Modeling of Lithium-Ion Battery Using MATLAB/Simulink

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***Abstract*—Lithium-ion battery is potentially to be adopted as energy storage system for green technology applications due to its high power density and high energy density. An accurate battery model in simulation platform is very important to design an efficient battery-powered system. In this paper, an electrical battery model is developed in MATLAB/Simulink. The structure of model is explained in detail, and a battery model for a lithium ferro phosphate battery is presented. The developed battery model is validated from the experiment results. From the comparison, it reveals that the developed model is capable of predicting current-voltage performance accurately. Although the model has been developed for lithium ferro phosphate battery, it is expected that it can be applied for other types of battery.**

Keywords—Li-ion, battery model, Simulink.

I. INTRODUCTION

Rechargeable battery is an electrochemical device which converts electrical energy to chemical energy during charging and converts chemical energy to electrical energy during discharging. Rechargeable battery plays important role in future technology since it is potentially to be applied as energy storage element in green technology applications, such as electric vehicle (EV) and photovoltaic (PV) system. The renewable energy source can be stored in battery packs and thus help to reduce the reliance on fossil fuels.

In the aspect of technology, the rechargeable battery is improved from lead acid battery to nickel-based battery and from nickel-based battery to lithium-ion (Li-ion) battery. Lithium-ion battery has higher terminal voltage, higher power density and higher energy density compared to the other rechargeable batteries. Nowadays, Li-ion battery is widely adopted in portable electronic devices, such as laptop computers, smart phones and digital cameras.

Accurate battery information such as state-of-charge (SOC), current and voltage are vital for circuit designer to manage the energy consumption of battery-powered system. Moreover, handling on battery is necessary to avoid battery from overcharged or over-discharged. Therefore, an accurate battery model is vital as a guide in circuit design process to forecast the characteristics of battery.

Numerous studies conducted on battery modeling techniques are published in various scientific journals. Equivalent circuit model is popularly used by circuit designers since it can be easily applied in circuit simulator [1-2]. Reference [1] has proposed an accurate and intuitive equivalent circuit model for battery as shown in Fig. 1. This battery model with two resistor-capacitor (RC) parallel networks is proven to have high accuracy and capable to predict runtime and current-voltage (I-V) performance of battery [1].

MATLAB/Simulink is a powerful simulation tools for circuit and system designs. It provides a lot of simple, powerful and user friendly toolboxes or simulation blocks. A battery model is included in MATLAB/Simulink SimPowerSystems library as proposed in [3]. However, the model is built based on Sheperd equation, is not capable to characterize the nonlinear current-voltage performance of battery [4]. Therefore, a new battery model which based on equivalent circuit model should be developed in MATLAB/Simulink in order to give a more accurate simulation results. For instance, a Simulink model of Li-ion battery has been developed in [5] using Simulink blocks. Average values of RC circuit parameter are applied in the Simulink model for model simplification.

In this paper, an equivalent circuit model for battery is developed in MATLAB/Simulink. The parameters of battery model are determined from experiment results. In contrast to the model proposed in [5], the model's parameters are varied with state-of-charge (SOC) and current [1,6] and it allows circuit designer to set the parameters according to the battery behaviors. Moreover, the proposed model can be easily connected to another circuit blocks in MATLAB/Simulink and give real time SOC estimation.

The rest of paper is organized as follow. Section II introduces the proposed model and explains the structure of simulation blocks. Battery test system and model extraction are

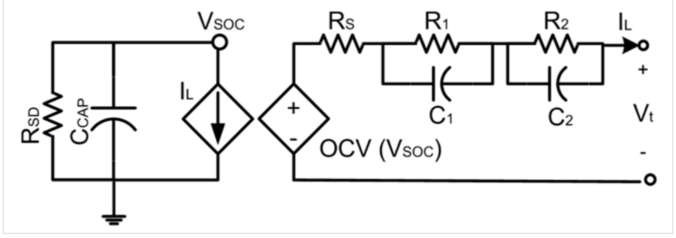


Fig. 1. Equivalent circuit model in [1].

