

LiFePO₄ Dynamic Battery Modeling for Battery Simulator

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Abstract—This paper proposes dynamic battery modeling for LiFePO₄ battery simulator. LiFePO₄ battery of Li-ion type battery has best characteristic in other type of batteries. So this paper describes LiFePO₄ battery model for battery simulator. LiFePO₄ battery's voltage waveform is non-linear and changed by transient load. So the shepherd model is applied to describe this non-linear waveform and thevenin battery model is applied to present characteristics of behavior corresponding to the changing of transient load. Also, in order to apply battery model to battery simulator, proposed battery model is converted to discrete time model. Parameters of proposed battery model are estimated in experimental. The proposed battery model is compared getting the voltage waveforms of the battery using experiment with simulation's waveforms is verified.

Keywords—Battery simulator, Shepherd model, Thevenin battery model, Li-ion battery, LiFePO₄ battery

I. INTRODUCTION

Recently, Renewable energy and the second battery are drawing attention due to depleted fossil energy and greenhouse effect. But, the renewable energy has disadvantages that are low-density energy and irregular electricity production. The second battery, on the other hand, has advantages that are higher energy density and constant electricity production than the renewable energy. Thus, the utilization of the battery is increasing through energy storage device; ESS or BESS [1].

In the second batteries are Lead-Acid, Ni-Cd, Ni-MH, Li-ion and Li-Polymer batteries. Li-ion battery has the best characteristics in other type of batteries. As a result, Li-ion battery is used for EV, HEV, ESS and portable device [2]. Otherwise, it is expensive and dangerous about explosion when battery is over-charges or deep-discharges. For this reason, to stably experiment the system including the battery, battery simulator consisted of controllable DC power supply instead of the actual battery is essential [3][4]. The advantage of using battery simulator is that is easy to change battery specifications and there is no risk of explosion. And, Second battery's performance characteristics depend on C-rate and temperature. Therefore, research about the battery modeling and the C-rate, temperature changing characteristic of the battery are needed [5].

The battery-models are electrochemical, mathematical, and electrical circuit models. Electrochemical model is appropriated for electrode and electrolyte of battery's modeling. But, it has a disadvantage that too much time is spent on calculating because the physical properties of battery are expressed in partial differential equation. Mathematical model is estimated with available times, efficiency and capacity using stochastic access methods and empirical formula. However, this model is not involved to I-V characteristic curve of the battery and is uncertain model because of large errors. Also, electrical model is circuit based model. Electrical models are expressed with resistance, capacitance and inductance which have physical characteristics of the battery. In addition, it can be usefully taken in the electrical system and simply analyzed in the simulation of the electrical circuit [6]. There are simple battery model and thevenin battery model, etc in electrical model. Simple battery model has only battery's internal resistance; R_i so, it can't cover the transient behavior of the battery. On the other hand, the thevenin battery model, including parallel RC circuit, can represent its transient characteristic [9].

Also, LiFePO₄ battery model is proposed that is focused on variance of OCV owing to transient load current. Proposed battery model represents the non-linear OCV(open-circuit-voltage) of the battery when using the shepherd model and the behavior of the transient-state applying the thevenin battery model. As proposed model is applied to controller in the MCU of Fig. 1, t-domain of proposed model is converted to programmable language using z-domain [6]-[8]. The proposed battery model is verified by comparing the experimental voltage waveforms with simulation waveforms at transient-state.

This paper is divided into three sections. In the first section, OCV model, electrical model and proposed model are presented. The second section presents how to estimate the parameters of proposed battery model through the battery discharging experimental. In the third section, validity of the proposed battery model that is compared getting the voltage waveforms of the battery using experiment with simulation's waveforms is verified. Also, using the parameters of the battery datasheet, the proposed model is proved suitable for battery simulator by simulation. The paper ends with a conclusion.

