An Improved Ampere-hour Method For Battery State of Charge Estimation Based on Temperature, Coulomb Efficiency Model and Capacity Loss Model

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***Abstract*—Coulomb efficiency and available capacity affect the precision of Ampere-hour method. Both coulomb efficiency and available capacity vary with temperature and discharge current rate. In this study, some experiments of a 27Ah Nickel Metal Hydride battery were undertaken to determinate the coulomb efficiency. These experiments were undertaken at -18℃, -12℃, 0℃, 25℃ with 1/3C, 1C, 3C charge rate and 1/3C discharge rate. Then, an improved coulomb efficiency model was proposed, which is based on temperature and charge rate. Moreover, an available capacity loss model was built based on experiments of 1/3C discharge rate at -18℃, -12℃, 0℃, 25℃. In addition, an improved Ampere-hour method based on temperature, coulomb efficiency and capacity loss model was built to estimate battery state of charge. The proposed method is verified by experiment and the result shows good precision.**

Keywords- coulomb efficiency; available capacity; capacity loss; temperature; Nickel Metal Hydride battery; Ampere-hour; state of charge

I. INTRODUCTION

Ampere-hour method is the most common method of battery state of charge estimation in electric vehicles, mobile equipment and solar photovoltaic system. The main shortcoming of Ampere-hour method is accumulated error caused by current sensor [1]. In addition, the initial state of charge is not able to estimate with Ampere-hour method. There are some good ways to solve the two shortcomings talked above. The initial state of charge can be predicted with the relationship of SOC and electromotive force. Accumulated error can be decreased by choosing high precision current sensor. However, coulomb efficiency and available capacity also affect the precision of Ampere-hour method. Coulomb efficiency is a key factor which brings error of current. Moreover, the battery available capacity varies with discharge rate and temperature [2, 3]. The available capacity of lithium lion battery varies with discharge rate and temperature is analyzed in [2]. Paper [3] discussed the available capacity of lead acid varies with discharge rate and temperature. The study of lithium polymer batteries coulomb efficiency and available capacity varying with temperature and current rate are analyzed in paper [4]. But in literature, there are not too much analysis of coulomb efficiency and available capacity for Nickel Metal Hydride battery at different temperature and current rate in detail. In this study, experiments of coulomb efficiency for a 27Ah Nickel Metal Hydride battery were carried out at -18℃, -12℃, 0℃, 25℃ and 1/3C, 1C, 3C current rate. Moreover, experiments of available capacity at 1/3C discharge rate were undertaken.

II. COULOMB EFFICIENCY MODEL BASED ON TEMPERATURE

Coulomb efficiency is important to Ampere-hour method. The definition of coulomb efficiency is that the ratio of the Ampere-hours removed from a battery during a discharge to the Ampere-hours required to restoring the battery to the state of charge before the discharge was started [5].

A 27Ah/1.2V Nickel Metal Hydride battery was used in this study. In order to determinate coulomb efficiency, some experiments under -18℃, -12℃, 0℃, 25℃ were undertaken that battery charging at 1/3C, 1C, 3C charge rate respectively to upper limited voltage 1.5V and battery discharging at 1/3C discharge rate to end of voltage 1V. Coulomb efficiency equals the ratio of discharge capacity to charge capacity. The coulomb efficiency at 1/3C, 1C, 3C under -18℃, -12℃, 0℃, 25℃ shows in Table Ⅰ. Formula (1) is the linear curve fitted formula of coulomb efficiency and charge rate at different temperature. The coefficient of A and B is shown in Table Ⅱ.

TABLE I. COULOMB EFFICIENCY AT DIFFERENT CHARGE RATE UNDER DIFFERENT TEMPERATURE

	9A	**27A**	**81A**
-18℃	0.9259	0.913	0.901
-12℃	0.9554	0.926	0.915
0℃	0.9902	0.963	0.935
25℃	0.996	0.975	0.956

$$\eta = (AI+B)/100 \qquad (1)$$

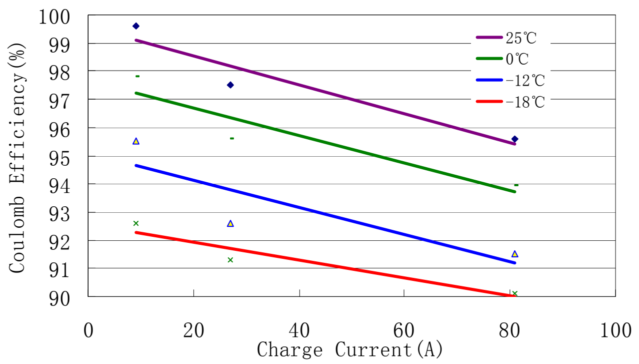

Fig.1 Coulomb Efficiency

TABLE II. COEFFICIENT OF A AND B

	A	B
-18℃	-0.0317	92.568
-12℃	-0.0459	95.08
0℃	-0.0491	97.66
25℃	-0.0509	99.55

The experiment result shows that the coulomb efficiency decreases with the current rate increasing under the same temperature. In addition, it also shows that coulomb efficiency decreases with temperature increasing under the same current rate. The reason of the coulomb efficiency decreasing is that the activity of battery electrode active material decreases with temperature decreasing and charge rate increasing.

In order to determinate coulomb efficiency at any charge rate under any temperature, an improved coulomb efficiency model is proposed, which is based on temperature and current rate. As shown in Fig.1 and Fig2, there are the fitted curves of coefficient A, B and temperature. The curve fitted formulas of A and B are shown in formula (2) and (3) respectively. As shown in formula (4), there is the proposed improved coulomb efficiency model, which is related with temperature and current. The estimation value of coulomb efficiency model is shown in TableⅢ and the error of coulomb efficiency is shown in Table Ⅳ.

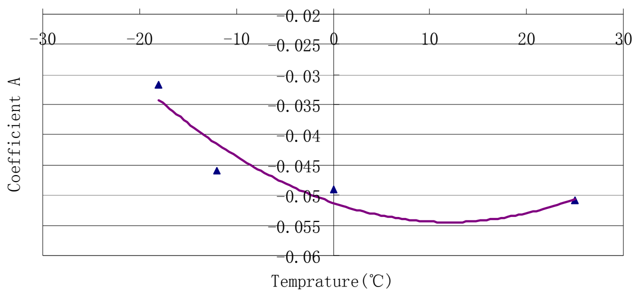

Fig.2 The curve fitted curve of A and temperature

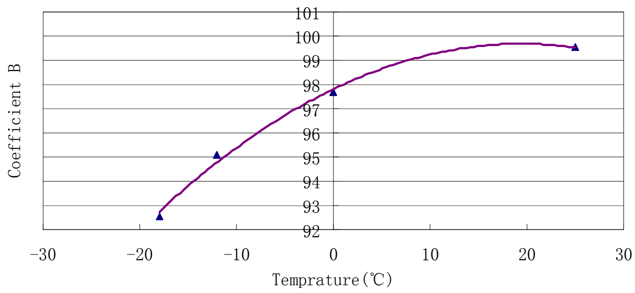

Fig.3 The curve fitted curve of B and temperature

$$A=0.00002*T^2-0.0006*T-0.051 \quad (2)$$

$$B=(-0.0048)*T^2+0.1955*T+97.604 \quad (3)$$

$$\eta_{I,T}=((0.00002*T^2-0.0006*T-0.051)*I+(-0.0048)*T^2+0.1955*T+97.604)/100 \quad (4)$$

TABLE III. THE ESTIMATION VALUE OF COULOMB EFFICIENCY MODEL

	9A	27A	81A
-18℃	0.9223	0.9162	0.898
-12℃	0.9478	0.9401	0.9169
0℃	0.9714	0.9623	0.9347
25℃	0.9901	0.9805	0.9516

TABLE IV. THE ERROR OF COULOMB EFFICIENCY

	9A	27A	81A
-18℃	-0.39%	0.35%	-0.33%
-12℃	-0.8%	1.52%	2.1%
0℃	-1.9%	-0.072%	-0.032%
25℃	-0.59%	0.56%	-0.46%

III. AVAILABLE CAPACITY LOSS MODEL OF 1/3C DISCHARGE RATE BASED ON TEMPERATURE

In electric vehicles field, it often names the available capacity of 1/3C discharge rate under room 25℃ as the nominal capacity. Therefore, in this study, four discharge experiments of 1/3C discharge rate under -18℃, -12℃, 0℃ and 25℃ were undertaken. The difference between available capacity and nominal capacity 27Ah is the available capacity loss. The available capacity loss of 1/3C discharge rate is shown in TableⅤ. From TableⅤ, it shows that the capacity loss rises with temperature decreasing. Because the active material involved in the chemical reaction reduces in low temperature and reduces the available capacity of battery. The linear fitted curve of capacity loss of 1/3C discharge rate and temperature from -18℃ to 0℃ is shown in Fig.4. As shown in Fig.5, there is the linear fitted curve of capacity loss of 1/3C discharge rate and temperature from 0℃ to 25℃. An available capacity loss model is built and shown in formula (5). Moreover, a SOC loss model of 1/3C discharge rate based on temperature is built and shown in formula (6). The error of available capacity loss model is shown in Table Ⅵ. The precision of available capacity loss model is less than 3.16%.