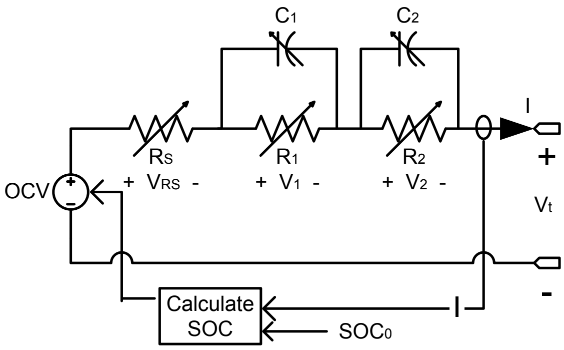


Fig. 2. Dynamic equivalent circuit model.

presented in Section III and Section IV respectively. Section V discusses on the model validation and Section VI concludes the paper.

II. THE PROPOSED MODEL

For simulation study, a dynamic equivalent circuit model shown in Fig. 2 is proposed. The model circuit consists of a dc voltage source, a series resistance and two RC parallel networks. Dc voltage source is used to represent open circuit voltage (OCV) of battery, series resistance (R_S) is used to represent internal dc resistance, and RC parallel networks (R_1, C_1, R_2, C_2) are used to characterize transient response of voltage and terminal voltage is represented by V_t [1-2]. Rate capacity effect is also considered in this model where the usable capacity is varied with current [7,8]. The SOC of battery is calculated based on the value of usable capacity. In this model, the parameters are dependent on SOC and current.

Fig. 3 shows the proposed simulation model with MATLAB/Simulink. Terminal voltage (V_t) of battery is represented by controlled voltage source while five subsystems are used to control the voltage value of battery model; they are SOC calculation, OCV calculation, RC values, Voltages of RC parallel networks and V_{RS}. Current measurement block is used to give the current value to the subsystems. The initial SOC is represented by SOC_0 whereas the real time SOC is represented by SOC_n. The structure of each subsystem is explained in the following sections.

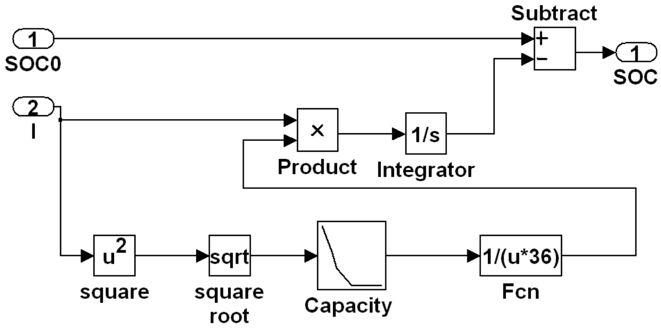


Fig. 4. SOC calculation

A. SOC Calculation

Equation (1) is used for SOC calculation, where SOC_0 is the initial SOC, I represents current and α^U is usable capacity. Fig. 4 shows the structure of the subsystem of SOC calculation. There are two inputs in this subsystem, one is initial SOC (SOC_0) and another one is current (I). A lookup table is used to characterize rate capacity effect of battery where the usable capacity (α^U) is varied with the magnitude of current. The output of this subsystem is the real time SOC.

$$SOC = SOC_0 - \int \frac{I \times 100}{\alpha^U \times 3600} dt \tag{1}$$

B. OCV Calculation

Open circuit voltage is the voltage of battery during equilibrium state. It is one of the important parameter to be realized. The value of OCV is dependent on SOC. The OCV-SOC relationship can be characterized with polynomial equation. Therefore, for this subsystem, a mathematical relationship between OCV and SOC is established as a block diagram shown in Fig. 5.