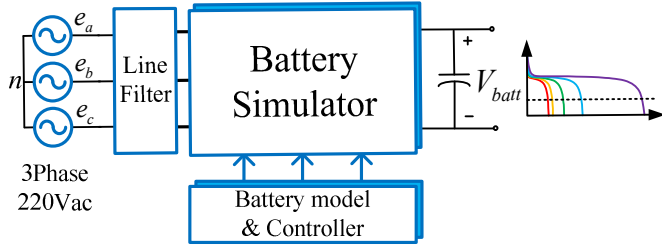


Figure 1. Battery simulator diagram

II. BATTERY MODEL

A. OCV Model

Fig. 2 shows a non-linear voltage waveform of LiFePO₄. The shepherd model of the electrochemical battery is applied to describe this non-linear waveform. Shepherd model can be expressed by following (1), (2). And each described parameters are presented in Table 1. This model consists of the open circuit voltage(OCV) or electromotive force(EMF), E_0 and the terminal voltage of the battery, V_t and the internal resistance, R_i and the discharging current, i and the state-of-charge(SOC), Q . This model describes electrochemical behavior of the battery [9]. The shepherd model has an advantage which can describe battery's performance characteristic that providing parameter value in battery datasheet. But, it has a disadvantage that can't describe transient performance characteristics.

$$E = E_0 - K \frac{Q}{Q - \int idt} + Ae^{(-B \cdot \int idt)} \quad (1)$$

$$V_t = E - R_i \cdot i \quad (2)$$

TABLE I. PARAMETERS DESCRIPTION

Parameter	Unit	Description
E	V	Open circuit voltage
E_0	V	Battery constant voltage
K	V	Polarization voltage
Q	Ah	Battery capacity
A	V	Exponential zone amplitude
B	Ah^{-1}	Exponential zone time constant inverse

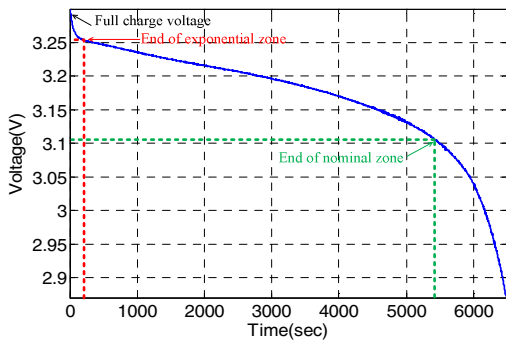


Figure 2. LiFePO₄ battery discharge curve

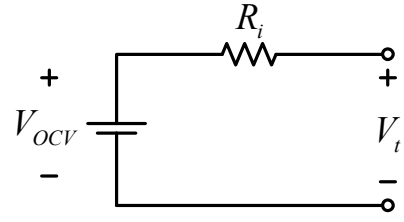


Figure 3. Simple battery model

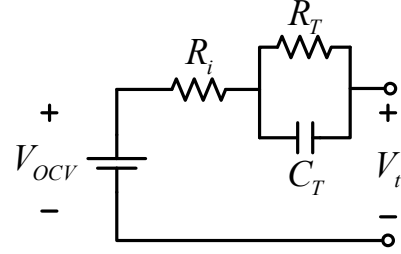


Figure 4. Thevenin battery model

B. Electrical circuit model

Simple battery model is shown Fig. 3. It consists of the OCV(open circuit voltage), V_{OCV} and the battery terminal voltage V_t and the internal resistance, R_i . This model represents polarization of the battery using internal resistance, R_i . So, it can be represented as DC characteristic but, not represented as transient characteristics. While, thevenin battery model with the additional parallel RC circuit in Fig. 4 can represent characteristics of behavior corresponding to the changing of transient load. And they represent the physical meaning of the battery. The transient resistance R_T is described as a non-linear resistance of the battery's contact resistance. And the transient capacitance C_T represents its capacitance of the parallel plate [10].

C. Proposed battery model

In this paper, proposed model is following Fig. 5. This model is coupled with shepherd model and the thevenin battery model. The shepherd model describes unique non-linear OCV waveform of LiFePO₄ battery. Also, the battery datasheet's parameter values what using a shepherd model can describe battery's open circuit voltage. And the thevenin battery model which added RC circuit represents transient characteristics of the battery.

