

Modeling and Experiment Validation of the DC/DC Converter for Online AC Impedance Identification of the Lithium-Ion Battery

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ABSTRACT

The lithium-ion battery plays an important role in saving energy and lowering emissions. Many parameters like temperature have an influence on the characteristic of the battery and this phenomenon becomes more serious in an electric vehicle. In this paper, the application of a boost DC/DC converter to the battery system of high power for online AC impedance identification is proposed. The function of the converter is to inject a current excitation signal into the battery at work and the normal output current is drawn by a load. Through analyzing the average state space equations and deriving the small signal model of the converter, the gain function is deduced of the fluctuated current signal against the fluctuated duty cycle which controls the converter. The control algorithm is designed and the system model is verified using Matlab/Simulink with respect to the disturbance current signal generation, the gain function and its variation with frequency range. Then the converter is designed and implemented to conduct the experiment on a power battery of 175Ah and the nominal voltage is 100V. The measured AC impedance of several single cells is presented and it demonstrates the feasibility of applying this DC/DC converter to the practical electric vehicle.

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INTRODUCTION

Nowadays the energy crisis and environment pollution problem have become more and more serious. Attention from all over the world has been paid to the lithium ion batteries due to properties like high energy density [1][2] and low emissions and the lithium ion battery are used in various applications such as battery packs in electric vehicles and hybrid electric vehicles [3][4]. The electrochemical impedance spectroscopy, abbreviated as EIS, has been widely used in the lithium ion battery research related to aging states and its influence on the application as well as the temperature estimation and expansions [5][6][7].

The principles of the EIS method are that a small voltage or current signal at some frequencies is superimposed on the battery and then after acquiring the voltage and current signal simultaneously the resistance can be obtained by performing FFT processing of the two signals. The EIS method has three basic assumptions, namely linearity, casualty and stability [8]. The linearity of the battery is ensured by controlling the amplitude of the added current or voltage fluctuation signal. The casualty is obvious because if no excitation signal is added, no corresponding signal can be measured. The stability means the system can return to the normal state when the added signal is removed and this is satisfied.

In general, the impedance acquisition of the battery can be classified into two groups, namely the impedance measurement approach and the online estimation approach. The impedance measurement approach relies on the experiment equipment and after being measured, the

important work is to estimate physical parameters of the battery. The impedance characteristic of the battery depends on the battery conditions such as the state of charge, the temperature, the current rate and eventually the previous history [5][9][10]. The state of charge of the battery has a high variation of the impedance in this frequency range, so the comparison and accuracy analysis of the impedance-based method is proposed in [11]. The relation between physical parameters and the impedance spectroscopy can be established by the equivalent circuit model such as the Randles' model and the transmission line model [12][13]. In [14], it is stated that the real part of the battery impedance is related to the battery temperature and the sensitivity analysis reveals that a high variation of impedance with temperature can be found for low frequencies. The impact of the charging methodology on the battery lifetime is investigated and the comparative study between charging techniques is presented through characterizing the batteries using the EIS method [15].

The online estimation approach of the impedance parameters considers the significant change of the battery characteristics during its lifetime due to aging [16]. In this group, the Kalman filter technique is a common used method and it is a recursive estimator [15]. The single Kalman filter can be used to estimate the battery state of charge based on the equivalent circuit model [17]. For consideration of nonlinearities in the battery model, the advanced versions of Kalman filter are employed, such as the extended Kalman filter or the sigma point Kalman filter. Some recent publications have considered the nonlinearity between the state of charge and the open circuit voltage [18][19][20].

Though much progress has been made in the impedance acquisition, the application of these methods to the actual battery packs is limited in many aspects. The impedance measurement needs the laboratory equipment which is usually of high price and its cost cannot be tolerated in practical systems. The online estimation requires a lot of calculations involving matrix operations and the implementation on an ordinary low-cost microcontroller is in fact difficult to achieve. Furthermore, the complex matrix operations can lead to numeric instabilities [16]. Hence, the combination of online measurement of the impedance and the online estimation method would be very meaningful. The first thing that needs to be done towards this target is to design the device for online measurement of the impedance. However, there is not much known literature in this aspect.

