CHARACTERIZATION AND THERMAL BEHAVIOR OF BATTERY MODEL PARAMETERS

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Abstract— The Lithium-ion battery cell are electrochemical elements widely used in application that requires a high energy density and a compact element, all these characteristics are better implemented for electric vehicle applications. It is known that some factors are harmful to the battery degrading it faster and not being efficient as expected, one of the factor is the temperature. With the goal to know the battery behavior and to prevent possible failures, electric models of the battery are developed. Using an automatic setup to measure the quantities, it was made experimental procedures to define the capacity behavior of the battery in relation to temperature, using a constant current to realize the experiment, and to define the electric model parameters, doing the experiment with pulsed current, with these model parameters are possible to analyze the uncertainties associated to them making relation with temperature. Experimental results from the battery were obtained through the charge and discharge procedure for the temperature of $10°C$ and $40°C$, determining the variations of the parameters of the battery in relation to the temperature. In this paper, it was possible to determine the minimal number of branches for electric model to require less computational effort, being analyzed the relation between the R-C parameters of the electric model with the temperature along the State-of-Charge (SoC), where we could concluded that the battery suffers losses in your capacity when it is used in low temperature which does not occur to high temperature.

Keywords— Lithium-ion, Battery, Electric Model, Uncertainties, Parameter Identification

1 Introduction

The lithium-ion battery become one of the most promising power supply, due to high energy density, long cycle life, no memory effect and slower discharge rate, this is good for some application, like electric vehicle (Yang et al., 2017). Industrially, the lithium-ion battery cell are made with a high homogeneity at component level, with the goal to decrease the intolerance of the parameters to the uncertainties. However, these uncertainties are hard to eliminate completely due the differences between the battery physics-chemistry properties that they are unstable and random, affecting directly the battery cell temperature during the work cycles, the charge and discharge. It has security problem during the operation of Lithium-ion battery that can be attributed to the variations of yours internal temperature, which are associated with the parameters uncertainties as the property of the material and the operational conditions (Tong et al., 2015).

According with international regulatory agencies, International Electrotechnical Commission's (IEC) Technical Committee, and company standard procedures, like Moura Accumulators, with the purpose of evaluating the parameters uncertain of the battery tests can be performed considering different operational conditions of charge, discharge or relaxation cycles. As well as, it can be imposed thermal cycles during the battery operation, increasing and decreasing the temperature. Although these tests can be realized, they have a high financial cost and impracticality due to the large number of hours to realize the tests. To resolve these limitations, many mathematical models of the battery are used, allowing the accomplishment and the propagation of the uncertainties of the battery model parameters mainly due to the chemistry changes inside of the battery (active material, internal polarization and kinetic factors) (Tong et al., 2015).

Some works have developed analysis of uncertainties using mathematical model of the battery in the frequency domain. However, it still persist the limitations to the analysis of the battery parameters uncertainties, due the difficulty to separate the individual variations of the parameters, making complex the analysis about the battery security. Therefore, with the goal to increase the security of the battery, it is interesting to develop scientific methodology to identify the parameters that cause the variations in the battery temperature and to quantify the individual contributions of the uncertainties under the battery parameters.

In this paper, it will be performed two types of experiment with the goal to evaluate the behavior of the battery capacity for a temperature variation, this experiment will be used the constant current procedure. The other goal of this paper is to determine the R-C electric model parameters for a temperature variation, analyzing the influence and the losses that happen in the battery associated to the temperature for each different

SoC value.

2 Lithium-ion Battery

This battery is manufactured by A123 Systems, one of the important parameter of the battery is the nominal capacity which reflects the amount of charge that an accumulator is capable to store, for this battery is 20 Ah (*Battery Pack Design, Validation, and Assembly Guide using A123 Systems AMP20M1HD-A Nanophosphate Cells*, 2014).

To define the battery model of this paper, it been usedd a lithium-ion battery that is illustrated in the Figure 1. From the manufacturer manual was possible to collect some physical parameters specified in the Table 1.

