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Optimizing Electric Vehicle Performance: Advances in Battery Management Systems for Enhanced Efficiency and Longevity

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Abstract

The management of electric car batteries has taken front stage in automotive research and development as more people choose electric vehicles (EVs). Optimal performance, safety, and lifetime of electric vehicles depend on effective battery management systems (BMS). To address this, we developed software for system functionality testing and a BMS prototype with an AVR ATmega family micro-controller. The originality of this work is the practical application of Arduino platform for BMS development, offering a scalable and reasonably priced solution that goes beyond past efforts by including the most recent technological developments and addressing modern challenges in the field. Conclusions drawn show that overcoming present battery performance constraints by developing BMS technology will open the path for more general EV acceptance.

Keywords: electric vehicles, battery management systems, power management.

1 Introduction

Globally attempts to lower greenhouse gas emissions and dependency on fossil fuels depend critically on the shift to electric vehicles (EVs). The electric car battery, a sophisticated and expensive component needing careful management to guarantee optimal performance, safety, and lifetime, is central to the viability and usefulness of EVs. Comprising several purposes including monitoring battery state, balancing charge across cells, thermal management, and safeguarding against operational anomalies, the Battery Management System (BMS) is in charge of this work.

The worldwide drive toward sustainable energy solutions have hastened the acceptance of electric vehicles (EVs), so bringing a major change from internal combustion engine vehicles to batterypowered substitutes. Advanced lithium-ion batteries enable electric vehicles, which present a potential answer to these problems. Maximizing the performance, safety, and lifetime of these batteries depends on their effective management, thus sophisticated Battery Management Systems must be developed.

An indispensable part of the running of electric vehicles, a battery management system is the "brain" of the battery pack. Thanks to this feature, which assures that the battery runs within safe limits, its performance is enhanced, and its lifetime is extended. Among the main parameters the BMS is in charge of monitoring of the state of charge (SOC), state of health (SOH), temperature, and voltage of every individual cell that compiles the battery pack. This approach helps to prevent overcharging, deep discharging, and thermal runaway—all of which might cause the battery to fail.

The whole efficiency, dependability, and safety of electric cars directly correlate with the effectiveness of a BMS. By means of appropriate management, one can greatly extend the lifetime of a battery, enhance the vehicle's performance, and lower the expenses related to battery replacement and maintenance. Furthermore, overcoming the constraints of current battery technologies by means of developments in battery management systems (BMS) technology opens the path for the general acceptance of electric vehicles (EVs).

A BMS performs several critical functions, including:

1. State of Charge (SOC)Estimation: Predicting the remaining driving range and guaranteeing effective energy consumption depend on accurate SOC estimation. Often used for SOC estimation are methods including Coulomb counting, Kalman filtering, and machine learning algorithms.

2. Monitoring: SOH monitoring evaluates power capacity and deliverability of the battery. This is absolutely essential for planning maintenance and estimating battery lifetime [2].

3. Thermal Management: Good thermal control guarantees the battery within ideal temperature ranges and helps to prevent overheating, so improving safety and performance. This is especially crucial since thermal problems might lower battery performance and, in severe cases, create safety risks [3].

4. Cell Balancing: Ensuring homogeneous charge across all battery cells helps to avoid imbalances that might cause lower efficiency or battery failure. Different balancing techniques—active and passive balancing among others—are used to keep cell equilibrium [4].

New developments in BMS technology have concentrated on including smart sensors, advanced materials, and complex algorithms. Silicon and solid-state batteries—which have better energy densities and safety profiles. Furthermore, improving the functionality of contemporary BMS are smart charging solutions and predictive maintenance approaches.

Using Arduino platform for BMS prototyping is one important advance in the field. For creating and testing BMS capabilities, Arduino-based systems provide a scalable, flexible, reasonably priced solution. By monitoring and regulating many facets of the battery, this approach offers a useful stage for experimentation and invention.

The specialized literature approaches this topic with great enthusiasm; the results are rather encouraging. In [5] the authors introduce an IoT-based battery monitoring system meant to increase the safety and efficiency of electric vehicle (EV) batteries. Using sensors to track important values including voltage, current, and temperature, the system offers consumers real-time data via mobile appplication. IoT technology's integration helps remote monitoring and data collecting, so improving maintenance plans and general battery performance. The study emphasizes how well the system keeps problems like overcharging and overheating under control, which are absolutely important for preserving battery life.

