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Improving Lithium-ion Battery Longevity through Predictive Thermal Management

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Abstract

Lithium-ion batteries are vital in various storage applications like electric vehicle, renewable energy system and industrial applications. One of the major drawbacks with lithium-ion batteries are overheating. A cost-effective thermal management system is proposed where predictive analysis is employed to reduce thermal stress, thereby increasing reliability and longevity of batteries. Linear regression techniques is employed to forecast temperature fluctuation and activate cooling system when temperature of the lithium-ion battery reaches unsafe limit. The proposed methodology is developed and validated by a low-cost hardware.

Keywords: Lithium-ion Batteries, Thermal Management, Predictive Analytics, Linear Regression, Battery Safety, Real-Time Monitoring.

1. Introduction

The growing demand for enhanced cooling systems of lithium-ion batteries is largely attributed to the prevalent use of battery-operated devices and electric vehicles. This initiative

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presents an innovative cooling solution that integrates both hardware and software components to enhance battery safety, efficiency and longevity.

Enhancing the longevity, security and effectiveness of lithium-ion batteries—especially in electric vehicles (EVs) requires predictive thermal management. Numerous research highlights sophisticated thermal tactics, such as proactive temperature management [8], cooling methods to avoid overheating [6] and predictive electrothermal models for temperature regulation [1]. In order to provide real-time and data-driven cooling solutions, machine learning has been thoroughly investigated for state-of-charge (SOC) prediction [4], battery health monitoring [5] and thermal management optimisation [2,7]. Additionally, researchers have suggested hardware-based solutions like Arduino and GSM- based systems for smart battery monitoring, automatic cooling. and fan control through microcontroller. Furthermore, research emphasises how discharge rates affect battery longevity [3] and how early problem identification might prevent thermal runaway [10]. Wireless power transfer [1] and innovative cooling strategies also enhance the reliability of the system through reducing thermal stress. Real time temperature sensing enables timely intervention.

The basic studies of heat generation and dissipation mechanisms are useful for the development of efficient thermal management models [9]. Thus, it is important to incorporate predictive modelling, machine learning and intelligent thermal management policies to improve the reliability and safety of lithium-ion batteries employed in electric cars. At the software layer, a linear regression algorithm uses historical trends to make predictions on temperatures. This feature enables the mechanism to proactively turn on a cooling fan to maintain the temperature of the battery within the safe limits. For optimal heat management, the fan speed is controlled based on the predicted temperatures of the battery. From the experimental data, it is evident that the system is effective in heat control and forecasting of battery temperatures and thus forms a solid base for improved battery management systems in various applications.

2. Proposed System

2.1 Block Diagram

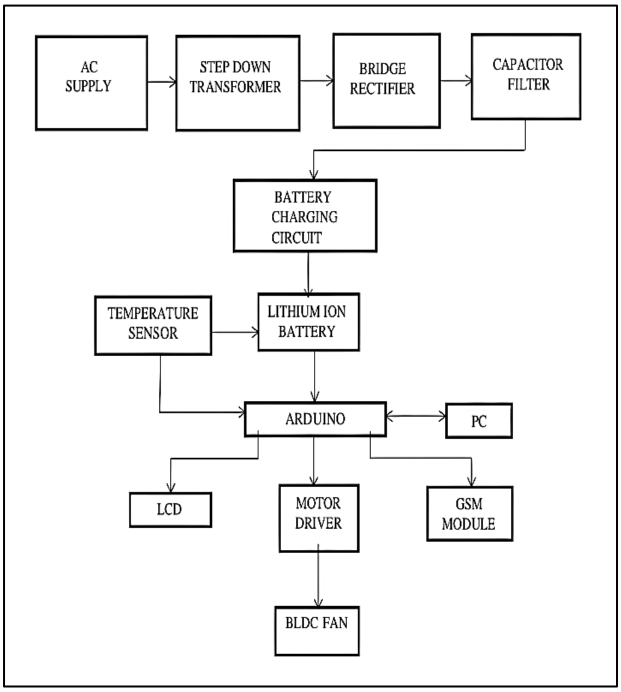

Figure 1. Block Diagram

The hardware block diagram in Figure 1 illustrates the essential components and operational flow within the lithium-ion battery management and monitoring system. The AC supply is stepped down by a transformer and directed to the battery charging circuit, facilitating the charging of the lithium-ion battery. This battery then connects to a number of peripheral devices and powers a load, in this case a DC motor. The Arduino microcontroller receives real-time data from a temperature sensor that tracks the battery's thermal state. An LCD for real-time information display, a GSM module for remote communication, and a motor driver for a BLDC fan that powers the cooling mechanism are just a few of the linked devices that the Arduino reads and controls. Moreover, a computer running a machine learning program to predict temperatures is integrated into the device [5]. This system anticipates the heat levels of the battery based on the temperature readings, from sensors. Enhancing cooling methods and minimizing risks enables heat regulation through predictive abilities; thus, guaranteeing safety and optimal performance of the battery.