Figure 1: Battery cell utilized to model

The optimal operational voltage of a battery is when does not have a high variation of voltage during the a determined SoC interval, so it is when the voltage remains constant, in your linear condition. At 25°C, it operate from 3.0 V until around 3.3 V.

To very high value of temperature, the battery can be damaged, the same occur to very low temperature. So, it has a variation of temperature that the battery works in an optimal condition which is from −30°C to 45°C.

Table 1: Physical property of the battery

Thickness	0.00725 m
Height	0.160 m
Width	0.227 m
Volume	2.6332 x 10^{-4} m^3
Area	0.0391 m^2
Mass	0.496 Kg

One of the battery modeling goal is to analyze the parameters of the battery cell relating to the unwanted operations, like explosion, quick discharge (Tong et al., 2015).

Also, the modeling is used to reproduce some conditions of operations to realize may require material cost, degrading the battery and others equipment, or human damage (Feng et al., 2016).

Among the types of models, the most common models are electric and thermal (Lin et al., 2014).

2.1 Electric Model

The electric model is used to estimate the State-of-Charge (SoC) and the open circuit voltage of the battery.

Usually, the most common model is the electrical equivalent circuit, comparing with the finite element model, the electric model requires lower computational effort. Also, it can easily be embedded in an electronic system to estimate some parameters, like: SoC and State-of-Health (SoH) (Sangwan et al., 2016).

As it is illustrated in the Figure 2, the complete electric model is composed by a resistor in series that represents the internal resistance of the battery and an finite number of branches formed by resistor and capacitor in parallel. These branches determines the dynamic response response from the battery cell.

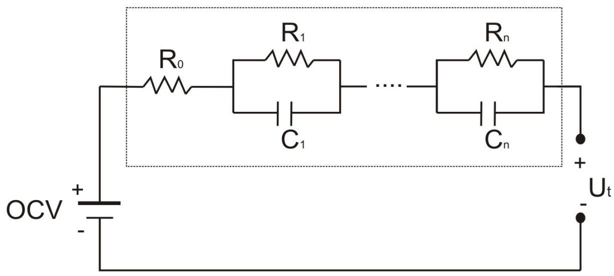

Figure 2: Complete electric modeling

Related to the complete electric model, the U_t represent the voltage between the battery terminals, in the left of the figure, the Open Circuit Voltage (OCV) represents the internal power supply from the battery. From the circuit theory, when the circuit is constituted by an internal power supply, so it has an internal resistance named R_0 associated to this internal power supply.

The resistances in parallel (R_1, R_2,...,R_n) at each branch represent the polarization resistance, the capacitors (C_1, C_2,...,C_n) of the branches are the transient dynamic voltage response that occur during the charge, discharge or relaxation operations.

The general equation of the circuit is solved through the Kirchhoff's Voltage Law. The Equation 1 define the circuit solution.

$$U_t(t) = V_{R_0} + V_1(1 - e^{-t/T_1}) + ... + V_n(1 - e^{-t/T_n}) \quad (1)$$

where:

- U_t is the voltage circuit output;
- V_{R_0} is the resistor R_0 voltage;

- V_1 is the voltage from first branch;
- T_1 is the dynamic response time from the first branch;
- V_n is the voltage from 'n' branch;
- T_n is the dynamic response time from the 'n' branch;

The quantity of branches used in the circuit determine the complexity and the computational effort that will be required to solve the simulations.

To define the minimal number of branches, it is used the terminal voltage data collected through the experiments. It is made a curve fit of these data and with the exponential equation 1 that the quantity should satisfy the best curve fit of the terminal voltage for the model could have a best approximation without losses of generality to the battery, with a less computational effort compared to the general model.

Due to the electric model limitation and known that occur electro-chemistry reactions, it was observed that the reactions directly influence in the battery behavior, increasing or decreasing the battery surface temperature. So, to estimate in detail the behavior of the temperature distribution throughout the charge and discharge processes, it is created a thermal model.

2.2 Thermal Model

The thermal model can be associated to the parameters from electric model, being able to determine the equations with the temperature and SoC as variables from each parameters defined to the electric model (Purwadi et al., 2014).