The research in [21] puts forward a solution which uses the power converter to excite the battery for impedance spectroscopy at any working point and the impedance spectroscopy is performed by the control system without additional power hardware. The limitation of this method is that the output current of the battery is much smaller than the practical current of the battery packs in vehicles. The similar work of the online impedance measurement can also be found in the area of the hydrogen polymer electrolyte membrane fuel cell system. The system for AC impedance measurement of fuel cell in vehicles is proposed in [22] and via the on-board system the function of this system has been validated. However, no more information is provided about the controllable high voltage DC/DC converter except the key frequency point of the excitation frequency of 300Hz.

The power converter does not exist in all the applications of the lithium-ion battery so in this paper, a new impedance measurement method is proposed that yields a wide frequency range and this method is applicable to all kinds of batteries system without much increase in the system cost. To do so, the topology of the impedance measurement system is given consisting of a power converter for excitation signal generation and a cell voltage monitor device for acquiring signals and calculating impedance. The average state space equations of the power converter are deduced to check the controllability and observability of the target input current of the converter. Based on these state space equations, the small signal model is derived to calculate the gain amplitude of the fluctuated current signal against the only control variable namely the duty cycle of the PWM of the power semiconductor. This helps to design the control algorithm and will allow for the verification of the proposed system topology. By setting up the model of power systems in Matlab/Simulink, the system function is verified. After design this power converter, the experiment is conducted on a high power LiMnO₂ battery and the feasibility of the converter in online impedance measurement is validated in a wide frequency range.

The organization of the paper is as follows. The system configuration and the mathematical model of the power converter are presented in detail in Section 2. Then the function of the system is verified with respect to the gain amplitude of the excitation current signal and the comparison of the calculated impedance is made with the theoretical equivalent circuit model in Section 3. Subsequently, the power converter and the cell voltage monitor are designed and implemented

to a high power battery pack and the validation of the converter model and the online impedance measurement is obtained in Section 4. Conclusions are drawn in Section 5.

SYSTEM MODELING

To start with, the system configuration is described, including the DC/DC converter, the lithium-ion battery pack and the load. Then the modeling of the lithium-ion battery and the converter is presented successively.

System Configuration

The system for online AC impedance identification of lithium-ion battery, as shown in Figure 1, is made up of a Lithium-ion battery pack with BMS (Battery Management System), a cell voltage monitor, a shunt resistor, an electronic load and a DC/DC converter as well as a resistor for its power consumption. The lithium-ion battery pack with BMS is regarded as the voltage source of the DC/DC converter and the electronic load. The BMS helps to monitor the normal operation state of the battery pack, which provides information of temperature, state of charge and state of health and so on. The electronic load is controlled to draw constant current from the battery pack and is like a kind of constant current sink.

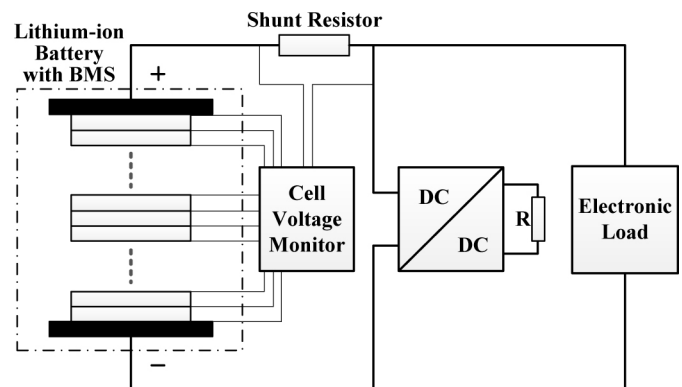


Figure 1. System configuration

Usually, the DC/DC converter is a power conversion device but in this system it is implemented to generate current excitation signal which will be superimposed on the battery pack. This current signal is the summation of a sinusoidal current part and a direct current part because the input current of the converter cannot be below zero. The controller of the converter is responsible for the function realization. For the power conversion of the DC/DC converter is not effectively utilized but just to produce heat, the operation time should be as shorter as possible and the direct current part should be as lower as possible if to be used in a practical system.

