliver this certain voltage during the specific time with present conditions, temperature and current. So the criteria to evaluate a BS's SOF can be formed as Criterion 2 below:

Conditions, deliver a specific voltage for 5 seconds at +25°C with a constant current at 300 A (I_{+25}).

(1) $U_{batt}^{2s} > 14\ V$

(2) $U_{batt}^{5s} > 14\ V$

Conditions, deliver a specific voltage for 5 seconds at -20°C with a constant current at 700 A (I_{-20}).

(1) $U_{batt}^{2s} > 17\ V$

(2) $U_{batt}^{5s} > 15\ V$

The BS should be able to identify if the LAB could deliverer voltage as within the determined criterion. This can be done only if both (1) and (2) are fulfilled, which can be seen in Table 9. Figure 38, in subchapter 6.4.2, shows this graphically and it could also be seen in Appendix D.

Table 9: Criteria to fulfilled for a successful engine start (Criterion 2)

Both (1) and (2) = Engine start succeed	(1) but not (2) = Engine start failed
(2) but not (1) = Engine start failed	Neither (1) or (2) = Engine start failed

6.3 Evaluation criterion for SOH

Batteries health changes slowly and therefore SOH also generally changes slowly. It's because of that the SOH value doesn't have to be very accurate all the time as long as the estimation doesn't leap. It's more important that the value decreases continuously as predicted, that the countdown follows a pattern so that the users can predict and plan their battery changes. Because of this Scania's earlier requirement specification is used as criterion, a maximum 10 percent error (Criterion 3A). It should then be combined with that the estimated SOH shouldn't alter and leap to a higher values, it should only be lowered or the same (Criterion 3B). It's due to this as well as because LAB' often are change after two to three years (Kovacevic 2014), which approximate is a SOH value around 50 percent, a rather good limit. 50 percent SOH for a battery pack, 225 Ah, denotes the present maximal capacity to 112.5 Ah. Therefore it's a rather big safe margin before the LAB' have to be changed because of critical performance. To obtain a mathematical SOH criterion the SOH error could be calculated with Equation 17, where SOH_{est} is the BS's estimated SOH and SOH_{ref} is the actual SOH, calculated with Equation 6 and the present maximum capacity deduced from a total discharge test or according to the evaluation method.

$$SOH_{error} = \frac{SOH_{ref} - SOH_{est}}{100} \tag{17}$$

Criterion 3 limits SOH estimation so the estimation should be good enough as base for decision making of battery changes. It limits the estimation to not alter and be lowered only, as well as to ensure that the battery sensor's estimation will be near the actual SOH, maximum 10 percent error. The criterion is mathematical defined as Criterion 3 below.

$$-0.1 \leq SOH_{error} \leq 0.1 \text{ (Criterion 3A)}$$

$$0 \geq SOH_{estimated}(t) - SOH_{estimated}(t-1) \text{ (Criterion 3B)}$$

The variable t is a sample point, time step. To manage the Criterion 3 the estimated SOH should accomplish both criterion 3A and 3B for all sample points.

How SOH should handle temperature is a difficult question and it's not obvious. The battery performance is affected by temperature, which can be described linear as one percent capacity loss for each 1°C lowered. Perhaps SOH should disregard the temperature but then drivers have to be aware of this. Contrariwise, if SOH is influenced by the temperature the drivers can be misled. If the vehicle is started in a warm garage it could leap to a much lower level when driving out because of the temperature difference. Of course the battery pack is sealed, so the temperature differ shouldn't be so extreme but it's still a critical question. Due to this and that both tested BS didn't calculate SOH with temperature this thesis work considers SOH disregarded temperature. It's neglected because the temperature is constant for evaluation in laboratory. The users have to be aware of this.

6.4 Evaluation methods

To examine if the evaluation criteria are fulfilled requires evaluation methods. Different evaluation methods are needed for different criteria as well as different specific conditions. Therefore this chapter has been divided into evaluation methods for different criteria and measurements. Some of them are quite similar but all of them have a specific purpose to examine some BS's calculations. These methods are based on both theoretical and practical factors, testing in 6.1.2 have been an important reference to formulate these methods.

To obtain similar condition at the evaluations new or at least non-degraded 225 Ah batteries should be used if nothing else is mention. To be sure that the batteries not are stratified all evaluation methods uses EN-standard to charge the batteries to fully charge initial, for more information see SEK (2006). It's also recommended to wait at least 15 minutes between installation and testing an BS according to 5.1.3 as well as BS1 (2014). To obtain right temperature approximation more time is needed, around 30 minutes. Therefore it's recommended to wait 30 minutes, after installation an BS or when the temperature changes, before evaluation.

6.4.1 **Evaluation methods for SOC**

To evaluate if a battery sensor manage the determined SOC criterion some methods have been created. These methods were formed to evaluate if the battery sensor could manage the specific conditions which it might be exposed to in field. The first evaluation method is a total discharge.

First part – Total discharge

It's important that the BS estimation could follow a discharge so the users are given accurate information about the batteries SOC level during discharge. Deep discharge is not unusual for vehicles in field, which is a reason to perform this test. Another reason is to determine the batteries' present maximal capacity, the amount of ampere hour at fully charge batteries, for later tests.

The initial procedure is to ensure that the batteries are fully charged, this is done according to EN-standard. To evaluate the BS in different conditions the test is performed in two different temperatures, +25°C and -20°C which represent extreme points for an average temperature range in Sweden. For more information see 5.2.1. Figure 35 shows a total discharge for any temperature, the black line is the batteries SOC level and the red dotted lines are the boundaries from the evaluation criteria.

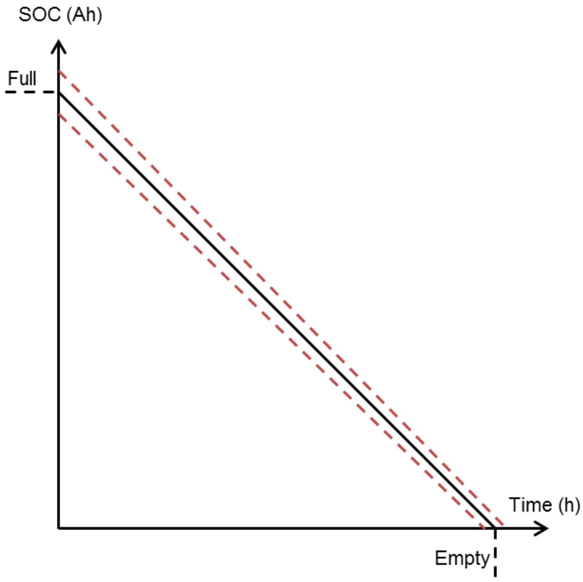


Figure 35: Total discharge to empty batteries, for any temperature.

For all temperatures a constant discharge current, I_{C20} is used. I_{C20} is defined as one twentieth of the batteries capacity. This current is used to rate LAB in a C20 test. A C20 test is design to check if a battery can deliver I_{C20} current for 20 hours without dropping under 10.5 V SEK (2006). Therefore, I_{C20} for this test is 11.25 A and the discharge should take around 20 hours because of non-degraded 225 Ah LAB.

The test is aborted when the battery voltage reached 21.0 V because at this level the battery is empty according to EN-standard. To obtain evaluation criterion the current, voltage, estimated SOC and amount of discharge ampere hours should be recorded. To obtain the actual SOC, the recorded current is time integrated, coulomb counting is used. By the actual SOC the allowed evaluation criterion can be calculated.

