POLITECNICO DI TORINO

Master's degree course in Mechatronic Engineering

Master's Degree Thesis

Development of battery diagnostic for commercial vehicles using onboard battery sensor

Candidate:

Davide Lava

Supervisor:

Prof. Carlo Novara

Internship supervisor:

Ing. Maurizio Quaggiotto

Academic Year 2019-2020

Abstract

In this thesis it will be shown the usage and the exploitation of a battery sensor, already used by Iveco onboard of the vehicles, with a diagnosis purpose. The strength of this approach is the possibility to take advantage of something already present onboard of the vehicle, but also the possibility to have an historical trend of the measurement and of the states of the battery. In addition, the standard among the dealers of truck makers sometimes offers not reliable measurements leading to a wrong replacement of the batteries, so a new approach in the method of the diagnosis is required.

The proposed method consists in the usage of an Intelligent Battery Sensor (IBS) that continuously estimates SOC, SOH and the internal resistance value, and measures the temperature, the voltages and the battery current. Together with the IBS also a Universal Diagnosis Tool (UDT) is developed, which, once connected to the On Board Diagnostic (OBD) port of the vehicle, can retrieve the data coming from the sensor and, on the base of them, estimates another value of SOH and returns a diagnosis on the batteries. To state the reliability of the measurements performed and to choose between the two computed values of SOH, some thresholds are introduced to identify the quality level of the measurement. The final output of the UDT, in addition to the state of the battery, can be:

- Battery OK: no necessity to substitute the battery;
- Battery 1 KO: necessity to substitute the battery 1;
- Battery 2 KO: necessity to substitute the battery 2;
- Batteries to be charged: recharge the batteries then perform again the measurement;
- Measure again: something during the process went wrong so the process must be repeated;

After the proposal of the method and the analysis of the architecture of the system inside the vehicle, two different testing campaigns are done: the first one has the purpose to characterize the performances of the batteries in terms of residual capacity and ability to perform the cold cranking current as defined by the proper norm; the second test campaign has the scope to build a database that relates SOC, temperature, SOH and internal resistance value for the computation of the SOH inside the UDT.

The validation of the tool has been considered impossible due to the company restrictions caused by the spreading of the SARS-COV2 virus, but some qualitative tests

are performed to compare the outputs of the UDT tool and the shelf tool,and a validation procedure for the tool is proposed.

Summary

List of Figures

List of Tables

1. Introduction

The sector related to the optimization of the energy management on commercial vehicles has experienced a great growth in the last years. The raising interest on the climate change issue, but also the need for the truck makers to manage relevant costs and to respect the regulations on the CO_2 emissions, lead to the necessity to improve the energy management and this necessity will grow through the future, thanks to the electrification of the automotive world.

Nowadays the management of the energy coming from batteries is a relevant issue since a correct estimation of the quantities related to the battery and its capacity to store and provide energy will lead to an optimization of the performance of the batteries, of the use of energy, but more important it can prevent unexpected stops or cranking failure of the vehicle.

Another significant aspect related to the commercial vehicle field that determines the necessity to have a very precise energy management is the increase of comfort delivered to the driver, considering that the technology of the battery employed has not improved a lot during the last years.

The worst situation happens when the energy that comes from the battery is required to supply all the electronic devices in the cabin during stops, look at Figure1.

FIGURE 1: TRUCK HOTELING FUNCTIONS

In particular, the parking cooling system, i.e. the air conditioning and the fridge while the vehicle is parked, is the system that requires the greatest amount of energy, especially during one night parking, when the vehicle must perform the so called "hoteling function", in which the cabin of the truck is used as if it is a hotel room.

For all these reasons an accurate method for the estimation of the battery status and for the management of the energy is more important than ever.

The energy management of the batteries is based on the estimation of two main parameters that can characterize their condition: the State of Charge (SOC) and the State of Health (SOH).

1.1. Battery quantities

To define SOC and SOH it is necessary to define some quantities related to the batteries as done in Table1[2][14].

Name	Symbol	Unit	Description
Rated capacity or nominal capacity	C_N	Ah	The rated or nominal capacity is the value for the capacity given by the manufacturer at nominal operating conditions (defined by temperature of 25°C, current and end-of-discharge voltage of 10.5 V). As a standard the 20 h capacity (N = 20) should be used. A transformation between any temperature between 10 to 30°C and the nominal temperature is possible with the given equation.
Initial capacity	C_0	Ah	The initial capacity is the capacity available at a capacity test with I_{20} down to 1.75 V/cell at 25°C (according to EN50342-1[17]) starting at full state of charge, after taking the battery into operation according to the manufacturer's instructions.
Measured capacity	C_m	Ah	The measured capacity is the capacity available at a capacity test with I_{20} down to 1.75 V/cell (according to EN50342-1[17]) starting at full state of charge, FULL at any time after taking the battery into operation.
Charge balance	Q_b	Ah	Net discharged charge from a battery since the last full state of charge $Q_b = \int I_B \, dt, \;\; I_B = battery\ current$
Depth of discharge	DOD	%	The depth of discharge is the ratio of the charge balance and the rated capacity. The depth of discharge is 0 when reaching the full state of charge and 1 after a net discharge of the rated capacity. $DOD = \frac{Q_b}{C_N}$
Open circuit voltage	OCV	V	The open circuit voltage is the voltage measured at a battery at open circuit (I_B = 0) while the voltage changes less than a threshold for more than a certain time.

TABLE 1: BATTERY QUANTITIES

1.2. State of Charge

The State of Charge parameter, from now SOC, is defined as the level of charge of an electric battery relative to its capacity[11][14]; doing an automotive metaphor, SOC is for a battery what the level of fuel in the tank is for an internal combustion motor vehicle. It is defined as:

$$SOC = 1 - DOD = \frac{C_N - Q_b}{C_N}$$

In this definition it is clear that if the charge balance is equal to the nominal capacity of the battery, the SOC will be zero and the battery will be completely discharged. On the contrary, when the charge balance is zero, the SOC will be 1, that is 100%.

Also other definitions are possible depending on the capacity chosen as a reference, for example considering C_m. There is not a unique method to obtain the SOC of a battery, in fact many methods can be found in literature[1], even if in this thesis only two algorithms are considered.

The first algorithm is called Coulomb counting method and defines the SOC as the integration of the battery current I_B, which is considered positive when entering the battery (charging phase) and negative when exiting the battery (discharging phase), over the usage period.

$$SOC = SOC(t_0) + \int_{t_0}^{t_0+\tau} (I_B - I_{loss})dt$$

Where I_{loss} is the current that is lost in the circuit, τ is the usage time and $SOC(t_0)$ is the initial value at the initial time of the SOC. The accuracy of this method strongly depends on the precision of the initial value of SOC and the measurements of the currents. Another drawback is that the more time passes, the more inaccurate becomes the integration of the current.

Another way to obtain an estimation of the SOC is to exploit the relation, given by the manufacturer, between the SOC and the OCV, but this estimation can be affected by different operating conditions between the real working condition and the testing conditions, an example could be the temperature that affects the OCV value.

The two methods described enhance the problem of the estimation of a correct SOC that must consider many different parameters like the environment conditions and the battery aging; moreover, the Coulomb counting method needs to be initialized very precisely but the only moments in which the SOC of a battery is certainly known are when the battery is full charged or full discharged; for commercial vehicles the condition of a full charged battery is reached easily during long missions, so the SOC can be initialized properly.

1.3. State of Health

The State of Health parameter, from now SOH, is a quantity used to characterize the condition of a battery, compared to its ideal condition; going on with the automotive metaphor, it could be thought as the odometer on a motor vehicle. The SOH is typically given in percentage, so a new battery will have a SOH of 100% and this value will decrease with the age and with the usage of the battery[12][13][14].

A definition of this parameter can be the following

$$SOH\_C = \frac{C_m}{C_N}$$

Thanks to this definition a possible estimation of the SOH can be retrieved measuring the capacity of the battery and comparing this measure to the capacity declared by the manufacturer, the weakness of such a measurement is the difficulty in gauging the whole capacity of the battery. For this reason, another way of estimation is possible considering the cold cranking current, which is a parameter that describe the performance of the battery and it is defined as the current that a full charged battery can deliver at -18°C for 30 seconds. The SOH definition based on the cold cranking current is the following:

$$SOH\_I = \frac{ICC_m}{ICC_N}$$

Being difficult to monitor the cold cranking current, because of the particular condition under which it must be measured, the most important value that can give information about the cold cranking current is the value of the internal resistance of the battery and due to this, considering the battery as a Thevenin equivalent circuit, the SOH can be expressed also in function of the internal resistance value, exploiting the relation between that value and the aging of the battery, as done in many case-study in literature[3][4][5]. Generally, the value of the internal resistance increases with battery aging.

Following this approach, a very precise measurement of R_i is extremely important because, being the resistance very small, even a little difference between the result of the measure and the real value could lead to a big discrepancy between the estimated SOH and the real battery status.

The two ways of estimation of the SOH, called SOH_C the former based on the capacity and SOH_I the latter based on the cold cranking current, lead to a different value of the parameter because of the procedure required to estimate them. The SOH_C value indeed, is measured during a slow discharge in which the chemical substances inside the battery can diffuse correctly and the loss of capacity is due to the change of the concentration of the reagents inside the battery. On the contrary, the SOH_I is measured during a fast discharge in order to estimate the value of the internal resistance; the reaction in this condition happens quickly and the reagents have no time to diffuse inside the battery.

The standard among commercial vehicles dealer shops today is to use tools developed from other companies which base the estimation of the SOH on a single measure of the battery parameters, injecting a small AC current into the battery, measuring the internal resistance value and retrieving the value of the SOH based on that value. This method introduces more imprecision because of the lack of an historic behaviour of the battery parameters.

1.4. Today's used methods

The analysis of the literature in the battery status estimation field shows that this is an ambit of particular interest among the researchers of the world. The strong trend to the electrification of the automotive world also contributes to the deepening of the research in this field.

In the last years many innovative methods for the estimation of the SOC and SOH of the batteries are introduced, but with the advent of the lithium-ion batteries, the most innovative ones, based also on Kalman filters and on the possibility to forecast the battery behaviour, focuses on this battery type, so they are of little interest for what concern this thesis work.

Considering the lead acid batteries, that are the type of battery used onboard of the vehicle on which the tool is developed, the methods for the estimation of the SOC and the SOH are based mainly on the measurements of the battery quantities, such as the voltage at the terminals and the current provided, and on the curves obtained plotting the current and the voltage[7][8]. In particular, the relation between the slope of the curves or their form and the total capacity of the battery is studied to retrieve the SOH value, while the SOC is obtained from the measurement of the open circuit voltage and the integration of the current, that nowadays is a standard approach for the SOC evaluation.

Studying the literature, it is noticeable the nonlinear behaviour of the batteries, so also many methods based on Look Up Tables are developed, trying to correlate the measurements obtained to a specific condition of the battery; however these methods, even if they are the simplest to implement, require a lot of testing and training to know the battery behaviour in different conditions.

Nevertheless, truck makers are investing lot of resources in the development of methods for the estimation of the battery status because, considering the trend of the market to provide to the driver as many services as possible, an optimal energy management will result in a greater competitiveness on the market. For this reason, a new approach based on the presence of an Intelligent Battery Sensor onboard of the vehicle can be a strong added value for the company.

Anyway, this field of interest is subject to a strong development because an accurate estimation of the SOC and SOH will lead to an optimal energy management that improves the performance and the efficiency.

1.5. Proposed solution for SOC and SOH estimation

To overcome the problems that arise during the estimation different algorithms are proposed thanks to the installation of an Intelligent Battery Sensor to monitor the battery parameters during time. Considering the SOC estimation, the Coulomb counting method is improved integrating the current measured by the sensor and initializing the SOC value according to three different methods:

- End of Charge (EoC): the initial value of SOC is set at the full charged battery, but it is not necessarily 100% according to battery and environment condition;
- End of Discharge (EoD): the initial value for SOC is set at the full discharged battery;
- Open Circuit Voltage (OCV): when the current remains under a certain threshold for a long time, open circuit condition is verified, and the initial value of the SOC is set.

On the base of the initialization method also a quality value is set to the measure of the SOC.

According to the considered algorithm, the main drawback of the Coulomb counting method for the SOC estimation, that is the lack of the SOC initialization, is bypassed.

As for the SOH other algorithms are considered:

- Coulomb counting until end of discharge EoD;
- Progression of battery voltage during 60Ah discharges (Window 3 or W3);
- Look Up Tables (LUT) based;

The third algorithm is based on LUTs that correlate the cranking resistance, the temperature and the SOC value at cranking with the SOH of the battery. The LUTs are based on experimental data obtained performing battery aging cycles on the battery into the laboratory under monitored conditions.

The algorithms allow two estimations of the State of Health and a comparison between the results. Moreover, the use of an onboard sensor leads to a monitoring of the data during the time making possible a measurement also based on the historic behaviour of the parameters considered; overcoming the limit of the single measurement SOH estimation.

1.6. Scope of the thesis

The scope of the thesis work is to validate a tool that takes full advantage from the Intelligent Battery Sensor already present on a normal truck. In particular the tool must be able, according to the data of the battery parameters made available from IBS and to the estimation of the SOC and SOH, to perform a diagnosis on the state of the battery, providing, as output, the status of the batteries and the possible necessity to change battery or to charge battery.

The added value can result in an independence from the shelf diagnosis tool that nowadays is used to perform the diagnosis, which is made by a different company, becoming stand-alone for what regard the battery diagnosis. Also, the today standard produces often errors, which cause the wrong replacement of the batteries, and by consequence a loss of money and reputation for the company, so the scope of the developed tool is to improve the reliability of the estimation of the state of the batteries in order to avoid all these consequences.

The aim of the company is to apply the developed diagnosis tool as soon as possible because it is a great improvement with respect to competitors that nowadays do not have systems that perform this kind of analysis and diagnosis.

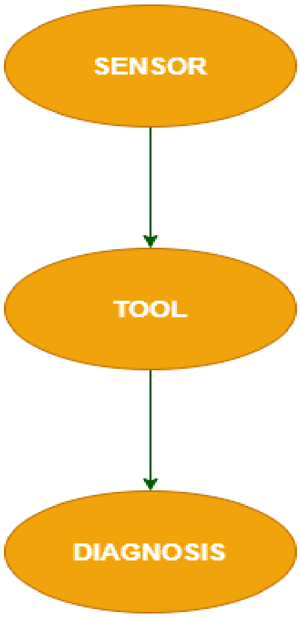


FIGURE 2: ANALYSIS FLOW CHART

2. System Description

The system considered during the thesis is the one implemented on the Stralis, in Figure3.

FIGURE 3: IVECO STRALIS

The Stralis is the heavy commercial vehicle produced by Iveco and it must be the leader in the commercial vehicles market in terms of technology and services provided to the driver, that typically spend many hours and eventually days inside the cabin, which is one of the most relevant features in a competitive market like this. The energy management on a truck like this is very challenging because the whole system must consider the habits of the driver and his need to use several electrical instruments for his comfort even when the truck is parked. In the last years the market of commercial vehicles improved a lot from the point of view of the comfort provided to the driver, just think about the possibility, in the last models, to connect up to eight USB devices, recharge the telephone plug the fridge or television on board of the truck and even more functionalities.

A typical example of this situation can be observed in Figure4, where the case of the energy consumption during a one night stop in different ambient conditions is shown.

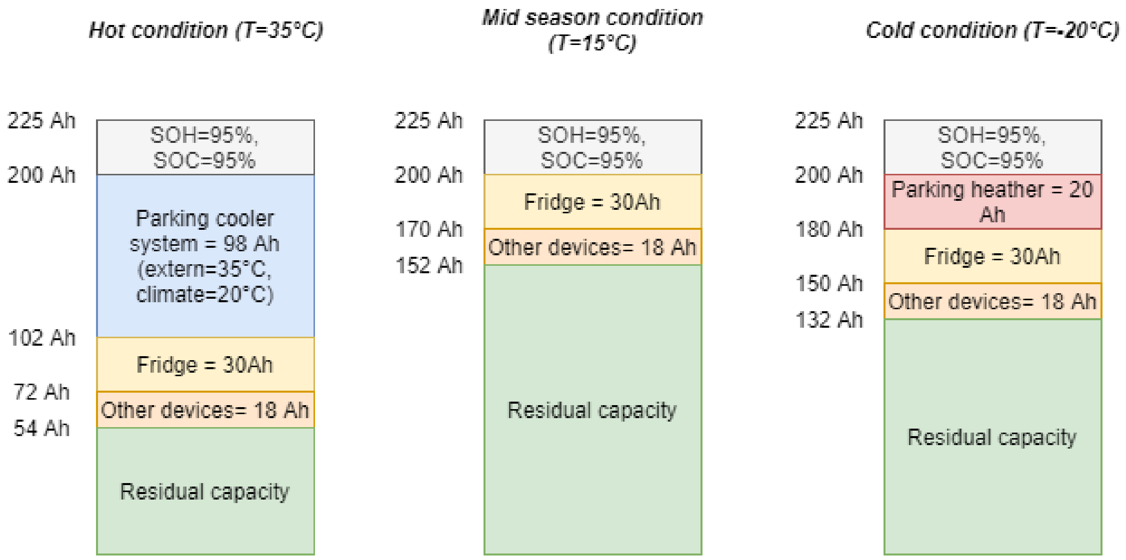


FIGURE 4: ESTIMATION OF ENERGY CONSUMPTION IN DIFFERENT AMBIENT CONDITIONS DURING 1-NIGHT STOP

From the figure it is evident that the most challenging situation is the hot condition when the driver makes use of the air conditioning and the fridge, which are the two most energy demanding functionalities that cause a great capacity loss because they must maintain a bigger delta of temperatures between the inside and the outside; during the mid season, the energy demanding typically decreases at the lowest level because of the lack of the necessity of a cabin temperature conditioning; instead, during the cold season, the energy demanding increases because of the internal heating system, even if it remains lower then the energy demanding in the hot season, nevertheless the cranking of the vehicles requires a bigger amount of energy coming from the batteries, so also the cold season can be very challenging.

When the vehicle is parked and there is no power source coming from the alternator, see Figure5, all the energy required by the driver's devices must be provided by the batteries, which must maintain the capability to provide the cranking current to start the vehicle engine; this situation is very demanding for the battery management system.

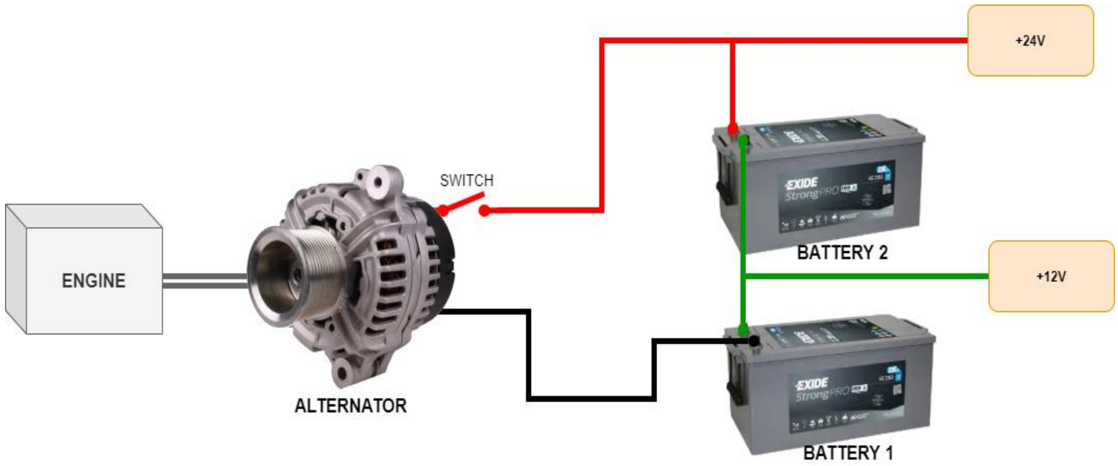


FIGURE 5: SYSTEM ELECTRIC CONFIGURATION

The system that provides electrical energy, is mainly composed by the engine, the alternator and the two batteries; the alternator is an electrical machine based on the magnetic induction law that converts the mechanical energy into electrical energy in the form of ac current; the batteries are two flooded acid batteries 12 V, 225 Ah and 1100 CCA, i.e. based on the presence of a liquid electrolytic substance free to move in the battery encasement. The described configuration can work mainly in two ways:

- With the engine on, the batteries are recharging (I_B>0), the energy comes from the alternator thanks to the mechanical energy provided by the engine that is converted in electrical energy used to recharge the batteries and to provide the power source to the electronic devices;
- With the engine off, the batteries are discharging (I_B<0) the energy comes from the batteries themselves that must provide the power source to the electronic devices and maintain the capability to crank the vehicle;

During the first phase the alternator provides the voltage and the current required by the devices connected and by the batteries to recharge; in the second phase the voltage and the current come from the batteries. Considering the behaviour of the system and considering also that the vehicle must be able to start the engine, an optimal energy management is required, and in particular a precise estimation of the batteries parameters.

