Diagnosis and restoration of Li-Ion batteries

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Abstract. The paper presents the results of testing the LT-LFP.300.11.01 Li-Ion cells under different conditions of charge by stable and pulse width modulation current. The shown study proves the possibility of approaching the diagnosis of battery cell before multi stage charging cycles. This approach helps to determine the real cell state of charge, which is important for the charger in turn for the determination of the initial current value at the very first stage of charge. Using the trickle charge algorithm, each battery cell may be charged individually in accordance with its initial state of charge, chemical condition and temperature. This approach should use a special charger acceptable for multi-cell charge or diagnosis of individual cells with a balancing apparatus. The same approach could be used for battery restoration.

1. Introduction

Compared to other rechargeable batteries, Li-Ion power sources have much higher energy density for weight and volume, providing longer running time between charges. In general, it is rather simple to charge such type of the battery: just charge it, applying 1C current (A) in a few hours [1], where C is capacity of the battery, measured in Ampere-hours. However, if the temperature of the charging battery will be higher than acceptable, the battery/cell will be soon more dead than charged [2,3]. Or even it may explode [4]. If one of the cells has very low voltage and others are well, anyway the battery will not be charged because it is “unbalanced” [5]. And finally if charge will be approached with 1C current, then the time of charge will be acceptable from the commercial point of view. To avoid the problem of run-free-charge, the charger has to be equipped with the apparatus and a software system of diagnosis. Otherwise, it will conduce the degradation of the battery charge by charge. Especially, when not all, but one of the cells is almost or fully dead. Therefore, before the charging procedure it is hard to chose between a trickle charger and maintenance battery charger [6]. However, using the below described approach, it is relatively simple to make a new or the third version of the charger using a special algorithm of the initial state of charge (SOC) determination. In addition to that, the Li-Ion cells have to be charged in full each time, as they also have a “memory effect” [7].

This paper presents experiments of the state of the charge increase, which in turn shows the possibility of diagnostics, its importance and investigation of the influence of trickle charge parameters on the battery state of the charge level. The presented material is the continuation of the research published in [8].

2. Diagnostics of battery SOC

Any battery starts losing its SOC sooner or later, basically from the date of production [9]. This
process is called a “degradation”, which is impossible to prevent. However, it is real to extend the lifetime of the battery significantly. Getting older, the battery SOC decreases step by step (or actually charge/discharge by charge/discharge). If the periods of time between discharge/charge cycles are longer, the battery degradation they cause is greater [10]. Especially when the battery is not charged in full each time [7]. When the battery loses its SOC up to 70% or even less, it is considered that the battery is almost unworkable [11]. The main reasons, causing battery degradation, are well known: temperature (extremely high or low) [12], fast charge-discharge cycles (big currents) [13], unbalance of cells (different degradation speed of cells). The approach described below may overcome all three problems.

To slow down the degradation, several approaches could be used. We have shown these algorithms of multi-stage charge in our earlier publications [2] and [8]. First of all, each battery should be a subject for diagnosis every charging cycle, as it is recommended in [14]. It means that each cell of the battery should be tested and determined if it still has normal SOC. Second, each cell in battery should be charged individually with the control of temperature. Different scientific and commercial groups propose many different methods and approaches for diagnosis of battery SOC and charge cycling for the cells [15-17]. And many experiments have shown that the individual cell charge increases the lifetime of battery in times, especially when in the beginning of charge procedure, the process starts with the trickle charge or charge-discharge cycles. The testing of the pulse charge on the trickle charge stage shows very good results, because it can make alive apparently dead Li-Ion cell [18]. The difference in SOC, when charging either stable or pulse width modulation (PWM) current, is not big, but essential to make an assumption of PWM preferable usage [19].

We used Li-Ion cells LT-LFP.300.11.01 in experiments [20-21]. Nominal voltage is 3.2V, nominal capacity is 300 A-hours. In accordance with manual, it is not recommended that the current would exceed 2C. On the base of this information, we assumed that the charging current pulse width modulation would have amplitude 1C (or 300 (A)), but the porosity should be variable.

In the beginning, we tested the charge with stable current I = 300 (A).

The first approach was to vary the pulse duty cycle and switching frequency (period), as it is shown in Table 1, in accordance with Fig.1. The similar method is proposed in [22]. However their approach is too expensive and long, compared with the presented below.

