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DETERMINING THE LOCATION OF OVERHEATING IN AN ELECTROCHEMICAL BATTERY

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Abstract. This paper presents a device and a method for early warning of the risk of thermal runaway in electrochemical batteries. The effectiveness of the proposed system was assessed using mathematical modeling applied specifically to the battery module of the Audi e-tron. Modeling of prismatic cell overheating and calculation of instantaneous operating modes were performed in Excel Microsoft 365. The results, presented in analytical graphs, demonstrate the ability of the system to detect battery cell overheating, which confirms both the operability of the device and the reliability of the method. The proposed solution is especially suitable for improving the safety of lithium-ion, nickel-cadmium and other multi-cell battery systems during operation, as well as for integration into new battery modules. Main applications: monitoring cell temperature in a multi-cell battery module; early warning of thermal runaway risk in a multi-cell battery module; providing emergency alerts in case of immediate and obvious thermal runaway danger.

Keywords: *Thermal runaway, multi-cell battery module, cell overheating detection, thin film thermistor, temperature monitoring, multi-cell battery thermal modeling.*

Rezumat. Această lucrare prezintă un dispozitiv și o metodă pentru avertizarea timpurie a riscului de fuga termică în bateriile electrochimice. Eficacitatea sistemului propus a fost evaluată folosind modelarea matematică aplicată specific modulului bateriei Audi e-tron. Modelarea supraîncălzirii celulelor prismatice și calculul modurilor de funcționare instantanee au fost efectuate în Excel Microsoft 365. Rezultatele, prezentate în grafice analitice, demonstrează capacitatea sistemului de a detecta supraîncălzirea celulelor bateriei, ceea ce confirmă atât operabilitatea dispozitivului, cât și fiabilitatea metodei. Soluția propusă este potrivită în special pentru îmbunătățirea siguranței sistemelor de baterii litiu-ion, nichel-cadmiu și alte sisteme multicelulare în timpul funcționării, precum și pentru integrarea în module de baterii noi. Aplicații principale: monitorizarea temperaturii celulelor modulului bateriei multicelular; avertizare timpurie a riscului de fuga termică modulului bateriei multicelular; furnizarea de alerte de urgență în caz de pericol imediat și evident de fuga termică.

Cuvinte cheie: *Fuga termică, modul baterie multicelular, detectarea supraîncălzirii celulelor, termistor cu peliculă subțire, monitorizarea temperaturii, modelare termică a bateriilor multicelulare.*

Abbreviations The following abbreviations are used in this manuscript:

ISC Internal short circuit

CAN BUS A controller area network bus (CAN bus) is a vehicle bus standard designed to enable efficient communication primarily between electronic control units (ECUs).

CANduino v4.0 Arduino-compatible development board designed for those working on automotive systems: the Canduino, with a built-in CAN bus.

LED A light-emitting diode (LED) is a semiconductor device that emits light when current flows through it.

GND is a reference point in a circuit from which voltage is measured

NTC stands for Negative Temperature Coefficient

1. Introduction

Thermal runaway in lithium-ion, nickel-cadmium, and other types of electrochemical energy storage devices is a phenomenon characterized by a chain of exothermic reactions within the battery. It is usually caused by an internal short circuit caused by defects or aging of the cell.

However, the most common cause is overheating, often caused by charging current flowing through a cell that has already reached full charge while other battery cells have not yet completed the charging process. In an overheated cell, exothermic reactions dramatically increase the internal temperature, which accelerates electrochemical activity and leads to excessive heat generation. This increase in temperature causes the release of flammable gases, an increase in internal pressure, and expansion of the outer casing, which can lead to an explosion and fire of the entire battery [1]. In three out of four cases, a fire breaks out during the charging phase **[**2]. Highlighting the importance of monitoring of battery cells.

Several technologies are known to prevent thermal runaway:

- Ultrasonic detection, which provides dynamic feedback on structural changes inside the cell for early warning systems;
- Detection of gas released during electrolyte decomposition using gas sensing devices to monitor chemical reactions;
- Voltage sensing using alternating topologies and multiple sensors to monitor terminal voltage of individual lithium-ion cells;
- Temperature monitoring is a fundamental method that allows real-time detection of abnormal increases in internal temperature [3].

Gas analyzers and ultrasonic scanning can detect electrolyte decomposition, signalling the onset of thermal runaway and cell failure. Voltage monitoring is a simple and reliable method for diagnosing internal short circuits (ISCs), especially when overcharging is a factor [4]. However, parallel connection of cells in battery modules complicates individual cell measurements. In addition, measuring internal resistance and voltage alone may not provide timely detection of thermal runaway [5].

Given these limitations, temperature monitoring is considered the most fundamental method for preventing thermal runaway [3]. Stopping the heating before the electrolyte decomposes can avoid battery destruction. However, both temperature monitoring and voltage monitoring require multi-wire circuits, which increases the system cost and reduces reliability. Common temperature sensors such as thermistors, thermocouples, and analog-to-digital sensors have disadvantages such as low detection accuracy and sensitivity to the environment.