3. Mathematical Modelling

The step-down transformer converts a primary voltage of 230V to a secondary voltage of 12V with a primary current of 0.052A and a secondary current of 1A. The power delivered is calculated as:

Primary Voltage (Vp): 230V

Secondary Voltage (Vs): 12V

Primary Current (Ip): 0.052A

Secondary Current (Is): 1A

$$Power\ (P)\ =\ Vs\ \times\ Is$$

$$P\ =\ 12\ \times\ 1\ =\ 12W$$

The load consists of a BLDC fan operating at 12V and consuming a current of 10mA. The power consumed by the fan is calculated as:

Voltage (V): 12V

Current (I): 10mA = 0.01A

$$Power\ (P)\ =\ V\ \times\ I =\ 12 \times 0.01\ =\ 0.12W$$

A current-limiting resistor ensures proper operation, maintaining a load current of 0.01A.

R = 1.2 kΩ

$$I\ =\ V/R\ =\ 12/\ 1.2 \times\ 10\hat{}-3\ =\ 0.01A$$

I = 0.01A (Load current)

$$Secondary\ side: Ps\ =\ Vs\ \times\ Is\ Ps\ =\ 12W$$

$$Is\ =\ Ps\ /\ Vs\ =\ 12\ /12\ =\ 1A$$

The transformer also maintains the voltage and current relationship as given below, ensuring efficient power transfer.

$$Vp \,/\, Vs \;=\; Np \,/\, Ns \;=\; 230\,/12 \;=\; 19.17$$

(where Np and Ns are the number of turns in the primary and secondary windings, respectively)

$$Is \,/\, Ip \;=\; Np \,/\, Ns \;=\; Vp \,/\, Vs$$

$$Ip \;=\; Is \,/\, Vp \;\times\; Vs$$

Ip = 1 / 230 × 12 = 0.052A

For an ideal transformer, primary power ($P1$) equals the secondary power ($P2$), Which is given as:

$P1 \;=\; P2$ (where $P1$ is the primary power and $P2$ is the secondary power)

$P1 \;=\; Vp \;\times\; Ip$ = 230 × 0.052 = 12W

The capacitor filter smoothens the rectified DC output. A ripple voltage of 10% of the output voltage is considered, along with a rectified output frequency of 100Hz and a load current of 1mA, the capacitance is calculated as:

$$V \;=\; 12V(DC)$$

Il = 10mA

Ripple Voltage, $Vr \;=\; Il \,/\, 2fC$

Vr = 10% of DC Output Voltage from rectifier

Vr = 10% of 12V= 1.2V.

Frequency, f = 50Hz (Supply)

Rectified Output frequency = 2f = 2 × 50 = 100Hz

Capacitance, $C \;=\; Il \,/\, 2fVr$

$$C \;=\; 10 \times\; 10\text{\^{}} - 3 \,/\, 2 \times 100 \times 1.2 \;=\; 0.04167 \;\times\; 10\text{\^{}} - 3\; F$$

C = 416.7µF~470µF

Capacitor Voltage = Twice the peak output voltage

$= 2\times 12 = 24V\sim25V.$

$C = 470\mu F, 25V.$

A standard capacitor value of 470µF, rated for 25V is chosen to handle twice the peak output voltage, ensuring reliable and stable DC output.

4. Circuit Diagram

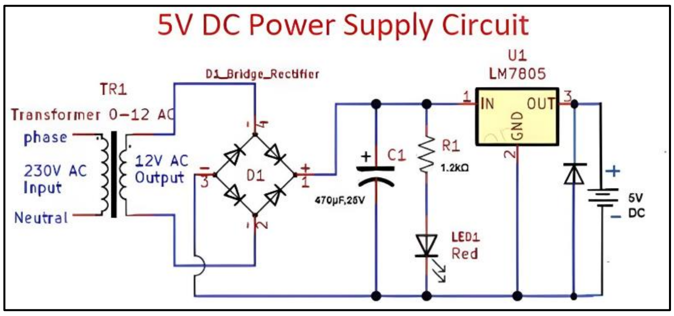

Figure 2. Circuit Diagram

The circuit, for the 5-volt DC power supply transforms the 230-volt AC voltage into a 5 volts DC. The DC output starts with a transformer (TR 1) which lowers the 230 volts input voltage to a level, for the system. The alternating current (AC) input is converted to 12 volts of AC power before being directed through a bridge rectifier labelled as D1. It transforms it into pulsating voltage before using a capacitor to even out the voltage levels. A capacitor, with a rating of 470µF and 25 volts capacity functions to smoothen out fluctuations and maintain a voltage output at 12 volts. The LM7805 voltage regulator converts the 12-volt DC power. Stabilizes it at a consistent 5-volt direct current output is maintained to provide a supply of voltage. There is an LED labelled LED 1, in the circuit. Using a 1200-ohm resistor (labelled as R_1) it serves as a power indicator by illuminating when the circuit's active. The 5-volt DC output is perfect, for running devices, with low voltage requirements. Electronic gadgets, like microcontrollers and sensors are often powered by batteries.