Second part – Charges and Discharges

To evaluate a BS's performance during repeated charges and discharges, which are ordinary in field, another cycle, Cycle 1, has been created, see Figure38. It's evaluated and records the same parameters as in the first part, apart from the amount of discharge ampere hours. As in the first part, this test is also repeated for the two different temperatures.

The earlier recorded amount of discharged ampere hours is the present maximum of ampere hours. For new batteries in +25°C it's close to the nominal 225 Ah but for other temperatures this amount is lowered, the capacity is lowered by about 1 percent for each 1°C. So the first part has determined the amount of ampere hour at 100 percent for the temperature range. This has been done to convert ampere hour to percent, because the following parts are presented in percent charge or discharge instead of ampere hour in purpose to not relate to a specific temperature. Due to this the method doesn't require to compensate for the temperature.

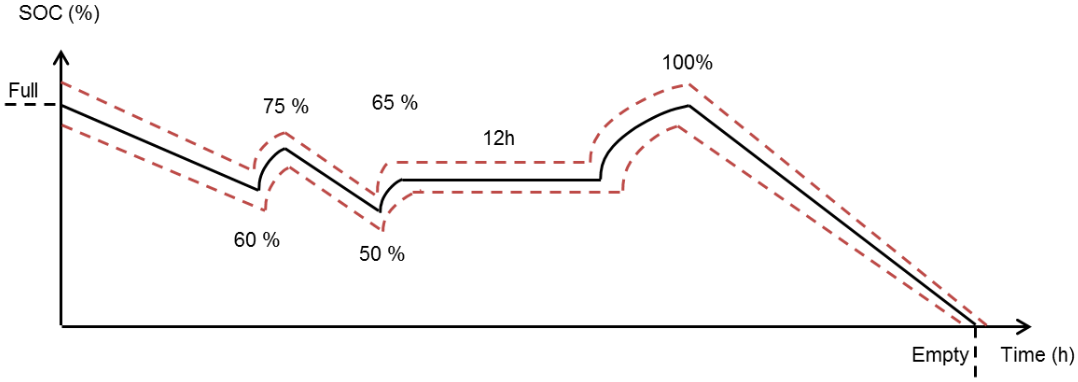


Figure 36: Defined Cycle 1, with repeated charges and discharges with varying duration and rest in percent.

Cycle 1 in Figure 36 is designed from Test 5 and shows the test procedure. As the first part, it's a constant discharge current, I_{C20} for all discharges. The charge current is based on a Scanias alternator and is therefore set to constant 28.3 V for +25°C and due to the lower temperature a slightly higher voltage is used for -20°C with a power supply capacity of minimum 45 A (Kovacevic 2014). The cycle is starting with fully charged batteries according to EN-standard. Then the following steps occur:

- Discharge to 60 % SOC (according to present maximum of ampere hours, present capacity)
- Charge to 75 %
- Discharge to 50 %
- Charge to 65 %
- 12 hour rest
- Charge to 100 %

The last step is a total discharge to empty battery, 21 V according to EN-standard. This is done to enable coulomb counting so that the actual SOC can be obtained.

Cycle 1 is based on previous preformed tests, Test 4 and 5, in 6.1.2. Test 4 can be referred to the regulations for drivers and is the beginning in the development to the cycle in Figure 36. The regulations for truck drivers permit a maximum of 4-5 hours driving per occasion and a maximum of 9-10 hours driving per day (Transportstyrelsen 2012). So if a vehicle has only one driver who drives it according to the regulations a cycle for a day, 24 hours, would be:

- 12 hours discharge (based on regulation to rest and sleep)
- 5 hours charge (based on regulations for coherent driving)
- 2 hours discharge (break)
- 5 hours charge (driving)
- Total discharge to empty

Test 4 can, as mentioned earlier, refer to these regulations. The test starts with a 12 hours discharge and ends with a 6 hours charge, with the exception of the total discharge to obtain actual SOH. This is similar to the regulations but Test 4 has a charge for just 2 hours instead of 5 hours. The different charging times is because of testing requests and also that the charge is ebbing with higher SOC. The first 2 hours of charge affect the capacity a lot, particularly after 12 hours discharge, and then it fades with higher SOC in the batteries. It can be seen in Figure 32, the difference, slope and time, between the first and second charge. It's also because of this Test 4 has a longer discharge than 2 hours so the BS won't obtain referent points, as fully charged batteries in the middle of a cycle. In consultation with BS' manufacturer Test 4 is developed to Test 5, which is the same cycle as Test 4 but with a longer break during a charge. The evaluation cycle, Cycle 1, in Figure 36 is based on Test 5 with a minor adjustment, that charges and discharges are defined in percent instead of times. So the regulations above make the evaluation cycle realistic and justify the use of it as evaluation method.

Third part – Longer perspective

The third part consists of longer cycle, Cycle 2, which is designed to examine the BS in a longer time perspective. The first two parts have evaluated the accuracy of the BS in a shorter perspective. It's therefore justified with a test to evaluate how the battery sensors perform in a longer time perspective as well. The test consists of repeated charges and discharges, more compared to the second part, to evaluate the BS' ability to estimate the SOC with stability over longer time. This part evaluates and records the same parameters as in the second part but it's not necessary to evaluated the BS for the two defined temperatures. It's enough with one because this part is evaluating the BS estimations stability, if the BS could deliver information with same accuracy as the first two parts but in a longer time perspective without reference points. This part is as the second part using I_{C20} as discharge current and the charge voltage is also same, 28.3 V or a slightly higher voltage is used depending on temperature.

The reason to that Cycle 2 shouldn't include reference points is that it could occur in field and also to try the BS', because a BS should estimate better with reference points that makes it possible to recalibrate. Figure 27 shows this, a cycle with two reference points for the BS to recalibrate after, it's the initial SOC and end SOC that is zero but it's even more obvious for Figure 30 and 31. In these figures the BS' recalibrate at full SOC, the BS' overestimate the SOC and when reaching 225 Ah it stops but the charge continues so the estimation becomes better. Therefore it's interesting to perform a test cycle of longer duration without these reference points. The last reference point, a total discharge in the end is not removed, because it's needed to obtain the time integrated current. Due to this Cycle 2 is designed to avoid very low and high SOC. The test starts with fully charged batteries according to EN-standard and ends with a total discharge to empty, 21.0 V, as the first and second part.

This cycle is divides into three sequences that are repeated at least ten times. The first sequence is starting with a discharge to 30 percent SOC (according to present maximum of ampere hours, present capacity, defined as in the second part) and then three repeated charges to 40 percent SOC is alternated with discharges to 30 percent. The second sequence is configured in the same way as the first, there are three repeated charges and discharges, but this time the batteries are charged to 60 percent and discharged to 50 percent. The third and last sequence of this cycle also consists of alternated charges and discharges which are repeated three times. In this sequence the batteries are charged up to 80 percent and discharged to 70 percent. One repetition of the three sequences ends at 70 percent but as Figure 37 shows, when it repeated the last discharge continues down to 30 percent which is the start in the first sequence.