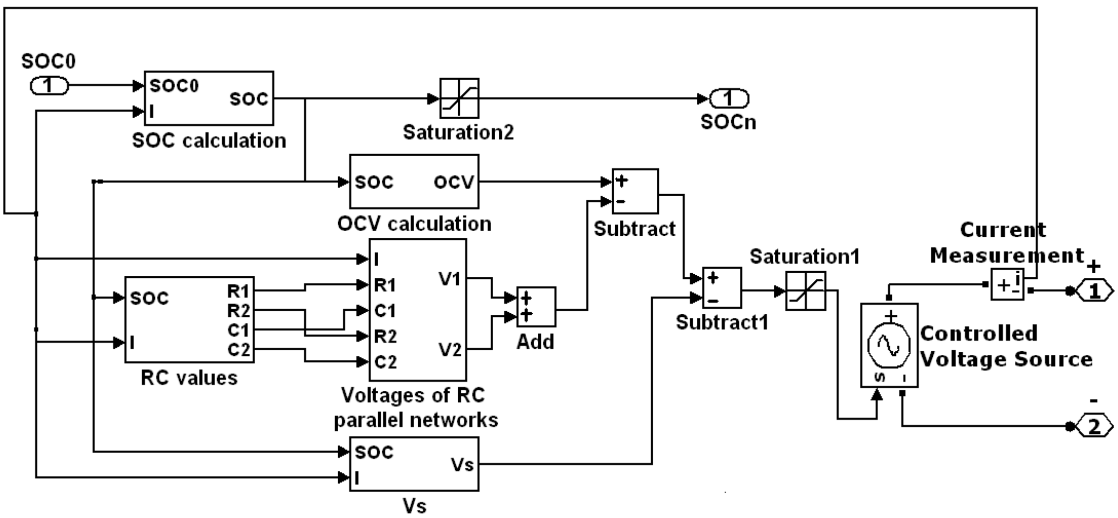


Fig. 3. Proposed simulation model in MATLAB/Simulink.

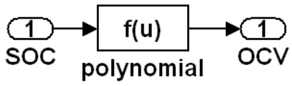


Fig. 5. OCV calculation.

C. RC Values

The value of RC parallel networks (R_1, C_1, R_2, C_2) are dependent on SOC and current. In this subsystem, 2-D lookup tables are applied to determine the parameters of RC parallel networks as shown in Fig. 6. By using 2-D lookup table, the model determines the most suitable value for parameters by using interpolation-extrapolation lookup method resulted to 3-D graphic representation.

D. Voltages of RC Parallel Networks

The voltages of RC parallel networks are corresponding to transient response of battery voltage. In order to establish the subsystem, the circuit of RC parallel network is analyzed.

The circuit component of a RC parallel network is shown in Fig. 7. By using s-domain, the voltage of RC parallel network can be expressed as below:

$$I = \frac{V}{R} + sCV$$
$$\frac{I}{sC} = \frac{V}{sCR} + V \tag{2}$$
$$\therefore V = \left(\frac{1}{s}\right)\left[\frac{I}{C} - \frac{V}{RC}\right]$$

Therefore, the simulation blocks for this subsystem can be arranged as shown in Fig. 8, where V_1 is the voltage for first RC parallel network and V_2 is the voltage for second RC parallel network.

E. V_{RS} Calculation

V_{RS} represents the voltage drop from dc internal resistance (R_S). The value of V_S can be simply calculated by using equation (3). In this section, the value of R_S is dependent in current and SOC. Therefore, a 2-D lookup table is used to represent the value of R_S. The most suitable value for R_S will be determined with interpolation-extrapolation lookup method.

