Determination of the charge and discharge modes duration effect on the LiFePO4 cells resource in the electric power source

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Abstract. The paper is devoted to the determination of the resource of LiFePO4 battery cells when they are used as a primary source of energy in an electric vehicle. The analysis of the WLTC driving cycle from the point of view of the currents arising in the battery of an electric vehicle was carried out, its main parameters were revealed, such as: the duration and magnitude of the charge and discharge currents and the duration of the pause. The results of experiments on determining the resource of an 18650 cell at various load cycles are presented. It was found that cells loaded with a low current with a high switching frequency of the operating mode are subject to the greatest degradation. The lowest degradation rate was observed in cells loaded with low current with short-term charging modes. The result obtained will make it possible to more accurately determine the remaining life of the battery cells. Also, the data can be used to improve the algorithms of the BMS in order to extend the battery life.

1. Introduction

The introduction and development of autonomous electric vehicles is highly dependent on energy storage technology. Thus, modern types of energy storage devices as part of a traction drive are represented by various types of lithium batteries.

To determine the operating modes that preserve the resource of the energy storage capacity without losing the dynamics of movement, it is required to establish the main factors causing its degradation. Today, the influence of such factors as:

• battery temperature;
• number of charge-discharge cycles;
• cycling range;
• charging and discharging currents.

In the study [1], for the first time, the aging processes of the battery were considered, as a result of which an almost linear dependence of the capacity in relation to the number of cycles was established. The study also noted that an increase in temperature during storage and an increase in the state of charge significantly affect the degree of degradation. In [2], the mechanisms of degradation were investigated depending on the depth of the discharge. It was found that a decrease in the discharge depth from 100 to 25% increases the number of cycles by more than 3 times (from 500 to 1800 cycles). According to the results of the study [3], it was found that the battery life is preserved to the greatest extent when charging-discharging with a current of 1C with partial use of the charge degree from 40 to 20%. In scientific work [4] it was revealed that cycling with currents of 0.25 and 0.5C causes a significant decrease in the battery life after forty cycles.
The specificity of operation of lithium accumulators as part of a traction drive assumes an uneven load with a frequent change in the direction of the energy flow. Therefore, in this work, the influence of the alternation of charge-discharge modes with different currents with different durations is considered.

2. WLTC analysis
The standardized WLTC cycle was used as a driving cycle that simulates traffic on the road (Figure 1). The World Light Car Test Cycle (WLTC) is a modern driving cycle standard that is part of the WLTP procedure for determining the fuel and energy consumption of cars and electric vehicles. The cycle consists of 4 sections with different vehicle control modes, the first two of which (Low and Medium) simulate traffic in an urban environment, and the next two (High and Extra High) simulate a suburban driving mode.

In order to study the cycle from the point of view of the currents occurring in the battery cell, the studied model of the electric vehicle adopted the Nissan Leaf with a 24 kWh energy storage device based on LiFePO4. The block diagram for obtaining the current diagram is shown in Figure 2.

In the block diagram, \( V \), \( \alpha_{\text{WLTC}} \) is the speed and acceleration given by the WLTC; \( \eta_{\text{traction}}, \eta_{\text{braking}} \) - traction and braking drive efficiency; \( U_b \) is the output voltage of the battery; \( N_{\text{parallel}} \) is the number of parallel branches of the accumulator.

Diagrams of the relative currents for the phases of the WLTC cycle are shown in Figure 3.
Figure 3. Diagrams of relative currents, a) Low, b) Medium, c) High, d) E. High.

Table 1. WLTC parameters.

| Speed mode | Discharge | Charge | Pause |
|------------|-----------|--------|-------|
|            | \(I_{\text{dis.av.rel}}\) | \(T_{\text{dis.av}}\) (s) | \(I_{\text{ch.av.rel}}\) | \(T_{\text{ch.av}}\) (s) | \(T_{\text{p.av}}\) (s) |
| Low        | 0.30C     | 9.1    | -0.20C | 5.93    | 24.2 |
| Medium     | 0.53C     | 15.94  | -0.44C | 6.76    | 33   |
| High       | 0.65C     | 22     | -0.44C | 6.40    | 33   |
| E. High    | 1.24C     | 65.75  | -0.45C | 13.5    | 6    |

3. Method of conducting experiments

A full factorial experiment was chosen to obtain a model of battery aging. Accepted factors:

1) Cell current in traction mode \(I_{\text{discharge}}\);
2) Cell current in braking mode \(I_{\text{charge}}\);
3) Duration of traction mode \(T_{\text{discharge}}\);
4) Duration of braking mode \(T_{\text{charge}}\);
5) Number of cycles \(N_{\text{cycles}}\).

