Letters

Case Study of an Electric Vehicle Battery Thermal Runaway and Online Internal Short-Circuit Detection

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***Abstract*—A thermal runaway happened in a battery cell of an electric vehicle during driving, and the fire spreads to other batteries in a few minutes. Based on the recorded battery operation data, this letter analyzes the battery thermal runaway process, and identifies the critical time points of fault signals like cell voltages and temperatures, etc., which depict the start and spread of thermal runaway in the battery pack. By tracing back the clues, it is concluded that the cause of the fire is battery internal short circuit (ISC), and battery overcharge is a potential cause of ISC. Then, three different patterns of battery cell voltage abnormalities are compared, including battery external short circuit, ISC, and poor-signal wire connection. A cell voltage difference-based method is proposed to diagnose ISC online, which is simple and reliable to implement in engineering.**

***Index Terms*—Electric vehicles (EVs), fire accident, internal short circuit (ISC), lithium-ion battery, thermal runaway (TR).**

I. Introduction

IN THE past decade, electric vehicles (EVs) have become a new direction of the automobile industry. Lithium-ion batteries are the primary power sources of EVs owing to their excellent performances in high energy density and long cycle life. With the development of battery technology, the driving range of EVs is increasing whereas the price of EVs is decreasing. However, with the increasing number of EV fire accidents, battery safety is still one of the major concerns, which hinders the widespread of EVs.

EV fire accidents are mostly caused by internal short-circuit (ISC) induced battery thermal runaway (TR). Feng *et al.* [1] and Wang *et al.* [2] summarize the mechanism and causes of TR. Battery manufacturing defects and battery abuse conditions like mechanical abuse, electrical abuse, and thermal abuse are common reasons of battery ISC and TR. Experiments including indentation [3], nail penetration [4], and overheating [5] were conducted to investigate the mechanism of ISC. TR propagation is also studied in [6].

The battery management system (BMS) should be able to detect ISC as early as possible based on the measured current, voltage, and temperature signals. A voltage curve correlation-based method is proposed in [7], and an electrochemical–thermal–ISC-coupled model is proposed in [8] to detect ISC.

To solve TR problems for EVs, it is necessary to investigate real EV TR accidents. However, most research works are based on the laboratory TR test. Comprehensive data analyses of real EV TR are very rare. Without a good understanding of real EV TR and its propagation as well as BMS signals, it would be difficult to develop a feasible theory to detect TR and guide the BMS design.

This letter elaborates the process of an EV TR accident, the TR propagation as well as fault voltage and temperature signals are illustrated. The voltage drops of self-induced ISC and overheating induced ISC are captured, and a unique voltage drop pattern is summarized, based on which a voltage-difference-based method is proposed to detect ISC online. This approach can detect ISC in the early stage, it can also avoid false alarms by distinguishing different voltage failure modes, and it is also easy to implement in the BMS software.

II. EV TR Process

A. TR Accident Description

The EV is a compact car with a battery pack of 150-Ah nominal capacity and 354-V nominal voltage, which can store 53 kWh of electricity. The battery material is lithium-nickel-manganese-cobalt oxide (LiNMC). The battery pack is composed of 17 submodules with 97 battery cells connected in series, and each submodule is equipped with two temperature sensors.

Fig. 1 shows the vehicle operation data of the day when TR happened. The vehicle started to operate from about 8:00 A.M. and operated normally during the day until TR occurred at 20:07:13 P.M. The battery temperatures were

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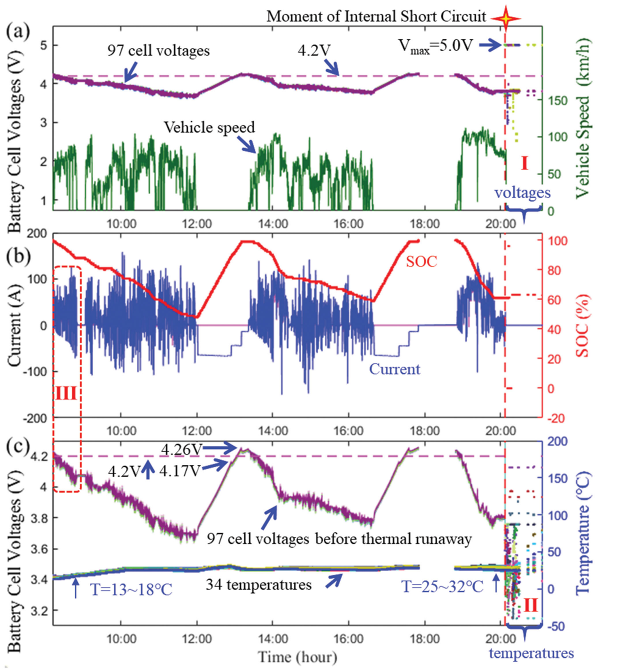

Fig. 1. EV operation data of the day. (a) Cell voltages and vehicle speed. (b) Current and state-of-charge (SOC). (c) Cell voltages and temperatures.

