

Real time estimation of Li-ion battery resistance used in the automotive industry

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Abstract—An essential characteristic of automotive applications is on-line decision capability/ on-line parameter estimation capability depending of input signals. The method for real time estimation of Li-ion battery internal resistance presented into this paper takes into consideration the characteristics of application which is powered by the battery and the load energy profile which shall be provided by the battery: current maximum value, discharge time, gradient of discharge current, voltage minimum value which is requested by the application in order to work properly.

Keywords: Li-ion battery, internal resistance, power capability of the battery.

1. INTRODUCTION

Internal resistance estimation shows the battery power capability, it shows if the battery is able or not to provide the power needed by the powered application. Li-ion batteries are used as backup energy supply for an electronic brake system concept which will be used in cars. The working principle of this fully electric brake system is based on wedge principle, it uses the kinetic energy of the car in order to brake it. The wedge profiles

are moved by the brushless DC motors (BLDC) in order to fulfill the driver requirements regarding the moment and amount of braking force.

Because dry-brake-by-wire-system concept is relatively new in the area of passenger car braking systems, the regulations which shall be observed by this braking system are the same as for hydraulic brake systems (ECE-R13H), but it should be adapted for the features of this revolutionary concept. The deceleration values to be achieved during one basic brake cycle were determined in agreement with several vehicle manufacturers. Brake deceleration required by law (Regulation ECE-R13H): for service brake is 6.43 m/s^2 and for secondary brake is 2.44 m/s^2 . Taking into consideration the above mentioned regulations and the energy demand for a proper and safety operation of brake system, the braking cycle shown in Fig.1 was defined. The dimensioning of the backup batteries for the brake-by-wire system is based on 20 consecutive cycles, each of which according to the shown profile and without any recharging of the batteries during the entire test cycle.

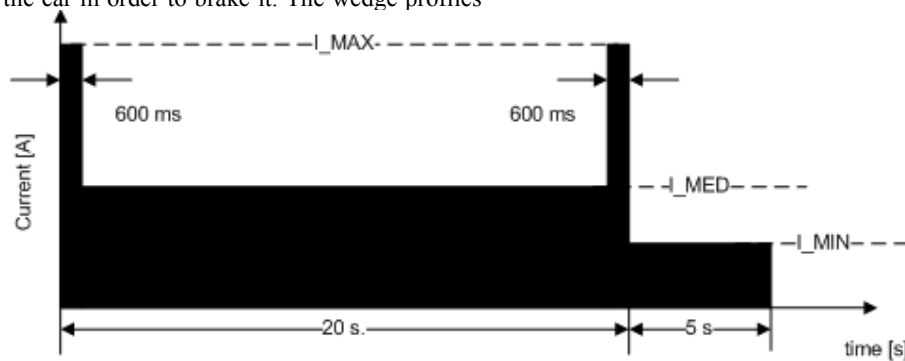


Fig.1 One brake cycle from the current consumption point of view

Li-ion Sony 26650 cells were chosen as backup energy storage system for electronic brake system. One battery is made of 6 cells in serial connection. Technical data for these cells are as follows: nominal voltage: 3.6 V; nominal capacity: 2.5 Ah for 0.2C discharge current; maximum charge voltage: 4.1 V; cell shape: cylindrical;

cell dimensions: diameter: 26 mm; height: 65 mm; mass: 89.5 g.

2. CALCULATION METHOD

There are different methods for battery internal impedance estimation, one of the most common is

electrochemical impedance spectroscopy (EIS). The first impedance measurements of batteries appear to have been made by Willihnganz in 1941 [2]. Afterwards other methods for determining battery impedance were developed. For example, the phase angle between the ac voltage across the battery terminals and the ac current through the battery (measured as a voltage through a sense resistor) was continuously monitored [3,4] in order to determine the battery impedance. In the system developed by Muramatsu in 1985 the relationships between the battery impedance at different frequencies (defined as impedance spectroscopy), remaining capacity and battery state of health is used to detect state of charge and state of health of the battery [5]. Predetermined values based on this relationship are stored in look-up tables and used in order to determine state of charge and state of health of the battery. Look-up tables are tables in which fixed values of measured parameters, such as voltage, current, impedance and temperature, can be stored and used in order to indicate the battery state of charge.