In this perspective, a role of particular importance is played by the Intelligent Battery Sensor (IBS), that can measure the quantities related to the batteries and their parameters; this device has been installed onboard of the vehicles with the purpose to fully exploit the functionalities of the updated smart alternator, that can manage the quantity of current provided to the batteries for the recharging phase and, in collaboration with the IBS, can optimize the charging phase of the batteries.

The quantities measured and estimated by the IBS are also used by the Universal Diagnosis Tool (UDT), that is a tool used with the employment of a PC in the mechanical workshop, which on the base of the data coming from the IBS, performs a diagnosis of the state of the two batteries.

The overall flow of the IBS and UDT tool employment is in Figure6, in which the comparison between the use of the tool developed and the use of diagnosis tools bought on the market is enhanced.

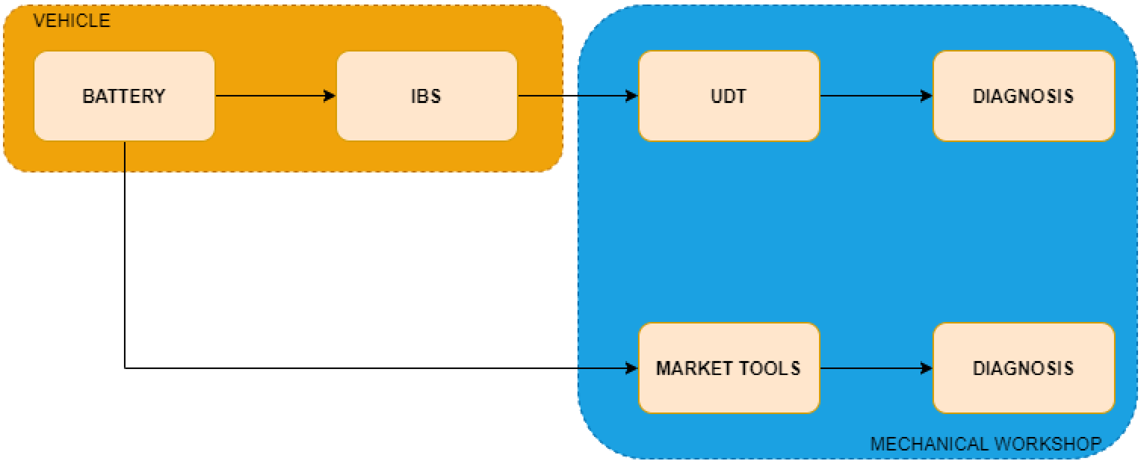


FIGURE 6: MARKET TOOLS VS. UDT ANALYSIS FLOWS

2.1. Lead acid batteries

In the automotive field, and in particular among commercial vehicles makers, the most used type of battery is the lead acid battery that is the objects of all the measurements performed in the thesis work. The Iveco Stralis specifically can be equipped with two 225 Ah capacity or two 180 Ah capacity but, given that the majority of the vehicles have 225 Ah batteries onboard, these are chosen for the tests. Lead-acid batteries are electrochemical devices that can store energy in a chemical form; when a load is connected, thanks to a chemical reaction, the battery can provide current[10].

To better understand the behaviour and the features of the work done, a closer look into the working principle is required.

2.1.1. Battery structure

The physical structure of lead-acid batteries used in automotive applications is made of a plastic case divided into six compartments, inside each compartment there are cells made of dissimilar materials plates, separators and connecting links; these cells are connected in series from the positive terminal of one cell to the negative terminal of the subsequent cell. Each compartment has a nominal voltage of 2 V, so that the total nominal voltage provided by a standard battery is 12 V.

The structure of each cell is composed by one positive lead plate covered with a paste of lead dioxide (PbO_2), one negative lead plate made of sponge lead (Pb) and liquid electrolyte made of water solution of sulfuric acid (H_2SO_4) free to move. The compositions of the plates and the electrolyte change over charging and discharging phase, thanks to the chemical reactions that occur in the two different phases.

The inner part of a flooded acid battery is visible in Figure7, in which the plates inside one of the six compartments are visible.

FIGURE 7: FLOODED ACID BATTERY

Thanks to the manufacturer collaboration, the cut of the case of the battery can show the inner part of the lead acid battery. From the figure it is possible to see one of the six compartments present inside the battery in which there are many plates, nowadays 23 plates are fitted into each compartment, divided by a plastic sheet with a high permeability degree that lets the electrolyte to pass but avoids the contacts between opposite plates and, by consequence, the short circuit condition.

The plates are made with a lead grid, which can be obtained from compression or from expansion of a lead sheet, covered by paste of lead dioxide or sponge lead with some additives to enhance some chemical properties.

2.1.2. Discharging phase

During the discharging phase, two reversible reactions occur near the plates. At the positive plate side, the reaction is:

$$PbO_2(s) + HSO_4^-(aq) + 3H^+(aq) + 2e^- \rightarrow PbSO_4(s) + 2H_2O(l)$$

From the lead dioxide in solid state and the sulfuric acid in aqueous state, with the addition of two electrons, are produced lead (II) sulphate in solid state and water in liquid state.

At the negative plate side, the following reaction occurs:

$$Pb(s) + HSO_4^-(aq) \rightarrow PbSO_4^-(s) + H^+(aq) + 2e^-$$

From the lead in solid state and the negative ion of the electrolyte, the negative ion of the lead (II) sulphate, the positive ion of the hydrogen and two electrons are produced.

Considering both the reactions it is possible to retrieve the complete reaction in the discharging phase:

$$Pb(s) + PbO_2(s) + 2H_2SO_4(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$$

The result of the conversion of the lead Pb into lead (II) sulphate $PbSO_4$ is the production of energy and water that will dilute the electrolyte into the cell. These chemical reactions occur at the contact surface between the electrolyte and the plates, so that the lead (II) sulphate is produced at the contact between them; this condition makes the plate to be covered by the sulphate that avoids the contact between the two reagents. Reaching the complete discharge state, the active surface of the plates is about 30-40% of the total surface, as shown in Figure8.

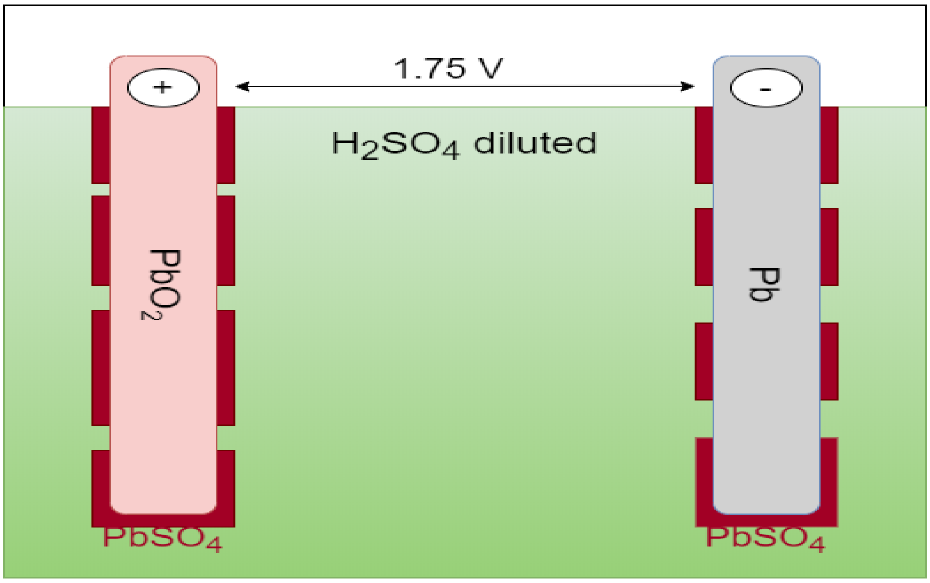


FIGURE 8: DISCHARGED BATTERY CELL

2.1.3. Charging phase

The reactions that occur during the charging phase are exactly the opposite compared with the ones of the discharging phase. At the full charged state, as visible in Figure9, the negative plate is made of lead, the positive plate is made of lead dioxide and the electrolyte has a higher concentration of aqueous sulfuric acid, which is the element that stores most of the chemical energy.

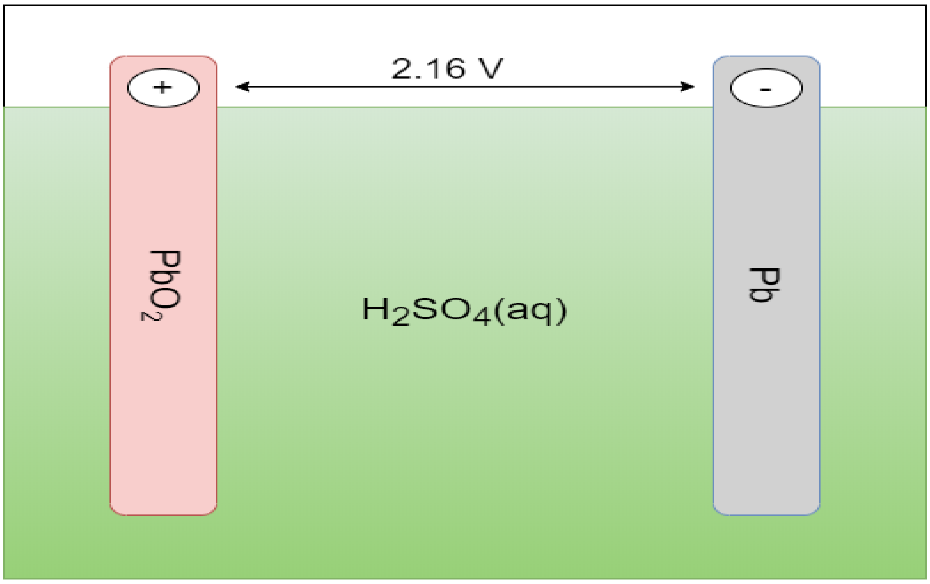


FIGURE 9: CHARGED BATTERY CELL

2.1.4. Battery model

The model considered for the battery, after all the considerations made, is the simplest model for a battery, that is a battery seen as an electrochemical generator with a resistance in series, which can be considered a correct model during the cranking phase of the vehicle[7][9], shown in Figure10.

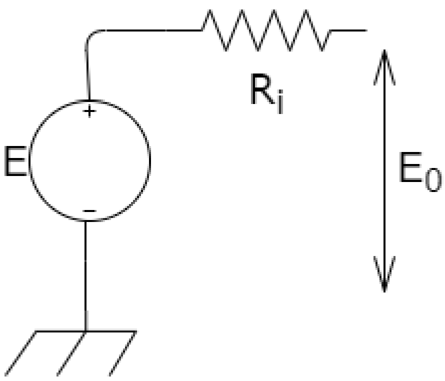


FIGURE 10: BATTERY BASIC MODEL

Three important parameters are considered into the model: E_0 is the open circuit voltage drop at the equilibrium condition, proportional to the amount of capacity stored into the battery and so proportional to the SOC; the second parameter is the internal resistance R_i that strongly depends on the concentration and the distribution of the electrolyte and the products of the chemical reactions during the charging and discharging phases; the third parameter, called E, is the voltage at the terminal of the battery, that is one of the quantities that can be measured during the testing phase.

This model is simple but can describe the behaviour of the battery, especially during the fast discharge of the battery, that is the condition in which the internal resistance is estimated, when the battery has a very marked ohmic behaviour; the weak point is the value of the internal resistance that is affected by many different factors.

2.1.5. Battery internal resistance

Considering the battery model above, special attention must be payed to the internal resistance value that can be used to verify the SOC and the SOH of the battery.

The major contributor to the variation of the internal resistance value is the alteration of the concentration of the electrolyte that strongly depends also on the temperature; for this reason it is not easy to relate the internal resistance value to a specific value of SOC and SOH.

In Figure11, it is shown the trend of the specific resistivity at different constant temperatures in relation with the variation of the concentration of the sulfuric acid solution that, as explained in the paragraph 2.1.2, decreases as a product of the chemical reactions happening during the discharging phase, for different constant temperatures[18].

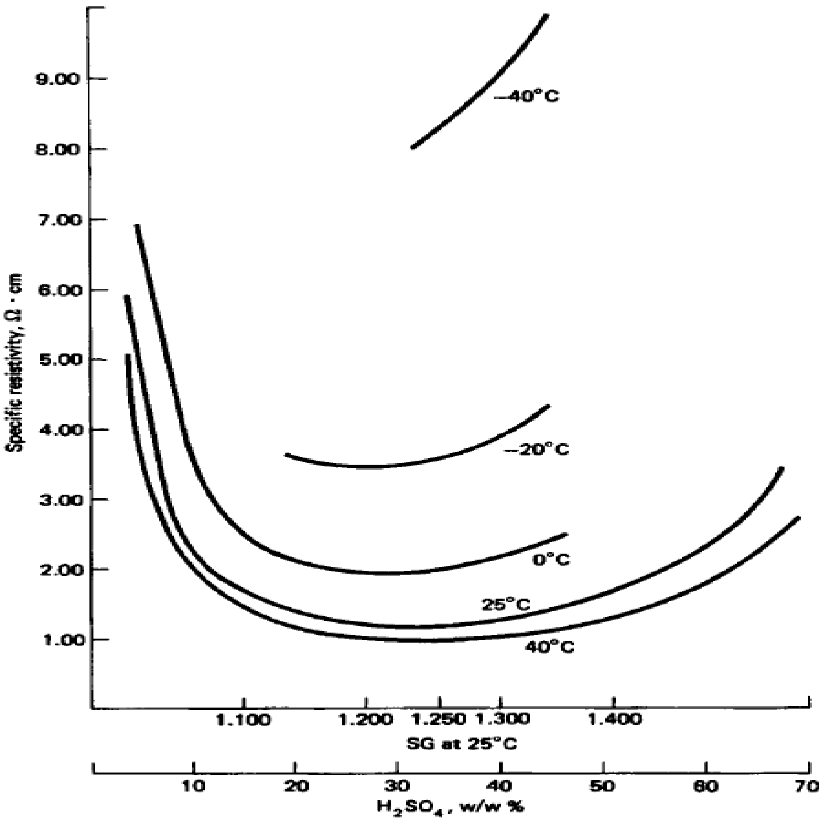


FIGURE 11: SPECIFIC RESISTIVITY OF SULFURIC ACID SOLUTION AT VARIOUS SPECIFIC GRAVITIES AND TEMPERATURES

Automotive lead-acid batteries have a specific gravity at full charged status of 1290 g/L, so looking at the graph it is possible to see that as the battery discharges, the specific gravity decreases and when the concentration of the sulfuric acid becomes low, the resistivity sharply increases leading to a rise of the internal resistance value.

2.2. Architecture description

From a physical perspective, to better explain the architecture of the system, it is worth to look at the real disposition of the batteries on board of the truck, at the back of the cabin, as visible in Figure12.

FIGURE 12: IBS SENSOR ON STRALIS BATTERIES

Looking at the image, the two batteries and the IBS sensor are noticeable, and it is possible to observe that the IBS sensor is connected at the negative pole of the battery labelled as battery 1 in the electrical circuit of Figure13.

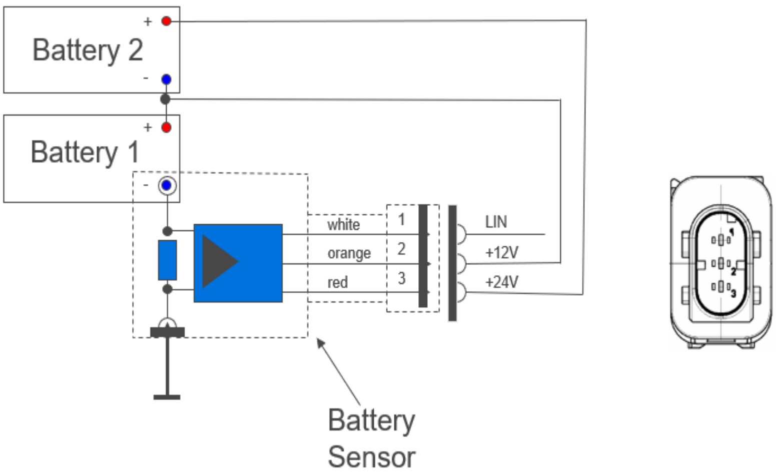


FIGURE 13: IBS ELECTRIC CONFIGURATION

The physical architecture of the system shown is quite simple and is composed by the two flooded acid batteries, connected in series to provide a 24 V voltage source, and the IBS, connected between the negative pole of the Battery 1 and the mass, according to its datasheet.

The IBS is a battery monitoring device that measures elements of vehicle battery health to improve the overall performance and life of the battery while helping increase fuel economy; to do that the device is able to precisely measure four parameters essential for the determination of the battery condition: the current (I_B), the temperature, the two voltages (+12V and +24V) and, through accurate algorithms explained in the following paragraph, the IBS estimates the State of Charge and the State of Health; the device features a LIN (Local Interconnected Network) interface for data and diagnostic communication. Looking at the internal configuration as shown in Figure14, it is possible to notice the behaviour of the component.

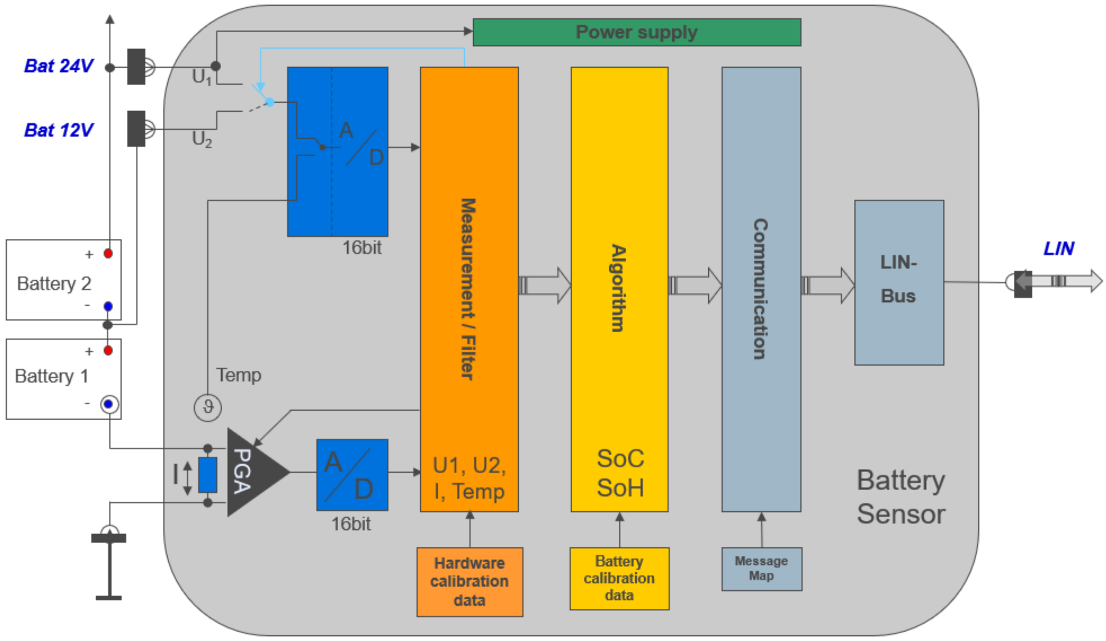


FIGURE 14: IBS BLOCK SCHEME

The current is measured thanks to the presence of a robust 100 μΩ resistance and a programmable gain amplifier, then by means of a 16-bit analog to digital converter the measured value is brought to the filter. Another 16-bit analog to digital converter provides to the filter, according to the switches configuration, the measurements of the temperature, the voltage value on the positive node of the battery 1 (12V) and the voltage value on the positive node of the battery 2 (24V). On the base of the measured values and of the algorithms explained in the following paragraph, the IBS estimates the internal resistance of each battery (R_i), the SOC and the SOH; then through the LIN interface it provides the data and the diagnostic messages. To understand how the data provided through the LIN interface are used, a closer look at the flow of the diagnosis process is required, and this is shown in Figure15.

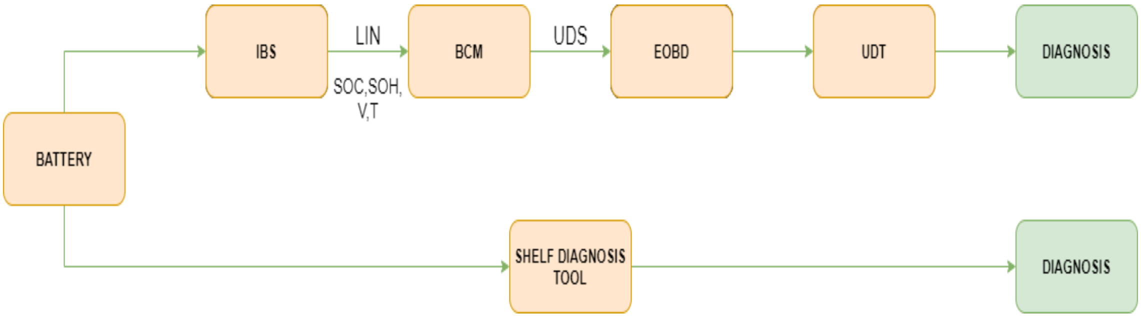


FIGURE 15: DATA FLOW

The messages produced by the IBS are delivered, through the LIN network, to the Body Computer Module (BCM) that can send messages through the Unified Diagnostic Services (UDS) protocol, based on CAN protocol. The messages sent through the UDS are reachable connecting the personal computer at the EOBD port, that is available under the truck dashboard at the passenger side into the cabin. Using the PC, it is possible to download all the data provided by the IBS and, once retrieved the data, it is possible to use the Universal Diagnosis Tool (UDT) to perform a diagnosis based on the data just acquired. The UDT can produce mainly four results:

- Battery OK: the batteries are healthy and no action is needed;
- To be recharged: the batteries must be recharged before trying again to perform a diagnosis;
- Measure again: something during the process went wrong so the process must be repeated;
- Battery 1 KO: the battery 1 must be substituted;
- Battery 2 KO: the battery 2 must be substituted.

2.3. Algorithms and software description

As visible in Figure6, the measurement of the state of the batteries takes place in two different steps and in two different devices. The first part of the measurement occurs inside the IBS sensor on board of the truck and allows the monitoring of the main quantities related to the batteries and the estimation of the SOC and the SOH based on the measured capacity of the batteries (SOH_C); all these values are available online, so in every moment the Body Computer Module can monitor them and act as a consequence of their values. The second step takes place in a mechanical workshop, with the usage of a PC with the UDT software installed and allows the estimation of the SOH based on the internal resistance value (SOH_I); in the end, the UDT processes the data and gives the final diagnosis on the batteries.

2.3.1. IBS algorithms

The Intelligent Battery Sensor, on the base of the measured quantities, such as temperature, the two voltages and the battery current, provides on the LIN bus, in addition to the parameters themselves, the estimation of the SOC, the SOH and the internal resistance. The algorithms used inside the sensor, are property of its manufacturer, so it is difficult to know the details in every functionality but, according to the documents provided, it is possible to understand the general mechanism of the estimation of SOC and SOH[15][16].

2.3.1.1. IBS operating mode

On the base of the condition of the system and of the vehicle, the Intelligent Battery Sensor can operate in different modes; the main differences between operating modes are the frequency at which the measures are taken and the quantities measured. In Figure16, the functional modes and the transitions between states are shown, while in Figure17 the cycle of measurements and its duration are shown for each operating mode.

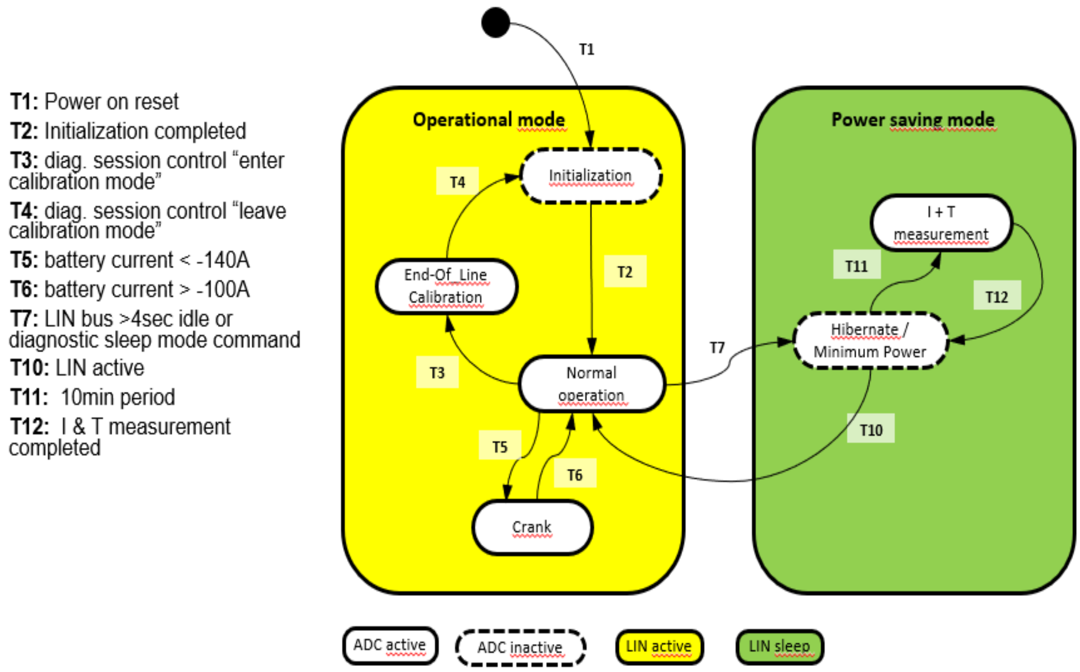


FIGURE 16: IBS FUNCTIONAL MODES AND TRANSITIONS

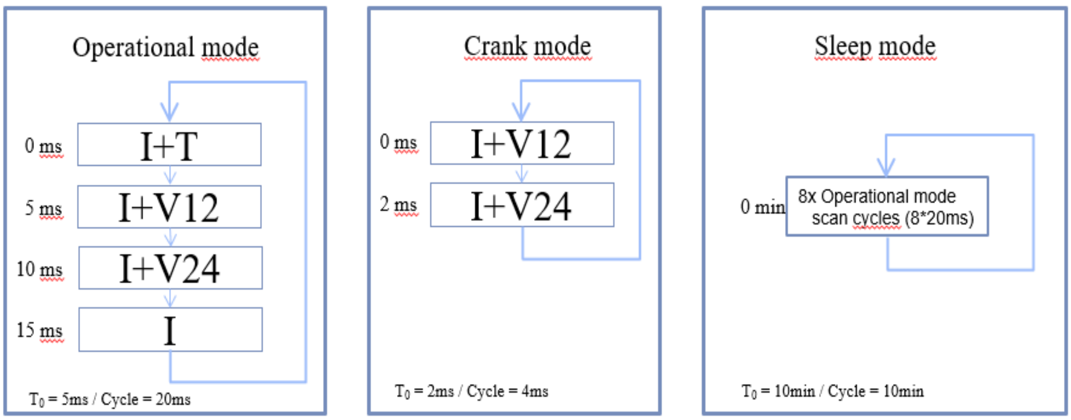


FIGURE 17: IBS MODES

It is noticeable that the frequency changes a lot between the different operating mode, passing from the 250 Hz of the crank mode, when the vehicle is starting, to the 50 Hz of the normal condition operational mode, to the frequency of one cycle every 10 minutes for the sleep mode. The difference between the operating modes is important both to save energy and to have a sufficient measurement during fast changings on the profiles of the measured quantities; in fact, it is reasonable to think that the transient condition during a start of the engine requires many acquisitions in a very short time, so the crank mode is required, while during the rest of the vehicle the acquisition can be slower, setting the IBS to a sleep mode.

All the measurements performed by the IBS are then passed through the LIN network to the Body Computer Module of the vehicle, with also the estimated parameters for the battery diagnosis, which algorithms are shown in the following paragraphs.

2.3.1.2. IBS SOC algorithm

The first parameter estimated by the IBS sensor is the State of Charge that is estimated implementing a coulomb counting algorithm with the addition of different methods for the initialization value of the SOC to improve the reliability of the estimation and to avoid the degradation of the estimated value. According to the following formula, the battery current measured by the IBS is integrated to find how much charge the battery has given or has received.

$$SOC = SOC(t_0) + \int_{t_0}^{t_0+\tau} I_B \, dt$$

In this case I_B is the measured battery current, and considering the position of the battery sensor, that is connected directly to the pole of the battery, it is possible to neglect the current losses (I_{loss}).

The main problems with this approach, as already explained in the introduction, are the precision of the current measurement and the initialization value of the State of Charge. Dealing with the first issue, the precision of the measurements made by the IBS is summarized in the following table, obtained from the technical datasheet provided by the manufacturer of the sensor[15]:

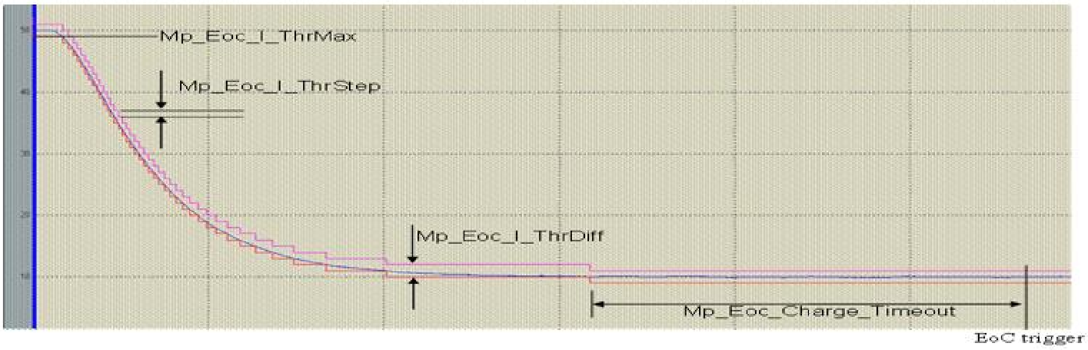
				IBS		
Version	**Value**	**mode**	**Unit**	**Range**		**Accuracy**
				From	**To**	
LIN	Operating voltage		V	16	32	NA
	Over Voltage (1hour, ISO 16750-2)		V		36	
	Quiescent current		µA		≤200	@23°C
	Stand By current		mA		5	MAX
	Operational current		mA		45	MAX
	Load Current Measurement	Max load current	A	-1500 (for 3 sec)	1500 (for 3 sec)	NA
		High Range (Crank)	A	-1200	300	±5% @23°C
		Mid Range	A	-300	300	±1% @23°C
		Low Range	A	-1	1	±10% @23°C
	Voltage Measurement	U1 – 12V Channel	V	6	18	±30mV
		U2 – 24 V Channel	V	14	32	±70mV
	Temperature		°C	-40	85	±3°C

TABLE 2: IBS PRECISION AND TOLERANCE

According to the specifications into the table, the current measurement is quite precise, in this way the error due to the measure of this quantity is small. Nevertheless, the integration process causes a strong decay of the precision of the coulomb counting method and to overcome this issue a frequent initialization of the State of Charge value is required. To face the problem of the initialization, three different ways are used:

- End of Charge (EoC)
- Open Circuit Voltage (OCV)
- End of Discharge (EoD)

The first method consists in updating the value of the SOC when the battery has reached the full charged state; this condition is triggered when the charging current does not decrease for a configured duration of time while generator is active and system voltage exceeds a configured level. The timeout for the current to stay in the range of 0.540 A is 1800 seconds and the voltage must be at least 27.5 V. The trigger of the EoC condition is well explained in Figure18.



Parameter default values

Mp_Eoc_I_FilterGain	0.000085 τ ≈ 570s	gain for input LP (1st order)-filter (voltage + current measurement)
Mp_Eoc_Charge_Timeout	1800 s	timeout for current to stay within range
Mp_Eoc_I_ThrStep	0.270 A	value to decrease I_thres of EoC detection
Mp_Eoc_I_ThrDiff	0.540 A	on exceeding of I_thres + this value reset EoC detection
Mp_Eoc_I_ThrMax	10 A	start value of I_thres for EoC detection
Mp_Eoc_I_ThrMin	0.02 A	lowest level
Mp_Eoc_I_activateMin	0.02 A	minimal charge current to activate EoC detection
Mp_Eoc_V_activateMin	27.5 V	minimal voltage to activate EoC detection

FIGURE 18: EOC CONDITION TRIGGER

Furthermore, the SOC initialization that is the result of the End of Charge method, is not always 100%, but depends on the temperature of the battery and on the charging voltage. In particular, the SOC is initialized with a value lower then the 100% when the recharge is done with a voltage lower than 14V or with a temperature lower than 20°C, as visible in the Figure19.

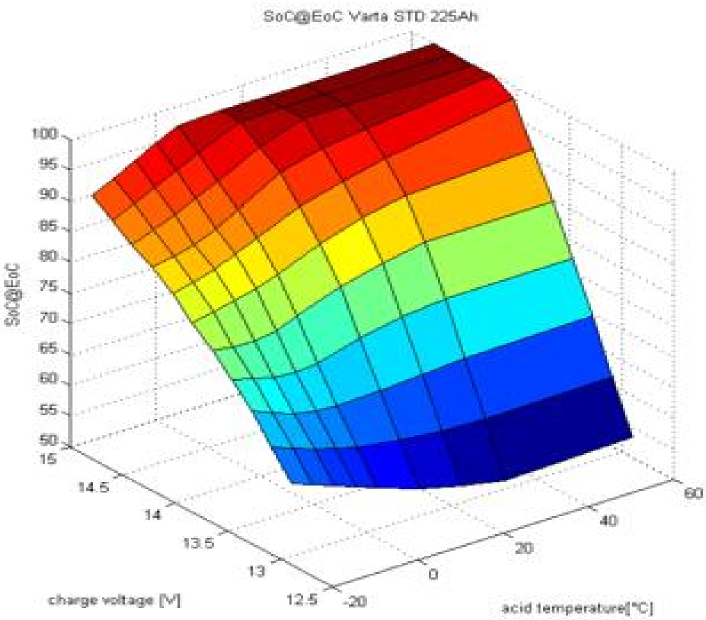


FIGURE 19: SOC AT EOC VS. CHARGE VOLTAGE VS. TEMPERATURE

However, considering the strong deterioration related to the coulomb counting method, this way to initialize the State of Charge is not enough because the condition of EoC does not happen when the vehicle is parked and the driver uses his own electronic devices.

Another way to initialize the SOC is done exploiting the relationship between the State of Charge and the open circuit voltage (OCV) provided into Look Up Tables. To trigger the open circuit voltage condition, it is necessary that the current coming from the battery remains below the threshold of 0.2 A for at least 44 hours. Being this condition very difficult to reach, a different way to provide the SOC initialization with the open circuit voltage, called Quick OCV SOC estimation, is implemented. The condition required by this method is triggered when, after reset, the sensor waits the inrush current to decay and the voltage to stabilize; after approximately 8 seconds the SOC is calculated on the base of the open circuit voltage measured when the battery current stays between -15 A and 0.05 A.

The last method used to initialize the SOC is called End of Discharge condition, in which the State of Charge is set when the battery reaches the full discharged state.

To consider the decay of the precision and to discriminate between these algorithms, three different "quality values" are assigned to the three different detection methods. These quality values are handled by means of SOC trust level signal called Q_SOC_TL (Quality SOC Trust Level), and they are set when the condition for a new initialization of the SOC is triggered. The decay of the quality values for the State of Charge can be summarized as:

- MpSOC_Grad_operational=0.25% per day for the operational mode;
- MpSOC_Grad_sleep=1.0% per day for the sleep mode, because of the lower sampling rate.

When a new condition suitable for the initialization occurs, a new value for the Q_SOC_TL is calculated and is compared to the currently valid Q_SOC_TL; then, the higher value is set as valid with its relative State Of Charge.

The starting quality values, i.e. the ones set when the specific condition occurs and a new value of SOC is calculated, for each initialization method are:

- Initial Q_SOC_TL for OCV = 95%;
- Initial Q_SOC_TL for EoD = 90%;

- Initial Q_SOC_TL for EoC is not constant but varies with the temperature and the battery voltage as shown in Figure20.

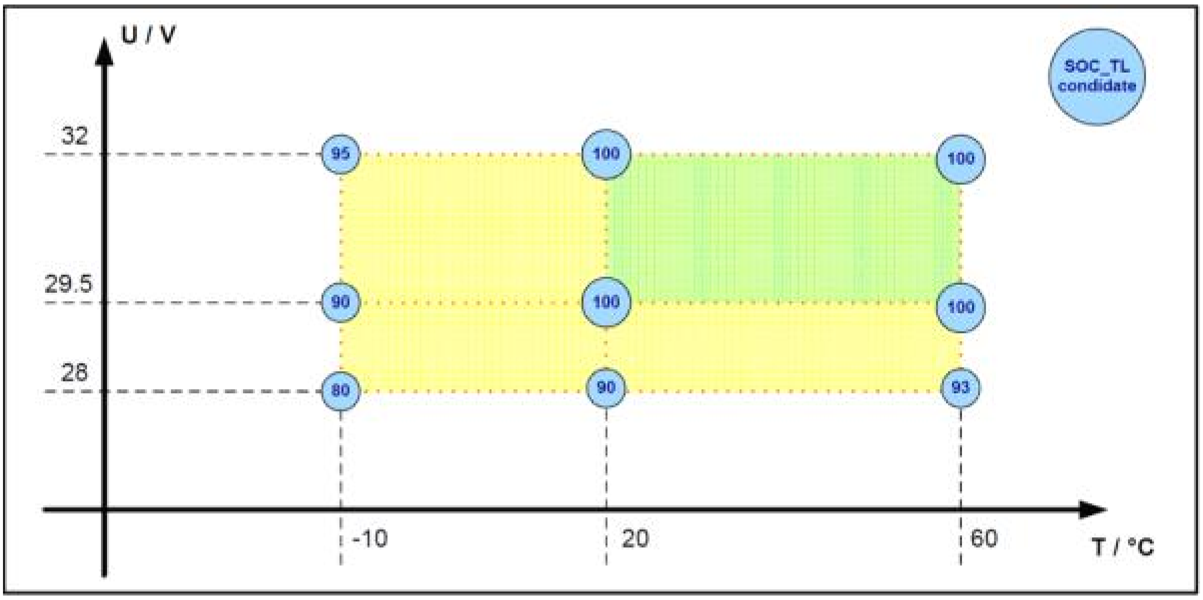


FIGURE 20: SOC QUALITY THRESHOLD VS. CHARGE VOLTAGE VS. TEMPERATURE

As visible, according with the SOC value estimation, also the quality threshold becomes lower for temperatures under 20°C and for voltages under 19.5V.

2.3.1.3. IBS SOH algorithm

The estimation of the State of Health inside the Intelligent Battery Sensor is done according to two different methods:

- The coulomb counting until the end of discharge;
- The progression of battery voltage during 60 Ah discharges, also called Window 3;

The first method is based on the measurement of the capacity of the battery until the end of discharge, condition that is triggered when the battery voltage reaches 10.5 V, and fully respect the formal definition of State of Health:

$$SOH\_C = \frac{C_m}{C_N}$$

Where the capacity C_m is the one measured, while the capacity C_N is the nominal capacity of the battery given by the factory. This method is the most accurate between the two, in fact the thrust value associated to is 99%.

The second method is based on the relationship between the voltage value during the discharging of the battery and the SOH value. Indeed, the curve of the voltage values during the discharge swipes down with the decreasing of the state of health[6]; monitoring the sequence of voltages for a 60 Ah discharge, it is possible to identify a curve of voltages and then to find the SOH related to that curve. However, this method is less accurate with respect to the previous one and for this reason the thrust value associated is 94%.

The thrust value related to the SOH is subject also to a decay that makes it lose 5% every 365 days, this is why every time a new value of SOH is estimated, it enters in a competition with the currently valid value, then the value with the highest thrust level win the competition and is set valid with its own thrust level.

2.3.2. UDT algorithms

The Universal Diagnosis Tool algorithm is based on the acquisition from the IBS of the SOC, SOH estimated from the sensor (SOH_C) and the value of the internal resistances; then, exploiting the acquired values, UDT estimates another State of Health called SOH_I, based on the relationship between the value of the internal resistance of a battery and the state of health of the battery itself and, according to thresholds, the UDT makes a diagnosis and delivers the result.

2.3.2.1. UDT: SOH_I estimation

The estimation of the SOH_I is done using Look Up Tables that connect the values of the temperature, the SOC of the battery and its internal resistance. This estimation is done with the batteries used on board of the vehicle, so that the UDT performs the estimation for each battery, obtaining from the BCM, through the OBD port, the required values:

- BATT_Type: battery identifier (the two batteries are identical): that is the identifier of the batteries mounted on the vehicle and monitored by the IBS;
- TB: battery temperature [°C]: that is the temperature measured on the negative pole of the low battery, the temperature of the two batteries is assumed to be the same;
- SOC maximum value between SOC_B1 and SOC_B2;
- SOC minimum value between SOC_B1 and SOC_B2;
- SOC_batt: a flag that if 0 states that the maximum SOC belongs to BL, if 1 otherwise;
- SOC_TL: thrust level of the State of Charge estimation on each battery;
- SOH_C maximum value between SOH_C_B1 and SOH_C_B2;
- SOH_C minimum value between SOH_C_B1 and SOH_C_B2;
- SOH_batt: a flag that if 0 states that the maximum SOH belongs to battery 1, if 1 otherwise;
- SOH_C_TL: thrust level of the State of Health estimated by the IBS on each battery;
- Ri_B1: internal resistance of the battery 1 estimated by the IBS at the last valid cranking;
- Ri_B2: internal resistance of the battery 2 estimated by the IBS at the last valid cranking;
- LOG_SCN: defines the contest of the diagnosis (plant, service, …), it is given from the user interface;

Once acquired these values the UDT performs the estimation of the SOH_I, doing the following steps:

1. For each of the z matrices Ri, in which there are values of the resistance in function of SOC and TB, is calculated the value of Ri correspondent to the

measured SOC and TB. This is done according to an interpolation method. The z matrices are related to z different values of SOH_I.