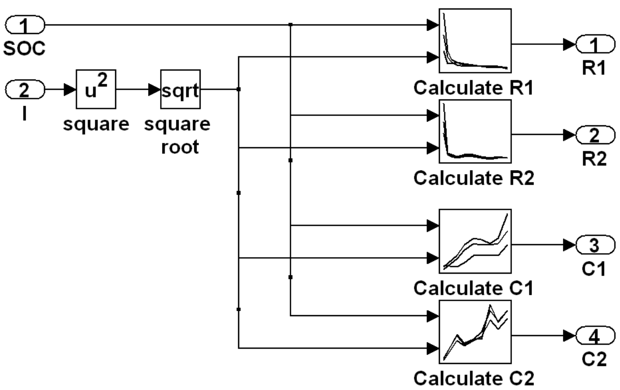


Fig. 6. RC values.

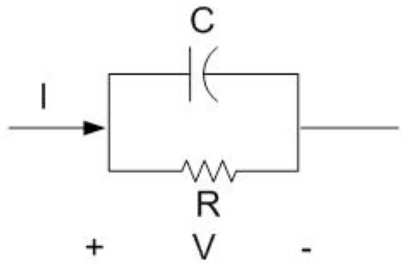


Fig. 7. RC parallel networks.

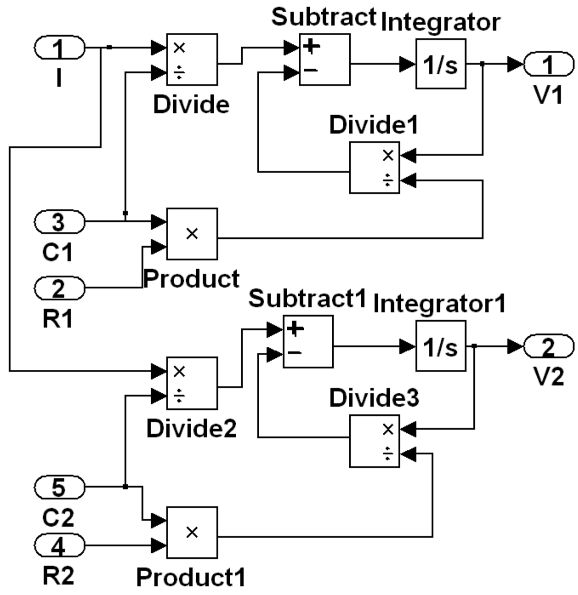


Fig. 8. Voltages of RC parallel networks.

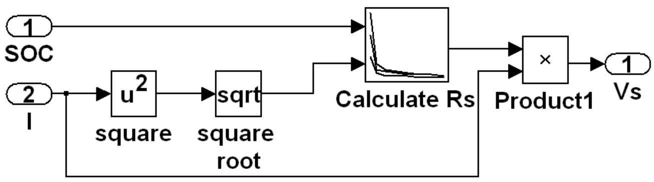


Fig. 9. V_{RS} calculation.

The structure of this subsystem is illustrated as Fig. 9.

$$V_S = I \times R_S \tag{3}$$

By connecting the subsystem blocks, the terminal voltage (V_t) of battery is calculated as denoted in equation (4).

$$V_t = OCV - V_1 - V_2 - V_S \tag{4}$$

III. Experimental Set Up and Battery Test

In this paper, a battery model for lithium ferro phosphate ($LiFePO_4$) battery is developed. Battery tests are conducted on the battery in order to indentify the parameters of the model. The parameters also can be identified using online parameterization algorithm as discussed in [6]. However, it is not included in the scope of this paper.

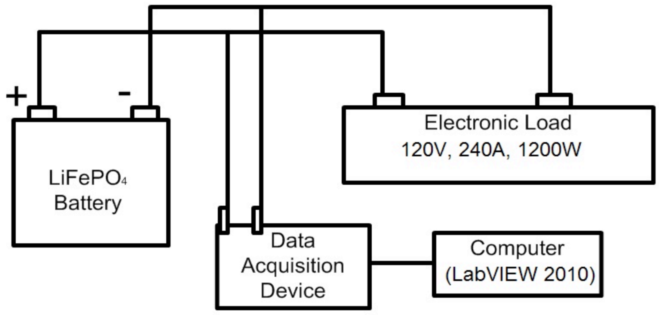


Fig. 10. Block diagram of battery test system.