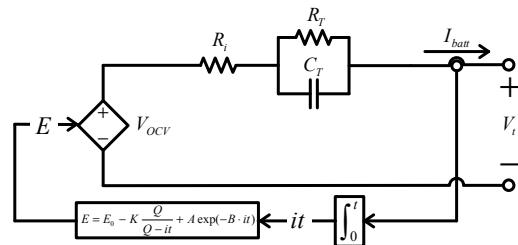


Figure 5. Proposed battery model

However, above model is difficult to adopt actual battery simulator because the proposed battery simulator is comprised in controller of the battery simulator. As shown in Fig. 5, continuous time model of the proposed model must be converted into the discrete time model since typical controller consists of the MCU or DSP [6]-[8]. To convert continuous time into discrete time model, we calculated transfer function changing from its t-domain's model to s-domain. In order to obtain the transfer function model more easily, proposed model was converted to an equivalent circuit model which is presented in Fig. 6. Transfer functions that are affected by OCV and I_{batt} changing V_R are obtained to use principle of superposition as following (3), (4). Also, discrete time model of transfer function calculated by Z-transform can be expressed as following (5) and (6).

$$\frac{V_R(s)}{V_{OCV}(s)} = \frac{R_{load}(1+s\tau_T)}{(R_i+R_T+R_{load})+s\tau_T(R_i+R_{load})} \quad (3)$$

$$\frac{V_R(s)}{I_{pulse}(s)} = \frac{R_{load}(R_i+R_T+sR_T\tau_T)}{R_i+R_T+R_{load}+s\tau_T(R_i+R_{load})} \quad (4)$$

$$y_{k(V_R)} = \frac{1}{T(R_i+R_T+R_{load})+2\tau_T(R_i+R_{load})} \cdot [R_{load}(T+2\tau_T) \cdot x_{k(V_{OCV})} + R_{load}(T-2\tau_T) \cdot x_{k(V_{OCV})-1} - \{T(R_i+R_T+R_{load})-2\tau_T(R_i+R_{load})\} \cdot y_{k(V_R)-1}] \quad (5)$$

$$y_{k(V_R)} = \frac{1}{T(R_i+R_T+R_{load})+2\tau_T(R_i+R_{load})} \cdot [-\{R_{load}(T(R_i+R_T)+2R_i\tau_T) \cdot x_{k(I_{pulse})} + R_{load}(T(R_i+R_T)-2R_i\tau_T) \cdot x_{k(I_{pulse})-1}\} - \{T(R_i\tau_T+R_{load}\tau_T)\} \cdot y_{k(V_R)-1}] \quad (6)$$

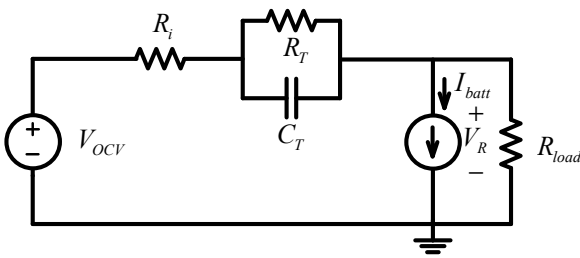


Figure 6. Equivalent circuit model

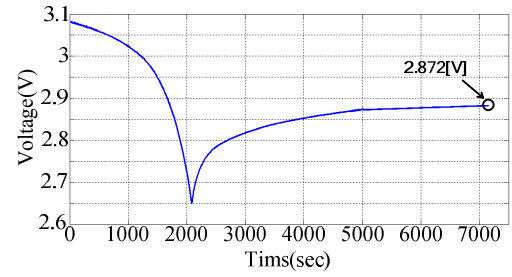


Figure 7. OCV of SOC 0%

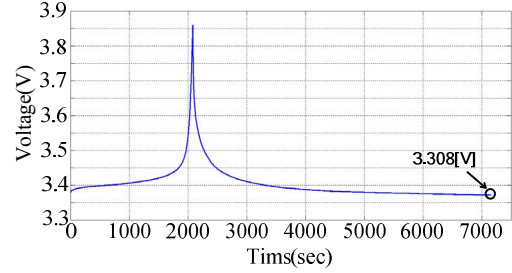


Figure 8. OCV of SOC 100%

III. PARAMETERS ESTIMATION

To extract the parameters of the proposed battery model, a REVO RVG-20 LiFePO4 Battery rated at 3.2V and 20Ah is used in this experiment. The experiment is implemented at room temperature; 25°C. First of all, Fig. 7 and Fig. 8 are experimented to measure OCV at the point of accurate SOC which is 0% and 100%.