2. From the z different values of Ri, related to z different SOH_I, coming from the previous step, another interpolation is done to exactly find the measured value for the Ri and by consequence the SOH_I value.

A simple representation of this algorithm is shown in Figure21.

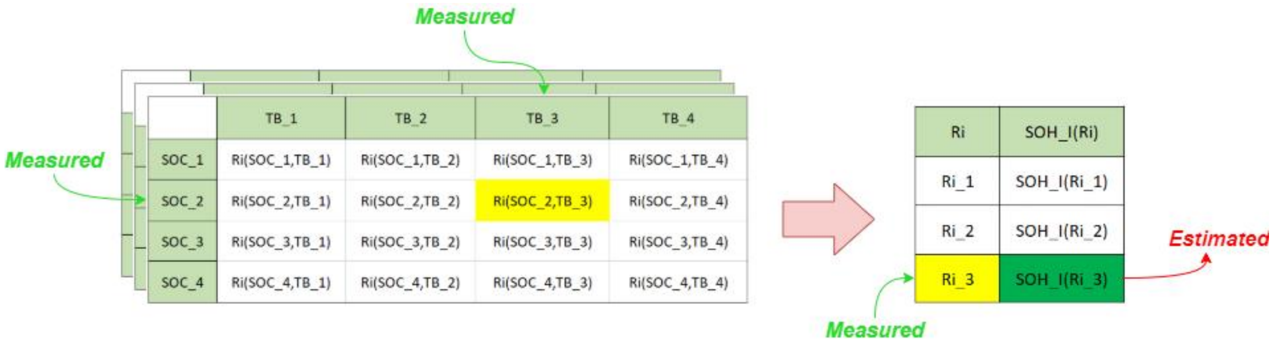


FIGURE 21: LUT BASED ALGORITHM FOR SOH_I ESTIMATION

Being this algorithm based on look up tables, it is very likely that the measured values of SOC, TB and Ri have not the right value into the tables, so an interpolation between the values present in the LUT is necessary. Also in this case a “quality value” called SOH_I_TL is associated to the SOH_I estimated, and this value is set equal to the SOH_C_TL given by the IBS.

Obviously, the estimation procedure is done for each battery.

2.3.2.2. UDT: SOH_C estimation

The UDT tool can also estimate the SOH_C value in the case of a lack of that value coming from the IBS sensor or in the case of a too low thrust level coming from the IBS. The algorithm used to find the SOH_C is very similar to the one used to estimate the SOH_I and it is based on a Look Up Table provided by the manufacturer of the battery sensor. In the same way of the algorithm used for the estimation of the SOH_I, the UDT estimates the SOH_C starting from the measured quantities of temperature, SOC and internal resistance, interpolating, if necessary, the values inside the Look Up Table shown in Table3.

		R					
Temp	SOC	0,00000	0,00200	0,00450	0,00600	0,00800	0,01500
-30	20	100,00000	89,33300	76,00000	68,00000	57,33300	20,00000
-30	40	100,00000	100,00000	82,57400	71,77300	63,75400	55,52000
-30	60	100,00000	100,00000	97,55200	86,75100	72,34900	27,44000
-30	80	100,00000	100,00000	100,00000	28,63500	10,00000	13,65200
-30	100	100,00000	100,00000	100,00000	10,00000	10,00000	10,00000
0	20	100,00000	83,84930	67,92950	57,43900	42,56100	15,71430
0	40	100,00000	99,93620	99,89750	46,41500	14,75470	17,65620
0	60	100,00000	99,96250	41,66670	14,72730	13,76670	16,85860
0	80	100,00000	99,96480	25,14630	11,73200	11,74960	12,86270
0	100	100,00000	100,00000	12,10530	9,42310	8,59890	5,71430
30	20	100,00000	82,72060	50,36360	17,62320	13,44970	11,42860
30	40	100,00000	99,70910	83,26790	17,72140	13,75590	11,05250
30	60	100,00000	99,82370	24,70780	12,01990	10,70180	8,71340
30	80	100,00000	99,89840	19,81410	10,81650	8,69030	6,07230
30	100	100,00000	100,00000	9,90620	8,50000	6,62500	1,42860
40	20	100,00000	88,00000	73,00000	64,00000	52,00000	10,00000
40	40	100,00000	88,00000	73,00000	64,00000	52,00000	7,50000
40	60	100,00000	88,00000	73,00000	64,00000	51,66667	5,00000
40	80	100,00000	88,00000	72,50000	62,50000	49,16667	2,50000
40	100	100,00000	86,66667	70,00000	60,00000	46,66667	0,00000

TABLE 3: SOH_C LOOK UP TABLE

2.3.2.3. UDT: diagnosis and thresholds

In the algorithm inside the UDT different thresholds are defined to give a diagnosis; firstly, the consistence of the acquired values is checked, monitoring the quality values, then the diagnosis is done comparing the estimated values and thresholds to decide if a battery must be replaced or not. The complete sequence of operations is the following:

1. Check the correspondence between the battery and the IBS sensor mounted on the vehicle, and check also the correspondence between the IBS and UDT;

2. Check the validity of the SOC value, i.e. SOC thrust level must be greater or equal to 4. If the value is not valid it is possible to:
    a. Wait until OCV method for SOC estimation produces a valid value;
    b. Recharge to produce a valid SOC through the coulomb counting method (EoC);
3. Acquired the SOC value, check if this value is sufficient to start the estimation of the SOH_C and SOH_I, the minimum threshold is called SOC_MIN_FOR_SOH and is set to 60%;
4. At the cranking performed by the operator, the tool estimates the internal resistance of the two batteries;
5. Check the quality level of the SOH_C, if this is lower than 4 the SOH_C is estimated;
6. SOH_I is estimated;
7. Check the SOH_C value for each battery, according to Table5 for the new batteries, the value must be higher than SOH_C_OK_TH, this threshold is function of the ambient conditions (LOG_SCN) and the battery type (BATT_TECH); for used batteries instead SOH_C_OK_TH is set to 63%;
8. Check the SOH_I value for each battery, according to Table6 for the new batteries, the value must be higher than SOH_I_OK_TH, this threshold is function of the ambient conditions (LOG_SCN) and the battery type (BATT_TECH); for used batteries instead SOH_I_OK_TH is set to 63%;
9. Set the SOH value as the minimum between SOH_C and SOH_I for each battery;
10. If one SOH value is under the threshold of 63% the battery must be replaced, and the SOH value for the new battery is set to 98%;
11. Check the difference between the SOH of the two batteries, this difference must be lower than 10%;

The algorithm explained is better shown in the flowchart in Figure22 that resumes the logic of the UDT tool.

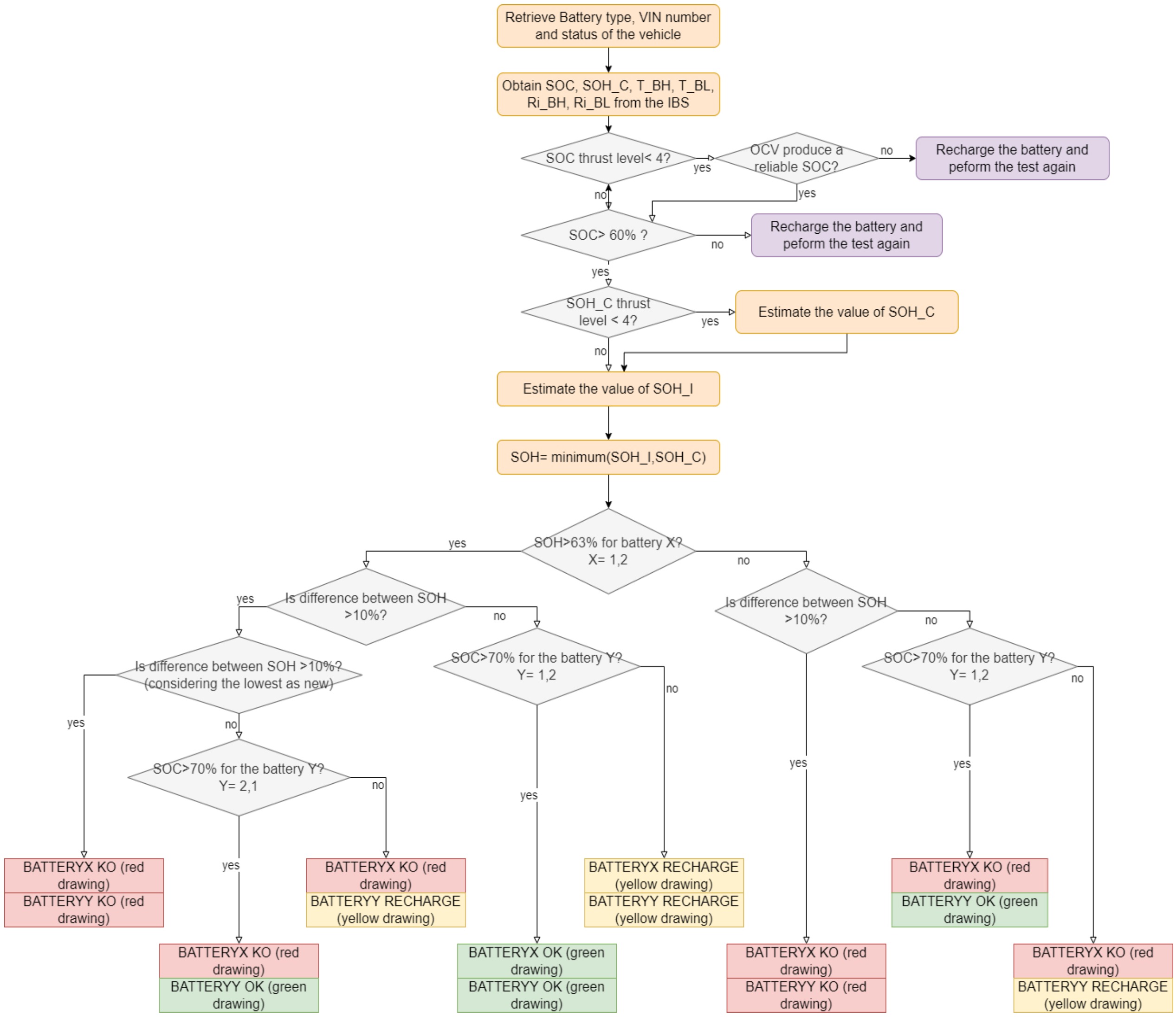


FIGURE 22: UDT ALGORITHM FLOWCHART

The following tables resume the values for three thresholds: SOC_OK_TH is the threshold for the SOC of the battery to be considered charged; SOH_C_OK_TH and SOH_I_OK_TL are the thresholds for a new battery to be considered ok. These thresholds are function of BATT_TECH, which is the type of battery and LOG_SCN, that is the place in which the battery is tested; in particular the different entries mean:

- Plant: the factory that produces the vehicle;
- Plant Yard: the place in which the vehicles are stocked before they are delivered;
- Body Builder: the place where the vehicles are modified to solve specific purposes, i.e. concrete mixer or garbage truck;
- Dealer- Pre PDI (Pre Delivery Inspection): at the dealer when the vehicle arrives;

- Dealer PDI (Pre Delivery Inspection): at the dealer when the vehicle is delivered to the costumer;
- Dealer- Post PDI (Pre Delivery Inspection): at the dealer after the vehicle is delivered to the costumer.

	Plant	Plant Yard	Body Builder	Dealer-Pre PDI	Dealer PDI	Dealer-Post PDI
SOC_OK_TH	LOG_SCN1	LOG_SCN2	LOG_SCN3	LOG_SCN4	LOG_SCN5	LOG_SCN6
BATT_TECH1	80%	75%	70%	70%	70%	70%
BATT_TECH2	85%	80%	75%	75%	75%	75%
BATT_TECH3	80%	75%	70%	70%	70%	70%

TABLE 4: SOC_OK THRESHOLD FOR NEW BATTERIES

	Plant	Plant Yard	Body Builder	Dealer-Pre PDI	Dealer PDI	Dealer-Post PDI
SOH_C_OK_TH	LOG_SCN1	LOG_SCN2	LOG_SCN3	LOG_SCN4	LOG_SCN5	LOG_SCN6
BATT_TECH1	90%	90%	85%	85%	85%	85%
BATT_TECH2	85%	85%	85%	85%	85%	85%
BATT_TECH3	90%	90%	85%	85%	85%	85%

TABLE 5: SOH_C_OK THRESHOLD FOR NEW BATTERIES

	Plant	Plant Yard	Body Builder	Dealer-Pre PDI	Dealer PDI	Dealer-Post PDI
SOH_I_OK_TH	LOG_SCN1	LOG_SCN2	LOG_SCN3	LOG_SCN4	LOG_SCN5	LOG_SCN6
BATT_TECH1	90%	90%	85%	85%	85%	85%
BATT_TECH2	85%	85%	85%	85%	85%	85%
BATT_TECH3	90%	90%	85%	85%	85%	85%

TABLE 6: SOH_I_OK THRESHOLD FOR NEW BATTERIES

For the purpose of this work, the values of interest are the ones related to the battery with BATT_TECH1 which means a flooded acid battery with 225 Ah capacity and 1100 CCA.

The tables show the importance of the differentiation between the different places where the battery diagnosis can be performed; in fact, it is reasonable that the batteries at the plant or the plant yard, when the vehicle as been just produced, must be very healthy, while they can have an SOH a little decreased at the Body Builder or in PDI phase.

3. Test Performed

The validation of the tool under analysis is necessarily subordinated to the execution of many tests with the aim of defining the behaviour of the batteries under test and of building the Look Up Table required by the algorithm explained in the paragraph 2.3.2.1 for the computation of the SOH_I value. Firstly, the battery must be characterized, then a current profile to simulate the cranking current is retrieved from real current profiles from vehicle crankings. In the end a test is performed using the simulated cranking current profile to build the Look Up Table required for the SOH_I estimation.

The tests performed typically require a lot of time to come to the end, so it is important to define the specifications and all the requirements in the proper way, to avoid a significant loss of time and money for both the companies that are interested in the test results.

3.1. Battery characterization test

The first test done is the characterization test on two new flooded acid batteries with 225 Ah of nominal capacity and 1100 CCA, which is an important task in order to know how a battery can behave and what to expect as the battery ages. This is done with the collaboration of the manufacturer, inside the laboratories inside the battery factory.

3.1.1. Battery characterization test: purpose

The objective of the first test conducted is to characterize the behaviour of the batteries and the trend of the SOH_C and the internal resistance value, in order to find the relationship between the cold cranking current and the internal resistance and by consequence the performance deterioration with the aging. In particular from the cold cranking current it is possible to retrieve the internal resistance value that is the wear indicator of the battery.

3.1.2. Battery characterization test: instrumentation

The battery characterization test is performed inside the laboratories of the battery manufacturer using the testbench visible at the left in Figure23. It is able to measure the instantaneous current up to 1500 A, the instantaneous voltage up to 18 V and, by means of a continuous integration of the current and voltage, the capacity loss.

FIGURE 23: TESTBENCH AND CLIMATIC CHAMBER FOR BATTERY CHARACTERIZATION TEST

The testbench is programmable, by means of a computer, to perform every kind of charge and discharge operation. For the conditioning of the battery at low temperature in this test is used the climatic chamber visible at the right in Figure23.

The object under test is one flooded acid battery with 225 Ah capacity and 1100 CCA and the test is repeated twice, in order to have a comparison.

3.1.3. Battery characterization test: configuration

The configuration consists in the connection of the battery under test to the testbench. The testbench can perform in an autonomous way all the phases of charge and discharge previously configurated on the workstation connected to the testbench itself, so no other configurations are required. The only exception is when a conditioning of the battery at a specific temperature is needed, so the battery connected must be placed inside the climatic chamber; as an example, during this test, after the control discharge a cold cranking current must be performed, so the battery must be conditioned at -18°C as defined by the normative, therefore the battery, which is already connected to the testbench, is placed inside the climatic chamber set at -18°C and the proper profile of discharge is performed.

3.1.4. Battery characterization test: procedure

The battery used for the characterization are two new batteries based on flooded acid technology, with 225 Ah of nominal capacity and 1100 CCA. To characterize the battery accurately, some aging cycles are performed according to the automotive normative for the batteries EN50342-1[17]. The aging cycles defined in this normative are structured as follows:

1. A two hours long discharging phase at 25°C at five times the current used to verify the nominal capacity of the battery; in this case the nominal current for the verification of the capacity is 11.25 A, so the current used for this phase of discharge is 56.25 A;
2. A five hours long charging phase at 25°C with a voltage of 15.6 V applied to the battery terminals and with a charging current limited to 56.25 A.

The aging cycle descripted above, is used to structure a test with the aim of checking the battery behaviour and verifying when the battery performances sharply decrease.

The first step is to verify that the battery is compliant with the specifications, so a full discharge and full recharge cycle at the temperature of 25°C at 56.25 A is performed to measure the capacity and, after another conditioning of the battery at -18 °C, a fast discharge test is performed to verify the cold cranking current and to simulate the vehicle cranking.

After the first characterization, the test continues by performing aging cycles in a variable number that can be three or six, depending on the deterioration of the performances of the battery; if the battery seems to wear then the aging cycles will be three, if the battery seems to be healthy they will be six.

To check the battery properties after the cycles, a control discharge is needed; it consists in a discharge at 56.25 A that lasts until the voltage at the terminal is 10.5 V, without any time limit. After this check the battery is recharged for 24 hours, left for other 24 hours to rest and then conditioned for other 24 hours at -18 °C to perform a cold cranking current test, that consists in a fast discharge at 1100 A for 10 seconds, a pause of 10 seconds and a discharge at 660A until the voltage is 6 V, always according to the normative EN50342-1[17].

After the fast discharge the battery is left 12 hours to rest at an ambient temperature, then recharged for 24 hours. The whole test is repeated until the control discharge lasts less than two hours.

The test procedure described must be followed very carefully because of the care required by the electrolytic substance which is the carrier of most of the chemical energy. Specifically, the rest time between the different phases must be respected to let the substance to stabilize and avoid unwanted comportments that can cause unpredictable behaviours and the retrieving of wrong results.

The complete test can be summed up as follows:

1. Discharge at 56.25 A at 25°C until there are 10.5 V at the terminals with no time limits;
2. Full recharge the battery for 24 hours at 25°C;
3. Conditioning of the battery at -18°C;
4. Fast discharge of the battery to verify the cold cranking current:
    a. Discharge at 1100 A for 10 seconds;
    b. Pause of 10 seconds;
    c. Discharge at 660 A (60% of 1100 A) until the voltage is 6 V;
5. Rest of the battery at 25°C for 12 hours for the electrolyte;
6. Recharge of the battery for 24 hours at 25°C;

7. Discharge at 56.25 A for 2 hours at 25°C;
8. Recharge with 15.6 V at the terminals and with the current limited to 56.25 A for 5 hours at 25°C;
9. Repeat steps 7 and 8 three or six times depending on the evolution of the battery performances;
10. Discharge at 56.25 A at 25°C until there are 10.5 V at the terminals with no time limits;
11. Full recharge for 24 hours at 25°C;
12. Rest of 24 hours at 25°C;
13. Thermal conditioning at -18°C for 24 hours;
14. Fast discharge of the battery to verify the cold cranking current:
    a. Discharge at 1100 A for 10 seconds;
    b. Pause of 10 seconds;
    c. Discharge at 660 A (60% of 1100 A) until the voltage is 6 V;
15. Rest of the battery at 25°C for 12 hours for the electrolyte;
16. Repeat steps from 6 to 15 until the step 10 requires less than 2 hours to complete. The test is resumed in the flowchart of Figure24.

