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doi:10.15199/48.2025.01.57

Study on properties of lithium ion battery in different load conditions

***Abstract**. This paper evaluates the properties of lithium-ion batteries at different discharge rates and temperatures, by determining the internal resistance of the battery through measurements of the battery's current and voltage during discharge. Resistance is calculated over the entire discharge cycle of the battery, for different initial battery temperatures. The internal resistance is a crucial parameter that influences battery efficiency and consequently the available operating time of the devices powered, which is especially significant in electric vehicles.*

Streszczenie.** Niniejszy artykuł służy ocenie właściwości akumulatorów litowo-jonowych przy różnych wartościach prądu rozładowania oraz temperatury, dzięki wyznaczeniu rezystancji wewnętrznej akumulatora na podstawie pomiarów napięcia i prądu podczas procesu rozładowywania. Rezystancja obliczana jest dla całego czasu trwania rozładowania, dla różnych początkowych wartości temperatury akumulatora. Rezystancja wewnętrzna jest kluczowym parametrem akumulatora, który wpływa na jego sprawność i w konsekwencji na czas pracy zasilanych urządzeń, co jest szczególnie istotne w pojazdach elektrycznych. **(Badanie właściwości akumulatora litowo-jonowego w zmiennych warunkach obciążenia)

Keywords: lithium-ion battery, internal resistance of lithium-ion battery, temperature influence on lithium-ion battery, discharge rate influence on lithium-ion battery
Słowa kluczowe: akumulator litowo-jonowy, rezystancja wewnętrzna akumulatora litowo-jonowego, wpływ temperatury na akumulator litowo-jonowy, wpływ prądu rozładowania na akumulator litowo-jonowy.

Introduction

Batteries are devices that convert the chemical energy of the active substances they contain into electrical energy through a series of chemical reactions. The well-known and widely used lead-acid (Pb) batteries have found a wide range of applications, especially in the automotive industry as starter batteries, as well as traction batteries in electric carts, pallet trucks, etc. Nickel-cadmium (NiCd) are the other popular type of batteries, known for over 100 years. Recognised for their reliability and durability, these batteries have been used in the power, mining, and railway industries where high reliability of power supply is required. In the past 30 years, electrochemical energy sources have developed rapidly. Nickel-cadmium (NiCd) cells, which have been known for many years, have been replaced by less environmentally harmful nickel-metal hydride (NiMH) cells [1]. High-temperature Na-NiCl batteries with operating temperatures ranging from 270 to 350 ° C [2] - [3] were tested for applications in electric vehicles. However, the breakthrough in battery power systems occurred with the development of lithium-ion cells [1]. These cells are characterised by the highest voltage among other batteries, ranging from 3.6 to 3.7 V, and the highest energy density per mass unit. Lithium-ion batteries are commonly used in almost every battery-powered device, from small mobile devices, such as phones and power tools, to high-power devices, like electric and hybrid vehicles. They are also used for stationary grid and industrial energy storage, as well as household energy storage coupled with solar power installations. Lithium-ion batteries are being increasingly adopted in industrial equipment on production lines where reliability requirements are very high. Understanding the properties of electrochemical batteries is crucial to ensure that they are exploited in the appropriate manner, allowing them to prolong their lifespan. The application of lithium-ion batteries in electric vehicles requires a number of tests which provide essential data used to, e.g. algorithmically extend vehicle range, and its proper estimation depending on external conditions and driving style. To accurately determine a battery's state of charge, the ability to obtain battery internal resistance value is essential.

The purpose of this paper is to investigate the properties of a lithium-ion battery and to determine the changes of its internal resistance depending on operating parameters such as load current, internal temperature, and depth of discharge. Laboratory tests were carried out to determine aforementioned changes.

Problems of electrochemical batteries application

Electrochemical batteries have specific performance parameters that make them preferable to implement in particular applications. For example, popular lead-acid batteries have different characteristics depending on their internal design, and can be used as starter batteries, traction batteries, or for energy storage in uninterruptible power supply (UPS) systems [4]. Lithium-ion technology has attracted significant interest because of its lower cell weight and size, as well as the higher cell voltage, compared to other electrochemical batteries. Lithium-ion batteries are also superior in terms of reliability and durability, as they offer low self-discharge rates, no memory effect, and well over a thousand charge/discharge cycles. Various chemical compositions of the cathode, anode, and electrolyte are used, allowing the optimisation of cell parameters for specific application requirements, whether it is high power, better durability, or improved safety [5] - [6]. They are commonly used as a power supply for handheld devices such as mobile phones, power tools, and garden tools. Additionally, they are replacing lead-acid batteries as energy storage in domestic installations and large-scale energy storage in electric grids. Lithium-ion batteries have contributed significantly to the rapid development of electromobility, which refers to electric and hybrid cars along with other vehicles.

