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DYNAMIC MODELING OF LITHIUM-ION BATTERY WITH TEMPERATURE EFFECT

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Lithium ion (Li-ion) batteries have become a promising alternative power source in electric vehicles (EVs) due to their high nominal cell voltage, high energy density, long life and not having a memory effect. However temperature effect and dynamic characteristic of the li-ion batteries greatly affects their performance. In this study, a dynamic model of li-ion battery has been developed by MATLAB/Simulink and simulated at different temperatures. Simulink model contains dynamic circuit parameters as a function of state of charge and temperature effect. Simulation results show that proposed dynamic model is effective and operational under the different temperature rates for dynamic output characteristic of li-ion battery.

Key words*: "Li-ion battery", "dynamic battery model", "temperature effect"*

1. Introduction

Lithium ion batteries are widely used in EVs with high energy density, high nominal cell voltage, long life among the various rechargeable batteries such as Lead-Acid batteries, Ni-based batteries and Na-based batteries [1,2]. Li-ion batteries cannot be used without battery management system (BMS) in EVs because of their safety, reliability and performance. BMS include several features such as cell measurement, cell balancing, thermal measurement, safety and reliability [3]. Performance of the li-ion battery related with predict state of charge (SoC) which is a key component of the BMS accurately. The SoC of a battery is defined as a ratio of the remaining capacity and maximum available capacity of a battery and cannot be measured directly. Therefore, SoC should be estimated by using the measured signals such as voltage and current via accurate battery model [4,5].

Several methods used for modelling of the lithium-ion battery in the literature [6-8]. These methods consist of four main groups such as analytical (experimental), statistical, electrochemical and electrical circuit models [9]. Analytical models based on developing physical model of the system with the help of physical equations and determine of model parameters with experimental results are simple and quick method. However, accuracy performance of the model is low [10]. Statistical model which is achieved model parameters by creating significant structures from data samples is a quick method with low accuracy. Electrochemical model based on the operation of the internal chemical structure of the battery is a complex method. Therefore, this method is hardly used [11]. Electrical circuit model, which enables mathematical operations on the equivalent circuit model is the most widely used method [12]. The electrical circuit models mainly include Thevenin model, PNGV

(Partnership for a New Generation of Vehicles) model, NREL (National Renewable Energy Laboratory) model, Randles model [13].

While modelling the li-ion battery, it is essential to consider temperature effect because the ambient temperature and the cell temperature are both greatly affects the behavior of the battery. Several modelling techniques have been proposed to represent the temperature effect of the battery. In reference [14], proposed a battery model which is able to simulate the effects on the battery behavior made by temperature. In reference [15], temperature-dependent cell model is presented to improve state of charge estimation. Temperature effect has become attractive research area topic for battery modelling in electric vehicle field.

In this study, a dynamic model of li-ion battery has been developed with second order Thevenin model by MATLAB/Simulink. Simulink model contains capacity-resistance change effect according to state of charge and ambient temperature effect for dynamic characteristic of the li-ion battery. Proposed dynamic battery model simulated under different temperature conditions.

2. Equıvalent Circuit Model

In this section, Second order Thevenin model shown in Fig. 1 is developed as the equivalent circuit model of the lithium-ion battery due to its high model accuracy and low complexity.

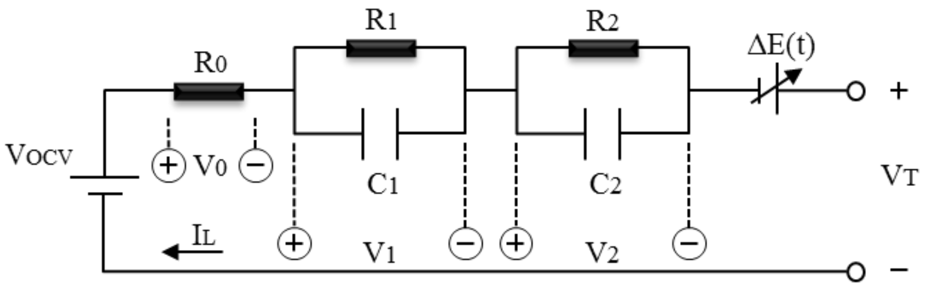

Figure 1. Second order Thevenin equivalent circuit model.

