Comparative study of state of charge estimation algorithms for Lithium-Ion Battery

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Abstract. Batteries are known to have found full applications in industries ranging from small electronic devices, mobile phones to complex systems such as electric vehicles and energy storage systems. The last one is characterized by the presence of large batteries with more than hundreds or thousands of batteries, so the process of estimation of their parameters becomes even more critical, demanding and complex. The evaluation of the state of batteries should be understood as finding the exact value of the following values: state of charge, capacity and internal resistance. The last two parameters are used to assess the health of batteries, to find available power and amount of energy respectively. Estimation the state of charge remains one of the most difficult tasks in the study of battery conditions. It is also one of the most important parameters that affect the correct operation of the battery, namely reliability, safety, performance. The main task of this paper is to present methods for reliable testing and evaluation of lithium batteries under different scenarios and conditions.

1. Introduction

The active development of generation based on renewable energy sources requires the use of electric energy storage systems. This is due to the stochastic nature of generation from such sources [1-5]. Lithium-Ion Batteries are the most common for power systems with a large share of generation from renewable energy sources. Optimization of energy storage is required. A large number of methods and models for assessing battery state of charge are currently available in the literature. In general, they can be divided into two large groups: electrochemical methods and empirical methods [6, 7]. Electrochemical methods are highly accurate, but they can only be applied in laboratory conditions because they are highly computationally complex.

The most widely used methods are based on empirical measurement, an engineering approach that allows online measurement because they do not require large computational resources, while their accuracy can hardly be proven in practical use. Unlike other parameters as the current voltage, which can be measured directly with measuring meters, the state of charge cannot be measured directly, this is due to the fact that this parameter is sensitive to thermodynamic and kinetic processes occurring inside the battery. The state of charge must be determined in a thermodynamic equilibrium state, but in practice the available useful energy is described under polarization conditions and will be a function of numerous factors regulated by kinetic regimes with electrochemical, mechanical and thermal...
deviations. Moreover, these factors are often interrelated, making measurement even more difficult, making empirical methods of correlation-based assessment ambiguous and difficult to understand [8]. This paper has considered two widely used empirical approaches to assessing battery charge status, such as the ampere clock method and the open circuit voltage method. The residual capacity was also determined and the Coulomb efficiency factor was calculated.

2. Methods

Charge status (SOC)
The evaluation of the state of charge using the empirical method is mainly carried out using the Coulomb account method, also called the ampere-hour counter. Its implementation requires knowledge of the battery charge at the first moment $t_0$. The following formula describes the state of charge:

$$SOC(t) = SOC(t_0) - \frac{\eta_i}{Q} \int_{t_0}^{t} i(t) dt$$

where $SOC(t)$ - indicates the state of charge of the battery at the moment $t$, $\eta_i$ - Coulomb efficiency factor (for charge $\eta_i < 1$ and for discharge $\eta_i = 1$) $Q$ - initial cell capacity, $i(t)$ - current flowing through the battery at moment $t$.

This is the common and least computationally demanding method of measuring SOC. The pendant counting method is part of many methods for assessing the state of charge of lithium-ion batteries. Although its simplicity in implementation, this method has a number of significant disadvantages [9]:

- the need to know the battery charge status at the start of time $t_0$ to correctly calculate the integral value.
- overestimating or underestimating the true value of the charge state may occur due to the denominator value of the nominal capacity.

However, the method can be reasonably accurate if there are good current measurements and sufficient recalibration points.

Open circuit voltage method (OCV)
The assessment of the state of charge can be made using a predetermined relationship between the open circuit voltage and the battery charge state. However, this algorithm requires a lengthy experiment in which the energy storage device must be decommissioned over an extended period of time to determine the above relationship, making this approach impossible to apply in real time. This type of battery charge measurement is more applicable in the laboratory. In the case of lithium-iron phosphate (LiFePO4), final balance can be achieved after the first 60 minutes after relaxation.

It is worth considering that, for LiFePO4 batteries, the OCV curve has a long constant part and also has a hysterical effect, which leads to significant deviations in the assessment of charge status [8, 10].

