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The improved interleaved voltage measurement method for series connected battery packs

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HIGHLIGHTS

- A concise derivation of valid basic interleaved measurement topology is provided.
- An improved topology without the constraint in invertibility is proposed.
- The noise level gain of the interleaved topology is mathematically formulated.
- The improved topology has a lower noise level than the basic interleaved topology.

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ABSTRACT

This paper proposes an improved interleaved voltage measurement method for battery packs in electric vehicles, which can distinguish between the sensor fault and cell fault without hardware or software redundancy. The coprime constraint in the basic interleaved measurement method is revisited with a new proof, and a graphical interpretation is introduced to visualize the constraint. Based on that, an improved measurement topology is developed to remove the coprime constraint which enables broader application. Moreover, the hardware implementation of the improved method is discussed based on cost and circuit design. The associated improvement in noise performance is mathematically formulated, and the noise limit and trend of the interleaved measurement method are derived. Simulation results match the noise analysis and experiments validate the broader application of the improved method.

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1. Introduction

Vehicle electrification has been identified to be an effective approach to coping with energy crisis and greenhouse effect. The electrification promotes electric vehicles and hybrid electric vehicles to achieve better overall powertrain efficiency and to reduce emissions [1]. The energy storage system is an essential component in the electrified vehicles, and the majority of the systems nowadays utilizes lithium-ion batteries, which possess high energy/power density and long service life [2]. The high energy/power property of the lithium-ion batteries improves the vehicle performance and extends the travel range, nevertheless, the appealing properties may result into unexpected severe fire hazards when the batteries are not treated properly [3–6].

To ensure safe operation in electrified vehicles, the battery management system (BMS) is incorporated into the lithium-ion battery systems [7]. The BMS monitors the voltage, current and temperature values of battery cells, estimates the states of the batteries, and actively maintains their safe operation conditions by fault detection and mitigation strategies [8–10]. Previous research has investigated that, among all the three measurements, the voltage is the most crucial for battery safety because of the prompt response and high sensitivity to major electric faults, including over charge, over discharge, external short circuit and internal short circuit [11,12]. Therefore, a reliable voltage measurement system is critical to identify the safety status of the lithium-ion battery packs.

The conventional voltage sensing system measures the voltage of each battery cell with one voltage sensor for each battery cell. The one-to-one correspondence guarantees that the voltage for

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every cell is monitored. Unfortunately, this voltage measurement approach is not fault-tolerant. In other words, the one-to-one mapping cannot distinguish between sensor malfunction and cell failure, when an abnormal reading is observed. However, the cost of the corresponding mitigation actions varies significantly. The sensor failure is a low level fault, and the electric vehicle can be switched to the "limp home" mode for future maintenance, whereas the short circuit failure on a cell is a high level fault, which requires immediate power interruption for protection purposes.

Therefore, a sensor fault detection and isolation approach is necessary to enhance the reliability of voltage measurement in the battery packs. In general, the fault detection and isolation approaches utilize the concept of redundancy, which can be grouped into hardware redundancy and analytical redundancy [13], as illustrated in Fig. 1. The hardware redundancy compares the output signals of duplicative sensors to a same measurement. Usually, in order to determine the root cause of the fault, it requires at least two additional sensors to implement the majority vote algorithm. The inherent drawbacks of the hardware redundancy are that, 1) the system cost, size and complexity are increased; 2) the overall system reliability is lowered due to additional components [14]. The analytical redundancy saves the extra hardware expenses at the cost of the increase in computational burden. First, battery models in different working conditions, including normal and various fault modes, are required to be constructed and identified beforehand. Then the voltage outputs in different scenarios are estimated based on the current input. Finally, the sensor output is compared with model outputs to identify the fault [15–18]. However, the disadvantages of the software redundancy lie in that: 1) abundant preliminary work is required to build accurate battery models [19]; 2) the robustness of the models cannot be guaranteed given the complex nonlinear behavior of batteries and disturbances in real applications; 2) when a fault is flagged, it can result from a sensor fault or a mismatched model.