The equivalent circuit model can be described by following equations:

$$V_T = V_{OCV} - V_1 - V_2 - V_0 + \Delta E(t) \quad (1)$$

$$V_0 = R_0 I_L \quad (2)$$

$$C_1 \frac{dV_1}{dt} = -\frac{V_1}{R_1} + I_L \quad (3)$$

$$C_2 \frac{dV_2}{dt} = -\frac{V_2}{R_2} + I_L \quad (4)$$

where R_0 is the ohmic resistance, R_1 and R_2 are the polarization resistance, C_1 and C_2 are the polarization capacitance, V_1 and V_2 are the polarization voltages, V_T is the terminal voltage, V_{OCV} is the open circuit voltage, $\Delta E(t)$ is the potential correction term and I_L is the load current.

3. Open Circuit Voltage

The general equation of the state of charge is expressed as follows:

$$SoC = SoC_0 - \eta \int_0^t i(\tau)\, d\tau \tag{5}$$

Where $\eta = 1/(3600C)$, SoC is the present state of charge, SoC_0 is the initial state of charge and C is the maximum available capacity. The open circuit voltage which is defined as electrical potential difference between the two terminal at the battery when it is disconnected from the electrical load has a non-linear relationship between the state of charge.

4. Equivalent Circuit Parameters

The dynamic parameter values of the equivalent circuit model and state of charge has a nonlinear relationship. In this nonlinear relationship, parameters of the equivalent circuit model have constant values at 20%-100% SoCs. However, parameters of the equivalent circuit model change rapidly due to the chemical reaction in the battery at 0%-20% SoCs. Dynamic parameters of the equivalent circuit model which is related with SoC defined as;

$$R_0 = k_1 \times e^{k_2 \times SoC} + k_3 \tag{6}$$

$$R_1 = k_4 \times e^{k_5 \times SoC} + k_6 \tag{7}$$

$$C_1 = k_7 \times e^{k_8 \times SoC} + k_9 \tag{8}$$

$$R_2 = k_{10} \times e^{k_{11} \times SoC} + k_{12} \tag{9}$$

$$C_2 = k_{13} \times e^{k_{14} \times SoC} + k_{15} \tag{10}$$

where $k_1, k_2, \ldots, k_{15}$ are constant values of the equivalent circuit parameters.

5. Simulation Results

MATLAB/Simulink is used to developed dynamic model of the li-ion battery. Proposed battery model contains $V_{OCV} - SoC$ block, equivalent circuit block, equivalent circuit parameters block and temperature effect block as shown in Fig. 2.

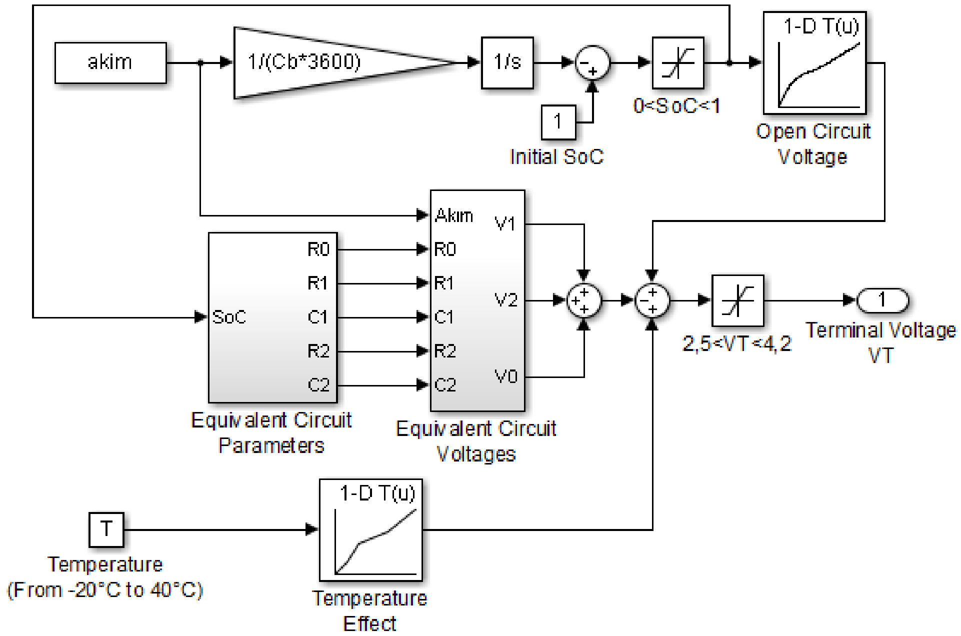

Figure 2. Dynamic Simulink model of li-ion battery.

