Study of Equivalent Circuit Model for Lead-acid Batteries in Electric Vehicle

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***Abstract*-The accurate estimation of lead-acid batteries state of charge (SOC) is very important for electric vehicles (EVs).However electrochemical reaction is a very complex process; it is difficult to simulate its dynamic behavior. Various equivalent circuit models have been studied, but can not show a good compromise between real-time and precision. In this paper, a revised model considering temperatures, discharge rates and different conditions is proposed based on a large number of experiments. These data are obtained from ARBIN, a battery testing device, and EVs. The simulated values are in good agreement with experimental data. And the associated error has been considered acceptable from an engineering point of view. It provided a model support for high accurate SOC estimation.**

Keywords-Equivalent circuit model;Lead-acid battery; Electric vehicle

I. INTRODUCTION

Electric Vehicles (EVs) have several potential advantages over traditional internal combustion engine vehicles. They promise zero emission and efficiency. Traditionally, most EVs have used lead-acid batteries due to their mature technology, high availability, and low cost. State of charge (SOC) is an important parameter for battery status. The SOC for a fully charged battery is 100% and for an empty battery is 0%.SOC is used to reflect the available capacity in a battery expressed as a percentage of rated capacity. Electric equivalent circuit models [3] [7] have been used to lead-acid batteries to estimate the SOC.

The components of the circuit represent the internal components of the battery (for example, electrode and electrolyte resistances). The accuracy of these models depends upon the number of characterization tests performed to identify the values of the circuit elements.

In this paper a lot of experiment data are firstly obtained form battery testing device ARBIN, through data fitting and analysis, the changes of parameters in the model is concluded, and then verified by EVs real situation.

The lead-acid battery studied here is used as main energy source for EVs. Lead-acid power battery module has two major statuses in normal running, discharge and idle. For charge, it's completed by off-line special equipment.

Therefore, the lead-acid battery model built in this paper is mainly based on these two conditions, which are lead-acid batteries discharge and no current output.

II. BATTERY MODEL

Lithium-ion battery equivalent circuit model has been well studied [1] shown by Fig.1. Fig.2 shows the terminate voltage when discharge current pulse of 20A are applied.

Form Fig.3, it is seen that lead-acid battery terminal voltage in response to current pulse is similar to Lithium-ion battery. Therefore, the assumption that lead-acid batteries discharge and zero input equivalent circuit model is also similar to that of Lithium-ion battery. Based on this, the parameters in the model are studied.

The model consists of a capacitor C0 to characterize the ability of the battery to store charge, an internal resistance R0,two first-order RC blocks, R1& C1and R2&C2(their time constant are τ1 and τ2). Therefore, the discrete formulas of terminal voltage are as following:

$$U(k) = U_{R0}(k) + U_{C0}(k) + U_{R1}(k) + U_{R2}(k) \quad (1)$$

$$U_{R0}(k) = I(k) \times R0 \quad (2)$$

$$U_{C0}(k) = U_{C0}(k-1) + I(k) \times \triangle t / Cap \quad (3)$$

$$U_{R1C1}(k) = I(k-1) \times R1 \times (1-\exp(-\triangle t/\tau 1)) \quad (4)$$

$$U_{R2C2}(k) = I(k-1) \times R2 \times (1-\exp(-\triangle t/\tau 2)) \quad (5)$$

$\triangle t$(s): The Sampling interval
Cap (V): Value of C0
I (A): the current, positive when the cell is charged

