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THE IMPACT OF BATTERY OPERATING TEMPERATURE AND STATE OF CHARGE ON THE LITHIUM-ION BATTERY INTERNAL RESISTANCE

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ABSTRACT

This paper studies the behaviour of the lithium-ion battery used in automotive application especially for electric vehicles (EVs) and hybrid electric vehicle (HEVs) by focusing on the impact of battery operating temperature and state of charge (SOC) on the battery internal resistance. An electrical battery model is used and developed in MATLAB/Simulink. The validation process was done by comparing the simulation results from the developed model with experiment results established by other researchers. From the comparison, it is shown that the developed model is able to predict the performance of the battery in terms of battery internal resistance in the function of operating temperature between 0^{o}C and 50^{o}C and SOC range of 0.1 to 0.9. The internal resistance of lithium-ion battery minimum when the operating temperature is 30^{o}C and SOC is 0.4.

Keywords : *battery, lithium-ion, internal resistance, state of charge, vehicle*

1.0 INTRODUCTION

Technology today had serve several choices in vehicle electrification that towards zero local emission like battery-electric vehicles (BEVs), hybrid-electric vehicles (HEVs) and hydrogen fuel cell electric vehicles (HFCVs). These technologies can be applied in passenger cars, trucks and transit buses [1]. The important tools that are required in electric vehicles are the battery itself and there are a few types of rechargeable batteries that available for the electric vehicles such as lead acid, nickel cadmium, nickel metal hydride, lithium-ion, lithium-ion polymer, and other chemistries [2].

By focusing on lithium-ion battery, there are two parameters that give impact to the battery internal resistance which are battery operating temperature and state of charge. Both parameters are important to study the behaviour of the lithium-ion battery used in automotive application especially for EVs and HEVs. In modelling practice, the internal resistance is represented by a complex equation in function of SOC and there are only few that consider operating temperature in determining the internal resistance.

A simulation model development of a complex system enables researchers to further study and analyse behaviours of the system by using different setting or parameters. A model can be modelled based on results from experiment and then the simulation can be done in order to get further results with low costs compared to if doing the whole experiment.

The sections in this paper are organized as follows: a battery model is developed using MATLAB/Simulink software package in the second section and the results is then compared with experiment results from other research to validate the model.

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In section three, based on the basic model, the model is then developed further with internal resistance in function of temperature, SOC, and both parameters temperature and SOC.
The results are discussed in section four and the conclusion in the last section five.

Battery is made up from two or more electric cells joined together to perform its function [2, 3]. The function of the cells is to convert the chemical energy into electrical energy. There are positive and negative electrode connected with electrolyte in the cells as shown in Figure 1 [2, 3]. The chemical reaction that occurs between electrode and electrolyte produces DC electricity [3]. At the two electrodes, between the positive and negative electrodes, there are spaces for movement of ion. Half-reactions will occur through an external load by the circulations of electrons and the half-reactions are divided into two reactions which are oxidation and reduction. The reduction process is where gain of electrons takes place in the cathode while the oxidation process which is loss of electrons takes place in the anode [4].

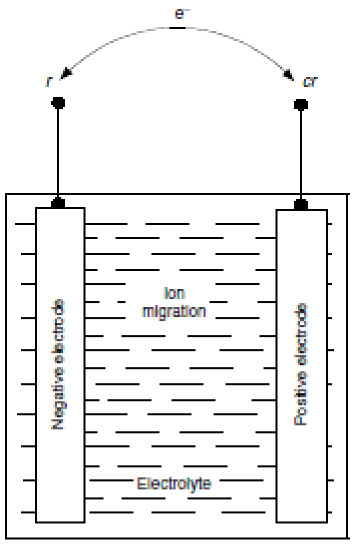

Figure 1: A typical electro chemical battery cell [2].

The main parameters that can be used to predict the behaviour and performance of a battery are cell and battery voltages, charge capacity, energy stored, specific energy, energy density, specific power, charge efficiency, energy efficiency, self-discharge rates, battery geometry, battery temperature and battery life cycles [3]. In EVs and HEVs application, they required batteries that have high specific power, high specific energy, long calendar and cycle life, low initial and replacement cost, high reliability and high robustness.

Recently, lithium-ion battery was still in development stages, however the lithium-ion battery has already chosen as energy storage for EVs and HEVs application. The reasons why lithium-ion battery is chosen as the best choice for EVs and HEVs are related to its excellent characteristics such as high power rating, high energy density, and high cycle life [2].

