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A model-based driving cycle test procedure of electric vehicle batteries①

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Abstract

The battery test methods are the key issues to investigate the energy-storage characteristics and dynamic characteristics of electric vehicle (EV) batteries. In this paper, the research advances of existing battery test methods as well as driving cycles are reviewed. An electric vehicle model that consists of EV dynamics model, battery model and electric motor model is built. The dynamic characteristics of the battery in frequency domain are analyzed. Based on the EV model and the frequency domain characteristics of the battery, a driving cycle test procedure of EV battery is proposed. The battery test procedure is able to reflect the real-world characteristics of EV batteries, and can be used as a universal EV battery test method.

Key words: battery test methods, lithium-ion battery, electric vehicle (EV), model, driving cycles

0 Introduction

Batteries are the most important energy storage part of electric vehicles (EVs), and have significant importance to the development of EVs. With larger EVs' penetration, the EV-grid interaction will impose greater effects on the EVs and the power system. The energy-storage characteristics as well as dynamic characteristics of batteries are important attributes that affect design decisions, such as the battery capacity, preferred chemistry, and size of electrical devices onboard. Meanwhile, the energy-storage characteristics of batteries are also the key factors that influence the interactions between EVs and grid. Therefore, in order to investigate the energy storage and dynamic characteristics of EV batteries accurately, we need urgently to propose a battery test procedure that can accurately reflect EV battery' energy storage characteristics as well as dynamic characteristics.

When conducting a battery experiment, we usually use constant current charge/discharge test procedures at a certain current C-rate[1-4] or pulse test procedures that meet some specific laws[2] to test the battery. The basic starting point of these battery test methods is to distinguish the transient and steady state of the battery. For instance, we usually use the constant C-rate of charge/discharge current to study the battery steady-state process, and use the rectangular pulse to investigate the battery transient-state process. These methods mentioned above can apparently simplify the working status of the battery, and provide an easy way to study the electrochemical reaction process inside the battery.

However, in actual driving cycles, the charge and discharge conditions of EV batteries are based on the real-time input/output power requirements, and rarely work in the single constant current charge/discharge or pulse states. Actually, the battery's actual working condition is always a combination of transient and steady state. Furthermore the actual transient state of the battery is not a simple rectangular pulse usually. Therefore, it is necessary to study the real-world driving cycles and their integration into the EVs. So that, a deeper understanding about the energy-storage and dynamic characteristics of EV batteries will be achieved.

This paper is organized as follows. Section 1 reviews the existing battery test methods as well as driving cycles, and also analyzes the research advances of battery test methods. In Section 2, an electric vehicle model that consists of EV dynamics model, battery model and electric motor model is built. In Section 3, the battery dynamic characteristics are investigated in frequency domain. And based on the EV model, a uni-

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versal driving cycle test procedure which can reflect the real-world characteristics of the EV batteries is proposed. Finally, we conclude the paper in Section 4.

1 Driving cycles

A driving cycle is a speed-time sequence developed for a certain type of vehicles in a particular environment to represent the driving pattern[5]. Several driving cycles[6] have been developed in different countries to represent the driving conditions, such as UDDS driving cycle of US, NEDC driving cycle of EU and JE05 driving cycle of Japan. The UDDS driving cycle is shown in Fig. 1.

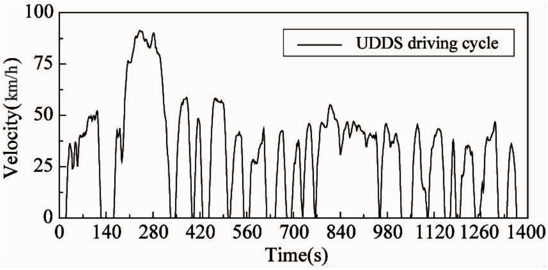

Fig. 1 Speed-time curve of UDDS driving cycle

When conducting a battery experiment, a test procedure which is described by current-time table is urgently needed. Thus we need to transform the speed-time formed driving cycles to the current-time formed battery test procedures. Ref. [1] simplified the federal urban driving schedule (FUDS) driving cycle, and introduced the current-time formed dynamic stress test (DST) procedure. Ref. [7] designed a current-time formed dynamic performance test procedure based on actual running data statistic. In Ref. [2] the hybrid pulse power characterization (HPPC) test procedure was proposed which intended to determine the dynamic power capability over the battery's usable charge and voltage range.