The thermal parameters, the heat generated, during the charge and discharge operation, is divided in two process, that are: the reaction heat (entropy) and the ohmic heating. The first process is result of the changes in the electro-chemistry processes, and the ohmic heating occur during when the current flows through the internal resistance when it is realized the battery operational processes (Chen and Li, 2014).

The heat generated is calculated according to the resistance losses that make up the electric model. If the model performed electrochemical simulations, other losses would be associated with the calculation. So, the equation 2 is to calculate the heat generated.

$$Q_{gen} = R_0.I_0^2 + R_1.I_1^2 + ... + R_n.I_n^2 \qquad (2)$$

where:

- R_0 is the internal resistance of the battery cell;
- I_0 is the current that flows through the R_0;
- R_1 is the resistance in the R-C 1 branch of the battery cell model;
- I_1 is the current that flows through the R_1;
- R_n is the resistance in the R-C n branch of the battery cell model;
- I_n is the current that flows through the R_n;

The variation of the internal energy according with the variation in the core of the battery cell, that is expressed in the equation 3.

$$dU = m.C_P.dT \qquad (3)$$

where:

- m is the mass of the battery cell;
- C_P is the specific heat;
- dT is the temperature variation between the core and the ambient temperature;

3 Experiment Procedure

To define the parameters from the electric and thermal model of the battery, some experiment procedure was necessary to be done, with the goal to collect the data to be used in the analyzes and to perform these experiments, a setup was mounted with electronic and mechanical system to perform automatically the experiments.

3.1 Setup Equipment

As it is illustrated in the figure 3, the setup is divided in two different parts: the electronic and the mechanical.

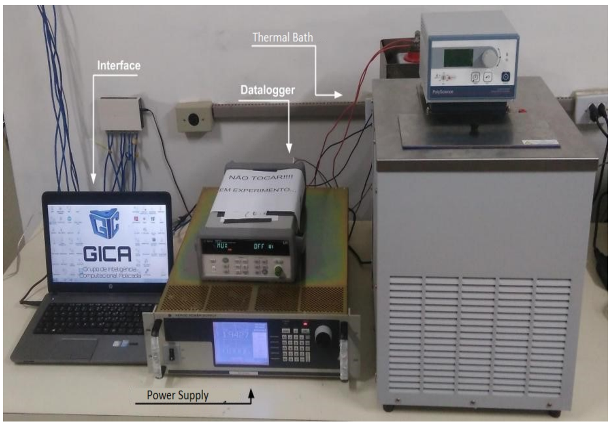

Figure 3: Battery measurement system of physical quantities

The electronic system is composed by equipment that perform the measure the physical quantities and equipment that control the charge and discharge process of the battery cell, that are: datalogger, power supply and a computer.

The other system, the thermal, is composed by the equipment that perform the process that change the temperature of the environment that the battery cell is inserted, performing the heat changes, that it is named by thermal bath, which is formed by a compressor.

The datalogger, from Keysight Technologies, is an equipment that monitor and register the analog quantities during the time. It acquires the quantities related to: temperature, humidity, voltage, current and frequency, recording the data or sending to a computer by USB or Internet by LAN. In this paper, it been used to record just the temperature and voltage with a good resolution of 22 bits to voltage and 0.1°C to temperature.

The power supply, from Kepco Inc., is an equipment that it is used to supply electric energy to a connected load. It is a bipolar power supply for the current to flow through the positive and negative pole, making possible to work as power supply, when the current is positive, and load, when the current is negative. In this paper, the power supply has current limits of -10.0A to 10.0A and voltage of -100 V to 100 V. It been used to perform the charge and discharge operation, connected to the computer through the USB port.

The interface is a software, developed using the C# (C Sharp) language, that has some experiment procedure develop in the back-end, and it is used to help automatizing the experiment procedure, sending to the equipment the commands that was set in the software to perform the charge or discharge process and also, recording the data collected by the data logger.