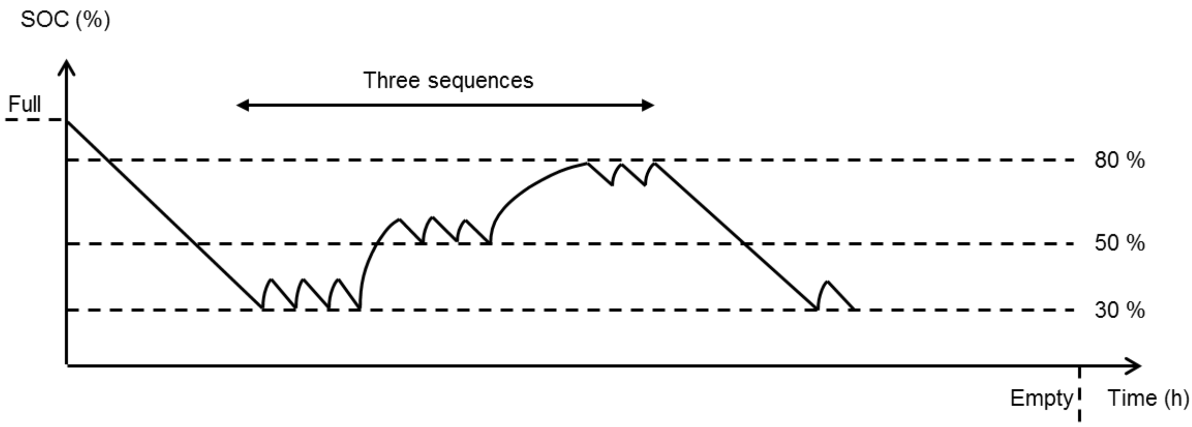


Figure 37: The first three sequences, marked, without repetition. Cycle 2 is these three sequences repeated at least ten times.

Figure 37 shows a short version of Cycle 2, it demonstrates all three sequences of this cycle but without repetitions. Due to the three sequences and their capacity levels the BS didn't have any reference points except the first, full charge, and the last, empty batteries. The three sequences are referred to as critical levels in reality-based situations and some regular SOC values. To avoid unsuccessful engine starts, it's recommended to have a least 60 Ah left according to subchapter 5.2.1, which for new and fully charged 225 Ah batteries is converted to around 30 percent of the capacity. Therefore the first sequence evaluates how a BS manages a low SOC. The second sequence represents a regular deep discharge of healthy batteries but at the same time it's an evaluation of a rather low SOC in a colder temperature. In the third sequence the battery charge alternates between 70 and 80 percent to evaluate if the BS manages higher values but also because this is a regular battery charge in new Scania vehicles (Kovacevic 2014).

This part evaluates a long time perspective and therefore it's more time consuming then the other parts. Cycle 2 is as mention the three sequences in Figure 37 repeated at least ten times. The first three sequences take around 46 hours to complete, the eight repetitions of this take around 336 hours and the last three sequences take around 58 hours because of the total discharge to empty. This result in that the whole Cycle 2 take around 440 hours which is two weeks and 5 days. This approximated time consuming in hours are based on that I_{C20} discharged 225 Ah in 20 hours but also from tests in 6.1.2, for instance in Figure 32, it can be deduce that 2 hours charge is around 80 Ah, from 70 Ah to 150 Ah. Hence it's approximate that each 10 percent discharge takes half an hour and corresponding charge takes around two hours, which also can be used to convert Cycle 2 charges and discharges from percent to time. This is of course also depending on the temperature but it is an approximated time consuming in room temperature, +20°C.

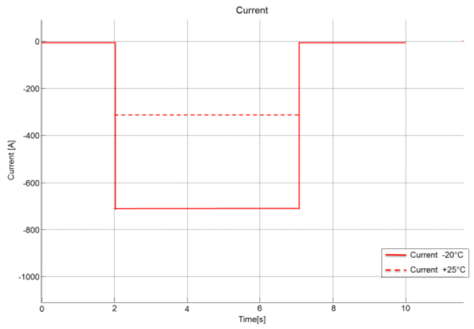
6.4.2 Evaluation methods for SOF

To evaluate SOF, or a minimum battery performance according to the criterion to ensure engine starts, requires a different evaluation method than for SOC. To obtain information about the batteries' performance this method records the LAB voltage for at least 5 seconds according to the evaluation criterion. The recorded values can then be compared through the criterion to evaluate if the BS is able to identify if the LAB' are functional or not, if the LAB' can deliver enough power according to the evaluation criterion, see Figure 38. Therefore the evaluation method for SOF gives a binary result, functional or not for the LAB and the BS' should be able to predict this.

Before the test start it has to be ensured that the batteries are fully charged according to EN-standard. The test procedure similar as the starting characteristics tests but this test is only repeated for the two extreme points in the temperature range, the same temperature as for the SOC evaluation method, -20 and +25°C. The test procedure has two steps that are repeated until no engine start is possible according to the evaluation criterion, Table 9. The first step is to connect a constant current load, specific to the temperature I_{+25} and I_{-20} , to the batteries in 5 seconds, see Figure C in Figure 38. During the first step, as mention the voltage (Bat. Voltage in Figure 38) should be recorded so it could be compared with the evaluation criterion, see Figure D in Figure 38. The second step is a discharge with a constant current, I_{C20} during half an hour because according to tests in subchapter 6.1.2, half an hour approximate is five percent of total capacity or 10 ampere hour, which could affect the starting possibilities according 5.2.1 and 5.2.2. It should be taken into consideration that the batteries are influenced by the test temperature and that the discharge time therefore might need to be adjusted for low temperature, so that it still is around five percent of total capacity or 10 ampere hour.

To summarize, the test procedure is sequential evaluation according to the constant current and sequential discharges until no engine start is possible according to the evaluation criterion, Table 9. Figure 38 shows the sequential evaluation and the evaluation criterion for both temperatures, there Figure C is the two constant current that is applied and Figure D is an example of successful voltage response. Figure C and D in Figure 38 could be seen in full scale in Appendix D, D1 and D2.

Figure C (D1) **Figure D (D2)**



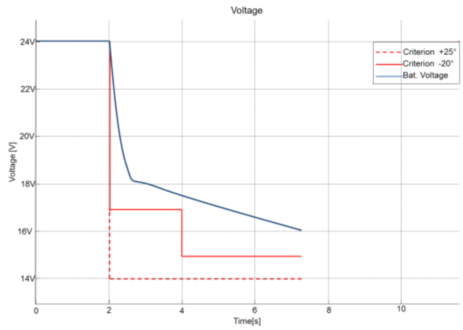


Figure 38: The sequential evaluation, the constant currents for both temperatures as well as an example of voltage response, which should be seen as a successful engine start according to Table 9.

6.4.3 **Evaluation methods for SOH**

To evaluate if and how well a BS estimate SOH for batteries, the batteries' condition and health have to alter. This requires a rather long time perspective because the batteries' health affects slowly by repeated use and ageing. So to evaluate SOH estimation a long cycle is required. To secure the evaluation a week or two isn't enough but a longer time is needed, as a year or two. It's in a time perspective like this the SOH estimation can be evaluated. It's not reasonable for Scania to evaluate during this long time (Kovacevic 2014) because it would take too much time to evaluate several BS. Therefore a limited, piecewise method based on changes in capacity to evaluate SOH estimation has been created. This method is enough to evaluate if a BS's estimation is suitable for the customers purpose, to plan battery changes.

The evaluation method for SOH is disposed in three steps. The method is based on samples from different batteries with different SOH levels, approximately 100, 75 and 50 percent. The first step starts with that the evaluated BS is installed on new and fully charged batteries according to EN-standard, hence the batteries' SOC and SOH should be near 100 percent. The batteries should then be exposed to a cycle from the SOC evaluation method, Cycle 1 from the second part in SOC evaluation. The reason to expose the batteries with a cycle is to enable calculations but also to ensure that the estimation doesn't leaps between different SOH values. Cycle 1 is the same test cycle as for SOC evaluation and it's used to save time, because two evaluation tests (SOC and SOH) can be run simultaneously. To evaluate the estimated SOH for the first step only the BS' estimated SOH should be recorded, because the actual SOH are near 100 percent for new batteries and therefore the estimation should be between 90 and 100 percent. Due to this Equation 17 and Criterion 3A is not explicit used; instead the estimated SOH should be between 90 and 100 percent for the first step but the estimated SOH should be evaluated based on Criterion 3B. The actual SOH could be verified and used, with Equation 6, present maximal capacity compared to nominal capacity, but it's not necessary. The present maximal capacity could then be obtained by a total discharge test, seen Figure 35.