TABLE V. THE AVAILABLE CAPACITY LOSS OF 1/3C DISCHARGE RATE UNDER DIFFERENT TEMPERATURE

Temperature	Discharge capacity	Capacity loss
-18℃	12.12	14.88
-12℃	16.2126	10.7874
0℃	25.196	1.804
25℃	29.07	0

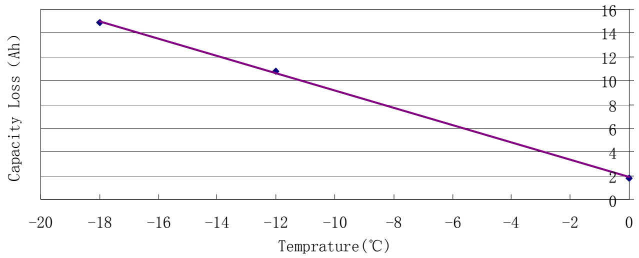

Fig.4 The fitted curve of capacity loss and temperature from -18℃ to 0℃

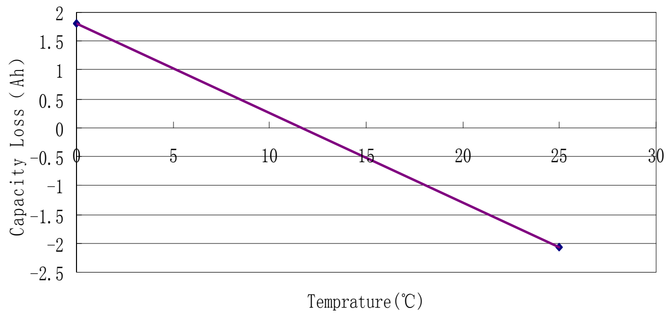

Fig.5 The fitted curve of capacity loss and temperature from 0℃ to 25℃

$$C_{T\_loss}=\begin{cases}(-0.7296)*T+1.861, & T\in[-18^{\circ}C,0^{\circ}C]\\(-0.0722)*T+1.804, & T\in[0^{\circ}C,25^{\circ}C]\end{cases} \qquad (5)$$

$$S_{T\_loss}=C_{T\_loss}/C_N$$
$$=\begin{cases}((-0.7296)*T+1.861)/27, & T\in[-18^{\circ}C,0^{\circ}C]\\((-0.0722)*T+1.804)/27, & T\in[0^{\circ}C,25^{\circ}C]\end{cases} \qquad (6)$$

TABLE VI. THE ERROR OF AVAILABLE CAPACITY LOSS MODEL

Temperature	Real Capacity Loss （Ah ）	Estimate Capacity Loss （Ah ）	Relative Error（% ）
-18℃	14.88	14.9938	0.76
-12℃	10.7874	10.6162	-1.59
0℃	1.804	1.861	3.16
25℃	0	0.000037	/

IV. IMPROVED AMPERE-HOUR MODEL BASED ON COULOMB EFFICIENCY AND CAPACITY LOSS

The improved Ampere-hour model used for SOC estimation is shown in formula (7). In the improved Ampere-hour model, the SOC loss with temperature and current efficiency are considered. In addition self-discharge and aging are considered too. As shown in formula (8) and (9), $\eta_{I,T}$ symbols current efficiency. When the battery charges, $\eta_{I,T}$ equals the improved coulomb efficiency model. In addition, current efficiency $\eta_{I,T}$ equals one when the battery discharge.

$$SOC(t)=SOC(0)-\int_0^t \frac{\eta_{I,T} I}{C_{nominal}}dt$$
$$-S_{Tloss}-S_D-S_{aging} \qquad (7)$$

Where

$SOC(0)$, the initial SOC

$\eta_{I,T}$, current efficiency

Current charge efficiency

$$\eta_{I,T}=((0.00002*T^2\text{-}0.0006*T\text{-}0.051)*I$$
$$+(-0.0048)*T^2+0.1955*T+97.604)/100 \qquad (8)$$

Current discharge efficiency

$$\eta_{I,T}=1 \qquad (9)$$

S_{T_loss}, the loss SOC of temperature in 1/3C discharge rate

S_D, the loss SOC of self-discharge

S_{aging}, the loss SOC of battery aging

V. VERIFICATION OF THE IMPROVED AMPERE-HOUR MODEL FOR SOC ESTIMATION

In order to verify the precision of the proposed method, An discharge experiment under -12℃ shown below was analyzed.