Furthermore, intriguing is the way the writers in [6] approach things. Particularly valuable for remote applications, this study presents a fresh approach for real-time monitoring of the state of charge (SOC) of batteries employing internal resistance measurements. The study underlines the need of precise SOC estimation in order to prevent overcharging and deep discharge so extending battery life and dependability. This approach shows great success in improving remote battery management; thus, it is a useful tool for uses when conventional monitoring techniques are difficult. The review [7] offers a comprehensive summary of battery management systems (BMS) applied in electric vehicles, covering main purposes including SOC and state of health (SOH) estimation, thermal management, and cell balancing. The paper emphasizes recent developments aiming to increase BMS accuracy and functionality including the integration of IoT technologies and artificial intelligence (AI). Emphasizing their vital importance in supporting the expanding EV market, the review also highlights the difficulties and future research directions required to develop more sophisticated and reliable BMS solutions. [8] investigates an IoT-based system for electric vehicle managing and energy consumption monitoring. The system generates real-time data on battery status including SOC and SOH using an ESP32 microcontroller and several sensors. By providing detailed and timely insights into their operational state, the integration of the Blynk IoT platform lets users access and monitor battery information via a mobile app, so greatly improving the efficiency and safety of electric vehicles.

In [9] the authors investigate an IoT-based system for tracking and controlling electric vehicle energy consumption. The system offers real-time battery status including SOC and SOH by means of an ESP32 microcontroller and diverse sensors. By means of a mobile application, the integration of the Blynk IoT platform enables users to access and monitor battery data, so greatly improving the efficiency and safety of EV batteries by providing comprehensive and timely insights on their operational state. Aimed at enabling vehicle-to-grid (V2G) operations, paper [10] presents a stochastic model for the state of charge (SOC) of EV batteries in a community. The work guarantees interoperability with home energy management (HEM) systems and other applications using CTA-2045 criteria. Using information from the national household travel survey (NHTS), the model generates synthetic communities and evaluates V2G service impact on the power distribution system. The results show that the suggested model can properly control power flow and preserve ideal SOC levels, so improving the integration of EVs into the grid. Offering a potential solution for advanced BMS in EVs, the paper [11] shows how well the adaptive dynamic programming (ADP) technique improves battery performance and lowers degradation. An ADP approach for battery management optimization in electric cars is also developed in this work. Through dynamically changing charging and discharging cycles depending on real-time data, the technique seeks to maximize battery life and efficiency. [12] authors address the safety and optimization of EV charging methods. The study investigates several charging situations in order to spot possible safety hazards and suggests ways to reduce them. The results underline the need of strong charging techniques and sophisticated monitoring systems to guarantee the safe and effective running of electric vehicles batteries.

According to [14] the performance and dependability of electric vehicles batteries may be much improved by including advanced power management technologies. This work examines several power management techniques for electric vehicles (EV batteries), with an eye toward extending battery life and best energy use. The work evaluates several techniques and control strategies to find the most efficient approaches for battery health maintenance and power distribution management. In [15] the design and implementation of a lithium battery management system (BMS) for electric vehicles is presented. Features in the system include cell balancing, thermal control, and SOC and SOH estimate. The implementation offers a practical answer for advanced BMS in EVs since it shows notable increases in battery monitoring accuracy and general system dependability. Focusing on their function in maximizing battery performance and energy efficiency, a review paper [16] addresses several energy management systems (EMS) applied in electric vehicles. The paper notes current developments in EMS technologies and suggests future study paths to handle current difficulties. The study emphasizes how important advanced EMS is to enhance the general sustainability and efficiency of electric vehicles. An introduction of battery management systems (BMS) together with their uses in the smart grid and electric vehicles is given in Article [17]. Important functions including thermal control, cell balancing, and SOC and SOH estimate are covered. In order to improve grid stability and energy management, the paper also investigates how BMS may be combined with smart grid technologies The results underline how important BMS is for enabling the switch to sustainable transportation and renewable energy.

Though much has been accomplished, several obstacles still exist in the evolution of BMS for electric vehicles batteries. These comprise enhancing thermal management systems, increasing SOC and SOH estimate accuracy, and creating reasonably priced cell balancing solutions. Furthermore, including IoT technologies and advanced materials into BMS offers possibilities as well as difficulties that call for more study.

Future studies are supposed to concentrate on the integration of artificial intelligence (AI) and machine learning (ML) algorithms into BMS, so enabling more accurate and flexible management strategies. Furthermore, the evolution of sophisticated materials like solid-state batteries calls for fresh methods of BMS design and application. Through addressing these issues, we can improve the lifetime, safety, and performance of electric car batteries, so supporting the wider acceptance of EVs.