The cell voltage monitor is developed for measuring the voltage of each cell. The shunt resistor measures the output current of the battery pack and transforms the current signal to a voltage signal which can be sampled by the cell voltage monitor. Combining the cell voltage monitor and the shunt resistor, the output voltage and current of each cell can be acquired simultaneously and after recording these signals, the impedance spectroscopy can be calculated using FFT technique. Different from the conventional analog signal processing circuit, the cell voltage monitor must be capable of extracting weak

fluctuated signals from the large direct current and voltage at the stable operating point. On basis of the cell voltage monitor and the DC/DC converter, the work in this paper can go on smoothly.

Lithium-Ion Battery Model

When studying the electrochemical impedance spectroscopy, the lithium-ion battery is thought to be a linear system around its operating point. To fit the impedance spectroscopy, many equivalent circuits have been tried and there are two commonly used models, namely the Randles' model and the model with a Warburg element as shown in Figure 2(a) and Figure 2(b) respectively. The term E_n is the Nernst voltage based on thermodynamics and the term R_m is sum of the contact resistance, the internal ion transfer resistance and the wire resistance. The term R_c means faradic resistance at the electrochemical interface and the term C_{dl} means the double layer capacitor. When considering the finite diffusion process of the lithium-ion inside the battery, the double layer capacitor is replaced with a Warburg element Z_w .

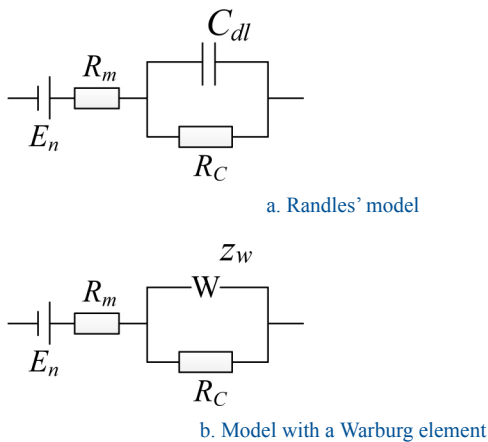


Figure 2. Equivalent circuit models

DC/DC Converter Model

The DC/DC converter, as shown in Figure 3(a), is a common boost converter comprised of an inductor L_1 , a switching power-semiconductor module G_1 , a diode D_1 and a capacitor C_1 . The resistor R_{L1} and R_{C1} are considered to approximate the parasitic power consumption of the inductor L_1 and capacitor C_1 respectively. The turn-on and turn-off power losses of the module G_1 and the diode D_1 are both included in the resistor R_{L1} because these processes are fairly complicated and in fact, no exact equation can be used to describe them quantitatively. A resistor R represents the load demand of the converter.

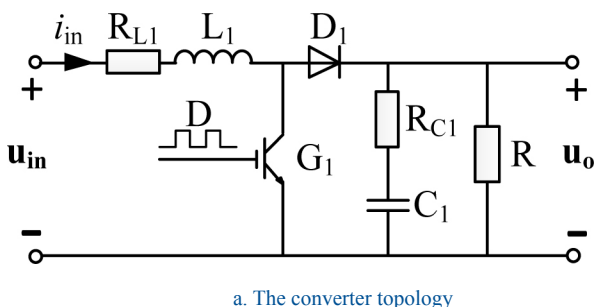


Figure 3.

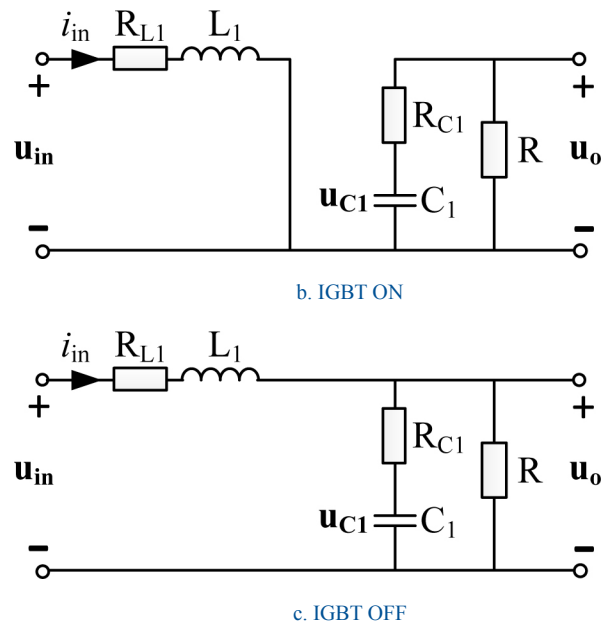


Figure 3. (cont.) The DC/DC converter

The converter is controlled to inject a fluctuated current signal to the battery pack. The fluctuated current signal may be of any wave form but to ensure high signal noise ratio (SNR), the sinusoidal current disturbance signal is chosen to be the target wave form. The frequency of the disturbance signal is extended to be as widely as possible while there is inherent limitation of DC/DC converter, one of which is the switching frequency of module G_1 , to realize the full range of frequency spectroscopy.