Fig. 7 shows the OCV experimental waveform at the 0% SOC. In order to measure accurate experimental result, rest time is given for an hour after implementing discharging test at 0.5C-rate. Because of polarization caused by the characteristic of the battery electrolyte, rest time is essential at battery charging/discharging operation. Due to the polarization, measured battery voltage is higher(charge) or lower(discharge) than the balance voltage of the battery. Therefore, the battery voltage should be balanced by taking some rest time. Generally, after 30 minutes from the battery charging or discharging operation, balanced voltage can be measured. Thus, it had a rest time of one hour. In Fig. 7, estimated voltage after an hour rest time is about 2.87V. Likewise, Fig. 8 was measured about 3.308V at a SOC 100% [11].

Fig. 9 shows repeating waveform at the 0.5C-rate 30 minutes discharging and an hour charging. And Fig. 10 is enlargement of a waveform of the Fig. 9. Through Fig10, battery parameters; R_i , R_T , C_T can be estimate. Fig. 10 is divided into two sections. In the first section, the discharge current flows through internal resistance and transient capacitance, C_T as shown in Fig. 11. So internal resistance, R_i can be calculated by (7). Also, the second section, current flow is like Fig. 12 so can be obtained to transient, C_T and R_T using (8), (9).

$$R_i = \frac{V_{R_i}}{I_{batt}} \quad (7)$$

$$R_T = \frac{V_{R_T}}{I_{batt}} \quad (8)$$

$$C_T = \frac{\tau_T}{R_T} \quad (9)$$

Finally, the parameter of the shepherd model that A, B, K and E_0 can be estimated through the Fig. 1 and (10) ~ (13). Fig. 1 is divided into 3 sections. In the first section, full charge voltage zone is full charged battery. And the end of the second section is the exponential zone which meets the initial point of the nominal voltage in the voltage of the battery. Finally, the end of nominal zone is part of the nominal voltage of the battery.

$$A = E_{full} - E_{Exp} \quad (10)$$

$$B = \frac{3}{Q_{Exp}} \quad (11)$$

$$K = \frac{(E_{Full} - E_{Nom} + A(\exp(-B \cdot Q_{Nom}) - 1)) \cdot (Q - Q_{Nom})}{Q_{Nom}} \quad (12)$$

$$E_0 = E_{Full} + K + R_i i - A \quad (13)$$

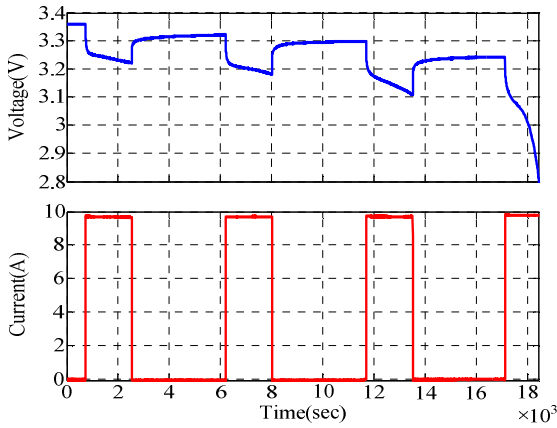


Figure 9. Experiment for discharge of LiFePO4 battery(0.5 C-rate)