A. Experimental Set Up

Fig.10 illustrates the block diagram of the battery test system. The test system consists of a $LiFePO_4$ battery which has nominal voltage and capacity of 3.2V and 18Ah respectively. Battery test is conducted by using ITECH electronic load IT8514C with the rating of 120V, 240A, 1200W. Data acquisition (DAQ) device which produced by National Instruments is interfaced with LabVIEW 2010 and a computer to record the results of battery tests. In this test, the room temperature is kept in 25 ˚C to avoid the temperature effect.

B. Battery Tests

Continuous discharge test (CDT) and pulse discharge test (PDT) are applied for parameter identification. CDT is conducted by continuously discharge the battery with constant current. In this paper, CDT for 6A (0.33C), 9A (0.5C) and 18A (1C) are conducted to identify the rate capacity effect of battery.

Besides, PDT is conducted by intermittently discharge the battery with constant current. Thirty minutes of rest time is applied for each cycle in order to identify OCV and voltage transient response of battery [3]. In this paper, PDT for 6A (0.33C), 9A (0.5C) and 18A (1C) are conducted. During the battery tests, the battery voltage is restricted from reach below the cut-off voltage (i.e. 2V) in order to avoid the permanent damage of battery as suggested by battery manufacturer.

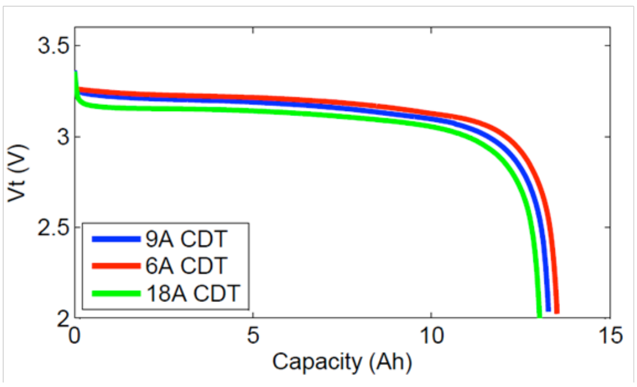


Fig. 11. Experimental results for 6 A, 9 A and 18 A CDT.

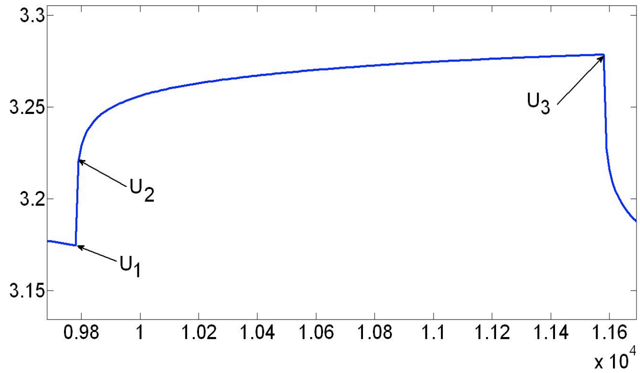


Fig. 12. Transient response of voltage during relaxation.

IV. MODEL EXTRACTION

A. Usable Capacity

The rate capacity effect of battery is identified from the results of CDT. Fig. 11 illustrates the results of CDT. In this aspect, 18Ah is the theoretical capacity which is determined based on the active material in the battery. The actual usable capacity is not necessary equal to this theoretical value as explained in [7]. Therefore, the usable capacity is lower than 18Ah. Based on the experiment result, the usable capacity (in the unit of Ampere-hour) of each current can be identified. The results are tabulated in the lookup table of SOC calculation block.

B. OCV, R_1, R_2, C_1, C_2 and R_S

The value of OCV, R_1, R_2, C_1, C_2 and R_S can be identified from the results of PDT. Fig. 12 shows the voltage curve of PDT during relaxation (I = 0A). OCV is the terminal voltage of battery at equilibrium state. Therefore, it can be represented by U_3. The OCV-SOC relationship is shown in Fig. 13. The OCV-SOC relationship is represented by a polynomial equation.