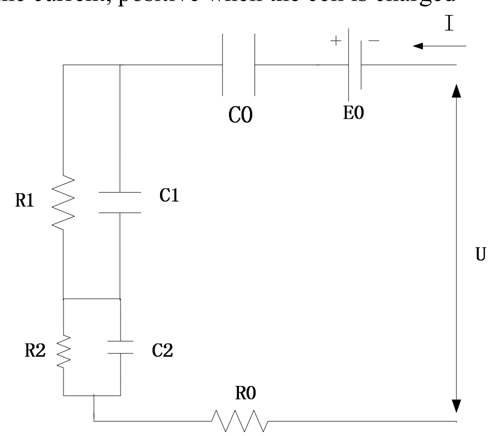

Figure 1. RC Lithium-ion battery mode

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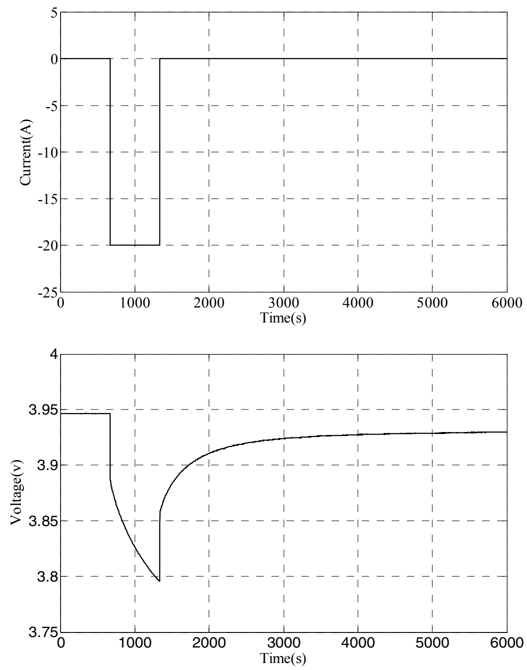

Figure 2. Lithium-ion battery terminal voltage when discharge current pulse of 20A are applied

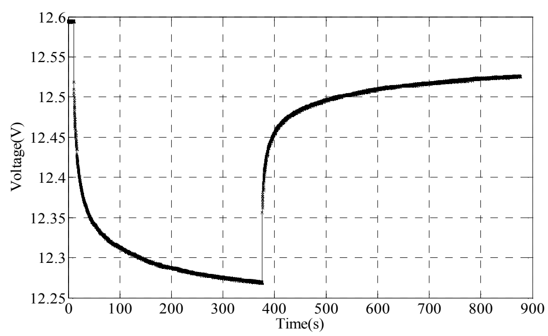

Figure 3. Lead-acid battery terminal voltage when discharge current pulse is applied

In order to get a more accurate model of lead-acid batteries, it is studied mainly by adjusting the parameters (R0, R1, R2, τ1, τ2) in the model and finding the law of changes.

A. *Battery Resistance*

The internal resistance (R0) of the battery is measured at different SOCs and temperature. Their relation is shown as Fig.4.

Through fitting test data shown as Fig.5, it is found that the value of R1 multiplied by the discharge current is a constant.

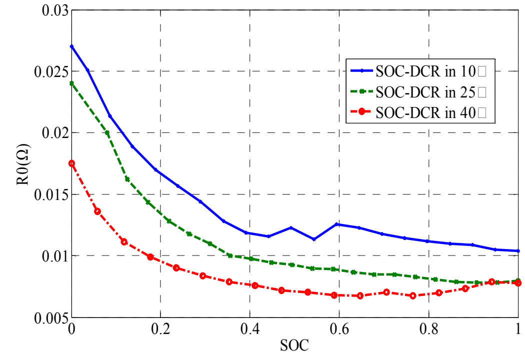

Figure 4. Relationship between R0 and SOC at different temperature

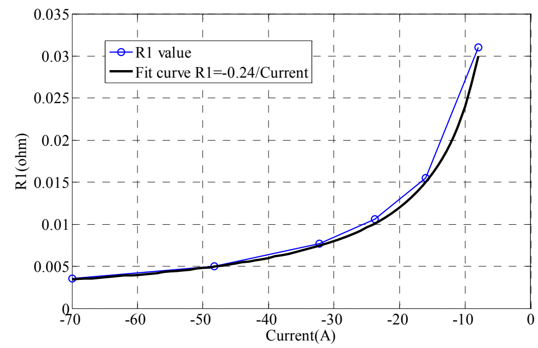

Figure 5. The correlation between discharge current and resistance R1

B. *Time constant τ1*

The terminal voltage response to different discharge current pulses, through experiment fitting and model simulating with parameters changes, is compared.

Form Fig.6 to Fig.9 is the terminal voltage response when discharging currents (8A, 16A, 32A, 48A) are applied. The discharge pulse response is equivalent a zero-state response and a zero-input response. Take Fig.6 for example, all 4 subfigures is the comparison of measured value with simulated value. The different is whether τ1 is constant in zero-state and zero-input phase or not. In Fig.6.1 subfigure, τ1 is constant; in Fig.6.2 subfigure τ1 gains with step time in zero-state response phase, while constant in zero-input response phase; in Fig.6.3 subfigure τ1 gains with step time in zero-input response phase, while constant in zero-state response phase; in Fig.6.4 subfigure τ1 gains with step time in pulse. It can be clearly seen that theFig.6.4 is well fitted.

It is also same to Fig.7, Fig.8 and Fig.9.Thus the changes of τ1 is concluded.

