

Electrical Modeling of Nickel-Metal Hydride Batteries for Personal Electric Vehicles

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Abstract

This article presents the electrical modeling of the nickel-metal hydride battery (NiMH), which is used in electric vehicles. According to the battery life cycle, the physical and electrical models of the proposed battery should be analyzed in detail for the condition to control the electric vehicle operation. This article focuses on the NiMH battery, which was used in personal electric vehicles. This type of personal electric vehicle is used to provide personal mobility for handicapped and elderly people. The proposed battery model is considered in both state-of-charge (SOC) and voltage-current characteristics to find the mathematical model of the NiMH battery. The proposed electrical model of the battery was studied under static and dynamic behaviors. The simulation results show that the proposed battery model can represent the behavior of a battery as the real behaviors. The MATLAB/Simulink environment is selected to analyze and simulate the battery model on both static and dynamic behaviors. Therefore, the proposed battery model can verify the study of the battery life cycle on the personal electric vehicle application for the future work.

Keywords: Battery, electric model, personal electric vehicle, electrochemical impedance spectroscopy, nickel-metal hydride batteries.
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1. Introduction

General electric vehicles can be classified into 5 types as follows: battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), hybrid electric vehicle (HEV), fuel cell electric vehicle (FCEV) and personal electric vehicle (PEV) [1-2]. The important elements of the general electric vehicle (EV) is the driving system, the car control and monitoring system, and the battery as the power source of the electric vehicle [3]. Different EV types from various manufacturers also use hybrid electric vehicle because of its high-power energy density. Figure 1 shows the diagram of a personal electric vehicle, which consists of a transmission system, an electric machine, a DC/AC

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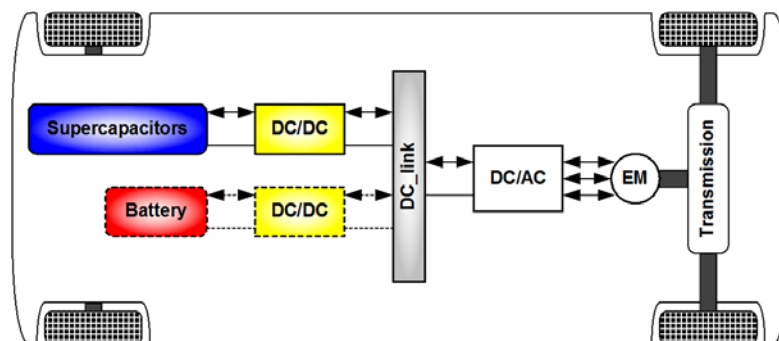


Figure 1. Basic diagram of a personal electric vehicle [4]

voltage of the battery is controlled by the DC/DC converter for the desired voltage value. Therefore, the state-of-charge of the battery was considered during the electric vehicle mobility.

The battery is a storage source of the electric vehicle that can be recharged by connecting with the charging cable at the charging station or household. The storage capacity of the NiMH battery is defined by parameters such as the voltage, current, and temperature. The state-of-charge condition of the battery is measured to analyze both dynamic and static behaviors. Therefore, the proposed study can classify the important features and electrical characteristics of the NiMH battery. The key factors to evaluate the NiMH battery are the SOC and state of health (SOH) of the battery. Meanwhile, the internal impedance modeling of the NiMH battery is considered under SOC and I - V characteristics [5]. The derivation of the internal impedance modeling was determined from the electrochemical impedance spectroscopy (EIS) technique. The voltage and current sinusoidal waveforms of the battery are shown in Figure 2.