To vary the ambient temperature, the battery cell is immersed in a metallic box filled with radiator solution, composed by 60% of distilled water and 40% of automotive radiator additive. The controller, from Polyscience, varies the liquid temperature that the battery is inserted. This temperature variation is between 10^oC to 40^oC, but it can operate between -20^oC to 120^oC.

3.2 Experiment Procedure

In this paper, it was performed two different experiments to verify the battery behavior and to characterize the parameters of the model to several different temperatures.

The first experiment is related to the behavior of the battery cell during the operation when the battery is required to be completely discharged with a current of 10% of your nominal capacity (0.1C). The voltage of this experiment procedure is illustrated in the figure 4. This is a good experiment because it is possible to analyze how much time the battery cell can delivered the capacity in a particular application and also, measure the delivered capacity to various different temperatures.

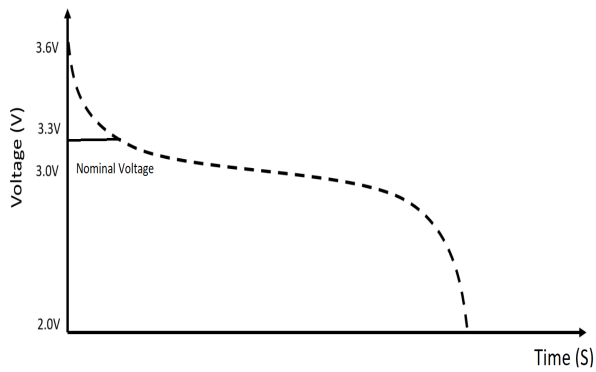

Figure 4: Voltage of Constant Current discharge procedure

The second experiment is used to determine the R-C parameters of the battery model and it is the best way to analyze the transient response of the battery cell, so it is used the pulsed current for discharge operation (Jackey et al., 2013). The current graphic of this procedure is illustrated in the figure 5.

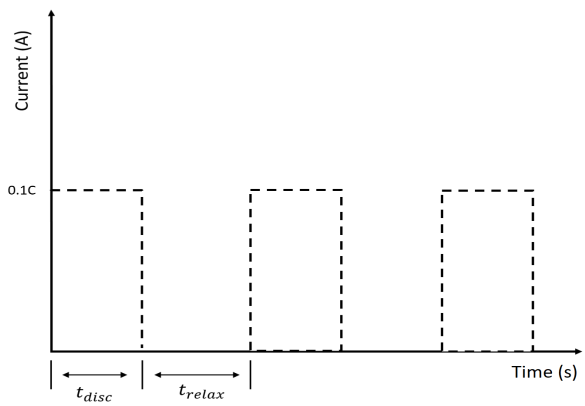

Figure 5: Pulsed current discharge procedure

These current pulses have short period, then a relaxation period. The current value used in the experiment is selected in according to just 1,0C during a time (t_{disc}) that the SoC decrease 10% of the previous SoC value. After the discharge process, it is performed a relaxation procedure, the current at 0A, during 2 hours (t_{relax}) to stabilize the chemistry property of the battery cell to enable the determination the R-C parameters of the battery.

3.3 Parameter Estimation Procedure

The values of the electric components also are determined by the terminal voltage data, collected through the experiments. In the figure 6 is illustrated how the parameters are found and how the components of the electric model are calculated (Jackey et al., 2013).

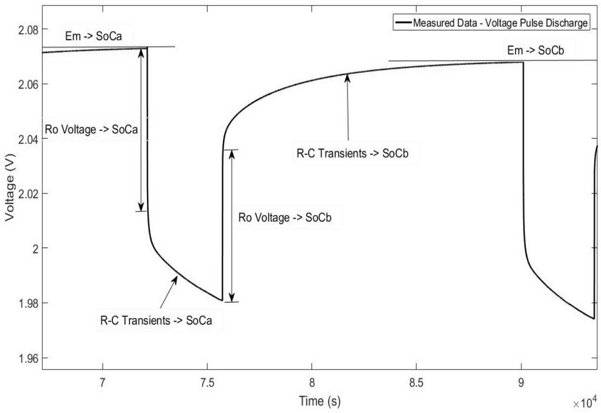

Figure 6: Graphic of the parameter estimation

To define the number of branches, the voltage data during the relaxation time is examined, the first sample after the change from discharge time is ignored and then it is fit closely one or more exponential equation 1 to the initial few data points in the transient.