Within the Politehnica University of Timisoara are teams in charge of building electric cars. Our team of research has created such a system to show the importance of battery management systems (BMSs) and guarantee efficient battery management of these vehicles.

2 Solution Architecture

In order to develop our own Battery Management System (BMS), our team studied such a system already established on the market, produced for BMW. For this project we used the TC375X microcontroller, from Texas Instruments. Communication with the microcontroller is done on CAN or CAN FD (1).

Battery cell monitoring is done using BQ7961X circuits, also from Texas Instruments, and communication with these circuits is done via the UART protocol. Such a circuit can monitor the voltage for up to 16 battery cells. The equipment can be done with either one 400 V battery or two 400 V batteries, 7 BQ chips will be needed to be able to monitor the cell voltage in the case with one battery and 14 in the case with two.

The BQ circuits, BQ79612-Q1, BQ79614-Q1, and BQ79616-Q1, provide high-precision cell voltage measurements in less than 200 μs for 12S, 14S, and 16S battery modules used in high-voltage vehicle battery management systems. There are different options for connecting channels in the same package, providing compatibility for a variety of pins. A number of filters are present that make it easy to measure the voltage and calculate the exact degree of charge.

Automatic balancing of the internal cells can be done by monitoring the temperature to automatically cut off in case of overload and exceeding the safe operating temperature. They have bidirectional ports that allow the possibility of using multiple BMS architectures. They have 8 GPIOs that can be used for temperature measurements with thermistors

3 Results

In what follows, the system developed by our research team is presented. The functionalities were mainly highlighted with the help of an Arduino Mega series development board, an I/O interface board and two batteries.

3.1 Hardware

The hardware side of the project was built using the following:

- Arduino Mega 2560 development board;

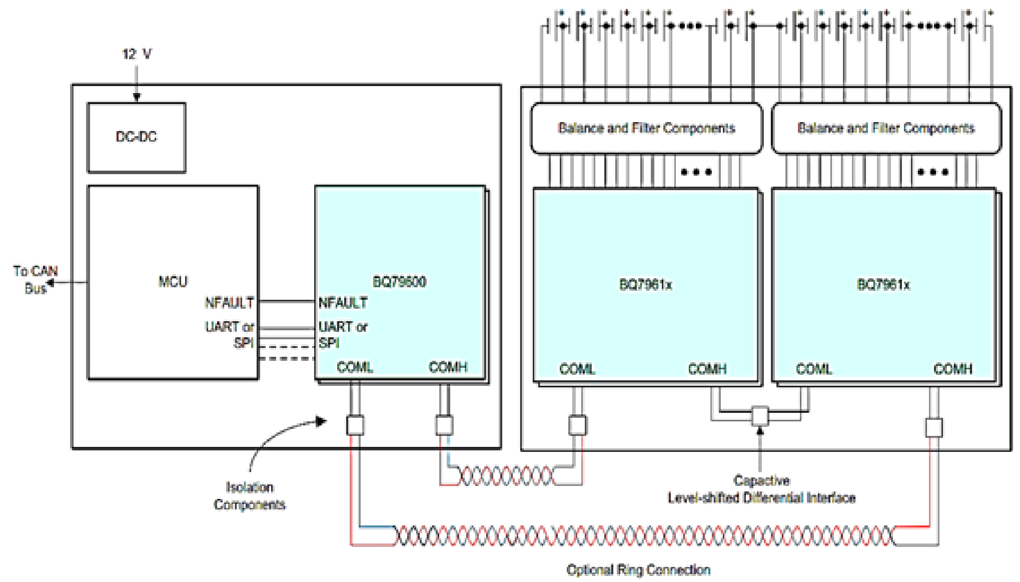

Figure 1: Simplified diagram of the BMS system

- Board (reffig2) with different input/output interfaces (buttons, contacts, low complexity but efficient human machine interface based on LEDs, potentiometers, relays etc.);
- Connection wires;
- Two batteries (HGL7-12 12V 7Ah).

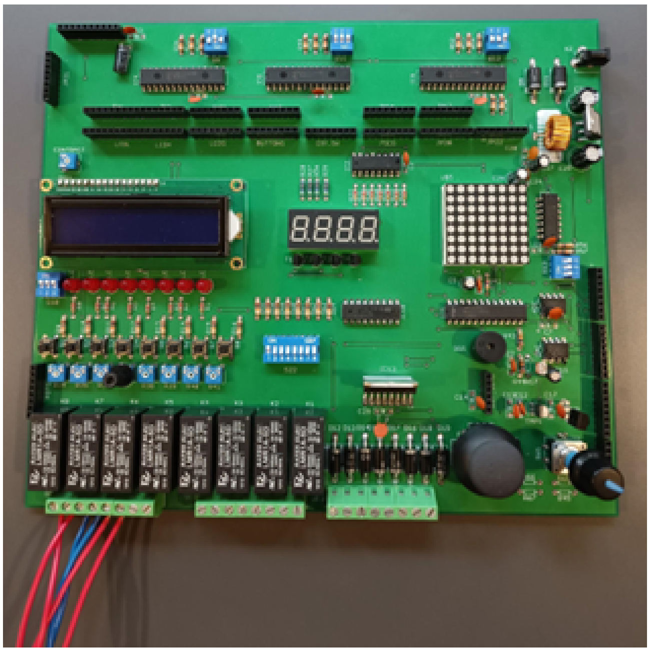

Figure 2: Input/output interfaces board

Seven potentiometers were used to represent seven battery cells. We have seven LEDs assigned to each cell to indicate when the voltage drops below the minimum limit. If the level of a battery drops by 20% compared to the nominal value, an LED will illuminate to indicate the voltage drop (Fig. 3). We simulated the temperature of the battery pack using an eighth potentiometer; if it exceeds the recommended maximum limit, an LED will flash and an audible signal will be triggered via a buzzer.

We used three contactors, a switch, and two accumulators to simulate the connection of two battery banks in series or parallel (Fig. 4). For electric car banks, the voltage must be 400 V in parallel (around

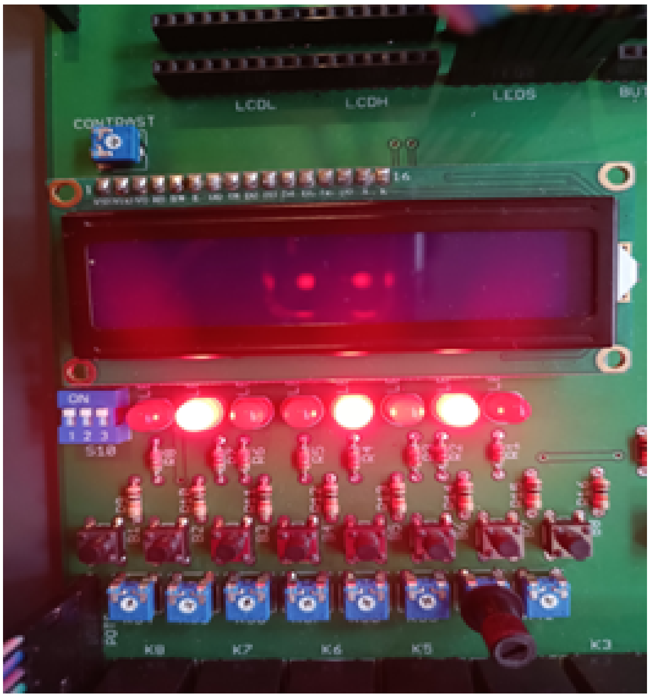

Figure 3: Signaling of falling below the minimum voltage threshold for cells 2, 5 and 7.

12 V in our case) and 800 V in series (around 24 V). The series and parallel connections are required because the charging stations supply different voltages, some at 400 V and others at 800 V.

Using these hardware components and the principles described above, was created two setups:

1. the first in which the accumulators were put in parallel, shown in figure 5
2. the first in which the accumulators were put in series, shown in figure 6

3.2 Software

After the hardware was properly built, the software component was designed to complete the battery management system. Given the development board used to control the device, the Arduino IDE was chosen for the software component implementation.

Following the defining constants associated to the I/O pins and the memory allocation for two integer-type variables with the purpose of tracking the cells operation and battery configuration, the utilized hardware registers were then initialized for operation as output in the Following the defining constants associated to the I/O pins and the memory allocation for two integer-type variables with the purpose of tracking the cells operation and battery configuration, the utilized hardware registers were then initialized for operating as output in the SETUP function. This was the first phase of the process illustrated in the following pseudocode.

