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A fault-tolerant voltage measurement method for series connected battery packs

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HIGHLIGHTS

- Developed a fault-tolerant voltage measurement method for series battery packs.
- Developed matrix interpretation to demonstrate the viability of the method.
- Developed methods to determine and isolate sensor or cell faults by location.
- Validated the condition for valid sensor topology with proof.
- Modeled and analyzed diagnostic confidence, cost and measurement accuracy.

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ABSTRACT

This paper proposes a fault-tolerant voltage measurement method for battery management systems. Instead of measuring the voltage of individual cells, the proposed method measures the voltage sum of multiple battery cells without additional voltage sensors. A matrix interpretation is developed to demonstrate the viability of the proposed sensor topology to distinguish between sensor faults and cell faults. A methodology is introduced to isolate sensor and cell faults by locating abnormal signals. A measurement electronic circuit is proposed to implement the design concept. Simulation and experiment results support the mathematical analysis and validate the feasibility and robustness of the proposed method. In addition, the measurement problem is generalized and the condition for valid sensor topology is discovered. The tuning of design parameters are analyzed based on fault detection reliability and noise levels.

1. Introduction

Lithium ion batteries are widely applied in electric vehicle applications due to their considerable improvements in energy density and power density [1,2]. However, this technology still demands many compromises be made in system level, among which safety is the primary concern [3]. Multiple violent incidents reported all over the world hinder the fast growth of lithium battery in the market place [4–6]. These incidents originates from various causes, but they all result in the worst scenario in which thermal runaway is triggered. Thermal runaway has been identified as a catastrophic failure of lithium battery systems and is typically induced by internal or external physical damage of the cell [7]. The initial temperature-rise from a failure cell triggers the exothermic chemical reaction that propagates the temperature-rise among battery packs and eventually lead to fire [8]. According to the post-accident reports, most of the incidents can be avoided or at least mitigated with proper and reliable management [4], which is also believed to be the key to the comprehensive development of lithium ion battery technology [9].

The management of onboard lithium ion batteries gives rise to battery management systems (BMS) [9,10]. The most fundamental task for a BMS is to ensure the safe working condition of batteries by monitoring voltage, current and temperature values [11]. Among all these measurements, research shows that voltage is the most critical information because of its high sensitivity to common electrical faults: including short circuits, over charge and over discharge [12,13]. Thus, it is necessary to enhance the safety level of electric vehicles with reliable and fault-tolerant voltage measurement.

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Today's widely applied voltage measurement method uses individual voltage sensors, or measurement integrated circuits (ICs), to measure the voltage values of individual cells [14]. This one-to-one correspondence ensures that the voltage of every single cell is monitored. To measure the voltages of a series string of batteries, instead of using one voltage measurement circuit for each of the cells, switches are typically applied to reduce cost in measurement circuits and analog to digital converters (ADC), [15–17]. The switches are turned on with pairs, such that the cell voltages in a string is updated one at a time sequentially. When any voltage reading shows abnormal values, the battery system will be stopped for protection purposes and mitigation methods will be employed.

It needs to be pointed out that sensors have their own reliability; in other words, a voltage sensor in fault condition may lead to a false positive cell fault detection, however, the mitigation methods for these two types of faults differ significantly. In the case of cell faults, some immediate, costly or even dangerous mitigation methods should be taken, including cutting the power from battery pack in the middle of drives and informing the fire department; while in the case of sensor faults, more moderate mitigation methods can be applied, such as switching the vehicle into limp home mode and pushing a request for battery pack maintenance. Thus, it is critical to distinguish between sensor faults and cell faults in order to apply proper mitigation and ensure reliable operation of electric vehicles.

Abundant researches have been conducted to investigate the methods to detect and isolate sensor faults. The most widely applied method is hardware redundancy, where measurements of the same signal are given by multiple sensors [18]. Clearly, this sensor fault detection feature is equipped at the cost of additional hardware expense and more complex system which may be more prone to failure. Analytical redundancy is then proposed as opposed to hardware redundancy, which utilize the output from mathematical models of the system and compare the output with sensor measurements [19]. This method does not require additional hardware, however, it is complex to maintain the robustness of the model given uncertainties, disturbances and various failure modes of the system [20].