Despite aforementioned advantages, lithium-ion technology does not completely meet the modern-day challenges of the high-power industries, the biggest problem being prolonged battery charge time and manufacturing cost. Environmental concerns are also taken into account. Therefore, optimisation of battery performance lays in the best interest of all.

The power supply for electric vehicle drives tend to show significant variations in the current value demanded from the batteries. Power losses are related to the RMS value of the current consumed by the drive and the internal parameters of the battery, primarily the internal resistance. According to the literature [7] – [10], the internal resistance of lithium-ion batteries is a variable parameter and its changes are a result of the chemical processes occurring inside the cell, strongly influenced by external conditions, battery state of health and state of charge.

A. Internal resistance measurement methods

Figure 1 shows a simplified electrical circuit diagram of the battery. Resistor R_1 represents the resistance of the connections within the battery and the transition resistance between the electrodes and the electrolyte. Resistor R_2 is the polarisation resistance, which depends on the state of charge. The internal resistance can be determined using various methods described in the literature [7], [11] – [14].

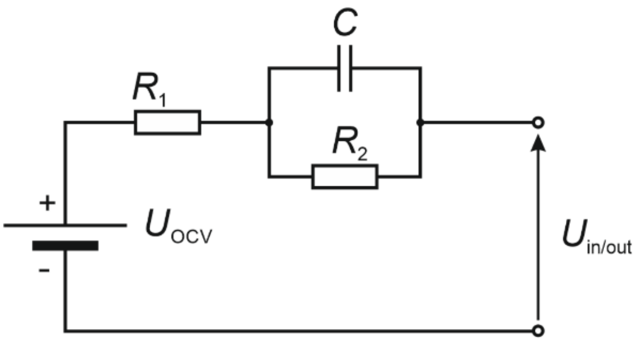

Fig.1. Simplified battery equivalent circuit

Internal resistance measurements

A. Battery parameters

During the tests, a lithium-polymer battery composed of four cells connected in series was used. Parameters of the single cell are shown below in Table 1.

Table 1. Parameters of a single li-ion cell

No.	Parameter type	Value
1	Type of cell	LiPo (NMC)
2	Rated discharge capacity	3200 mAh
3	Nominal voltage	3.7 V
4	Continuous current	20 A
5	Max. continuous current	40 A
6	Cell weight	84 g
7	Cell dimensions	Thickness: 4.7 mm Width: 43 mm Height: 128 mm

B. Test stand and resistance measurement method

In order to determine the internal resistance of the battery, a method based on voltage measurement was introduced. It consists of two voltage measurements, one in open-circuit state (U_{OCV}), and the second with a certain load (I_{CCmax}) applied to the battery (U_{OUT}).

Given these values, the internal resistance could be calculated using the following formula:

$$(1) R_B = \frac{\Delta U}{I_{CCmax}} = \frac{U_{OCV}-U_{out}}{I_{CCmax}}$$

The test stand used for the measurements is presented in Figure 2. The battery was tested with a Chroma programmable load, a Hameg signal generator, and a Yokogawa DL850 scope recorder. The programmable load was operating in constant current (CC) mode, which was controlled by an external signal from the programmable signal generator.