In 2006 Kazuo Onda *et al* [7] developed a new method for Li-ion and NiMH batteries internal impedance $Z(\omega)$ measurement. This method converts the voltage response signal to the current step or current pulse input signal through Laplace transformation for getting the impedance

of the electrochemical system at different frequencies $Z(\omega)$.

Although these methods are very useful for studying and developing new battery types, these are off-line methods which requires time and expensive apparatus and they are not fitting to an on-line battery diagnosis system requirements.

In Fig. 1 is shown the load current profile for an electric brake system as was presented above. For a safe and proper operation of braking system, during battery discharging process, the battery voltage shall not goes under 10 V. This means that the cell voltage shall not go under 1.7 V during discharging process.

In Fig.2 the voltage characteristic for 15 A discharging current is shown. Analyzing the shape of the voltage characteristic it could be seen a suddenly decrease of the battery voltage in the beginning of the discharge process – this corresponds to battery electrical resistance voltage drop –, after that the voltage curve slope decreases – this corresponds to electrochemical processes which occur inside the battery during discharging process (polarization, charge transfer, diffusion,...). The shape of the battery voltage curve for a constant discharge current of 15 A presented in Fig.2 shows that the electrochemical processes which occur inside the battery during discharging process have different time constant.

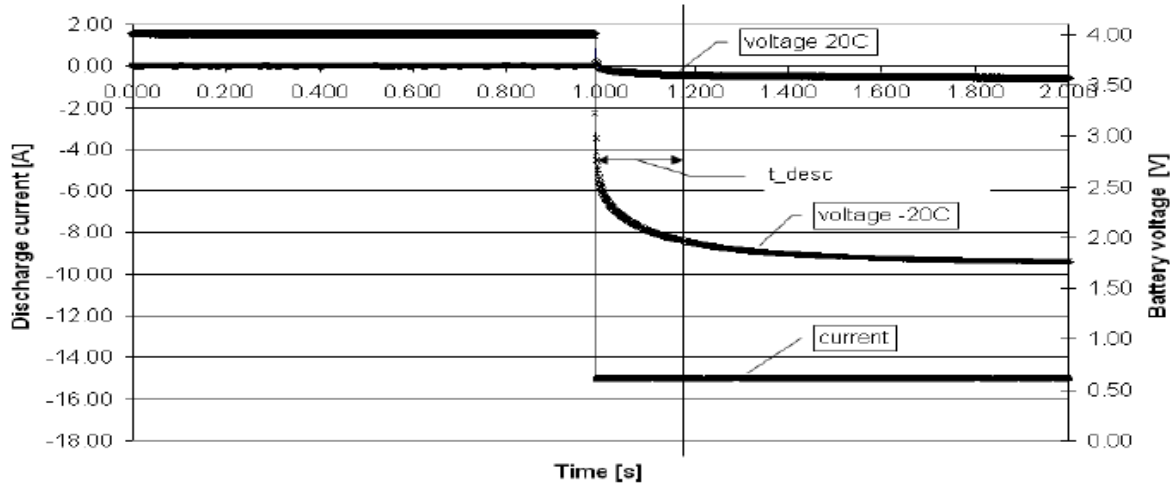


Fig.2 Li-ion Sony 26650 battery voltage during discharging process with 15 A constant current for 2 different battery temperatures: 20 °C and -20 °C

It could also be seen in Fig.2 the temperature influence upon the battery voltage during discharging process, the discharge current was kept the same in both cases: 15 A. The voltage drop over the battery internal resistance for low temperature (-20°C) is substantially bigger than the voltage drop over internal battery resistance at 20°C. So, the internal resistance for low temperature (-20°C) is bigger than battery internal resistance for 20°C.

The difference between the battery open circuit voltage (OCV) and the battery voltage during discharging process represents the voltage drop over battery internal resistance. Depending on the moment of time (t_{desc}) when the battery voltage is measured, the battery internal resistance value will be different and this value of internal resistance expresses other phenomena which occur inside

the battery during discharging process. In order to estimate the value for battery internal resistance following equation is used (1):

$$|R_{int}|_{t_{desc}} = \frac{U_{OCV} - U_{bat}|_{t_{desc}}}{I_{desc}} \Omega \quad (1)$$

Where: $|R_{int}|_{t_{desc}}$ - battery internal resistance for t_{desc} moment of time after the discharge current was applied; U_{OCV} - battery open circuit voltage, battery voltage before the discharge current is applied; $U_{bat}|_{t_{desc}}$ - battery voltage for t_{desc} moment after the discharge current was applied; I_{desc} - battery discharge current.

