An insulation diagnosis method for battery pack based on battery model

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Abstract: The collision and components aging of electric vehicles may lead to dramatic decrease of insulation performance in the complex application environment, which will reduce the insulation between battery pack and chassis, and will affect the performance of on-board equipment and electronic control unit, resulting in heat accumulation effect of leakage circuit and even vehicle fire. Therefore, it is critical to develop a real-time, accurate and reliable detection device to monitor the insulation resistance of the high-voltage system of electric vehicles, which is beneficial to the normal operation of electrical equipment, the safe operation of vehicles and the personal safety of passengers. In this work, an online estimation method of insulation resistance based on battery model is proposed.

1. Introduction

Electric vehicles are regarded as an effective way to solve energy and environmental problems, and have been strongly supported and promoted by various countries [1]. Unlike traditional fuel vehicle, batteries are the energy source of electric vehicles [2-3]. The battery system of electric vehicle has a high voltage characteristic with a range of 300-700V. Power battery packs are subjected to severe temperature, humidity, vibration, shock, corrosive gases and liquids as well as the reduced insulation performance. It has been reported that during the rapid acceleration process, the amplitude of the bus terminal voltage jitter changes very sharply, which directly affect the normal operation of the vehicle controller. Therefore it is required to be identified and eliminated promptly to avoid the traffic safety accidents [4].

With the constant upgrading of voltage specification, the requirements of insulation resistance between high-voltage electrical system and vehicle chassis also rises. The insulation performance of the electrical system will be reduced with the aging of cable insulation medium and the humid environment. Thus, it is necessary to detect the insulation resistance of battery system [5].

Various insulation resistance models of electric vehicle and detection methods have been
developed, including voltmeter method, current sensing method, balanced bridge method, and unbalanced bridge method [6]. These methods determine the insulation performance of the battery system with the bus current and voltage parameters. The voltmeter method is only suitable for off-line measurements, which requires to disconnect the battery pack from external electrical equipment. Therefore, it is complicated and can be implemented online.

The conventional sensor methods are to detect DC fault in system with current sensor [7]. The balanced bridge method is to construct a bridge composing of equivalent resistance on the positive and negative bus bars. This method has advantage of high accuracy, however, it cannot identify the branch fault and can only detect the asymmetry fault. The unbalanced bridge method is based on the principle of circuit voltage division. The insulation resistance value is obtained based on a function relationship between the resistance and the voltage. However, the voltage across the battery pack varies greatly, especially during transient acceleration and deceleration of the vehicle. There is a strong signal interference, which affects the calculation accuracy of the insulation resistance.

In this paper, the equivalent circuit of battery pack insulation model is provided, and the voltage and state of charge are also analyzed in the process of battery charging and discharging.

2. System modelling

High-precision battery model is the basis for establishing fault diagnosis methods. This section mainly introduces the insulation fault diagnosis model. Considering the complexity and accuracy of the model, the Thevenin equivalent circuit model is used as the battery model to characterize the dynamic performance of lithium-ion batteries. And the battery pack equivalent circuit model for insulation fault diagnosis is established with the battery model. The Thevenin model [6] is the most representative equivalent circuit model, which reflects the polarization resistance and polarization capacitance in the internal chemical reaction. The simulation of the dynamic and static characteristics of the battery, and its circuit structure is shown in Figure 1.

Where $U_{oc}$ represents the open circuit voltage of the battery, $R_r$ represents the ohmic resistance, $V_B$ represents the terminal voltage of the lithium battery, $R_p$ and $C_p$ are the polarized resistance and capacitance, respectively.

\[ E(t) = V(t) + i(t)R_r + V_{oc} \]  
\[ i = \frac{V}{R_r + C_p} \frac{dV}{dt} \]  

The difference equation of the model can be obtained by arranging the above equations using transformation and z transformation, as shown in the equation (3).

\[ E_k = V_{k-1} - a(V_{k-1} - E_{k-4}) + b \times i_k - c i_{k-1} \]  

If $\theta = \frac{R_1 + R_2}{R_1 R_2 C}$, then the coefficients $a$, $b$, $c$ can be described as follows.

\[ \begin{align*}
  a &= 1 - R_0 \left( 1 - e^{-\theta t} \right) \left( R_p + R_0 \right) \\
  b &= R_0 \\
  c &= R_0 e^{-\theta t}
\end{align*} \]  

