Estimation of State of Charge of Batteries for Electric Vehicles

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Abstract

State of charge (SOC) can be applied in various fields characterized as an important parameter for estimating residual capacity state of battery. It is obtained from current or collected data, such as voltage, current and temperature as well. The accuracy of estimation of SOC of power battery can be essential and premise in designing the battery management system. Researchers in the fields shall take it an important and challenging task, requiring lots of work and energy, in order to improve the accuracy in estimation of SOC for eletric vehicles (EV). The SOC estimation tasks have made it great headway from classical and typical methods. This paper has proposed the shortcomings over various existed estimation methods and discussed the definition of SOC in details in the application. Study on the principle and application of the SOC estimation algorithm against many existing technical difficulties of SOC estimation algorithm for power batteries is very necessary. This paper analyzes the influence of charge and discharge rate, temperature, self-discharge and aging on SOC. It has important meaning for the further development of power battery SOC estimation.
Keywords: Electric vehicle, State of charge, Kalman filter

1: Introduction

As the energy crisis is gradually approaching, the electric vehicle (EV) development of energy saving and environmental protection will be the future development direction. The batteries get more and more widely used in the electric car or hybrid power system. The battery SOC which describes the number of remaining battery power is an important parameter in the process of using. Accurately and reliably get the battery SOC is the most basic and the top priority to the battery management system. It is the basis to command the battery status and decide to reasonably use battery next. For example, disconnect the battery to make sure it will not discharge inordinately, change it when the battery is failure and provide the battery surplus work time for users, etc. But, due to the complicated battery structure and the influence factors such as discharge current, battery internal temperature, self-discharge, aging, which increased the difficulty of SOC calculation.
Therefore, it has great significance to study the principle and application of power battery SOC estimation methods. In the hybrid power system, the battery is in the typical work condition of changing current. The traditional SOC estimation strategy based on constant current far can't meet the need. In the drive of that background, battery SOC estimation research made great headway, many classic estimation methods appeared. The main consideration is more scientific and safe to choose and use the battery, not battery design and production. Against many existing technical difficulties of the power battery SOC estimation algorithm, this paper discusses and studies the power battery SOC estimation. It has the important meaning for the further development of power battery SOC estimation.

2: Definition Analysis

A precise definition of SOC is the premise for SOC estimation of electric car batteries. The battery SOC can be defined from power or energy. From the point of view of power, SOC can be defined as the ratio of remaining power and the rated capacity under the same conditions when the battery in a certain discharge ratio. The mathematics type is expressed as:

$$SOC = Q_c/C_I \tag{1}$$

Among them, is the rest of the battery capacity; is the capacity when the battery discharges on constant current . If the batterys full filling state is defined as SOC=1, so the definition type can be expressed as follows:

$$SOC = 1 - Q/C_I \tag{2}$$

where, Q represents the released power of power batteries. From the angle of energy definition type:

$$SOC = \frac{W_{left}}{W_{initial}} \tag{3}$$

where, W_{left} is the rest power of the power battery and $W_{initial}$ is the initial power battery. Also, if the batterys full filling state is defined as SOC=1, so the definition type can be expressed as follows:

$$SOC = 1 - \frac{W_{discharge}}{W_{initial}} \tag{4}$$

where, $W_{discharge}$ is the released electric power of power batteries.
In actual application of SOC estimation, especially electric cars and hybrid power system, the definition type of battery SOC estimation is far more complex than equation (1)-(4). In the work of [?], because in the process of battery SOC estimation, and be the most commonly used SOC estimation method. If the initial state of charging and discharging is SOC_0, then the current state of SOC is obtained as:

$$SOC = SOC_0 - \frac{1}{C_N} \int_0^t \eta I d\tau \tag{5}$$

where, C_N is the rated capacity; I is the battery current;η is the efficiency of charging and discharging, not constant. Ah counting method is actually a kind of open loop prediction method, in a short time, can realize the accurate power estimation. But with the increase of the accumulative error, the precision will become poorer. It is often used in combination with other methods so that we can get a better precision as is we should fully consider the factors of current, voltage, self-recovery, temperature, the rate of charging and discharging, cycling times and aging degree which have great influence on the battery SOC estimation. Such as South Korea KIA Motor Company has the different definition of SOC as follows:

$$SOC = \frac{Surplus usable energy}{Total usable energy} = 1 - \frac{W_h}{W_{hE}} = \frac{P_a \times t_{res}}{\int_0^t P(t)dt + P_a \times t_{res}} \tag{6}$$

The above conclusion of SOC definition regarded the monomer battery as the research object. The electric vehicle uses battery pack, so it is still a project to define the SOC of battery pack because of the battery modules which are not enough symmetrically. In the actual application, a simple method is regarding the battery pack as a cell battery monomer. To ensure the safety of the battery, it often utilizes the monomer battery of worst performance to define the battery pack SOC.