The dc internal resistance can be calculated from the instantaneous rise of voltage (U_2-U_1) using equation (5). The results of calculation are programmed in 2-D lookup table as shown in Fig. 14.

$$R_S = \frac{U_2 - U_1}{I} \tag{5}$$

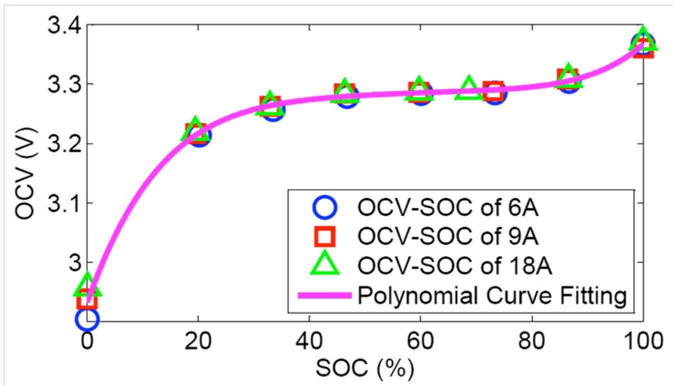


Fig. 13. OCV-SOC relationship.

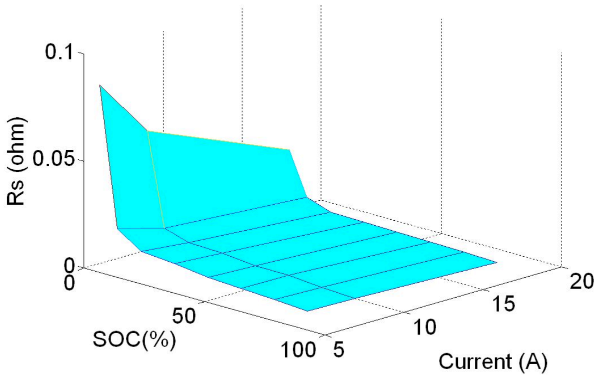


Fig. 14. R_S value.

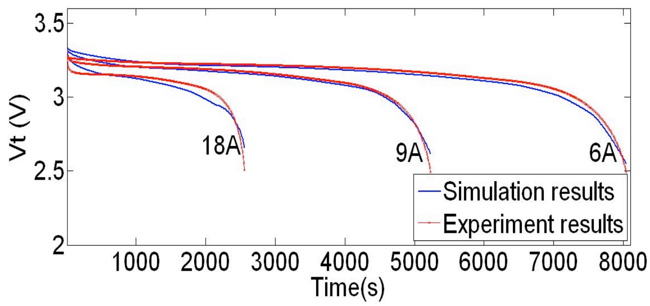


Fig. 16. Comparison between simulation and experiment results of CDTs.

The value of R_1, R_2, C_1 and C_2 are determined from the voltage transient between U_2 and U_3. Through the least square algorithm in MATLAB curve fitting tools (cftool), the value of each parameter in RC parallel networks can be identified as discussed in [1-2]. The value of parameters are tabulated in 2-D lookup table in RC values subsystem. The curve of R_1, R_2, C_1 and C_2 are illustrated in Fig. 15.

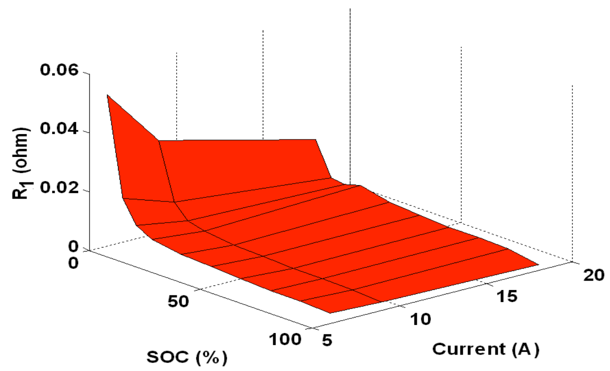
V. Model Validation

In order to validate the proposed model, the simulation results of CDT and PDT are used to compare with the corresponding experiment results. Moreover, a random load test is also conducted for model validation purpose.

