A Voltage Prediction Method of $LiFePO_4$ Batteries on Electric Vehicle During the Relaxation State after Discharging

HOU Jun-wei[a], LI Li-fu[b]

School of Mechanical and Automotive Engineering, South China University of Technology ,
Guangzhou 510640, China

[a]junweihou@foxmail.com, [b]pmlfli@scut.edu.cn

Keywords: Electric Vehicles; Lithium Iron Phosphate; Open-circuit Voltage; Prediction.

Abstract. As the electric vehicle experiences the acceleration and deceleration periods alternately, the power battery open-circuit voltage at the relaxation stte after discharging varies greatly, which brings difficulties in measuring the state of charge(SOC) and causes measurement errors. To solve this problem, a certain type of $LiFePO_4$ battery is taken as the research object. Based on electrochemistry and equivalent circuit theory, this research studies the relation between the open-circuit voltage at the relaxation stage after discharging of the $LiFePO_4$ battery in moving electric vehicle and time. Combined with system identification method, an open-circuit voltage prediction model of lithium iron phosphate batteries is established, and experiment has been carried out to verify the feasibility of the model.

Introduction

At present, lithium-ion batteries, which have the advantage of high energy density and high output power, are widely used as the power supply of electric-drive vehicles(EDVs)[1]. Being the basis of the electrical characteristics and the power(dynamic) system parameter matching of EDVs, the voltage characteristic of the batteries directly affects the monitoring process of battery SOC and the power allocation of power-transmission system [2][3]. However, lithium-ion batteries are in the state of alternating work and non-work when EDVs are in the acceleration and deceleration periods alternately. And based on the principles of battery electrochemical, battery open-circuit voltage(OCV) will be changed due to the polarization effect, especially the rest voltage after discharge, which is called discharge-rest voltage(DRV), will vary according to the driving cycle of EDVs and the rest time. As a result, using the common estimation method of SOC will cause great error and the control strategy of EDVs can’t be implemented. Therefore, taking the lithium iron phosphate battery (power battery) as the research object, this paper establishes a discharge-rest voltage prediction model based on electrochemical principle and equivalent circuit theory. The parameters of the prediction model are calculated through the system identification method based on least square method. Then the model is applied to study the variation rules of the discharge-rest voltage under different driving cycles, which offers technical support for improving the estimation accuracy of the SOC and ensuring the implementation of EDVs control strategy.

Study on Discharge-rest Voltage Prediction Method of Power Battery

According to the principle of EDVs, when EDVs are accelerating, the power battery is in the discharge stage, and the electrode potential relationship between positive terminal of the cell and the negative terminal is shown in Figure 1[4].