Although the above existing test procedures can provide test methods in the form of current-time table, there are several drawbacks as follows. First, these test methods are based on actual running data of vehicles, which take a lot of time, and limit their applications in the EV's design stage. Second, the test methods mentioned above do not take into account the difference between batteries as well as vehicle types. As a result, they do not have universal applicability.

Therefore, the core problem is to propose a current-time formed driving cycle test procedure that can be applied to different kinds of batteries and vehicles. In the following sections, we will use a model-based design method to propose a universal driving cycle test procedure for EV batteries.

2 Modeling of electric vehicles

In order to propose a current-time formed test procedure for EV batteries, the vehicle itself with its driveline components, as well as speed-time formed battery driving cycles has been modeled in MATLAB/Simulink. The modeled electric vehicle driveline is shown in Fig. 2, which consists of interconnected component blocks in Simulink, representing physical components, such as the gear box, the motor and the battery. All the necessary vehicle and component parameters were declared in an associated MATLAB m-file. The backward-facing simulation method was adopted to build the electric vehicle model.

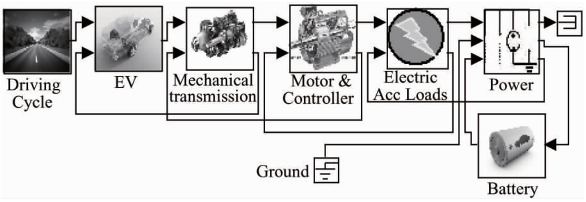

Fig. 2 Proposed electric vehicle model in MATLAB/Simulink

2.1 EV dynamics model

The EV dynamics model block mainly characterizes the force balance at the tire patch. Fig. 3 shows the block structure of EV dynamics in MATLAB/Simulink. The block uses the required vehicle speed, vehicle parameters, previous speed and classic straightforward Eqs(1) ~ (3) to determine the tractive force required at the tire/road interface. In addition, given the tractive force available, this block can use the same equations to determine the achievable speed. The mathematical expressions of the equations can be written as

$$F_t - (ma + mg\sin\alpha + F_w + F_f) = 0 \tag{1}$$

$$\alpha = \frac{V_t - V_0}{\mathrm{d}t} = \frac{0.5(V_{\mathrm{aver}} - V_0)}{\mathrm{d}t} \tag{2}$$

$$V_t = 2 \cdot V_{\mathrm{aver}} - V_0 \tag{3}$$

where,

$$F_w = 0.5 \cdot \rho \cdot C_d \cdot A \cdot V_{\mathrm{aver}}^2 \tag{4}$$

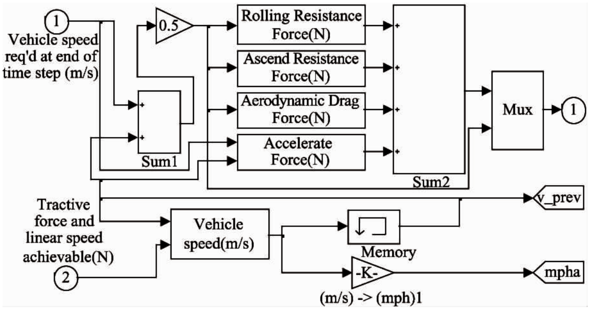

Fig. 3 EV dynamics model in MATLAB/Simulink

$$F_f = mg\cos\alpha(f_1 + V_{\text{aver}} \cdot f_2) \qquad (5)$$

In the equations above, F_t is the tractive force, F_w is the air resistance, F_f is the rolling resistance, V_0 is the initial velocity, V_{aver} is the average velocity, V_t is the achievable speed, C_d is the aerodynamic drag coefficient, A is the vehicle frontal area, ρ *is* the air density, f_1, f_2 are the rolling resistance coefficient of front and rear wheels, respectively. All these EV dynamics parameters were declared in the associated MATLAB m-file.

2.2 Battery model

Several models have been developed to characterize lithium-ion batteries. Detailed electrochemical models that simulate the internal dynamics of the cells[8-10] are usually time-consuming, computationally intensive, and results unsuitable for real-time applications. An alternative approach is to use the equivalent circuit models (ECM)[11-13]. Their level of complexity is decided as a trade-off between accuracy and computational complexity. ECM can capture dynamic phenomena, and yet avoid lengthy complex calculations. Therefore, they are especially suitable for system-level modeling.

Fig. 4 shows the proposed equivalent circuit model for the lithium-ion batteries. R_0 is the internal resistance, E_m is the open-circuit-voltage (OCV), two RC pairs R_1, C_1 and R_2, C_2 compute the dynamic behaviors of battery such as hysteresis phenomenon and polarization effect. Each element of Fig. 4 is a function of state-of-charge (SOC) and inner cell temperature T.

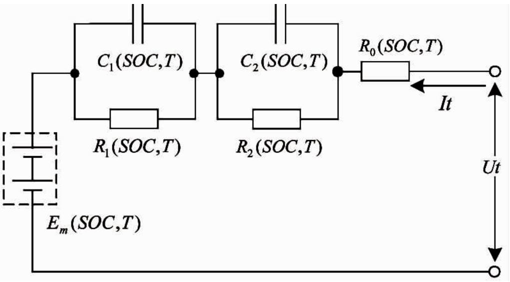

Fig. 4 Proposed equivalent circuit model

The inner cell temperature is assumed to be uniform, and is equal to the average temperature inside the cell. The temperature can be computed by solving the heat equation of a homogeneous body exchanging heat with the environment:

$$C_T \frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{T - T_a}{R_T} + P_s \qquad (6)$$

where, T is the inner cell temperature (℃), T_a is the ambient temperature, P_s is the power dissipated inside the cell, R_T is the convection resistance, C_T is the heat capacitance.

Then the SOC can be obtained through

$$SOC = SOC_{init} - \frac{1}{C_N}\int_{t_0}^{t} I\eta \cdot \mathrm{d}t \qquad (7)$$

where, SOC_{init} is the initial SOC, C_N is the rated capacity, I is the current, η is the coulomb efficiency.

In this paper, the ECM was created using Simscape™ blocks and Simscape™ language in Matlab[14]. The Simscape model in Fig. 5 represent the circuit diagram shown in Fig. 4. Each of the circuit elements is a subsystem consisting of custom electrical blocks, and blocks to calculate the properties of the circuit element such as SOC. which is derived based on the coulomb counting of the current drawn from the cell at each test step.

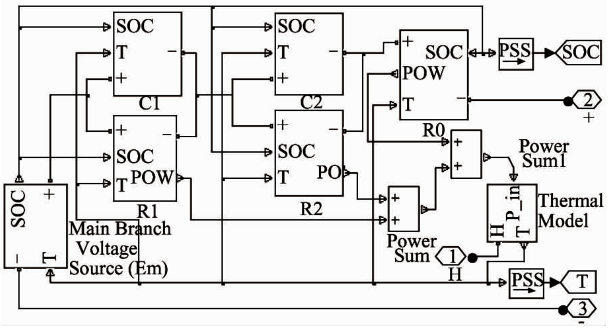

Fig. 5 Equivalent circuit model of battery in MATLAB/ Simscape™

In order to obtain the parameters of the ECM, a 3.2V, 50Ah lithium iron phosphate ($LiFePO_4$) battery module is chosen from the 294.4V, 50Ah EV battery pack, to conduct the battery characterization tests at 24℃. First, the battery is initially fully charged and then subjected to the 10% DOD 0.5C constant current discharge separated by one-hour rest period. Second, the cell is subjected to the 10% DOD 0.5C constant current charge separated by one-hour rest period. Last, single repetitions of step one and two were made until the end of the test.

After each one-hour rest, the cell returned to an electrochemical and thermal equilibrium condition, the charge/discharge voltages and internal resistance during each rest period are recorded to establish the cell's OCV-SOC and internal resistance-SOC behavior. The experimental internal resistance-SOC curve and OCV-SOC curve are shown in Fig. 6 and Fig. 7 respectively.