3: Methods Discussion

3.1: Discharge test method

Discharge test method is the most reliable SOC estimation method which utilizes the constant current to continuous discharge, the product of discharge current and the time is the remaining

power. Discharge test method which applies to all batteries is often used in the laboratory. It can also be used for the maintenance of the electric vehicle batteries. But it has two significant weaknesses. One is need a lot of time. The other is that it forced the battery to stop running. Discharge test method is not suitable for the moving electric car.

3.2: Ah counting method

Ah counting method uses the integral of load current to estimate SOC. If the current is measured accurately and has enough data of start state estimation, then it is a simple and stable method which can be used for all electric car batteries shown in the article [?]. First of all, Ah counting method requires the fixed start state of SOC for estimation. In fact, the hybrid power system may start work or end work at any time. Therefore, in the initial stage, SOC measurement errors appear larger. Secondly, Ah counting method is suitable only for stable load occasions. But when hybrid power system works, the working condition is complex and each work device for homework need different power. The change frequency is fast which causes the battery often working in the severe electrochemical reaction process and makes the accumulative measurement error of SOC larger.

3.3: Open-circuit voltage method

Open-circuit voltage method uses the corresponding relationship of battery open-circuit voltage and SOC to estimate SOC by measuring the battery open-circuit voltage. Open-circuit voltage method is a high precision and simple method, but it has a higher demand of rest time. The battery should be stalling for long time so that it can obtain the stable value of open-circuit voltage. It is only applicable to the electric car in the stop state, not for the dynamic battery SOC estimate. However, hybrid power system is frequent to start, charge and discharge, and the working conditions is complex and changeful. Due to the volatile working current, it is difficult for open-circuit voltage to be stable in a short time. And the needed time for stability influenced by many factors such as the stop state of SOC, discharge current, change frequency, is difficult to determine. The battery open-circuit voltage in numerical is close to the battery electromotive force as is described in the article [?].

3.4: Internal Resistance method

The battery internal resistance has two kinds of different, exchange impedance and DC resistance. They all have a close relationship with the SOC. The battery exchange impedance is the transfer function of battery voltage and current. It is a complex variable which indicates the resistance capacity of the battery to the alternating current. We need AC impedance instrument to measure it. The battery exchange impedance is heavily influenced by temperature. It is still controversial when to measure exchange impedance, so it's rarely used in the real cars. DC resistance represents the battery capacity to DC, in the same very short periods of time, the ratio of the battery voltage variation and current variation. DC resistance is affected by the size of calculation time. If the time is shorter than 10 ms, only the ohm resistance can be detected. If time is longer, resistance will become complicated. Resistance method will have a high precision and good adaptability for SOC estimate when the battery is in the end state of discharging. It is also can be used with Ah counting method. But it is difficult to accurately measure the battery monomer internal. This is the shortcoming of resistance method.

3.5: Neural network method

Artificial neural network has half a century of history. Currently it has got a wide range of applications which is the main research method of nonlinear dynamic system modeling. The battery is a highly nonlinear system which is hard to establish the accurate mathematical model of charging

and discharging process. Neural network has the nonlinear basic characteristic with parallel structure and learning ability. It can give the corresponding output to external incentives and approach complex nonlinear system in any precision. Neural network can obtain high prediction accuracy and prediction efficiency. So it can simulate the dynamic characteristics of the battery to estimate SOC.

Utilize three layers of typical neural network rate for SOC estimate: input layer, output layer and the middle layer. The number of neurons of input layer and output layer is determined by the actual need. Generally it is a linear function. The number of neurons in the middle layer depends on the complexity of the problem and analysis precision. The input variables to SOC estimate are commonly voltage, current, power, temperature, accumulated released power, resistance, environmental temperature, etc. Whether the choice of neural network input variables is appropriate or not will directly affect the accuracy of the models and calculation. Neural network applies to all kinds of battery. The defect is that it needs a large number of reference data for training and estimate error is heavily influenced by the trained data and training methods.

3.6: Kalman filtering method

The core idea of Kalman filter theory is to make the minimum variance in the sense of the optimal estimation of the power system state. The literature of $[?, ?, ?, ?]$ describes the Kalman filter structure. For the application of SOC estimate, the battery is regarded as a power system, and SOC is an internal state of the system. The general mathematics form of battery model State equation can be obtained as:

$$x_{k+1} = A_k x_k + B_k u_k + w_k = f(x_k, u_k) + w_k \tag{7}$$

Observed equation:

$$y_k = c_k x_k + v_k = g(x_k, u_k) + v_k \tag{8}$$

Where the system input vector u_k usually contains variables such as battery electric current, temperature, surplus capacity, resistance, etc. The output of the system y_k is usually the working voltage of the battery, and the battery SOC is contained in the state variable x_k. $f(x_k, u_k)$ and $g(x_k, u_k)$ are nonlinear equation determined by the battery model which should be linearized in the calculation process. The core algorithm of SOC estimate is a set of recursive formula which includes the number of SOC estimate and reflects the estimation error and covariance matrix. Use the covariance matrix to give the estimate error range. The equation is the basis which described SOC as the state vector in the battery model state equations:

$$SOC_{k+1} = SOC_k - \frac{\eta(i_k) i_k \Delta t}{C} \tag{9}$$

The research about Kalman filtering method to estimate the battery SOC began in recent years. This method is applicable to all kinds of battery, compared with other methods, especially suitable for the SOC estimate of hybrid car batteries whose current wave is very severe. It not only gives the estimate of SOC but also gives the SOC estimate error. The shortcoming of this method is the high requirements.

Open-circuit voltage method and discharge test method are used mainly in the laboratory. Open-circuit voltage method is used to roughly estimate battery SOC before the test. Discharge test method is used for the precise metering of the remaining power after the battery was used. In the laboratory of CENS Energy-Tech Co., LTD, we utilize the Ah counting method combined with open-circuit voltage method considered of the difference of the charge and discharge rate and self-discharge. We also study and evaluate the internal impedance method. But it is not used in the electric car on practical because of the influence of battery types, volume and uniformity. The Kalman filtering method is on researching. This method can make the estimate of SOC constant convergence to the real value when the initial SOC value is incorrect. It is very suitable to solve problems of battery self-discharge. Now the problem we need to solve is to make the battery model more accurate. We have no depth research about neural network method which is restricted by the battery number and task. We also considered the difficulty for the real car application.

4: Impact Factors

4.1: Charge and discharge rate

Utilize constant current for batteries discharging at different rate, the greater the current, the less power released. When charge batteries at different rate, the filled effective power is also different. We define that C_{rI} is the remaining battery power under the standard current I , C_{tI} is the totally released power under the standard current I (often C/3). Where C_{uI} is the actual net battery power at current I. The equation is obtained as:

$$C_{uI}(t) = \int_0^t \eta i d\tau, C_{rI} = C_{tI} - C_{uI} \tag{10}$$

where, η is the efficiency of battery charging and discharging. Except for doing a lot of experiments to get the η, the Peukert equation is widely used to describe the relationship of battery capacity and discharge current:

$$i^n \cdot t = K or C = K i^{1-n} \tag{11}$$

where, C is the battery capacity, current i, discharge time t. n, K are numerical number which are correlative with battery. Among them, is correlative with the current. From the Peukert equation, we can deduce that discharge efficiency (simplified):

$$\eta = \frac{C_I}{C_i} = (\frac{i}{I})^{n-1} \tag{12}$$

C_I is the released power at standard current I, C_i is the released power at different current i. We can use many kinds of Peukert constants to improve SOC estimate effect. Lithium battery is applied for these experiments. The lithium battery voltage is 24V and the capacity is 100Ah. Fig.1, Fig.2 have shown the charging electric voltage curve under 35A, 50A respectively.
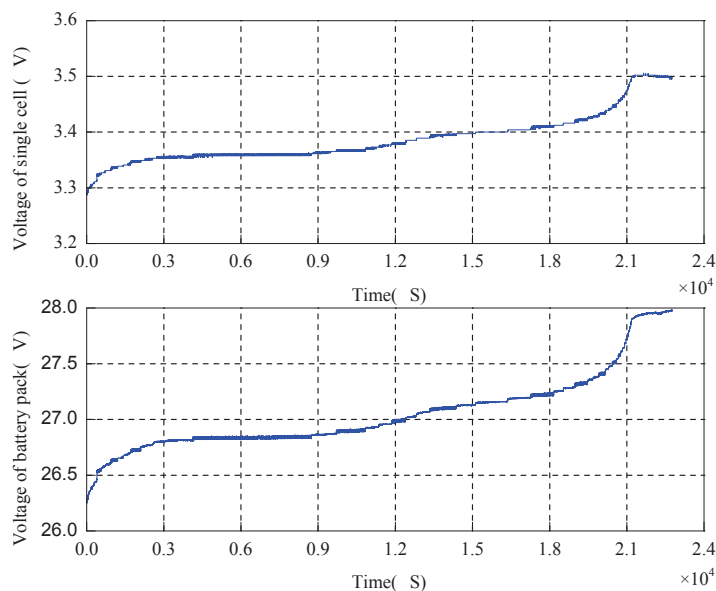

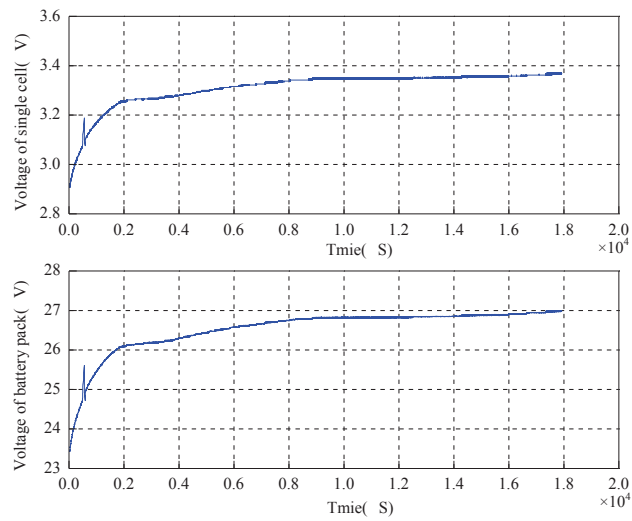**Figure 1. The charging electric voltage curve under 35A currents**

Figure 2. The charging electric voltage curve under 50A currents

Fig. 3 shows the discharging electric voltage curves under 35A and 50A current respectively.The experiment temperature is from 20℃to 30℃.
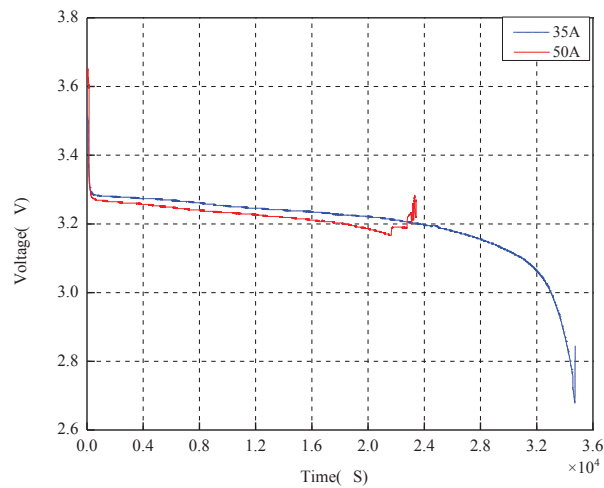

Figure 3. The discharging electric voltage curve under different currents

4.2: Temperature

The influence of temperature on lithium ion battery can be got through the experiments as is described in the earlier articles [?, ?]. The description model of temperature effect is commonly

used:

$$C = C_{25} \cdot [1 - \alpha \cdot (25 - T)] \tag{13}$$

where, C is the battery capacity in the temperature of T; C_{25} is the battery capacity at 25℃; α is the temperature coefficient which is different in different temperature range; T is the current temperature of the battery [?, ?].

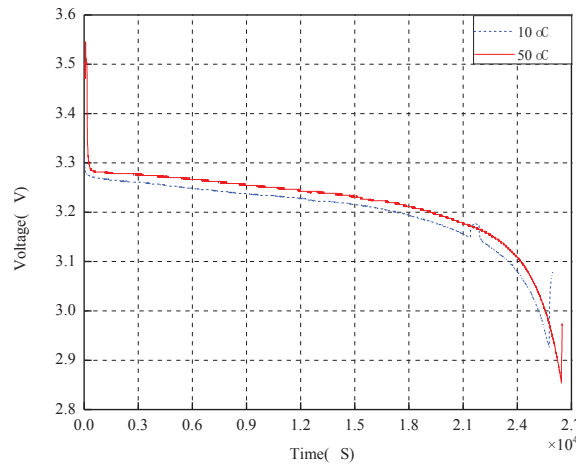Fig. 4 shows the discharging electric voltage curves under 50A current in the different temperature of 10℃and 50℃.

Figure 4. The discharging electric voltage curve under different temperatures

4.3: Self-discharge

The literature [5] gives the self-discharge diagram of MH/Ni battery. The self-discharge characteristic of lead-acid battery and lithium ion battery is similar with it. We can determine it through the experiments. The battery self-discharge is caused by the battery internal chemical reaction. In practice, it should be modified according to the curve given by battery manufacturer or the data acquired from the experiments [?].

4.4: Aging

Aging describes the phenomenon that the capacity will decay with the increase of battery cycles. The literature [6] describes the change rule of battery capacity with the cycles. Describe it as a linear process is the simplest method to resolve the aging problem. The more accurate method is to reflect the acquired characteristic from experiments in the SOC estimate. However, it is difficult to accurately judge the battery working cycle times.

5: Estimation of SOC Based on Extended Kalman Filter

Giving consideration about the factors affected SOC estimation, this paper has proposed extended Kalman filter (EKF) to conduct on-line estimation for battery for EVs. The EKF algorithm can

be applied to estimate the state of a dynamic system with given white noise, which has taken θ as variable with slow change rate. The non-linear state space model of the applied EKF can be described as follows:

$$\begin{cases} \theta_{k+1} = \theta_k + r_k \\ V_k = g(x_k, I_k, \theta_k) + e_k \end{cases} \tag{14}$$

The accuracy of SOC initial value should be guaranteed when selecting initial value with EKF algorithm, which requires the last stored SOC data in the computer but to conduct compensation in temperature for the value.

Fig (6) has shown the battery voltage with SOC estimation curves under 25℃, and fig (7) has indicated that the max error of estimation voltage of EKF and SOC is 1.68% and 1.36% respectively. The results has proved the estimation voltage of EKF can perform a better trace on real voltage under the restriction pure EV along with appropriate estimation accuracy.
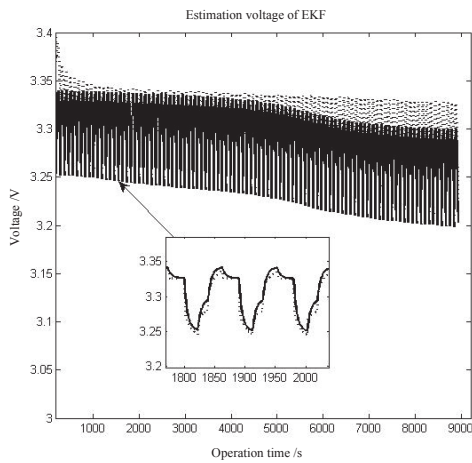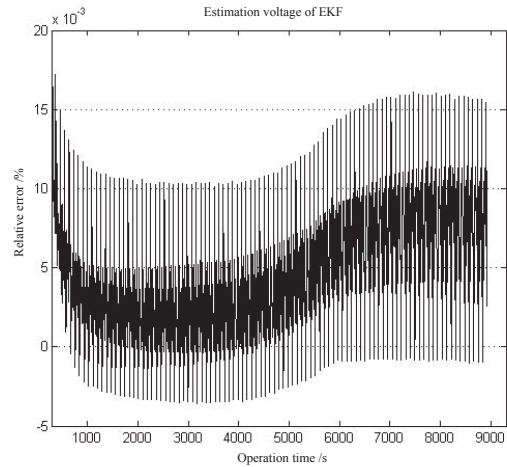

Figure (6). Estimation voltage of EKF

Figure (7). Relative error of voltage

6: Conclusions

In the point of research methods, there are many choices for SOC estimate. From the practical application, Ah counting method is the most commonly used method. It is often combined with other methods for use. For example, Ah-resistance method, Ah-Peukert equation method, Ah-open circuit voltage method. Neural network and Kalman filtering method are more promising approaches in the recent development. But they still need to continuously research and practice. The battery charge and discharge rate, temperature, self-discharge, aging and other factors have significant effects on SOC estimate. Any SOC estimation method should take them into consideration. How to accurately estimate battery SOC of electric vehicle in the changing current work conditions is still a difficulty. It also need us work hard to solve it.

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