If we define $y_k = E_k - V_k$, the corresponding difference equation can be expressed as follows.

\[ y_k = ay_{k-1} + bi_k + ci_{k-1} \]  

Constructing observation vectors and Parametric vector observation vectors $\varphi_k = \begin{bmatrix} y_{k-1}, i_k, i_{k-1} \end{bmatrix}^T$, Parametric vector $\theta_k = [a, b, c]^T$. The basic observation model can be described as follows.

\[ y_k = \varphi_k \theta_k \]
According to the relevant rules of the ampere-time integral method, the definition of battery charging state is described as follows.

\[ \text{SOC}(t) = \text{SOC}(t_0) - \frac{\eta}{Q_N} \int_{t_0}^{t} \text{Idt} \]  

(7)

Where \( \eta \) represents Coulomb efficiency coefficient, \( Q_N \) represents the rated capacity of the battery, I denotes the current, and \( \text{SOC}(t_0) \) is the state of charge at initial time.

Since the maximum leakage current occurs at the positive and negative electrodes of the battery pack, the positive and negative insulation resistances of the battery pack should be considered. The simplified model of the negative side insulation fault is shown in Figure 1 (b) and the battery pack voltage \( V_B \) can be defined as:

\[ V_B = \sum_{i=1}^{n} V_{oc,i} + i(t)R_{i,i} + V_i,oc \]  

(8)

3. On-board diagnosis of insulation fault

The equivalent circuit of battery pack insulation detection is shown in Figure 2. For the battery pack model, the pack voltage can be written as:

\[ V_{\text{pack}} = \sum_{i=1}^{n} (V_{oc,i} - iR_{oc,i} - V_{p,i}) \]  

(9)

where \( V_{\text{pack}} \) represents the pack voltage of the lithium-ion batteries, \( V_{oc,i} \) represents the cell open-circuit voltage of the \( i_{th} \) cell, \( R_{oc,i} \) represents the ohmic internal resistance of the \( i_{th} \) cell, \( i \) represents the current of the battery and \( V_{p,i} \) represents the polarization voltage of the \( i_{th} \) cell. To calculate the negative virtual insulation resistance, the following equations are obtained:

\[
\begin{align*}
(i_1 - i_3)(R_1 + R_2) &= V_p \\
(i_1R_1 + (i_3 - i_2)R_2 + (i_2 - i_1)(R_1 + R_2)) &= 0 \\
(i_2 - i_1)R_2 - V_p + i_2R_2 + V_s &= 0
\end{align*}
\]

(10)

Where \( i_2 = V_s/R_0 \). The negative virtual insulation resistance can therefore be calculated as:

\[ R = -\frac{R_2}{V_s}(V_p + V_s - \frac{R_3V_s}{R_2 + R_3} + \frac{R_1R_2}{R_1 + R_2}) \]  

(11)

Similarly, the positive virtual insulation resistance can also be written:

\[ R = -\frac{R_1}{V_s}(V_p + V_s - \frac{R_3V_s}{R_2 + R_3} + \frac{R_1R_2}{R_1 + R_2}) \]  

(12)

Figure 1 Equivalent circuit model  Figure 2. Battery pack insulation model  Figure 3. The topology of Battery pack

4. Experimental and discussion

This work intends to explore the dynamic response characteristics of battery pack, which consists of two batteries in parallel and twelve batteries in series, as shown in Figure 3. To further probe the dynamic characteristics of the battery during charging and discharging, the specific discharge curve of the battery is shown in Figure 4.

It can be observed from Figure 4 that the 12 batteries have the same current characteristics, however, the inconsistency of the internal resistance of the battery causes a certain deviation in the voltage. During the uniformly discharge experiment of the battery, the voltage difference is maintained at 0.015V when the state of charge is maintained between SOC 20%–90%. It indicates that the dynamic voltage has a great influence on the experimental results. When the battery voltage changes greatly, the estimation results of SOC will have a large estimation error, as shown in Figure 5.
5. Conclusions
In this paper, a novel method for insulation detection of lithium ion battery packs for electric vehicles based on thevin battery model is proposed to improve the insulation detection performance of electric vehicle battery system. In addition, a more reliable insulation detection scheme for battery system is developed.

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