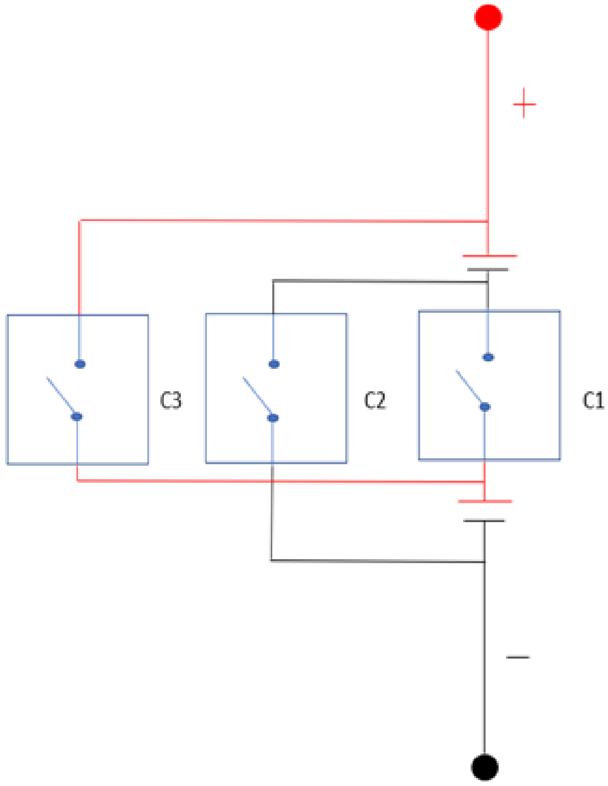

Figure 4: Contactors scheme

```
void setup()
{
  // pins 2-9 are used for the 8 LEDs
  pinMode(pinLed2, OUTPUT);
  pinMode(pinLed3, OUTPUT);
  pinMode(pinLed4, OUTPUT);
  pinMode(pinLed5, OUTPUT);
  pinMode(pinLed6, OUTPUT);
  pinMode(pinLed7, OUTPUT);
  pinMode(pinLed8, OUTPUT);
  pinMode(pinLed9, OUTPUT);
  // pins 11-13 are used for relay contacts
  pinMode(11, OUTPUT);
  pinMode(12, OUTPUT);
  pinMode(13, OUTPUT);
  // pin 1 is used to send signals to the buzzer
  pinMode(1, OUTPUT);
}
```

Following that, we proceeded to the next step, which was the development of the repetitive statement implemented in the body of the loop() function, which is where the majority of the operational process can be described. The following is an illustration of how an LED would be lit up in the event that the corresponding potentiometer was used to simulate a voltage value that was lower than the permitted tolerance.

