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Model based insulation fault diagnosis for lithium-ion battery pack in electric vehicles

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ABSTRACT

The condition monitoring and fault diagnosis of the lithium-ion battery system are crucial issues for electric vehicles. The shocks, blows, twists, and vibrations during the electric vehicle driving process may cause the insulation fault. In order to ensure the safety of the drivers and passengers, a real-time monitor to detect the insulation state between the high voltage and ground is required. However, the conventional battery management system only provides very simple and coarse-grained measurements to detect the insulation resistance. In this work, a model-based insulation fault diagnosis method is proposed. Firstly, the equivalent circuit model for insulation fault diagnosis is established using a high-fidelity cell model. Then, the recursive least-squares method is employed to identify the model parameters. Considering the system nonlinear properties, measurement noise and unknown disturbance, the Kalman filter based state observer is designed for joint estimation of both the battery voltage and state-of-charge using the identified battery model. Finally, the positive and negative virtual insulation resistance are quantitatively assessed based on the prediction results of the state observer. Experiments under different loading profiles are performed to verify the proposed method.

1. Introduction

Energy and environmental issues are crucial in sustainable development of human society. The electric vehicle as a kind of green transportations is a good solution for the energy and environmental issues [1]. With the rapid development of electric vehicles and growing concerns on energy and environmental problems, the demands for batteries have improved dramatically. The lithium-ion battery is one of the promising energy storage devices due to its long cycle life, high specific power and energy density [2,3]. The battery systems in electric vehicles usually consist of hundreds or thousands of single cells. Therefore the battery management systems are designed to provide monitoring, control and protecting functions to enhance the operation of the batteries [4,5]. The main task of the battery management system contains real-time battery state estimation [6–10], battery thermal management [11–13], cell equalization [14,15], on-board fault diagnosis [16–19] and other control and management functions. One of the main tasks of the battery management system is to ensure the safety of the batteries and protect the batteries from unsafe operations. In order to ensure the electric vehicles working in a safe environment, it is critical to develop a reliable fault diagnosis scheme for the battery power system [19].

The insulation monitoring is an important technology in the personal safety of electric vehicles. In general, the insulation resistance is defined as the resistance corresponds to the maximum leakage current when the power battery is short circuited to the ground or the chassis of the vehicle. The shocks, blows, twists, and vibrations of vehicles during the driving process may cause the change of the insulation state. Factors such as temperature, humidity, etc. will also affect the insulation resistance. In order to ensure the safety of the passengers and drivers, a real-time monitor to detect the insulation state between the high voltage and ground is necessary [20]. However, the conventional battery management system only provides very simple and coarse-grained measurements to detect the insulation resistance.

According to Ref. [21], the minimum insulation resistance of the battery system is 100 Ω/V. The conventional insulation detection methods include the voltmeter method, the electric bridge method, and the signal injection method. The voltmeter method provides an off-line method for insulation detection which cannot be used when the battery system is running. The electric bridge method can detect the insulation resistance without complicated circuit. However it is easy to appear undetected errors when the bilateral insulation resistances decrease at the same time. To

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overcome the drawbacks of the electric bridge method, Ref. [22] reported a method for monitoring the insulating property of electric vehicles. The low frequency signal is injected into an additional loop. Through sampling the real-time voltage value, the insulation resistance value of the electric vehicles can be detected. Since the amplitude of the injection signal is limited, the amplitude of the feedback signal is small when the external insulation resistance is large. In addition, the working conditions of the electric vehicles are very complex and the signals are easily disturbed by noises.

Considering the system nonlinear properties, measurement noise and unknown disturbance, the model based fault diagnosis for the lithium-ion batteries has attracted more and more attentions [23]. System identification and state estimation are important for the model based fault diagnosis. Wei et al. [24] presented an enhanced online model identification and state estimation approach for the lithium-ion batteries by using an improved recursive least squares method. In Ref. [25], a multi-timescale method for dual estimation of capacity and state-of-charge of the lithium-ion battery is presented. The model parameter estimator and the dual estimator are fully decoupled and executed with different timescales to improve the model accuracy and stability. For the battery systems, the model-based methods use models such as electrochemical model [26], equivalent circuit model [27] or neural network model [28] to establish relationships between observations and measurements. In this work, a model based insulation fault diagnosis method is firstly proposed based on the signal injection topology. Secondly, the equivalent circuit model for insulation fault diagnosis is established using a high-fidelity cell model. Then, the recursive least-squares method is employed to identify the model parameters. Considering the system nonlinear properties, measurement noise and unknown disturbance, the unscented Kalman filter based state observer is designed for joint estimation of both the battery voltage and state-of-charge. Finally, the positive and negative virtual insulation resistance are quantitatively calculated based on the prediction results. Experiments under different loading profiles are performed to verify the proposed method.