The change in temperature, affects the equilibrium potential. To compensate this temperature influence, $\Delta E(t)$ is used in Simulink model as potential correction term. Fig. 3 shows that change of $\Delta E(t)$ due to temperature can be found in Ref. [16]. Temperature effect block developed using Fig. 3 as a look-up table.

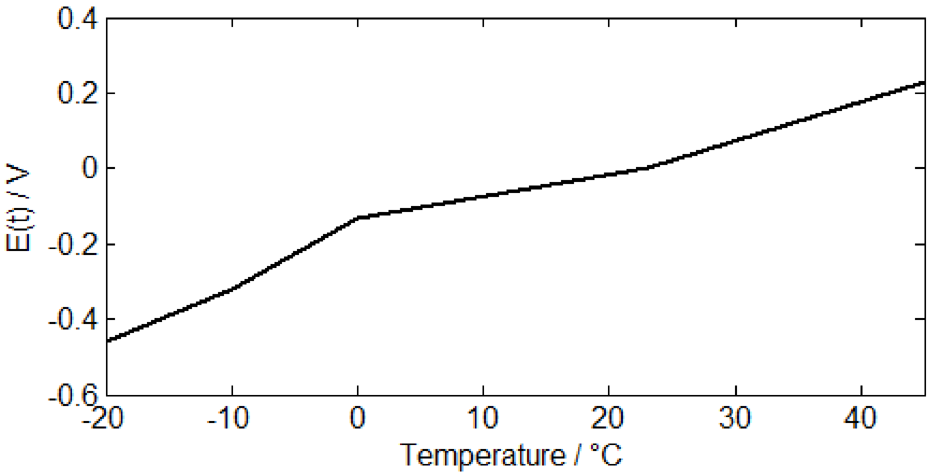

Figure 3. Temperature-dependent potential-correction term for the lithium-ion.

Fig. 4 shows the non-linear relationship between the V_{OCV} and SoC. Open circuit voltage of the battery as a function of SoC is assumed as a seventh-order polynomial equation. It can be represented as:

$$f(V_{OCV}, SoC) = 66.235 \times SoC^7 - 242.73 \times SoC^6 + 364.5 \times SoC^5 \\ -291 \times SoC^4 + 134.7 \times SoC^3 - 37.016 \times SoC^2 + 6.4617 \times SoC + 2.9007 \quad (11)$$

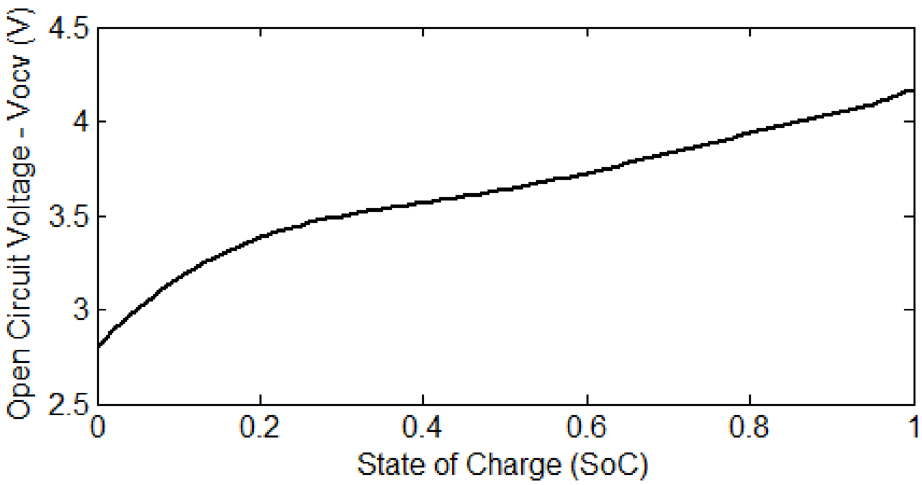

Figure 4. Non-linear relationship between open circuit voltage and state of charge.