3. TEST SYSTEM AND MEASUREMENTS RESULTS

In Fig.3 it could be seen the block diagram of the circuit used for performing the measurements during discharging tests:

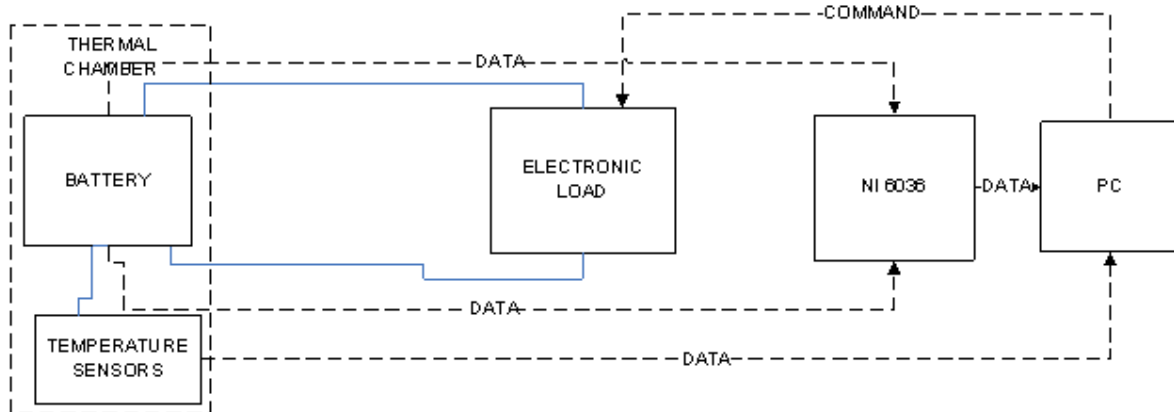


Fig.3 Measurement circuit block diagram

Battery: Li-ion Sony 26650, thermal chamber: Votsch 4002, electronic load: Agilent N3306A, temperature sensors: module NI USB 9162 with K thermocouples, acquisition board: NI 6036E.

Battery was discharged with different constant currents using electronic load Agilent N3306A. LabView programs were used to command the electronic load.

With the measurement circuit which is shown in Fig.3 several discharge tests were performed. The tests were

done for different battery temperatures: -20°C , -10°C , 0°C , 20°C , 40°C , 60°C and for different discharging currents: 23 A, 15 A, 10 A, 7 A, 2.5 A. The acquisition board NI 6036E was used for storing the battery voltage and current measurements data. The measurements were performed at each millisecond. Using equation (1) the battery internal resistance was calculated for discharge time t_{desc} between 1 ms and 500 ms. Some of the results can be seen in Fig.4-6 below:

