Research and Development of Fire Alarm Detection Device for Lithium Ion Battery Based on Strain Measurement

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Abstract. In order to realize the fire alarm of lithium ion battery, a fire alarm detection device is developed based on the principle of strain measurement. This paper makes a study of the detection principle and application circuit. Firstly, according to characteristic rule of thermal runaway process of lithium ion battery, the correlation between battery deformation, temperature and released gas is analyzed and a battery fire warning method based on strain measurement is proposed. Then, the strain measuring circuit is designed and circuit working principle is analyzed. In the end, the application effect of the battery fire warning method based on strain measurement is verified through thermal runaway experiment of lithium ion battery. The experimental results show that the method based on strain measurement can identify fire risks at the early stage when the lithium ion battery thermal is out of control, preventing fire from spreading. Basically it can meet the needs of lithium-ion battery fire warning.

1. Introduction
Lithium ion battery has become the main power source of new energy vehicles due to its excellent performance, such as high energy density, no memory effect and long life cycle[1-2]. However, higher energy means less thermal stability. It may lead to fire and explosion because of mechanical damage, short circuit, overcharge and other factors or some extreme abuse conditions. From a certain point of view, safety accidents, such as fire and explosion caused by overcharge, collision or short circuit, can be attributed to the problem of thermal runaway-- the phenomenon of uncontrollable temperature increase caused by exothermic reaction in the battery [3].

To solve the thermal runaway problem and improve the safety performance of lithium ion battery are key problems for further promotion and application of lithium ion battery in the field of new energy [4]. According to the characteristics of releasing gas and increasing ambient temperature when lithium ion battery heat is out of control, domestic experts put forward the composite detection technology of carbon monoxide and temperature, developing a composite fire detection device of carbon monoxide and temperature.

In this paper, thermal runaway characteristics of lithium ion battery are analyzed and method of measuring battery deformation is proposed to realize the early fire warning method. The measurement and analysis circuit are designed with the implementation of experimental verification. The research contents of this paper extend the lithium-ion battery fire detection technology. The experimental results show that the proposed method can realize fire warning during the early period of thermal runaway.
2. Principle and characteristic analysis of thermal runaway of lithium ion battery

As the most basic element of a battery pack, a battery monomer is usually composed of positive electrode, negative electrode, electrolyte and diaphragm. The structural diagram is shown in Figure 1 [5].

The diaphragm of the battery monomer can be used as the insulation between positive and negative electrodes. Once damaged, positive and negative short-circuit will occur in the monomer, resulting in large current discharge and a large amount of heat. When the heat accumulates to a certain degree, the heat will be out of control, which means the temperature rise further, the melting of insulation diaphragm between the positive and negative electrode, making internal short circuit more serious, and producing more heat. The continuous rise of temperature will not only cause combustion when the reactants reach the ignition points, but also accelerate the reaction of active substances and produce a large number of gases. The monomer will explode out of the sharp rise in internal pressure. Even in the normal charging and discharging process, the active substances in the monomer electrolyte will release heat due to chemical and electrochemical reactions, making the temperature rise. If the heat generated in monomer is faster than the heat dissipated, thermal runaway will also occur when heat is accumulated to a certain extent, leading to combustion or explosion [6-7].

During the process of thermal runaway, lithium ion battery will go through several stages, including initial stage, early stage, middle stage and complete thermal runaway. In the initial stage of thermal runaway, burrs and crystal dendrites will occur inside the battery, which can result in higher conductivity of the battery. There are no obvious changes in physical and chemical characteristics outside the battery, making it difficult to conduct effective detection. During the early stage of thermal control, burrs and crystal dendrites inside the battery will be further enlarged. When the membrane is punctured, internal short circuit will occur with electrolyte heating up and evaporation. The battery electrode temperature will increase greatly, internal pressure of battery will increase and micro-deformation will occur in the battery. Deformation detection technology and gas detection technology can be used for detection. In the middle stage of thermal runaway, surface temperature of the battery increases significantly with the occurrence and development of thermal runaway and further heat release. The battery pressure makes release a large amount of gases and produce smoke. Temperature detection technology and smoke detection technology can be used for detection. In the stage of
complete thermal runaway, the battery reacts violently, which produces a lot of smoke with burning and explosion of the ternary lithium battery.

For the thermal runaway experiment of a cylindrical monomer lithium-ion ferrous phosphate battery (3.2V, 20Ah; a diameter of 43mm and a length of 177mm), when the surface temperature of the monomer battery reaches 60℃, the surface of the battery begins to expand release gases, such as carbon monoxide, carbon dioxide, toluene, ethyl-benzene, styrene, xylene, ethylene, propylene. Carbon monoxide concentration can reach 1000PPM between 65℃ and 70℃; when the temperature exceeds 75℃, there will be electrolyte injection phenomenon.

To sum up, the detection method of measuring carbon monoxide and temperature can be used to give early and middle warning of thermal runaway. The deformation characteristics of lithium ion battery are earlier than that of carbon monoxide, so the warning time can be earlier by deformation analysis technology.