The battery characterization tests are conducted at the temperature of 24℃. The OCV can be considered independent of temperature. However, the internal resistance should be expressed as a function of temperature. In Ref. [15] an empirical equation was raised as follows:

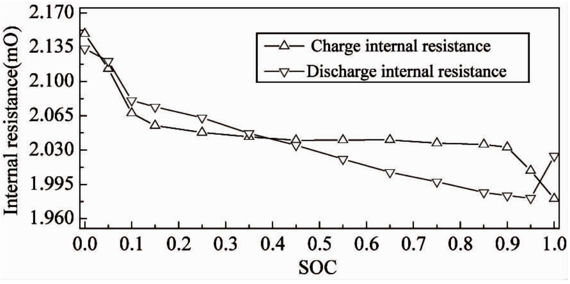

Fig. 6 Internal resistance-SOC curve of the tested cell at 24℃

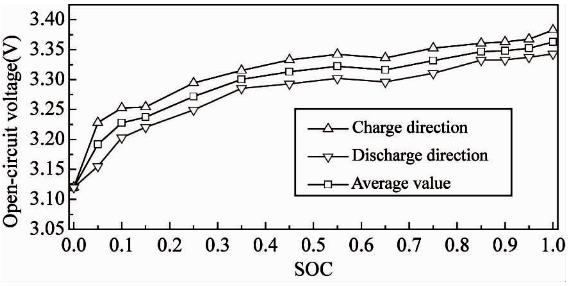

Fig. 7 OCV-SOC curve of the tested cell at 24℃

$$R_0(SOC,\ T) = R_0(SOC)\cdot e^{\left(\frac{E_{a,0}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)} \qquad (8)$$

where $E_{a,0}$ is the activation energy, R is the gas constant and T_{ref} is the reference temperature.

On the basis of above experimental data, a linear least squares recursive identification is used to estimate the two RC pairs of R1, C1 and R2, C2. So that, a lookup-table based parameterization method could be used in the Simscape$^{\text{TM}}$ model. The flow diagram of Fig. 8 illustrates the parameter estimation steps.

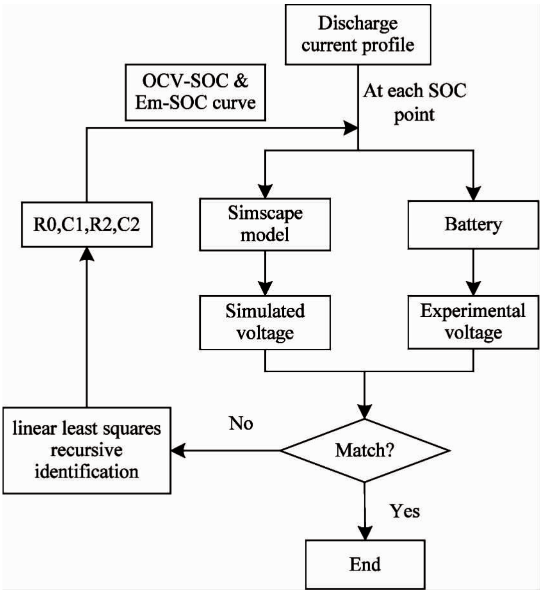

Fig. 8 Flow diagram of the RC parameter estimation procedure

2.3 Electric motor model

The proposed electric model consists of three parts: a motor, a motor controller, and a DC/DC converter. The motor block translates torque and speed requests into electric power requests, and then converts actual power input to torque and speed output. The motor control block ensures that the controller's maximum current is not exceeded and the motor shuts down when it is not needed. The DC/DC converter ensures the motor voltage remains constant. Fig. 9 shows the described motor model in MATLAB/Simulink.