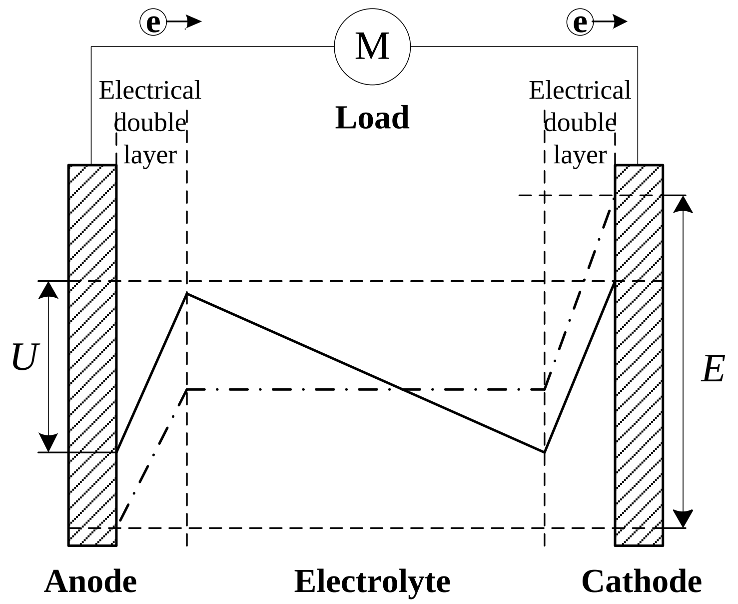

Fig. 1 Schematic of the positive and negative electrodes of the power battery

Where U represents the discharge voltage of battery, E represents the electromotive force (EMF) of battery. If R_Ω is the battery internal resistance, let u_c and u_a denote, respectively, the electrode over potential of positive and negative terminal, and let φ_{cE} and φ_{aE} denote, respectively, the electrode equilibrium of positive and negative terminal, then $U(t)$ can be written as:

$$\begin{aligned} U(t) &= \left[\varphi_{cE} - u_c(t)\right] - \left[\varphi_{aE} + u_a(t)\right] - I(t)R_\Omega \\ &= E - \left[u_c(t) + u_a(t)\right] - I(t)R_\Omega \end{aligned} \tag{1}$$

Where $U(t)$ will vary significantly as $I(t)$, $u_c(t)$ and $u_a(t)$, which are determined by driving cycle of EDVs, changes with time. Then, when the EDVs are in non-accelerating state, $I(t)=0$, and the battery is in the discharge-rest state. Thus, the open-circuit voltage $U_{ocv}(t)$, which is called discharge-rest voltage(DRV), can be written as:

$$U_{ocv}(t) = E - u_c(t) - u_a(t) \tag{2}$$

According to the electrochemical principles, the electrode will be in the unsteady transition process of electrochemical system when the battery is in the discharge-rest state. Therefore, $u_c(t)$ and $u_a(t)$ will differ depending on the rest time t, which directly affects the accuracy of the battery SOC estimation of driving EDVs.

In order to define the relationship between $U_{ocv}(t)$ and rest time t and increase the accuracy of SOC estimation, this paper proposes a discharge-rest voltage prediction method, which is based on the RC equivalent circuit principle.

The method can be expressed as follows: According to the electrode polarization characteristics and the electrical components characteristics[5], the electrons on the electrode not only change the structure of the electrical double layer, which leads to accumulation of charge on the electrode surface and makes electrode potential deviate from equilibrium state, but also participate in the electrode reaction, which plays the role of absorbing charge that is transferred by the movement of electrons and make electrode potential restore equilibrium state[6].

Supposing that the double-layer capacitance of positive electrode and negative electrode are equivalent to, respectively, the polarized capacitor $C_{c,d}$ and $C_{a,d}$, and the electrode reaction of positive electrode and negative electrode are equivalent to, respectively, the polarized resistor $R_{c,d}$ and $R_{a,d}$, the equivalent circuit can be shown in Figure 2[7].

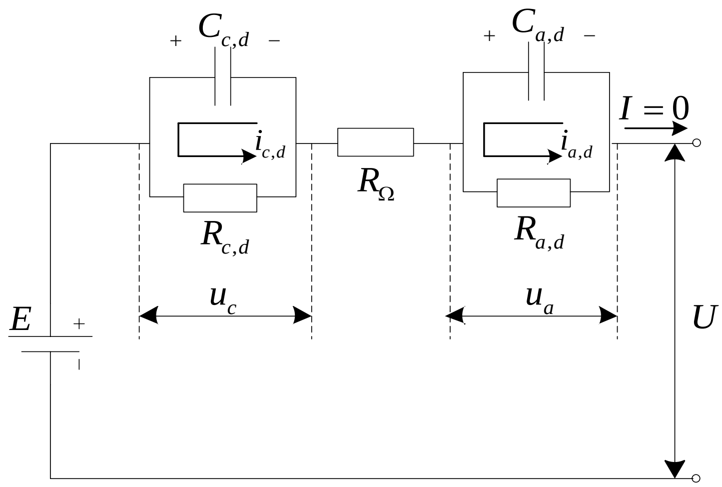

Fig .2 Equivalent circuit of battery at the relaxation state of the discharge respond