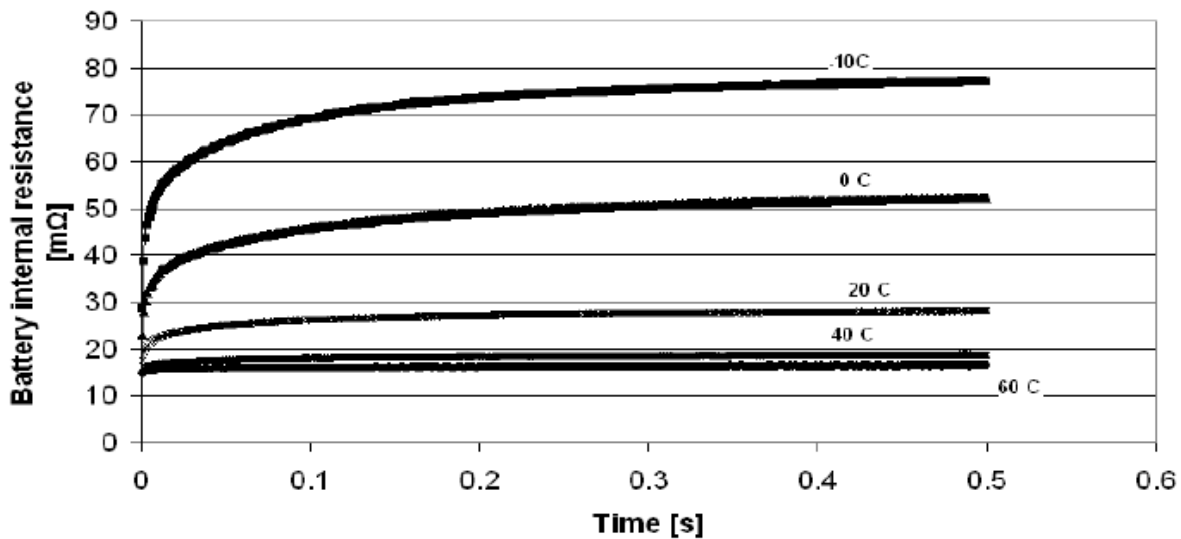


Fig. 4 Battery internal resistance for 23A discharge current at different temperatures

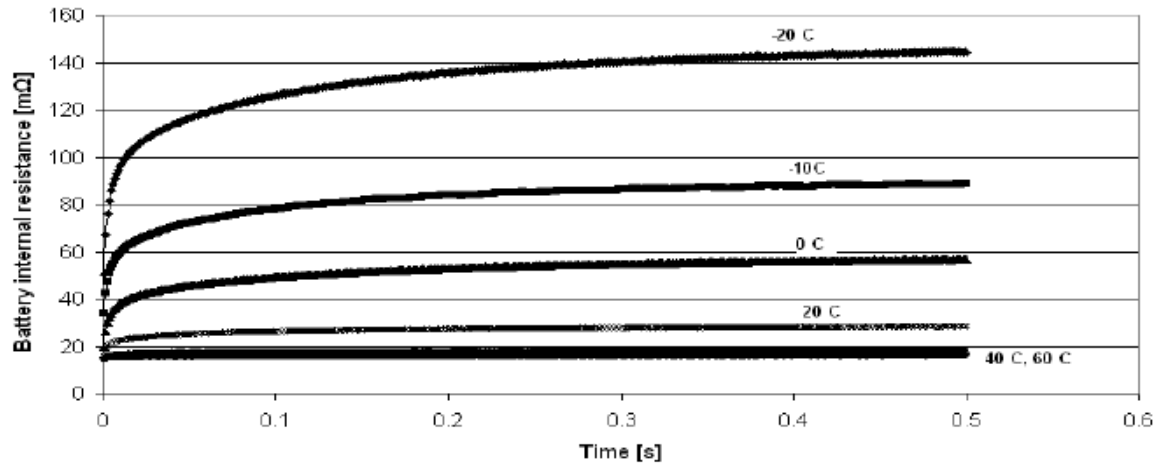


Fig. 5 Battery internal resistance for 15 A discharge current at different temperatures

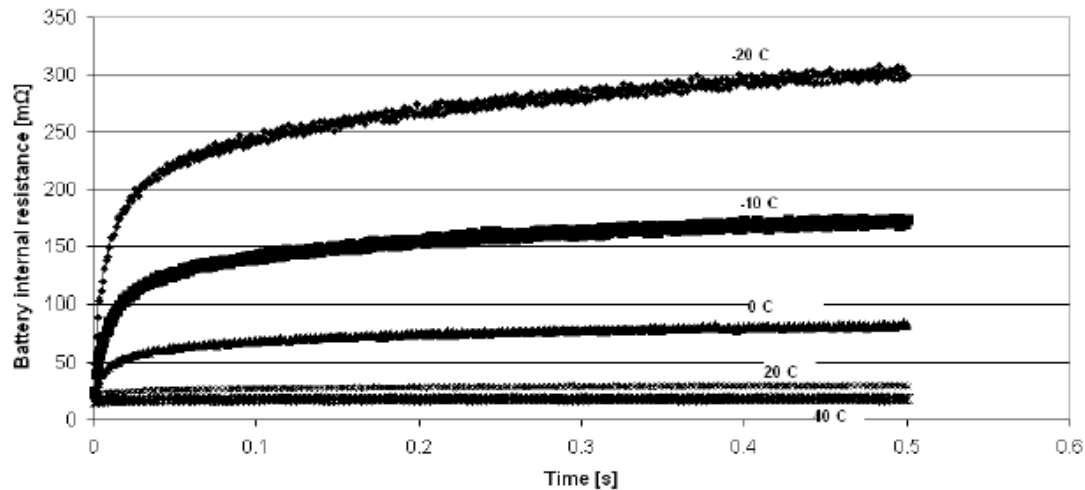


Fig.6 Battery internal resistance for 2.5 A discharge current at different temperatures