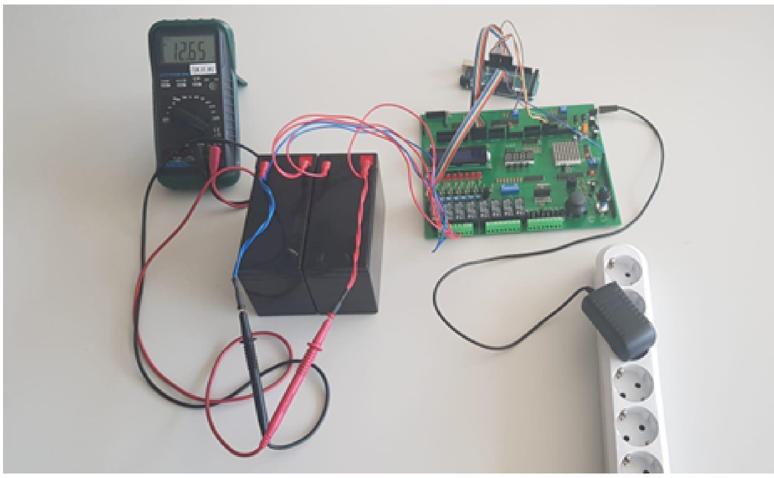

Figure 5: Accumulators in parallel

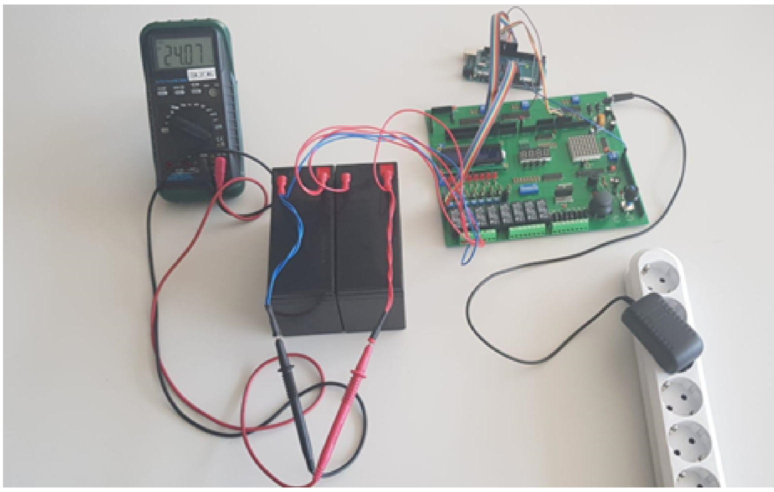

Figure 6: Accumulators in series

```
PROCEDURE VoltageMonitoring:
INPUT: cell monitored        // corresponding analog input
       VoltageLimitTreshold  // eg. 614 for 3 V
OUTPUT: cell status
Begin
    Read voltage level from analog input IN voltage-Level // eg. A0
    IF voltageLevel < VoltageLimitTreshold THEN
        Set pinLedPIN as HIGH
    ELSE
        Set pinLedPIN as LOW
    END IF
End
```

We correlated the values that the potentiometer produces with the voltage range that an electric car battery can normally be in, which is between 0 and 3.7 V. The potentiometer generates values between 0 and 1023. Based on the correlation, it has been determined that the value of 614 from the potentiometer corresponds to the value of 3 V, which is significantly lower than the value that is desired to be reached. When it came to the simulation of temperatures, we found a correlation between the range from 0 to 100 degrees Celsius and the range from the potentiometer. Mainly due to the fact that once the batteries reach a temperature of more than sixty degrees Celsius, they require cooling, we decided to use an LED that flashes and audible beeps to indicate that there is a critical problem.

The following pseudocode snippet illustrates how temperature monitoring and corresponding alarm are handled algorithmically.

```
PROCEDURE TemperatureMonitoring:
INPUT: cell monitored
// which analog inputs and alarm (eg. pinLed)
// correspond to this TemperatureLimitTreshold
// eg. 614 for 60 Celsius degree
OUTPUT: cell status and alarm
Begin
    Read temperature level from analog input IN temperatureLevel
    // eg. A7
    IF temperatureLevel < TemperatureLimitTreshold THEN
        Set pinLedPIN as LOW
        noToneAlarm()
    ELSE
        Set pinLedPINtoFlash()
        doToneAlarm()
    END IF
End
```

In accordance with the diagram presented in figure 4, the series and parallel connection was established by utilizing three contactors together. In order to avoid the situation, it is necessary to avoid having all three contacts closed.

```
PROCEDURE CellTopologyControl:
INPUT: Declare usedPins     // eg. pins 11, 12 and 13
OUTPUT: new series or parallel topology configuration
    Read pinContact status IN pinContactStatus // eg. A7
    IF NOT(pinContactStatus) THEN
        // eg. parallel configuration in our configuration
        Set pinContact as LOW
        For each pin IN usedPins NOT including pin-Contact DO
            Set pin as HIGH
        End
    ELSE
        // eg. series configuration in our configuration
        Set pinContact as HIGH
        For each pin IN usedPins NOT including pin-Contact DO
            Set pin as LOW
        End
    END IF
End
```

Combined all above mentioned procedures in a timed automaton model provides all the established BMS functionalities. This approach offers the advantages of both, programming language API level implementation, one based on a real-time executive approach or by using a real-time operating system API, when a higher level, portable and open solution is expected.

4 Conclusion

The increasing adoption of electric vehicles (EVs) has necessitated the advancement of efficient battery management systems (BMS) to ensure the optimal performance, safety, and longevity of EV batteries. This study contributes to this field by developing a BMS prototype using Arduino platform and a solution for batteries systems functionality testing. The practical application of Arduino based approach presents a cost-effective and scalable solution, extending beyond previous efforts by integrating the latest technological advancements and addressing contemporary challenges. The use of Arduino system-on-a-chip (SoC) platform for BMS development demonstrates a practical approach to creating affordable and scalable systems. This methodology provides a flexible platform for innovation, making advanced BMS technologies accessible to a broader range of applications and facilitating further research and development in the field. Despite significant progress, challenges remain in areas such as thermal management, accurate state estimation, and the integration of advanced materials. Future research should focus on incorporating artificial intelligence and machine learning algorithms into BMS for more advanced management strategies. Additionally, the development of solid-state batteries and other advanced materials will require new approaches to BMS design and implementation. Overall, this study highlights the critical role of new generation BMS technologies in supporting the transition to electric vehicles. By addressing existing challenges and leveraging new technologies, researchers and developers can create more reliable, efficient, and safe battery management systems, paving the way for a sustainable automotive future.

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