The experiment was shown in Fig.6 and was described as below. Firstly, the NiMH battery was charged to full state before discharge experiment. Secondly, put the battery in the ice box under -12℃ for 12 hour. Thirdly, the NiMH battery discharged under 2C rate for 889 seconds, and then it discharged under 1C rate for 424 seconds. The aim of the experiment is to estimate the SOC when the experiment was end to verify the proposed method.

The procedure of SOC estimation of proposed method shown in below. 1)As the battery was charged to full, the SOC of battery was 100%. 2) The capacity of 2C discharge rate was 13.34 Ah and the capacity of 1C discharge rate was 3.08 Ah.

Therefore, the formula $\int_0^t \frac{\eta_{I,T} I}{C_{nominal}} dt$ was 60.8%. 3) Because the available capacity loss of 1/3C discharge rate under -12℃ is 10.7874Ah, S_{T_loss} is 39.95%. 4) According the formula (7), the SOC when the experiment was end is -0.77%. As SOC>=0, the SOC when the experiment was end is 0.

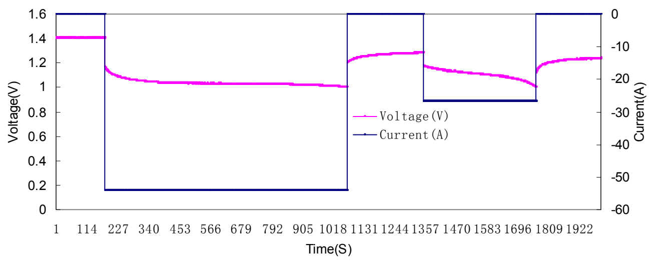

Fig.6 Discharge experiment under -12℃

The real SOC when the experiment was end is achieved by another discharge experiment under 1/3C rate, which is shown in fig.7. The real residual capacity when the experiment was end is 0.98, which means the real SOC is 3.6%.

Therefore the error of the proposed method in the discharge experiment is 3.6%.

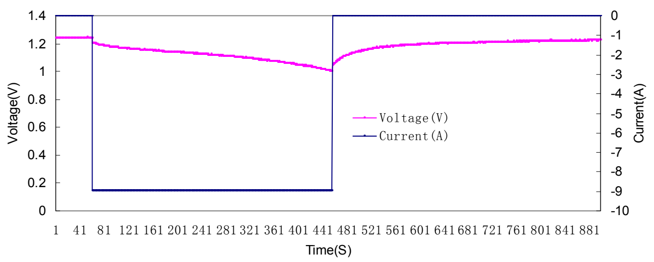

Fig.7 Discharge experiment at 1/3C rate under -12℃

VI. CONCLUSION

The experiment results of Nickel Metal Hydride battery were presented which show that the coulomb efficiency decreased with temperature increasing in the same charge rate and the coulomb efficiency decreased with current rate increasing in the same temperature. It is benefit for ampere-hour method to predict SOC that the coulomb efficiency keeps high level even in low temperature and high charge rate. The improved coulomb efficiency model considers that coulomb efficiency varies with temperature and charge rate. Available capacity loss model embodies available capacity decreases with temperature decreasing, especially, the capacity decreases rapidly in low temperature. The improved ampere hour model for SOC estimation shows good precision in room temperature and low temperature. In the future, the study of coulomb efficiency and available capacity loss in high temperature should be considered, which are important for SOC estimation too.

REFERENCES

[1] Terry Hansen,Chia-Jiu Wang, “Support vector based battery state of charge estimator,” Journal of Power Sources, vol. 141, 2005, pp. 351–358.

[2] D. Doerffel, S.A. Sharkh, “A critical review of using the Peukert equation for determining the remaining capacity of lead-acid and lithium-ion batteries,” Journal of Power Sources, vol. 155, No.2, 2006, pp. 395–400.

[3] C.C. Chan, E.W.C. Lo, Shen Weixiang, “The available capacity computation model based on artificial neural network for lead–acid batteries in electric vehicles,” Journal of Power Sources, vol. 87, 2000, pp. 201-204.

[4] Kim B.G., Tredeau F.P., Salameh Z.M, “Performance evaluation of lithium polymer batteries for use in electric vehicles,” IEEE Vehicle Power and Propulsion Conference, 2008, pp. 1 – 5 .

[5] USABC Electric vehicle battery test procedures manual, 2003, pp. APPENDIX-F-6.