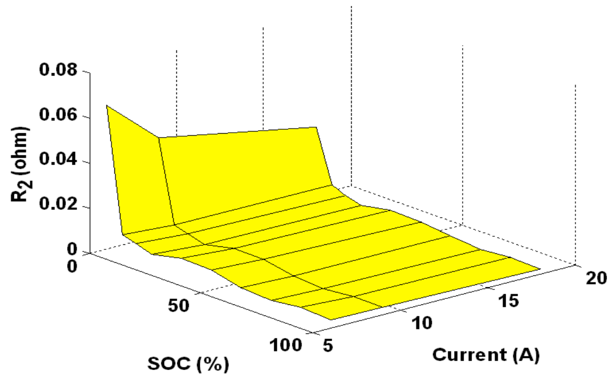
Comparison between simulation and experiment results for CDT tests are shown in Fig. 16. The comparison shows that the curves are superimposed, which reveals that the model can perform accurately in continuous discharge conditions. The RMS error of voltage in CDT is 66mV, which is 2% to the nominal voltage of battery.

Fig. 17 shows the comparison between simulation and experiment results for PDT. The voltages curves of simulation and experiment results are well matched. The RMS error of voltage in PDT is 37.5mV, which is 1.17% to the nominal voltage of battery. This reveals that the model can perform accurately in pulse discharge conditions.

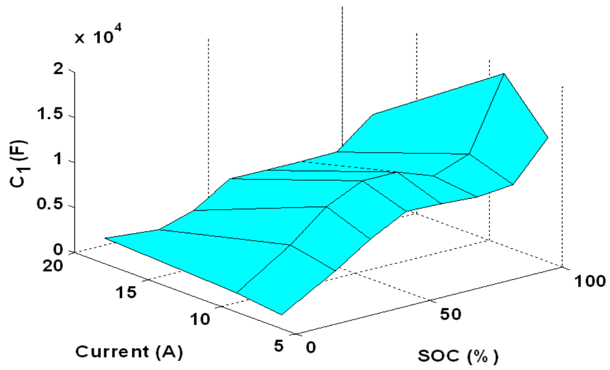
A random load test is conducted to further validate the battery model. The current profile for random load test is shown in Fig. 18(a). In this random load test, various current pulses are included, such as 3A, 12A, 13.5A, and 36A. Moreover, some charging conditions are included by



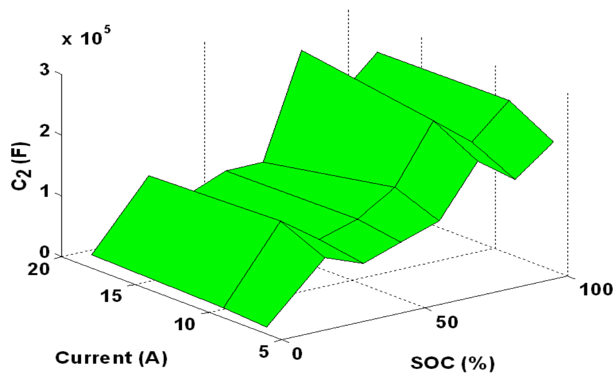
(a)



(b)



(c)



(d)

Fig. 15. Value of (a) R_1, (b) R_2, (c) C_1 and (d) C_2.

considering the regenerative breaking condition in EV application. The SOC curve of the random load test is shown in Fig. 18(b) whereas the comparison between simulation and experiment results is shown in Fig. 18(c). The comparison result shows that the voltage curves of simulation and experiment results are matched. The RMS error of voltage in random load test is 20.32mV, which is 0.635% to the nominal voltage of battery. This proves that the developed model can perform accurately in random load condition.

