Diagnostics and reliability of lithium-ion batteries

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Abstract. Lithium-ion storage batteries are the most promising direction in the field of energy storage. This article provides an overview of this type of battery. A comparison of the main types of batteries is also provided. The issue of the durability and reliability of batteries is touched upon.

1. Introduction
The autonomous operation of all kinds of devices, from mobile gadgets to personal electric vehicles, is provided by batteries. Taking into account the required values of capacity and voltage, they are combined into storage batteries. The key characteristics of the battery - capacity, voltage, weight, charge replenishment time, permissible temperature regime - depend on the type of chemistry used [1].

For the autonomous power supply of modern technology, lithium-ion batteries are successfully used. They have a long cycle life, low self-discharge, a wide temperature range, and a solid specific capacity. The cathode of such elements is made of lithium derivatives [2], and the charge is transferred by Li-ions [3]. Next, we will take a closer look at the device of Li-ion batteries and how they work [4].

2. Materials and methods
2.1. How AB works
A lithium-ion battery is a rechargeable battery in which lithium ions move between the anode and cathode, creating a flow of electricity useful for electronic applications. In the discharge cycle, lithium in the anode (carbon material) is ionized and released into the electrolyte. Lithium ions pass through a porous plastic separator and are inserted into atomic-sized holes in the cathode (lithium oxide). At the same time, electrons are freed from the anode. This becomes an electrical current going into an external electrical circuit (see Figure 1). During charging, lithium ions are transferred from the cathode to the anode through the separator. Since this is a reversible chemical reaction, a battery can be used [5, 9].
Figure 1. Discharge mechanism of a lithium-ion battery.

A lithium-ion battery cell has four main components: cathode, anode, electrolyte, and separator. Table 1 shows the functions of the main components of the composition of materials [6].

| Components | Functions | Materials (edit) |
|------------|-----------|-----------------|
| Cathode    | Emit lithium ions from the anode while charging | Lithium Metal Oxide Powder |
|            | Take lithium-ion battery during discharge      |                             |
| Anode      | Accept lithium ions from the anode while charging | Graphite powder             |
|            | Emit lithium ions during discharge              |                             |
| Electrolyte| Pass lithium ions between cathode and anode    | Lithium salts and organic solvents |
| Delimiter  | Prevent short circuit between cathode and anode | Microporous membranes       |
|            | Pass lithium ions through the pores in the separator |                             |

2.2. The advantages of lithium-ion batteries for cars

Lithium-ion batteries are the most suitable current technology for electric vehicles because they can deliver more energy and power per unit mass of the battery, which makes them lighter and smaller than other batteries (see Figure 2). These features also explain why lithium-ion batteries are already widely used in consumer electronics such as cell phones, laptop computers, digital cameras/camcorders, and portable audio/game players. Other advantages of lithium-ion batteries over lead-acid and nickel-metal hydride batteries are high energy efficiency, no memory effects, and relatively long battery life (see Table 2). The memory effect in nickel-cadmium batteries means a decrease in energy intensity after a shallow discharge of the battery. The battery retains a lower capacity and cannot be fully charged after that. Lithium-ion batteries do not have this memory effect, so the battery can always be recharged even before its stored energy is depleted [10-14].
Figure 2. Power and energy depending on the type of battery.

Table 2. Specifications for existing battery types.

| AB-type            | Lead-acid | Ni-Cd    | Ni-MH    | Lithium-ion |
|--------------------|-----------|----------|----------|-------------|
| Energy density, Wh/kg | 35        | 40–60    | 60       | 120         |
| Specific power, W/kg | 180       | 150      | 250–1000 | 1,800       |
| Charging cycles    | 4,500     | 2000     | 2000     | 3500        |
| Cost, $/kWh         | 269       | 280      | 500–1000 | Household appliances: 300–800; Transport: 1000-2000 |
| Battery characteristics | High reliability, memory effect | Best value for money | The best mass and size qualities |
| Application area    | Car battery, backup power | Flashlight battery | Onboard energy storage | Household appliances, on-board energy storage |

Considering the advantages of lithium-ion storage batteries, one cannot fail to note the energy density of these batteries [15-17].