The internal resistor value R_0 is calculated according with the Ohm law, determine that the resistance be constant and the to calculate your value is defined by the rate between the potential difference and the current that flows through the component. To the internal resistor, the potential difference is the first value of the voltage in the moment that the battery cell is turned to relaxation process and the posterior moment. (Jackey et al., 2013)

The R-C values of each one of the branches, the time constant (T_1,T_2) that establish the dynamic voltage response of each relaxation moment of the battery cell, this is known as accommodation time. The equation 4 defines the calculation of constant.

$$T_x = R_x.C_x \tag{4}$$

where:

- T_x is the time constant to establish the dynamic voltage response;
- R_x is the resistance in the R-C 1 branch of the battery cell model;
- C_x is the capacitance in the R-C 1 branch of the battery cell model;

Through the equation 1, each constant that multiplies each exponential, given the possibility to perform the calculation of resistance linked to the branch, with this, the time constant will help to define the capacitance of the other component of the branch (Jackey et al., 2013).

4 Results

For the purpose to analyze the dynamic behavior of the battery model and the influence due to the thermal variations, this section will presented the experimental results for the two experiments that are: the battery behavior during a fully discharge with the constant current of 0.1C, and the relaxation experiment, using a pulsed current, to determine the R-C parameters of the battery model and the thermal influence between these parameters.

4.1 Constant Current Experiment

Performing the first experiment with the three different temperature: 10°, 25° and 40°, with the constant current of 10% from the nominal capacity (0.1C), it was possible to create an histogram, that is illustrated in the figure 7 where the y-axis is the temperature, the x-axis is the SoC and the layers are the terminal voltage, with the vertical scale indicating the value, during the experiment

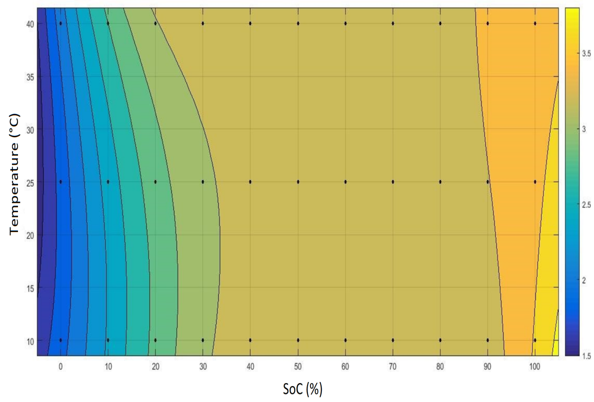

Figure 7: Histogram Voltage vs Temperature vs SoC

The manufacture manual (*Battery Pack Design, Validation, and Assembly Guide using A123 Systems AMP20M1HD-A Nanophosphate Cells*, 2014) specify that the behavior of the battery during the discharge process, to the negative temperatures, the battery has a high voltage variation between them, staying less time in the optimal stage of operation, when the time that the battery is between 3.0V and 3.3V.

Still according to manufacture manual, to positive temperatures, the battery voltage have a big drop in the initial instant of discharge, reflecting to more time at the optimal stage of operation, however, the battery voltage has a instantaneous drop when the capacity reaches around 20%.

To verify this information, it was performed the first experiment that the current is constant where the battery starts fully charged and the experiment finish when the battery is completely discharged. Through the Figure 8 is possible to verify that to low temperature 10° close to 0° when the SoC achieve about 20%, the voltage begin to drop down until the minimum acceptable.

Whereas, to high temperatures for the battery good operation, the element remains in the optimal operation state for more 10% of SoC than to low temperature. Also, the drop down to high temperature is more accentuated, representing that the battery reach the minimal operational voltage in short time.