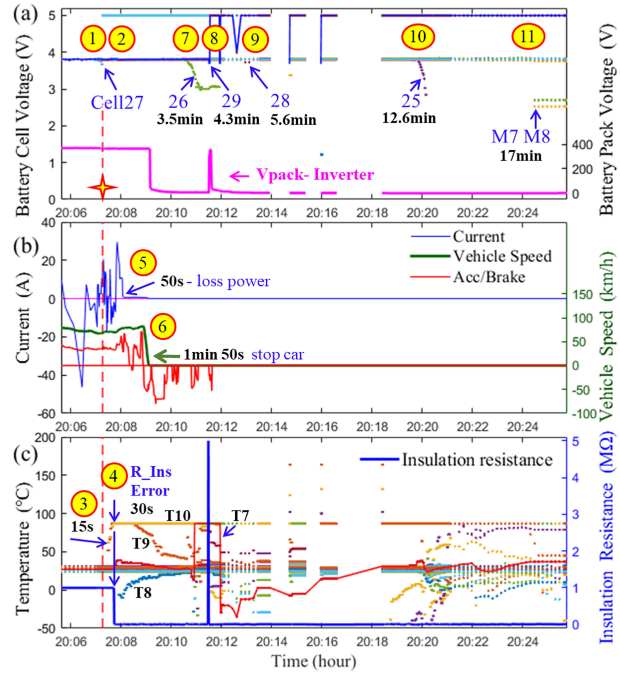

Fig. 2. Battery TR and its propagation. (a) Battery cell voltages and battery pack voltage. (b) Current and vehicle speed. (c) Temperatures and insulation resistance.

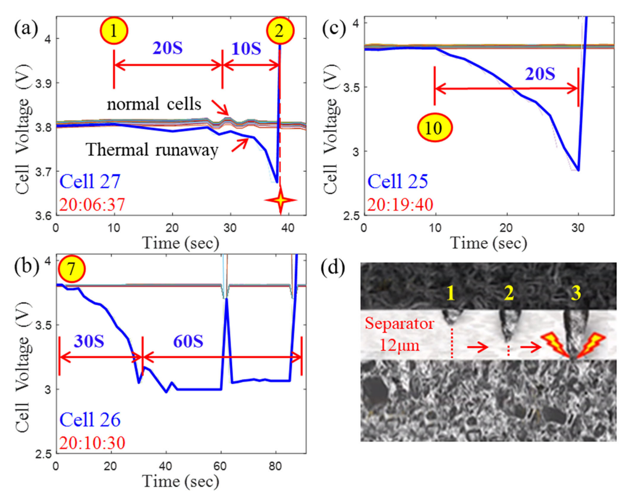

Fig. 3. Voltage drop of battery TR. (a) TR of battery cell 27. (b) TR of battery cell 26. (c) TR of battery cell 25. (d) Separator pierce process of cell 27.

between 13 °C and 32 °C, and the maximum charging/discharging currents were below 1 C-rate. The vehicle was driven more than 400 km during the day. The odometer reading was about 10 000 km, which suggests the vehicle was fairly new.

After TR started at 20:07:13 P.M., many signals began to show fault readings, as depicted in regions I and II of Fig. 1. A zoomed-in figure after TR is shown in Fig. 2. The battery cell voltages scattered between 2 and 5 V. Some batteries experienced continuous voltage drop, including cell 27, 26, and 25, as illustrated in Fig. 3(a)–(c).

Due to the BMS setting, the measured battery voltages out of normal range (i.e., 2.8–4.3 V) were recorded as 5 V to indicate error state. Therefore, in Fig. 3, the voltage readings jumped to 5 V during the voltage drop process, although in fact the voltages were still dropping.

