Analysis and research of the causes and course of degradation of lithium batteries

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Abstract. Energy storage devices based on lithium technology are confidently leading the respective market due to their significant advantages over other technologies in the industry. Despite their relatively recent history of appearance, they managed to undergo many modifications of both physical and chemical components. One of the constant goals of all research in this field is the formation of knowledge about the degradation processes occurring inside a given chemical current source, and ways to influence them. Systematization and identification of the fundamental reasons for the decrease in the performance of lithium batteries still remains a topical issue of today, and therefore is considered in this article. And no matter how studied this issue looks, taking into account the existing many long-term experimental data of a huge number of scientists and a number of different types of companies, but still, optimization of work is impossible without identifying and eliminating as many destructive factors as possible in battery operation. The difficulty of this process lies also in the fact that, taking into account all the high-tech production processes in the world, there are no two identical lithium current sources. On the example of a single battery, the ability to maintain high performance, close to nominal, was demonstrated from a source that, due to its lifetime, should not have had them. The data obtained during the experiment, which confirmed the high performance, show once again that the issue of degradation of lithium current sources can and should be studied further.

1. Introduction

Currently, an active transition to the use of batteries based on a lithium electrochemical system as energy storage devices continues and is only growing, including this applies in particular to lithium-ion batteries. First of all, this is due to the fact that in terms of their energy-mass and power characteristics, lithium-ion batteries are significantly superior to analogs of the nickel electrochemical system [1]. The well-known main advantages of lithium-ion batteries are:

– weight reduction of the battery due to a higher energy/weight ratio, which for lithium-ion batteries reaches 40%;
– low heat generation and high energy efficiency during the charge/discharge cycle with low self-discharge;
– a more technological manufacturing process that provides good repeatability of characteristics, high reliability and low cost.

However, there are a number of serious disadvantages of lithium-ion batteries. The most important of which is that lithium-ion batteries inevitably begin to age from the moment they are manufactured. The second major disadvantage is that batteries require built-in security systems.

Nevertheless, due to its growing demand, unrelenting prospects and the widest distribution throughout the world, lithium batteries have today taken a leading position in the global market for chemical current sources and, despite this, continue to increase their influence. This can be confirmed not by a gradual, but by an avalanche-like decrease in prices for 1 kW of power produced by energy storage devices of this type over the past few years, which is associated both with the development of technologies and with the rapid growth of demand and supply in the world market for consumer and industrial purposes. Comparative analysis of the technical characteristics in table 1 [2] shows a huge number of advantages of using lithium-ion technology over the rest.

The study of the processes occurring inside lithium batteries in active (charge / discharge) and passive (without load) modes is the basis for determining the condition of the battery as a whole and its constituent parts in particular in order to create optimal conditions for use and obtain the highest efficiency over the longest time. And knowledge of the consequences of the influence of external factors, taking into account the

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course of internal processes, will allow in the future to preserve the battery life as much as possible, including giving an understanding of the possibility of their recovery.

To date, there are a huge number of researches devoted to the study of lithium current sources. A huge contribution to the advancement and development of scientific and practical foundations for the construction, application, analysis and synthesis, degradation processes and many other issues related to the production, operation and diagnosis of the state of lithium batteries, in many of his works, as well as recent works [3-6] made by such scientists in the field of studying energy storage devices as professor Dirk Uwe Sauer, Philipp Dechent and other from RWTH Aachen University, Institute for Power Electronics and Electrical Drives (ISEA), Aachen, Germany.

Table 1. Characteristics of commonly used rechargeable batteries

Specifications	Lead Acid	NiCd	NiMH	Li-ion Cobalt	Li-ion Manganese	Li-ion Phosphate
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low
Cycle life (80% DoD)	200–300	1,000	300–500	500–1,000	500–1,000	1,000–2,000
Charge time	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h
Overcharge tolerance	High	Moderate	Low	Low. No trickle charge		
Self-discharge/ month (room temp)	5%	20%	30%	<5% Protection circuit consumes 3%/month		
Cell voltage (nominal)	2V	1.2V	1.2V	3.6V	3.7V	3.2–3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75V	1.00V		2.50–3.00V		2.50V
Peak load current Best result	5C 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C (–4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C (32 to 113°F)		
Discharge temperature	–20 to 50°C (–4 to 122°F)	–20 to 65°C (–4 to 149°F)		–20 to 60°C (–4 to 140°F)		
Maintenance requirement	3–6 months (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free		
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory		
In use since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very high	Very high	Low	Low		
Coulombic efficiency	~90%	~70% slow charge ~90% fast charge		99%		
Cost	Low	Moderate		High		