The second step is to ensure that the battery sensors could calculate the SOH without reference points because in field it's unusual with completely full or empty batteries. The second step is formed as the first step with a minor difference, that the BS should be installed on batteries with a SOH around 50 percent. The SOH level is determined through a total discharge test and with Equation 6 as to calculate the actual SOH in the first step. The batteries are then exposed with the same cycle as the first step, Cycle 1 from SOC evaluation method's second part. Remember that this cycle starts with 100 percent SOC, don't mix up SOC and SOH values. In this part the estimated SOH but also the present maximal capacity that occurs in the end of the cycle, the total discharge to empty should be record. Due to the present maximal capacity the actual SOH value could be calculated with Equation 6. The actual SOH is then used to calculate the SOH error that is evaluated according to Criterion 3A. The second step as the first also evaluated in every sample point according to Criterion 3B.

The third and last step is similar to the other two but with two differences, the batteries should have a SOH level around 75 percent and a different cycle should be used. The batteries should be exposed to a modification of Cycle 2 from SOC evaluation. It should be modified to contain reference points after each three sequences before repetition, as Figure 39, the first three sequences of Cycle 3, shows. The modification enables detection of change in SOH because the reference points give updated present maximal capacity to calculated, as in the second step, new actual SOH. This can then be used to evaluate the estimated SOH against actual SOH at all reference points in the cycle, approximated every 50-60 hour. It's evaluation according to Criterion 3 as the second part.

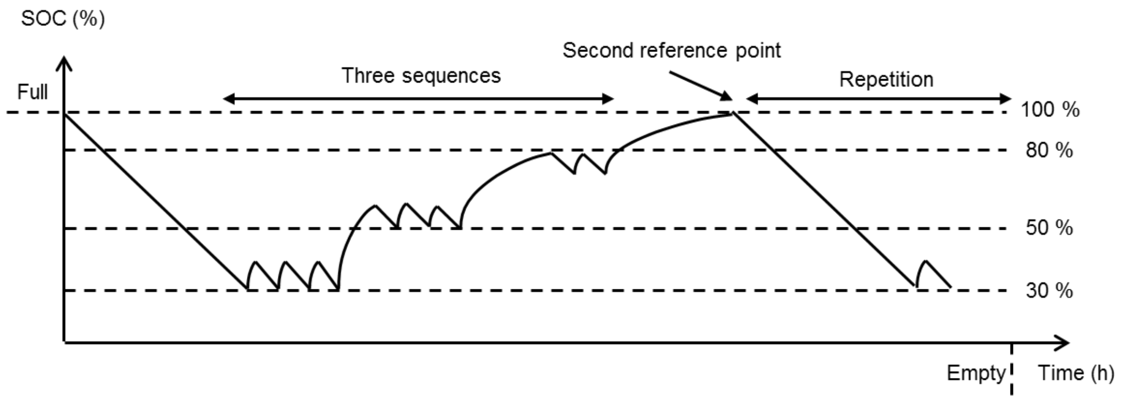


Figure 39: Cycle 3 – a modify Cycle 2. It contains reference points before every repetition to obtain changes in SOH, which is used to evaluate the SOH estimation.

Figure 39 shows the first and second reference points but with repetition of the three sequences, for at least ten times, it will result in at least eleven points to evaluate the estimated SOH. To obtain reference points and ensure 100 percent SOC, completely charge batteries, EN-standard is recommend to be used but another acceptable definition of 100 percent SOC according to (Moseley et al 2004) is then the battery current isn’t changing during 2 hours constant charge voltage and temperature.

These steps evaluates if the BS could estimate the SOH with required accuracy according to evaluation criterion, Criterion 3 in subchapter 6.3. The temperature in all steps for this method should be constant. It’s not important which temperature that is chosen but it’s recommended to use room temperature (20°C). The reasons to the second step is tested with batteries at 50 percent SOH and the third step with batteries at 75 percent SOH are that Cycle 1’s deepest discharge is 50 percent SOC meanwhile Cycle 2 has deeper discharge. It’s to not discharge the batteries to low, because 225 Ah batteries with 50 percent SOH and 50 percent SOC as well as 75 percent SOH and 30 percent will result in around 50-60 Ah left. The SOH levels that are used in the evaluation method are chosen due to that they represents new (100 percent), worn (75 percent) and batteries needed to be changed (50 percent).

6.4.4 **Applicability of evaluation methods**

The applicability of the evaluation methods and there evaluation criteria has already partially been discussed in the description of them but this chapter continue the discussion to immerse the applicability and limitations with the method and there criteria.

The discharge current in all evaluation methods, except of the specific current to evaluate engine starts, is I_{C20} and as mention it’s before it’s a regular test current that is specified. It’s also hard to know and formulated an actual general discharge current for a vehicle because the discharge current differ a lot and is also individual based on used the load, the electric consumer.

SOC method

The evaluation method and criterion to evaluate SOC is determined based on a comparison between actual SOC and estimated. The method and criterion as well as the compared reference, the actual SOC, are all formulated by coulomb counting. This is sufficient, verify by research and both tested BS’s at Scania are estimated the SOC without engine cranks or other procedures that isn’t include in the method. Still it has to be mention that this is a limitation because perhaps other BS are using different estimation methods based on, example engine cranks. These BS perhaps could manage the criterion in a vehicle but not for the evaluation method due to the lack of engine cranks.

Coulomb counting is as mention used to determine actual SOC and therefore this techniques limitation has to be discussed. Coulomb counting is an accurate and reliable technique to obtain SOC but as mention in chapter 3 it’s often use in combination with other methods or only in a short time perspective. The method is combined with other methods because it has problem to estimate the initial value, something that not is needed for this evaluation method. The total discharge in the end of all cycles result in that it can integrate the current backwards to obtain the initial value. The reason that it often only is used in short time perspective is the dude to current loss coefficient. It's a coefficient of the polarization, that not all measured current could be reserved by the batteries. Simply not all charged current is transformed to ampere hours. It's a very small coefficient but in the long run it will affect the result if no recalibrations or the coefficient are used. It should also be mention that this coefficient is larger for higher current, higher current gives higher losses and vice versa. The amounted ampere hour that the battery is able to receive is also affected by ageing and other conditions such as temperature but in a laboratory practical environment this conditions is constant for all test.

The effects of the coefficient for the evaluation cycles in this thesis work are small because of the cycle's length and design. Still it's important to investigate the coefficient further. To observe the impact from the coefficient a longer cycling over a year for some specific LAB batteries, Gel-LAB, were done at Scania. This cycling indicated that Coulomb counting without coefficient excess the capacity with around 6 Ah for only one day if the batteries are hard used, which is defined as cycling around three times a day with a discharge at around 60 Ah and then a charge to full. Figure 40 shows one day of this longer cycling with similar subplots as earlier.