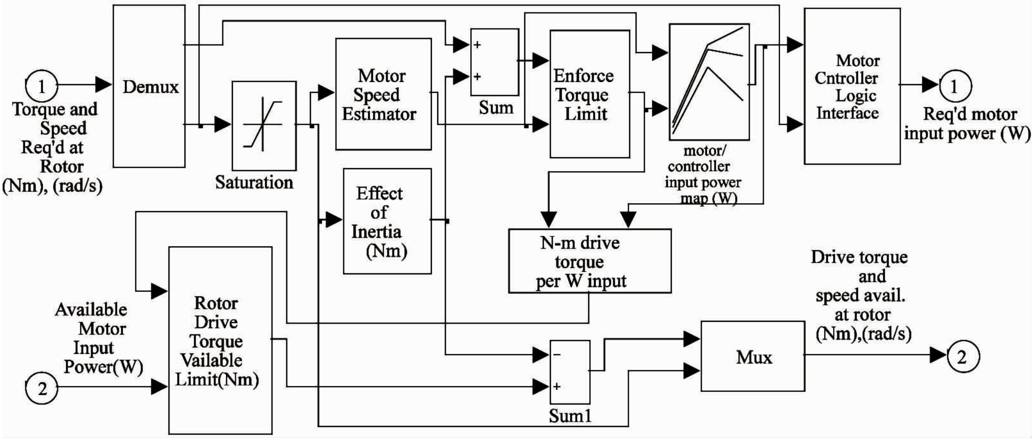

Fig. 9 Electric motor model in MATLAB/Simulink

The motor model includes the effects of electrical motor efficiency, rotor inertia, and the motor's torque speed-dependent torque capability. Electric motor efficiency is the ratio between the shaft output power and the electrical input power, and is usually handled as a 2-D lookup table indexed by rotor speed and output torque. The motor's maximum torque capacity is enforced using a 1-D lookup table indexed by rotor speed in the model. When computing the available torque, we assume that the ratio of rotor torque to input (electric) power is the same for the actual situation as was computed for the request. Thus the available torque can be calculated from available power directly, which is equivalent to assuming the motor/controller efficiency mathematically.

In order to obtain the efficiency and torque performance of the EV motor, the motor characterization tests were conducted on a dynamometer testing platform. The tested motor is a 20kW three-phase AC induction motor operating at 180V. Fig. 10 shows experimental data of the motor efficiency when working in the motoring mode. From Fig. 10 we can see that the motor has a steady high efficiency of 80% during most test conditions. And the efficiency would drop in low speed or low torque operation.

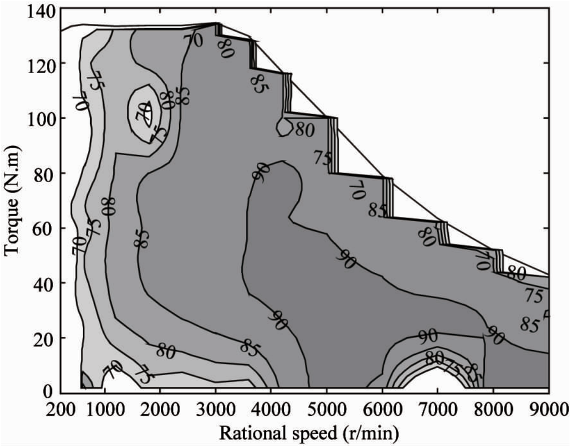

Fig. 10 Efficiency map of the EV motor in the motoring mode

Different from the industrial applications of motors, the motors used in EVs usually require high rates of acceleration and deceleration, frequent starts and stops, and a very wide speed range of operation. The application of EV motors requires the motors to operate in motoring mode as well as generating mode, including forward motoring, forward braking, backward motoring, and backward braking. Fig. 11 shows the motor efficiency map when the motor works in the generating mode.

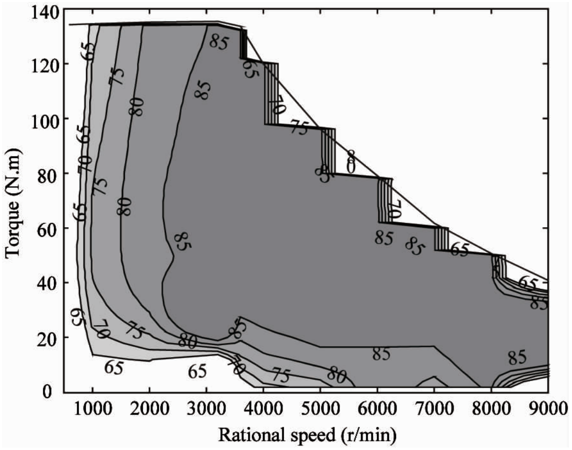

Fig. 11 Efficiency map of the EV motor in the generating mode

The single lines in Fig. 10 and Fig. 11 show the relationships between maximum torque and rotor speed in motoring mode as well as generating mode, respectively.