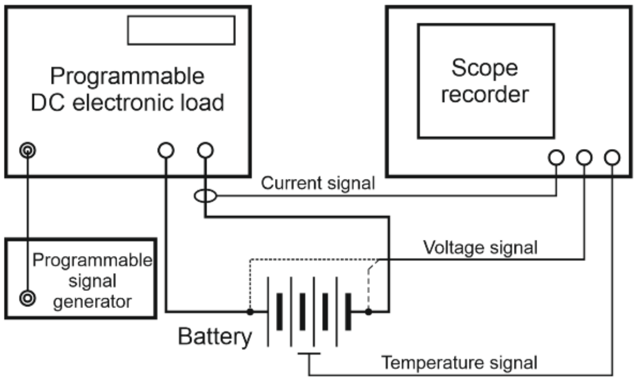

Figure 2. Block structure of the laboratory test stand

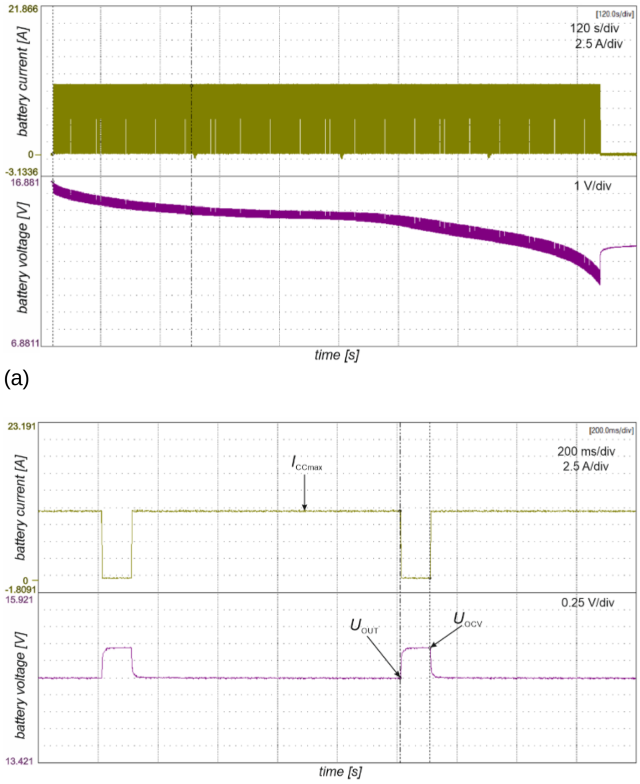

Figure 3. Oscillograms of battery current and voltage: full discharge cycle (a), magnified (b)

The rectangular waveform control signal had a frequency of 1 Hz and a duty cycle of 90% (Figure 3b), which corresponds to battery load set at I_{CCmax} for 0.9 s, and 0 A for 0.1 s, when the U_{OCV} voltage was measured. This signal facilitated the measurement of the internal resistance from full charge to full discharge. The battery temperature was also measured during the test cycle, as it significantly affects its internal resistance. Figure 3 shows a representative oscillogram of the discharge current and voltage of the battery. Figure 3a shows the waveforms of the entire discharge period, while Figure 3b contains the waveforms for a shorter period.

Figure 4 shows a view of the test stand. The battery was automatically disconnected by the programmable load when it reached the nominal cutoff voltage. The scope recorder was used to observe and record parameters of interest, such as current, voltage, and battery temperature.

