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Overview of Lithium-ion Battery SOC Estimation

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***Abstract*— In this paper, different types of batteries are summarized which are used in electric vehicles. The performance of the battery, including material, duration, environment impact such factors can seriously restrain the development of renewable vehicles. Battery state-of-charge (SOC) plays an important role in vehicle driving regulation. Hence, the methods of battery SOC estimation based on different kinds of lithium-ion batteries are discussed. Each methods has its own advantages and disadvantages in the SOC estimation. Only the combination of two or more methods for SOC estimation can provide full and more accurate SOC estimation in all applied situations, i.e., driving or still states.**

***Index Terms*— Lithium-ion battery, State of Charge (SOC), Equivalent model, Measurement**

I. Introduction

With the development of science & technology and economy, the demand for transportation tools from the society is booming. However, the traditional fuel vehicles are largely dependent on the non-renewable oil resources. Considering the gradually exhausting of non-renewable resources and environmental pollution brought from fuel vehicles, electric vehicles (EVs) have been received more and more attention due to their energy saving and environmental preservation advantages, which is also regarded as one of the most important development directions in vehicle industry [1][2]. Battery technology is one of the main factors to restrain the popularization of electric vehicles [3].

The battery is the main energy resource for EVs and only the battery pack operating in normal condition can guarantee the vehicle driven functionally. However, one of the shortages for EVs is the battery life, more efforts should be put for the battery material and battery management system (BMS) due to several reasons. The cost of the battery packs takes nearly 1/3 percentage of the EVs cost. Besides, the battery discharging process is an electrochemical process, where the over charging or discharging could reduce the activity of battery chemical substances and substantially decrease the battery life, thus causing battery scrappage eventually. Another difficulty is the battery remainder charge estimation, denoted as battery SOC (State-of-Charge).

The power battery in vehicles has been through three main development phases:

I) **lead acid batteries**, mature technology, low cost, but low power density, low cycle life.

TABLE I
The peformance comparison of different batteries

Technical index	Lead acid battery	Nickel cadmium battery	Nickel metal hydride battery	Lithium-ion battery
Working voltage (V)	2	1.2	1.2	3.6
Weight energy ratio / (Wh/kg)	30-35	30-35	35-65	100-160
Volume energy ratio (Wh/L)	130	150	200	270-360
Recycle times (capacity decay 20%)	200	500	500-1000	500-2000
Temperature (c)	-10 $\sim$ 50	0 $\sim$50	0 $\sim$ 60	-20 $\sim$ 70
Memory effect	No	Strong	Weak	No
Environment impact	Large	Large	Weak	Weak

II) **nickel cadmium, nickel metal hydride batteries**, higher power density and service life, mainly used for hybrid vehicles. However, the price is rather high, and the performance of battery packs could be jeopardized by the huge difference from single units.

III) **lithium ion batteries**, much higher power density compared to the nickel metal hydride batteries, longer service life, better safety.

The comparison of different batteries are list in Table I. Here, methods of SOC estimation for lithium-ion batteries are focused in paper [4] since it is with high quality and bright application prospect. The paper is organized as follows. Section II introduces different types of lithium-ion batteries and Section III discusses different methods for SOC estimation and analysis is also presented for the comparison in Section IV. Conclusions are given in Section V.

II. Lithium-ion battery description and SOC definition

Different types of lithium-ion batteries are shown in Table II. Compared to other types of batteries, lithium-ion battery possesses high specific energy, high monomer battery voltage and small self-discharge rate characteristics.