Temperatures in Fig. 2(c) scattered between −40 and 85 °C, which is the limit of temperature readings in the BMS. Negative temperature coefficient (NTC) sensors are usually used to measure temperatures. High sensor resistance indicates low temperature. When the NTC signal wires got burned in the fire during the accident, the resistance of the signal wires would increase dramatically, thus inducing low-temperature readings in the BMS. After the fire went out, temperature readings would recover gradually. Therefore, subzero temperature readings can be used as evidences of fire in the battery pack.

Fig. 4 shows the battery cell voltage and temperature fault signals propagation in the battery pack. The gaps in the signals suggest that the BMS was waken up nine times after TR.

B. Time Steps of TR and Its Propagation

A series of critical events happened in the TR accident, 12 time points are identified and labeled in Figs. 2–4 to depict the time axis. Time step 2 is the moment TR occurred in battery cell 27, it is considered as zero-time reference to other time steps.

Step 1: 20:06:47 (−26 s before TR): Fig. 3(a) shows that the voltage of battery cell 27 (V27) started to diverge from other batteries gradually, which indicates ISC began to develop inside battery cell 27.

Step 2: 20:07:13 (0 s—the moment of TR): V27 started to plunge quickly, suggesting a violent TR happened. The BMS should have already detected the cell voltage abnormality.

A possible theory of the TR is that a lithium dendrite or burr was growing on the surface of anode or cathode, and finally it pierced through the separator after hundreds of charging cycles and caused micro short circuit, as illustrated in Fig. 3(d). Heat

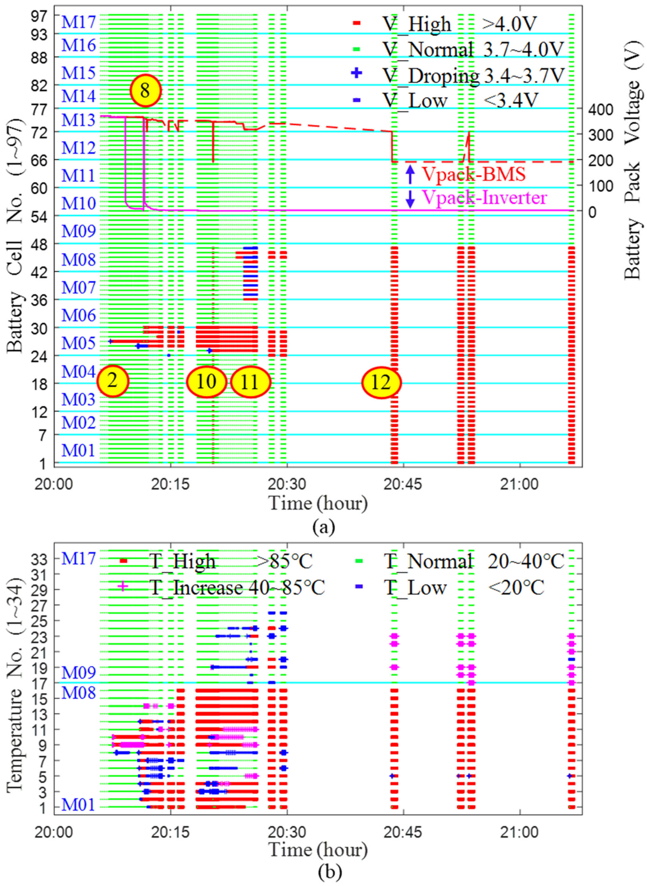

Fig. 4. Battery cell voltage and temperature fault signals propagation map. (a) Battery cell voltage error propagation (b) Temperature error Propagation.

and gas generated in the process aggravated the short circuit, and 26 s later, a violent TR occurred.

Step 3: 20:07:28 (15 s): Temperatures 9 (T9) and 10 (T10) of submodule 05 (M05) rose to above 60 °C. Both the high temperatures and their rising rate should have triggered the warning in the BMS.

Step 4: 20:07:43 (30 s): T9 and T10 rose to above 85 °C, whereas T8 dropped to subzero. The insulation resistance ($R_{\_\mathrm{Ins}}$) dropped from 1 MΩ to zero, which means there was a high-voltage leakage to the vehicle chassis. The clues indicate that the flame had burst out of submodule 5. Then, in the next 3 min, T8 and T9 recovered toward normal temperature gradually, indicating the flame of battery cell 27 went out gradually.

With the voltage error, temperature errors and $R_{\_\mathrm{Ins}}$ error, the BMS should have already detected TR at this moment and given the driver the highest level warning to escape.