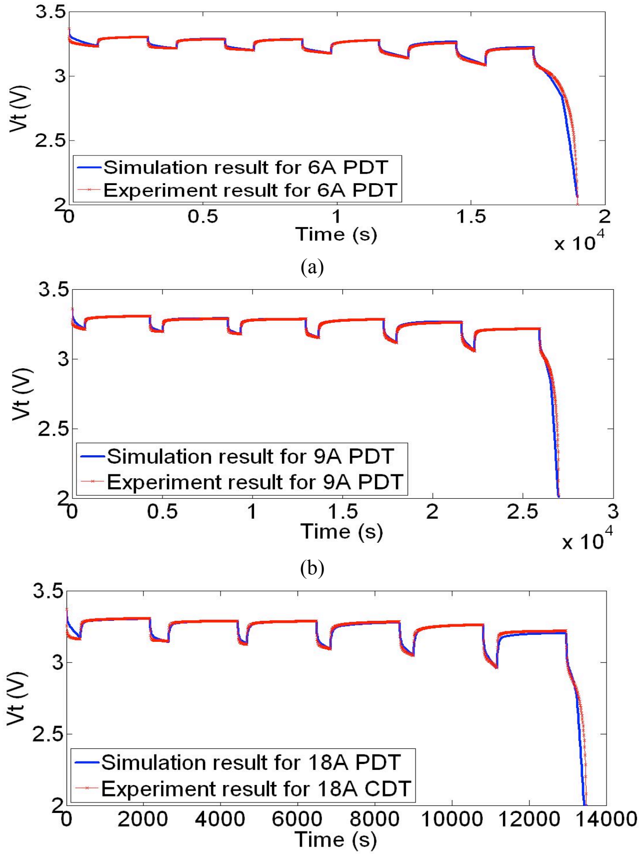


Fig. 17. Comparison between simulation and experiment results of (a) 6A, (b) 9A, and (c) 18A PDTs.

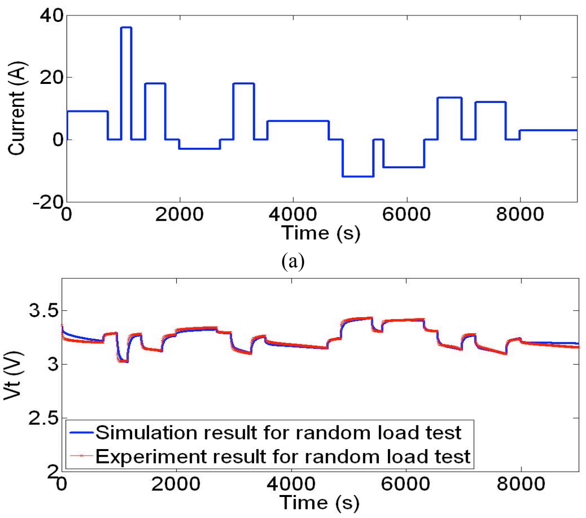


Fig. 18. (a) Current profile and (b) comparison between simulation and experiment results of random load test.

In this paper, temperature effect is not considered due to non availability of the temperature chamber in the lab. If the temperature effect is considered, modeling effort as presented in reference [9] is compulsory. With minor modification, temperature effect can be included by using 3-D lookup table.

VI. Conclusion

An accurate MATLAB/Simulink battery model has been proposed to characterize the dynamic characteristics of battery. The structures of each subsystem of the proposed model have been explained in detail. A battery model for a lithium ferro phosphate battery has been developed and the accuracy of the proposed model has been proven with experiment results. It is expected that the model is applicable for other battery chemistries, such as lead acid battery or nickel-based battery. Circuit designers can easily build up their battery model since there is not involve any complex computation. This simple yet accurate battery model in simulation platform will eventually accelerate the development of energy storage system in green technology application.

VII. Acknowledment

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