5. Working Methodology

Lithium-ion battery performance data was gathered and a thorough testing was done by charging the battery with a load, for 2 to 3 Hours using an Arduino. The data was saved in an Excel file and a linear regression model was used. A machine learning model using Python programming language was developed. The generated code is transmitted to the Arduino for temperature monitoring purposes. A sensor is utilized to measure the temperature of the battery. The information is then transferred to the Arduino board which then sends it to the laptop for analysis, by the machine learning model to forecast the temperature trends based on the data provided. The LCD display screen shows the temperature reading well as the future temperature reading, along with the variance, between them. The speed of a BLDC fan adjusts based on temperature changes to manage the battery's state effectively; additionally, it is intended to make sure quick measures are taken to prevent overheating and extend the battery's lifespan by sending an alert when the battery temperature reaches a threshold level.

6. Result

The temperature sensor detects the current temperature and sends it to the Arduino microcontroller when the load is powered by lithium-ion batteries. This temperature reading is then transmitted to the PC through the Arduino. After processing the received temperature data, the machine learning model forecasts the next temperature value, which is subsequently transmitted back to the Arduino. The next responsibility for the LCD display unit is to show the expected and actual temperature values as well as the computed difference between them. The fan is turned on in accordance with the temperature difference. The Hardware setup is illustrated in the Figure 3.

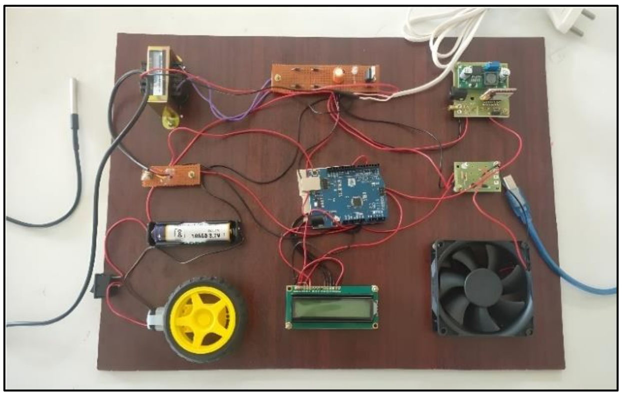

Figure 3. Hardware Working

The experimental results are presented Figure 4. The image 4(a) displays the current temperature (TMP), the predicted temperature (PREDICTDTMP) and the difference between them (D). The image 4(b)shows the speed of the BLDC fan (FAN) and its speed as a percentage.

(a)

(b)

Figure 4. (a), (b) Hardware Output

During hardware testing, the system displayed the current temperature value of 27.81°C on the LCD. This real-time temperature data was acquired by the temperature sensor, transmitted to the Arduino microcontroller and subsequently forwarded to the PC. The machine learning model running on the PC processed the received temperature data and predicted the temperature value after a 5-minute interval to be 30.30°C. The difference between the real-time temperature and the predicted temperature values is calculated, which is 2.49°C. This temperature difference is also displayed on the LCD. Based on this temperature difference, the BLDC fan was activated at a speed of 40%. This observed output during hardware testing is captured in the image above. The table provided further illustrates the correlation between the temperature differences and the corresponding fan speeds.

The relationship between the fan speed adjustments and the temperature difference is further illustrated in a Table 1 given below:

Table 1. Fan Speed Regulation

Temperature Difference (DIFF)	Fan Speed (PWM Value)	Fan Speed (%)	Action
0 ≤ DIFF < 1	0	0%	Fan OFF
1 ≤ DIFF < 2	50	20%	Low fan speed
2 ≤ DIFF < 3	100	40%	Medium-low fan speed
3 ≤ DIFF < 4	150	60%	Medium fan speed
4 ≤ DIFF < 5	200	80%	High fan speed
DIFF ≥ 5	255	100%	Full fan speed

7. Conclusion

A predictive thermal management system for lithium-ion batteries which uses linear regression to predict the variation in temperature and thus select the appropriate cooling methods is being proposed. This way, the system combines real time temperature data with predictive analysis to accurately predict the thermal fluctuations and control the cooling systems accordingly. The experimental validation proves that it can improve the battery lifetime, the system is controlled by temperature predictions and hence controls the heat release in a very energy efficient manner. Furthermore, the integration of GSM based alert system enhances the safety by sending real time alerts to avoid battery from overheating. In general, this approach can be a scalable and economical solution for lithium-ion battery thermal management and may be improved further with the help of advanced machine learning algorithms and adaptive cooling strategies.

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