According to the RC equivalent circuit principle, when the power battery is in the rest state after discharging (when t>0), the polarized capacitor $C_{c,d}$, and $C_{a,d}$ discharge through the polarized resistor $R_{c,d}$ and $R_{a,d}$, respectively. And the equation of equivalent circuit according to figure 2 can be written as:

$$\begin{bmatrix} R_{c,d}C_{c,d} & 0 \\ 0 & R_{a,d}C_{a,d} \end{bmatrix}\begin{bmatrix} \dfrac{du_c}{dt} \\ \dfrac{du_a}{dt} \end{bmatrix}+\begin{bmatrix} u_c \\ u_a \end{bmatrix}=\begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{3}$$

Through solving Eq. (3), the expression of $u_c\left(t\right)$ and $u_a\left(t\right)$ under rest state after discharging can be written as:

$$\begin{bmatrix} u_c\left(t\right) \\ u_a\left(t\right) \end{bmatrix}=\begin{bmatrix} U_{c0} & 0 \\ 0 & U_{a0} \end{bmatrix}\begin{bmatrix} e^{-\frac{t}{R_{c,d}C_{c,d}}} \\ e^{-\frac{t}{R_{a,d}C_{a,d}}} \end{bmatrix} \tag{4}$$

Where U_{c0} and U_{a0} denote, respectively, initial value of polarization overpotential of positive and negative terminal. From Eqs. (2) and (4), the relationship between the discharge-rest voltage of power battery and rest time is established:

$$U_{ocv}\left(t\right)=E-U_{c0}e^{-\frac{t}{\tau_c}}-U_{a0}e^{-\frac{t}{\tau_a}} \tag{5}$$

Where τ_c=$R_{c,d}C_{c,d}$, $\tau_a=R_{a,d}C_{a,d}$. When the battery is in the initial moment of the rest state after discharging, in other word, when $t=0$, the discharge-rest voltage can be written as $U_{ocv}=E-U_{c0}-U_{a0}$, and U_{ocv} increases with the increase of the rest time t while $U_{c0}e^{-\frac{t}{\tau_c}}$ and $U_{a0}e^{-\frac{t}{\tau_a}}$ decrease at the same time. As the rest time t increases to t', $U_{c0}e^{-\frac{t'}{\tau_c}}=U_{a0}e^{-\frac{t'}{\tau_a}}=0$, $U_{ocv}\left(t'\right)=E$. At this time, the battery will be in a stable state of rest after discharge. Therefore, Eq. (5) can be used as the theoretical prediction model of discharge-rest voltage.

However, according to Eq. (5), the prediction model is a nonlinear function, and the unknown parameter vector, which follows the equation $\theta=\left[E,U_{c0},U_{a0},\tau_c,\tau_a\right]$, has a complex relationship among different parameters. Therefore, according to the system identification principle and Eq. (5), if we process the discharge-rest voltage of different discharge state based on the criterion that finds a minimum residual sum of squares of least-squares, we can obtain the model parameter θ. And its expression can be written as[8]:

$$\min_{\theta}\left\|e(\theta)\right\|_2^2=\min_{\theta}\left\{\sum_{i=0}^{N}\left[e_i(\theta)\right]^2\right\} \tag{6}$$

Where $e_i(\theta)=\hat{U}_{ocv}(t_i)-U'_{ocv}(t_i)$, t_i is the sampling point of time in the discharge-rest experiment, N is sampling number of the experiment. When substituting the parameter θ into the Eq. (5), we can get the discharge-rest voltage prediction model of battery under different discharge conditions. Then, this model can predict the real-time relationship between discharge-rest voltage and rest time when the battery discharge to a certain state, which will provide a basis for estimating the SOC of EDVs in an accurate way while vehicles are running.

