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A real-time insulation detection method for battery packs used in electric vehicles

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HIGHLIGHTS

- The low frequency signal injection topology is applied for insulation detection.
- The Kalman filter is applied to improve the signal to noise ratio.
- The recursive least squares algorithm is applied to solve the result mutation.
- The robustness of the algorithm is verified by static and dynamic experiments.

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ABSTRACT

Due to the energy crisis and environmental pollution, electric vehicles have become more and more popular. Compared to traditional fuel vehicles, the electric vehicles are integrated with more high-voltage components, which have potential security risks of insulation. The insulation resistance between the chassis and the direct current bus of the battery pack is easily affected by factors such as temperature, humidity and vibration. In order to ensure the safe and reliable operation of the electric vehicles, it is necessary to detect the insulation resistance of the battery pack. This paper proposes an insulation detection scheme based on low-frequency signal injection method. Considering the insulation detector which can be easily affected by noises, the algorithm based on Kalman filter is proposed. Moreover, the battery pack is always in the states of charging and discharging during driving, which will lead to frequent changes in the voltage of the battery pack and affect the estimation accuracy of insulation detector. Therefore the recursive least squares algorithm is adopted to solve the problem that the detection results of insulation detector mutate with the voltage of the battery pack. The performance of the proposed method is verified by dynamic and static experiments.

1. Introduction

As green transportation, electric vehicles have been favored by people [1]. The power of electric vehicles comes from rechargeable batteries, which are environmentally friendly [2,3]. In recent years, reports of fire and explosion caused by batteries have been widely reported. The safety of batteries has aroused widespread concern. Three different polymer electrolytes have been proposed in Refs. [4–6], which effectively improves the safety performance of the battery. For the battery pack, there is also a problem of security. In general, the battery pack of the electric vehicle is composed of many single cells connected in series and parallel [7–9]. The insulation resistance is the most basic insulation index of the battery pack, which is defined as the equivalent resistance between the direct current (DC) bus of the battery pack and vehicle chassis. The insulation resistance is easily affected by temperature [10,11], humidity [12–14], air pressure [15], and other factors. In order to ensure the safety of the passengers and the operation of vehicles, it is necessary to detect the insulation resistance of the battery pack in real time. The national standard of China GB/T 18384.3–2015 [16] and the international standard BS ISO 6469–1–2009 [17] claim the electric vehicle insulation resistance should be greater than 100 V/Ω. Otherwise, it belongs to insulation fault.

The traditional methods of insulation detection can be divided into online and offline types [18]. The commonly used methods include voltmeter method [19], balance bridge method [20], bridge unbalance method [21], etc. The voltmeter method is only available for offline measurement which requires disconnecting the battery pack from the external electrical equipment during measurement. So this method is complex and can't be implemented online. The bridge balance method

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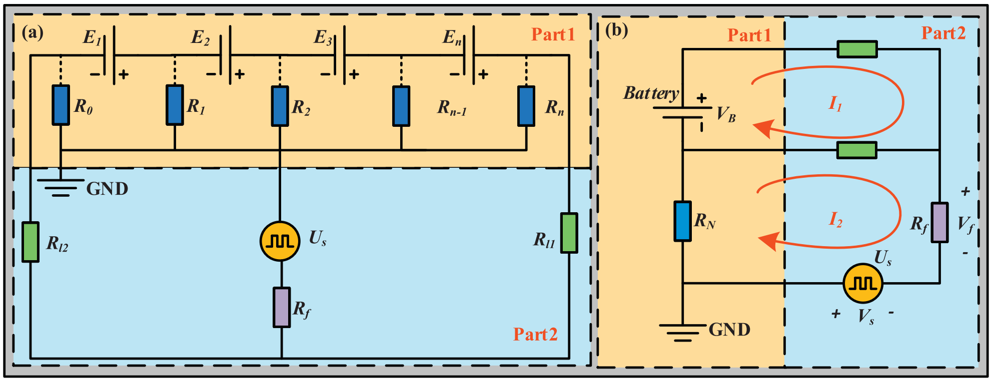

Fig. 1. Equivalent circuit of battery package insulation detection: (a) Circuit model. (b) Negative side insulation fault simplified model.