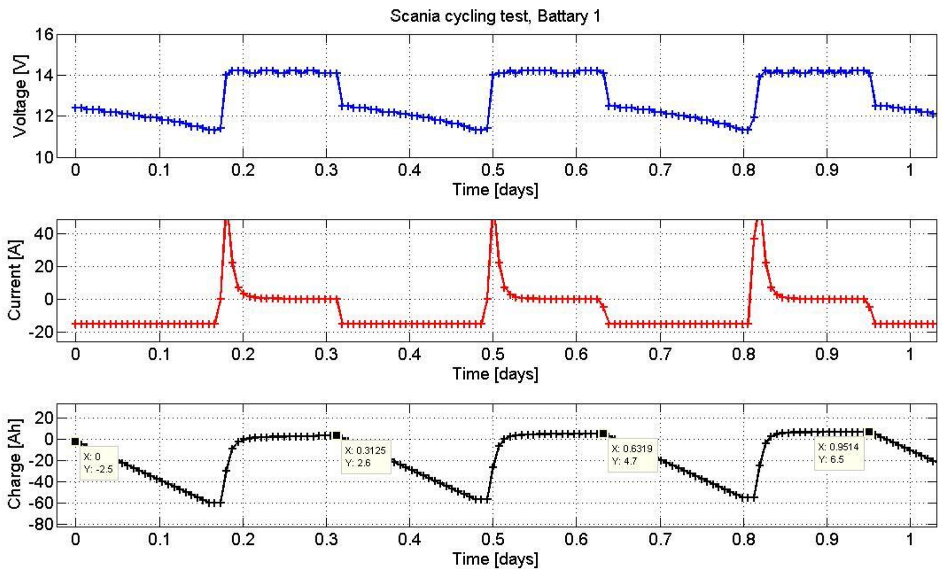


Figure 40: The first day of one year's cycling to investigate the current loss coefficient's impact on Coulomb counting for Gel-batteries (notice, not flooded LAB).

Figure 40 indicates that Coulomb counting overestimated the capacity with around 3 Ah for every cycling, charge and discharge 60 Ah, then actual battery capacity. It indicates that every cycling has a factor around 1.059, which excesses the estimation against the actual capacity. To investigate the impact on cycles similar to the evaluation cycles, this factor was added to the coulomb counted SOC for a test cycle, see Figure 41. It was divided with the Coulomb counted SOC and then compared against coulomb counting without factor. Figure 41 indicated a small differ between the Coulomb counted SOC with and without factor. The largest differ amount is around 10-12Ah. It's important to considerate this coefficient and recalibrate the coulomb counting method or use a factor to minimise the risk for error at longer cycles. It's important to have kept in mind but for this thesis work when analysing SOC, SOF and SOH this impact shouldn't be as large as 10-12 Ah. It's due to that the current loss coefficient not is a constant factor as well as the applied factor, in Figure 41, isn't produce based on same batteries, neither type nor size, than the evaluation method is based on. The cycling that the applied factor is based on has also used higher current, for both discharges and charges which could be seen Figure 40, and it increases the current loss coefficients impact. To verify that Coulomb counting not affected the evaluation methods that much, Cycle 3 to evaluate SOH could be used. The reference points make it possible to examine if the present maximal capacity is change over a time, in around three weeks. This will show exactly how much the Coulomb counted estimation is differing from the actual value for each 50-60 hours cycle. The purpose with Figure 41 is to illustrate the problematic and to show that it's important to take in consideration.

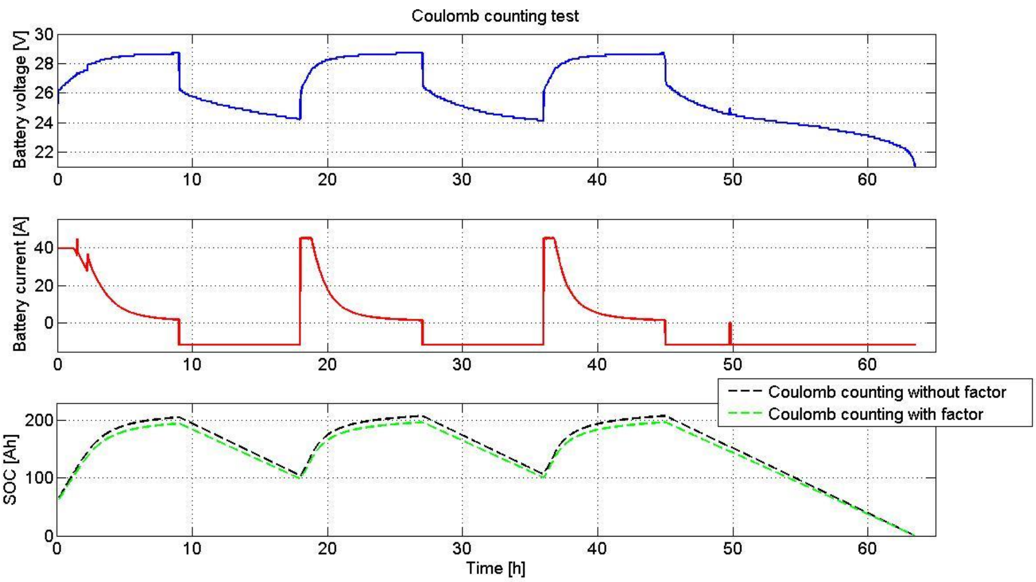


Figure 41: Coulomb counting test – shows differences between coulomb counting with and without a constant current loss coefficient (at 1.059).

SOF method

The evaluation method and criterion to evaluate SOF is well supported from tests at Scania. This methods problematic is based on the formation of both method and criterion, the assumption that a constant current instead of an alter current for engine starts. It's difference between a constant current than a cranking current in an actual starting process. On the other hand it's require more of a battery to deliver a constant high current then if the current cranking and the evaluation criterion is also in the upper edge because it requires a voltage based on a constant current according to mean values from engine starts.

The tests that both the method and evaluation criterion are based on, used new and non-degraded batteries. It should therefore be taken into consideration that age or worse batteries could require other preferences to deliver the power. Still the evaluation method is based on current and voltage deliver from the batteries to ensure starting; therefore it should be functional for age batteries as well.

It's also worth mention again that this method not take into consideration other parameters than the batteries performance. It's a lot of other parameters that affect the starting procedure but the BS should and could only be evaluated by the batteries performance.

SOH method

The evaluation method and criterion to evaluate SOH is only based on battery capacity. The actual SOH is determined based on Coulomb counting and Equation 6. Therefore this method has same limitation as the SOC method based on the Coulomb counting. It's a limitation that should be notice the actual SOH only is based on differences in maximal capacity. Perhaps a method that also takes the inner resistance in consideration should be more accurate but at the same time, these parameters then have to be weighed against each other. This problematic but also issues with measuring inner resistance as well as demanded accurate for evaluation purpose motivated a more practical method, such as the capacity. According to the two tested BS' at Scania this also should be enough to evaluate their estimations of SOH. Other BS indicates that this could be insufficient because engine cranks give information to recalibration the SOH estimation but at the same time cranks not ensure an accurate SOH value, which indicated that other parameters are more or at least very important for the estimation. Therefore this evaluation method is a sufficient accurate method for the two tested BS at Scania and BS's that estimated SOH similar.

The evaluation method has not been verify practical, it's instead an entire theoretical approaches based on literature, tests and conditions. The choice to do this method entire theoretical was not difficult because according to tests and present estimations by BS it was not able to evaluate practical, see Figure 42. The actual SOH is only decreasing and according to the evaluation criterion, to be enough accurate as decision basis for battery changes, the estimated SOH neither should leap. Figure 42 is a representative BS estimation of SOH and it indicates that the BS's estimation both is increase and leaps.

Figure 42 is the SOH estimation for Test 3, a Repeated Charge-Discharge cycle, see subchapter 6.1.2. In Appendix E another figure for an easier cycle, a total discharge, is showed but still the SOH estimation couldn’t manage any of the defined criterion.