3 Model-based battery test procedure

3.1 Simulation and statistical analysis

The UDDS driving cycle in Fig. 1 is selected to investigate the battery test procedure based on the above described EV model. The simulation results show that the actual vehicle speed-time curve is completely consistent with the UDDS driving cycle. The input and output currents of the EV battery pack are collected during the simulation. Fig. 12 shows the simulated current-time curve of the EV battery pack in the UDDS driving cycle.

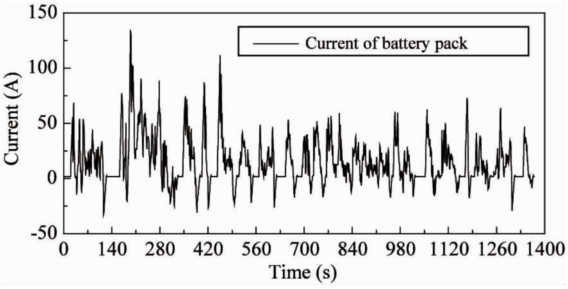

Fig. 12 Current-time curve of the battery pack in UDDS driving cycle

In Fig. 12 the data above zero represent the discharge mode. On the contrary, the data below zero represent the charge mode. It should be noted that, Fig. 12 can be easily translated to the load currents of a single battery or a battery pack by multiplying a constant coefficient in accordance with the electrical connections of the battery pack. Thus, the load currents in Fig. 12 can be used as the input excitation when we conduct a battery test. However, the current-time curve is not suitable for quantitative analysis due to its transient characteristics. Therefore, we need to transform the curve in Fig. 12 to a simpler one.

Considering that the output current of the battery can not be accurately determined at a time point, while the distribution of the load currents is statistically significant in time domain. Therefore, based on the statistical analysis of Monte Carlo method, we further investigate the current curve in Fig. 12. The current distribution of the EV battery pack and the detailed statistical parameters of the battery pack currents are shown in Fig. 13 and Table 1, respectively.

Table **1** Detailed statistical parameters of the battery pack currents

	Total Time	Driving Time	Standing Time	Accelerating Time	Cruising Time	Decelerating Time	Braking Time
Time(s)	1369	1180	189	506	247	427	271
Proportion(%)	100%	86.1%	13.8%	36.96%	18.04%	31.19%	19.8%

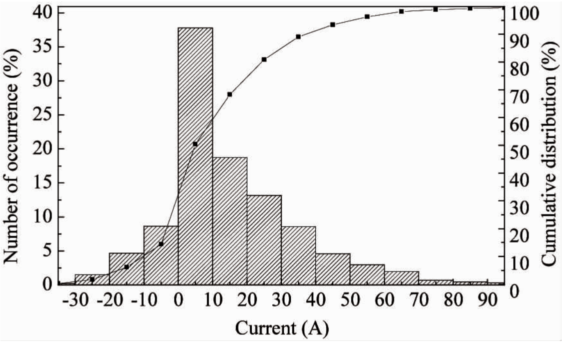

Fig. 13 Currents distribution of the EV battery pack

In the histogram shown in Fig. 13, the width of every rectangle represents the range of currents, the length of the rectangle represents the probability of occurrences within the scope of each rectangle.

3.2 Battery characteristics in frequency domain

In order to obtain a good test result, the test profile (input current) should be able to excite the dynamic characteristics of the battery's as much as possible. That is to say, the bandwidth of the test profile should include that of the battery's in the frequency domain. However we usually do not know the bandwidth of the battery in advance. Various characteristic quantities of the system allow us to get a rough estimate of the battery's bandwidth. One such quantity is the rise time of the step response. In this research, we use the step response to characterize the bandwidth of the battery.

The step response test in Fig. 14 is used to conduct the experiment from 0% SOC to 90% SOC with 10% ? SOC intervals. We first sample the output voltage (the marked curve in Fig. 14) at a high sampling frequency. Then based on the data set of the voltage response, we apply the Fast Fourier Transformation (FFT) algorithm to compute the amplitude spectrum of the battery. Therefore, we can find the bandwidth by inspecting the signal's amplitude spectrum.