Lithium-ion batteries have great potential to further increase energy density through the use of modern anode and cathode materials. The energy density of lithium-ion batteries is increasing rapidly (see Figure 3). In contrast, the specific energy of nickel-cadmium (Ni-Cd) and nickel-metal hydride (Ni-MH) batteries has stabilized since 1995 and 2000, respectively (METI, 2009a).
3. Results and discussion

The rapid introduction of lithium-ion batteries into the automotive industry is driving the improvement in the performance of this type of battery. The most pressing issues are durability and safety.

Durability as a property of storage batteries to maintain their operability for a long time until failure or the limit state of residual capacity can be quantified by several indicators, among which, first of all, the average operating time (operating time) of the storage battery before failure should be mentioned. If the law of distribution of the starting current $i$ is known, then it is possible to determine the mathematical expectation, which has the physical content of the average value, that is:

$$M[T] = \int_0^\infty if(i) \cdot di = \int_0^\infty P(i) \cdot di = \int_0^\infty [1 - F(i) \cdot di] = T_{avg}$$

As an indicator of durability, it is advisable to use the mean time between failures, which is the ratio of the total operating time $T_\Sigma$ batteries of the same type to the number of their failures $n_{fb}$ during this time:

$$T_{avg} = \frac{T_\Sigma}{n_{fb}} = \frac{1}{\omega_{avg}},$$

where $\omega_{avg}$ is the average value of the parameter of the flow of failures; $n_{fb}$ is the number of batteries failures.

Also, an important indicator of durability is the average operating time. $T_{pi}$ is period between maintenance and repairs, during which the batteries are serviced, recharged, and checked for technical condition. In this case, one should distinguish between the normative values of $T_{pi}$, which are established by regulatory documents, and the actual values of $T_{pi}$, which are determined by statistical data. $T_{pi}(i = 1, 2...k)$ overhaul runs are determined by the structure of the adopted repair cycle, which refers to the types of maintenance, current, and major repairs [2, 18-20].

The warranty service life of batteries after installation on a locomotive. $T_{guar}$ is the service life during which the battery manufacturer guarantees the serviceability of the battery and bears material responsibility for malfunctions arising from the observance of the technical operating conditions. Service life (resource) before disposal of batteries. $T_{servl}$ is the calendar duration of battery operation.
until failure or other limiting states, after which restoration of serviceability and further operation is impossible or economically inexpedient.

The reliability of a storage battery is determined by a complex property; complex indicators are used for assessment, which simultaneously depend on reliability, durability, maintainability, and preservation. Availability ratio: $K_G$ is an indicator, the value of which depends on the frequency of failures and the duration of recovery:

$$K_G = \frac{T_E}{T_E + T_{td}}$$

where $T_E$ is the total operating time of the fleet of locomotives in working order for the analyzed period;

$T_{td}$ – the total downtime of locomotives for repairs due to failure of the diesel starting system for the same period.

The failure rate of starting systems is calculated by the formula:

$$K_{td} = \frac{T_{td}}{T_E + T_{td}} = 1 - K_G$$

Safety: Lithium-ion batteries are susceptible to short circuiting and overcharging. Lead acid, nickel cadmium and nickel metal hydride batteries work reliably even after short circuiting and overcharging because they have low energy storage capacity and use a flammable electrolyte. However, when a lithium-ion battery is short-circuited, large flows of electricity are created and the temperature of the battery rises to several hundred degrees in seconds, heating up neighboring cells and causing the battery to completely ignite. When lithium-ion batteries are inadvertently overcharged, the chemical structure of the anode and cathode breaks down and some of the lithium ions form snowflake-shaped lithium metal deposits called “dendrites” that can short circuit the battery or worse.

4. Conclusion

Considering the current trends in the development of storage batteries, a comparison of various batteries was made. In the course of the analysis, it turned out that lithium-ion batteries have better weight and dimensions and are able to store more energy per unit mass. It also turned out that the energy density limit of lithium-ion batteries has not been reached. Therefore, development is underway to increase the energy density.

Calculations were presented that allow one to establish such important characteristics of AB, such as durability and reliability. To carry out such calculations, it is necessary to have a fairly broad statistics of failures and repairs of storage batteries.

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