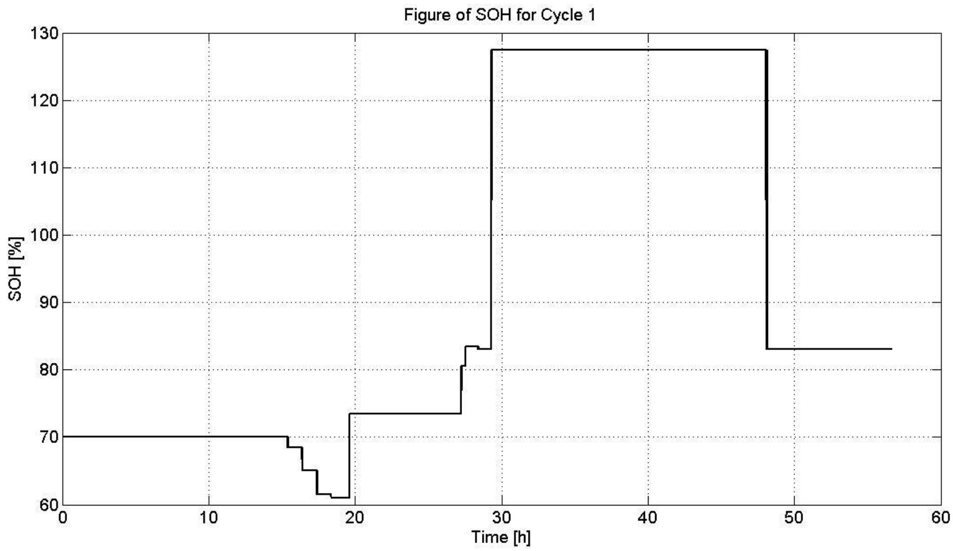


Figure 42: BS2’s SOH estimation for Cycle 1. It’s representative for the poor BS’ estimations of SOH.

It’s a limitation that it could be difficult to obtain batteries with the different SOH values that the evaluation method is need, but it’s affordable according to that it not has to be precisely this values. At last it’s worth mentioning again that this method neglect temperature, which users have to be aware of. The method is also restricted; it only piecewise ensured that the estimation is limited according to the evaluation criterion but it’s enough to fulfill the purpose with the criterion, the customers benefit to plan battery changes.

7. Conclusions

The thesis work has developed evaluation criteria and evaluation methods to assess battery sensors ability to deliver competent information about batteries SOC, SOF and SOH. The evaluation methods are produced to evaluate if the criteria are fulfilled or not. If the evaluation criteria are fulfilled, the deliver information from the battery sensor could be used to ensure the electric system functionality in vehicles.

The battery sensors should therefore be evaluated in terms of SOC, SOF and SOH. The evaluation criteria for these terms are individual. The SOC is evaluated with Criterion 1, which limit the estimation to be within the boundaries for the criterion. The SOF is evaluated with two criteria but both have to be fulfilled to accomplish the evaluation criteria, Criterion 2. The SOH is evaluated with Criterion 3, which consists of two criteria that should to be fulfilled.

The evaluation methods are developed with consideration to all these criteria. This means of course that it's specific for each criterion. The SOC evaluation method is consists of three defined cycles, for which the estimation should be compared against the evaluation criterion. These cycles are a total discharge, Cycle 1 and Cycle 2 which can be seen in Figure 35, 36 and 37. The SOF evaluation method is based on sequential tests with a determined constant current for specific conditions. The recorded information from the BS could then be compare with the criterion, see in Figure 38. The SOH evaluation method is as the SOC evaluation method based on three defined cycles with specific conditions. Two of these three cycles are from the SOC method, a total discharge and Cycle 1. The third cycle, Cycle 3, is a modification of the SOC method's Cycle 2. This modification, the defined specific conditions for these cycles and conditions for all other methods have to be read in each chapter about the specific evaluation method.

7.1 Reliability analysis

The limitations with methods and criteria have already been discussed in chapter 6.4.4. The purpose with this thesis work was to develop generalizable method and criteria to evaluate BS. The conclusion is that these methods and criteria are generalizable based on the investigated BS, BS1 and BS2. The developed methods and criteria could be used to evaluate other BS but it should be taken into consideration that it only is generalizable for BS estimating similar to the investigated BS and the thesis work conclude that not all BS do that.

The methods and criteria are also determined based on vehicles, or three specific engines, from Scania. This means for example that requested parameters and minimal battery performance is specific for these vehicles. Therefore evaluation if a BS could ensure an engine start, SOF, is specific and only direct generalizable for these three engines. The three engines have different design as well as number of cylinders which passably should be representatively for more engines then only these three. Hence generalizations could be done with cautions and if it's done, ensure similar engine conditions.

It should be mentioned again that the thesis work only takes two BS' into consideration. It should also be mention that it's only the batteries performances that are evaluated engine starts, not the entirely process and it's evaluated with a constant current instead of cranking. Another source of error is the conversion of BS2's SOC estimation, which is converted for percent to ampere hour. This conversion results in that the SOC is depending on the SOH. It means that a weak SOH estimation impair the SOC estimation. The SOH is in turn estimated from the SOC. Due to this the SOC estimation could impair further; a weak non-converted SOC estimation causes a weak SOH estimation which in turn affects the converted SOC estimation. Therefore a converted SOC estimation almost is punished double for a weak non-converted SOC estimation. Through the thesis work this has been kept in mind, specific at the tests and some corrections has been done to eliminate this problematic when evaluate SOC.

7.2 Further work

Of course it would be interesting to work further with verifying and testing of the evaluation methods and criteria. To investigate if the manufacturers could manage these criteria or even more to ensure even better estimations. It's particular interesting to investigate SOH further, verify if this theoretical method and criterion could be used. Otherwise it should be considered to evaluate SOH based on inner resistance. It's a promising method but probably a combination of capacity and inner resistance is to prefer. One problem with this is how the capacity and inner resistance should be weighed against each other.

Something that has to be work further on is also the investigation of Coulomb counting, about the current loss coefficient's impact and a first step could be done with the Cycle 3. It's important to acquire a more accurate actual SOC to improve the evaluation. To generalize the SOC evaluation criterion for other battery sizes then 225 Ah, a further work could be to translate this thesis work's Criterion 1 to a criterion independent of the battery size. To formulate a battery size independent criterion a first step could be to evaluate if the tolerance amplitude could be calculated as the battery size divided by 22.5, which is based on that 225 Ah LAB then results in tolerance amplitude at 10 Ah.

Finally it also should be useful and even more similar to the reality if a varying testing current could be developed to evaluate SOF and engine starts. The thesis work's constant current is well established but this would eliminate all doubt for SOF.