Step 5: 20:08:03 (50 s): The electric motor stopped to provide power, although the dc bus voltage of the inverter was still normal.

Step 6: 20:09:03 (1 min 50 s): The vehicle speed was about 61 km/h, then the driver stopped the car, and the dc bus voltage of the inverter was disconnected. However, the Acc/Brake pedal signal in Fig. 2(b) shows that the driver did not evacuate immediately but tried to restart the vehicle 2 min later on Step 8.

Step 7: 20:10:52 (3.5 min): TR started in battery cell 26 due to overheat, as depicted in Fig. 3(b). V26 dropped from 3.8 to 3.0 V in 30 s, then sustained for 60 s before it dropped out of the normal range. This is because the separator holes were closed under 140–170 °C [1]; thus, the TR was stopped temporarily, then with a totally melt down of the separator, a violent TR happened again [7].

Step 8: 20:11:32 (4.3 min): The driver tried to restart the vehicle, and simultaneously V29 jumped to 5 V.

Step 9: 20:13:07 (5.6 min): V28 jumped to 5 V. However, because there was no voltage drop process recorded on V29 and V28, so it is not clear whether the cause was TR or signal wire failure.

Step 10: 20:19:53 (12.6 min): TR occurred in battery cell 25, as depicted in Fig. 3(c). Then, the explosion caused the battery measurement unit (BMU) to restart, thus V1–V47 signals were offline for a few seconds, as shown in Fig. 4(a).

Step 11: 20:23:09 (17 min): Battery voltage signal errors of V36–V47 (M07 and M08) were detected. But the pattern seems like signal wire or BMS failure but not a TR.

Step 12: 20:43:29 (37 min) to 21:06:00 (1 h): In M01–M08, all signals (V1–V47 and T1–T14) were offline. This suggests the BMU was damaged in the fire. It is not clear whether TR spread to other submodules besides M05. In M09–M17, all battery cell voltages were normal, suggesting TR was not spread to these submodules. However, there were still high temperatures detected in M09–M11.

In summary, after TR occurred in battery cell 27, the BMS could detect TR in 30 s based on the fault signals. Then, the power was lost in 20 s. TR spread to adjacent battery cell 26 and 25 after 3.5 min and 12.6 min, respectively. Although high temperatures were detected in M01–M08, TR was confined inside M05 in the first 17 min, thus providing enough time for the driver to escape.

TABLE I
CHARGING INFORMATION OF THE EV

Stage	Current (A)	Time (min)	Charged capacity (Ah)	Start/ End SOC (%)	dSOC (%)	Extra energy (kWh)
1	65.0	49.2	53.3	59/ 89	30	
2	44.7	16.0	11.9	89/ 98	9	4.9
3	13.5	14.5	3.3	98/100	2	1.3

C. Battery Overcharge Issue

According to the previous analysis, this EV did not have mechanical abuse, thermal abuse, or battery aging issues. Thus, manufacturing defect and overcharge issue are the most likely causes of the ISC of battery cell 27.

Fig. 1(c) shows that each charging process consists of three stages: 65 A charging to 4.17 V, then 44.7 A, and 13.5 A charging to 4.26 V, respectively. For most LiNMC traction batteries, the charging cutoff voltage is set to 4.2 V, and many OEMs are trying to avoid fully charging the batteries to ensure safety and prolong battery cycle life. However, the OEM of this EV is trying to overcharge the batteries to achieve a longer driving range. According to Table I, approximately 10% more energy (6 kWh) was charged to the batteries in stages 2 and 3, which could extend the EV driving range by 44 km (13.5 kWh/100 km). Area III in Fig. 1(b) also shows that this EV allows braking energy recovery

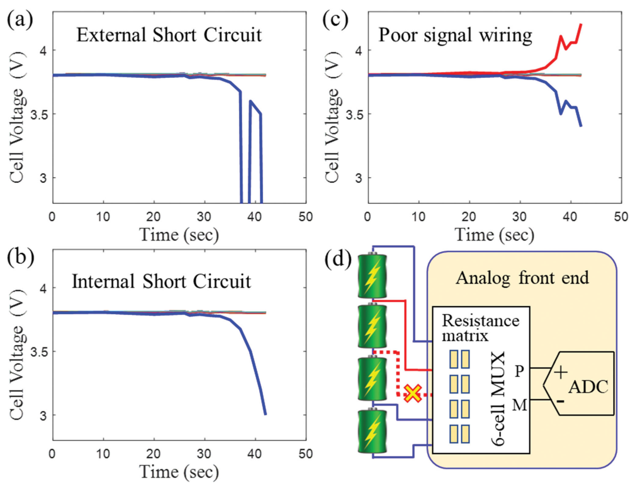

Fig. 5. Different patterns of battery cell voltage fault signals. (a) Battery external short circuit. (b) Battery ISC. (c) Poor voltage signal wire connection. (d) Voltage measurement and poor signal wiring.

from 100% state-of-charge (SOC), which should be prohibited above 95% SOC.