Graphite anode is normally adopted by commercial lithium-ion battery. Since the lithium exists in the form of ion in the graphite layers, which can successfully overcome

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TABLE II

THE COMPARISON OF DIFFERENT LITHIUM-ION BATTERIES

Battery type	Cobalt lithium	Lithium manganate	Lithium polymer	Lithium iron phosphate
Working voltage (V)	3.6-3.7	3.6-3.7	3.5-3.7	3.2-3.4
Weight energy ratio / (Wh/kg)	> 150	> 100	> 150	> 130
Recycle times (capacity decay 20%)	> 600	> 600	> 600	> 1000
Safety	low	higher	higher	high
Thermal stability	unstable	relatively stable	relatively stable	stable
Transitional metal resources	Poor	Rich	Rich	Rich
Material cost	Expensive	low	High	Low

the safety risks brought via anode lithium surface deposition. Many materials can be used for cathode lithium batteries, i.e., metal oxides, phosphates such embedded compounds. The electrolyte is a non aqueous solution made of organic agents and $LiPF_6$ mixture and more detailed knowledge about lithium ion battery characteristics can be referred [5].

Battery SOC is also called battery charge state, representing the ratio of the maximum usable capacity of the battery to the nominal capacity of the battery, i.e. the available duration of the battery. When SOC=0%, it denotes battery in empty state and SOC=100% denoting battery in full charged state. When the vehicles are in driving status, it is difficult to obtain accurate battery condition with low precision of SOC. The battery SOC estimation is the primary task in battery management system. On the other hand, related management techniques have to be designed for battery optimal usage in order to extend the battery aging and avoid the safety failure.

The technology of the battery SOC estimation was first proposed in 1963, where Curtis apparatus company has developed a device for remainder battery capacity indication based on the battery voltage variation under the different current intensities [6]. Dowgiallo proposed the concept of battery impedance test in 1975, then the electrochemical impedance spectrum method has been applied in battery SOC estimation [7].

The battery SOC estimation via ampere hour integral method (also called Coulomb counting method) was first shown in [8]. The research on lithium-ion battery SOC started from 1984, Peled et al calibrated on the battery off-line open circuit voltage (Open Circuit Voltage, OCV) and SOC online estimation can be realized through look-up table. Neural network and fuzzy logic can also be used for SOC estimation [9]. Kalman filter is the method that can be used for lithium-ion SOC estimation via adjusting parameter continuously [10].

With the advances in battery technology, lithium-ion battery has gradually become the primary selection in power battery pack in EVs. Due to its unique electrochemical mechanism, there is a great difference of battery SOC estimation methods to those used in lead-acid batteries and nickel metal hydride batteries. Currently, direct measurement, tracking and recording system state method and other new methods are mainly used in lithium-ion battery SOC estimation for the battery management.

III. LITHIUM ION BATTERY SOC ESTIMATION METHOD

A. Static discharge method

The static discharge method (SDM) is the most reliable method for estimating the battery SOC via battery discharging process. Within the controlled ambient environment around the battery, the battery are discharged slowly until depletion and the initial battery capacity can be obtained through the measurement and integration of the discharging amount. The method requires the complete charge release of the battery, which can not satisfy the real-time requirements with longer discharging duration. Besides, the battery cannot be used after complete discharge.

Although SOC estimation from this method is highly accurate, it cannot meet the online battery SOC estimation demand during vehicle driving. SDM is suitable for calibration of battery maximum capacity in the laboratories.

B. Direct measurement method

The basis of the direct measurement method (DMM) relies on a number of cell parameters that can be reproduced and have significant correlation with battery SOC, which should be easily measured in practice, i.e., battery voltage (V), battery impedance (Z) and voltage response relaxation time (τ) excited by step current. The advantage of the DMM is that it can be carried out immediately once the battery connected, and the cell SOC is calculated from f_T^d function, shown as,

$$SOC = f_T^d(V, Z, \tau) \tag{1}$$

where the superscript $'d'$ in f_T^d denotes the DMM and subscript $'T'$ represents the temperature.

The disadvantage of the method is the determination of the function f_T^d, since it can only be obtained via the relationship between the battery variable and the SOC in all possible circumstances. DMM mainly includes open circuit voltage (OCV) method and internal resistance measurement method.

1) ***Open circuit voltage method****:* The principle of the OCV method is that the remainder of battery charge and its open voltage remains certain relationship. The value of the open circuit voltage of the battery is close to the electromotive force. The current battery SOC can be read from the diagram fitted via OCV-SOC. However, due to the flat variation of some battery voltages, there is no obvious change in SOC, which limits the OCV method application in practice. Moreover, it requires long time for the battery to attain the stable state, which would cause certain difficulties in measurement.

