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A comparative study of commercial lithium ion battery cycle life in electric vehicle: Capacity loss estimation

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HIGHLIGHTS

- A dynamic cycle life experiment is designed according to the EV application and five different cells are tested.
- Capacity loss is simulated using a semi-empirical model based on the experiment results and identified aging mechanism.
- An on-board battery capacity loss estimation method is proposed.

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ABSTRACT

Now the lithium ion batteries are widely used in electric vehicles (EV). The cycle life is among the most important characteristics of the power battery in EV. In this report, the battery cycle life experiment is designed according to the actual working condition in EV. Five different commercial lithium ion cells are cycled alternatively under 45 °C and 5 °C and the test results are compared. Based on the cycle life experiment results and the identified battery aging mechanism, the battery cycle life models are built and fitted by the genetic algorithm. The capacity loss follows a power law relation with the cycle times and an Arrhenius law relation with the temperature. For automotive application, to save the cost and the testing time, a battery SOH (state of health) estimation method combined the on-line model based capacity estimation and regular calibration is proposed.

1. Introduction

The EVs are developing very fast nowadays. The batteries are among the most critical parts of the EV and the lithium ion batteries are widely accepted as the best choice owing to such factors as their high energy density and power density, environmental friendship, long cycle life and calendar life, etc. The cycle life is one of the most significant characteristics for power batteries in EV [1].

From an automotive engineer's perspective, there are only two things need to be known about the batteries: how much power the battery system could supply, and how much energy is stored in the battery system. It is simpler to estimate the results of these two questions for a new cell, but for an aged cell, there would be large estimation error without knowing the amount of battery capacity loss. Thus, the battery capacity loss modeling and estimation are very important. With a precise capacity loss model, the battery management system could make an accurate estimation of the battery capacity and derive the batter SOH (state of health). And then all the other battery management algorithm would get better results.

The cycle life of batteries with different cathode and anode materials are different. At present, the positive electrode materials used in commercial lithium ion batteries mainly include $LiMn_2O_4$ (LMO), $LiFePO_4$ (LFP), $LiNi_xCo_yMn_{1-x-y}O_2$ (NCM), etc., and the most commonly used negative electrode material is Carbon (C). In recent years, the lithium ion batteries with $Li_4Ti_5O_{12}$ (LTO) as the negative electrode material are developing very rapidly and the LTO is currently regarded as one of the promising choice to be used in lithium ion batteries instead of the carbon based anode material owing to its excellent performance under low temperature, long cycle life, etc [2,3].

The battery life includes calendar life and cycle life. In this study, we focused only on the cycle life of lithium ion batteries. As the

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cycle life of batteries is influenced by many factors such as temperature, SOC (State of charge), ΔSOC, charge and discharge current, charging cut-off voltage and discharging cut-off voltage, charging method, etc., different researchers design different battery cycle life test profiles as a result of different research objectives.

For instance, P. Ramadass et al. [4] investigate and compare the cycle life of batteries at room temperature, 45°, 50° and 55°. And Sheng Shui Zhang [5] investigates how three different charging methods, including CCCV, constant power–constant voltage (CPCV) and multistage constant current–constant voltage (MCCCV) charging methods, affect the cycle life of batteries. And Soo Seok Choi et al. [6] investigates the influence on the battery cycle life of charge cut-off voltage, discharge cut-off voltage, constant voltage charging time, charging current, discharging current, etc., respectively. Jiuchun Jiang et al. [7] investigate the long term cycling performances of $LiFePO_4$/graphite batteries in different SOC ranges.

The above literature design cycle life test to find the influence of separate factors on the cycle life of batteries respectively, which means in each group of tests only one factor is involved. There are also some literature which investigate the impact of multiple factors on the cycle life of batteries, which means the coupling of different factors is also investigated. For instance, I. Bloom et al. [8,9] take $LiNi_{0.8}Co_{0.2}O_2$/C batteries as research object, conduct the durability test of batteries of different SOC of 80% and 60%, with different ΔSOC of 3% and 6% and under different temperatures including 40 °C, 50 °C, 60 °C and 70 °C. And John Wang et al. [10] conduct the battery durability test at different temperatures (−30 °C, 0 °C, 15 °C, 25 °C, 45 °C and 60 °C), different ΔSOCs (90%, 80%, 50%, 20% and 10%), different charge and discharge rates (1/2 C, 2 C, 6 C, 10 C). The test costs huge manpower and material resources, and it requires long test duration for the cycle life test and large amount of batteries required for experiment, since that every possible combination of different levels of different factors should be tested.

There are also some researchers design the battery cycle life test according to the vehicles in which the batteries would be used. At present, there have been many hybrid electric vehicles (HEV) in the market like Prius, Volt, etc. Thus there have been some literature which have made profound researches on the cycle life of lithium ion batteries for HEV. For instance, for some commonly HEV, the batteries tend to be charged and discharged at a specific SOC and a small ΔSOC. J. Belt et al. [11] designed a special working cycle for life test according to the actual working condition of HEV and test the cycle life of batteries under temperature of 40 °C and the batteries are cycled between SOC about 60%–80%, 45%–65% and 30%–50%, respectively.

For plug-in hybrid electric vehicles (PHEV), the batteries would be working under different working conditions depend on the different control strategies. Currently the control strategy commonly used in PHEV is CDCS strategy (charge-depleting, charge-sustaining), that means, batteries work first in CD mode until the SOC reaches a certain set value, then work in CS mode. M. Ecker et al. [12] taking NCM/C batteries and LMO/C batteries as research object, conduct CD cycle test, CS cycle test of batteries respectively under different temperatures of 40 °C, 50 °C, 60 °C and 70 °C.

At present, based on the cycle life experiment results, research on capacity loss modeling of lithium ion batteries mainly includes capacity loss modeling based on the battery aging mechanism, and some researchers build empirical or semi-empirical capacity loss models based on the battery cycle test results under different cycle parameters.

For lithium ion batteries with carbon anode, one of the most important aging mechanism is the loss of lithium ions caused by the formation and continuous thickening of SEI (Solid Electrolyte Interface) film on the surface of anode particle. Based on this principle, the capacity loss models could be built and are studied in many literature [13,14]. The stress due to the lithium ion insertion/extraction of the electrode particles is also one important aging mechanism. R. Deshpande [15] introduces the capacity loss model based on the SEI formation and the mechanical fatigue caused by the diffusion induced stress in the carbon anode particle. Y. Dai [16] introduces a mathematical model to simulate the stress in the LMO cathode particle. For lithium ion batteries with LMO cathode, a capacity fade model considering the manganese (Mn) dissolution is built by R.E. White [17]. However, mechanism models are very complicated, many parameters and massive calculation are involved. Meanwhile, usually the mechanism model can only focus on one or two certain side reactions which affect the battery life, and various side reactions are still unknown or very hard to be investigated and considered in the mechanism model. Thus, the mechanism model may be impossible to accurately reflect the battery aging, especially under the real working conditions which are usually very complicated and different from the cycling conditions of the experiment in labs. Thus it is quite hard to employ the mechanism model in the BMS (battery management system) of vehicles. However, the battery aging mechanism could be utilized to guide the semi-empirical capacity loss model development.

There are already some researches on the semi-empirical models of lithium ion batteries cycle life. The related literature [11,18–20] etc., point out that a power law exists between the battery capacity loss and the cycle numbers. N. Omar [21] introduces a complicated capacity loss model considering the influence of the working temperature, charge and discharge rate, depth of discharge. In our previous work [22], capacity loss model considering the temperature, charge and discharge rate, end of charge and discharge voltage is built. Though the aging mechanism is not considered, now the empirical models can be used to find the battery capacity loss under different cycling conditions and are easier to be applied in BMS for predicting the battery capacity fades because fewer parameters are involved and the calculation would be simple. Thus in this paper, the battery capacity loss would be fitted by a semi-empirical model.

However, in all these researches, a lot of cells would be cycled with different cycle parameters, i.e., under different temperatures or with different charge/discharge rates, many cells and long testing times are needed, but for a certain cell, the cycle parameters are constant. Nevertheless, in a real vehicle the cells would be continuously working under various conditions, so the semi-empirical model introduced in the former works could not be directly used in the BMS. Thus, in this study, the semi-empirical model would be developed according to the aging mechanism and then transformed to a discrete version. The aging mechanism identification of all the cells used in this study has been shown in our previous work [23].

Considering that in real EV, the battery working condition changes, especially the ambient temperature changes with the seasons, in this study, five different commercial lithium ion cells would be cycled under a specific cycle with dynamic temperatures. The experiment design is shown in Section 2. Based on this particular experiment, only one cell is tested and the capacity loss model could be built. Thus huge time and cost could be saved. The capacity loss model parameter fitting by genetic algorithm is shown in Section 3. For the real automotive application, to save time and improve the capacity estimation precision, a battery SOH (state of health) estimation method combined the on-line model based capacity estimation and regular calibration is proposed in Section 4. And the conclusion is shown in Section 5.