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Appendix

Appendix A

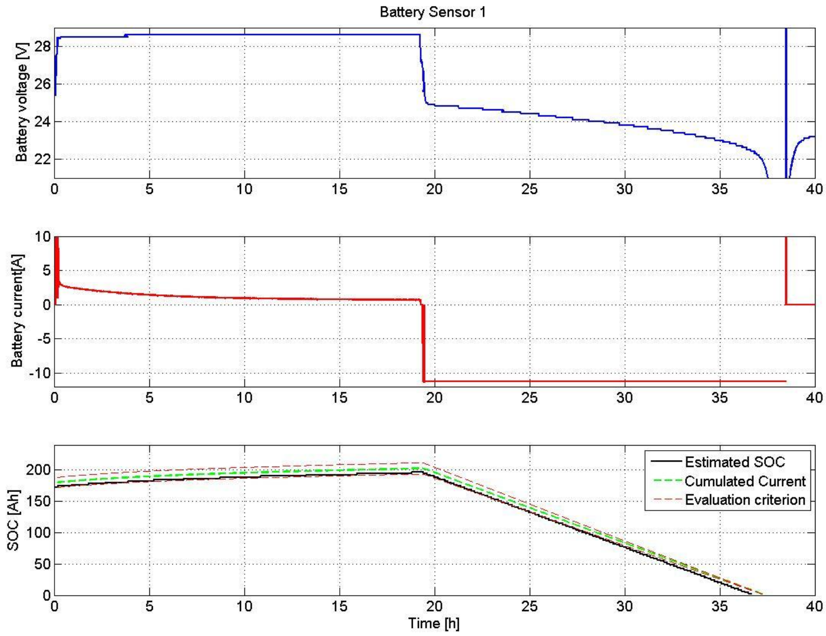

Figure A1: Charge-discharge cycle- BS1. Current, Voltage and SOC. Evaluation criterion based on Equation 15 - tolerance amplitude at 10 Ah.

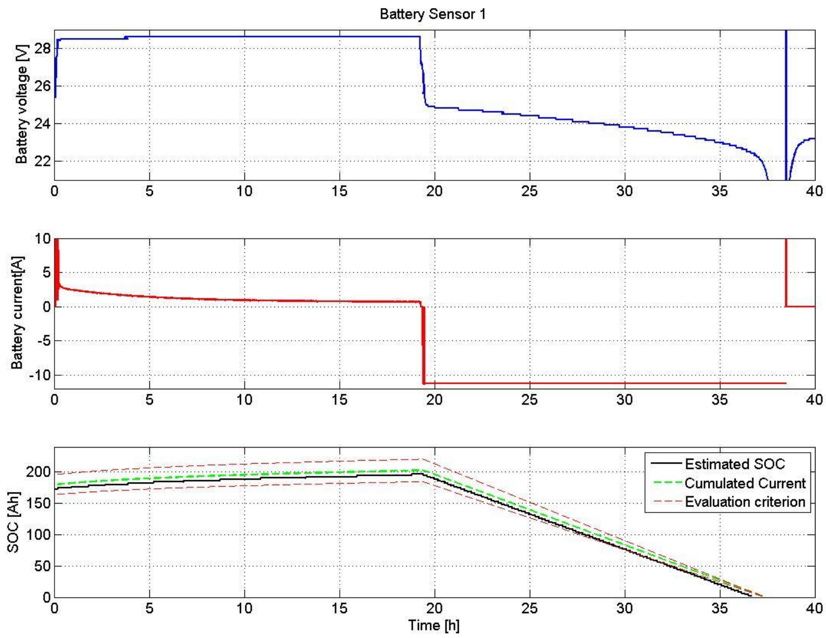

Figure A2: Charge-discharge cycle- BS1. Current, Voltage and SOC. Evaluation criterion based on Equation 15 - tolerance amplitude at 20 Ah.

Appendix B

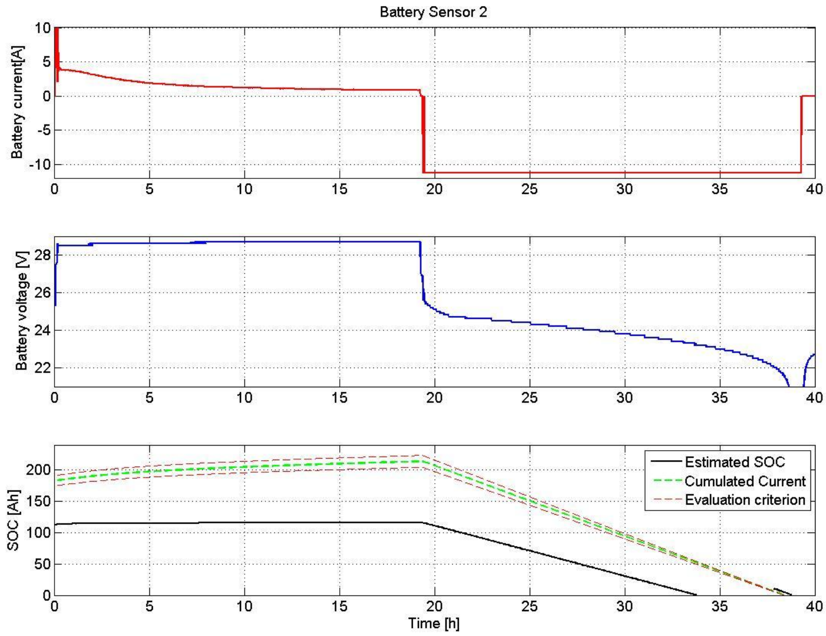

Figure B1: Charge-discharge cycles – BS2. Current, Voltage and SOC. Evaluation criterion based on Equation 15 - tolerance amplitude at 10 Ah.

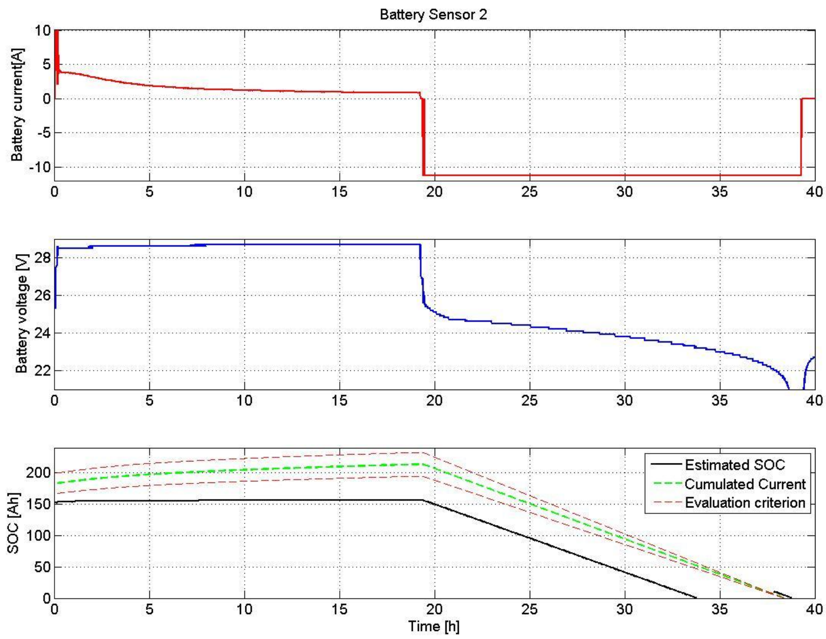

Figure B1: Charge-discharge cycles – BS2 with calculation correction. Current, Voltage and SOC. Evaluation criterion based on Equation 15 - tolerance amplitude at 20 Ah.