3. Early warning detection device based on strain measurement

3.1. Principle of resistance strain measurement
The resistance strain gauge is used to measure the strain. Its operating principle is based on the "strain-resistance" effect of conductor which means when the conductor deforms, its resistance will change accordingly.

Resistance strain gauge to measure general strain process is as follows: the strain gauge is pasted or installed on the component surface to be tested. Then it can access measurement circuit with mechanical deformation. The strain gauge of sensitive grid can also deform, causing its electrical resistance change. After amplifying circuit amplification and collecting signal, there will be data processing after analog-to-digital conversion.

3.2. Strain measurement circuit design
In this paper, Wheatstone bridge is adopted to design the strain single-arm measurement amplifying circuit as shown in Figure. 3.
The circuit consists of voltage reference source circuit, Wheatstone bridge circuit and differential amplifier circuit.

In the circuit, U5 adopts TL431 controllable precise voltage stabilizer chip, forming a 2.5V precise voltage stabilizer circuit with resistor R3, capacitor C14, C15 and C16, so as to supply power to Wheatstone bridge.

The strain gauge is connected with P4 in the circuit and constitute Wheatstone bridge circuit with resistors R9, R10 and R17. The model of strain gauge is BF350-3AA, steady operating resistance is 350Ω, R9, R10 and R17 selects 348Ω resistance with 1% accuracy. If the strain gauge resistance is R, the output voltage of strain gauge bridge arm is U1 and output voltage of resistance bridge arm is U2, then the output values of U1 and U2 are shown in equations (1) and (2).

\[
U_1 = 2.5 \times \frac{R}{R + 348} \quad (1)
\]
\[
U_2 = 1.25V \quad (2)
\]

U7 is an operational amplifier with model of TP09. Resistors of R14, R15, R13, R18 and TP09's second operational amplifier institute a differential amplifier to amplify the output voltage of Wheatstone bridge. According to the "virtual short circuit" and "virtual open circuit" of operational amplifier, if the second operational amplifier output of TP09 is set as Uo, the relationship between Uo and U1, U2 is shown in equation (3).

\[
U_1 \times \frac{R_{13}}{R_{14} + R_{13}} = (U_2 - U_0) \times \frac{R_{18}}{R_{15} + R_{18}} + U_0 \quad (3)
\]

In the circuit, R13, R18 selects 348kΩ resistance with 1% accuracy, R14, R15 selects 6.98kΩ resistance with 1% accuracy. Through equation (3), equation (4) can be obtained.

\[
U_0 = \frac{U_1 - U_2}{1.02} \approx U_1 - U_2 \quad (4)
\]

There is addition and subtraction operation amplifier circuit, including the first operational amplifier of TP09, resistors R21, R22, R7 and adjustable resistors R11. The voltage Uadj of forward
input of operational amplifier can be adjusted by R11 resistance value. If the first output of TP09 is set as \(U_{o2}\), the relationship between \(U_o\) and \(U_{o2}\) is shown in equation (5).

\[
\frac{U_o-U_{adj}}{R_{21}} = \frac{U_{adj}-U_{o2}}{R_{22}}
\]  

(5)

\(R_{21}\) selects 8.66k\(\Omega\) resistance with 1% accuracy. \(R_{22}\) selects 348k\(\Omega\) resistance with 1% accuracy. The equation (6) can be obtained.

\[U_{o2} = 41.18U_{adj} - 40.18 \times (U_1 - U_2)\]  

(6)

The circuit adopts single power supply of 5V and the variation range of \(U_{o2}\) is 0 ~ 5V. The circuit null point can be adjusted through R11.

With STM32F103C8T6 single-chip microcomputer, this paper designs AD sampling circuit, display drive circuit and buzzer drive circuit, developing detection device circuit board as shown in Figure 4. Besides the function of strain measurement, the circuit board can also measure temperature data which is collected by thermocouple.

4. Experiment

4.1. Experiment conditions

In order to verify the performance of lithium ion battery fire warning detection device based on strain measurement, thermal control detection experiment of lithium ion battery is carried out, collecting carbon monoxide gases and the battery electrode temperature during thermal runaway process. This experiment adopts cylindrical monomer lithium-ion ferrous phosphate battery (3.2V, 20Ah; 43mm in diameter and 177mm in length) as shown in Figure 5.
After thermal runaway of battery, the deformation near the pressure relief hole is the largest, so the strain gauge is set near pressure relief hole in the experiment. Meanwhile, a K-type thermocouple is installed on the electrode to monitor electrode temperature as shown in Figure 6.

![Strain gauge and thermocouple arrangement](https://example.com/image6)

Figure 6 Strain gauge and thermocouple arrangement

The battery thermal runaway experiment is carried out in an experimental box of 1200×505×475(mm). The layout of the experimental box is shown in Figure 7.

![Experimental box of battery thermal runaway](https://example.com/image7)

Figure 7 Experimental box of battery thermal runaway
Carbon monoxide monitor is installed in the experimental box to monitor carbon monoxide concentration produced during the experiment. The deformation data and electrode temperature data on lithium-ion ferrous phosphate battery are collected through detector circuit board.