The remainder of the paper is organized as follows: In Section 2, a high-fidelity battery model is first presented. Then the pack model for insulation fault diagnosis is introduced. In Section 3, the model-based fault diagnosis methods applied in this work are discussed. The recursive least-squares method with forgetting factor is described for model parameter identification. Then, the unscented Kalman filter based state observer for insulation monitoring is proposed. In Section 4, experiments are conducted on the lithium-ion batteries to verify the proposed method. The conclusions are given in Section 5.

2. System modelling

A battery model with high accuracy is essential when using the model-based fault diagnosis methods. This section mainly introduces the model for insulation fault diagnosis. Considering the model complexity and accuracy, the Thevenin equivalent circuit model is utilized as the cell model to characterize the dynamic performance of the lithium-ion battery [29]. Then the battery pack equivalent circuit model for insulation fault diagnosis is established using the cell model.

2.1. Cell model

The schematic diagram of the cell equivalent circuit model is shown in Fig. 1(a). Based on Fig. 1(a), the electrical behavior of the battery model can be described as follows:

$$\dot{V}_p = -\frac{V_p}{R_p C_p} + \frac{i_b}{C_p} \tag{1}$$

$$V_t = V_{ocv} - R_o i_b - V_p \tag{2}$$

where V_p represents the polarization voltage, V_t represents the terminal voltage, V_{ocv} represents the cell open-circuit voltage, i_b represents the battery current, R_o represents the ohmic internal resistance, R_p and C_p represent the polarization resistance and polarization capacitance, respectively.

According to Ref. [30], the polynomial fitting function of the open-circuit voltage can be expressed in the following equation:

$$V_{ocv}(z) = k_0 + k_1 z + k_2/z + k_3 \ln(z) + k_4 \ln(1-z) \tag{3}$$

where z represents the cell state-of-charge (SOC), $k_0 \sim k_4$ are polynomial coefficients of the fitting function.

2.2. Pack model for insulation fault diagnosis

The battery pack equivalent circuit model for insulation fault diagnosis based on the signal injection topology is shown in Fig. 1(b). The resistances R^+ and R^- represent the positive and negative virtual insulation resistance, respectively. R_f represents the reference resistance. R_1 and R_2 represent the sampling

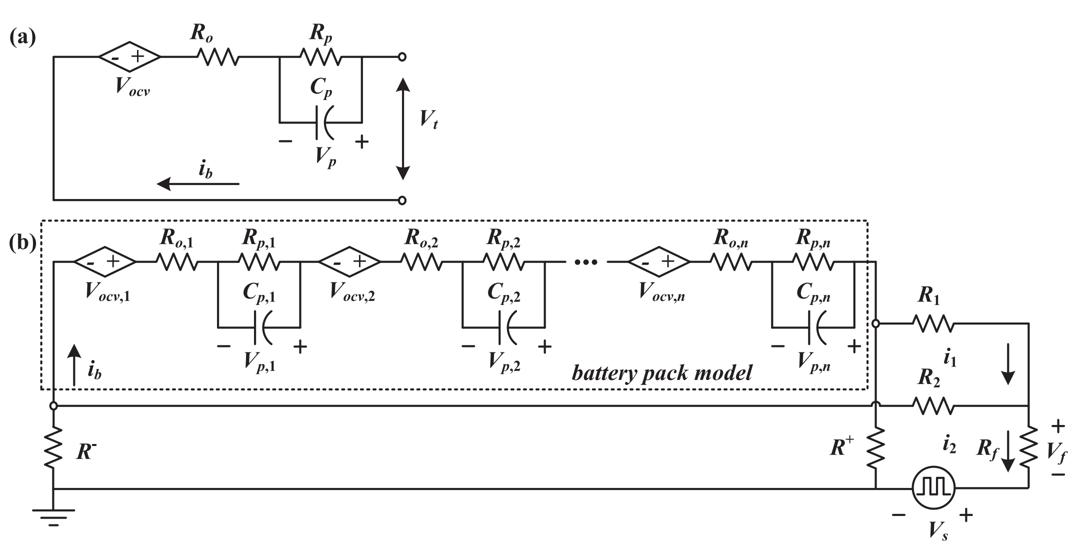

Fig. 1. Equivalent circuit model for insulation fault diagnosis: (a) Cell model. (b) Pack model.