The OCV method has similar applicable environment as SCM, and it is more appropriate to be used in still state. Compared OCV with SCM, it will not waste the energy in the battery but a series SOC-OCV curves with high precision are required to determine the current battery capacity. During normal driving process, the output power is quite stable so the acquired battery SOC estimate is accurate.

2) ***OCV based on cell model:*** Since OCV has better performance with stable battery condition, it could greatly restrain its application. An online open circuit voltage method based on battery model is proposed to allow SOC estimation when the battery is in motion state [11].

A simple battery model is adopted in one online OCV method, where the model is similar to the R_{int} model but with one more polarized resistance, described as [12]:

$$U = U_{oc} - U_R - U_p \tag{2}$$

where U is the battery terminal voltage; U_{oc} is the battery open circuit voltage; U_R is the expected voltage variation caused by the battery internal resistance; U_p is the voltage variation caused by the polarization effect of the internal battery. Through the measurement, the battery open circuit voltage can be easily obtained, and the battery SOC can thus be acquired by checking the OCV-SOC table or OCV-SOC curve. It has shown that more accurate battery model used in the online OCV method and more accurate SOC estimation can be obtained.

C. Ampere-hour measurement

The method of Ampere-hour measurement is based on the integration from the battery current measurement and current along with the time, also known as Coulomb counting method. The relationship between SOC and system variables are described as:

$$SOC = SOC_0 - \frac{1}{C_N}\int_0^t \mu I d\tau \tag{3}$$

where I is the current through the battery; C_N is the battery rated capacity; μ is the battery charging and discharging efficiency. It is simple and stable and regarded as one of the most used SOC estimation methods [13]. The method relies on the accuracy of the initial battery SOC_0, and has higher requirement on the current sensor and voltage sensor.

The accumulated measurement error could be accepted within short integration time but cannot be accepted with heavier effect of the larger accumulated measurement error on the final measurement output. In addition, the Coulomb effect of the battery is subject to the battery working environments (i.e., current, temperature, battery remaining capacity, etc), so μ is difficult to be nominated. Therefore, Coulomb counting method is always used with other methods at the same time.

D. Neural network algorithm

Neural network (NN) is one of the algorithms based on BP neural network, which use its nonlinear characteristic to estimate the battery SOC via training a large amount of training data [14]. No accurate battery model is required during the NN application, which is suitable in a variety of batteries with good generality. However, the SOC estimation precision is largely dependent on the training data and training method, which plays an important role in the procedure.

Commonly used chip in the battery management system (BMS) is unable to meet the computational requirements of NN and DSP chip are usually applied in BMS. When there are a large number of monomer batteries in the battery pack, more DSP chip will be used for SOC estimate in real-time. So the cost of SOC estimate based on the neural network algorithm is rather expensive, which is generally used in the battery pack with fewer monomer units.

E. Fuzzy logic algorithm

Fuzzy logic algorithm and neural network algorithm share certain similarities, where accurate battery model is also not necessary in the SOC estimation. By use of a large amount of experimental data, test curve and reliable expert knowledge, fuzzy logic can be used for online identification of battery measurement. An original battery model is developed at the initial stage of the measurement process, then the calculated result with data from fuzzy logic system is compared with the actual measurement, from which the feedback from the error is used to adjust the fuzzy system and determine the system parameters [15]. After several continuous correction, an relatively ideal battery model can be obtained with high precision on battery SOC estimation. However, more training data are required in the system and computational load is quite heavy as well.

F. Alternate current method–electrochemical impedance spectroscopy method

1) ***The principle of electrochemical impedance spectroscopy method for lithium ion battery SOC estimation:*** The electrochemical impedance spectroscopy can measure the battery impedance under different frequencies so as to discriminate the effect on the SOC. Furthermore, battery equivalent circuit can be established via the impedance parameters. As for Lithium iron phosphate battery, there is still accumulation error in SOC estimation with the ampere-hour measurement, which is difficult to be corrected via real-time voltage due to the flat voltage platform during discharging process. With the aid of electrochemical impedance spectroscopy, the internal characteristics of the battery and SOC can be studied with the probability of new SOC estimation technique formation.

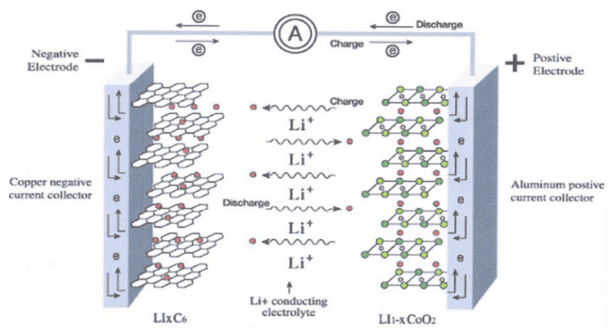

Fig. 1. The reaction diagram of the lithium-ion battery

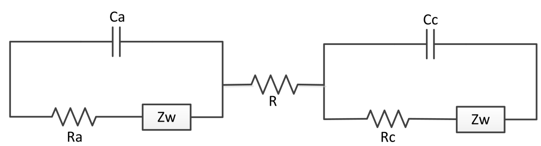

Fig. 2. The diagram of the equivalent battery capacitor resistor network

The electrochemical impedance spectra has close relationship with the internal reaction mechanism of the battery, shown in Fig.1.

Let take the discharge process as an example. When the lithium ion battery is working, the lithium ions in the anode occur charge transfer reaction at the material surface and prolapse from the lattice entering into the electrolyte. Then these lithium ions move towards anode under the function of electric field and concentration gradient. The procedure of intercalation and de-intercalation of Lithium ions between the electrode structure accompanied by the charge transfer can be described by the Bulter-Volmer function:

$$i = i_0[e^{-\alpha nF\mu/RT} - e^{(1-\alpha)nF\mu/RT}] \quad (4)$$

where i_0 is the exchange current density; α is the transfer function; n is the number of electron moles in the reaction; F is the Faraday constant; R is the air constant; T is the absolute temperature. According to Taylor series approximation ($e^x \approx x+1$, with small x), Eq.(4) can be approximated as

$$i = -i_0 nF\mu/RT \quad (5)$$

While the voltage is small enough, the relationship between the voltage and current on the surface can be expressed via the transfer resistance R_{ct}, and $R_{ct} = \frac{RT}{nFi_0}$. When lithium ions on the electrode surface are consumed, the bigger lithium ions in the electrolyte will diffuse to the electrode surface under the function of chemical potential, which is called Warburg impedance phenomena. The electrochemical reaction can be equivalent to a resistor capacitor network, as shown in Fig.2.

When AC is connected with the battery, different reaction will be generated by the battery system with different frequencies of AC. Impedance spectra can discriminate the contribution from different impedances only from the terminal measurements, which could allow the maximum impact factor for power loss to be determined. On the other hand, the accuracy of the developed model of the voltage and current for the battery can be verified via the impedance spectroscopy method and the model parameters for the specific model can also be obtained. Therefore, battery SOC can be identified via impedance spectroscopy.

*2) **The methods of electrochemical impedance spectroscopy for battery SOC estimation**:* According to the previous derivation, only small amplitude sinusoidal AC signal can be adopted to perturb the electrochemical power system in the electrochemical impedance spectrum method to guarantee the linear relationship described in Eq.(5). At the same time, electrochemical impedance spectroscopy is a measurement method in frequency domain, which can measure a wide range of frequency impedance spectroscopy to the study of electrode system. Compared to other conventional electrochemical methods, it can acquire more dynamic information and structure of electrode interface.

A real-time SOC and electrical impedance estimation method for lithiumion batteries based on a hybrid battery model is proposed in [16]. A particle swarm optimization based online parameter identification algorithm is designed to estimate the electrical impedances and open circuit voltage of the battery model. A SOC compensator is then designed to correct the error in SOC estimation, and a polymer lithium-ion battery cell is used as the test object.

Stephan and Marc Buller studied the electrochemical impedance spectra of the battery under different SOCs [17]. It concludes that the semicircle denoting charge transfer resistance will increase remarkably along with the SOC reduction. Therefore, the charge transfer resistance is the main factor that cause the battery SOC variation.

The equivalent circuit diagram with correction is used to study the internal properties of the battery via the relationship among the SOC and component parameters & impedance [18], shown in Fig.3. It concludes that the electrochemical impedance spectra of the acid lithium battery is composed of inductive arc at high frequency and capacitance arc at low frequency. Among all parameters, the frequency at the highest semicircle, angle, equivalent series capacitor can be regarded as the appropriate parameters for SOC estimation.

From the mentioned study, it demonstrate that the lithium-ion battery SOC estimation via the electrochemical impedance method is focused on the single parameter along with the variation of SOC. Since the internal mechanism of the electrochemical system is very complex, SOC estimation by one parameter would cause major error. Therefore, it is important to find the key factors which determine the SOC variation and to develop accurate electrochemical model. With the aid of such equivalent circuit for battery SOC esti-

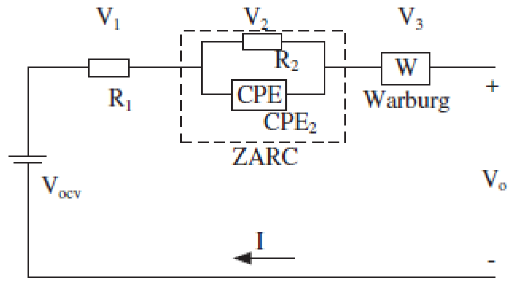

Fig. 3. The diagram of equivalent circuit of the impedance model

mate is the future emphasis in the electrochemical impedance.

G. Kalman filter algorithm

Kalman filter (KF) was proposed by Rudolf E. Kalman in the sixties of the last century [19]. The method can predict the location coordinates and velocities according to the observed sequence of the objects. Kalman filter has been widely used in aircraft orbit prediction, radar communications, computer vision and many other engineering applications. A series research on Kalman filter has also been explored, such as extended KF, unscented KF.

*1) **The basic Kalman filtering algorithm** :* The Kalman filtering algorithm is a self regression algorithm in time domain. During estimation, recursive algorithm and actual observation are used to reduce observation model error and measurement noise. The advantage of this method lies in the low requirement on the accuracy of the observation model [20]. Based on the recursive algorithm, the state, x_{k-1}, from the $(k-1)$ moment and the observation, x_k, from the current moment can be used to deduce the current estimation, $\hat{x}_k$. The historical info has little effect on the estimation procedure, which acquires less data and lowers the hardware requirement for the system considerably.

When Kalman filter is used to estimate the system states, it requires observation values in time domain and kalman filter model, i.e., including two equations: process equation and observation equation. Suppose at k moment, the process equation of the system can be described as:

$$x_k = F_k x_{k-1} + B_k u_k + w_k \tag{6}$$

where x_k is the system state, F_k is the transfer matrix from k moment to $(k-1)$ moment, u_k is the control variable; B_k is the related matrix; w_k is the process noise with 0 expectation followed by normal distribution,

$$w \sim N(0, Q_k) \tag{7}$$

where Q_k is the covariation matrix, and the observation equation is shown as,

$$z_k = H_k x_k + v_k \tag{8}$$

where z_k is the measurement; H_k is the observation matrix reflected from observation to actual values; v_k is the Gauss white noise with $v_k \sim N(0, R_k)$ and R_k is the covariance matrix. The initial state of the system (x_0) and the noise $\{w_1, w_2, w_3, \ldots, w_k, v_1, v_2, v_3, \ldots, v_k\}$ are independent between each other and the prediction and update processes are described as follows.

Prediction process:

$$\begin{aligned} \hat{x}_{k|k-1} &= F_k \hat{x}_{k-1|k-1} + B_{k-1} u_{k-1} \\ P_{k|k-1} &= F_k P_{k-1|k-1} F_k^T + Q_k \end{aligned} \tag{9}$$

Update process:

$$\begin{aligned} \tilde{y}_k &= z_k - H_k \hat{x}_{k|k-1} \\ S_k &= H_k P_{k|k-1} H_k^T + R_k \\ K_k &= P_{k|k-1} H_k^T S_k^{-1} \\ \hat{x}_{k|k} &= \hat{x}_{k|k-1} + K_k \tilde{y}_k \end{aligned} \tag{10}$$

The advantage of Kalman filtering method is that it is not sensitive to the initial SOC error and the disadvantage is that it acquires high precision of the battery performance model and high calculation capability of the battery management system.

*2) **Extended Kalman filtering (EKF) algorithm**:* Kalman filter algorithm can only be applied in linear model, extended kalman filtering algorithm is then designed for nonlinear complex system. The nonlinear model of the extended Kalman filtering algorithm is as follows:

$$\begin{aligned} x_{k+1} &= f(x_k, u_k) + w_k \\ z_{k+1} &= g(x_k, u_k) + v_k \end{aligned} \tag{11}$$

where $f(.)$ and $g(.)$ are the the first-order Taylor expansion of the state equation and measurement equation, respectively. Besides, Jacobi matrix has to be calculated during EKF, so the calculation burden is much heavier than that in KF.

*3) **Unscented Kalman filtering algorithm (UKF) method**:* Unscented Kalman filter can also be applied in nonlinear systems,where unscented transformation are combined with kalman filter [22]. Certain mean values and covariance are selected to satisfy the sigma points of the priori random variables. Each point possesses related weight with the summation of all weights equal to 1. Then these points are transformed via a nonlinear model to obtain the corresponding points. Estimation results can thus be achieved according to the calculation of weights of the points.

The unscented Kalman filter can reduce the influence of nonlinearization during estimation via multi-points reflection. Furthermore, less computation would be required for UKF than EKF since no Jacobi matrix calculation is necessary.

IV. Comparison of SOC estimation methods

There are many different methods to deal with battery power consumption issues, each of which has their own advantages and disadvantages and applicable conditions.

Based on the difference of applied environments, two or more SOC estimation methods can be combined together and used in different stages during the calculation procedure. For instance, OCV is the ideal estimation method in vehicle still state and NN has obvious advantage in vehicle driving state, where both methods do not require the battery model assistance.

Besides, OCV and ampere hour integral method can be used together, where more accurate SOC estimation can be achieved from ampere hour integral method but with higher precision requirement on the initial battery SOC value. OCV can just provide such information so that OCV is used for initial SOC estimate and ampere hour integral method takes responsible for the task during vehicle driving. The combined methods requires less parameters with fast and simple estimation.

In addition, the estimation values from Kalman filtering algorithm can be used to compare with the sensor measurement continuously so that the difference between them could be useful for correction of system error and measurement error [23]. The algorithms could be used with the combination of KF in order to decrease the effect of measurement error on the SOC estimation.

A method of combining two or more of less related methods is proposed, where each method will be used for SOC estimation separately and take certain weights simultaneously. The final SOC can be obtained according to the weights of each method,

$$SOC = \sum_{i=1}^{n} W_i \times SOC_i \tag{12}$$

where W_i is the weights of each battery estimation algorithm and satisfy $\sum_{i=1}^{n} W_i = 1$. The selection of the weight of each SOC estimation algorithms is crucial for the final result.

V. Conclusion

With the gradually increasing importance of the battery power consumption estimation, more and more efforts have been put into practice for better solution. In this paper, the generally used SOC estimation algorithms for lithium-ion battery are summarized. Each method has its own advantages and disadvantages. However, the precision of battery SOC is not only determined by the estimation algorithm but vehicle driving state, battery material, battery model such impact factors. Therefore, to deal with diversified battery types and complex application environments, more lab experiments and field experiments have to be performed to configure ideal battery structure model and related battery SOC approaches.

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