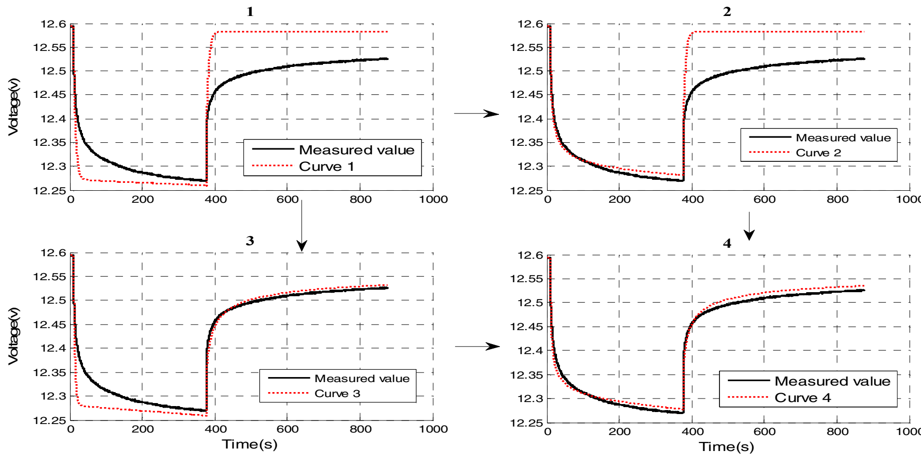

Figure 6. Voltage response to 8A discharge current pulse

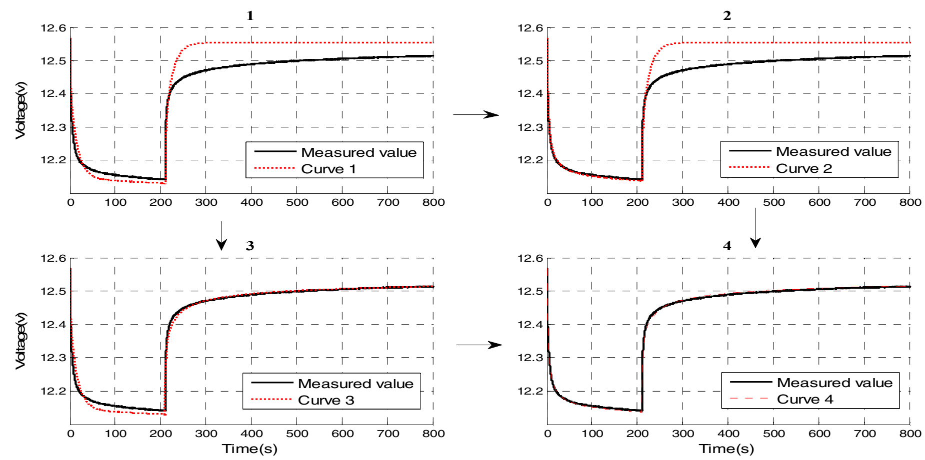

Figure 7. Voltage response to 16A discharge current pulse

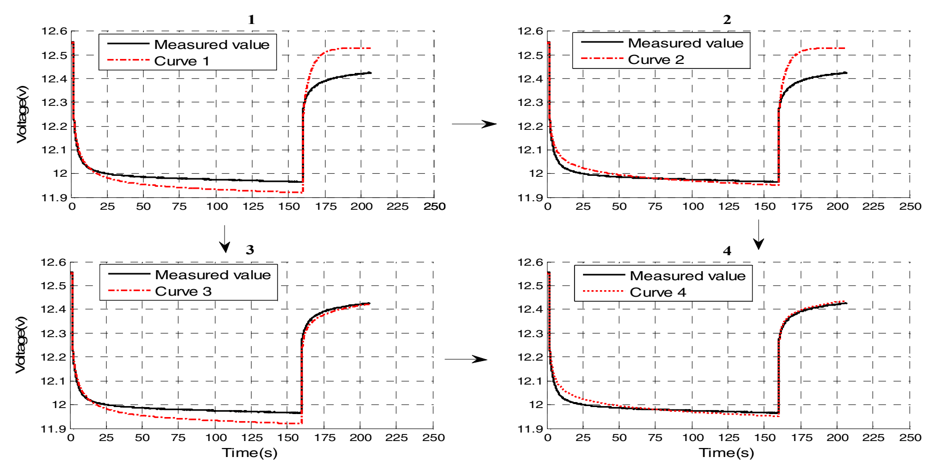

Figure 8. Voltage response to 32A discharge current pulse

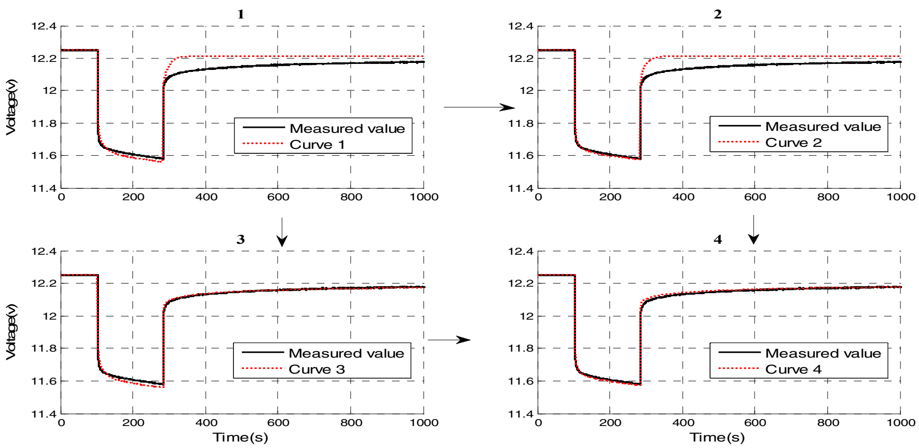

Figure 9. Voltage response to 48A discharge current pulse

C. Revised Model

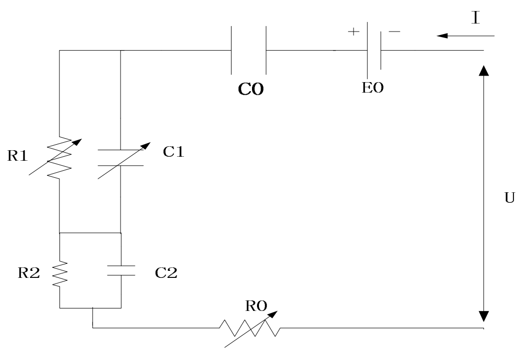

Figure 10. The revised model

It is also found that changes of C0, R2 andC2 have little effect on the model. In addition to the analysis of voltage response of constant current pulse discharge and internal resistance changes, the model is revised as Fig.10.