Given the inherent disadvantages of the redundancy-based sensor fault diagnostic methods, this paper introduces a fault-tolerant voltage measurement method that can distinguish between a sensor fault and a battery cell fault without any additional sensors. Instead of measuring the voltage values of individual cells, the voltage sensors are used to measure the voltage sum of multiple cells. In this way, a cell voltage value is linked with multiple voltage sensors. When a cell fault occurs, its corresponding voltage sensors will indicate the fault at the same time, thereby identifying the fault.

This paper first provides analysis to sensors with simultaneous measurement. Matrix analysis is used demonstrate the validity of the new measurement topology. Simulation and experiment results prove that the proposed concept can isolate the type and location of a fault robustly.

Then, the proposed method is generalized, which shows the prevailing sensor topology is a special case of this generalization. The reliability prediction analysis is performed to demonstrate the capability of reducing false positive detections. The probability theory is applied to characterize the noise level increase associated with this method.

Next, the impact of sequential measurement to the proposed method is discussed and a procedure is provided to convert sequential measurement to simultaneous measurement in realization. The condition for a valid measurement topology is presented with mathematical proof.

Finally, the tradeoff among different combinations of design parameters are analyzed and discussed in detail.

2. A fault-tolerant design

The drawback of the prevailing voltage measurement method lies in its one-to-one correspondence of voltage sensors and cell voltages, as shown in Fig. 1(a). In real applications, the voltage sensors have their own reliability, and thus a sensor fault may lead to a false positive cell failure detection.

In many industry applications, a second sensor is added to each measurement to provide the redundancy. The data from the second group of sensors will provide validation of the measurement of the first group. Fig. 1(b) shows its embodiment if applied to voltage monitoring for series connected battery packs. The sensors can tell the cell fault in case both sensors give consistent outputs. When the two sensors corresponding to the same cell have different readings, we normally treat it as a sensor fault. However, this method adds significant cost to the system. In particular, the battery packs in electric vehicles consists of hundreds of cells in series. Therefore, the redundancy sensors can add significant cost to the hardware system.

One common solution to this problem is to add a sensor redundancy within a group of measurements, as shown in Fig. 1(c), in which a string voltage sensor is added in addition to the five voltage sensors for the cells. This method improves cell failure detection, but it still cannot distinguish between sensor failure and cell failure when the sensors show inconsistent readings. For example, if the nominal voltage of the five cells in Fig. 1(c) is 3 V, V_1 shows 0 V, V_2 through V_5 show 3 V and V_6 shows 15 V, the fault diagnostic result is different depending on which voltage sensor is trusted. When V_1 is trusted, it indicates C_1 is in external short circuit condition and V_6 is stuck at 15 V due to circuit failure. When V_6 is trusted, it indicates that V_1 is in sensor fault condition and C_1 is in normal condition.

Another voltage measurement topology is illustrated in Fig. 1(d). This topology measures an accurate reference voltage from an IC as the last measurement in one sampling period, which can be used to calibrate sensor offset and detect sensor fault. However, this method requires a precision voltage reference IC for each of the voltage measurement circuit, and it increases the voltage update period by one clock cycle. Except that, this method will always attribute switch/trace malfunction to cell fault.

2.1. Design description

Fig. 1(e) illustrates one embodiment of the proposed fault-tolerant voltage measurement method. In this topology, each voltage sensor measures the voltage sum of two cells, including V_5, which measures the voltage sum of C_1 and C_5. The schematic in Fig. 1(e) ensures that the voltage of each cell is associated with the measurements of two sensors. For example, the voltage value of C_2 is included in the measurements of V_1 and V_2. When C_2 is in external short circuit condition, its terminal voltage drops to zero, and its abnormal voltage value will be revealed by V_1 and V_2 as they both drop from 6 V to 3 V. On the other hand, when a sensor fault occurs, it can be identified immediately in that it is impossible for only one of the sensed voltage values to change. For example, if V_1 through V_5 show 6 V, and suddenly only V_2 changes from 6 V to 0 V, V_2 is certainly in fault condition, otherwise the voltage values of C_1 and C_4 will be 6 V, and C_5's will be 0 V. The latter condition involves the same overcharge level on C_1 and C_4 and an external circuit fault on C_5, which are almost impossible to occur at the same time.

2.2. Matrix interpretation of measurement topologies

The relation between sensor measurements **V** and cell voltage values **C** can be expressed as: