Influence factors and identification of state-of-health for traction battery

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Abstract: According to state of health parameters and management system function, the properties of parameters are detailed to satisfy requirements of electric equipment for traction battery. The result shows that: many parameters, such as the ways of charge and discharge, temperature and state of charge, have apparently effect on state of health in propulsion battery. Battery cycle life reduces obviously when much depth of discharge is applied. Low temperature limits attenuation morphology of power battery. And high temperature weaken solid-electrolyte interface. Different types of battery agree with specific law during capacity reduction. Based on battery power, resistance and reduction characteristics, it should be considered in battery health management research, which includes identified parameters and accurate equivalent model.

1. Introduction
As a key part of power system, power battery effects significantly on power, economy and safety for the whole system. Traction battery should output enough electrical power to ensure operation mode of equipment. It is a challenge for researchers how to predict and improve the daily life of battery system. Although there are many types of chemical battery, several characteristics need to be concerned, such as power density, output power, and storage property. Actually, these critical parameters have an important influence on application of electrical equipment for power battery system [1].

Decay of battery system is a series of complicated process with chemical responses continuously. Some factors can be quantified as specified parameters to identify the attenuation of battery system. One of the parameters used to describe this attenuation is state of health (SOH). In the application of description, accuracy and efficiency are necessary for online operation mode. Although lots of high accuracy algorithm are available and studied by researchers, most of them cannot be applied in electrical devices for difficulty of complicated calculation.

2. Battery demand and state of health

2.1. Battery demand of electrical equipment
As a key technology, whether the battery technology can make a breakthrough has also become the key factor for the electric vehicle industry to get out of the current predicament. The battery in the electrical equipment should meet the minimum performance requirement. The only source of electricity in electric equipment is the power battery. To ensure the normal
driving range of electric equipment, the battery should output enough capacity. However, if the power battery is designed for larger capacity, the volume and mass of the power battery system will also increase correspondingly, which will affect the layout and power performance of the equipment. The power battery is selected according to the design goal of electric equipment and the driving condition. Therefore, pure electric modes need to be taken into account to meet with power battery requirements.

2.2. State of health and management of power battery
Nowadays, lithium ion battery is widely used in the electric equipment. The study on the life of lithium ion batteries mainly investigates the indicator of state of health. It is the ratio between the actual capacity and rated capacity of the battery under a certain charging and discharging condition or storage environment. When the battery performance, namely SOH, fails to meet the service requirements, the battery is considered to be invalid and discarded to reach the service life. During the life cycle of a battery, performance parameters such as capacity, power and internal resistance change [2]. Common methods of SOH calculation include maximum capacity definition, internal resistance definition, available capacity definition and battery startup power definition and so on. The easiest definition of SOH is based simply on the number of cycles [3]:

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SOH = 100 × (1 - \text{Cycle Number}/\text{Nominal Total Number of Cycles})
\]

SOH also can be evaluated based on the passage of time:

\[
SOH = 100 × (1 - \text{Age}/\text{Rated Calendar Life})
\]

When SOH is evaluated based on the relative actual capacity:

\[
SOH = 100 × (1 - \text{Actual Capacity}/\text{Nominal Capacity})
\]

When SOH is evaluated based on the relative actual resistance:

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SOH = 100 × (1 - \text{Nominal Resistance}/\text{Actual Resistance})
\]

The power battery pack is composed of modules (single battery in series and parallel). Lots of factors affect during charging and discharging process will lead to the inconsistent characteristics of single cells, the overcharge or undercharge phenomenon of individual batteries, or even the whole battery system can't work normally [4]. The health management system can measure the real-time voltage, charging and discharging current, temperature and other parameters of battery, and diagnose the operation state through these parameters, so as to prevent the early damage of individual batteries. The key points of its management are: select the charging mode, judge and execute the charging process according to the collected data; Use various warning functions to protect the battery, prevent battery damage and ensure the safety of use; To provide a stable and reasonable communication scheme for the vehicle electronic control system.

3. Influential factors in the power battery
When a power battery is used in a certain cycle, if actual capacity of battery decays to 60%~80% of the rated capacity, its life closes to end generally. For the power type of battery system, there is no relevant standard for how much the power performance reduction counts as a termination of life. The power capacity is usually reflected by the internal resistance of the power battery. In the application of electric vehicles, the internal resistance of the battery is mostly used to reflect the SOH of the battery system [5]. The attenuation of power battery is caused by many reasons. Charging and discharging method, temperature, DOD (Depth of Discharge), SOC (State of Charge) and other factors will affect the performance attenuation of battery in different ways.

3.1. The method of charging and discharging and DOD
Charging method has great influence on battery attenuation. The value of current, cutoff voltage and depth of charge and discharge all affect the performance of the battery. For example, when the constant voltage charging method is used for a long time, this condition keeps the electrode potential at the charging cut-off voltage. And it is close to the decomposition potential of electrolyte, which is easy to cause electrolyte decomposition and side reaction to capacity attenuation. Lithium-ion battery is particularly sensitive to the charging and discharging cut-off voltage. Whatever in case of high
charging or low discharging cut-off voltage, side effects will happen and produce gas to affect daily life of battery. When battery system is charged and discharged, the voltage of each cell must be monitored to prevent over-charge and over-discharge. DOD reflects the SOC application range of power batteries. Different DOD charging and discharging processes result in different cycle life of battery. For example, when the battery is fully charged and discharged, the cycle life is 1000 times. While ranging from 40% to 70% SOC, more than 20000 cycles can be reached. It is different that DOD effects decay of battery life by the way of different types of battery. Figure 1 shows the maximum battery capacity and the cycle life as a function of the voltage applied to the battery during charging.

![Figure 1](image)

Figure 1. Maximum battery capacity and cycle life as a function of battery voltage for a Li-ion battery [6].

3.2. Temperature and SOC

Temperature has a great influence on battery life. Currently, it is generally believed that the Arrhenius model can be used to describe the influence law of temperature on battery life. And the accelerated test of battery life is carried out at high temperature. High temperature will cause irreversible loss of battery capacity, and the influence is that the deteriorated SEI (Solid Electrolyte Interface) of battery is mainly accelerated at higher temperature. During battery charging and discharging, the force of charge transfer process is called charge transfer resistance that happens at the electrode/electrolyte interface. The greater electrochemical reaction resistance becomes, the higher over-potential voltage requires [7]. SEI film resistance and interfacial charge transfer resistance may be the main factors to affect the performance of power battery at low temperature. The input power, output power and charge and discharge capacity of the battery will decrease rapidly when temperature is lower. At low temperature, the main attenuation is power rather than capacity attenuation for lithium iron phosphate battery. For example, after 600 cycles at -10°C, the capacity and power attenuates by 25.8% and 77.2%, respectively.
4. Identification of state of health for power battery

4.1. State of sub-health
Due to the complexity and importance of attenuation problem for lithium-ion battery, namely sub-health, it has been the focus of research in the industry for a long time. It is mainly shown that the attenuation of capacity and power are caused by a series of comprehensive effects, and most of them do not occur alone because various processes and reactions are complicated. The decline of attenuation performance for the power battery is usually caused by the decay of capacity or power performance. When the capacity or power cannot meet the requirements of electric devices, the end of the service life achieved for power battery. Studies [8] have shown that: capacity attenuation of nickel metal hydride power battery conforms to the law of exponential attenuation. It follows the law of mean square root for manganese series lithium-ion power battery. Combining with the prediction model of terminal voltage for power battery, the internal resistance data of power battery is identified, and then state of health can be predicted.

4.2. Equivalent and data-driven model
The mainstream research method of battery SOH is equivalent model algorithm, which quantifies the battery decay process based on measuring or calculating the battery parameters of the battery decay process, according to the common parameters of capacity and internal resistance [9]. The other method to study battery attenuation is establishing specific model, including the equivalent circuit model established by means of AC impedance spectrum, the electrochemical analysis model established by means of complex internal reaction mechanism of the battery, and the data-driven analysis model established by mathematical methods [10]. It is the most direct method to judge the SOH by the change rule of the battery discharge capacity. This method establishes a model to determine the attenuation law of battery capacity and internal resistance data, by means of capacity experiment data, data-driven model and mathematical fitting methods.

4.3. Models and Recognition
When power battery is described by a formulaic model, there are a series of unknown parameters need to be identified. Even if these parameters can be obtained from the measured data, they cannot be applied directly. Because the measured data must be various in different batteries tests, the same problem will be found in different charging cycles. And the values of the given cycle parameters may be unstable. In order to predict state of health for power battery, there are several models can be used, such as particle filter model which contains inaccurate, nonlinear and unsteady non-Gaussian noise. The capacity attenuation method based on pattern recognition can also be used. The core idea of this model is that the chemical characteristics of the battery will be found obviously, when high consistency is kept during charging and discharging. By comparing the charging and discharging characteristics of the battery and the voltage curve at the specified constant current rate, the capacity of the two batteries is considered to be consistent if the waveforms are matched between the unknown and the known capacity battery [11]. After carrying out waveform identification and establishing mathematical model to predict capacitance quantity, the SOH of power battery can be estimated finally.

4.4. Further research
In order to monitor and predict real-time SOH of batteries, the rationality of the model is need for high requirements, such as the statistical parameter model used to predict the fault-free working time, or the battery capacity prediction model based on impedance spectrum, or the extended Kalman filtering algorithm, neural network and other data-driven algorithms. It is the key and difficult point how to design a complete equivalent circuit model, monitor the status of health online accurately, and estimate the battery life quickly to reflect the internal characteristics of the battery.
5. Conclusions
Based on the demand of power battery, this paper analyzes the health influencing factors and status of health model, according to the main characteristics of power battery. The main conclusions are as follows:

(1) Health management system of power battery is reflected in capacity, power and internal resistance characteristics, which is the external demand of electric devices.

(2) The attenuation of power battery is comprehensively affected by SOC, temperature and the methods of charge and discharge.

(3) The accuracy of health research method depends on the model construction for power battery.

As a core technology of electric vehicles with adaptive characteristics, health management system of power battery also involves high-precision algorithm of SOC estimation, active and passive equilibrium management, thermal management and other research fields. Those topics need to be further discussed.

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