Although we cannot draw a concrete conclusion that overcharge is the cause of this TR accident, it is still highly recommended not to overcharge the batteries.

III. Identification of Battery ISC

Fig. 5 compares three different battery voltage fault signal patterns. When an external short circuit occurs, the battery voltage would drop dramatically to nearly zero, and may jump back and forth. In the case of ISC, there would be a continuous voltage drop process. Poor voltage signal wiring is usually caused by a loose connector. In this case, usually the two adjacent voltage readings would diverge to opposite directions, because the poor contacted voltage signal is floating while the upper voltage channel loses ground reference, as depicted in Fig. 5(c) and (d). Therefore, the continuous voltage drop is a unique feature of battery ISC, and this feature can be used to detect ISC online.

In the BMS, the maximum battery cell voltage difference $\Delta V_{\max}$ is continuously monitored

$$\Delta V_{\max} = V_{\max} - V_{\min} \quad (1)$$

where $V_{\max}$ and $V_{\min}$ are the maximum and minimum battery cell voltages, respectively. The derivative of $\Delta V_{\max}$ is

$$\Delta V'_{\mathbf{max}} = \frac{d\Delta V_{\max}}{dt} = \frac{\Delta V_{\max\_N+1} - \Delta V_{\max\_N}}{\Delta t} \quad (2)$$

where Δt is the fixed time step interval, and N is the time step. Under normal conditions $\Delta V'_{\max}$ should be around zero. When battery ISC occurs, $\Delta V_{\max}$ would continue to increase, and its derivative $\Delta V'_{\max}$ will fall into a positive range. Table II lists the $\Delta V'_{\max}$ signals of the battery pack when ISC occurred in battery cells 27, 26, and 25. It is clear that in the battery voltage drop processes, $\Delta V'_{\max}$stayed in the range of 5–150 mV/s.

Based on the analysis, in the BMS software, a 10-s time window could be established to monitor the latest $\Delta V'_{\max}$ value. If the signal is detected to be continuously in the range of 5–150 mV/s for more than 8 s, and if the possibility of signal wiring failure could be ruled out, then the BMS could confirm that a battery ISC occurred.

TABLE II
Signal Window to Detect Battery ISC

Cell27		Cell26		Cell25	
Time (s)	$\Delta V'_{\max}$ (mV/s)	Time (s)	$\Delta V'_{\max}$ (mV/s)	Time (s)	$\Delta V'_{\max}$ (mV/s)
0.0	0.00	16.0	4.5	10.0	0.0
20.0	0.60	18.0	17.5	12.0	25.5
27.0	0.14	20.0	31.5	14.0	15.0
29.0	2.00	22.0	37.0	16.0	28.5
31.0	-0.50	24.0	20.5	18.0	31.0
33.0	5.50	26.0	26.5	20.0	39.0
35.0	12.50	28.0	61.5	22.0	43.5
37.0	36.00	30.0	109.5	24.0	25.5
39.0	42.00	32.0	-60.0	26.0	52.5
41.0	533.00	34.0	10.5	28.0	126.5

In this approach, ISC could be identified even before a high temperature is detected. Thus, the warning could be advanced by at least 15 s, i.e., from Step 3 to Step 2 in Fig. 2. False alarms could also be avoided by considering different voltage failure modes. The simplicity and reliability of the method make it promising for engineering applications.

IV. Conclusion

This letter shows the process of an EV TR accident and analyzes from the perspective of BMS design, aiming to provide valuable reference and inspiration for future TR research and engineering development. Twelve steps are used to depict the TR and its propagation. ISC is identified to be the cause of TR. The overcharge issue is analyzed, and it is found that approximately 10% more energy was charged to the batteries in the charging process. An ISC detection method is proposed according to the unique voltage drop pattern. It can detect ISC in the early stage and avoid false alarms. The proposed detection method is also easy to implement in the BMS software.

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