All experiments are carried out with the same ambient temperature and pause time between iterations. For the factor levels, the values corresponding to the average values of current and time in the Low and E. High phases in the Nissan Leaf battery with an energy intensity of 24 kWh are taken. The main characteristics of the used cell are presented in Table 2.

To simulate the movement of the vehicle in a certain phase of the cycle, a diagram consisting of sequential discharge, charge and pause modes was used (Figure 4).

The test algorithm is shown in Figure 5. The voltage and current setting levels are as follows:

- \(U_{\text{max}} = 3.2V\) - maximum voltage without load (stabilized);
- \(U_{\text{min}} = 3V\) - minimum voltage without load (stabilized);
- \(U_{\text{max.charge}} = 3.8V\) - maximum voltage under load;
• $U_{\text{max, discharge}} = 2.5V$ - minimum load voltage;
• $I_{\text{charge to max}} = 0.5C$ - charge current up to $U_{\text{max}}$.

Table 2. LiFePO$_4$ cell characteristics

| Parameter               | Dimension | Value  |
|-------------------------|-----------|--------|
| Form Factor             |           | 18650  |
| Capacity                | mAh       | 1600   |
| Minimum voltage         | V         | 2.5    |
| Nominal voltage         |           | 3.2    |
| Maximum voltage         |           | 3.65   |
| Maximum charge current  | A         | 1.6 (1C) |
| Maximum discharge current| A        | 4.8 (3C) |
| Operating temperature   | ℃         | -20÷60 |

Figure 4. Simulation current diagram.

Figure 5. Block diagram of the testing algorithm.
4. Method of conducting experiments
The results of measurements of the residual capacity of the battery cells after cycling are presented in Figure 6, and Table 3 shows the parameters of the load cycle. It can be seen from the results obtained that cells No.15 and No.16, cycled by low currents with a high switching frequency, are subject to the greatest degradation. The longest service life is achieved by cell No.1 loaded with low current for a long time with a short charging stage.

Comparing cells No.2 and No.12, it was found that, in contrast to the traditional dependence, an increase in the traction current with frequent switching of operating modes provides a longer service life. Also, the rate of aging was significantly influenced by the magnitude and duration of the charge current - cell 1 has an increased resource than cell No.11 due to a shorter charge and then cell No.8 due to a higher current.

![Figure 6. Dependence of LiFePO₄ cell service life on the charge-discharge rate.](image)

Table 3. Parameters and results of experiments.

| №  | I_{discharge}, C | I_{charge}, C | T_{discharge}, sec | T_{charge}, sec | Q/Q_{cell}, % | N_{cycles} |
|----|-----------------|---------------|-------------------|----------------|----------------|------------|
| 1  | 0.3             | 0.45          | 66                | 6              | 99.83          | 267        |
| 2  | 1.24            | 0.2           | 10                | 6              | 95.51          | 246        |
| 3  | 0.3             | 0.2           | 66                | 13             | 96.61          | 176        |
| 4  | 1.24            | 0.2           | 10                | 13             | 96.78          | 135        |
| 5  | 1.24            | 0.45          | 10                | 13             | 96.27          | 130        |
| 6  | 1.24            | 0.2           | 66                | 13             | 91.44          | 300        |
| 7  | 1.24            | 0.45          | 66                | 6              | 89.83          | 297        |
| 8  | 0.3             | 0.2           | 66                | 6              | 89.49          | 300        |
| 9  | 1.24            | 0.45          | 66                | 13             | 93.64          | 164        |
| 10 | 0.3             | 0.45          | 10                | 13             | 93.00          | 165        |
| 11 | 0.3             | 0.45          | 66                | 13             | 93.39          | 152        |
| 12 | 1.24            | 0.2           | 66                | 6              | 85.00          | 300        |
| 13 | 0.3             | 0.45          | 10                | 6              | 90.00          | 138        |
| 14 | 1.24            | 0.45          | 10                | 6              | 73.73          | 261        |
| 15 | 0.3             | 0.2           | 10                | 13             | 89.83          | 57         |
| 16 | 0.3             | 0.2           | 10                | 6              | 88.56          | 43         |

5. Conclusion
On the basis of a full factorial experiment, it was determined that the life of a LiFePO₄ battery cell largely depends on the duration of the charge and discharge modes. A set of dependencies was
obtained for various combinations of charge and discharge currents and their duration. It was revealed that the greatest decrease in the resource is observed when cycling with low currents with a high switching frequency, and the greatest - with a long discharge with a low current with a short stage of charging with a high current.

Acknowledgments
The reported study was funded by RFBR according to research project №20-38-90210_Postgraduate students.

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