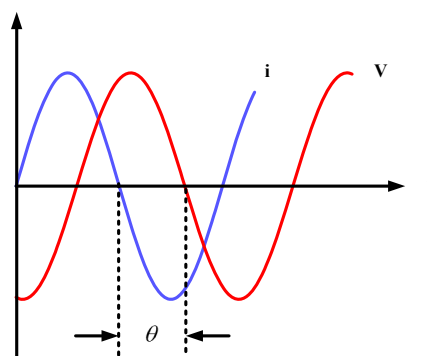


Figure 2. Signal voltage and electrical current at the terminal of the NiMH battery

The waveform of the voltage and current at the terminal of NiMH battery can be classified to find the difference in angle between current and voltage. The phase angle can be used to compute the battery impedance by using a Nyquist plot based on the sampling rate of the waveform. Therefore, we will propose the electrical modeling of the NiMH battery in a personal electric

vehicle, which provides personal mobility to support handicapped and elderly people. The proposed battery model is considered in both state-of-charge (SOC) and voltage-current characteristics to find the mathematical model of the NiMH battery.

2. Materials and Methods

2.1 NiMH Battery Testing

The NiMH battery was tested by using the test battery machine (TBM). The impedance equivalent models of the NiMH battery can be computed by measuring the value. The simulation of the EIS method was selected to define by varying the voltage range from 9.6 to 14.4 V and the ampere-hours rate is 6.5 Ah. Therefore, the voltage and ampere-hour rates are specified from the NiMH battery rate. Meanwhile, the charge and discharge time of the NiMH battery are defined from the ampere-hour rate and pulse charging condition. The voltage-current and phase shift angle of the battery can be presented as the portal angle, and the model diagram in Nyquist plot is shown in Figure 3 [6].

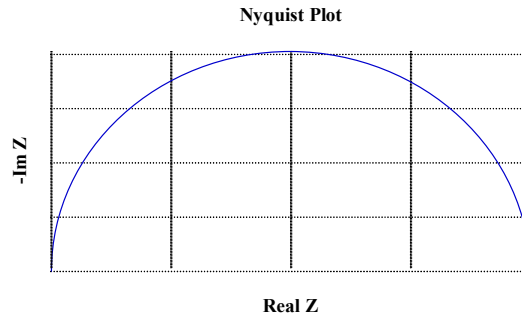


Figure 3. Nyquist plot of the battery model

Figure 3 shows a Nyquist plot of the NiMH battery as the impedance electric circuit. This cycle shows the real and imaginary values of the NiMH battery impedance, which are the resistance and capacitance values. The Nyquist plot also shows the size and phase of the impedance represented by the vector size of $|Z|$ as shown in equation (1).

$$Z = \frac{V \angle 0^\circ}{I \angle \theta} = |Z_m| \angle -\theta \quad (1)$$

This NiMH battery model shows the parameters that are considered under the state-of-charge (SOC) and I -V characteristics. The nominal voltage parameter of the cells was varied from 9.6 to 14.4 V, and the ampere-hour magnitude is 4.5 Ah. A cell of the NiMH battery was tested to find the model as the electrical equivalent circuit model. The electrical characteristic of the NiMH battery was measured and analyzed using the electrical equivalent circuit [7]. The battery model can be formed in Thevenin equivalent circuit, which can calculate a voltage source as an open-circuit voltage. The resistance and capacitance (RC) are the dynamic electric models of the NiMH battery. The internal resistance (R_i) of the battery is normally the combination of the parameter, which has

been suggested by Chen and Rincon-Mora [8]. The dynamic behavior is modeled as polarization resistances R_1 , R_2 and effective capacitances C_1 , C_2 . The model is used to characterize the transient response during the transfer of battery power. The electrical equivalent circuit of the battery can be determined by using equations (2) and (3), and the circuit model is presented in Figure 4.

$$V_{cell} = V_{oc} - \frac{V_1}{R_1 C_1} + \frac{I_1}{C_1} - \frac{V_2}{R_2 C_2} + \frac{I_2}{C_2} - R_i I_{batt} \quad (2)$$