Equivalent circuit block developed using Equations (1)-(4). Dynamic parameters of the equivalent circuit model which is related with SoC in equivalent circuit parameters block defined as;

$$R_0 = 2,2236 \times e^{-33,8871 \times SoC} + 0,016 \quad (12)$$

$$R_1 = 0,000124 \times e^{-25,0869 \times SoC} + 0,1656 \quad (13)$$

$$C_1 = 732,6083 \times e^{-11,6207 \times SoC} + 690,5780 \quad (14)$$

$$R_2 = 44,6259 \times e^{-333,6240 \times SoC} + 0,0257 \quad (15)$$

$$C_2 = 6191,5 \times e^{-10,6698 \times SoC} + 4470,1 \quad (16)$$

Proposed battery model is tested using 0.2C (0.65 A) discharge test data with different temperature condition such as $-20°C$, $-10°C$, $0°C$, $10°C$, $20°C$ and $40°C$. Fig. 5 displays the change of terminal voltage for dynamic battery model with different temperature effect.

The change in temperature has deeply affected terminal voltage. The terminal voltage and the temperature affect each other negatively. When the temperature increases, the terminal voltage is decrease as shown in Fig. 5.

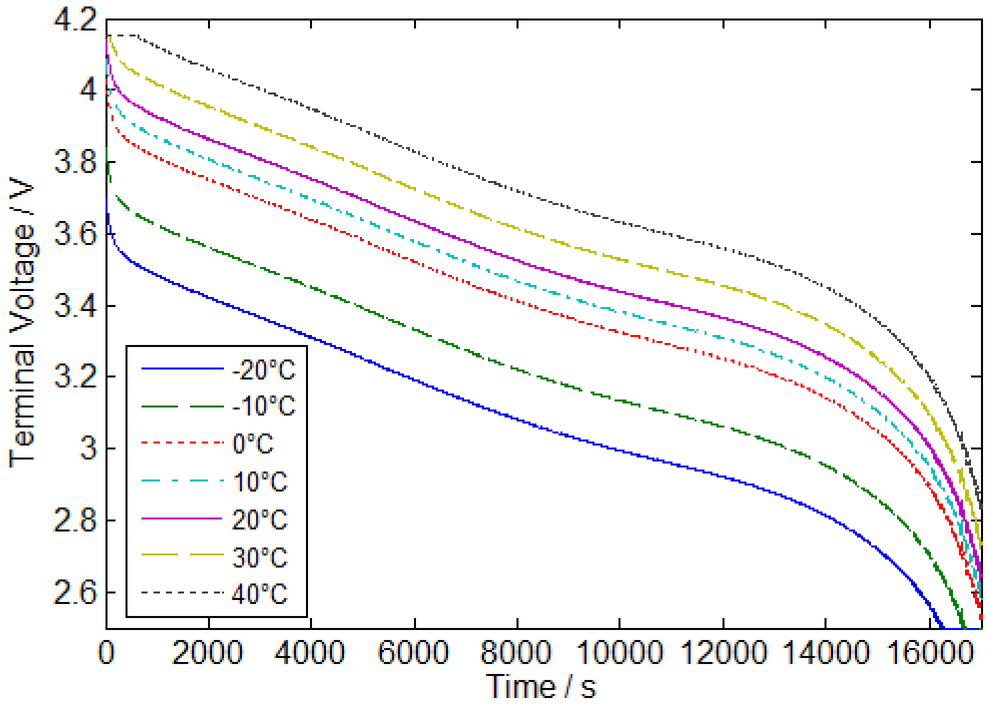

Figure 5. The change in battery runtime for a 0.65 A discharging condition at different temperatures.

Conclusion

In this study, dynamic battery model including capacity-resistance change effect at dynamic characteristic of the li-ion battery is proposed. Dynamic battery model developed by MATLAB/Simulink is tested using 0.2C (0.65 A) discharge test data and different temperature effects at $-20°C$, $-10°C$, $0°C$, $10°C$, $20°C$ and $40°C$. Simulation results show that developed temperature depended dynamic model can reflect the output characteristic of li-ion battery effectively.

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