It could be seen in all three cases presented above: 23 [A], 15[A] and 2.5[A] constant discharge current that the battery internal resistance estimated after several milliseconds differs from battery internal resistance estimated after several hundreds of milliseconds. Therefore it is important to establish which is the most relevant moment of time for the supplied application and for that moment of time the battery voltage will be measured and battery resistance will be estimated. All further estimation shall be done after the same time interval after the discharge current was applied to the

battery. These requirements are important because we'll want to compare the resistance estimated values during battery lifetime. During battery lifetime the internal resistance will change due to the battery ageing process.

Summarize the obtained measured data during discharging tests done with different currents and at different temperatures, two families of resistance curves were obtained. In Fig.7 are presented these curves for two different time intervals: 2 milliseconds and 500 milliseconds from the moment when discharge current was applied.

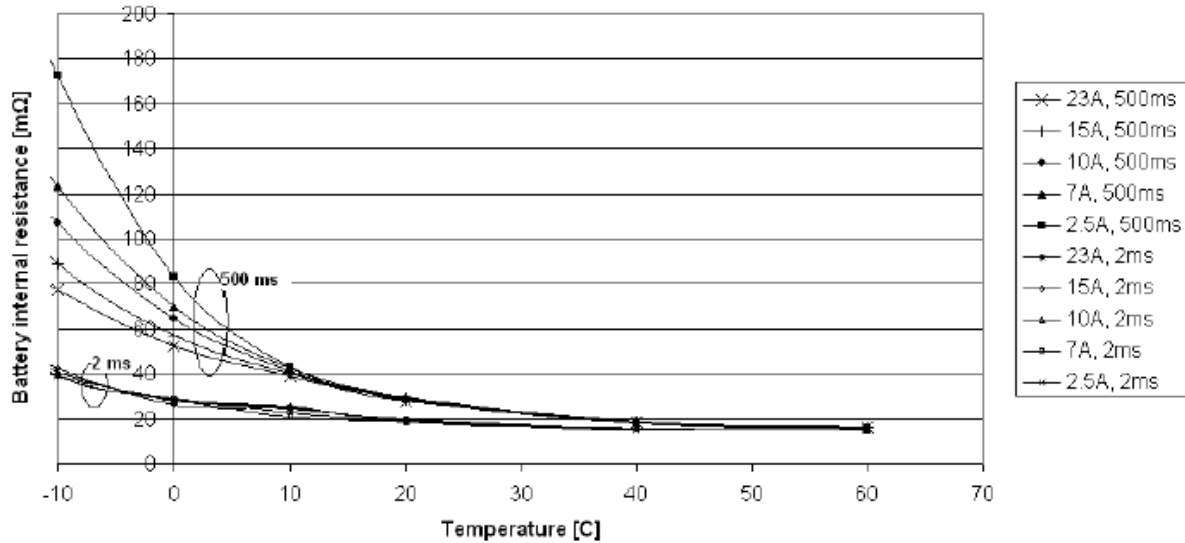


Fig.7 Battery internal resistance curves for two time intervals: 2 ms and 500 ms from applying the discharge current

For the temperature values under 40°C internal resistance values for 2 ms time interval differ than resistance values for 500 ms. Additionally, for temperature values under 10°C internal resistance value depends on discharge current value – see Fig.7. Analyzing the current load profile from Fig.1 which is specific for electrical brake system presented before, the proper time interval for battery voltage measurement and for internal resistance estimation was chosen 500 ms.