4.2. Experimental data

This paper adopts overcharging method to make thermal runaway of lithium-ion ferrous phosphate battery. The capacity of lithium-ion ferrous phosphate battery used in experiment is 20Ah and charging current is set as 0.3c which means 3A. After being fully charged for about 35 minutes, the battery experienced complete thermal runaway. The variation curves of deformation voltage, carbon monoxide concentration and temperature are shown in Figure 8.

![Figure 8 Experimental data curve of thermal runaway in lithium ion battery](image)

In the Figure 8, the x-coordinate is experiment time, the main y-coordinate on the left is the deformation detection voltage, and the two auxiliary coordinates on the right are the carbon monoxide concentration value and electrode temperature value respectively.

The lithium ion battery overcharged from 15:30:22 and electrode temperature was 36.2℃. At 16:03:22, the battery completely had thermal runaway and the temperature was 98.5℃. At this stage, electrode heating rate was about 2℃/min. After complete thermal runaway, electrode heating rate increased and temperature continued to rise. At 16:04:14, the temperature reached a maximum of 135.4℃ with heating rate at this stage of about 41℃/min. At the beginning of 16:04:15, temperature began to drop as the battery's relief valve fully opened to spray a large amount of electrolyte and temperature thermocouple fell off from electrode.

At 15:30:22, carbon monoxide concentration in the laboratory chamber is 0 when the lithium ion battery starts overcharging. At 15:50:22, electrode temperature reached 73.4℃ with a small amount of carbon monoxide beginning to be released. At 16:03:22, the battery were completely thermal runaway, electrode temperature reached 101.3℃ with carbon monoxide concentration of 90ppm. When there was complete thermal runaway, the battery pressure relief valve was fully opened to release a large amount of carbon monoxide. At 16:03:37, electrode temperature reached 111.6℃ and carbon monoxide concentration was 2000ppm. Since the carbon monoxide monitor has a range of 2000ppm, carbon monoxide concentration does not change after reaching full range.

At 15:30:22, the deformation detection voltage was 0 as the lithium ion battery started overcharging. Although no deformation occurred in the initial stage of the battery thermal runaway, the strain gauge generates temperature drift due to continuous rise of battery temperature. Under the
influence of temperature drift, deformation detection voltage was below 0.1V. At 15:53:22, obvious deformation occurred near the battery pressure relief hole and deformation detection voltage reached 0.44V. After that, the deformation gradually increased. At 16:03:23, pressure relief hole was fully opened and deformation detection voltage reached the maximum value of 1.5V, which remained at around 1.5V all the time.

When carbon monoxide is used as detection technology, the alarm concentration value is generally set at 190ppm in order to prevent false alarm. In the experiment, the time when the carbon monoxide concentration exceeded 190ppm was 16:03:29 and the time when the obvious deformation occurred near pressure relief hole of lithium ion battery was 15:53:22. In the experiment, the time of deformation detection and warning was nearly 10min earlier than that of carbon monoxide detection and warning.

In conclusion, the battery fire warning method based on strain measurement can realize detection and warning at the early stage of thermal runaway in lithium ion batteries, which can effectively improve the level of lithium ion fire detection technology.

5. Conclusion
In this paper, fire warning method based on strain measurement is proposed and application circuit is designed by analyzing the characteristics of thermal runaway process of lithium-ion battery. Through thermal runaway experiment of lithium ion battery, it is verified that the strain measurement technology can realize the early detection of thermal runaway when applied to the fire alarm detection of lithium ion battery. Compared with carbon monoxide detection and alarm technology, its warning time is nearly 10min earlier.

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References
[1] Luo Qingkai, Wang Zhirong, Liu Jingjing, et al. (2016) Influencing factors of thermal runaway of 18650 Lithium ion battery. Power Supply Technology, 40(2):277-279.
[2] Huang Xuejie. (2015) Electric Vehicles and Lithium-ion Batteries. Physics, 44(1):1-7.
[3] He Xiangming, Feng Xuning, OuYang Minggao. (2016) Safety of automotive Lithium ion battery system [J]. Science and Technology Bulletin, 34(6):32-38.
[4] Li Hui, Ji Wei Xiao, Cao Yu Liang, et al. (2018) Thermal runaway technology for lithium-ion batteries. Energy Storage Science and Technology, 7(3):376-383.
[5] Christopher D.Rahn, Chao-Yang Wang. (2014) Battery system engineering, translated by Hui Dong, Li Jianlin, Guan Yibiao, et al. Machinery Industry Press, Beijing: 14-15.
[6] Liu Haowen. (2018) A brief analysis of the main factors affecting the safety of lithium ion battery. Natural Science, 6(5): 391-394.
[7] Huang Caixia, Huang Wen, Yang Gang. (2018) Causes of explosion of lithium-ion battery packs for electric vehicles and preventive measures. Battery, 48(1): 60-62.