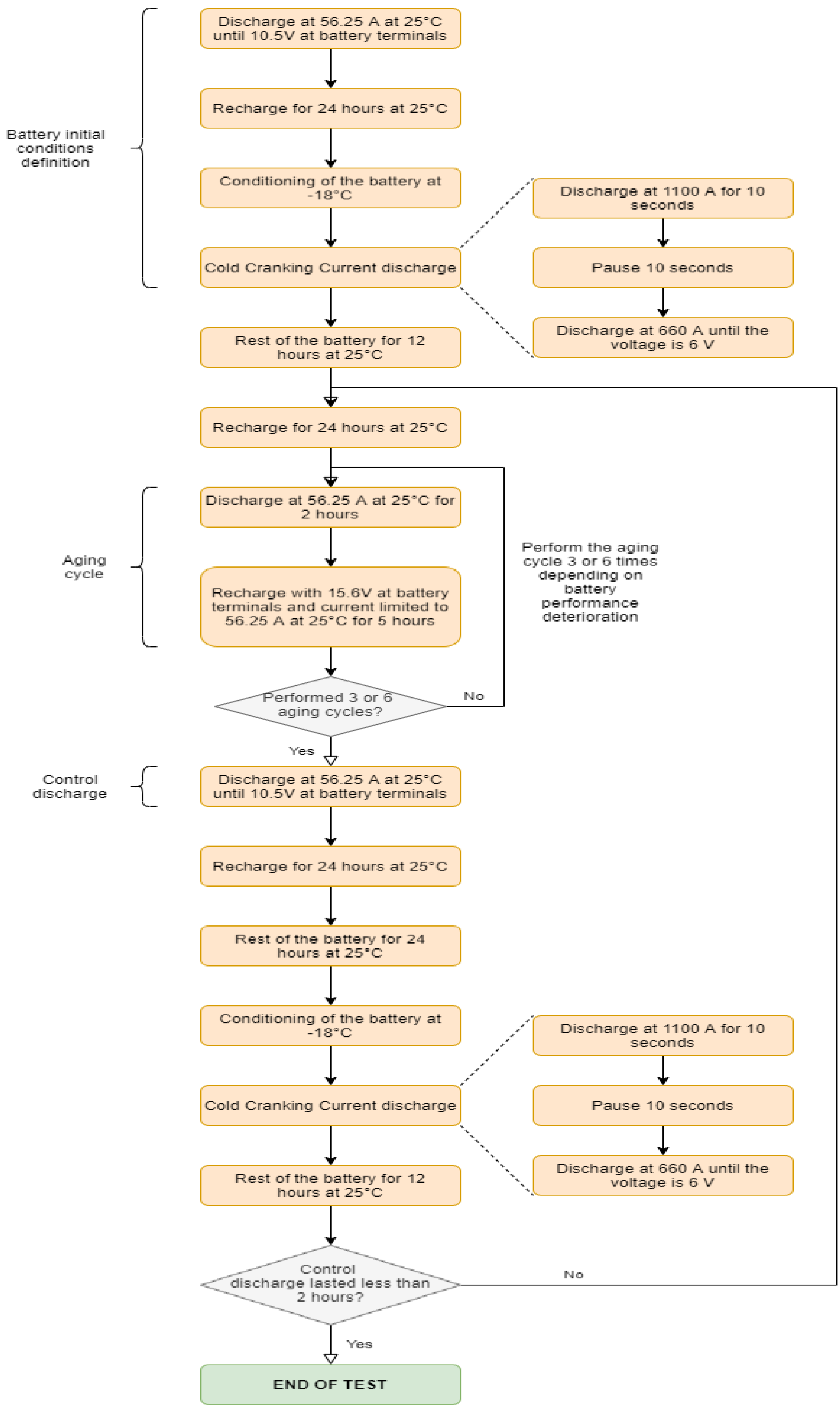


FIGURE 24: BATTERY CHARACTERIZATION TEST FLOWCHART

3.1.5. Battery characterization test: results

The results coming from the test procedure previously explained are very meaningful because can represent in exhaustive manner the battery behaviour as expected; the data are obtained directly from the testbench and show the trend of the voltages and the currents after the different phases of the test. Reaching the end of the test, the battery quantities sharply decrease, so the battery cannot provide the same performances and, in this conditions, cannot guarantee the cranking of the vehicle because of the too low providable cold cranking current.

The test is performed twice on two different new flooded acid batteries with 225 Ah capacity and 1100 CCA. The results of the cycling on the two batteries are shown in the following graphs.

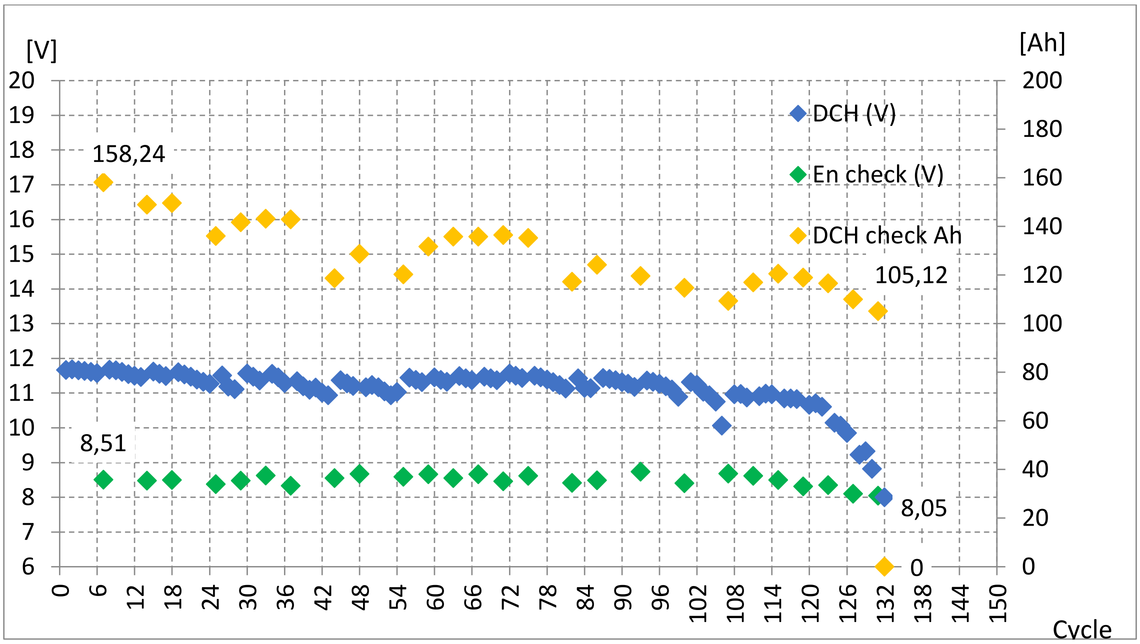


FIGURE 25: TEST RESULT ON BATTERY 1

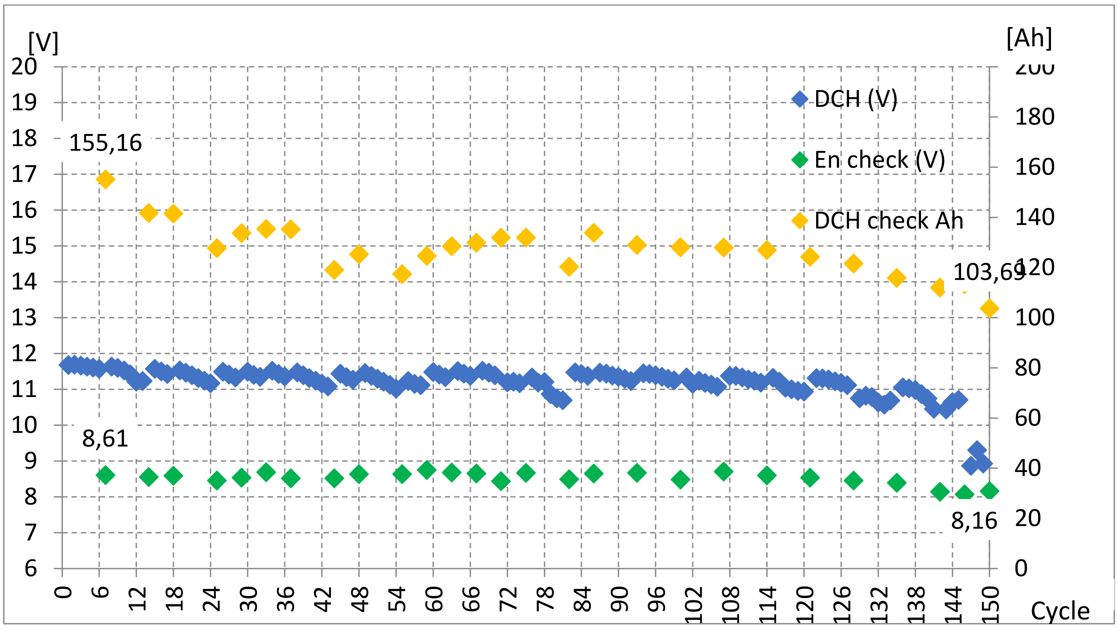


FIGURE 26: TEST RESULT ON BATTERY 2

The behaviour of the batteries under test is represented in the two graphs, and the three quantities shown are:

- The voltage drop at the end of the two hours discharge at 56.25 A after each aging cycle, that is the discharge at step 7 of the list above; this quantity, called DCH (V) into the graphs, is plotted in blue and it is one of the parameters that can resume the status of the performance of the battery;
- The battery capacity after three or six aging cycle depending on the battery performances. This capacity, called DCH Check Ah and plotted in yellow into the graphs, is measured during the step 10 using a control discharge as explained in the previous paragraph;
- The voltage drop after the cranking current, that is the discharge at the step 14.a, called En check (V) and plotted in green into the graphs;

These three parameters can resume properly the evolution of the battery performances.

The first battery, which is shown in Figure25, is called battery 1 and is measured at the beginning of the test to define the starting condition following the steps from 1 to 6 of the procedure. The initial values of the parameters are 11.67 V for the discharging voltage, 175.7 Ah for the capacity and 8.23V for the cranking discharging voltage. Comparing the starting values to the values of the graph, it is evident that the capacity drops immediately with the start of the aging cycles; this behaviour is peculiar of the flooded acid batteries that at the beginning of their life have a sort of adaptation on the working condition, losing a lot of maximum capacity at the beginning but maintaining this capacity as constant as possible until the battery is exhaust. This peculiarity is very evident in the graph, where after a first strong step, the capacity of the battery decreases slowly until the end of the test.

At the end of the graph is evident a sharp fall of the discharging voltage and the capacity, this means that the battery has lost its performance and the control discharge takes place in less than two hours. The battery is considered exhausted.

All these considerations can be done also for the battery 2, Figure26; the only difference is in the duration of the characterization that for battery 1 lasted 131 cycles, while for battery 2 lasted 150 cycles.

3.1.6. Battery characterization test: conclusions

Another interesting consideration can be made considering the two States of Health of the batteries that can be retrieved from these tests. The first, called SOH_C, is computed as the ratio between the measured capacity, that is the capacity measured during the control discharge at point 10 of the test, and the maximum capacity, i.e. the capacity at starting condition 175.7 Ah for battery 1 and 173.51 for battery 2, multiplied by 100 and plotting the results as shown in Figure27.

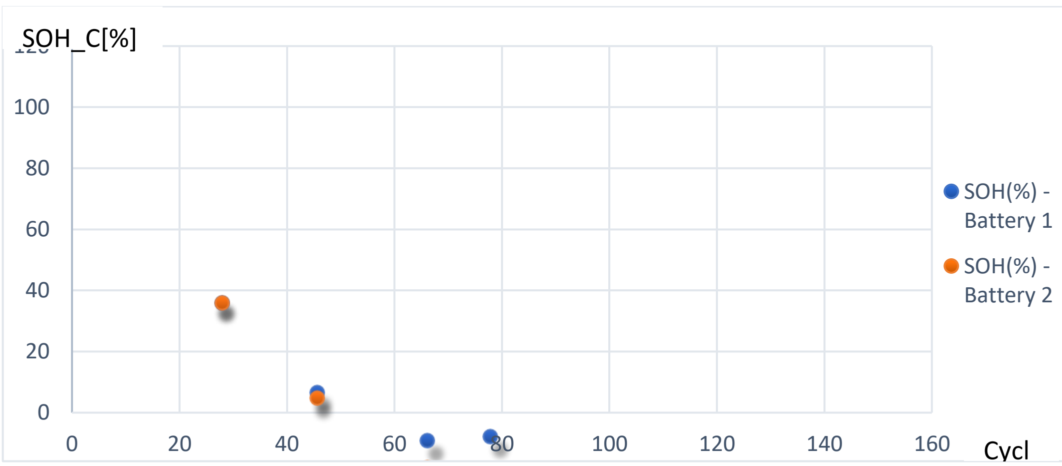


FIGURE 27: SOH_C BATTERY 1 AND SOH_C BATTERY 2 COMPARISON

Looking at the graph it is noticeable that the State of Health is not monotonous because it depends on many factors, for example it is evident that the SOH decreases sharply when six aging cycles are performed before the next measurement, while performing three aging cycles between two measures makes the curve more uniform.

The other important parameter that is considered is the so-called SOH_I, that is the SOH computed from the value of the internal resistance; this value can be retrieved considering the fast discharging phase that simulates the cranking of the vehicle. In particular, the internal resistance value is computed starting from the model of the battery in Figure10. During the fast discharge the value of the voltage drop at the terminals and the current are measured, then according to the model it is possible to retrieve the value of the internal resistance with the following formula:

$$R_i = \frac{(E_0 - E)}{I}$$

As explained in the paragraph 2.1.4, the parameters measured by the battery sensor are the current I and the voltage at the terminals E. The open circuit voltage drop E_0 is considered to be 12.8 V because the fast discharge phase is performed after a full recharge of the battery, so the open circuit voltage drop can be considered the one with SOC equal to 100% and with a temperature of -18°C.

The values of the voltage drop at the terminals and the current is measured with a frequency of 10 Hz during the fast discharge (phase 14.a of the test) this allows to consider many estimations of the internal resistance values at each test. To choose the right value of the resistance only the measurements performed between instants 0.5 s and 1.5 s are considered; the reason is that the temperature of the battery increases during the fast discharge, affecting the real value of the parameter so the values of interest are at the beginning of the discharging phase, while the starting instant at 0,5 s is set to prevent the transient to affect the estimation.

Mathematically, the value of the internal resistance of the battery is computed as the mean value of the ten measurements between 0,5 and 1,5 seconds; the resulting graphs are shown in Figure28 and Figure29.

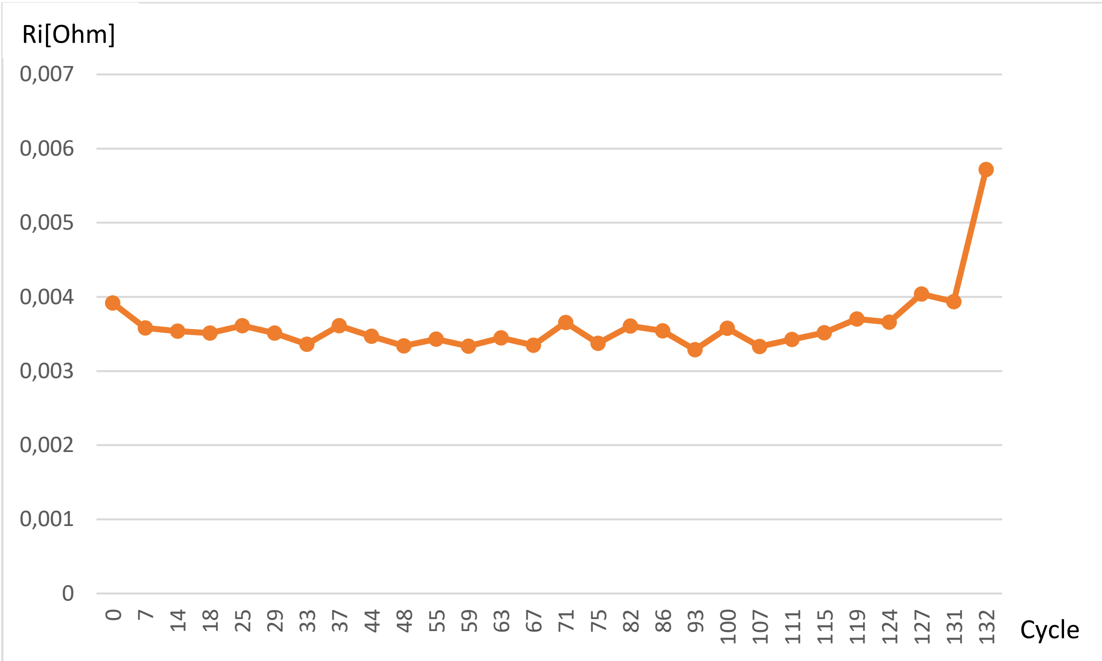


FIGURE 28: BATTERY 1 INTERNAL RESISTANCE

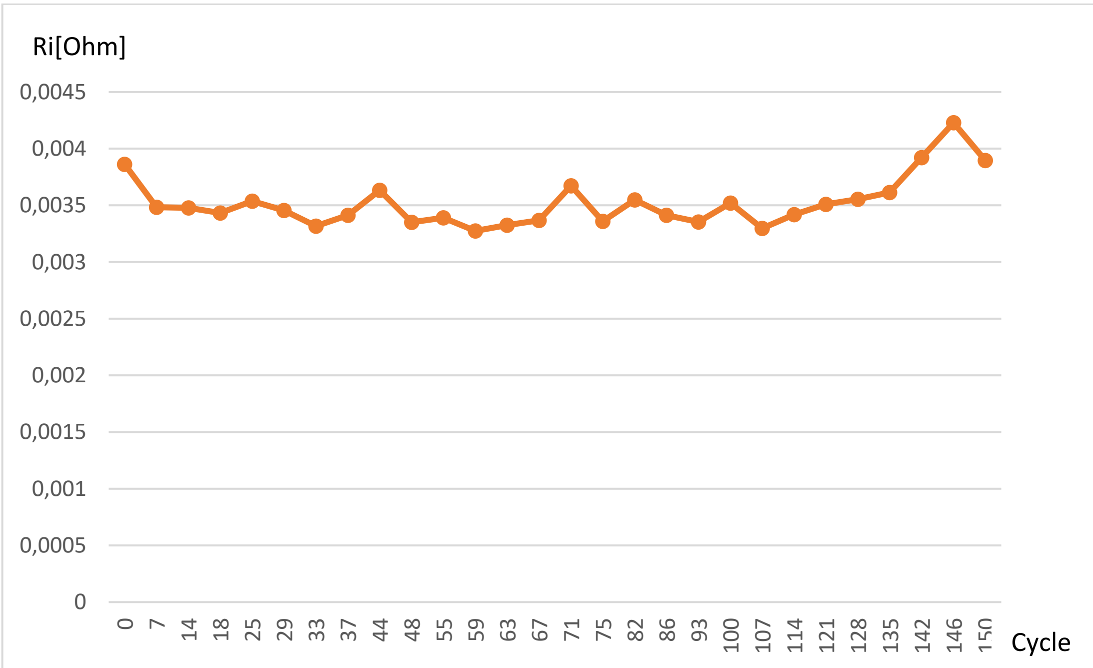


FIGURE 29: BATTERY 2 INTERNAL RESISTANCE

After an initial decrease caused by the battery getting used to the cycling procedure, the value of the resistance remains flat until the battery begins to weak its performances, then it starts to sharply increase as expected from the theory.

The relationship between the trend of SOH_C obtained from the ratio between the capacities and the trend of the internal resistance, and by consequence of the SOH_I deduced from its value, is interesting and it is shown in Figure30 and Figure31.