$$V_{cell} = V_{oc} - V_1 - V_2 - R_i I_{batt} \quad (3)$$

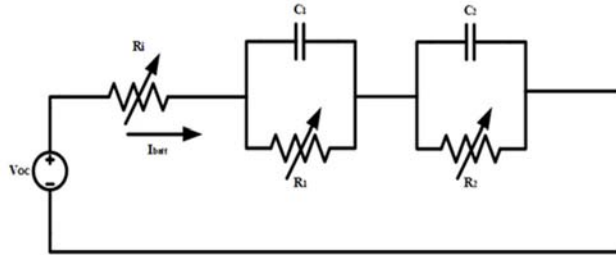


Figure 4. Equivalent circuit model of the NiMH battery

2.2 Electrical Parameter Calculation of the NiMH Battery

The internal resistance (R_i) of the NiMH battery appears when the charge stops with reference, which is an abrupt voltage decrease. The contiguous voltage decrease is associated with the internal resistance of the cell. The battery has a process of charge and discharge at various SOC. The internal resistance can be calculated by equation (4).

$$R_i = \frac{V_1 - V_0}{I_{batt}} \quad (4)$$

The battery voltage was measured by using the open-circuit cell connection, where the cell voltage depends on the ambient temperature and the SOC [9-11]. The parameter behavior of an NiMH battery is nonlinear. The parameters are changed by the ambient temperature and SOC of the battery. The SOC model setting is used to set the temperature and difference number between charge and discharge. The parameters show the state-of-charge of the battery via the measurement of battery conditions. The initial capacity of the battery is determined in terms of the SOC and ampere-hours using equation (5).

$$V_{oc} = f(SOC) \quad (5)$$

$$SOC = SOC_0 - \int \frac{I_{batt}}{C_{init}}$$

The frequency response analysis determines the change in pulse charge in the operation frequency range of 40 Hz - 3 kHz with the 4.5-A, 14.4-V test circuit as shown in Figure 5.

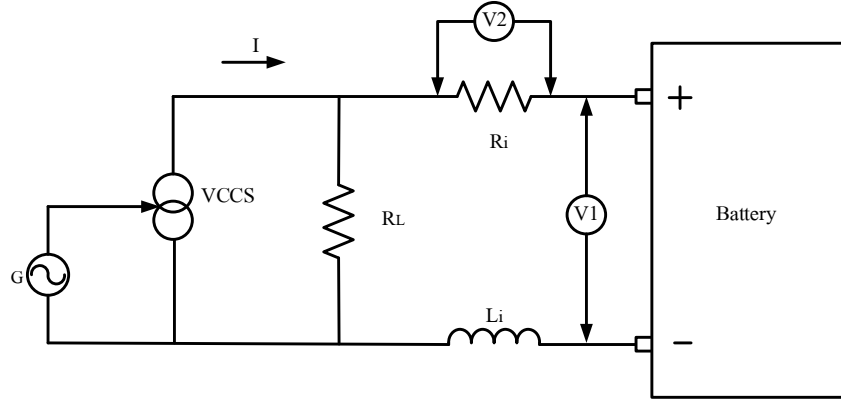


Figure 5. Electrical circuit for the frequency response testing of the batteries

Figure 5 shows that the frequency signal consists of a voltage-controlled current source (VCCS), a current detection resistor (R_i), a voltage divider resistor (R_L), and an external inductor (L_i). The variable inductance (L) in the tested battery can be computed by equation (6).

$$L = \frac{l}{\left(\frac{f_{r1}}{f_{r2}} \right)^2 - 1} \quad (6)$$

Where L is the inductance of the internal battery, l is the external inductor, f_{r1} is the test frequency that is not divided by the external inductor, and f_{r2} is the test frequency that is divided by the external inductor in a circuit. The spatial frequency response was analyzed by measuring the effects of each cycle of measurement. The phase difference was a measurement of the electrical current and the voltage of the load resistance. The resistance phase difference was varied from 100 mHz to 5 kHz, which was equal to 0 degree. The electrical circuit did not affect the phase difference in the frequency range. The operation frequency was used to find the equivalent circuit to prepare for the conditions before the battery testing. The battery must be controlled at ambient temperature before test setting. The two voltage waveforms were measured by an oscilloscope at the terminals of the battery (V_B) and voltage bracket resistance (V_{Ri}) as shown in Figure 6. Therefore, the impedance of the battery can be computed using equation (7).