At the same time, such issues as the mechanism of non-destructive testing of parameters, the problem of recycling, and increasing the service life, including by reusing and giving a “second life” to a lithium battery, remained insufficiently studied, many of which can be answered based on determining their health condition. It is generally accepted that today there is no fast, accurate and simple way to determine the current state of lithium current sources, which could be performed with minimal labor and resources, and which would not require the use of special laboratory measuring equipment and a lot of time. At the same time, developments in this area continue at the present time.

2. Purpose of the study

The purpose of this work is a concise systematization of knowledge about the processes that lead to a deterioration in the performance of lithium batteries, highlighting the main informative parameters about their health status, as well as methods for determining it.

3. Classification of the causes of lithium battery malfunctions

The previously mentioned aging of lithium-ion batteries is associated with a number of degradation processes inside the battery. The rate of such processes strongly depends not only on external factors, but also on operating modes [7]. The problem of electrode degradation during cycling is one of the most important in battery research.

Lithium battery failures are divided into productivity failures and safety failures.

Productivity failure includes capacitance loss, life shortening, abnormal voltage, abnormal current, excessive internal resistance, self-discharge, high and low temperature aging, etc.

Safety failure includes thermal runaway, short circuit, liquid leakage, lithium precipitation, expansion deformation, puncture (extrusion).

The reasons for the failure of lithium batteries can also be divided into internal and external.

Internal causes mainly refer to the nature of the physico-chemical changes in failure, the scope of research can be traced back to the atomic and molecular scale of studying the thermodynamic and kinetic changes in the failure process.

External factors include impact, puncture, corrosion, high temperature combustion and other causes.

Let us consider in more detail some of the reasons for the failure of a lithium battery and get acquainted with the physics of the process.

First, consider the effect of the interface between solid electrolytes.

The essence of this phenomenon lies in the fact that in the process of charging lithium is attracted to the negative electrode, thereby changing the voltage potential of the battery. Removing lithium during discharging does not completely reset the battery. A network of lithium atoms forms on the anode surface, which is called a stable electrolyte interface (SEI).

The SEI layer is composed of lithium oxide and lithium carbonate, and they grow as the battery cycles. This mesh becomes thicker and eventually causes clogging, making it difficult to interact with the graphite. The longer the battery stays in this state, the worse it gets.

The second reason is the voltage effect. Assume that the charging voltage increases beyond the required high cell voltage, excessive current causes the formation of a lithium coating and overheating. Lithium plating occurs due to excessive lithium ions caused by overcharging. Excess lithium ions cannot be placed between the carbon anode layers and lithium ions. Thus, they accumulate on the anode surface and are deposited in the lithium metal.

This deposition of lithium metal on the anode results in a reduction in the amount of free lithium ions, hence an irreversible loss of battery capacity. This then causes a short circuit between the cathodes. The lithium plating also causes low temperature operation.

It should also be noted here that the formation of a lithium metal coating on the anode, caused by a long over-rated charge, causes the cathode material to become an oxidizing element and lose stability, contributing to the formation of carbon dioxide (CO_2). In this case, the pressure in the battery increases, and if the charge continues under current conditions, a protective device is activated, which is responsible for the safe operation of the battery. If the pressure continues to rise, the diaphragm will rupture and eventually the battery may ignite.

Undervoltage can also lead to battery failure. If the battery voltage drops below two volts, the battery will fail. The reduced voltage leads to the dissolution of the copper anode in the electrolyte. This then increases the battery's self-discharge rate, but as the voltage rises above two volts, the copper ions disperse throughout the electrolyte. Dispersed copper ions precipitate to metallic copper. This can lead to a short circuit between the negative electrodes. For a better perception and visualization of the electrochemical processes that occur during the charging and discharging of a lithium-ion battery, an illustration is given in figure 1 [18].

The third powerful influencing factor is temperature effects. Heat is the main catalyst for the degradation of lithium batteries. High or low temperatures can damage lithium batteries.

The effect of low temperature is to reduce the transformation of active chemicals in the cell. This then leads to a decrease in the current holding capacity of the cell, both when charging and when discharging. Low temperatures also reduce the rate of the chemical reaction, thereby slowing down the incorporation of lithium ions into the intercalation space. Consequently, the power is reduced and the lithium coating of the anode is reduced with loss of capacitance.

High temperatures cause another set of problems that lead to complete battery damage. The reaction rate increases, hence higher currents cause higher heat dissipation and therefore even higher temperatures.

In fourth place in terms of influence on performance indicators is age, which is a description of the processes of physical aging. Batteries become weak with age. Thus, the batteries cannot perform their primary function because they have gone through many recharge cycles. Over time, the plates become coated with grid-like chemicals. This will permanently damage the lithium battery.

The fifth reason is mechanical fatigue. The negative electrodes of lithium cells expand and contract as they are charged or discharged. This is due to the effect of lithium ion incorporation into and out of the crystalline electrode structure.

The voltage of the electrodes leads to cracking of the particles, which in turn leads to an increase in the internal impedance as the cells age or the anode fails. This can lead to overheating and eventually battery failure. This also includes cracking and peeling, loss of contact between individual fragments of the active substance with the current collector, structural changes, etc.

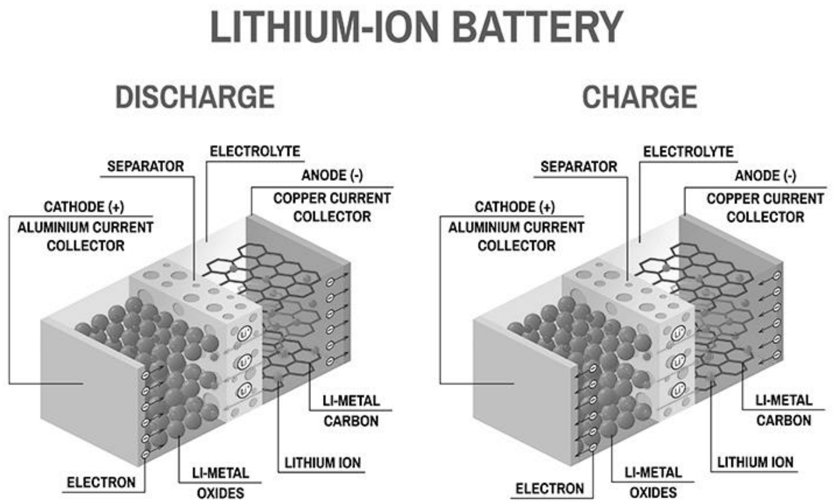


Fig. 1. Electrochemical processes occurring during charging and discharging of a lithium-ion battery

4. Degradation processes occurring in lithium-ion batteries

From an electrotechnical point of view, lithium-ion batteries degrade in three different ways: loss of conduction (CL), loss of active materials (LAM) and loss of lithium reserves (LLI). Over the past few years, researchers have developed many methods for non-invasive analysis of such modes [7]. But before proceeding to their consideration, the first thing to do is to decide what specific battery health indicators can and should be studied.

The degradation of lithium-ion batteries is an inevitable process that occurs not only in batteries in operation, but also in batteries in storage. In order to systematize the idea of the degradation processes of lithium-ion batteries, let's list the main ones [9-11]:
– degradation of the crystal structure of the positive electrode;
– lithium metallization;
– the formation of passivation layers on the electrodes (SEI and SPI) with a noticeable ohmic resistance, which can increase during cycling;
– change in the mechanical properties of the electrodes caused by volume changes during the cycling process;
– consumption of usable lithium as a result of side reactions;
– growth of unbalance of electrodes and batteries throughout the entire service life;
– decrease in the area of the active mass of electrodes involved in current-generating reactions;
– loss of the active mass of the electrode due to its dissolution;
– conductivity of the electrode;
– corrosion of battery cells;
– an increase in internal resistance during cycling with high currents, which leads to an increase in temperature and accelerated degradation;
– destruction of organic electrolytes and salts solvents;
– delamination of the active mass of the electrodes from the current collectors;
– chemical decomposition of the active substance in the electrodes as a result of side reactions;
– electronic isolation of the active material from the electrolyte;
– reduction of coupling between the particles of the active mass of the electrodes;
– shrinkage or melting of the separator;
– internal short circuits caused by impurities or dendritic growth.

The mechanism of degradation processes is shown in fig. 2 [13].

As can be seen from the above, a decrease in capacity and a drop in power of lithium-ion batteries is a consequence of the simultaneous occurrence of a number of processes, as well as their interaction [10-14]. The task of determining the health status of batteries is to highlight the most informative indicators, which in turn would be the easiest and fastest way to measure.

Separately, it is necessary to add some information about the features of degradation processes in a lithium-ion battery experimentally established by Japanese scientists [15]. Their research showed that one of the main indicators of aging – the decrease in capacity – occurs almost linearly with respect to the number of cycles. But a three-month storage of a fully charged battery (emf 4.2 V) leads to almost the same drop in capacity (11%) as after 500 charge-discharge cycles. As a result of a year of storage of fully charged batteries, irreversible capacity loss is 30% [16].

In addition, Sony lithium-ion battery tests were carried out, stored at temperatures of 20 and 60 ºC, which showed that in the case of potentiostatic maintenance of 4,2 V, capacity losses during the year amounted to 23%, of which 18% were irreversible losses. Storage at normal temperature and constant maintenance of the charge contribute to an increase in the degradation rate of lithium-ion battery, while at elevated temperatures this factor is not so critical [17]. In addition, exceeding the threshold value of the charging voltage or a long-term charge of the lithium-ion battery at a voltage of 4,2 V has an extremely negative effect on the battery performance. The main cause of lithium-ion battery degradation in this case is the electrochemical oxidation of the electrolyte on the surface of the positive electrode [18].

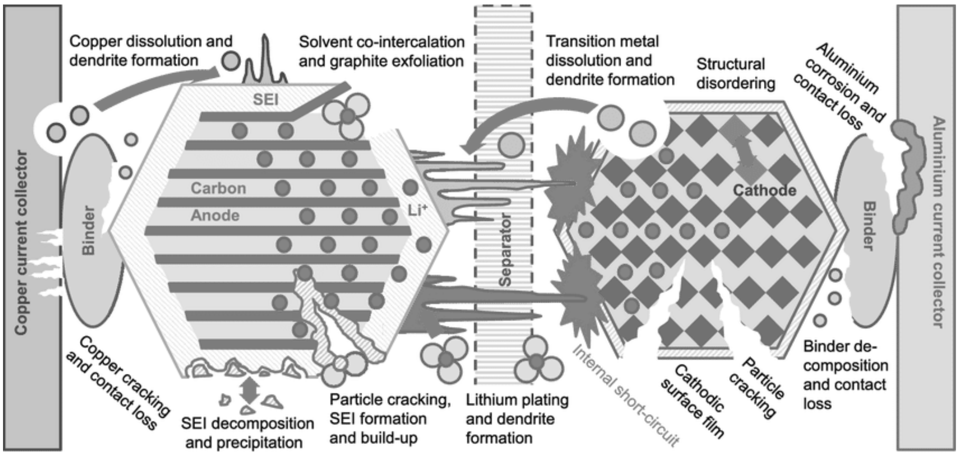


Fig. 2. Degradation mechanisms in Li-ion cells

5. Approach to assessing the state of health of the lithium batteries

Manufacturers and distributors of lithium-ion batteries declare a capacity discharge life under a standard cycle test of at least 90% of the initial capacity when the number of cycles reaches 500 cycles. Or, upon reaching 1000 cycles, the discharge capacity should not be less than 30% of the initial capacity, if the power drops sharply in the standard range of cycles, then this phenomenon is the capacity decay [19]. In this case, the average degradation rate is in the range of about 0,02-0,03% per cycle.

Lithium-ion batteries are complex electrochemical devices with non-linear behavior. Their characteristics strongly depend on their internal and external conditions.

To keep track of these characteristics, batteries are always equipped with a management system, which is part of the battery management system. Its role is to ensure the safe use of the battery and to assess as accurately as possible the main parameters of the battery system, such as its state of health (SOH), state of power (SOP) and state of charge (SOC).

The SOC provides information about the current amount of energy stored in the battery. The SOP indicates the ability of the battery to provide the required power to the consumer. Meanwhile, as the SOH is a quality indicator that indicates the level of degradation of the battery. The accuracy of the SOH assessment is directly proportional to the accuracy of the SOP and SOC assessments. Different methods are used to assess the condition of a battery. Regarding assessing the SOH of a battery, there are three main indicators that determine its condition: internal resistance, impedance and its capacity. Battery capacity reflects the amount of energy a battery can store [20, 21], while internal resistance and impedance are indicators of its power. The impedance of a battery is a combination of its internal resistance and reactance [22].

The SOH depends on the change of these indicators, which depend on the battery mode used. How they change over the course of a battery's life, including aging, is an indication of the battery's ability to continue to perform its intended tasks.

The internal resistance of a battery is considered an important indicator of the SOH. It is determined by the voltage drop when current is applied to the battery. The internal resistance of a battery is highly dependent on battery aging and degradation. The value of internal resistance is comparable to the maximum battery charge, so it is often used as an indicator to assess the charge.

An increase in the internal resistance of a lithium-ion battery will be accompanied by a decrease in energy density, voltage and power, battery heat generation and other failure problems. The main factors leading to an increase in the internal resistance of lithium-ion batteries are divided into the main materials of the battery and its use environment.

A battery can also be examined by analyzing the change in its capacitance (IC) and differential voltage (DV) curves [23], as these parameters also change during battery operation.

Each of the three main methods for determining the state of a battery, based on measuring internal resistance, impedance and energy level, has its own advantages and disadvantages. The advantages of measuring internal resistance are the accuracy and simplicity of the study, and the disadvantages of this method include the impossibility of real-time monitoring of the parameters and the time of the study. The advantages of the impedance measurement method include the accuracy of the data obtained, as well as the ability to identify the cause of battery degradation, the disadvantage of this method is the need to determine the chemical composition for the battery under study. The method of measuring the battery capacity is one of the fastest and most accurate methods for examining a battery, but the disadvantages of this method include the need to fully charge the battery before research.

As previously mentioned, there is currently no single method for determining the current SOH of a lithium battery. In various sources, it is possible to draw certain conclusions about the degradation mechanism of individual electrodes and the battery as a whole by analyzing the shape of the discharge and charge galvanostatic curves and their changes during cycling.

For such an analysis, it is necessary to use the discharge and charge curves in the normalized form. In this case, not the absolute value of the charge is plotted along the abscissa axis, but the ratio of the charge at the current value of the potential to the capacitance of the electrode at this half-cycle. The application of this approach showed that, with a trivial loss of the active substance, the normalized galvanostatic curve does not change at all during cycling. But with an increase in the ohmic resistance of the electrode (during the formation of passive films and for other reasons), the normalized galvanostatic curve shifts along the ordinate axis parallel to itself as it cycles. Finally, with various structural changes, the shape of the normalized curves noticeably changes (although these curves coincide at the initial and final points) [24–26].

To date, there is a huge amount of research for lithium battery technology, which has been in active use for several decades. However, lithium-ion battery testing is still costly and time consuming, so public battery test datasets are a valuable resource for comparison and further analysis. Comparison of open datasets for testing lithium-ion batteries [27] in the public domain allows you to save many hours that turn into years of work, providing access to experiments performed according to generally accepted methods from reputable sources.

6. Experimental research

To study and conduct experiments, a battery was taken, shown in figure 3 with a nominal voltage of 3,7 V (at this voltage, the appliance operates at maximum power for a long time), with a capacity of 3200 mAh. This battery was used in the tablet for more than three years and, due to the inability to continue to perform its functions, was removed from it in June 2018 and stored in a discharged state at room conditions for 5 years until June 2023.

The first measurement over the years showed a residual charge level of 2,3 V. Connecting a load of 1.0 Ohm for 10 seconds with a discharge current of just over 0,6 C (2 A) caused the charge to drop to 1,8 V. Further measurement readings voltage at the terminals of this battery during the day in the disconnected state are listed in table 2.

a *b*

Fig. 3. Test specimen: a) – general view; b) – board BMS

Self-healing charge levels over time is a sign that the battery has retained a certain amount of capacity over such a long period of storage. This capacity also could not be realized for a short-term connection of the load.

Table 2. Charge level self-healing voltage

Time	0 s	1 s	2 s	1 m	1,5 m	2 m	4 m	7 m	10 m	12 m	15 m	17 m	27 m	35 m	45 m	1 h	1,25 h	1,5 h	2 h	3 h	6h	9 h	12 h	15 h	18 h	21 h	24 h
U, B	2,3	1,8	1,93	1,98	2,00	2,03	2,05	2,06	2,07	2,08	2,09	2,10	2,11	2,12	2,13	2,14	2,15	2,16	2,17	2,18	2.19	2,20	2.21	2,22	2,23	2.24	2,24

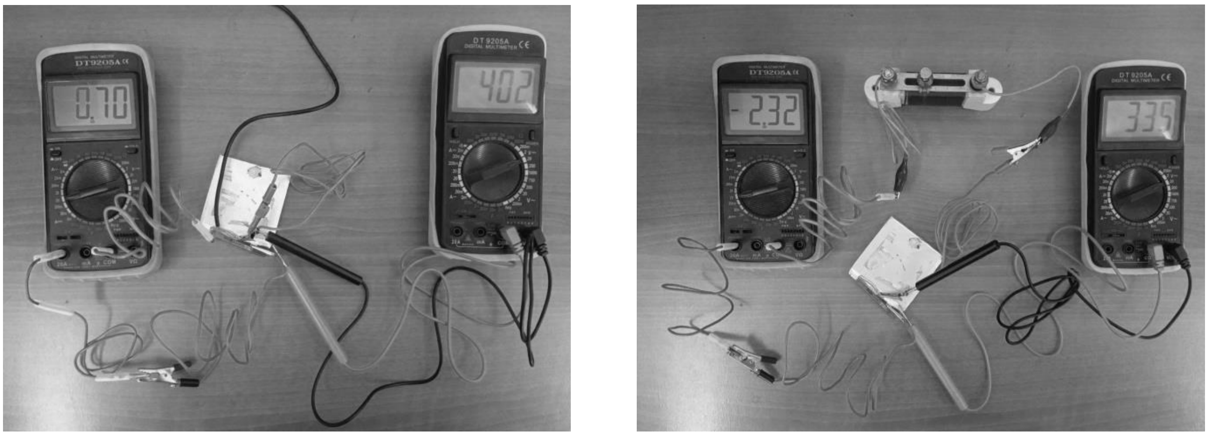
Further study of the prototype implied its charge. An example of connection for charging and discharging the battery is shown in figure 4. In the figure in the measuring circuits, the multimeter is connected on the left as an ammeter, and on the right as a voltmeter.

Since the battery was in a state of deep discharge (< 2,5 V), at first a so-called precharge was applied to it - a constant low current of 0,01 C (0,032 A) to warm it up and also prevent swelling and ignition. Further, after reaching a charge level of 2,8 V, the battery was connected to a charging current of 0,22C (0,7 A) and the voltage was raised to 4,2 V. It is believed that in this state the battery reaches 70-80% of its full capacity. In order for it to get the remaining capacity, further charging was carried out at a constant voltage of 4,2 V until the charging current decreased to a value of 0,05 C (0,16 A).

The flow of charge is displayed in the form of a table 3. It summarizes average values collected from more than 26 experiments.

To consider the process of discharging, a load of 1,2 Ohm was connected to a fully charged battery up to a voltage of 4,2 V. Taking into account the connecting wires, the total resistance was 1,68 Ohm. The voltage at the connection of the circuit decreased to a value of 3,85 V. The process of discharging the battery is presented in the form of table 4. It also summarizes average values collected from more than 26 experiments.

Based on the data in table 4, even with a rough calculation of the remaining capacity in the test sample, which will be equal to the product of the average current in the circuit (2,218 A) during the entire discharge time (1,3 h), in this case, the remaining capacity is about 2883 mAh, which is 90% of the declared. In this case, it should also be noted that the battery during the discharge process only slightly warmed up and became barely warm. This suggests that this battery has retained its parameters well and is still able to do the work.



a b

Fig. 4. Working view of the measurement scheme: *a)* – charging process; *b)* - discharge process

Table 3. Battery charging process

Time	0 m	10 m	20 m	30 m	40 m	50 m	1 h	1h 10 m	1h 20 m	1h 30 m	1h 40 m	1h 50 m	2 h	2 h 10 m	2 h 20 m	2 h 30 m	2 h 40 m	2 h 50 m	3 h	3 h 10 m	3 h 20 m	3 h 30 m	3 h 40 m	3 h 50 m	4 h	4 h 10 m	4 h 20 m	4 h 30 m	4 h 40 m
I, A	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,65	0,52	0,40	0,33	0,25	0,18	0,15
U, B	2,8	3,07	3,19	3,30	3,34	3,38	3,42	3,46	3,50	3,54	3,58	3,62	3,66	3,71	3,76	3,82	3,88	3,95	4,02	4,10	4,17	4,2	4,2	4,2	4,2	4,2	4,2	4,2	4,2

7. Results

Despite the fact that this battery was tested in a single copy, it clearly demonstrated that the lithium energy storage technology has a sufficiently high resource and safety margin, and the products are able to maintain their functions for a long time.