After a lot of tests performed with Li-ion 26650 Sony batteries it was obvious that the most difficult to fulfill part of the discharge characteristic is that with 23 A discharge current for 600 ms. For battery temperature of -20 °C the battery is not able to provide the discharge current specified in the Fig.1 – see Fig.8 below: Although

the discharge profile prescribed for the battery was that specified in Fig.1 the battery was not able to provide the prescribed current – see Fig.8. Several tests were done for different battery temperature above -20 °C: -18 °C, -15 °C, -13 °C. Starting with -15 °C the battery was able to provide the specified discharge current profile. Taken into consideration the tests results, the minimum reference temperature value for battery was chosen -10 °C. This value was chosen in order to cover the deviations between different battery cells and the deviations which will occur during battery service life. When environment temperature is below -10 °C the battery shall be equipped with a thermal management system in order to bring it to a temperature at least equal to -10 °C.

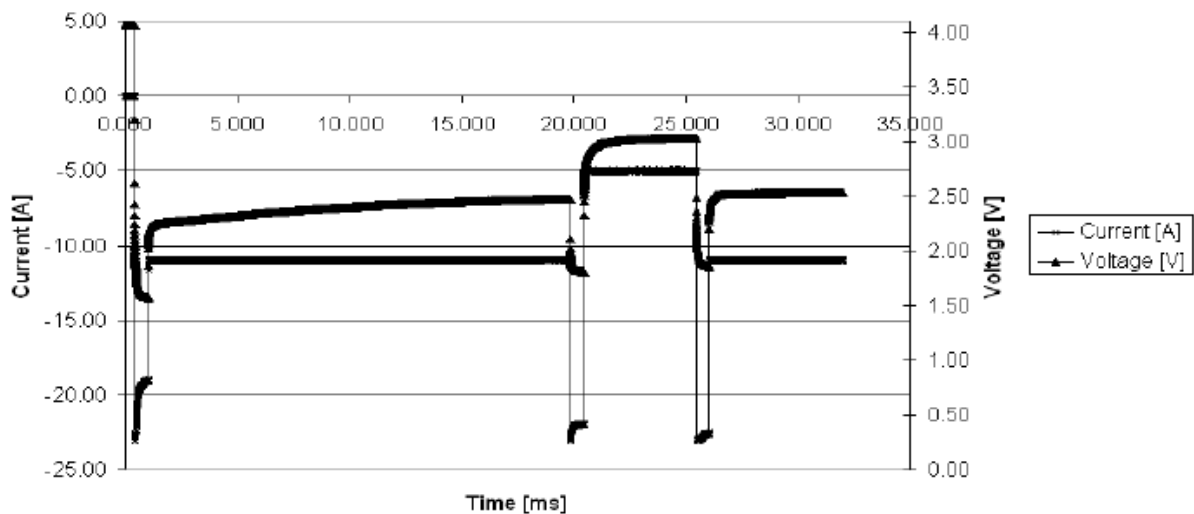


Fig. 8 Brake cycles current profile discharged from a battery at -20 °C

The battery internal resistance shall be calculated on-line, continuously, while the car is running. Each time when the algorithm decides that the discharge current is greater than a prescribed threshold, after time interval of 500 ms since the discharge began, using equation (1), battery internal resistance is calculated. Calculated value of battery internal resistance shall be adapted for the most difficult situation for the battery: discharging with 23 A discharge current for 600 ms time interval at -10°C battery temperature. For this situation the battery shall be able to provide the energy in order to stop the car in safe conditions. Look up tables will be used in order to adapt the calculated value of battery internal resistance. If the battery internal resistance value is greater than a prescribed threshold, that means that the battery is not able to provide the energy with the required parameters, the battery shall be replaced immediately.

4. CONCLUSIONS

Real time estimation for internal resistance of the Li-ion battery which is used as backup energy supply for a dry-brake-by-wire-system is presented into this paper. After a lot of tests were performed, battery discharged curves and application requirements were analyzed, it was established a method for internal resistance estimation. Equation (1) and a time interval of 500 ms was used for internal resistance estimation. The time interval of 500 [ms] was established as the most relevant for the application which is supplied by the battery. Another important remark for this estimation is that each time when internal resistance is calculated the time interval between applying the discharge current and measuring battery voltage shall be kept the same (500ms). Observing this rule the internal resistance value can be traced back during battery service life. Because the application

supplied by these batteries is safety critical, the battery shall be replaced immediately when the algorithm estimates that the internal impedance is greater than a prescribed threshold – that means that the battery cannot provide the required power.

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