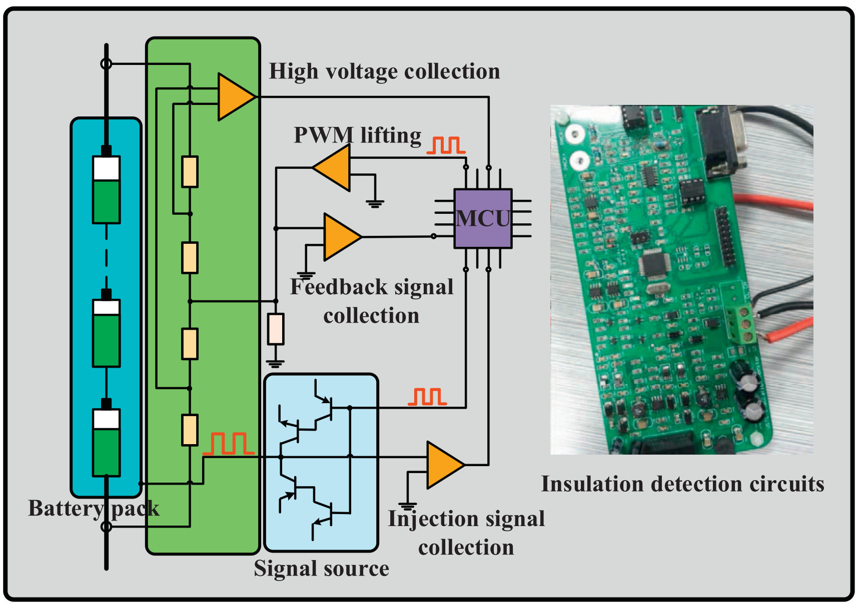

Fig. 2. The topology of the battery pack insulation detection.

Table 1
The implementation process of Kalman filter algorithm.

1. Initialization:

$$\begin{cases} \hat{X}_0 = [V_{s,0} \quad V_{f,0} \quad V_{B,0}]^T \\ P_{1,k=0} = \begin{bmatrix} P_{s,k=0} & & \\ & P_{f,k=0} & \\ & & P_{B,k=0} \end{bmatrix} \end{cases} \quad (6)$$

2. Update the predicted value $\hat{X}_k^-$ and covariance matrix $P_{1,k}^-$:

$$\begin{cases} \hat{X}_k^- = \hat{X}_k \\ P_{1,k}^- = P_{1,k-1} + Q_k \end{cases} \quad (7)$$

where Q_k represents the covariance of the system process.

3. Calculate the Kalman gain $K_{1,k}$ and the estimated value $\hat{X}_k$:

$$\begin{cases} K_{1,k} = P_{1,k}^-/(P_{1,k}^- + R_k) \\ \hat{X}_k = \hat{X}_k^- + K_{1,k}(y_k - \hat{X}_k^-) \end{cases} \quad (8)$$

where R_k represents the measurement covariance,
$y_k = [V_{s,k} \quad V_{f,k} \quad V_{B,k}]^T$ represents the signal measured at the kth.

4. Update covariance matrix $P_{1,k}$:

$$P_{1,k} = (I - K_{1,k})P_{1,k}^- \quad (9)$$

Table 2
The implementation process of RLS algorithm.

1. Initialization:

$$\begin{cases} \psi_{k|k=0} = V_{B,k|k=0}/2 - |V_{f,k|k=0}| \\ \theta_{k|k=0} = 2R_f/(2R_f + 2R_{k|k=0} + R_l) \\ P_{2,k=0} = \kappa_1 I \ (\kappa_1 = 1) \\ \lambda \in [0.9, 1] \end{cases} \quad (13)$$

2. Calculate algorithm gain $K_{2,k}$:

$$K_{2,k} = \frac{P_{2,k-1}\psi_k}{\lambda + \psi_k P_{2,k-1}\psi_k} \quad (14)$$

3. Calculate error covariance matrix $P_{2,k}$:

$$P_{2,k} = \frac{P_{2,k-1} - K_{2,k}\psi_k P_{2,k-1}}{\lambda} \quad (15)$$

4. Calculate the error e_k and update the parameter θ_k:

$$\begin{cases} e_k = y_{2,k} - \psi_k \theta_{k-1} \\ \theta_k = \theta_{k-1} + K_{2,k} e_k \end{cases} \quad (16)$$

5. Calculate insulation resistance R_k:

$$R_k = \frac{R_f}{\theta_k} - \left(R_f + \frac{R_l}{2}\right) \quad (17)$$

is a kind of static measurement method. It's not suitable for the case where the bilateral insulation resistances drop at the same time. It also easily leads to false alarms when the difference between positive and negative insulation resistance is too large. A novel detection method based on unbalance bridge is proposed in Ref. [22], which overcomes the shortcomings of the balanced bridge method. Even if the bilateral insulation resistances drop at the same time, this method can also accurately detect the insulation resistance. However, it is necessary to switch the measurement resistances in the process of measurement constantly, and the unilateral voltage needs a certain transition time to stabilize after switching. Moreover, its hardware is very complex. Due