Experiment and Analysis

In order to verify the effectiveness of the discharge-rest voltage prediction model of the power battery, a domestic lithium-ion power battery labeled LS#1 with the nominal capacity of 12Ah was used as the study object, and the HT-V5C100D100-16 battery testing system produced by the Guangzhou Qingtian Industrial Limited Company was used in the charge-discharge experiment. The experiment was made up of two procedures - battery data test and data processing. The battery data test procedure mainly included using the battery test system in the constant-current mode with environment temperature remaining 25℃, with constant discharge current of 6A, discharge cut-off voltage of 2.0V and then obtaining discharge-rest voltage $U'_{ocv}(t_i)$. According to the system identification method and the least squares method, we used the Matlab/Simulink software and values of $U'_{ocv}(t_i)$ to identify the prediction model parameter θ and obtained the expression of predictive experimental value $U_{ocv}(t_i)$ while the power battery discharging to 2.0V, the expression of $U_{ocv}(t_i)$ is as follows:

$$U_{ocv}(t_i)=2665.78\text{-}259.89e^{\left(\frac{-t_i}{288.07}\right)}\text{-}210.16e^{\left(\frac{-t_i}{26.01}\right)} \tag{7}$$

The curves of relationships between $U'_{ocv}(t_i)$, $U_{ocv}(t_i)$ and the rest time t_i are shown in Figure 3, where the corresponding square of correlation coefficient is 0.999.

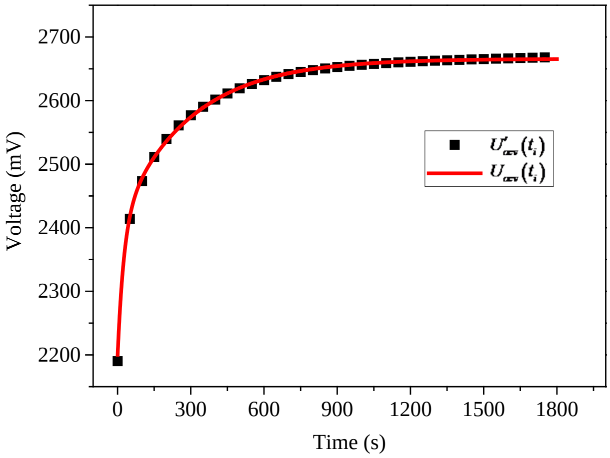

Fig .3 $U_{ocv}(t_i)$ and $U'_{ocv}(t_i)$ curve of LS#1 battery

Figure 3 shows that the relationship between $U_{ocv}(t_i)$ and t_i can be expressed by the exponential function. As t_i increases, $d\left(U_{ocv}(t_i)\right)/dt$ will decrease gradually. And when $t_i=0\text{s}$, $d\left(U_{ocv}(t_i)\right)/dt=8.98\text{mV/s}$; when $t_i=1800\text{s}$, $d\left(U_{ocv}(t_i)\right)/dt=0.0017\text{mV/s}$, $U_{ocv}(t_i)=2.67\text{V}$. As the moment, the power battery turns into a stable situation of rest after discharge.

In order to further verify the feasibility of predict-experimental model based on Eq. (7), we used the battery test system to put the battery LS#1 and the same batch one LS#2 on constant current charge-discharge test and resting test, and got values of $U''_{ocv}(t_i)$, the battery voltage of LS#2 $U''_{ocv}(t_i)$ under the discharge-rest process. And the curves of contrast between $U''_{ocv}(t_i)$ and predict-experimental value $U_{ocv}(t_i)$ and their error are shown in figure 4.