The principle of the DC/DC converter is founded on the pulse width modulation (PWM) and the duty cycle D and the switching frequency are two key parameters of PWM. When the module G_1 is on as shown in Figure 3(b), the converter operates in one way and the state equations are described by Equation 1. When the module G_1 is off as shown in Figure 3(c), the converter operates in the other way and the state equations are described by Equation 2.

$$\begin{cases} u_{in} = i_{in}R_{L1} + L_1 \frac{di_{in}}{dt} \\ C_1 \frac{du_{C1}}{dt} (R_{C1} + R) = -u_{C1} \\ u_o = -RC_1 \frac{du_{C1}}{dt} \end{cases} \quad (1)$$

$$\begin{cases} u_{in} = i_{in}R_{L1} + L_1 \frac{di_{in}}{dt} + u_o \\ u_{C1} + R_{C1}C_1 \frac{du_{C1}}{dt} = u_o \\ i_{in} - C_1 \frac{du_{C1}}{dt} = \frac{u_o}{R} \end{cases} \quad (2)$$

$$\begin{cases} u_{in} = i_{in}R_{L1} + L_1 \frac{di_{in}}{dt} + (1-D)u_o \\ u_{C1} + R_{C1}C_1 \frac{du_{C1}}{dt} + DRC_1 \frac{du_{C1}}{dt} = (1-D)u_o \\ (1-D)Ri_{in} = u_o + RC_1 \frac{du_{C1}}{dt} \end{cases}$$

Where,

u_{in} = input voltage of the converter

i_{in} = input current of the converter

u_o = output voltage of the converter

u_{c1} = voltage over the capacitor C_1

t = time

After taking the duty cycle D into consideration, the average state equations are deduced as Equation 3. The re-arranged equations are described by Equation 4 in order to acquire input variables X , state variables U and the output variable i_{in} as well as corresponding coefficient matrix A , B , C and T .

$$\left\{ \begin{aligned} \begin{bmatrix} \frac{di_{in}}{dt} \\ \frac{du_{c1}}{dt} \end{bmatrix} &= \begin{bmatrix} -\frac{R_{L1}}{L_1} & 0 \\ 0 & -\frac{1}{R_{C1}C_1 + DRC_1} \end{bmatrix} \begin{bmatrix} i_{in} \\ u_{c1} \end{bmatrix} \\ &+ \begin{bmatrix} \frac{1}{L_1} & -\frac{1-D}{L_1} \\ 0 & \frac{1-D}{R_{C1}C_1 + DRC_1} \end{bmatrix} \begin{bmatrix} u_{in} \\ u_o \end{bmatrix} \\ i_{in} &= \begin{bmatrix} 0 & -\frac{C_1}{(1-D)(R_{C1}C_1 + DRC_1)} \end{bmatrix} \begin{bmatrix} i_{in} \\ u_{c1} \end{bmatrix} \\ &+ \begin{bmatrix} 0 & \frac{DR_{C1}C_1 + (D^2 + 1 - D)RC_1}{R(1-D)(R_{C1}C_1 + DRC_1)} \end{bmatrix} \begin{bmatrix} u_{in} \\ u_o \end{bmatrix} \end{aligned} \right. \quad (4)$$

According to Equation 4, the state space equations can be described by Equation 5 and all variables and coefficient matrices can be described by Equation 6.