$$Z = \frac{V_B \times R_i}{V_{R_i}} \times (\cos \theta + j \sin \theta) \quad (7)$$

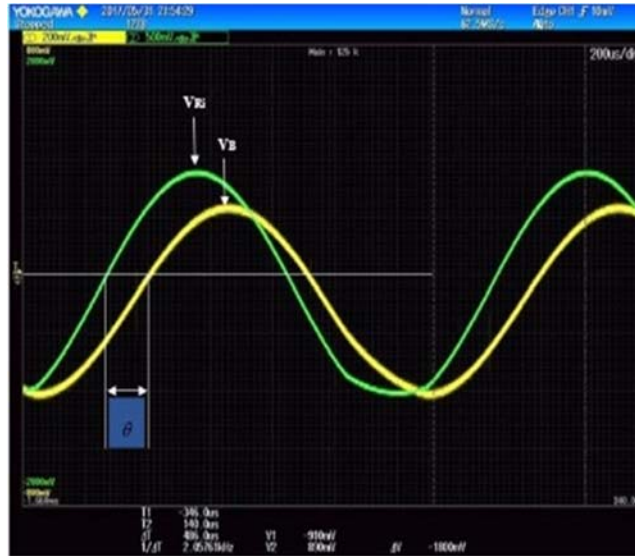


Figure 6. Two voltage waveforms of the proposed battery

Where Z is the impedance, V_B is the dropout voltage of the battery, V_{Ri} is the dropout voltage of resistance, and R_i is the internal resistance.

The model of the NiMH battery for the personal electric vehicle was found based on the electrical circuit model. The test voltage range of the NiMH battery was 9.6-14.4 V. The TBM was used to collect the experiment result to model the battery properties to the electrical circuit model. The experimental system was composed of an NiMH battery with a nominal voltage of 14.4 V and the ampere-hour of 4.5 Ah. The TBM used a data acquisition (DAQ) device and recorded the battery testing results. The experiment temperature was controlled at 25 °C to avoid the temperature effect. The TBM can charge and discharge a battery at a maximum current rate of 20 A. The TBM was arranged to measure 9 parameters as follows: the constant-current, final voltage, voltage/time, last voltage, constant power, constant ampere pulse, last voltage, pulse last voltage and final ampere-hour. It comprised the voltage, current, SOC measurements and a computer interface with summarized specifications of the TBM using the condition of pulse last voltage.

The testing of the NiMH battery obtained the SOC of the battery. The battery ampere-hour was 4.5 Ah for the testing condition. The pulse last voltage was presumed to compass the battery SOC value if the OCV value remained for a sufficient amount of time. The NiMH cell cannot operate in the steady-state mode during 600 s. However, the cell voltage increased after discharging and decreased after 600 s at the same SOC and OCV values.

3. Results and Discussion

The two waveforms can be calculated from the parameters in the electrical model of the proposed battery. The initial tests to measure the battery cell voltage were applied at regular intervals of 100 s to V_0 , which was equal to 10.1 V. The proposed battery was charged from 4.5 V to 11.5 V until the highest voltage reached 10.9 V. The voltage was constant, but the electricity supply was

reduced to the final value. When the battery charging was full at 200 s, the battery discharging began at 4.5 A. The final voltage was equal to 9.6 V; then, the battery reached the equilibrium point. Figure 7 can be analyzed using the relationship between voltage and time to compute the battery parameters, which are shown in Figure 8.