D. Multi-Pulse Fitting and Model Verification

In order to verify the model, multi-pulse current activated voltage response is simulated and compared.Fig.11 is the curve of discharge current pulse,. It can be clearly seen from Fig.12 that the simulated result is very close to real situation. The max absolute error is less than 0.1v shown in Fig.13, thus the model is reasonable

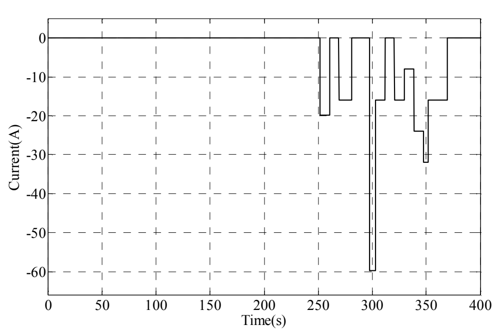

Figure 11. Multi-Pulse discharge current condition

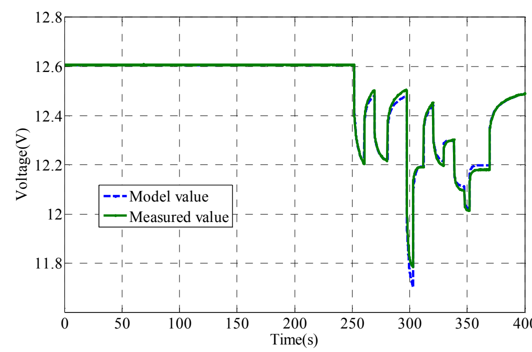

Figure 12. Comparison of measured and simulated cell voltage in multi-pulse discharge current condition

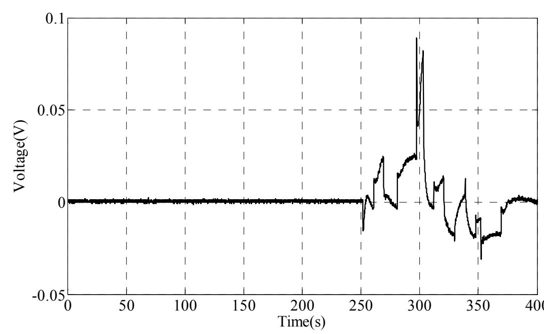

Figure 13. Absolute error.