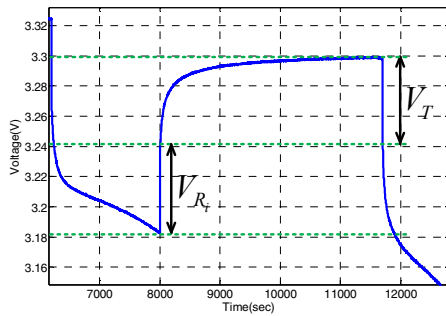


Figure 10. Experiment enlarge waveform for discharge of LiFePO4 battery

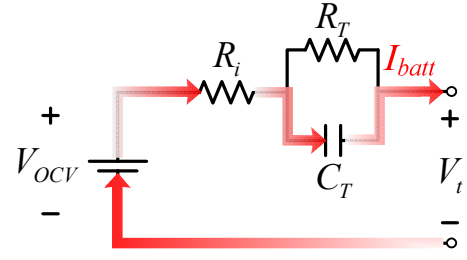


Figure 11. The discharge current flow of the first section

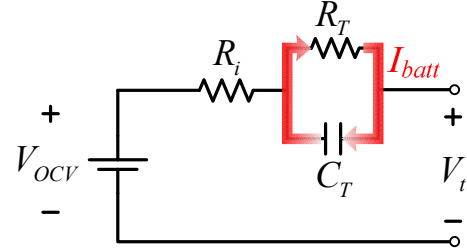


Figure 12. The discharge current flow of the second section

IV. MODEL VALIDATION

To validate the proposed model, simulation is implemented by the PSIM of the simulation tool using the parameters obtained in the previous section. The parameters of proposed model are shown in Table 2. Simulation condition is 0.5C-rate same as the experiment. Moreover, experimental voltage waveforms and simulation waveforms in Fig. 13 are compared to verify the validity of the proposed battery model. Maximum error comparing to real waveform with simulation's waveform is 6mV so it was founded to be very similar. And Fig. 14 shows the simulation result through the data of battery datasheet in Table 3. The simulation is performed at the condition of 0.5C-rate discharge current. The characteristic of battery voltage can be described only using battery datasheet through this simulation.

TABLE II. BATTERY MODEL PARAMETERS

Parameter	Unit	Value
R_i	Ω	0.005
R_T	Ω	0.0052
C_T	F	0.52
E_{Full}	V	3.308
E_{Exp}	V	3.251
E_{Nom}	V	3.122
Q	Ah	18
Q_{Exp}	Ah	16.44
Q_{Nom}	Ah	5.6
A	V	0.057
B	Ah^{-1}	0.1825
K	V	0.331
E_0	V	3.632

TABLE III. REVO RVG-200 LiFePO4 BATTERY

Parameter	Unit	Specification
Rated capacity	Ah	200
Nominal voltage	V	3.2
Internal impedance	$m\Omega$	0.6

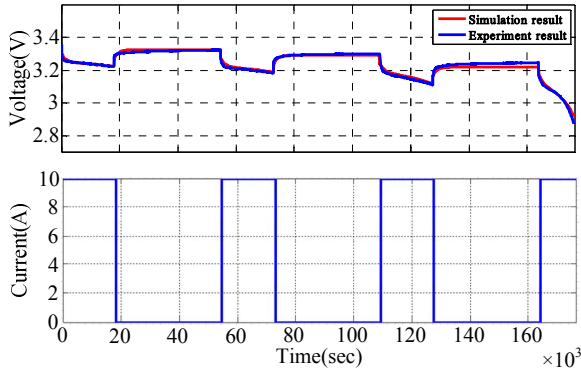


Figure 13. Comparing simulation results with experimental results

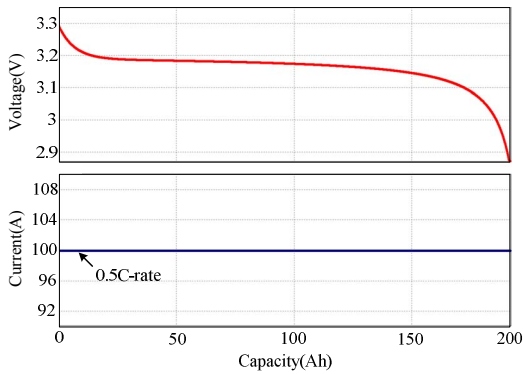


Figure 14. Simulation results of REVO RVG-200 LiFePO4 battery

V. CONCLUSION

This paper proposes the electrical battery model considering transient state characteristic of the LiFePO4 battery. The shepherd model and the thevenin battery model is applied to express that nonlinearly changing OCV of the battery and transient-state characteristics. Also, the Z-transformed battery model is proposed to apply to the battery simulator. Suitability of battery model for battery simulator is verified by performing the simulation using battery datasheet. And, the validity of the model is verified by comparing the simulation results using the PSIM with a voltage waveform of actual battery. Maximum error comparing to real waveform with simulation's waveform is 6mV so it was founded to be very similar. Also, suggested to apply for the battery simulator which can express the dynamic characteristic and the transient state of the battery.

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