2.0 RESEARCH METHODOLOGY

In this section, the detail of the method will be explained and the developed subsystem according to equation presented in the previous research paper [6] is shown. For the basic lithium ion battery, the model is developed based on electrical battery model. The parameters required to develop the equation of the model are battery output voltage, battery open circuit voltage, usable battery capacity, and capacity fading effect. In addition, other research papers such as Awarke *et al.* [7], Lin *et al.* [9], and Baronti *et al.* [10] are used to develop battery model that is able to predict the battery internal resistance in function of temperature, SOC, and the combination of both temperature and SOC.

2.1 Basic Battery Model

According to Chen and Mora [5], they propose an electrical battery model that depends on battery SOC that is able to measure the battery runtime and *I-V* performance (*I* represents for current and *V* for voltage) by combining three supportive element which are the transient behaviours of battery, the internal resistance and the open circuit voltage. However, the equation of the model was then improved by Erdinc *et al.* [6], adjusting the battery dynamics by including battery output voltage, battery open circuit voltage, usable battery capacity and capacity fading effect. This changes the storage time, temperature, and cycle number together with the potential correction term in function of capacity fading effect. The correction term is then added to battery voltage calculation to verify the temperature changes.

2.2 Internal Resistance as a Function of Temperature

According to Awarke *et al.* [7], the battery internal resistance as a function of temperature is as in Figure 2. Based on that graph, one model can be developed using MATLAB/Simulink in order to predict the impact of temperature on battery internal resistance.

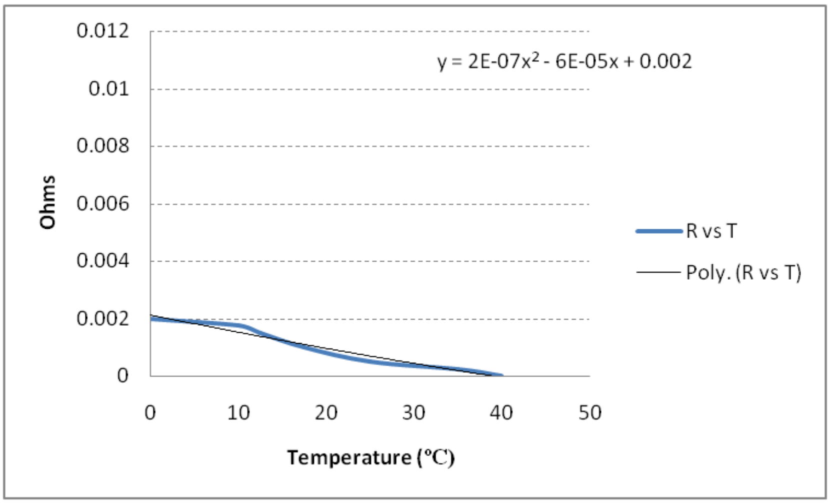

Figure 2: Internal resistance as a function of temperature [7].

2.3 Internal Resistance as a Function of SOC

According to Lin *et al.* [9], the battery internal resistance as a function of SOC is as presented in Figure 3, and based on that graph, one model can be developed using MATLAB/Simulink in order to predict the impact of SOC on battery internal resistance.

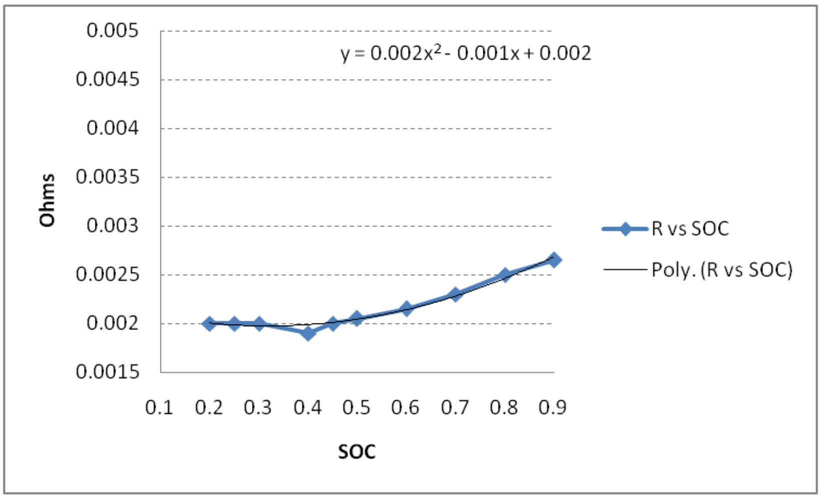

Figure 3: Internal resistance as a function of SOC [9].