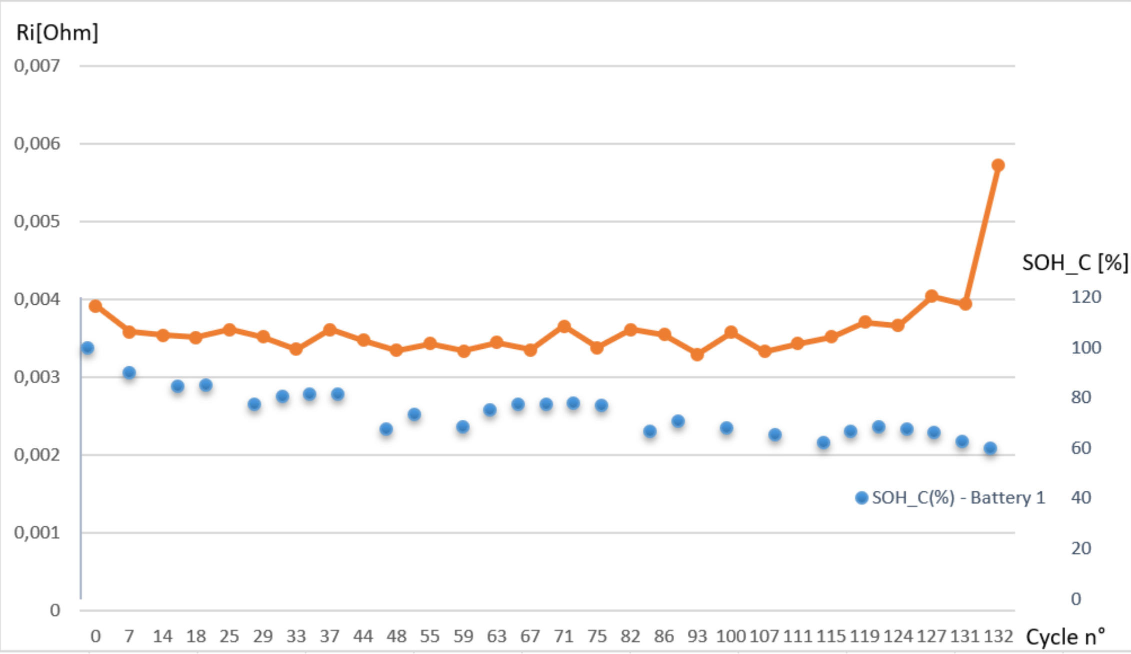


FIGURE 30: BATTERY 1 INTERNAL RESISTANCE AND SOH_C COMPARISON

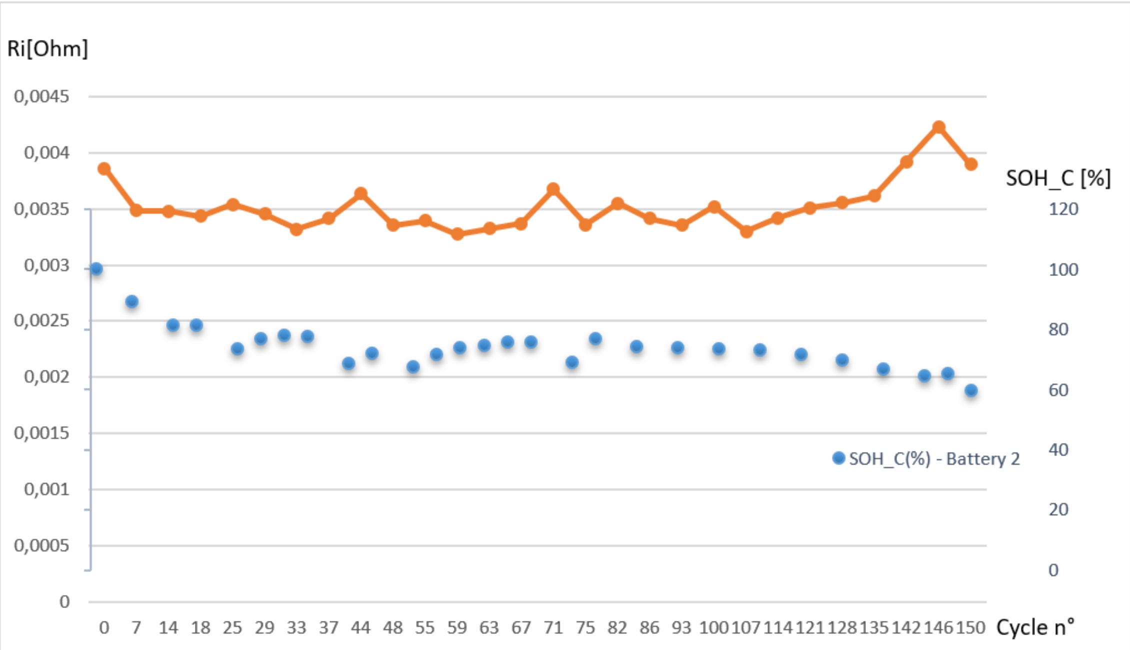


FIGURE 31: BATTERY 2 INTERNAL RESISTANCE AND SOH_C COMPARISON

The two graphs put in evidence that the quantities are very difficult to relate, because the two quantities are retrieved from two different processes; in fact the SOH_C is calculated from the capacity computed during the control discharge, phase 10 of the test, in which the current that causes the discharge is not high, and for this reason the voltage drop that can be reached during this phase is not high; this phase can be considered as the vehicle performing an “hoteling” purpose, that is the vehicle parked with the driver using its own devices. For the estimation of the internal resistance and by consequence the SOH_I, the situation is opposite because the current is very high, looking the phase 14.a, and the cinematic phenomena that happen into the battery cause the SOH_I drop; this is the “cranking” condition.

The result of these considerations is that the two ways to find the SOH value are not always consonant and this could lead to a priority based algorithm that must choose if protect the vehicle cranking or provide the maximum availability of services during the “hoteling” functionality of the vehicle.

Anyhow, this characterization of the two batteries can be used as a starting point to validate the UDT tool and in particular with these tests it is possible to know what to expect as a result from the tool.

3.2. Cranking simulation test

In order to build the Look Up Table for the determination of the SOH_I value with the algorithm explained in paragraph 2.3.2.1, different tests are performed with the collaboration of the battery manufacturer. The cranking simulation test is thought to exploit the period during which the battery has a strong ohmic behaviour and the battery model can be considered a Thevenin equivalent as explained in paragraph 2.1.4. Taking advantage of this battery behaviour, it is possible to retrieve the value of the internal resistance of the battery during the cranking phase.

3.2.1. Cranking current profile analysis

The first preliminary step is to perform an analysis on the cranking profile of the vehicle. To do that, a real cranking is analysed and the quantities of current, voltage and temperature are measured with a frequency of 10 kHz. The cranking of the vehicle is done in three different temperature conditions such as 30°C, 0°C and -30°C to be able to exploit different scenarios of the usage of the vehicle and fill the Look Up Table in different conditions. As an example, in Figure32 it is possible to see the real cranking of the vehicle at 30°C.

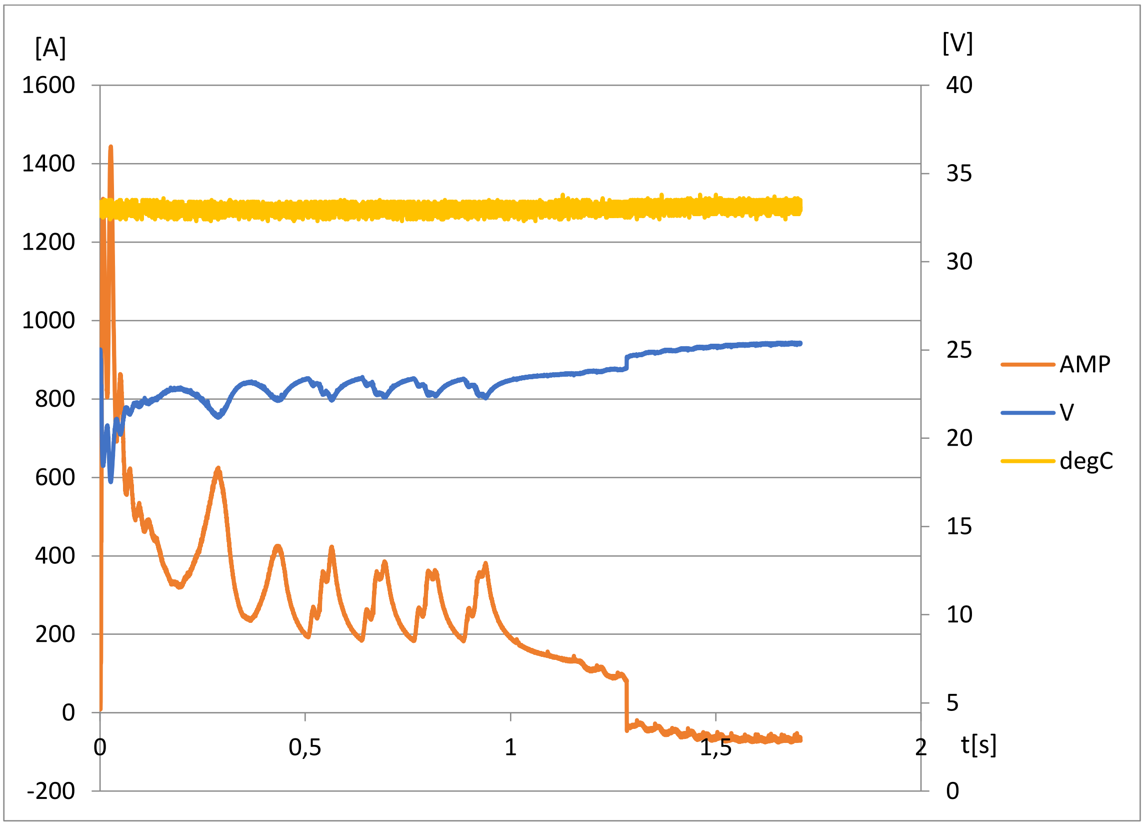


FIGURE 32: CRANKING PHASE AT 30°C

Looking at the graph the three plotted quantities are: the temperature, in yellow, is maintained as constant as possible around 30°C; the voltage, in blue, is the voltage measured as output of the two batteries; the current in orange is the current provided, that is the profile that should be imitated to perform the simulation.

However, the current profile is impossible to replicate exactly the same on testbenches, so as an approximation of this behaviour the current profile is considered to be a sequence of constant current steps as shown by the grey line in the Figure33.

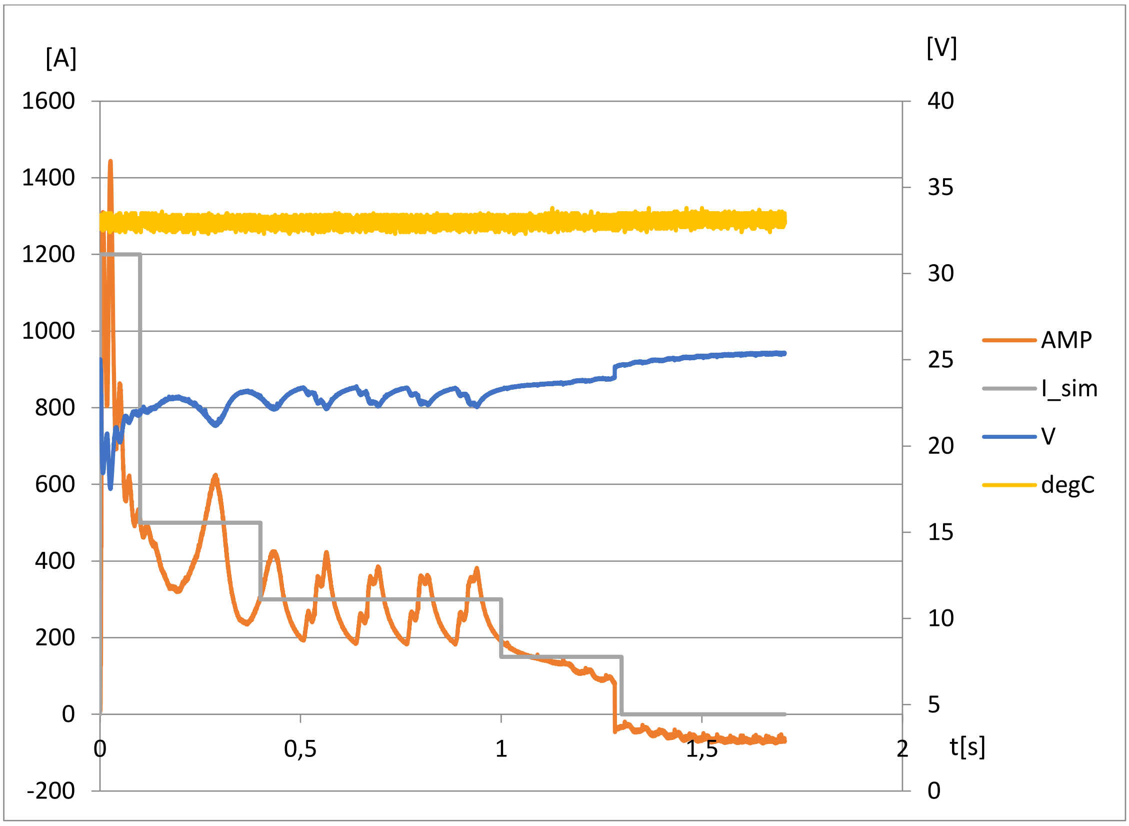


FIGURE 33: CRANKING PHASE AND CURRENT PROFILE SIMULATION AT 30°C

The strength of this approach is the easiness to reproduce constant steps of current on testbenches and the good relationship between the capacity loss of the real cranking and the capacity loss of the simulation, thanks to these two considerations this profile is considered to be a good compromise to test the effective cranking of the vehicle.

The result of this approach is a simulation of the cranking phase based on the following steps:

- Step 1: discharge at 1200 A for 0,1 seconds;
- Step 2: discharge at 500 A for 0,3 seconds;
- Step 3: discharge at 300 A for 0,6 seconds;
- Step 4: discharge at 150 A for 0,3 seconds;
- Step 5: discharge at 25 A for 1 second;

This cause a total capacity loss of 520 As, that is 0,144 Ah and so about the 0,1% of the total capacity of the battery.

The same procedure has been done at 0°C as visible in Figure34, in which the current is in grey, the voltage is in orange and the current profile for the cranking simulation is in yellow.

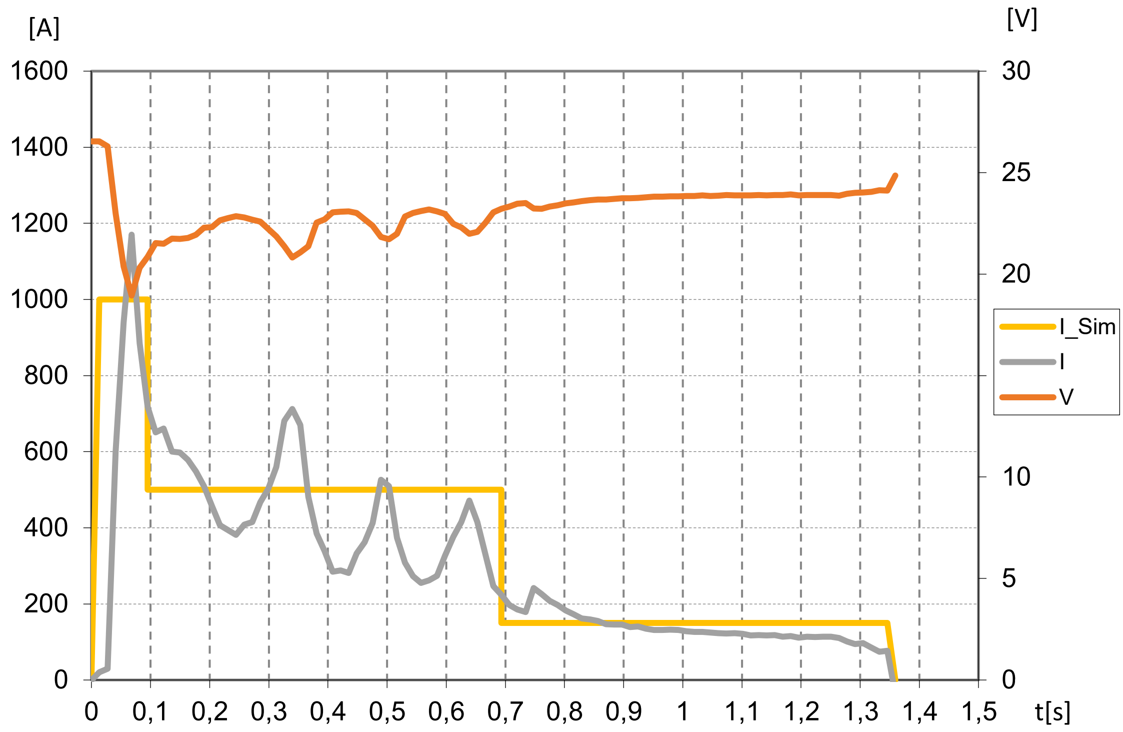


FIGURE 34: CRANKING PHASE AND CURRENT PROFILE SIMULATION AT 0°C

The resulting steps are:

- Step 1: discharge at 1000 A for 0,1 seconds;
- Step 2: discharge at 500 A for 0,6 seconds;
- Step 3: discharge at 150 A for 0,8 seconds;

The total capacity loss is therefore 520 As, i.e. 0,144 Ah as above.

The third time the procedure has been done at -30°C, Figure35.

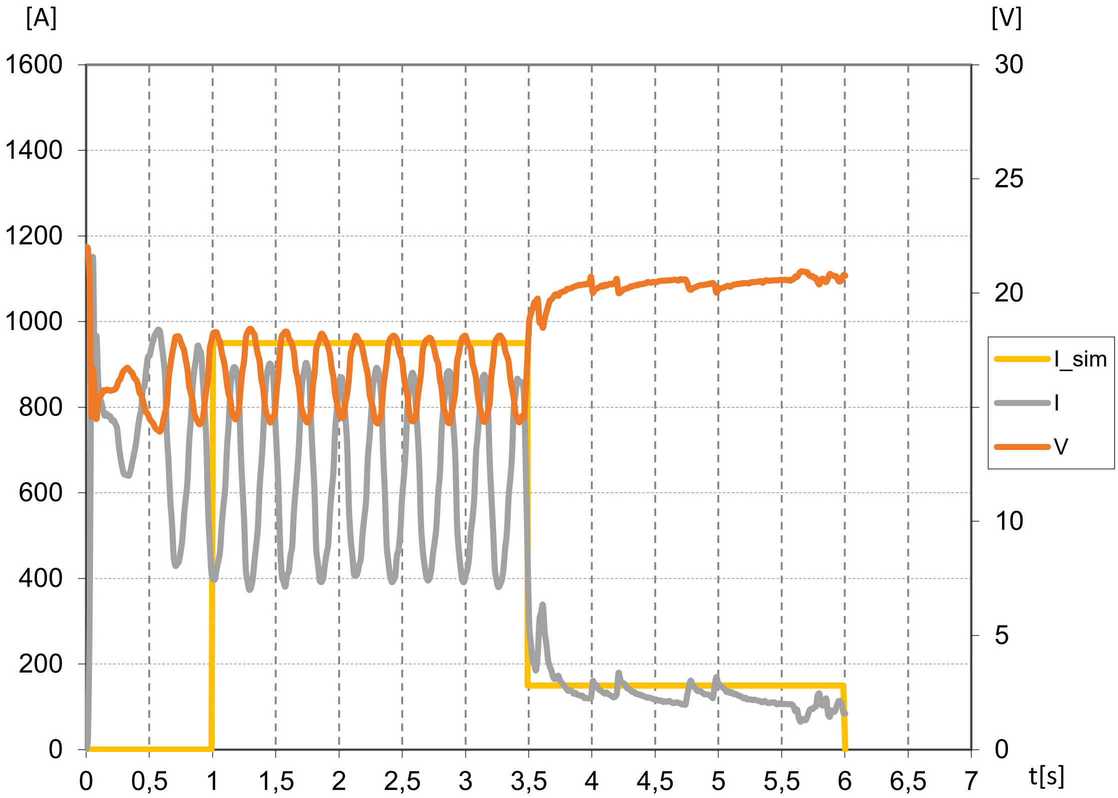


FIGURE 35: CRANKING PHASE AND CURRENT PROFILE SIMULATION AT -30°C

Therefore, the steps for the simulation of the cranking phase at -30°C are:

- Step 1: discharge at 950 A for 2,5 seconds;
- Step 2: discharge at 150 A for 2,5 seconds;

The total capacity loss is 2750 As, i.e. 0,764 Ah and this shows that the cranking requires more energy in cold conditions.

3.2.2. Cranking simulation test: purpose

The objective of the cranking simulation test is to produce a database of internal resistance values at different levels of SOC and different aging, in order to build the Look Up Table required by the algorithm for the computation of the SOH_I, explained in paragraph 2.3.2.1. The test's purpose is also to give the chance to characterize the cranking phase in relation with the aging and the temperature, making easier the considerations on the guaranty that the battery can start the engine, relating the SOH value to the capability to crank the vehicle.

3.2.3. Cranking simulation test: instrumentation

The cranking simulation test is performed into the laboratories of the battery manufacturer and the instrumentation used consists in the parallel of four testbenches; each of them can provide up to 300 A and 12 V, so the parallel of four can provide up to 1200A. For the conditioning of the battery at low temperatures a climatic cell is used. The object under test is a flooded acid battery with 225 Ah capacity and 1100 CCA.

3.2.4. Cranking simulation test: configuration

The configuration for the test consists in the parallel of the four testbenches connected to the battery as shown in Figure36. The conditioning at low temperatures is done inside the climatic chamber while the temperature of 30°C is reached inside a bath filled water at the desired temperature, see Figure37.

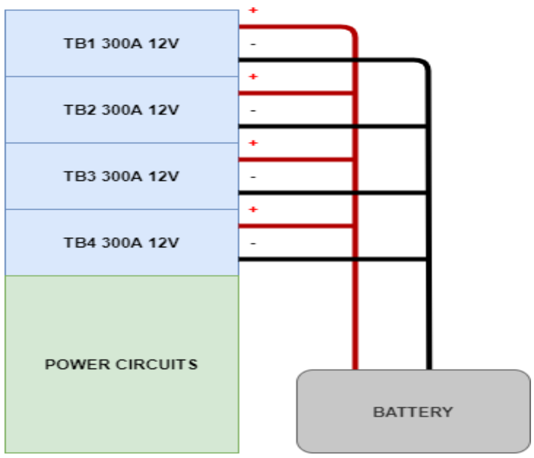


FIGURE 36: TESTBENCHES AND BATTERY CONNECTION

FIGURE 37: CLIMATIC CHAMBER (LEFT) AND BATH FILLED WITH WATER (RIGHT)

3.2.5. Cranking simulation test: procedure

After the realization of the cranking current profile for the different conditions, a new tests sequence is conducted and performed to verify the capability of the battery to crank the vehicle in different conditions and at different aging.