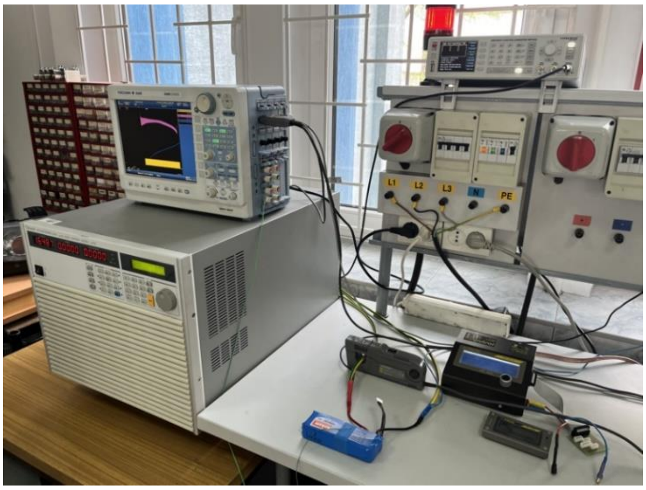

Figure 4. View of the test stand

Test results

Laboratory tests were performed for three different initial battery temperatures: -15 °C, 0 °C and 22 °C. For temperatures -15 °C and 0 °C measurements were made for load current values 3 A and 10 A with 90 % duty cycle of the current control signal. For an initial battery temperature of 22 °C, 3 A, 10 A and 30 A current values were tested, identically with the 90% duty cycle. The average battery load current for the aforementioned cases was 2.7 A, 9 A and 27 A, respectively. Based on the results obtained and using relation (1), the internal resistance (R_B) of the tested battery was calculated. The results are presented in Figs. 5 – 7. Figure 5 shows the results for initial temperature of 22 °C, Figure 6 for 0 °C, and Figure 7 -15 °C. When analysing the relation of the internal resistance of a battery to its depth of discharge, it can be observed that this parameter is not constant and depends on both the value of the load current, the state of charge of the battery and the temperature. The profile of internal resistance variation is influenced by both the battery temperature and the load current. The internal resistance of a battery is crucial for the reliable operation of powered equipment, particularly in electric vehicles where the battery is the only power source. Therefore, understanding how the internal resistance of a battery changes with the state of charge and temperature is very important. This information enables the development of algorithms that control the vehicle's performance to maximise range. Figures 5a, 6a and 7a indicate that temperature decrease to -15 °C level results in significant internal resistance increase. The high losses result in a notable decrease in the range of the powered vehicle. Current flowing through the internal resistance results in heat generation, thus while operating, battery gradually heats itself through the discharge process, which reduces its resistance when the temperatures are lower than 10 °C. Since the temperature rises above 10 °C, further self-heating does not significantly affect resistance until the end of normal discharge. Ideally the battery temperature should be maintained at a constant value through the entire discharge cycle. The equipment used for battery cooling unfortunately would not allow that, especially for lower temperature and high discharge current. The cooling system was not efficient enough to dissipate all the generated heat. However it is worth noting that in real life conditions the batteries do not maintain constant low temperature, and are rather deliberately heated, so the presented results are still valid.

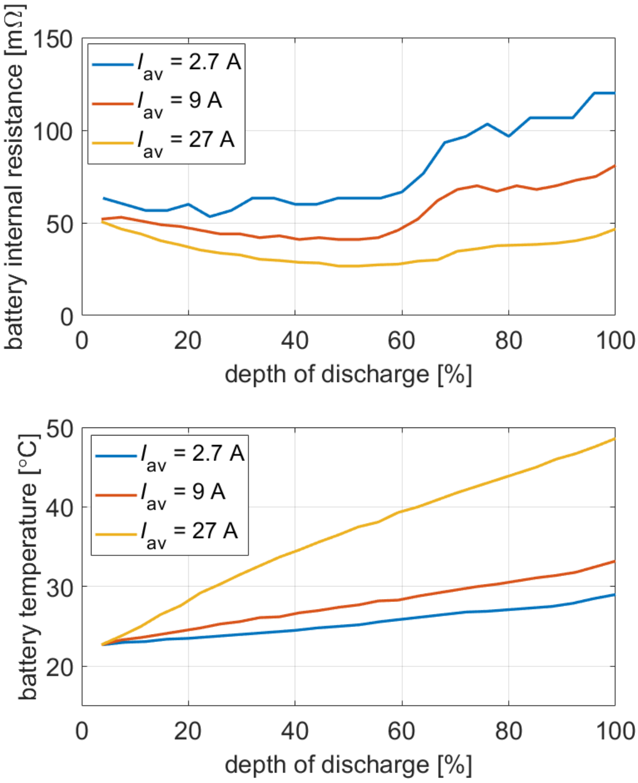

Figure 5. Relation of the initial resistance, temperature and DOD (depth of discharge) of the battery for the initial temperature of 22 °C and different load currents