All variants of charge start from 80% of SOC. The time of each charge experiment is 30 minutes. The first charge has the duty cycle of PWM = 10 msec, switching period or time f between pulses is 5, 10 and 15 msec. The second, accordingly, is the duty cycle of PWM=100, f is 3, 10, 20 msec. The third one is the duty cycle of PWM=500, f is 3, 10, 50 msec. And the fourth is the duty cycle of PWM=1000, f is 3, 10, 50 msec.

| Table 1. Dependence of SOC on PWM (duty cycle) and switching frequency |
|-----------------|----------|----------|----------|----------|----------|----------|----------|----------|
| PWM (duty cycle) | stable 10 | 10 | 10 | 100 | 100 | 100 | 500 | 500 | 500 | 1000 | 1000 | 1000 |
| f (μsec) | 0 | 5 | 10 | 15 | 3 | 10 | 30 | 3 | 10 | 50 | 3 | 10 | 50 |
| SOC final (%) | 84 | 83 | 82 | 81 | 83 | 82 | 82 | 84 | 84 | 84 | 85 | 85 | 84 |

The final SOC under the stable charging current was 84-85%, which is worse than when charging by the duty cycle of PWM = 1000 msec. It is obvious that the SOC is getting better when charging by PWM. However, the PWM is different for different battery types and even, as the experiment showed, for different cells. From the economic and technical point of view, it is worth doing the extra research in determination of optimal PWM for a specific battery. Then the charger can remember the cell and the battery and an approach to individual charge. This approach may save a lot of time and power losses compared to [23].
Figure 1. Trickle charge options of LiFePO$_4$ cells (charge only).

The next experiment involves the same PWM charging approach, but with discharge cycles with the current of $0.1I_3$. The results are shown in Fig. 2 and Table 2.
Figure 2. Trickle charge options of LiFePO₄ cells (charge and discharge alternation).

All variants of charge start again from 80% SOC. The time of each charge experiment is 30 minutes. The first charge has the pulse duration of PWM = 10 msec, time f between pulses is 5, 10 and 15 msec. The second, accordingly, is the pulse duration of PWM=100, f is 3, 10, 20 msec. The third one is pulse duration of PWM=500, f is 3, 10, 50 msec. And the fourth is pulse duration of PWM=1000, f is 3, 10, 50 msec. The discharge PWM in each case was equal to charge PWM in time, but the amplitude was 1/10 of charge PWM. From the technical point of view, this approach is not more complex than the previous one.

Table 2. Dependence of SOC on PWM (duty cycle) and switching frequency

| PWM (duty cycle time) | stable | 10 | 10 | 10 | 100 | 100 | 100 | 500 | 500 | 500 | 1000 | 1000 | 1000 |
|-----------------------|--------|----|----|----|-----|-----|-----|-----|-----|-----|------|------|------|
| f (μsec)              | 0      | 5  | 10 | 15 | 3   | 10  | 30  | 3   | 10  | 50  | 3    | 10   | 50   |
| SOC final (%)         | 84     | 83 | 82 | 81 | 84  | 83  | 82  | 86  | 85  | 85  | 88   | 87   | 87   |
Table 2 shows that the final SOC in this case of charge-discharge is better even when we discharge the battery. It shows that the battery is “training” and may absorb more energy than in the first experiment. The final SOC in the end of trickle charge stage is absolutely real and can be used as the basic value for the charger.

Another hybrid approach could be used with the determination of voltage at this stage and disconnecting each cell by the individual schedule and/or voltage and/or the current value. It means that for good cells the main charge can be started individually and immediately after SOC determined. For other cells, the main charge should follow the trickle charge. This approach could be used in the grids with alternative energy sources when the peak power is sensitive. Anyway, the hybrid approach could be automated and actually remove the so-called balancing, eliminating the extra apparatus required.

3. Restoration of battery
It is obvious that the similar approach could be used for restoration of the battery. If the charger “learns” to diagnose and charge with control each cell of the battery, then the problem of balancing will be solved as it is shown in [24]. And the problem of restoration is to be solved as well. If we apply smaller current 0.1C – 0.2C for trickle charge and alternate it with the discharge for each cell, we will get the desired “training” of the battery when each cell will be charged to initial SOC acceptable for the normal charge. The similar experiments were presented in [24]. In this case we can apply even up to 6C current controlling the temperature every 100 ms. This time is enough to trace the temperature changes. This approach opens very wide perspectives for the restoration of Li-Ion batteries.

To develop this topic we are planning to make a series of experiments with different Li-Ion batteries studying the possibility of restoration in the field conditions. Since the currents required are very small, the charge could be made using almost any small power source like the autonomous renewable energy plant or small charger. Using this approach and small inexpensive device, anybody can “treat” the dead Li-Ion battery and then use it in full.

To analyse the idea related to the charger software for individual determination and charge of the cell, it is required to develop the algorithm of trickle charge, preliminary charge and normal charge. The charger may determine the voltage and current levels as well as PWM frequency for each cell individually.

4. Conclusion
The shown experiments prove the possibility of approaching the diagnosis of battery cell before multi-stage charging cycles. Using the trickle charge and/or training charge algorithm, each battery cell may be charged individually in accordance with its initial state of charge, chemical condition and temperature. This approach should use a special charger with the software acceptable for multi-cell charge or diagnosis of individual cells with balancing apparatus. The same approach could be used for battery restoration. The important condition for trickle charge stage is testing a temperature in accordance with the manual requirements of the seller. The first steps were already made by [23] relatively the chargers of future using special algorithms.

5. Acknowledgments
The study was awarded by the RF Ministry of Education and Science under Subsidy Agreement # 14.577.21.0154 of 28.11.2014 (Unique Identifier of Agreement RFMEFI57714X0154).

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