The test procedure, done on a flooded acid battery with 225 Ah and 1100 CCA, after a first characterization of the battery equal to the one done for the test shown in paragraph 3.1, is structured as follows:

1. Full discharge of the battery at 56.25 A until there are 10.5 V at the terminals with no time limits at 25°C, to measure the capacity of the battery;
2. Full recharge the battery for 24 hours at 25°C;
3. Rest of the battery for 12 hours at 25°C;
4. Perform the cranking simulation test at -30°C:
    a. Conditioning of the battery at -30°C;
    b. Perform the -30°C cranking current profile simulation;
    c. Discharge the battery of 10% of the total capacity, i.e. 22,5 Ah, at 25 A which is the typical current requested by the loads on a vehicle;

    d. Perform steps from a to c until the cranking current profile simulation fails;
    e. Rest of the battery for 12 hours at 25°C;
5. Full recharge the battery for 24 hours at 25°C;
6. Rest of the battery for 12 hours at 25°C;
7. Perform the cranking simulation test at 0°C:
    a. Conditioning of the battery at 0°C;
    b. Perform the 0°C cranking current profile simulation;
    c. Discharge the battery of 10% of the total capacity, i.e. 22,5 Ah, at 25 A which is the typical current requested by the loads on a vehicle;
    d. Perform steps from a to c until the cranking current profile simulation fails;
    e. Rest of the battery for 12 hours at 25°C;
8. Full recharge the battery for 24 hours at 25°C;
9. Rest of the battery for 12 hours at 25°C;
10. Perform the cranking simulation test at 30°C:
    a. Conditioning of the battery at 30°C;
    b. Perform the 30°C cranking current profile simulation;
    c. Discharge the battery of 10% of the total capacity, i.e. 22,5 Ah, at 25 A which is the typical current requested by the loads on a vehicle;
    d. Perform steps from a to c until the cranking current profile simulation fails;
    e. Rest of the battery for 12 hours at 25°C;
11. Full recharge the battery for 24 hours at 25°C;
12. Rest of the battery for 12 hours at 25°C;
13. Discharge at 56.25 A without time limit until there are 10.5 V at terminals at 25°C;
14. Full recharge the battery for 24 hours at 25°C;
15. Rest of the battery for 12 hours at 25°C;
16. Discharge at 56.25 A for 2 hours at 25°C;
17. Recharge with 15.6 V at the terminals and with the current limited to 56.25 A for 5 hours at 25°C;
18. Perform steps 13 and 14, i.e. the aging cycle, six times;
19. Perform steps from 2 to 18 until the step 13 requires less than 2 hours to complete.

The flowchart of the test is shown into the Figure38.

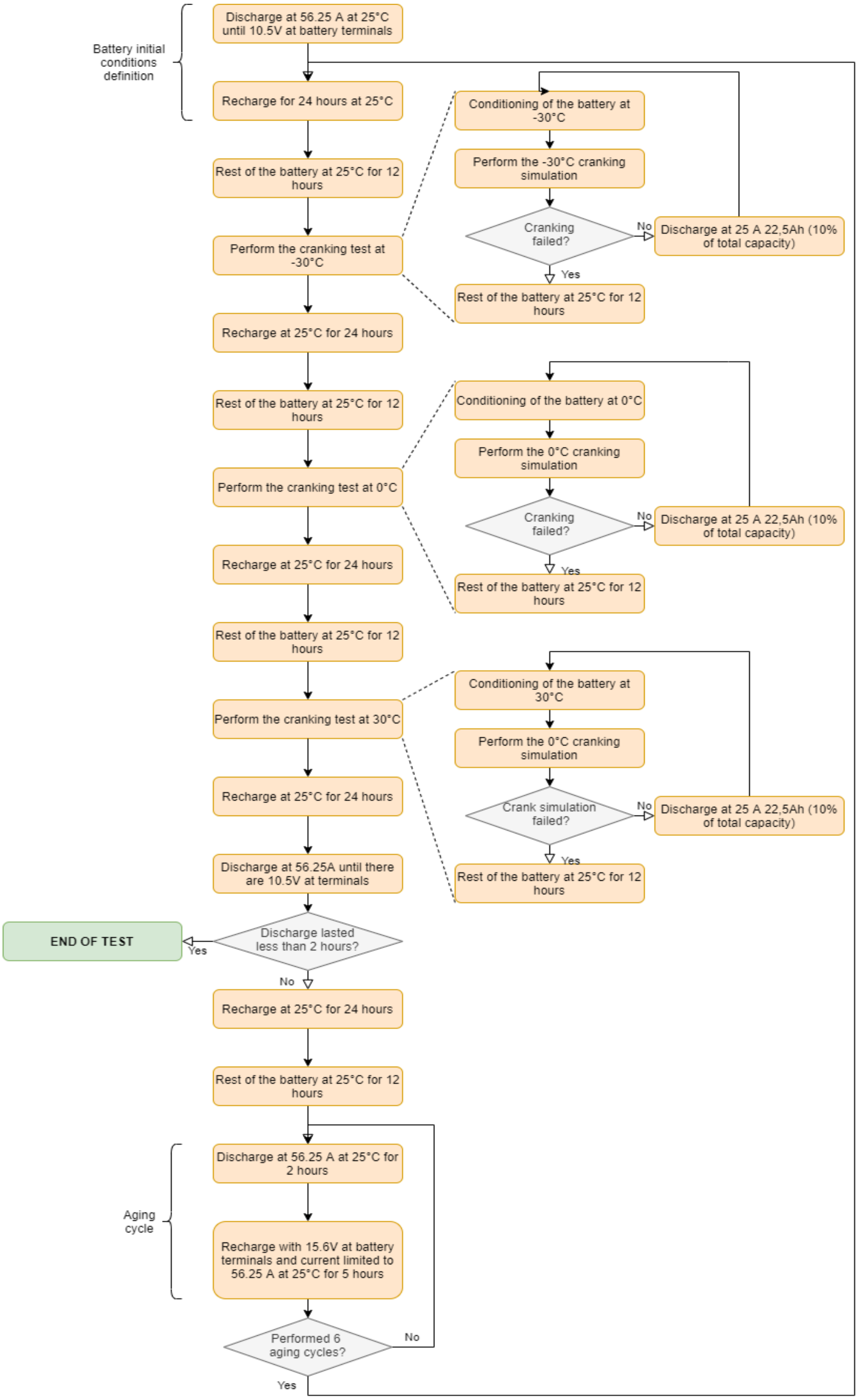


FIGURE 38: CRANKING SIMULATION TEST FLOWCHART

3.2.6. Cranking simulation test: results

The cranking simulation test is made to reproduce the cranking phase at different State of Charge, different State of Health and different temperature, in order to map as well as possible the possible behaviours of the battery during the cranking phase, which is the critical phase for a commercial vehicle application.

Another main function of this test is the possibility to observe the trend of the internal resistance during the cranking phase and, as a consequence, to assign a value of SOH_I to that value of resistance; in fact, at every cranking simulation it is possible to find the value of the internal resistance of the battery plotting the voltage and the current and finding the inverse of the angular coefficient of the line that interpolate every measurement. An example of this procedure is shown in the Figure39 in which are shown the lines at 30°C at different SOC values and with a battery at its last cycle.

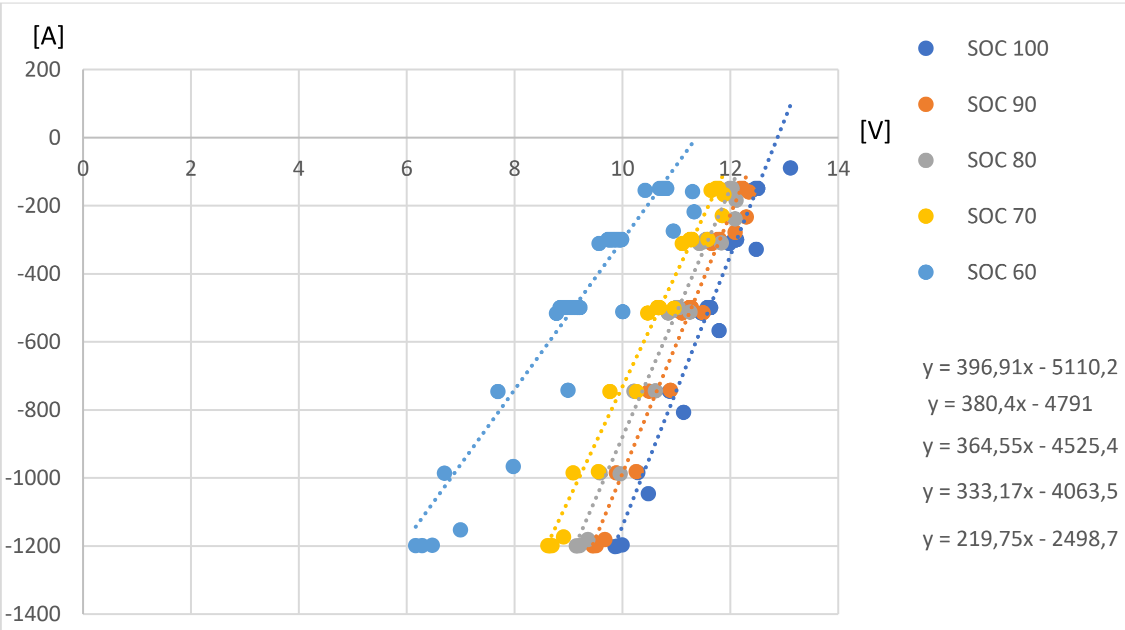


FIGURE 39: CURRENT VS. VOLTAGE AT DIFFERENT SOC DURING CRANKING SIMULATION

Looking at the figure it is possible to see the voltages as abscissa and the currents as ordinate. Plotting one point every measurement of voltage and current, done at a frequency of 100 Hz, and interpolating them to obtain a line, the internal resistance value is the inverse of the angular coefficient. In this case, the internal resistance values are summed up in the following table in which it is possible to see the comparison between the retrieved values at 30°C at the first cycle and at the last cycle of the test.

SOC	$R_i[\Omega]$ (1st cycle)	$R_i[\Omega]$ (last cycle)
100	0,00253	0,002519
90	0,00255	0,002629
80	0,00259	0,002743
70	0,00267	0,003001
60	0,00278	0,004551

TABLE 7: RI VALUES VS. SOC AT 30°C – 1ST CYCLE VS LAST CYCLE

It is possible to see that the internal resistance remains almost constant for high values of SOC while decreasing the SOC the difference between a healthy battery with one exhausted is marked.

3.2.7. Cranking simulation test: conclusions

The scope of the cranking simulation test is to rebuild the Look Up Table for the computation of the SOH_I with the algorithm explained into the paragraph 2.3.2.1.

Unfortunately, the battery considered for the test was not new, so it was impossible to have a complete map of the battery behaviour. Due to this reason a new cranking simulation test should be done, but because of the Coronavirus pandemic all the tests have been stopped.

Anyhow the results can show that the internal resistance value can be considered as a parameter to estimate the SOH_I and in particular to preserve the cranking capability of the battery.

3.3. SOH_I Look Up Table

The completion of the cranking simulation test has been considered impossible because of the lack of time and the spreading of the Coronavirus pandemic, so the construction of a detailed Look Up Table is infeasible. To overcome this inconvenient, the SOH_I is estimated using the same table used for the SOH_C estimation, visible in Table3. The lack of the LUT created with this procedure will probably affect the output of the UDT tool, for this reason the cranking simulation test should be performed as soon as possible to improve the tool, considering also that this procedure will take some months to conclude.

4. Validation Test

The original scope of the thesis work is to validate the UDT tool by means of a testing campaign based on the comparison between the output provided by the tool and the one provided by the shelf diagnosis tool that nowadays is the standard used among the truck makers.

Even if a structured testing campaign has been considered impossible because of the lack of time and resources caused by the pandemic that is afflicting the world, the validation test procedure has been thought and it is explained through the following paragraph.

4.1. Validation test structure

The structure of the validation test is thought very similar to the structure of the tests described in paragraph 3.1 and in paragraph 3.2.2 in order to have a good comparison between the measurement done on the testbench and the results coming from the UDT and the shelf diagnosis tool.

The structure of the test can be described as follow:

1. Full discharge of the battery at 56.25 A until there are 10.5 V at the terminals with no time limits at 25°C, to measure the capacity of the battery;
2. Full recharge of the battery for 24 hours at 25°C;
3. Rest of the battery for 12 hours at 25°C;
4. Perform validation test at -30°C;
    a. Conditioning of the battery at -30°C;
    b. Perform the measurement of SOC and SOH with the UDT tool;
    c. Perform the measurement of SOC and SOH with the shelf diagnosis tool;
    d. Discharge the battery of 10% of the total capacity, i.e. 22,5 Ah, at 25 A which is the typical current requested by the loads on a vehicle;
    e. Perform steps from a to d until the cranking fails;
    f. Rest of the battery for 12 hours at 25°C;

5. Full recharge the battery for 24 hours at 25°C;
6. Rest of the battery for 12 hours at 25°C;
7. Perform validation test at 0°C;
    a. Conditioning of the battery at 0°C;
    b. Perform the measurement of SOC and SOH with the UDT tool;
    c. Perform the measurement of SOC and SOH with the shelf diagnosis tool;
    d. Discharge the battery of 10% of the total capacity, i.e. 22,5 Ah, at 25 A which is the typical current requested by the loads on a vehicle;
    e. Perform steps from a to d until the cranking fails;
    f. Rest of the battery for 12 hours at 25°C;
8. Full recharge the battery for 24 hours at 25°C;
9. Rest of the battery for 12 hours at 25°C;
10. Perform validation test at 30°C;
    a. Conditioning of the battery at 30°C;
    b. Perform the measurement of SOC and SOH with the UDT tool;
    c. Perform the measurement of SOC and SOH with the shelf diagnosis tool;
    d. Discharge the battery of 10% of the total capacity, i.e. 22,5 Ah, at 25 A which is the typical current requested by the loads on a vehicle;
    e. Perform steps from a to d until the cranking fails;
    f. Rest of the battery for 12 hours at 25°C;
11. Full recharge the battery for 24 hours at 25°C;
12. Rest of the battery for 12 hours at 25°C;
13. Discharge at 56.25 A for 2 hours at 25°C;
14. Recharge with 15.6 V at the terminals and with the current limited to 56.25 A for 5 hours at 25°C;
15. Perform steps 13 and 14, i.e. the aging cycle, six times;
16. Rest of the battery for 12 hours at 25°C;
17. Full recharge for 24 hours at 25°C;
18. Full discharge of the battery at 56.25 A until there are 10.5 V at the terminals with no time limits at 25°C;
19. Rest of the battery for 12 hours at 25°C;
20. Repeat steps from 2 to 19 until the step 18 requires less than 2 hours to complete.

The test, which flowchart is shown in Figure40, is made to allow a comparison between the evolution of the battery measured on the testbench by the manufacturer and the measurements made with UDT and the shelf diagnosis tool.

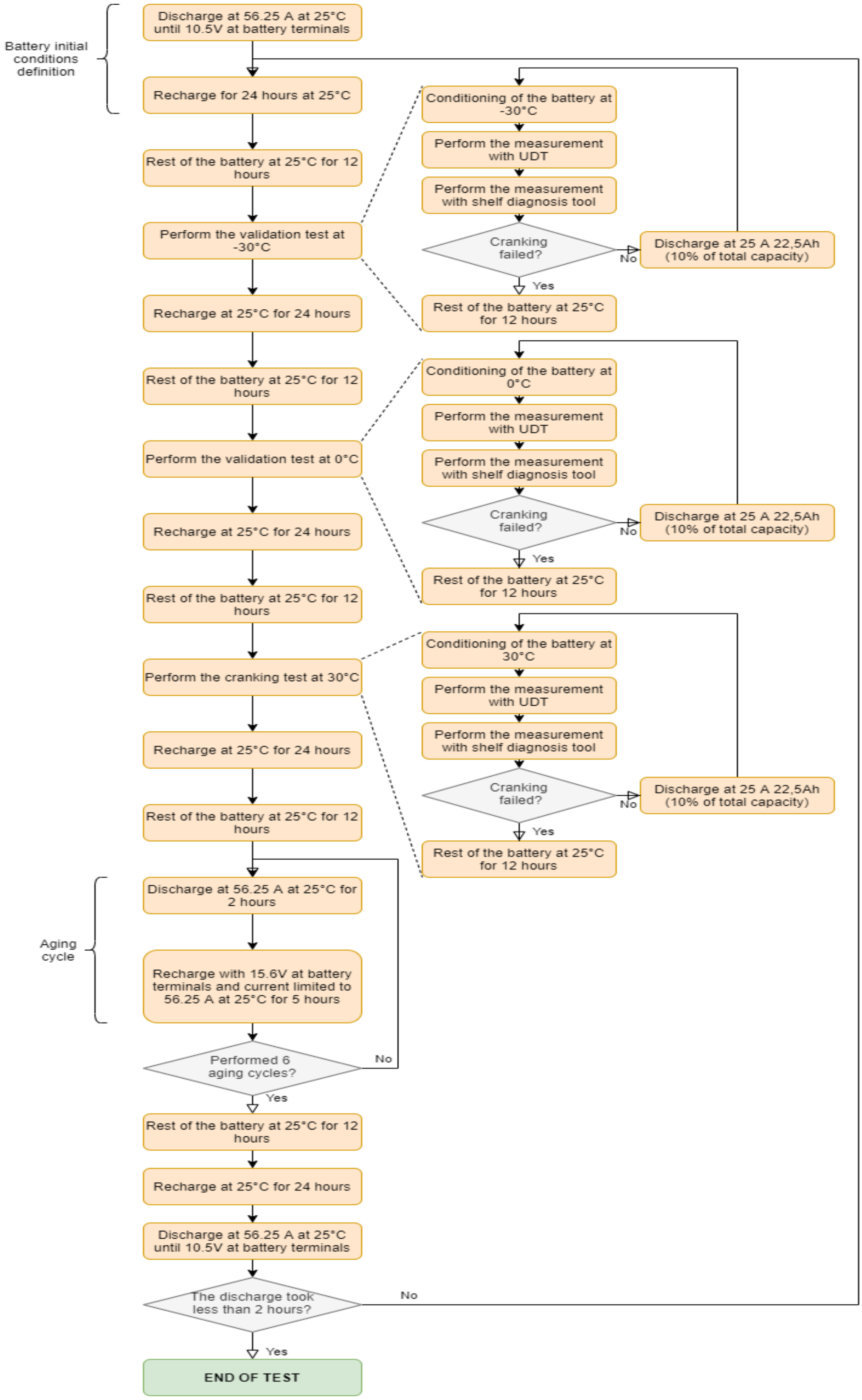


FIGURE 40: VALIDATION TEST FLOWCHART

4.2. UDT test procedure

To accomplish the step 4 of the validation test, it is required the knowledge of the UDT tool and of the correct procedure to perform the measurement.

1. Connect the PC to the OBD port using the OBD scanner, shown in the following figure, located under the dashboard at the passenger side;

FIGURE 41: OBD SCANNER AND OBD PORT CONNECTION

2. Launch the UDT tool from the PC and turn the vehicle key on, after the retrieving of the vehicle information, such as the Vehicle Identifier Number and the type of batteries mounted on the truck, the tool displays the "Main Menu" screen, in which the "Test" panel must be chosen;
3. From the "Test" panel, choose "Advanced Test";

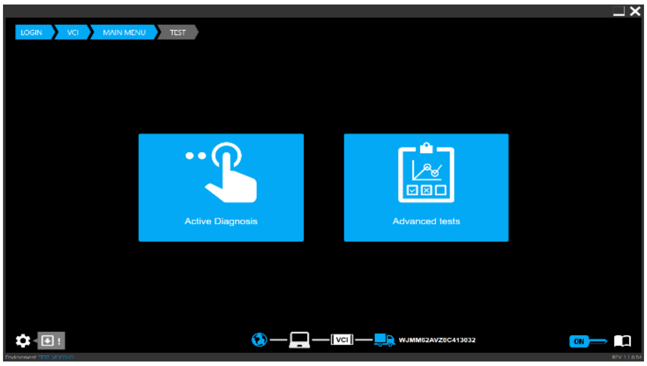


FIGURE 42: UDT TEST PANEL

4. Choose from the left side menu "Multiplexer", then from the menu in the centre choose "Battery Test" and click on the "Run" button.

