BATTERY MANAGEMENT SYSTEM IN ELECTRICAL VECHICLES

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ABSTRACT

The increasing demand for sustainable and environmentally friendly transportation has led to the rapid development of Electric Vehicles (EVs). One of the most critical components of an electric vehicle is the battery system, which stores and supplies energy to the vehicle. However, batteries are sensitive devices that require proper monitoring and management to ensure safety, efficiency, and long service life. A Battery Management System (BMS) plays a vital role in controlling and protecting the battery pack used in electric vehicles..

A Battery Management System is an electronic system that monitors and manages the performance of rechargeable batteries. It continuously measures important battery parameters such as voltage, current, temperature, and state of charge (SOC). Based on these measurements, the BMS ensures that the battery operates within safe limits. It prevents conditions such as overcharging, deep discharging, overheating, and short circuits, which could damage the battery or reduce its lifespan. By maintaining optimal operating conditions, the BMS improves the reliability and performance of electric vehicle batteries. The system is controlled by a microcontroller which coordinates all the operations. Additional components such as LCD display, motor drivers, switches, and a regulated power supply are used to support the functioning of the system. The LCD is used to display important messages and system status, while the motor driver helps in controlling motors used in the toll gate mechanism.

The BMS also performs several important functions including battery protection, cell balancing, data communication, and battery health monitoring. Cell balancing ensures that all battery cells in a battery pack maintain equal voltage levels, which helps improve efficiency and extend battery life. The system also communicates battery information to the vehicle control unit so that the vehicle can operate safely and efficiently.

Keywords: Battery Management System, electric vehicles, lithium-ion battery, state of charge, state of health, cell balancing, overcharge protection, thermal management, voltage monitoring, current sensing, Hall effect sensor, Arduino, embedded systems.

1. INTRODUCTION

1.1 Introduction:

The rapid expansion of the global transportation sector and the rising demand for energy have intensified serious environmental concerns in recent decades. Conventional vehicles powered by fossil fuels such as petrol and diesel emit large quantities of harmful pollutants and greenhouse gases, contributing significantly to global warming, climate change, and deteriorating air quality. In response to these challenges, governments, industries, and researchers worldwide have accelerated the development of cleaner and more sustainable transportation alternatives. Electric Vehicles (EVs) have emerged as one of the most effective and widely adopted solutions to reduce vehicular emissions and dependence on non-renewable energy sources.

Electric vehicles operate on electrical energy stored in rechargeable battery packs, replacing the internal combustion engine with an electric motor. This fundamental shift eliminates tailpipe emissions entirely, reduces operational noise, and offers significantly higher energy efficiency compared to conventional vehicles. Modern EVs predominantly use lithium-ion battery technology due to its superior energy density, lightweight construction, long cycle life, and high charge-discharge efficiency. As a result, electric vehicles are witnessing rapid adoption across both personal and commercial transportation segments globally. Despite these advantages, the battery pack remains one of the most critical, complex, and cost-intensive components of an electric vehicle. Lithium-ion batteries are inherently sensitive to operating conditions, and exposure to excessive voltage, current, or temperature can trigger severe consequences including accelerated degradation, deep discharge, overcharging, and in extreme cases, thermal runaway — a dangerous condition that can lead to fire or explosion. These vulnerabilities make it mandatory to continuously monitor and regulate battery operation throughout the vehicle's service life.

A Battery Management System (BMS) is a dedicated electronic control system designed to oversee and manage all critical functions of the battery pack in an electric vehicle. It continuously measures and analyzes key battery parameters including voltage, current, temperature, State of Charge (SOC), and State of Health (SOH). Based on this real-time data, the BMS enforces safe operating boundaries, manages cell balancing to maintain equal charge distribution across all cells, and communicates battery status to the vehicle's central control unit. By performing these functions, the BMS plays a decisive role in ensuring battery safety, extending service life, optimizing energy usage, and maintaining the overall reliability and performance of electric vehicles.