Given the limitation of the redundancy based sensor fault detection methods, the authors proposed a fault-tolerant voltage measurement method for series connected battery packs, which does not require additional sensors or any effort in modeling [20]. For n battery cells connecting in series, the proposed method requires n voltage sensors. More importantly, each voltage sensor measures the voltage sum of k battery cells ($2 \leq k < n$) in an interleaved manner. In this way, each cell voltage is coupled with multiple voltage sensors. If any cell is in fault condition, the abrupt change in cell voltage will be captured by multiple voltage sensors. For example, the embodiment of $k = 2$ is illustrated in Fig. 2(b). C2 is coupled with both V1 and V2. If C2 is decreased suddenly because of a fault occurrence, then a decrease with same amount should be observed in both V1 and V2. Since it is less possible for two voltage sensors to be in the same fault condition at the same time, a cell fault can be determined. Similarly, one sensor reading is also linked with multiple cell voltages in the inverse calculation. When a sensor fault occurs, the voltage of multiple cells will change abnormally in a specific pattern, and the sensor fault can be determined. Except the fault detection and isolation, the previous work also 1) discussed the feasibility of the method in real implementation; 2) demonstrated the associated noise level increase; 3) analyzed the effect of k on the confidence level of cell/sensor fault detection and 4) derived that n and k should be coprime such that the measurement matrix is invertible, or the cell voltage can be calculated from the sensor readings, i.e., the sensor topology is valid. More detailed analysis and comparison with the existing measurement methods can be found in Ref. [20].

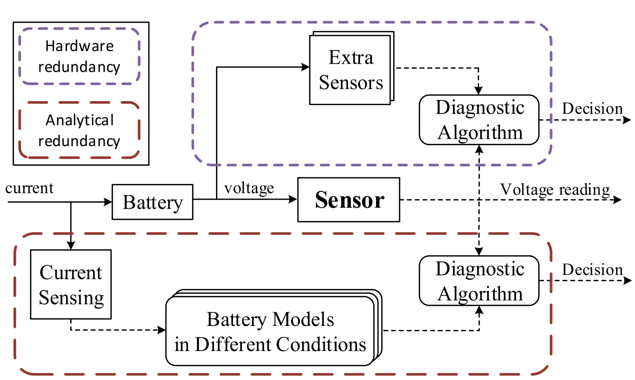

Fig. 1. Illustration of redundancy based fault detection and isolation.

This manuscript is an extension of the previously proposed interleaved voltage measurement method. The contributions of this paper are: 1) a more concise derivation for the condition of valid sensor topology is provided; 2) based on the new derivation, an improved sensor topology is proposed which is not constrained by the coprime relation of n and k; 3) the associated noise level increase is mathematically formulated and the limit of the noise level is derived; (4) the improved sensor topology is proved to have a lower noise level than that of the previous work.

The paper first briefly introduces the key properties of the interleaved voltage measurement method. Then, a new proof for the condition of valid sensor topology is derived with the concept of the circulant matrix. A graphical interpretation is introduced to visualize the relation of n and k on the invertibility of the measurement matrix, based on which an improved sensor topology is developed. Next, the hardware implementation is discussed for the newly proposed sensor topology. After that, the noise level increase is mathematically formulated. The lower limit of the noise level is found, and the improved sensor topology is proved to have a lower noise level than that of the previously proposed topology. Finally, simulation results confirm the noise analysis and experiment results validate the feasibility of the improved interleaved measurement method.

2. Brief review of the previous work

Mathematically, the voltages of n battery cells in series connection are correlated with the voltage readings from n voltage sensors by (1).

$$\mathbf{V} = \mathbf{AC} \tag{1}$$

where $\mathbf{V}$ is an $n \times 1$ matrix that includes the voltage sensor readings, $\mathbf{C}$ is an $n \times 1$ matrix that includes the cell voltages, and $\mathbf{A}$ is an $n \times n$ matrix that characterizes the sensor topology. Conversely, cell voltage values can be calculated from the voltage sensor readings by

$$\mathbf{C} = \mathbf{A}^{-1}\mathbf{V} = \mathbf{BV} \tag{2}$$

where $\mathbf{B}$ is the inverse of the $\mathbf{A}$ matrix.

The conventional voltage sensor topology is illustrated in Fig. 2(a), whose $\mathbf{A}$ and $\mathbf{B}$ matrices are given in (3) and (4), respectively.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & & \vdots \\ 0 & 0 & 1 & \ddots & \vdots \\ \vdots & & \ddots & \ddots & 0 \\ 0 & \cdots & \cdots & 0 & 1 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{bmatrix} \tag{3}$$