2.4 Internal Resistance as a Function of Both Temperature and SOC

According to Baronti *et al.* [10], the data for the battery internal resistance as a function of temperature and SOC can be presented with equations shown in Figure 4. Based on that graphs, one model can be developed using MATLAB/Simulink in order to predict the impact of both temperature and SOC on battery internal resistance.

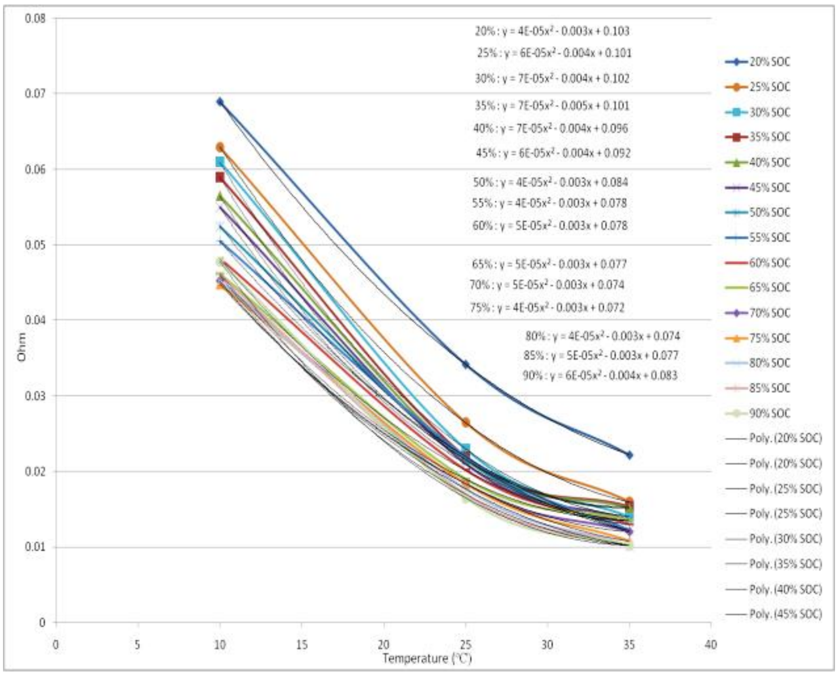

Figure 4: Internal resistance as a function of temperature and SOC [10].

3.0 RESULT AND DISCUSSION

In this section, the results are discussed. Validation process is stated to make sure the results from the developed model are reliable and correct for the lithium-ion battery for automotive application. The validation process is done by comparing the results from simulation in MATLAB/Simulink and the results obtained from experiments done and established by available research paper.

3.1 Impact of Temperature on Internal Resistance

In Figure 5, it is shown that the battery internal resistance decreases when the temperature increases [6]. The optimum battery operation temperature for lithium-ion batteries is in the range of 20 ºC to 65 ºC [8]. Starting from 0°C to the limit of efficient operating temperature range, the battery internal resistance decreases until achieving 0 Ohms for internal resistance at 40°C. This is because the increasing of electrolyte transport properties which include the bigger diffusivity of lithium (Li) in the solid host materials together with bigger reaction kinetics at the host-electrolyte interface are affecting the battery internal resistance [6]. Figure 6 represents the result from MATLAB/Simulink developed model and it shows the same trend compared to results in Figure 5.

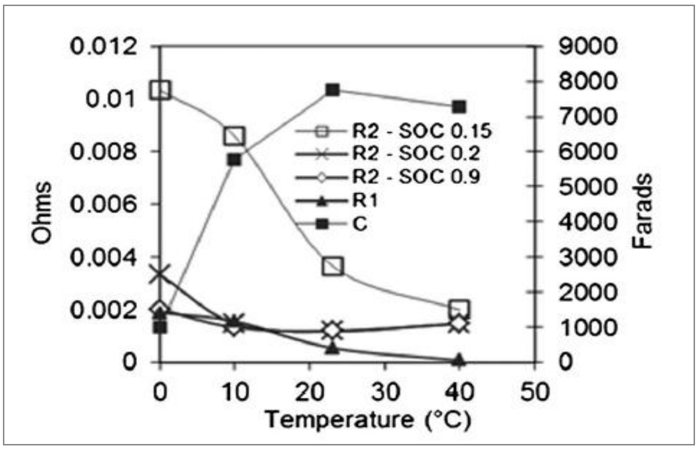

Figure 5: Identified equivalent circuit model parameters as a function of temperature and SOC [7].