It is also undeniable that this battery was not subjected to destructive processes both from the outside and inside itself, due to the technological features of the structure and composition of the batteries of this sample, as mentioned earlier. But it is also impossible to lose sight of the fact that, despite such a long period of use and storage, the prototype demonstrated very high-performance indicators, which indicates the great potential of the technology as a whole.

Table 4. Battery discharge process

Time	0 m	1 m	2 m	3 m	4 m	5 m	6 m	7 m	8 m	9 m	10 m	11 m	12 m	13 m	14 m	15 m	16 m	17 m	18 m	19 m	20 m
I, A	2,5	2,48	2,46	2,44	2,42	2,41	2,40	2,39	2,38	2,37	2,36	2,35	2,35	2,35	2,35	2,34	2,34	2,33	2,33	2,32	2,32
U, B	3,85	3,82	3,80	3,78	3,75	3,72	3,68	3,65	3,62	3,59	3,56	3,53	3,49	3,49	3,48	3,47	3,47	3,46	3,45	3,45	3,44

Time	21 m	22 m	23 m	24 m	25 m	26 m	27 m	28 m	29 m	30 m	31 m	32 m	33 m	34 m	35 m	36 m	37 m	38 m	39 m	40 m	41 m
I, A	2,31	2,31	2,30	2,30	2,30	2,29	2,28	2,28	2,28	2,27	2,27	2,26	2,26	2,26	2,25	2,25	2,25	2,24	2,24	2,23	2,23
U, B	3,43	3,42	3,42	3,41	3,41	3,40	3,39	3,39	3,38	3,38	3,37	3,36	3,36	3,36	3,35	3,35	3,34	3,33	3,32	3,31	3,31

Time	42 m	43 m	44 m	45 m	46 m	47 m	48 m	49 m	50 m	51 m	52 m	53 m	54 m	55 m	56 m	57 m	58 m	59 m	60 m	61 m	62 m
I, A	2,22	2,22	2,22	2,22	2,21	2,21	2,20	2,19	2,19	2,18	2,17	2,17	2,17	2,16	2,15	2,15	2,14	2,13	2,12	2,11	2,10
U, B	3,30	3,30	3,30	3,29	3,29	3,28	3,27	3,26	3,25	3,25	3,24	3,23	3,22	3,21	3,20	3,19	3,18	3,17	3,16	3,15	3,13

Time	63 m	64 m	65 m	66 m	67 m	68 m	69 m	70 m	71 m	72 m	73 m	74 m	75 m	76 m	77 m	78 m
I, A	2,10	2,08	2,08	2,07	2,06	2,04	2,03	2,02	2,01	1,99	1,96	1,95	1,92	1,92	1,88	1,86
U, B	3,12	3,10	3,09	3,08	3,06	3,04	3,01	3,00	2,99	2,96	2,91	2,90	2,87	2,85	2,8	2,77

8. Conclusions

It should be noted that there are a huge number of reasons leading to a decrease in the service life, charge level and / or capacity of the battery, which greatly affects their ability to perform their functions.

Research on these reasons for the degradation of lithium batteries shows that, despite a large number of factors that lead them to decrease in performance and inability to continue to perform the work they were intended to do, they may still be able to continue to perform at a high level of their tasks. At the same time, an attempt to systematize such causes and identify the most significant among them leads to an understanding of the need to take into account the individual characteristics of the operation of each individual sample. Proof of which can be considered an experiment performed on a used battery and subsequently lain in a discharged state for a long time.

Therefore, the systematization of knowledge about the processes that lead to a deterioration in the performance of lithium batteries, the identification of the main informative parameters about the state of their health, as well as methods for determining it, in the priority search for ways to extend the service life of batteries of this type, should be carried out taking into account the individual parameters of a single sample.

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