One of the known thermal runaway warning devices [6] involves the use of temperature-sensitive tape sensors that melt when overheated. These disposable tapes must be replaced after activation, which makes them impractical due to labor-intensive and unreliable operation. Therefore, safety management methods and systems for electrochemical devices continue to evolve.

Based on the above, the objective of this work is to investigate the performance of the proposed thermal runaway risk early warning system [**7**], in particular, in the temperature monitoring mode of the battery module cells in the electrochemical battery system of the Audi e-tron [8].

2. Model for Studying of the proposed Overheated Cell Detection and Early Warning System for the Audi e-tron Electrochemical Battery Module

Electrochemical battery modules, in particular those used in electric vehicles, may differ in the number and shape of individual cells. To select the appropriate type and resistance parameters of flexible thin-film sensors, as well as the iterative selection of a constant resistance resistor for the proposed overheated cell detection system of the electrochemical battery module [8], it is necessary to study the operating modes of the system using a mathematical model. This study allows optimizing the device parameters for a specific battery module.

However, to develop a universal algorithm and test the corresponding software module for use in various types and configurations of batteries, a physical prototype is required - a test bench. This section presents a model of the proposed cell overheated detection and early warning system [7], specially adapted for the Audi e-tron electrochemical battery module [8].

The schematic diagram of the proposed overheated cell detection system is shown in Fig. 1.

The diagram includes the following components:

- Sensor unit (1): Consists of a flexible thin-film sensor (2) with a high-temperature nonlinear resistance coefficient. Identical sections (10) of which are attached to the corresponding cells of the electrochemical module of the battery.
- Control unit (3) includes:
    - controller (4) based on CANduino v4.0;
    - constant resistance resistor (5);

Alarm unit (6) includes: LED indicator (7) and buzzer (8).

This configuration provides thermal contact between each section of the sensor and the housing of the corresponding cell, covering two equal groups of cells inside the module.

The electrical connections of the proposed overheated cell detection system are as follows:

- one end of the flexible thin-film sensor (2) is connected to the +5 V voltage source of the controller (4) via the electrical conductor (11);
- the other end of the sensor is connected to the analog input A7 of the controller (4) via the electrical conductor (12);
- the constant resistance resistor (5) is connected between the ground contact (GND) and the analog input A7 of the controller (4);

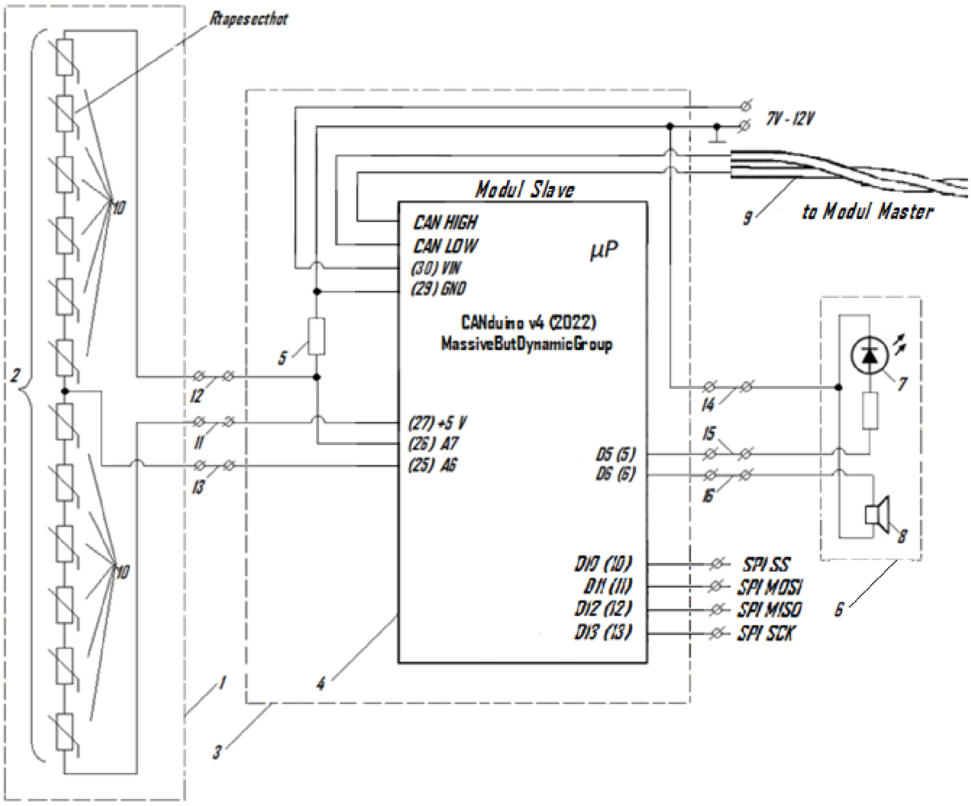

Figure 1. Overheated cell detection system in a twelve-cell lithium-ion battery module of the Audi e-tron [8].

- the midpoint of the sensor film is connected to the analog output A6 of the controller (4) via the electrical conductor (13);
- the +5 V DC output of the controller (5) is connected to the common power supply wire of the alarm unit (6) via the electrical conductor (14);
- the LED indicator (7) of the alarm unit (6) is connected to the digital output D2 of the controller (4) via the electrical conductor (15);
- the control output of the controller (4) is connected to the buzzer (8) of the alarm unit (6) via the electrical conductor (16).

3. Selection of sensors and controller for the system for determining the location and early warning of overheating in the battery module of electrochemical batteries

For monitoring the prismatic cells in the Audi e-tron lithium-ion battery module [8], a flexible thin-film sensor is considered the most suitable option. This type of sensor enables more reliable thermal contact across a larger surface area of the battery elements. However, such sensors are not yet commercially available.

Interest in flexible thin-film sensors stems from a series of successful experimental studies conducted by Tsung-Shine Ko et al. at the Department of Electronic Engineering, National Changhua University of Education, Taiwan [9]. Their research demonstrated that bulk thin-film $Mo_xW_{1-x}S_2$ has significant potential as a thermal sensor, and its future production is anticipated.

Since this promising material is still in the experimental phase and not yet manufactured, the characteristics of the NTC thermistor 1AE103R44T5A - produced by North Star Sensors, LLC [10] - are used to model the behavior of sections (10) of the flexible thin-film sensor (2). The specifications of the NTC thermistor 1AE103R44T5A are presented in Table 1.

Table 1

NTC thermistor characteristics

Part Number	Resistance at25 °C,R_{25}, (kΩ)	Temperature Tolerance, (°C)	R/T Curve	25 °C / 85°C ß	Recommended Measurement Current, (μA)
1AE103R44T5A	10	± 0.5 from 0 to 70	44	3978	< 50

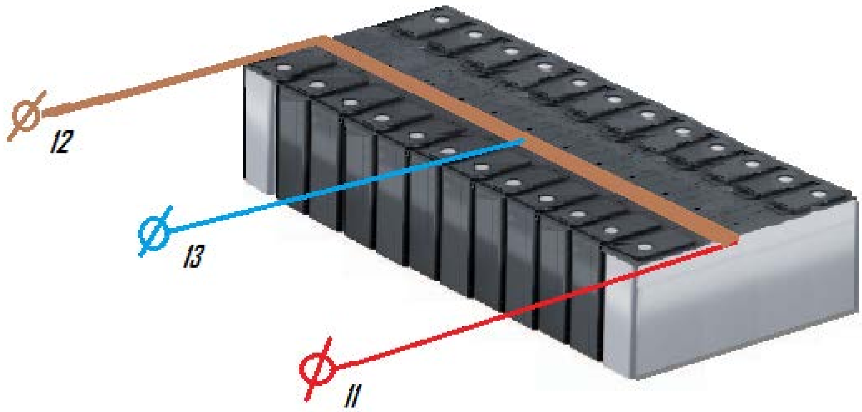

Figure 2. Prismatic lithium-ion battery (cell) module with flexible thin-film sensor.

Further research by Tianqi Yang et al. (2025) [11] examined temperature distributions in prismatic battery modules approaching thermal runaway. Their findings revealed that the highest temperatures occur at the top of the prism, between the cell poles. Based on these findings and recommendations [12], flexible thin-film sensors for detecting cell overheating in the twelve-cell prismatic lithium-ion battery module of the Audi e-tron [8] can be arranged as shown in Fig. 2. Let us consider the operation of the overheating detection system as applied to this module (Fig. 2).

Table 2

CANduino v4.0 Technical Specifications

Specification	Parametr
Microcontroller	ATmega328PA
Operating Voltage Cell modules	5 V
Input Voltage Range	7 V – 12 V
Digital I/O Pins	14 (6 with PWM)
Analog Input/Output Pins	8 (ADC channels)
Maximum current	40 mAh from one output
Flash memory	32 kb
Interface	SPI & CAN with USB Type-C
CAN controller / transceiver	MCP25625
Analog pins measure voltage with an accuracy	of 0,005 V

Since no publicly available information exists regarding the type of controller used in the Audi e-tron GT Quattro battery module, the CANduino v4 [12] is selected as the controller for the battery control unit (4). The technical specifications of the CANduino v4, designed by MassiveButDynamic in Germany, are provided in Table 2 [13].

The CANduino v4 interface supports CAN V2.0B with a speed of 1 Mbit/s and can be used to communicate with the master battery control processor via a twisted pair CAN Bus.

According to these data, we will accept the supply voltage of the sensor unit Ussupply = 5 V. In this case, the voltage of the midpoint of the flexible thin-film sensor, in the absence of overheated cells, will be Utest = 2.5 V.

4. Methodology for determining the location and early warning of overheating in the module of an electrochemical battery

To monitor the average temperature of the module cells and improve the accuracy of detecting when an overheated cell reaches the thermal runaway risk threshold, we calculate the voltage drop Utape across a constant resistor Rconst. This voltage drop varies as the resistance Rtape of the flexible thin-film sensor circuit changes in response to cell temperature fluctuations.

We use the RESISTANCE RATIO Rt/R25 ratio from the NORTH STAR SENSORS CURVE 44 specification to calculate the change in resistance of the flexible thin-film sensor sector [10]. We enter the calculation results in Table 3. To measure the average temperature of the module cells, we plot the dependence of the voltage drop on the resistance of the constant value Rconst in the flexible thin-film sensor circuit when the temperature Thotcell of the module cells changes, which increases from 20 °C to 100 °C.

To do this, we calculate the equivalent resistance Rtapeeqw of flexible thin-film sensor 2, consisting of ns = 12 sectors (Fig. 2), using formulas (1) and (2), taking into account the change in temperature:

$$\text{Rtapeeqw} = \sum_{i=1}^{ns} \text{Rtapesect (i)} \quad (1)$$

Current IC flowing in the resistance Rconst of a constant resistor 5 (Fig. 3):

$$IC = Ussupply / (Rtapeeqw + Rconst) \quad (2)$$

Let's calculate Utape, the value of the voltage drop as a function of the change in the operating temperature of the module cells:

$$Utape = IC \bullet Rconst \quad (3)$$

The calculations will be performed under the condition that the supply voltage of the flexible thin-film sensor will be equal to Ussupply = 5.0 V, the resistance of the sector of the flexible thin-film sensor at 25 °C (thermistor) will be R25 = 10 kΩ, the resistance of the constant-value resistor will be equal to Rconst = 1.4 kΩ. The calculation results are presented in Table 3 and in the graph of Fig. 3.

Table 3

Dependence of the voltage Utape on the temperature of the thin-film sensor Ttape

Ttape, (°C)	**20**	**40**	**60**	**80**	**100**
Ω RATIO **Rt/R25**	1.24927	0.53266	0.24869	0.12554	0.06784
Rtapesecthot, (kΩ)	12.493	5.327	2.487	1.255	0.678
Ic, (mA)	0.0330	0.0765	0.160	0.304	0.524
Utape, (V)	0.0463	0.1072	0.2241	0.4251	0.7337

Let us assume that the overheated cell has a thermal contact with the sector Rtapesecthot in the right part of the flexible thin-film sensor from the midpoint. Let us calculate the absolute value of the voltage deviation $dUtest_{20\,°C}$, that is, the modulus of the difference Utest voltage of the midpoint of the flexible thin-film sensor (in the absence of overheated cells) and $Utape_{20\,°C}$ of the midpoint voltage of the flexible thin-film sensor at the operating temperature of the module cells Tcelloper = 20 °C, when the resistance of each sector of the flexible thin-film sensor does not change and is $Rtapesect_{20\,°C}$ = 12.493 kΩ, except for the resistance of the sector Rtapesecthot in the right half of the thin-film sensor in contact with the cell, the temperature Thotcell of which increases from 20 °C to 100 °C.

We will calculate the absolute value of the voltage deviation $dUtest_{20\,°C}$ using the formula:

$$dUtest_{20\,°C} = ABS\ (Utest - Utape_{20\,°C}) \quad (4)$$

The voltage $Utape_{20\,°C}$ of the midpoint of the flexible thin-film sensor as a function of Thotcell with a change in the resistance of the sector Rtapesecthot in the right half of the thin-film sensor in contact with the cell, the temperature of which Thotcell increases from 20 °C to 100 °C, is determined by the formula:

$$Utape_{20\,°C} = Rrightside_{20\,°C} \bullet Itape_{20\,°C} \quad (5)$$

The resistance $Rrightside_{20\,°C}$ as a function of Thotcell of the right half of the flexible thin-film sensor at a module cell temperature of 20 °C with a change in the resistance of the sector Rtapesecthot as a function of Thotcell in the right half of the thin-film sensor is determined by the formula:

$$Rrightside_{20\,°C} = Rtapesect_{20\,°C} \bullet (ns/2 - 1) + Rtapesecthot \quad (6)$$

The current of the flexible thin-film sensor $Itape_{20\,°C}$ with a change in the resistance $Rtape_{20\,°C}$ of the flexible thin-film sensor as a function of Thotcell is determined by the formula:

$$Itape_{20°C} = Ussupply\ /\ Rtape_{20°C} \quad (7)$$

The total resistance of the flexible thin-film sensor $Rtape_{20\,°C}$ as a function of Thotcell is determined by the formula:

$$Rtape_{20°C} = Rrightside_{20°C} + Rleftside_{20°C} \quad (8)$$

The resistance of the left half of the flexible thin-film sensor $Rleftside_{20°C}$ at a module cell temperature of 20 °C is determined by the formula:

$$Rleftside_{20°C} = Rtapesect_{20°C} \bullet ns\ /2 \quad (9)$$

The calculation results are presented in Table 4 and in the graph of Fig. 4.

Table 4

Dependence of the deviation of the voltage of the midpoint of the dUtest sensor when one cell in the module overheats

Thotcell, (°C)	**20**	**40**	**60**	**80**	**100**
$dUtest_{20\,°C}$, (V)	0.000	0.126	0.179	0.203	0.214
$dUtest_{40\,°C}$, (V)	-	0.000	0.116	0.170	0.196

We repeat the calculation using formulas (4) - (9) at Tcelloper = 40 °C, when the resistance of each sector of the flexible thin-film sensor does not change and is $Rtapesect_{40°C}$

= 5.327 kΩ, and the temperature of which Thotcell in the right half of the thin-film sensor in contact with the cell increases from 40 °C to 100 °C.

The calculation results are presented in Table 4 and in the graph of Fig. 4.

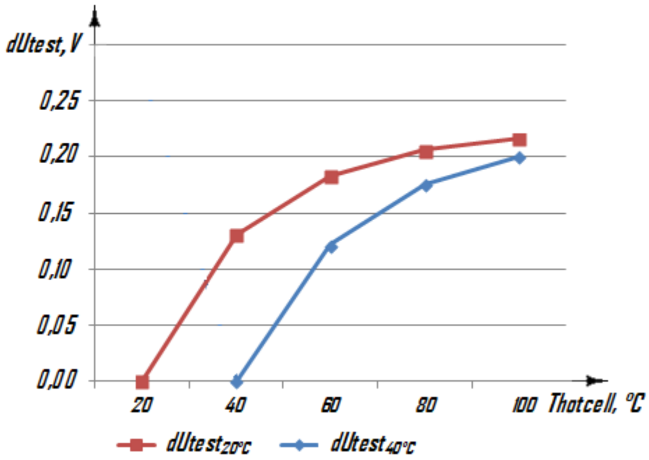

Figure 4. Dependence of the deviation of the midpoint voltage of the dUtest sensor when one cell in the module overheats at a temperature of the remaining cells of 20 °C or 40°C.

The graphs in Fig. 4 show that for practical application it is necessary to find a method for processing the results of measuring the midpoint voltage of the sensor to increase the accuracy.

One possible method may be to reduce the curves of the deviation of the midpoint voltage of the sensor dUtest to the temperature threshold point of the risk of develop-ing thermal runaway of the battery module cell. For this purpose, we use the value of the voltage drop Utape on the constant-value resistor Rconst, measured when deter-mining the average temperature of the module cells using a flexible thin-film sensor (Fig. 3).

We will compose a sum consisting of the absolute value of the difference between the test voltage Utest and the potential dUtape of the midpoint of the flexible thin-film sensor, and add to it the voltage drop Utape on the constant-value resistor obtained when calculating the average temperature of the module cells and obtain the value of dUtest':

dUtest' = ABS (Utest - dUtest) + Utape(10)

Let us calculate the change in $dUtest'_{20\,°C}$ when the temperature of the overheated cell Tcellhot changes from 20 °C to 100 °C using formula (5) for an average temperature of the module cells of 20 °C.

Let us calculate the change in $dUtest'_{40\,°C}$ when the temperature of the overheated cell Tcellhot changes from 40 °C to 100 °C for an average temperature of the module cells of 40 °C. The calculation results are given in Table 5. The graph in Fig. 5 is constructed based on the calculation results.

Table 5

Change in $dUtest'_{40°C}$ with change in temperature of superheated cell Tcellhot

Specification	**Parametrs**				
Thotcell, (°C)	20	40	60	80	100
$dUtest'_{20°C}$ by $Ttape_{20°C}$, (V)	0.046	0.174	0.228	0.253	0.264
$dUtest'_{40°C}$ by $Ttape_{40°C}$, (V)	-	0.107	0.228	0.284	0.311

The intersection point of the curves of the deviation of voltage $dUtest'_{60\ °C}$ of the flexible thin-film sensor midpoint during overheating of one of the module cells in Fig. 5 is determined by the value of the voltage drop Utape on the constant-value resistor Rconst.

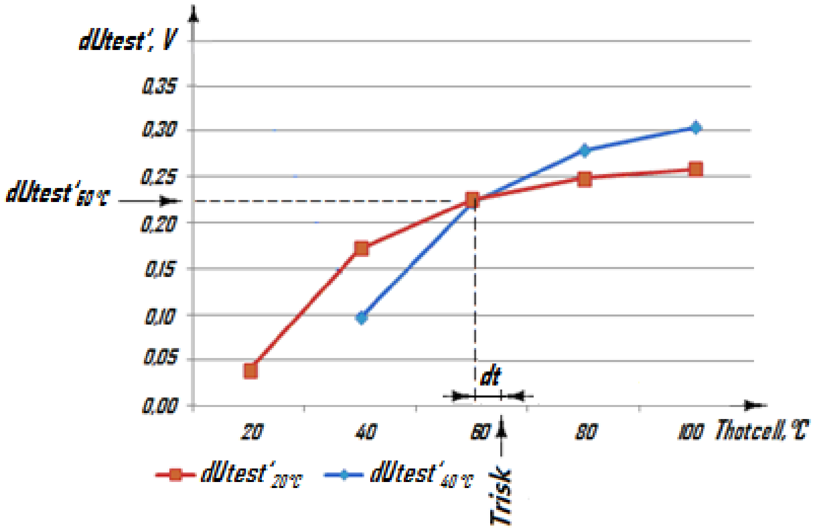

Figure 5. Corrected deviation of voltage dUtest' of the flexible thin-film sensor midpoint during overheating of one of the module cells at the temperature of the remaining 20 °C or 40 °C.

Thus, to bring the curves together at the required overheating temperature of one of the module cells, it is necessary to iteratively select the parameters of the constant value resistor Rconst on a mathematical model created by means of Excel Microsoft 365. The convergence of the curves in Fig. 5 allows one to set the threshold of the temperature of the risk of thermal runaway of the overheated module cell, uniform in value for any operating temperature of the remaining module cells. How-ever, to control the occurrence of the thermal runaway hazard of an overheated cell in a module, it is impossible to set a single temperature threshold at any operating temperature of the remaining cells in the module, since the curves diverge when the temperature of the overheated cell rises above the thermal runaway risk threshold Fig. 5.

Therefore, the algorithm provides for checking the efficiency of cooling the battery module and, if as a result of the measures taken, the temperature of the overheated cell decreases, the thermal runaway risk signal will be disabled, and if the temperature of the overheated cell, measured after the reaction time Treact, is higher than the risk temperature threshold Trisc, the sound signal warning about the danger of thermal runaway of the cell is activated. Where Treact is the time for the module temperature to decrease by 1°C at the maximum cooling mode.

It is advisable to study the practical application of the system for determining the location and early warning of thermal runaway of a lithium-ion battery on a model. The diagram is shown in Fig. 1. It is proposed to use the CANduino v4.0 microprocessor, which is equipped with an analog-to-digital converter (ADC), as a controller.

The A0-A5 contacts of the CANduino v4.0 microprocessor are used to read ana-log voltages. The ADC converts the voltage into bits that the microprocessor can understand. The ADC of this microprocessor has a 10-bit resolution, which means that it can represent the analog voltage with 1024 digital levels. [14]. The analog pins A0-A5 measure the voltage with an accuracy of dPv = 0.005 V (Table 1). Let us determine the accuracy in degrees with which the ADC can determine the cell surface temperature using a flexible thin-film sensor Ttape when the cell temperature changes from 40°C to 60°C. Let us plot the ratio of the ordinate to the abscissa of the graph in Fig. 3, based on the data in Table 2:

$$(Utape_{60\,°C} - Utape_{40\,°C}) \text{ is related to } (Ttape_{60\,°C}\, Ttape_{40\,°C}) \text{ as} \quad (11)$$
$$dPv \text{ is related to } dPg$$

Let's substitute the values and determine the measurement accuracy in degrees – dPg:

$$dPg = 0.005\ V \bullet (60°C - 40°C) / (0.2241V - 0.1072\ V) \quad (12)$$
$$dPg = 0.86\ °C$$

The analog outputs A0–A5 can measure the cell temperature with an accuracy of dPg = 0.86 °C, which allows the use of the CANduino v4.0 microprocessor for building a test bench, as well as for the battery module temperature monitoring system.

5. Determination of Temperature Thresholds for the Risk and Danger of Thermal Runaway in Lithium-Ion Batteries

Thermal runaway in lithium-ion batteries is typically divided into three stages:

- Self-heating stage: 50 -140 °C;
- Runaway stage: 140 - 850 °C;
- Termination stage: 850 °C down to ambient temperature.

Some literature sources indicate that the mass melting temperature of the separator begins around 140 °C [5]. LiFePO4 batteries can typically operate in a temperature range of -20 °C to 60 °C (-4 °F to 140 °F), but optimal performance is achieved at temperatures of 0 °C to 45 °C (32 °F to 113 °F) [15].

The exothermic reaction before thermal runaway of the battery is mainly caused by the decomposition and regeneration of the anodic solid electrolyte interface (SEI). Researchers Jin, C. et al. (2024) [16] found that SEI can start to decompose above 70 °C. Therefore, the decomposition of the anode SEI can be considered as the beginning of the thermal runaway of the battery, which the proposed system should not allow. The exact decomposition temperature of the anode SEI is related to the chemistry of the specific battery, the thickness of the SEI and the state of the SOC [5], so for each specific application of the proposed system it should be taken into account when setting the thermal runaway risk threshold.

Research by Kisseler, N. et al. (2024) [17] showed that in large-format high-energy prismatic battery cells, the temperature difference between the internal temperature and the external surface temperature of the cell can reach 1.8 °C during cycling under natural convection conditions, even at low charging currents of 0.25 °C, which are likely to be significantly higher at higher charging currents.

Based on this, we adopt a correction for the temperature difference between the internal temperature and the external surface temperature of the cell equal to dt = 5 °C for the cells of the module under consideration.

Taking into account the correction dt, we set the thermal runaway risk temperature threshold of the battery module cell Trisk = 60 °C. By iteratively selecting the resistance of the resistor of constant value Rconst, we achieve the intersection of the curves of the voltage deviation dUtest' of the midpoint of the flexible thin-film sensor, when one of the module cells is overheated, at a point with a temperature equal to Trisk = 60 °C (at a temperature of the remaining cells of 20 °C and, accordingly, 40 °C). In Fig. 5, the dashed line shows that for any operating temperature of the cells of the module under consideration, the value of the temperature threshold for the overheated one will correspond to the same calculated voltage dUtest' = 0.225 V, at the actual temperature of the overheated cell Thotcell = 65 °C.

6. Operating algorithm of the system for determining the location and early warning of overheating in the battery module

The operating algorithm of the system for determining the location and early warning of overheating of the battery module is shown in Fig. 6. Before the start of the operation of the early warning system and determining the location of overheating of the electrochemical battery module, the data of the battery module in question are entered into the memory of the slave controller CANduino Slave v4 for monitoring by the proposed system:

Initialization

S10 : The following constants are assigned:

Urisk : Calculated voltage threshold for thermal runaway risk
Udngr : Calculated voltage threshold for thermal runaway danger
Utest : Test voltage, equal to half of Ussupply
Flag : Timer activation flag, initialized as Flag = 0
ns : Number of sensor sections in the battery module
Treact : Time required by the cooling system to reduce the module temperature by 1 °C in forced mode

Additionally, the data from Table 2 - representing the dependence of Utape on cell temperature Ttape - are stored in the controller's memory.

Temperature Measurement

S20: To determine average module temperature:

Apply Ussupply = 5 V from Controller (4) to one end of the flexible thin-film sensor (2)
Connect the other end to GND via constant resistor (5)
Disconnect pin A6, connect pin A7 to the ADC, and read Utape
Use Table 2 to determine Ttape, the average module temperature

Iterative Monitoring Loop

S30: Decrement variable i = i − 1
S40: Using the digitalWrite(A7, 0) function, set ground GND on pin A7 of controller (4).
S50: Measure the voltage dUtest of the midpoint of flexible thin-film sensor (2) on wire (13) using the analog-to-digital converter of analog input A6 of controller (4) of battery control unit (3). Calculate the magnitude of the difference modulus Utest of the test voltage and dUtest of the midpoint voltage of flexible thin-film sensor (2), then add the value Utape of the voltage drop at the beginning of the constant resistor (7) and assign to constant dUtest'.
S60: Compare the obtained value dUtest with the threshold value Urisk of the thermal runaway risk voltage, if it is less, then go to S50 to perform the next cycle, if it is greater than or equal to Urisk, then go to S90.
S70: Decrement i = i − 11
S80: If i = 0, return to S20; if i ≠ 0, go to S40.

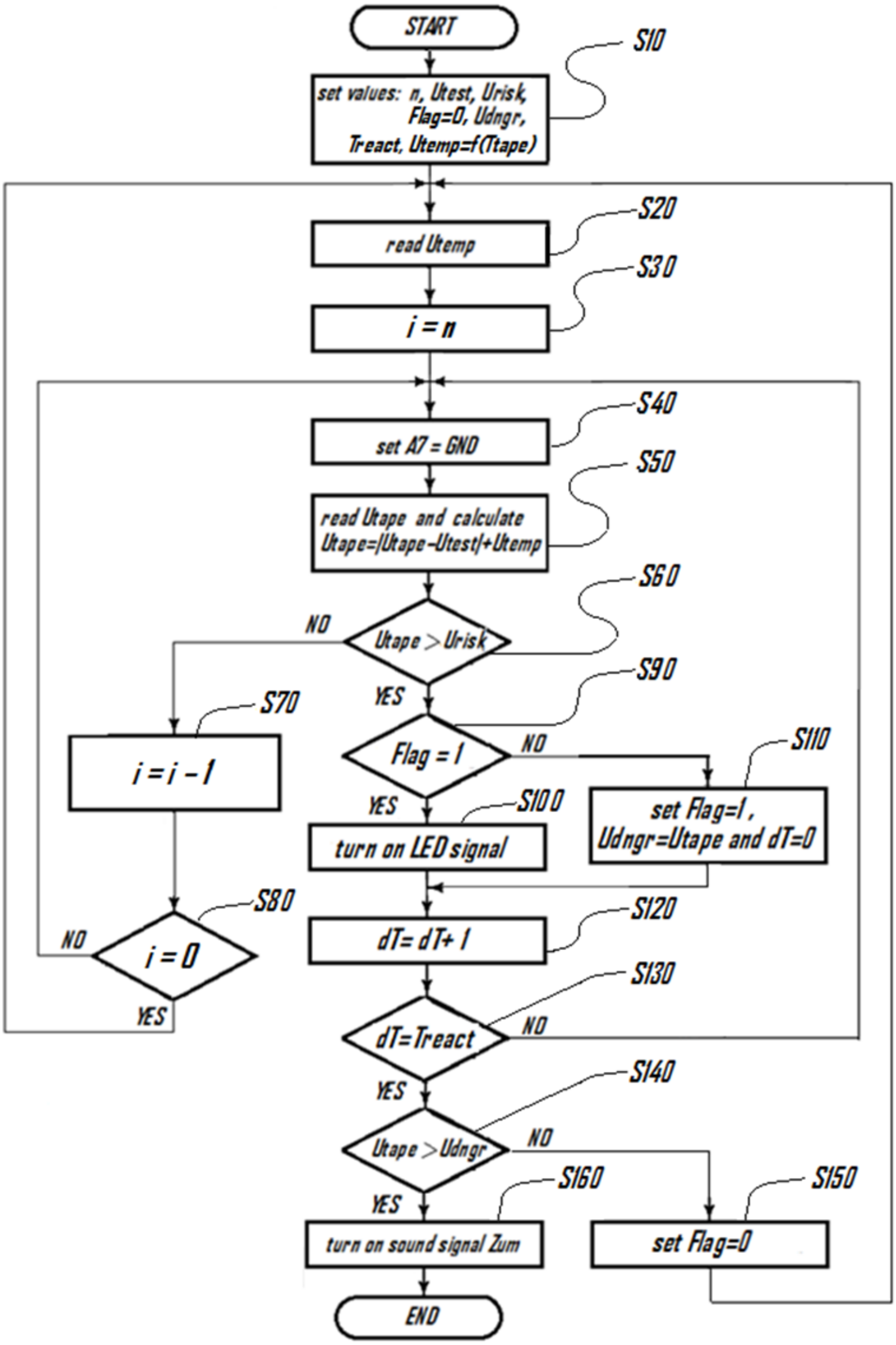

Figure 6. Algorithm of operation of the system for determining the location and early warning of overheating in the battery module.

Response Logic

S90: Check Flag = 1.

If true, go to S100

If false, go to S110

S100: Activate LED indicator and send signal to the battery regulation control unit to:

Turn on cooling fans at full power

Halt charging/discharging of the module or entire battery

S110: Assign: Flag = 1, Udngr = Utape, dT = 0
S120: Assign to the variable dT = dT + 1
S130: Compare dT = Treact. proceed to S140; otherwise, return to S40
S140: Compare dUtest' > Udngr
If true, go to S160
If false, go to S150
S150: Assign: Flag= 0 and go to S20.
S160: Activate buzzer (8) and send signal to the battery regulation control unit to: Trigger the active fire extinguishing system for the module or entire battery

8. Results

Audi, like most manufacturers, monitors the temperature, current and voltage of each cell to protect against thermal runaway, and intervenes if necessary. The pro-posed technical solution reduces the number of wires for monitoring the cell temperature by almost an order of magnitude, and also increases the accuracy of determining the average temperature of the module cells and reduces the effect of the operating temperature on the accuracy of determining the temperature threshold at which the operation of the cell is associated with the risk of thermal runaway.

9. Conclusion

This paper presents a system for monitoring the temperature of battery module cells using flexible thin-film thermistors. The system is designed to ensure that the accuracy of detecting an overheated cell remains unaffected by temperature variations in the other cells within the module.

To investigate the proposed temperature monitoring system, a basic application diagram of the system for monitoring a real electric vehicle battery module was developed. The operating modes of the system were analyzed using mathematical modeling of the conditions under which cell overheating occurs.

The technical outcomes of the proposed monitoring system include:

- Early detection of an overheated cell in an electrochemical battery module-prior to the onset of cell degradation-enabling timely signaling of both risk and danger associated with thermal runaway if the temperature rise is not mitigated.
- Precise identification of the moment when a cell reaches the critical temperature threshold, beyond which continued operation poses a risk of thermal runaway, independent of the overall temperature of the module.
- Cost reduction in components and electrical connections, achieved by using flexible thin-film sensors instead of individual sensors for each cell.
- Sustained monitoring capability after the temperature of the overheated cell drops below the thermal runaway hazard threshold.

Data Availability Statement The battery data used in this paper are from the public source. No new data were created in this study.

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