E. Real Situation Fitting and Model Verification

In order to further demonstrate the performance of the model, the real vehicle condition is applied. In the following figures parameters in model 2 is constant, while parameters in model 1follow certain rules that concluded by this paper.

Curves in Fig.14 and Fig.18 are real-time current in different conditions .These data are obtained from EVs. Fig.15 and Fig.19 is the comparison of measured and simulated battery pack voltage (10 cells). It is obvious that model 1 is better shown as enlarged Fig.16 and Fig.20.Also relative error is small as Fig.17, 19 and Table 1, 2. Relate error is calculated as following:

Relative Error= (model value-measured value)/measured value

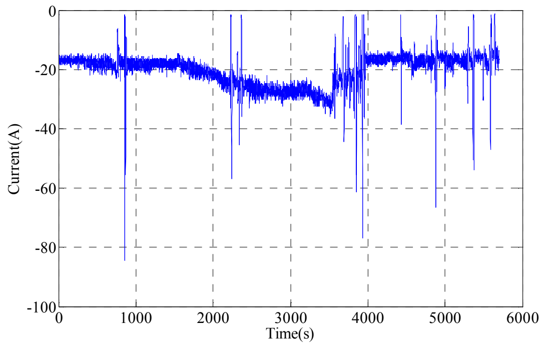

Figure 14. Real condition 1

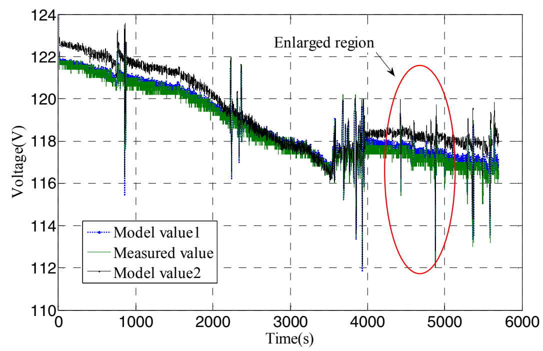

Figure 15. Comparison of measured and simulated battery pack voltage in condition 1.

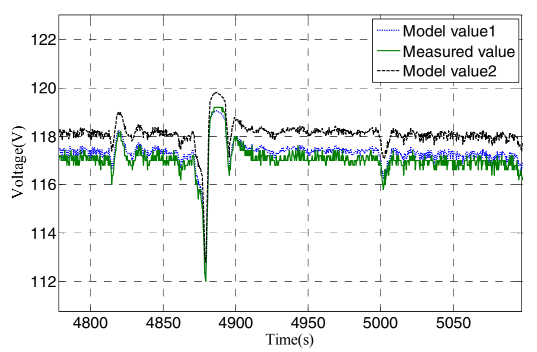

Figure 16. Enlarged area of Figure 15

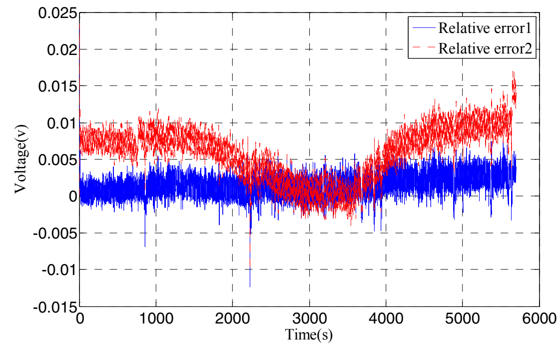

Figure 17. Relative Error

TABLE I. COMPARISON OF ERROR BETWEEN MODEL 1 & 2

	The average relative error	*The variance of relative error*	*Maximum error*
Model 1	0.0015	2.2730e-006	0.01237
Model 2	0.0059	1.2157e-005	0.01702

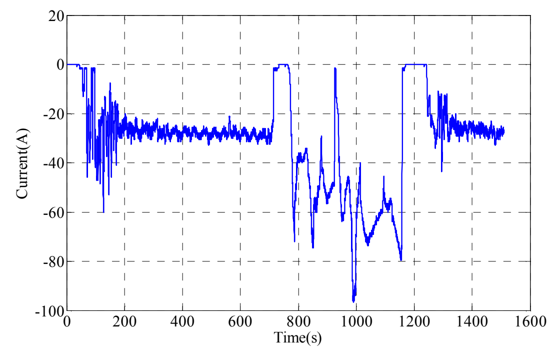

Figure 18. Real condition 2

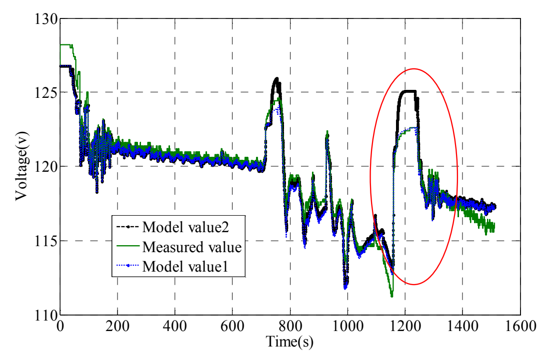

Figure 19. Comparison of measured and simulated battery pack voltage in condition 2

