Laboratory facility development for studying the heavy charge and discharge modes effect on the degradation of lithium-ion batteries

E Y Abramov, S I Dedov

Novosibirsk State Technical University, 20, Karla Marksa ave., Novosibirsk, 630073, Russia

E-mail: ewgeniyabramow@gmail.com

Abstract. The article is devoted to the laboratory facility development for studying the lithium-ion batteries (LIB) characteristics in severe operating conditions, typical of electric vehicles. The electrical schemes of charging and discharging modules for 18650 batteries are shown. A feature of the modules is the ability to set any form of current (change the amplitude and frequency of the signal, change the average value, change the direction of current flow). The operating principle of the control program is described, which allows independent testing of three batteries using a single microcontroller. The created laboratory facility is presented, which provides the possibility of simultaneous testing of up to 30 batteries with different test programs. An example of the laboratory facility operation in the form of a current, voltage and temperature oscillogram fragment of the experiments is given.

1. Introduction

In recent years, the most promising area of LIB application has become electric transport and other electrical engineering complexes that require operation under conditions of sharp drops in the load current and randomly varying charge and discharge cycles in time [1]. So, for energy sources of electric vehicles, currents reaching 2-5C (nominal battery capacities), reversal of the load 2-3 times per minute, as well as the presence of an impulse component in the load current are characteristic [2].

With this use of the battery, non-equilibrium physical and chemical processes can be observed in it, due to a faster change in the characteristics of the electrode material compared to the characteristic diffusion times of lithium ions. This leads to a significant heterogeneity of the current distribution over the electrode material, the formation of anode and cathode zones, dendrites, etc., which inevitably affects the acceleration of battery degradation [3, 4]. However, at present, the causes of degradation of the functional materials of a lithium battery (cathode, anode materials and electrolyte) during operation in severe conditions are not sufficiently studied.

Random and rapid changes of the charge-discharge voltage of can be represented as the amplitude and frequency modulated effect of an electric current on a battery [5]. Therefore, the occurring processes in materials can be studied systematically using the action of an alternating voltage with a signal of a given shape. This approach is new in the study of the battery life in intensive and severe cyclic modes.
of charge and discharge. The information obtained will be useful for predicting degradation processes and can be used to establish the limiting parameters of the charge and discharge of batteries and their control in order to prevent the degradation of energy storage devices [6, 7].

2. Setting goals
The aim of the planned studies is to obtain the dependences of the parameters of the degradation of lithium-ion batteries on a number of factors characterizing the operating mode of the battery as part of an autonomous electric vehicle. As a result, it is planned to obtain a regression model that will describe the influence of the key factors of the battery operating mode on its characteristics.

To perform such studies, it is necessary to develop a laboratory facility that should provide the solution of the following tasks:
1) cyclic testing of 18650 batteries with a synthesized electrical signal of any given shape;
2) modeling of the battery charge-discharge modes corresponding to the operating conditions on the vehicle, obtained on the basis of standard driving cycles and statistical data on real driving modes;
3) recording the current, voltage and temperature values of the batteries directly during their testing;
4) periodic measuring of batteries energy consumption during their testing;
5) simultaneous cycling of up to 30 batteries according to various programs to obtain the results of a complete factor experiment in a reasonable time;
6) for each battery, there must be software protection for temperature and voltage, which must be duplicated at the hardware level.

3. Charge-discharge module development
To solve the set tasks, it is required to implement two main electrical circuits in the module for testing one battery. The first circuit should work as a controlled current source for charging the battery from an external power source. The second circuit should act as a controlled electronic load. The power section that combines these two circuits is shown in Figure 1.

![Figure 1. Power circuit of the charging and discharging module.](image-url)

Switching between charge and discharge modes is performed using relay P2, and relay P1 serves to disconnect the battery from the circuit. The current regulation for charging and discharging the battery is carried out using the IRFB4615 field-effect transistor, which operates in a linear mode.

To control the power transistor, a voltage-controlled current source circuit based on the operational amplifier U2.4 is used, which, together with other control circuits, is shown in Figure 2.

The I2 signal, which sets the battery current, is generated by a microcontroller (not shown in the diagram) in the form of a PWM. The value of the battery current changes with the duty cycle of the PWM signal, which is smoothed using a low-pass filter on R14 and C2. To eliminate self-excitation of the operational amplifier U2.4, a capacitor C3, selected empirically, is used. The feedback is realized with the ACS712-20 current sensor, the U1.2 operational amplifier, which performs signal offset and scaling, and a precision rectifier based on the U1.4 operational amplifier, which inverts the negative current signal in the battery discharge mode.
There is hardware protection for temperature and battery voltage. Temperature protection is implemented using the LM335 sensor, the U1.2 operational amplifier for signal biasing and scaling, the Schmidt trigger on the U2.1 operational amplifier and the Q4 transistor, which controls relay P1 disconnection.

Battery voltage protection is performed using two Schmidt triggers on operational amplifiers U2.2 and U2.3, transistor Q3, which pulls the current control signal to zero. This solution provides an individual setting for the minimum and maximum battery voltage. For stable operation of hardware protections, they have a wide hysteresis.