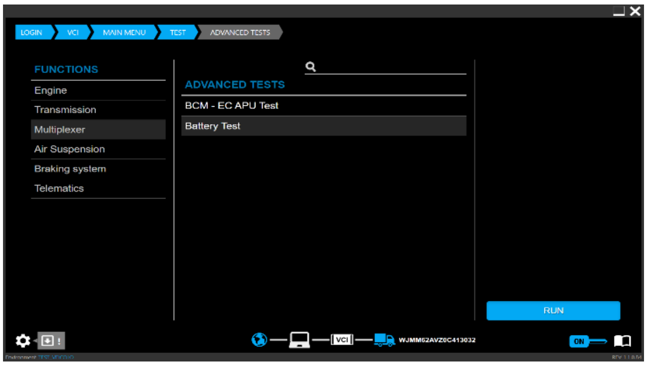


FIGURE 43: UDT ADVANCED TEST PANEL

5. When the message asking the cranking of the vehicle appears, start the engine;

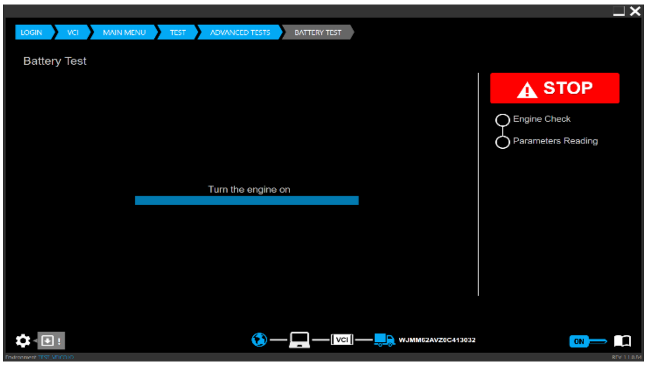


FIGURE 44: START THE ENGINE MESSAGE

6. After the cranking, the UDT shows the diagnosis with the SOC and the SOH of the two batteries;

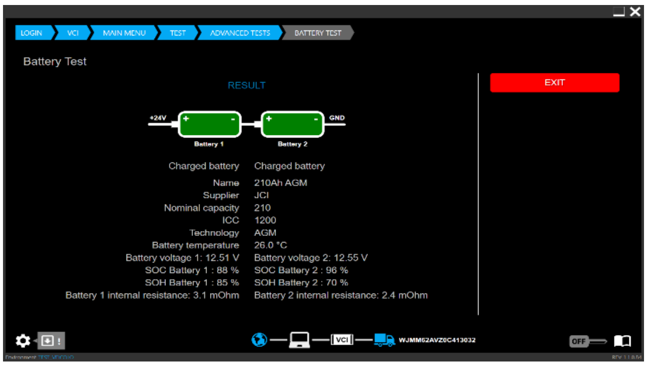


FIGURE 45: UDT BATTERY DIAGNOSIS RESULT

This procedure must be used every time a measurement with the UDT tool is required.

4.3. Validation test: results

The results of the tests performed has been obtained on a Stralis equipped with flooded acid batteries, but it has been impossible to perform the whole test procedure because of the lack of possibility to run structured tests caused by the spreading of the SARS-COV2 pandemic and the company restrictions to avoid the diffusion of the virus.

Anyway, the comparison between the UDT and the shelf diagnosis tool has been done on a Stralis available in Iveco. The vehicle under test is used by the engineering team to perform different kinds of test, so the previous usage of the batteries is impossible to be known, by consequence the expected output of the diagnosis could be not reliable.

The comparison between the two diagnosis tool is done at different SOC levels. The first diagnosis is done with charged batteries, and the results are shown in the Figure46 and the Figure47.

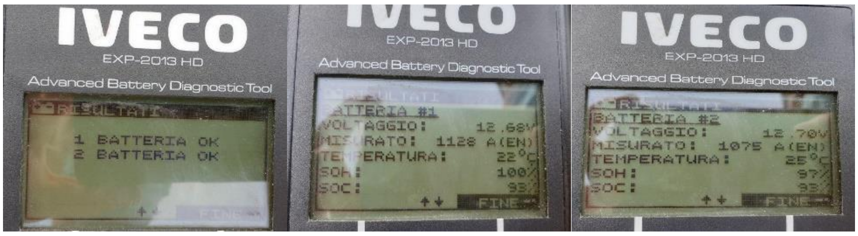


FIGURE 46: FIRST TEST SHELF DIAGNOSIS TOOL OUTPUT

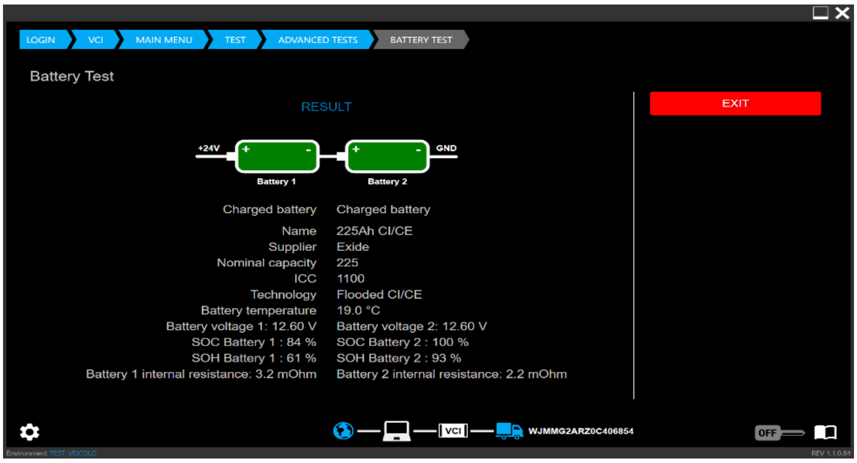


FIGURE 47: FIRST TEST UDT OUTPUT

NOTE: the name of the batteries on the UDT screen are inverted because of an issue during the testing phase.

The second test is done after the discharge of the batteries by turning on some electrical devices, approximately 30 A, for 15 minutes. The results are shown in the Figure48 and the Figure49.

FIGURE 48: SECOND TEST SHELF DIAGNOSIS TOOL OUTPUT

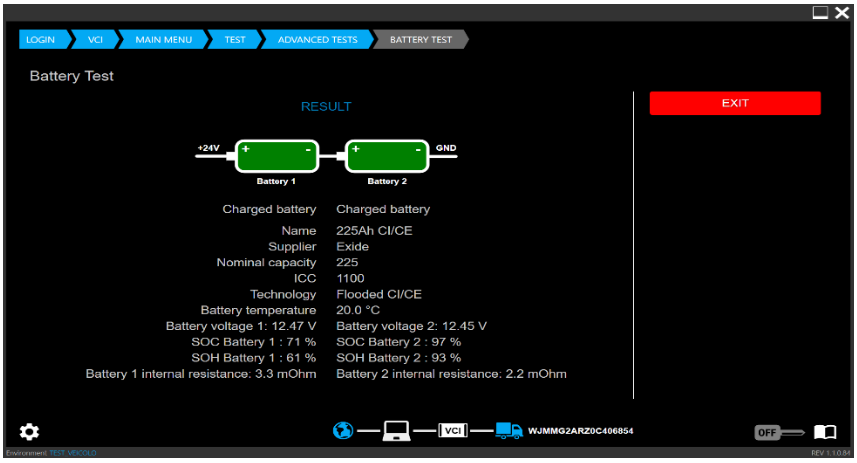


FIGURE 49: SECOND TEST UDT OUTPUT

The third test is done after having discharged the batteries by 30 A for approximately 10 minutes; the results are shown in Figure50 and the Figure51.

FIGURE 50: THIRD TEST SHELF DIAGNOSIS TOOL OUTPUT

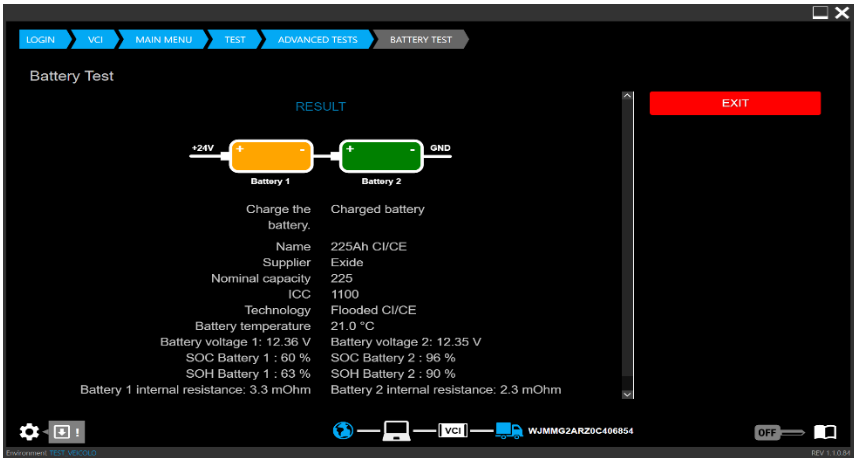


FIGURE 51: THIRD TEST UDT OUTPUT

The results of tests performed are summarized up in the Table8. in which all the measured and estimated parameters are present, and it is possible to compare the two outputs.

	SOC shelf tool		SOC UDT		SOH shelf tool		SOH UDT		TEMP shelf tool		TEMP UDT	Rint UDT		DIAGNOSI MIDTRONICS		DIAGNOSI UDT	
	BATT 1	BATT 2	BATT 1	BATT 2	BATT 1	BATT 2	BATT 1	BATT 2	BATT 1	BATT 2		BATT 1	BATT 2	BATT 1	BATT 2	BATT 1	BATT 2
Test 1	93%	93%	100%	84%	100%	97%	93%	61%	22°C	25°C	19°C	2,2 mOhm	3,2 mOhm	OK	OK	OK	OK
Electrical loads on for 15 minutes (fridge, radio, lights,...) [30 A approximately]																	
Test 2	79%	79%	97%	71%	100%	89%	93%	61%	32°C	30°C	20°C	2,2 mOhm	3,3 mOhm	OK	OK	OK	OK
Electrical loads on for 10 minutes (fridge, radio, lights,...) [30 A approximately]																	
Test 3	65%	51%	96%	60%	100%	95%	90%	63%	27°C	28°C	21°C	2,3 mOhm	3,3 mOhm	RECHARGE	RECHARGE	OK	RECHARGE

TABLE 8: OUTPUT COMPARISON BETWEEN UDT AND SHELF DIAGNOSIS TOOL

Even if the tests are performed on a vehicle whose batteries previous usage was unknown, therefore the tests cannot be considered for the release of the tool, but the outputs of the test can provide some useful qualitative information. The figures and the table of the results show the misalignment between the two tools; from the first test, it is evident the difference between the SOH and the SOC estimated for battery 2. The two estimations remain very different also for the other two tests. Another important consideration is that the value of the SOH evaluated by the shelf tool has some peaks, which is an unrealistic behaviour, while the SOH evaluated by the UDT remains almost constant as expected.

Considering battery 1, the outputs from the two tools are very similar at the first test, but as the battery discharges, the estimations start to diverge, in particular the SOC value decreases only a little according to the UDT, while it decreases a lot according to the shelf tool.

Regarding the value of the internal resistance, the UDT shows a value higher for the battery 2 leading to the lower value of SOH as defined by the algorithms previously explained.

Another consideration is related to the difference between the temperatures provided by the tools, which can be due to the two different measurement method; in fact, the UDT obtain the temperature at the terminal of the battery measured by the IBS, while the shelf tool measures the temperature on the case of the battery by means of an infrared sensor.

Considering only the UDT measurement is then possible to notice a coherence between the estimated values with the misalignment between the SOC values, perfectly explained by the difference of SOH, in fact a battery with a lower SOH will have a lower total capacity, and it will result in a faster drop of the SOC value.

The last issue noticeable is the wrong final diagnosis of the UDT tool, that, according to the thresholds defined by the algorithm explained, should mark the battery with the lowest SOH to be replaced, both because it is less than 63%, and because the difference between the two SOH is higher than 10%; nevertheless the UDT returns the battery healthy or to be recharged.

Even considering these issues, the final diagnosis returned by the two tools are similar.

At the end of the thesis collaboration, an issue has been found into the software installed inside the BCM of the vehicle under test, which was a prototype; this bug causes the BCM to send a wrong signal to the IBS passing an erroneous battery configuration which makes the IBS to use a different set of look up tables, leading to a possible wrong parameters estimation. The problem occurs when the BCM passes the configuration of the batteries to the IBS, especially the battery type, through the LIN network. Considering that when the IBS receives an unexpected value, it retains the previous configuration, it is impossible to know the configuration of the IBS. The LIN frame visible in Figure52 shows the two configuration messages that provide unexpected values and possibly cause the wrong measurements of the parameters.

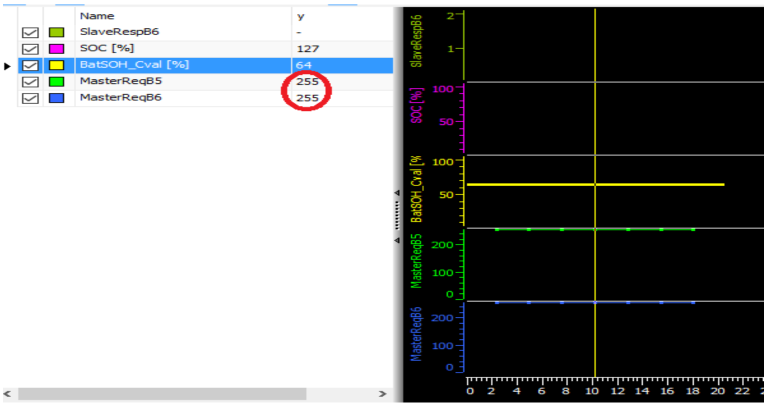


FIGURE 52: LIN FRAME

From the frame obtained it is possible to see that the two signal related to the battery configuration, i.e. MasterReqB5 and MasterReqB6, are always set to 255, which is an erroneous value.

4.4. Validation test: conclusions

The validation test campaign has been interrupted because of the spread of the SARS-COV2 pandemic that is afflicting the world. For this reason, a complete validation campaign has been considered impossible to carry out, and only a few comparisons between the output of the UDT tool and the shelf diagnosis tool has been done.

As visible from the results the measurements coming from the two tools are different and, considering that the diagnosis given by the shelf tool are not always reliable, to know which tool has performed the right evaluation a full discharge on a testbench is needed.

However, the tests performed must be considered first qualitative tests because they are not structured, the batteries do not rest after the discharge, and it is impossible to know what to expect from the tools, so a deepen opinion about the tool must be postponed after a complete validation test is done.

Another important aspect to consider is related to the bug in the software that can cause the misalignment between the estimated parameters, that must be fixed before the repetition of the tests.

In any case the tool must be improved because of the lack of the Look Up Table related to the SOH_I estimation and because of the wrong output provided during the tests.

5. Thesis conclusions

The work done can well describe the state of art of the system for the estimation of the SOC and SOH of the batteries mounted on the Iveco heavy vehicles. Unfortunately, the spreading of the pandemic of SARS-COV2 stopped the work and caused the impossibility of the conclusion of the work, making the validation of the tool an unreachable task.

Anyway, the test performed on the battery characterization showed that the performances of the flooded acid batteries, after an initial drop caused by the battery that must get used to the work conditions, tend to stay constant for all the life cycle. The measured capacity during the test, and by consequence the SOH_C value, is strongly affected by the battery history, in fact it is evident that the measured capacity trend changes if the battery performs three or six aging cycles; the internal resistance measured during the cold cranking current, remains almost constant until the battery reaches the end of life, when the value strongly increases.

These considerations, which fully respect what expected, enhance the difficulty to forecast the behaviour of the battery and its internal resistance as a wear indicator, so the most suitable approach remains the one based on look up table and on the construction of a databased experimentally built to know the status of the battery, according to the measured parameters.

The test named cranking simulation test shows one possible way for the construction of the look up table to relate the SOC, the temperature and the internal resistance value, measured at the cranking of the vehicle, to the SOH value. The test shows some useful results, but the look up table has not been built because of the wrong usage of batteries that were coming from on field endurance test, so it was impossible to relate a value of SOH to a value of measured resistance.

Even if the look up table for the SOH_I computation has not been built in the way explained in the paragraph 3.2, the validation test procedure has been thought. Because of the pandemic of coronavirus and the company restrictions, the only possible tests are shown into the paragraph 4.3, that is three measurements at different SOC, from which it is possible to see that the parameters coming from the two tools are misaligned, even if the final diagnosis are similar. The UDT tool shows also a behaviour slightly different from the specifications, probably due to bugs in the software and in the thresholds definition. During the last part of the thesis work an issue has been found in the BCM software that causes the wrong configuration of the IBS sensor, and it has made the measurements unreliable.

However, the work done put in evidence that the undertaken route can produce very useful results but with some limitations:

- The approach is strongly dependent on the battery technology, i.e. the test and the calibration done is suitable only for the flooded acid batteries with 225 Ah and 1100 CCA. A variation of the onboard battery involves the reconstruction of the database for the new employed battery;
- The model used for the estimation of the internal resistance is a very simple Thevenin generator, while the behaviour of the battery is strongly nonlinear and depends on chemical and cinematic phenomena happening inside the battery that implies capacitive and inductive behaviours. For this reason, the estimated parameters cannot be fully precise, and the real state of the battery may differ a little;

In conclusion, the method chosen for the estimation of battery parameters is considered valid as the battery behaviour is strongly nonlinear, so the approach based on Look Up Tables is the most suitable.

What emerged from this thesis work is that the IBS sensor could be successfully used for diagnosis purposes, by means of the UDT tool. The approach and the algorithm used has an intrinsic value, proved by the qualitative results obtained during the work, in which it is possible to notice the consistency and the coherence of the estimations given by the UDT. As a result, even if the tool must be improved and the tests must be performed again, the approach is approved and the work on the developing of the UDT will continue.

6. Future works

Considering the work done and the results achieved, the main task for the future improvement of the UDT tool is the repetition of the tests on a vehicle with the BCM software fixed and fully functional.

According to the output of the UDT tool in comparison with the diagnostic shelf tool, a better calibration of the tool for the SOH_I is required so it is evident the lack of a proper look up table for the computation of the SOH_I based on the results of the cranking simulation test.

In addition, a revision of the software of the UDT is required to find the reason why the final diagnosis does not consider the threshold on the SOH value, returning a battery OK while it should be returned KO.

In the end, to improve the UDT tool it is necessary to perform the cranking simulation test described in paragraph 3.2 and retrieve the database that relates in the correct way the SOC, the temperature, the internal resistance and the SOH, from which it will be possible to obtain the SOH_I value. After this modifications the validation test described in paragraph 4 must be performed on a vehicle with batteries which status is well known, to evaluate the improvement of the results in comparison with the shelf diagnosis tool and verify properly the reliability and the precision of the UDT tool.

Bibliography

[1] Martin Murnane, Adel Ghazel – *A Closer Look at State of Charge (SOC) and State of Health (SOH) Estimation Techniques for Batteries*, in "Analog Devices, ahead of what's possible", a.2017;

[2] Dirk Uwe Sauer, Georg Bopp, Andreas Jossen, Jürgen Garche, Martin Rothert, Michael Wollny – *State of Charge – What do we really speak about?*, in "INTELEC 99", June 1999;

[3] Arijit Guha, Amit Patra – *State of Health Estimation of Lithium-Ion Batteries Using Capacity Fade and Internal Resistance Growth Models*, in "IEEE Transaction on Transportation Electrification, a 2018, vol. 4, n. 1, March 2018;

[4] Jürgen Remmlinger, Michael Buchholz, Markus Meiler, Peter Bernreuter, Klaus Dietmayer – *State of Health monitoring of lithium-ion batteries in electric vehicles by on-board internal resistance estimation*, in "ScienceDirect - Journal of Power Sources", n.196, a.2011;

[5] Lin Chen, Zhiqiang Lü, Weilong Lin, Junzi Li, Haihong Pan – *A new state of health estimation method for lithium-ion batteries through the intrinsic relationship between ohmic internal resistance and capacity*, in ScienceDirect – Measurement, n.116, a. 2018, 2018;

[6] Daniel Le, Xidong Tang – *Lithium-ion Battery State of Health Estimation Using Ah V Characterization,* in Annual Conference of the Prognostics and Health Management Society, Warren, MI 48090, USA, 2011;

[7] Ryan J. Grube, Xiaodong Zhang, Kefu Xue – *Automotive Battery State of Health Monitoring Methods,* Wright State University, Dayton, Ohio, USA, 17 December 2008;

[8] Ross Kerley, Dong S. Ha, Kwan-Jin Koh, Qiang Li – *Automotive Lead-Acid Battery State Of Health Monitoring System,* Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA, 30 July 2014;

[9] Hongwen He, Rui Xiong, Jinxin Fan – *Evaluation of Lithium-Ion Battery Equivalent Circuit Models for State of Charge Estimation by an Experimental Approach*, in Energies, 4, 582-598, 2011;

[10] Wikipedia contributors – *Lead-Acid Battery,* Wikipedia: the Free Encyclopedia, <https://en.wikipedia.org/wiki/Lead%E2%80%93acid_battery>;

[11] Wikipedia contributors – *State of Charge,* Wikipedia: the Free Encyclopedia, <https://en.wikipedia.org/wiki/State_of_charge>;

[12] Wikipedia contributors – *State of Health,* Wikipedia: the Free Encyclopedia, <https://en.wikipedia.org/wiki/State_of_health>;

[13] Woodbank Communications Ltd – *State of Health (SOH) determination*, in Electropedia - Battery and Energy Technologies <https://www.mpoweruk.com/soh.htm>;

[14] Battery University – *BU-105: Battery definitions and what they mean*, Battery University <https://batteryuniversity.com/learn/article/battery_definitions>;

[15] DELPHI - *Delphi battery sensor technical information*, Klaus Amann, 23 May 2013;

[16] IVECO STD. 21-2215 – *Intelligent Battery Sensor for State of Charge (SOC) and State of Health (SOH) Estimation,* 20 November 2019;

[17] Normative CEI – EN 50342-1:2016, *Lead-acid starter batteries – Part 1: General requirements and methods of test,* 28 January 2016;

[18] Thomas B. Reddy, Alvin J. Salkind, Anthony G. Cannone, Forrest A. Trumbure – *Handbook of Batteries – Chapter 23: Lead-Acid Batteries*, David Linden Editor, Thomas B. Reddy Editor, Third Edition, 2002;