However, the SOC-OCV curve is ideal for the same batch of lithium-ion batteries, allowing experimental curves for online measurements to be used [11]. In addition, the OCV hysteresis can usually be neglected at medium and high temperatures [12]. Direct assessment of SOC based on OCV has very low computational complexity and relatively high accuracy.

Capacity
Determining the actual capacity of a battery pack is one of the most important testing methods and is usually the first step in determining its condition. The nominal capacity of a battery is exponentially dependent on the load current, as described by Pakert's empirical formula (2), which was presented by B. by Pakert in 1897 [13]. The inability to accurately account for this effect leads to significant errors in the determination of nominal capacity, especially at high discharge currents of the accumulator. The value of full capacity is determined by laboratory tests for a specific cell design.
where: \( C \) is the theoretical capacity of the battery expressed in Ah, \( T \) is the discharge duration (time) in h, and \( n \) is the Pukert number constant for a given battery. In practice, the value is between 1.01 and 1.4 and for an ideal battery \( n = 1 \) [13].

3. Parameter measurement

**Capacitive test**

The battery cell used for testing is a standard 100 Ah LiFePO4, with a maximum charge voltage of 3.6 V and a minimum discharge voltage of 2.8 V.

The battery is discharged at various direct currents of 1C, 2/3C and 1/3C to determine the actual capacity of the battery. The results of the experiment are shown in Figure 1. The discharge rate of the battery has a significant effect on the voltage curve - as the battery increases, the voltage curve shifts down noticeably. When the discharge current is high (100 A), the discharge curve will deform and the battery capacity will noticeably decrease.

Table 1 shows the results of the test, from which it can be seen that the highest actual battery capacity was extracted at the lowest current.

![Figure 1. Results statistic capacity test](image)

**Table 1. Results of static capacitive test**

| Current (A) | Capacity-Charge (Ah) | Capacity-Discharge (Ah) | Average |
|------------|-----------------------|-------------------------|---------|
| 1C         | 29.11                 | 27.15                   | 28.13   |
| 2/3C       | 40.48                 | 43.56                   | 42.02   |
| 1/3C       | 51.14                 | 52.18                   | 51.66 (max) |

A 10 year old battery was used for the test, but the number of charge cycles was small, so the reason for the loss of capacity is more related to the cell self-discharge. The degree of capacity loss was about 50% according to the test results. The calculated actual capacity was used to assess the state of the charge using the ampere-hour method.
**OCV Test**

The OCV-SOC correction curve is often used to correct the current integral errors during the ampere-hour charge evaluation. This curve is used when the battery is at rest (not charging or discharging) for a sufficiently long time (30-60 minutes) and it is assumed that the battery voltage at the terminals is approximately equal to the OCV value [10]. A cell charge and discharge test with an impulse direct current of 100A was used to remove the OCV. The duration of the pulse phase is 25 s while the relaxation phase is 30 s. Figures 2-3 shows the results of voltage measurements during a complete experimental discharge and charge under the action of a pulse current. The open circuit voltage corresponds to the points marked with a marker in the diagrams below. The OCV-SOC curve is obtained by averaging the curve of charge and discharge as shown in Figure 4. The interpolation of the curve can be obtained by using a polynomial of sixth degree.

![Figure 2. OCV-Discharge test](image)

![Figure 3. OCV-Charge test](image)
As it can be seen from the graph, the distance between the discharge and the OCV curve is large enough to reflect the hysterical effect that could lead to a charge error in the future. In fact, the hysteresis is related to the relaxation duration of the stress, with the hysteresis level decreasing as the relaxation period between pulses increases due to diffusion of lithium ions inside the cell.

![OCV-SOC relationship](image)

**Figure 4. OCV-SOC relationship**

4. **Conclusion**

The analysis of the state of the battery, by determining the residual capacity and coulomb efficiency, confirms the previously mentioned battery age, however, the battery can still be used with alternative energy sources or as an uninterruptible power supply. The accuracy of the method for the estimation of the amperes of a watch depends on a correctly set residual capacity. As the lifetime of the battery increases, it decreases significantly; late calibration may lead to an error in the determination of the charge and, as a result, irreversible damage to the battery. The charge assessment can also be assessed using the OCV-SOC ratio curve, but the hysterical effect must be taken into account.

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