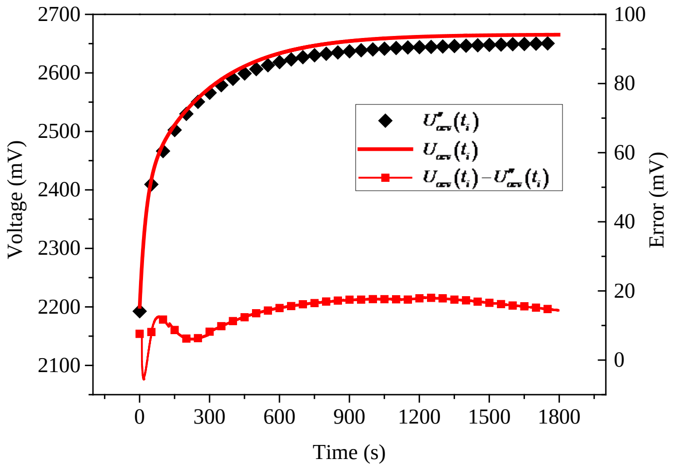

Fig .4 Error curve and voltage ($U''_{ocv}(t_i)$, $U_{ocv}(t_i)$) curve of LS#2 battery

As the figure 4 shows, the $U''_{ocv}(t_i)$ and $U_{ocv}(t_i)$ are consistent in the trend of changing, and the maximum prediction error is 18.15mv, which verifies the feasibility of the experimental model (Eq. (7)) after the power battery discharge-rest experiment.

The driving cycles of electric vehicles determine the magnitude of the prediction model parameters- $U_{c0}, U_{a0}, \tau_c, \tau_a$. Therefore, combining the test data of power battery discharge-rest voltage under conditions of different ambient temperature, discharge rate, depth of discharge and using the discharge-rest voltage prediction method based on RC equivalent circuit principle, the prediction model library of power battery discharge-rest voltage can be constructed. And this can provide technical support for the establishment of forecasting methods of the battery SOC while electric vehicle are running.

Conclusions

Based on the RC equivalent circuit of the power battery, the paper deduces a predictive model of the rest voltage of the power battery in electric vehicle based on the driving process. The model reflects the time-dependent relationship between the rest voltage of the power battery after discharge. By using the system identification method based on the least squares method, the parameters of the battery discharge-rest voltage prediction model and their prediction curve varying with time are obtained through charging, discharging and resting experiment of lithium iron phosphate power battery. And the same batch batteries have also been used to verify the model. The experimental result shows that the predicted voltage data is consistent with the experimental voltage data, and its prediction error is less than 18.15mV. In other words, the model can reflect the changing trend of the resting voltage after the discharging in an accurate way. And this model is of great technical value in optimizing the accuracy of battery SOC estimation and realizing the goal of implementing power control strategy during the process of driving.

Acknowledgement

In this paper, the research was sponsored by Science and Technology Planning Project of Guandong Province, China (Collaborative Innovation and Platform Environment Construction, Project No. 2014B090901054)

References

[1] Fei Gao, Kai Yang, Dong Hui, et al. Cycle-life Energy Analysis of $LiFePO_4$ Batteries for Energy Storage[J]. Proceedings of The Chinese Society for Electrical Engineering. 2013, 33(05): 41-45.

[2] Bin Zhang, Liandui Guo, Zhongbin Cui. Voltage Characteristics of Li-ion Power Battery for EVs[J]. Chinese Battery Industry. 2009, 14(06): 398-403.

[3] Qingquan Chen, Fengchun Sun. Hybrid Electric Vehicle Foundation[M], Beijing Institute of Technology Press, Beijing, 2001.

[4] Di Li. Electrochemical Theory, third edition[M], Beihang University Press, Beijing, 2008.

[5] Guoguang Wen. The Electrochemical Battery[M], Publishing House of Electronics Industry, Beijing, 1995.

[6] Decai Yang. Safety of Lithium ion batteries – Principle/Design/Test[M], University of Electronic Science and Technology of China Press, Chengdu, 2012.

[7] Devarakonda L, Hu T. Effects of rest time on discharge response and equivalent circuit model for a lead-acid battery[J]. JOURNAL OF POWER SOURCES. 2015, 282: 19-27.

[8] Petzl M, Danzer M A. Advancements in OCV Measurement and Analysis for Lithium-Ion Batteries[J]. IEEE TRANSACTIONS ON ENERGY CONVERSION. 2013, 28(3): 675-681.