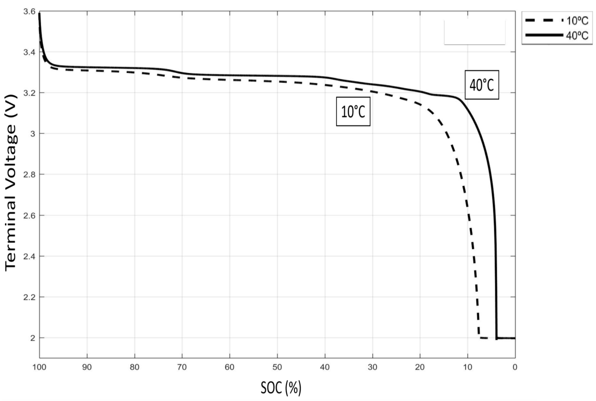

Figure 8: Experimental graphic of Voltage vs SOC

4.2 Relaxation Experiment

This experiment was performed with pulsed current, with the battery fully charged, which the discharge operation occur during 1 hour with a current 10% of battery nominal capacity, then the current is set to 0A, during 2 hours, with the purpose to determine the model parameters. This is necessary to stabilize the chemistry property of the battery cell, until the battery become fully discharged.

As it was shown above, the battery electric model is composed by many R-C branches, so defining the minimal number of branches through the voltage curve fitting. According with this, it was defined that two branches well represents the electric model of the battery cell, resulting less computational effort during the simulation. The equation 5 rules the electric model.

$$U_t(t) = V_{R_0} + V_1(1 - e^{-t/T_1}) + V_2(1 - e^{-t/T_2}) \quad (5)$$

In the figure 9, the resistance R_0 from the electric model presents a greater temperature dependence than SoC (Jaguemont et al., 2016).

When the SoC become low, to low temperature, the internal resistance drop down tending to equal to the high temperature internal resistance.

When the temperature R_0 decrease the resistance increase, it is due to the increased viscosity and the reduction of the ionic conductive in the electrolyte (Feng et al., 2016).

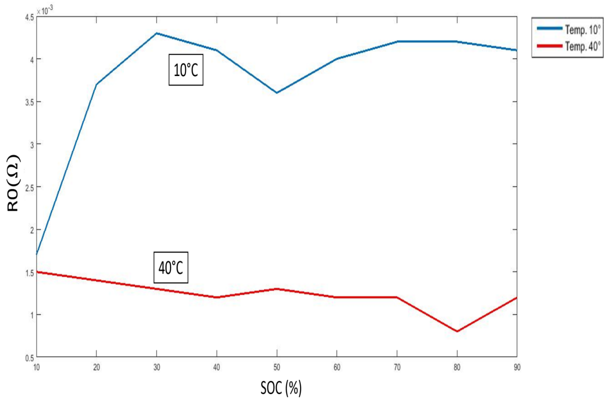

Figure 9: Resistance R_0

The first R-C branch of the electric model, through the figure 10 is possible to perceive that the time of the dynamic transient response (τ_1) of this branch present a dependence more significant to the temperature, different to the SoC, not being consistent with the parameters, presenting ascents and descents.

According with (Martemianov et al., 2015), the electric model parameters values present more uncertainties when are in the extreme value of the SoC, like at 0% and 100%, resulting in a high variation of the values. This behavior was observed in the experimental results to obtain the R_0 and the τ_1 as they are observed in the figure 9 and figure 10.

To low temperatures, when the SoC is between the values 20% and 70%, the τ has a small variation with the average about 2044s. So, to high temperatures, the average value of τ is smaller than to low temperature, being around 1390s.