Appendix C

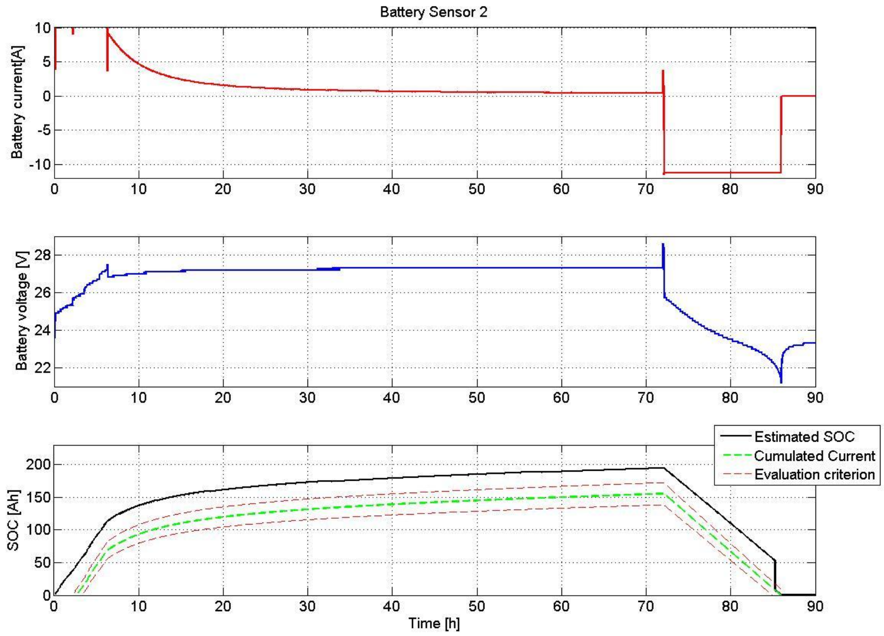

Figure C1: Charge-discharge cycle- BS2. Current, Voltage and SOC. Evaluation criterion based on Equation 16 - tolerance amplitude at 10 Ah.

Appendix D

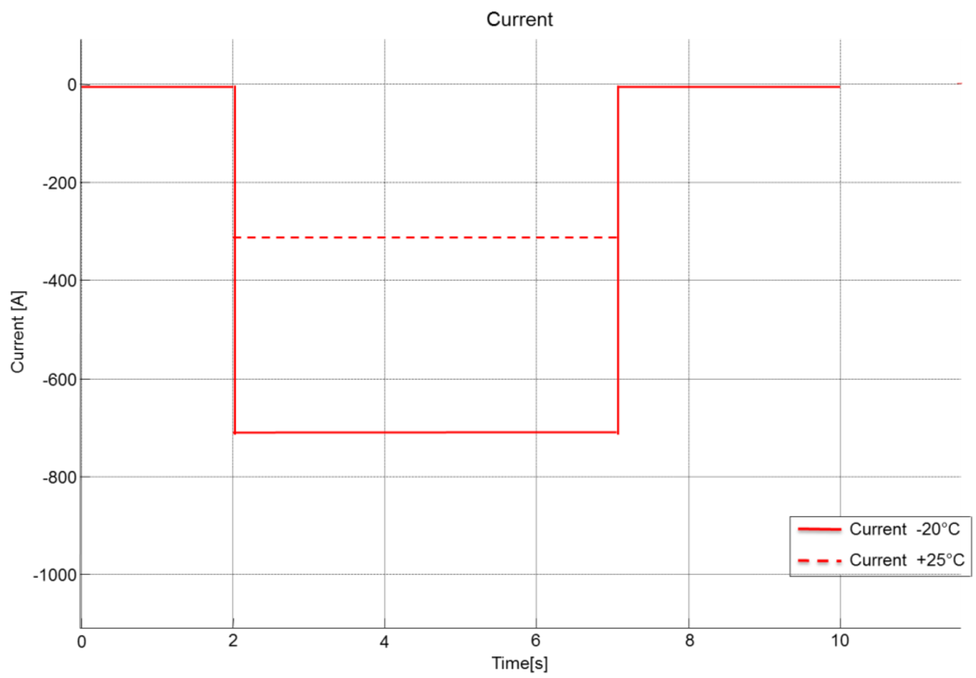

Figure D1: The sequential evaluation - the constant currents for both temperatures that should be applied to the LAB to evaluate the voltage responses.

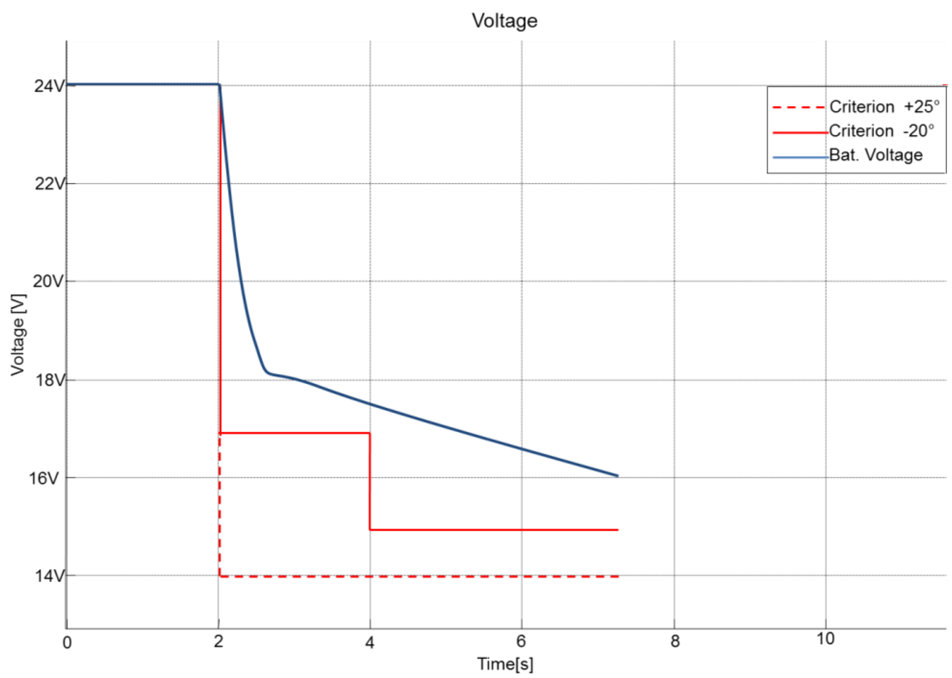

Figure D2: The sequential evaluation - an example of voltage response and the minimal battery performances to ensure a successful engine start according to Table 9, both temperatures.

Appendix E

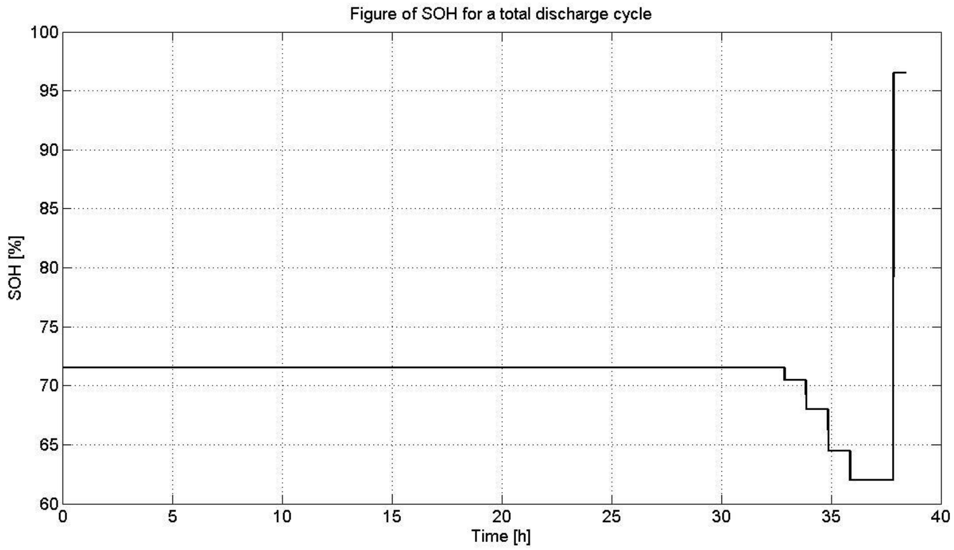

Figure E1: BS1's SOH estimation for a total discharge cycle.