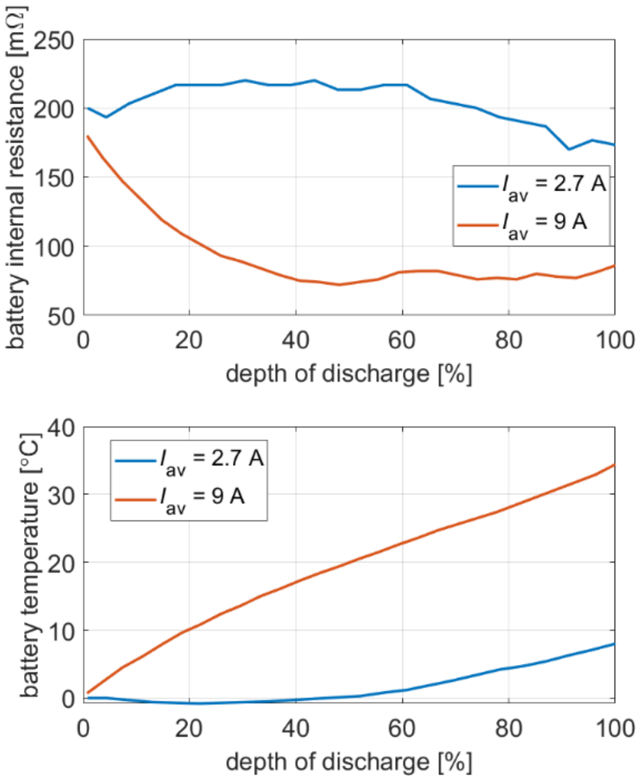

Figure 6. Relation of the initial resistance, temperature and DOD of the battery for the initial temperature of 0 °C and different load currents

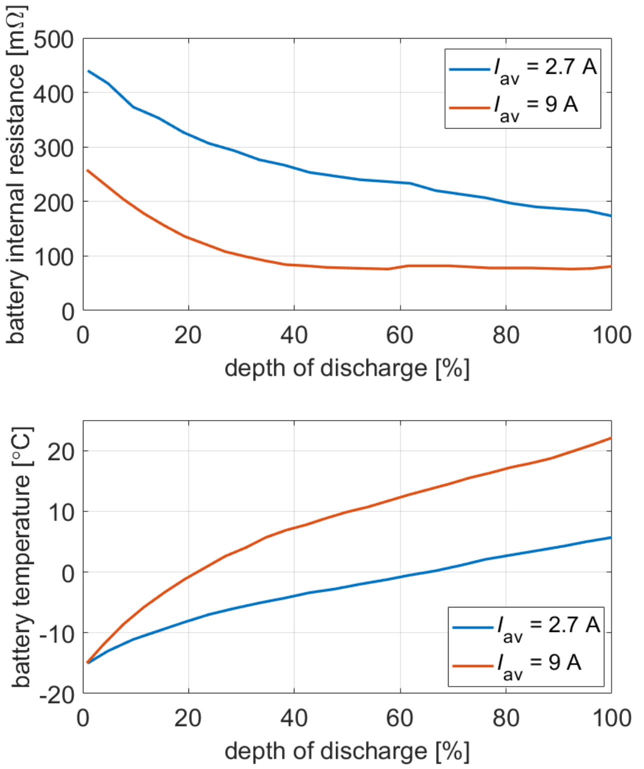

Figure 7. Relation of the initial resistance, temperature and DOD of the battery for the initial temperature of -15 °C and different load currents

Due to the significant change in the battery's internal resistance along with temperature and load current, it is crucial to maintain the electric drive's RMS current value as close as possible to its average value in order to minimize losses within the battery.

Conclusions

Laboratory tests of lithium ion batteries are very complex due to complicated nature of the chemical processes occurring inside of the cell. They are also time consuming since the battery charge and discharge cycle could take several hours to complete, depending on the charge/discharge currents. However their importance is undoubted, particularly when dealing with a wide range of operating temperatures and load currents. The results provide crucial insights of the battery operation, necessary for their modelling and predicting overall performance. Better understanding of the battery behaviour allows for its proper management that could lead to e.g. expected lifetime prolongment, extending the powered device single-charge operating time etc.

This article presents experimental tests conducted on a 14.4 V, 3200 mAh lithium-ion battery pack under various load currents and different initial operating temperatures. The results indicate that:

- Temperature drop below 10°C results in significant increase of the internal resistance.
- Comparing the initial resistance of battery in – 15 °C and 22 °C, negative temperature results in multiple times higher battery resistance, which has negative impact on the level of battery losses.
- The current value also influences the internal resistance. Greater discharge rate corresponds with lower resistance value, which could be beneficial for high power applications.
- Internal resistance changes during the discharge cycle; while the changes might not be as significant as those triggered by the temperature, they are still apparent, especially near the end of the discharge.

Authors plan to further investigate the nature of lithium-ion cells, especially in terms of the impact of varying load current. All the gathered data will help to develop new solutions oriented on improving overall battery efficiency, by optimizing its operating conditions to minimize internal resistance changes evoked by external operating conditions.

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