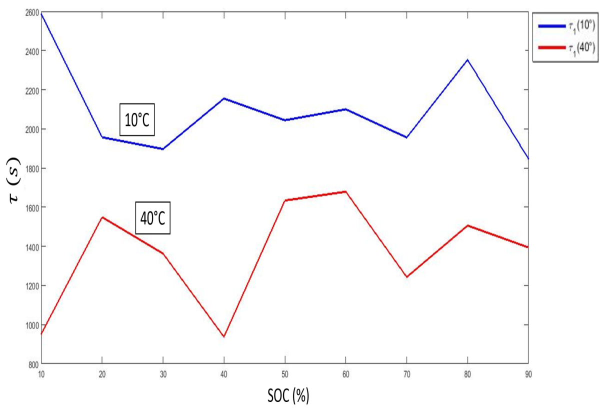

Figure 10: Time Constant of branch R-C 1

With increasing temperature, the dynamic transient response tends to be faster than in low temperature due the influence of the capacitor present in the branch. This capacitor makes a temperature and SoC dependence, with the increasing temperature, the capacitor become bigger and the same occur with the increasing SoC. According to the equation 4, the resistance become the inverse of the capacitor, decreasing with increasing temperature.

The second R-C branch of the electric model, the dynamic transient response (τ_2), presented in the figure 11, the temperature increase makes the dynamic transient response faster, presenting a significant SoC dependence when this parameter is close to 0%, making it slower at this percentage with decreasing temperature. Also, it is possible to note, the average value of τ to low temperature is higher than to high temperature, being around 202s and 149s, respectively.

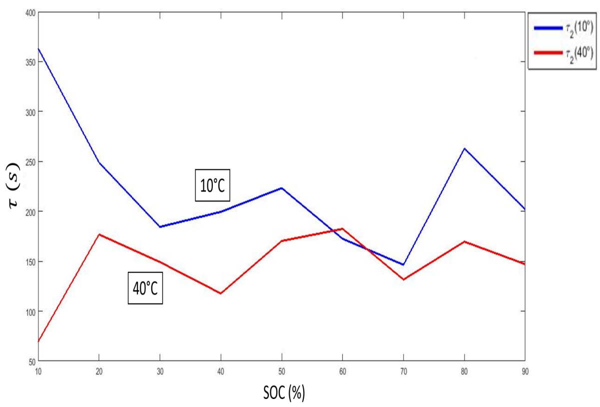

Figure 11: Time Constant of branch R-C 2

It has been noted that the dynamic transient response (τ) for the first branch is higher than the second branch. This is illustrated in the figure 12.

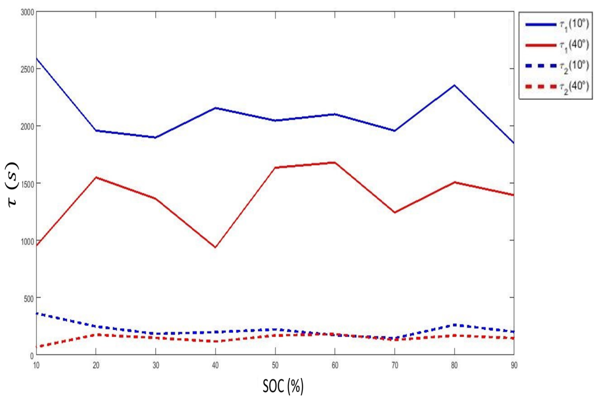

Figure 12: Time Constant between the two branches

This occur due the first R-C branch is a current dependent, and the second R-C branch is slower due to the capacitor be much more smaller than the first capacitor branch, beyond the second branch makes reference to the hysteresis effect (Jackey et al., 2013).

5 Conclusions

Through the constant current experiment procedure, it was possible to evaluate the behavior of the battery with relation to the temperature, with the low temperature supplying power for less time than to the high temperature. Using the pulsed current experiment procedure, it was possible to determine the R-C parameters of the battery electric model for 2 temperature used in the experiment. And it was possible to evaluate that some parameters of the model have a dependence with the temperature and the SoC, being related to the battery losses, like the capacitor in the transient dynamic response for the branch R-C 1. One way to evaluate the thermal modeling with fidelity is using the finite element model method. This method enables the analyzes of others physical quantities, like the current and temperature gradient, representing your distribution through the battery cell surface. The electrical and thermal constant estimated in this work, it is possible to utilize them to adjust the parameters for the simulation with the finite element model.

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