$$\begin{cases} \dot{X} = AX + BU \\ Y = CX + TU \end{cases} \quad (5)$$

$$\left\{ \begin{aligned} X &= \begin{bmatrix} i_{in} \\ u_{c1} \end{bmatrix} \\ U &= \begin{bmatrix} u_{in} \\ u_o \end{bmatrix} \\ A &= \begin{bmatrix} -\frac{R_{L1}}{L_1} & 0 \\ 0 & -\frac{1}{R_{C1}C_1 + DRC_1} \end{bmatrix} \\ B &= \begin{bmatrix} \frac{1}{L_1} & -\frac{1-D}{L_1} \\ 0 & \frac{1-D}{R_{C1}C_1 + DRC_1} \end{bmatrix} \\ C &= \begin{bmatrix} 0 & -\frac{C_1}{(1-D)(R_{C1}C_1 + DRC_1)} \end{bmatrix} \\ T &= \begin{bmatrix} 0 & \frac{DR_{C1}C_1 + (D^2 + 1 - D)RC_1}{R(1-D)(R_{C1}C_1 + DRC_1)} \end{bmatrix} \end{aligned} \right. \quad (6)$$

The controllability matrix Q is described by Equation 7 and the observability matrix R by Equation 8. It is easy to find that this system is completely controllable but not observable because the theoretical voltage u_{c1} of the capacitor C_1 is not measurable.

For the DC/DC converter, the directly adjustable parameter is the duty cycle and to realize the generation of the periodic current wave, the small signal model of the DC/DC converter needs to be setup at first. Then the amplitude gain of periodic current signal against the periodically changed duty cycle around their stable values is to be analyzed, which contributes to having a better knowledge of system properties in this special application.

$$\left\{ \begin{aligned} Q = [B \quad AB] &= \begin{bmatrix} \frac{1}{L_1} & -\frac{1-D}{L_1} \\ 0 & \frac{1-D}{R_{C1}C_1 + DRC_1} \end{bmatrix} \\ \text{rank}(Q) &= 2 \end{aligned} \right. \quad (7)$$

$$\left\{ \begin{aligned} R = \begin{bmatrix} C \\ CA \end{bmatrix} &= \begin{bmatrix} 0 & -\frac{C_1}{(1-D)(R_{C1}C_1 + DRC_1)} \\ 0 & \frac{C_1}{(1-D)(R_{C1}C_1 + DRC_1)^2} \end{bmatrix} \\ \text{rank}(R) &= 1 \end{aligned} \right. \quad (8)$$

$$\begin{cases} i_{in} = I_{in} + \hat{i}_{in} \\ u_o = U_o + \hat{u}_o \\ u_{c1} = U_{c1} + \hat{u}_{c1} \\ u_{in} = U_{in} + \hat{u}_{in} \\ D = D_o + \hat{d} \end{cases} \quad (9)$$

$$\begin{cases} L_1 \frac{di_{in}}{dt} = u_{in} - i_{in}R_{L1} - (1-D)u_o \\ RC_1 \frac{du_o}{dt} = (1-D)Ri_{in} - u_o \end{cases} \quad (10)$$

$$\begin{cases} L_1 \frac{d\hat{i}_{in}}{dt} = \hat{u}_{in} - R_{L1}\hat{i}_{in} - (1-D)\hat{u}_o + U_o\hat{d} \\ RC_1 \frac{d\hat{u}_o}{dt} = (1-D)\hat{i}_{in} - I_{in}\hat{d} - \hat{u}_o \end{cases} \quad (11)$$

To derive the small signal model, small dynamic signals are added to all the related parameters and variables as Equation 9. The term $\hat{i}_{in}$ stands for the dynamic signal of small amplitude compared to the stable value I_{in} . The term $\hat{u}_o$, $\hat{u}_{c1}$, $\hat{d}$ and $\hat{u}_{in}$ are dynamic small signals of the output voltage, the capacitor voltage, the duty cycle and the input voltage respectively. Meanwhile, the term U_o , U_{c1} , D_o and U_{in} represent the stable value of the output voltage, the capacitor voltage, the duty cycle and the input voltage accordingly.

When the Equation 9 is substituted into Equation 4, the summation of stable variables in every equation is zero and the small signal model can be proposed by neglecting the twice order infinitely small items. However, through analyzing Equation 4 simply, the duty cycle D is part of dominators of all coefficient matrices and to do the Taylor expansion of these matrices needs a lot of efforts but it has no much influence on what to be emphasized, which will be analyzed later. In consequence, to simplify the state space equations, an assumption is made that the equivalent internal resistor of capacitor C_1 can be neglected, which means the term R_{C1} is equal to zero. Then the term