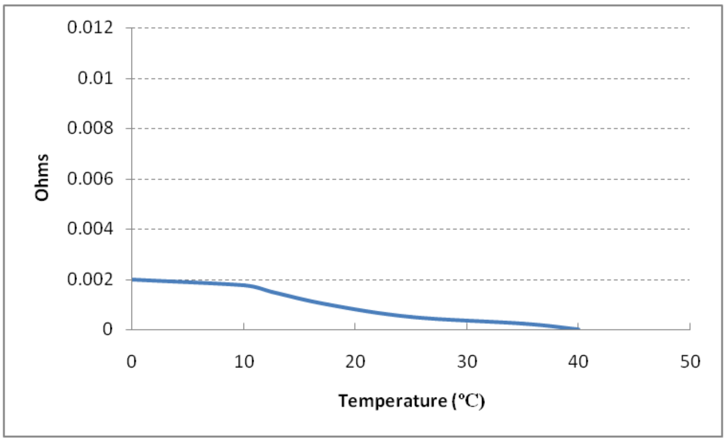

Figure 6: Battery internal resistance as a function of temperature.

In Figure 5, the internal resistance is represented by R1 which is at 0.002 Ohms at 0°C decreasing to around 0.0018 Ohms at 10°C, to 0.0008 Ohms, 0.0005 Ohms at 20°C and 30°C respectively until it drops to 0 Ohms at 40°C. Since this resistance is not a linear relationship in function of temperature, the representation has to be made with lookup table in Matlab/Simulink program.

3.2 Impact of SOC on Internal Resistance

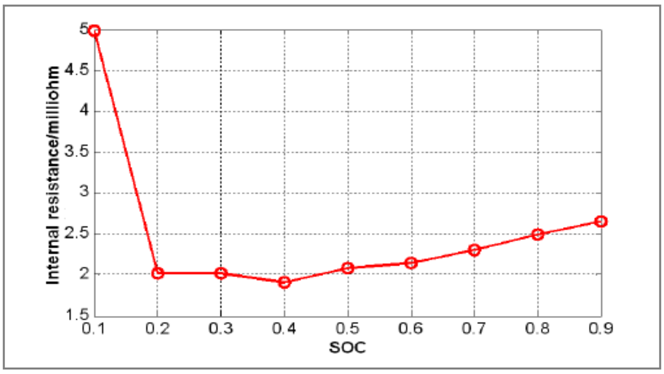

Figure 7: Relationship of internal resistance and SOC [9].

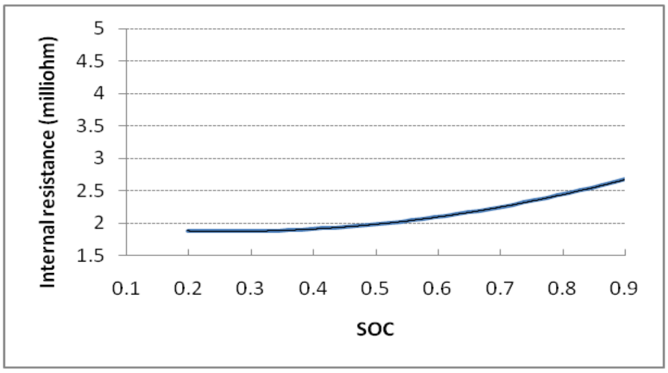

Figure 8: Battery internal resistance as a function of SOC.

Based on Figure 7, it is shown that during discharging, when the SOC drops from 0.9 to 0.2, the battery internal resistance will also decrease. However, from 0.2 to 0.1 SOC, the value of the battery internal resistance suddenly increases from 2 milliohm to 5 milliohm [7]. Same behaviour can be observed in Figure 8, the result from MATLAB/Simulink developed model shows the same pattern where the battery internal resistance decreasing starting from point of discharging at 0.9 SOC until when the percentage of SOC left is 0.2.