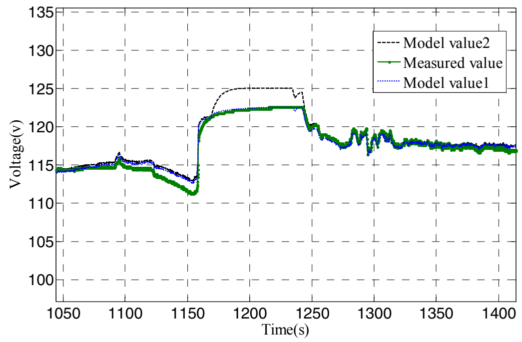

Figure 20. Enlarged area of Fig.19

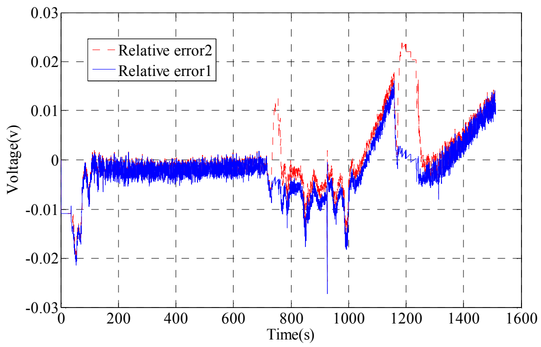

Figure 21. Relative Error

TABLE II. COMPARISON OF ERROR BETWEEN MODEL 1 & 2

	The average relative error	***The variance of relative error***	***Maximum error***
Model 1	1.4709e-004	5.1498e-005	0.02723
Model 2	-0.0022	3.0372e-005	0.02382

Through comparing the fitting result of the 2 real conditions based on the model structure, it can be concluded that the model 1 is better than model 2.Thus it is verified that changes of the model parameters is reasonable.

III. CONCLUSION

Based on lead-acid batteries in electric vehicles condition, this paper studied the equivalent circuit model in the state of discharge and no energy output. The structure of the model is established by comparing the voltage response to current discharge pulse between lithium-ion battery and lead-acid battery. According to experiment data fitting, the changes of parameter s in the model are concluded and verified by multi-pulse discharge currents. And another two groups of real EVs condition is studied and error is analyzed to further verify the model's accuracy and rational.

This paper provided a model support of assess the design of EVs power system, real-time simulation used in hardware in the loop and SOC estimation for a more accuracy.

REFERENCES

[1] WEI Xuezhe.SUN Zechang,TIAN jiaqing. “Parameter Identification and State Estimation of Li-ion Power Battery in Hybrid Electric Vehicle”,Journal of Tongji University Natural Science,Shanghai, 2008.

[2] United States Idaho National Engineering & Environmental Laboratory. Freedom CAR battery test manual for power assist hybrid electric vehicles [R]. Washington D C : US Department of Energy ,2003.

[3] Amir Vasebi , Maral Partovibakhsh, S. Mohammad Taghi Bathaee.A novel combined battery model for state-of-charge estimation in lead-acid batteries based on extended Kalman filter for hybrid electric vehicle applications, Journal of Power Sources 174 (2007) 30–40.

[4] Tetsuro Okoshi, Keizo Yamada, Tokiyoshi Hirasawa, Akihiko Emori. Battery condition monitoring (BCM) technologies about lead–acid batteries. Journal of Power Sources 158 (2006) 874–878.

[5] Phillip E. Pascoe, Adnan H. Anbuky. A VRLA battery simulation model. Energy Conversion and Management 45 (2004) 1015–1041

[6] Chyuan-Yow Tseng , Chiu-Feng Lin. Estimation of the state-of-charge of lead–acid batteries used in electric scooters. Journal of Power Sources 147 (2005) 282–287

[7] Impedance-Based Simulation Models for Energy Storage Devices in Advanced Automotive Power Systems.