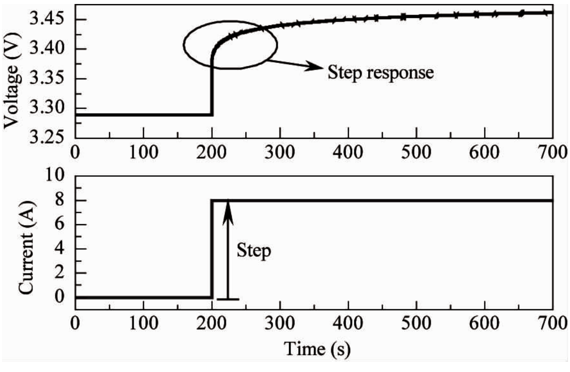

Fig. 14 Proposed EV battery test procedure

Fig. 15 Shows the amplitude spectrums of the battery at different SOC. It can be observed that the differences of the spectrums at different SOC are very small. Setting 0.1 as the lower limit of the amplitude, we can easily get the following conclusions from Fig. 15:

(1) The main bandwidth the cell is from 0Hz to 0.04Hz.

(2) The cell's minimum time constant $\tau = 1/0.04 \approx 25\text{s}$. That means the battery should be persistently excited by a certain constant current for at least 25s, so that the dynamic characteristics of the battery can display completely.

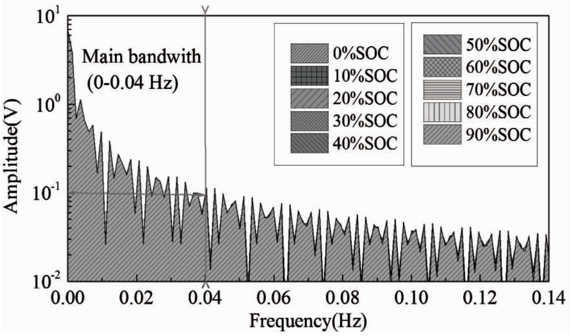

Fig. 15 The amplitude spectrum of the battery at different SOC

3.3 Battery test procedure

Based on the statistical analysis and the frequency domain characteristics of the battery, a current-time formed battery test procedure for a single battery was proposed in Fig. 16, where the minimum pulse width is 25s. The pulse width of the test procedure was built in accordance with the statistical distribution of the driving sequence: accelerating, cruising, decelerating and braking. The currents that are larger than zero represent the discharge mode, while the opposite-direction currents illustrate the charge mode. It should be noted that, if one want to build a test procedure for a battery module, he can easily achieve it by multiplying the proposed procedure with a constant battery size factor.

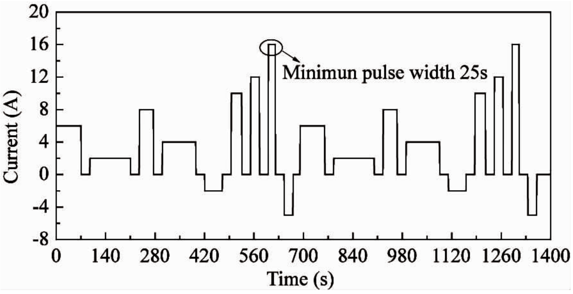

Fig. 16 The proposed EV battery test procedure

4 Conclusions

In this paper, the EV battery test method which can simulate the real-world driving cycles of EVs is investigated. The electric vehicle model as well as the battery frequency domain characteristics are studied. Based on the EV model and the battery frequency domain characteristics, a model-based driving cycle test procedure of EV batteries is proposed. The proposed battery test procedure has the following advantages:

(1) The battery test procedure is based on EV models, it can change flexibly with the model structure and model parameters, such as battery capacity, motor size and vehicle type.

(2) The battery test procedure contains both charge and discharge modes, and the pulse width of the test profile is changed in accordance with the real-world driving cycles. Thus, the test profile can be used to simulate the real-world driving cycles of the electric vehicles.

(3) The application of the battery test procedure is universal. After modified by multiplying a constant battery size factor, the procedure can be applied to different kinds of batteries. In addition, it can be easily customized according to different drive patterns in different cities and different countries.

(4) The battery test procedure can be used to optimize and determine the EV parameters such as the battery capacity, preferred chemistry, and sizes of other electrical devices on-board.

In conclusion, the battery test procedure proposed in this paper is flexible, universal and is helpful to parameter optimization of EV. Further study could be taken in the follow areas, including better understanding of realistic driving cycles, charge demand of EVs, and user behavioral patterns.

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