3.3 Impact of Both Temperature and SOC on Internal Resistance

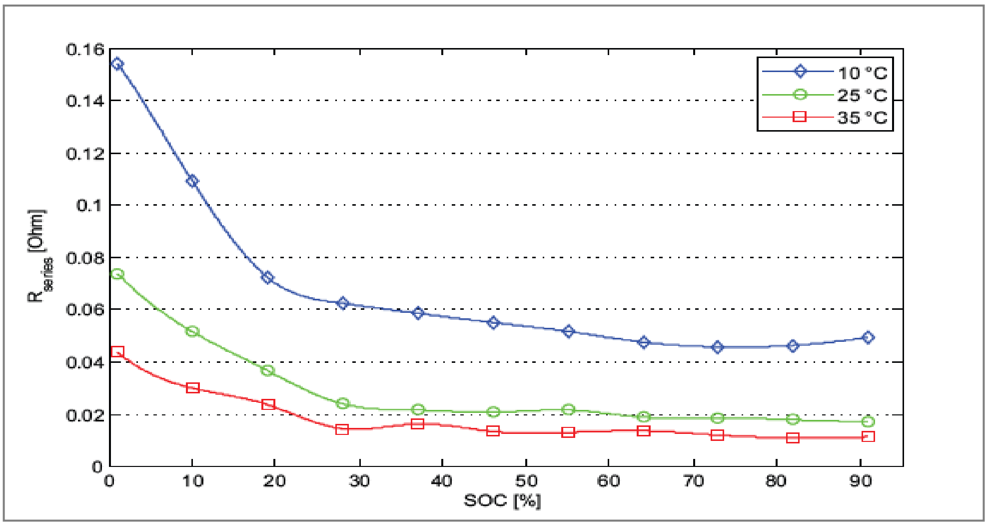

Figure 9: R_{series} for different temperatures – charging current of 1C [10].

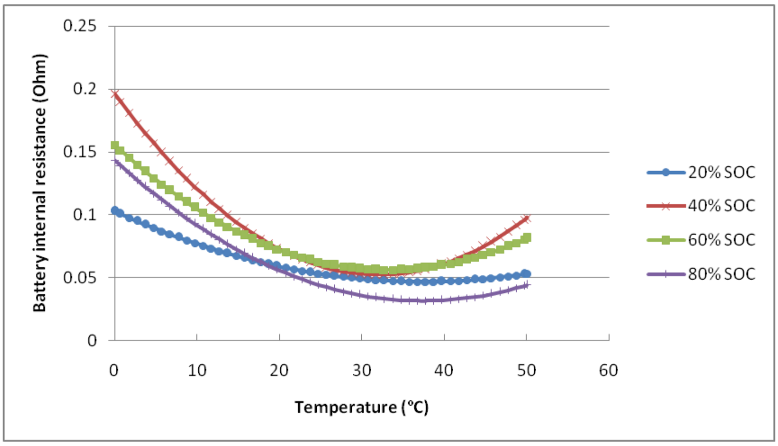

Figure 10: Battery internal resistance as a function of both temperature and SOC (SOC domain).

From Figure 9, it is shown that when the temperature increases, the battery internal resistance will decrease. It can be stated that at 25ºC and 35ºC, the battery internal resistances only have slight difference in terms of trend, but at 10°C, the battery internal resistances seem to increase all along the value of SOC. In Figure 10, the trends analysis is made for the same value of SOC for a range of temperature from 0^oC to 50^oC. It can be seen that the internal resistance decreases when the temperature rises from 0^oC to 30^oC, and then it will increase slightly after that when the temperature increases from 30^oC to 50^oC. Based on Figure 10, it can be concluded that the minimum battery internal resistance will be between 20^oC to 40^oC as can be observed from the trend of the graphs. This is the optimum operation temperature of Lithium-ion battery. The internal resistance shows less difference when the temperature is between 20^oC and 35^oC.

4.0 CONCLUSION

As a conclusion, the lithium-ion battery model developed is able to predict battery internal resistance as a function of temperature and SOC. There are three battery models developed in order to study the battery internal resistance, one model as a function of temperature, one model as a function of SOC, and one model with combination of both temperature and SOC. In purpose of developing the model, an electrical battery model was used as a reference. Equations from previous research papers were used as an input to develop the model and to validate the model developed in MATLAB/Simulink.

Based on the results, for the battery internal resistance in a function of temperature, the battery internal resistance decreases from 2 milliohms until 0 milliohms at 0°C to 40°C, which shows that the battery internal resistance will decrease when the temperature are increased. Next, the battery internal resistance in function of SOC during discharge, it can be seen that when the SOC of the battery reduced from 0.9 to 0.2, the battery internal resistance will also decrease. Lastly, for the battery internal resistance in function of combination of both temperature and SOC, the internal resistance will decrease as the temperature increase and will further decrease during discharge which is from 0.8 to 0.4 of SOC. However, it is better to avoid discharging the battery when it reached SOC 0.3, because the battery internal resistance will suddenly increase when the SOC is below 0.3.

Until today the optimum operating temperature for the battery lithium-ion is still in the range of 20°C to 65ºC. There are still no researches that able to obtain the behaviour of the battery above that range. It will become a big contribution to the world of automotive industry especially electric vehicles if there are researches that can go until that level.

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