To control the modes of the power circuit, discrete signals from the microcontroller D1 and D2 are used, which, using transistors Q2 and Q5, control relays P1 and P2. LEDs LED1-5 show the current operating mode of the power circuit. To obtain the required voltage levels for the control circuit, TL431 microcircuits were used, the connection of which is shown in Figure 3.

The appearance of one charging and discharging module for testing 18650 batteries, made according to the described schemes, is shown in Figure 4.

Considering the selected components, the presented charging and discharging module can provide charging and discharging of a battery with a current of up to 10A with an arbitrary shape. The range of
the measured temperature is 0...100°C. Temperature protection can be set in the range of 40...90°C, for the minimum voltage in the range of 0.8...2.6V, for the maximum voltage in the range of 3.3...3.8V.

4. Charge-discharge modules control algorithm
The Atmel ATmega328P microcontroller is used to control the charge-discharge modules. The type of microcontroller was chosen for the memory size sufficient for storing long test cycles (up to 30 minutes), high (0.05V) resolution of the ADC, and the number of input-output channels sufficient for simultaneous control of three investigated batteries. The values of the currents in the load cycle are stored in the program memory of the microcontroller. With a memory capacity of 32 kB, simultaneously with the control program, it is possible to store a cycle with a duration of up to 15 thousand seconds.

The control program has two levels. The task of the upper level is to select charge or discharge currents. The lower level provides the formation of signals at the control outputs, as well as the start of the ADC for measurements. Permission to turn on and setting the direction of the battery current are set by discrete signals. The formation of the current settings is performed by pulse-width modulation based on the built-in timers of the microcontroller.

The top-level program is executed 1 time per second. Since the battery has a large capacity, the voltage across it does not have time to change significantly (by an amount comparable to the resolution of the ADC) during this time. To make decisions about the operating mode in the upper-level program, an algorithm is implemented, the block diagram of which is shown in Figure 5.

![Figure 4. External view of the charge-discharge module.](image)

![Figure 5. Block diagram of the battery testing algorithm.](image)
The algorithm implements one of two control modes: calibration and simulation of electric vehicle storage. The choice of the mode is made in the initialization state when the microcontroller is loaded according to the value of the external control signal.

If the calibration mode is selected, the sequence of operations described in GOST R ISO 12405-1-2013 is performed. A full charge and subsequent full discharge of the battery are sequentially performed, after which the battery is disconnected from the circuit.

The main duty cycle of the battery testing process is highlighted in Figure 5 with a bold line. After loading the microcontroller in the battery test mode, the following states are sequentially implemented:

1) constant current charge;
2) a pause to stabilize the voltage after the current flows through the battery;
3) decision making and transition to the discharge state;
4) in the state of discharge, the imitation of the load on the battery is performed when the electric vehicle is moving in the selected load cycle;
5) a pause to stabilize the voltage after the current flows through the battery.

The described operating cycles are implemented for each battery independently. To protect the battery, the program provides the ability to prematurely interrupt the states of charge and discharge, which duplicate hardware protections.

5. Discussion of the results
To create a laboratory facility, 30 charge-discharge modules were manufactured, which are controlled by 10 microcontrollers. Each microcontroller controls three modules. Moreover, each module is capable of functioning according to an individual experiment program. The number of independent modules is determined by the design of the experiment, the first stage of which involves varying the values of four factors and several hundred cycles for each combination of these factors. The external view of the laboratory facility for testing batteries in operation is shown in Figure 6.

The laboratory facility also includes five external power supplies 5V, 300W, used to charge the batteries, five bipolar power supplies +/-15V, 18 W, toggle switches for turning on / off each charging and discharging module, three USB recorders «ADClab S-Recorder L» for continuous recording of current, voltage and temperature of each battery, as well as three PCs for working with data files and visualizing the experiment process.

As a demonstration of the laboratory facility results, Figure 7 shows fragments of the measurement data of the battery parameters in one of the experiments.

The data shown is for heavy duty battery life tests. These tests involve cyclic loading of the battery with fixation of energy parameters and carrying out periodic test cycles to assess the key characteristics of the battery in an automatic mode.

Based on the results of these tests, a regression model will be obtained, which will describe the influence of key factors of the operating mode of the battery on its characteristics.

![Figure 6. External view of the developed laboratory facility.](image1)

![Figure 7. Current, voltage and temperature oscillogram fragment of one battery in one of the experiments.](image2)
6. Conclusion
The laboratory facility has been developed that allows for life tests of 18650 batteries with the fixation of the main operational parameters. The installation allows simultaneous testing of up to 30 cells, while their test programs may vary. The stand also includes a set of high-precision measuring instruments and recorders. The stand is controlled by a microprocessor system, which makes it possible to carry out life tests according to a given program without the direct participation of the operator. A feature of the stand is the ability to set for each battery any form of current (change the amplitude and frequency of the current signal, change the average current value, change the direction of current flow). For each cell, hardware adjustable temperature and voltage protections are provided, which are duplicated in software. The ability to adjust the protection settings allows tests to be performed within the limits recommended by the battery manufacturers, as well as tests outside these recommendations.

Thus, the developed laboratory facility fulfils the assigned tasks for the planned experiment, and can also be used for further research of batteries.

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