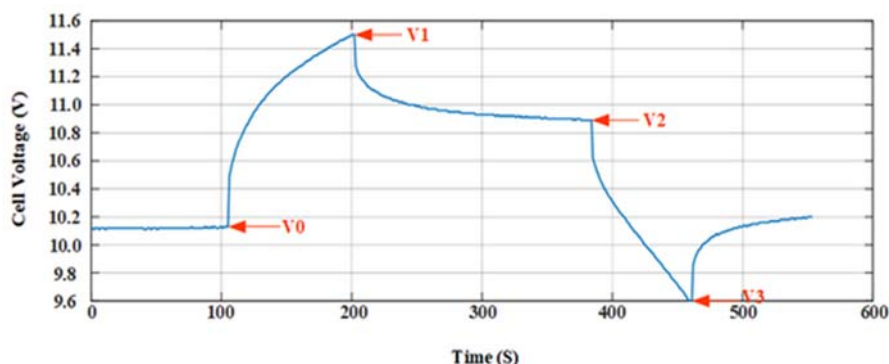


Figure 7. SOC voltage curve

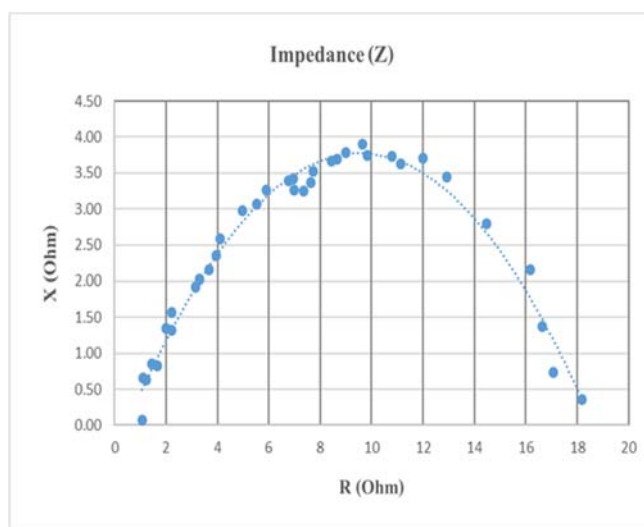


Figure 8. Nyquist plot of the frequency range from 100 mHz to 5 kHz

The equivalent circuit model of the proposed battery can be found by measuring the phase difference of the electrical current and voltage of the load resistance. The phase difference was varied from 100 mHz to 5 kHz. Using the Nyquist plot, we could calculate the inductance and R_2 and C_2 with the input voltage phase. It is more understandable that the capacitor discharge and discharge rates are not equal under the same cycle. The charging rate in the electrical model can be considered constant. The discharge testing had a longer time period than the charge time period. For the frequency response, the impedance of the battery can be calculated from the change rate of the phase difference. All variable parameters can be drawn in the equivalent circuit model as shown in Figure 9.

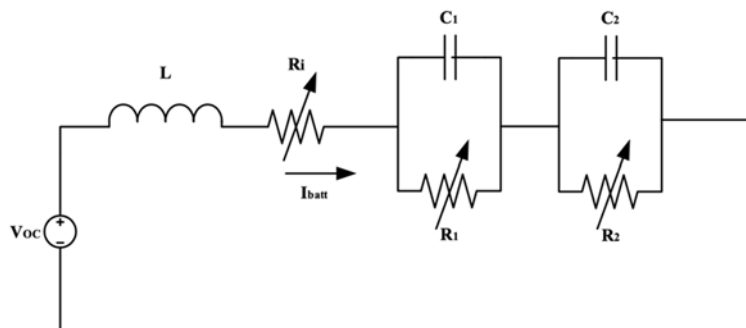


Figure 9. Electrical model of the NiMH battery

4. Conclusions

This article presents the electrical modeling of batteries with a focus on NiMH batteries in personal electric vehicles. The proposed battery model was considered in both SOC and voltage-current characteristics to find the mathematical model and electrical circuit model of the NiMH battery. The simulation results show that the proposed battery model can express the behavior of an NiMH battery. The MATLAB/Simulink environment was selected to analyze and simulate the battery electric model on both static and dynamic behaviors. The equivalent circuit model of the proposed battery can be found by measuring the phase difference of the electrical current and voltage of the load resistance. With the Nyquist plot, we can calculate the inductance and R_2 and C_2 using the input voltage phase. The charging rate in the electrical model can be considered constant. The discharge testing had a longer time period than the charge time period. For the frequency response, the impedance of the battery can be calculated from the change rate of the phase difference. Therefore, the proposed battery model can verify the study of the battery life cycle in personal electric vehicle applications in future work.

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