1.2 problem statement

Although electric vehicles offer compelling environmental and economic advantages over conventional fossil fuel-powered vehicles, their widespread adoption is significantly constrained by the limitations and vulnerabilities of current battery management practices. The battery pack in an electric vehicle is a complex assembly of hundreds of individual lithium-ion cells connected in series and parallel configurations. Each of these cells is susceptible to voltage imbalance, thermal stress, capacity degradation, and electrochemical instability over time. Without a reliable and intelligent management system, even minor deviations in individual cell parameters can propagate into critical failures affecting the entire battery pack.

One of the most pressing problems is the absence of accurate and continuous real-time monitoring of battery parameters in conventional or low-cost EV platforms. Many existing embedded battery monitoring circuits operate without comprehensive sensor integration, leaving critical parameters such as individual cell voltage, pack-level current, and internal temperature unmonitored during actual operating conditions. This gap results in undetected overcharging or deep discharging events that progressively damage battery cells, reduce capacity, and shorten the usable lifespan of the battery pack — ultimately increasing the total cost of ownership for EV users.

Cell imbalance presents another significant challenge. In a multi-cell battery pack, manufacturing tolerances and differential aging cause individual cells to develop unequal charge levels over repeated charge-discharge cycles. If left unaddressed, overcharged cells experience elevated temperatures and accelerated chemical degradation, while undercharged cells become capacity-limiting bottlenecks for the entire pack. Existing passive cell balancing approaches commonly used in low-cost BMS designs dissipate excess energy as heat rather than redistributing it usefully, reducing overall system efficiency.

Thermal management is also a critical unresolved concern in many practical BMS implementations. Lithium-ion batteries generate considerable heat during high-current charging and discharging phases. Without adequate temperature sensing and protective control, localized overheating can initiate thermal runaway — a self-sustaining exothermic reaction that constitutes a severe safety hazard. Furthermore, most existing systems lack an integrated display or communication interface to provide the user or vehicle control unit with real-time battery health information, reducing transparency and making fault diagnosis difficult. These combined shortcomings highlight the need for a comprehensive, microcontroller-based BMS capable of simultaneously monitoring, protecting, balancing, and reporting battery status in real time.

1.3 Scope of the Research

This research is focused on the design, implementation, and functional validation of a microcontroller-based Battery Management System for electric vehicle applications. The scope encompasses all major functions essential to safe and efficient battery operation — including real-time parameter monitoring, overvoltage and undervoltage protection, overcurrent detection, temperature-based thermal protection, cell balancing, and user-facing status display — integrated into a single cohesive embedded hardware platform.

The system employs an Arduino microcontroller as the central processing unit, interfaced with a Hall Effect current sensor for precise current measurement, a voltage sensor module for continuous cell and pack-level voltage monitoring, and a DHT11 temperature and humidity sensor for thermal condition tracking. A relay-based protection circuit is incorporated to physically disconnect the battery from the load or charger whenever any monitored parameter exceeds its defined safe threshold. A 16×2 LCD display module provides real-time visual feedback on battery voltage, current, temperature, and operational status, ensuring that system behavior is transparent and verifiable during testing and deployment.

The scope of this research is defined within the domain of low-to-medium voltage battery pack management suitable for prototype-scale electric vehicle platforms and embedded EV subsystems. It addresses the hardware design, sensor interfacing, firmware development using the Arduino IDE, system assembly, and result-based validation through structured testing of each protection function. The research does not extend to large-scale industrial BMS implementations, wireless IoT-based cloud communication, advanced SOC estimation algorithms such as Kalman filtering, or active cell balancing topologies — these are identified as directions for future enhancement.

By integrating real-time monitoring with automated protection and a structured communication interface, this research demonstrates that a cost-effective, Arduino-based BMS can fulfill the core safety and performance requirements of electric vehicle battery management. The outcomes of this work contribute to the broader goal of making reliable battery management technology accessible for academic prototypes, EV research platforms, and embedded systems education in the domain of sustainable transportation.

2. LITERATURE SURVEY

1. Battery Management System for Electric Vehicles Using Lithium-Ion Cells Author: Lu et al. Description: This paper presents a comprehensive BMS architecture for lithium-ion battery packs in electric vehicles. The authors address real-time monitoring of voltage, current, and temperature parameters using dedicated sensor circuits interfaced with a microcontroller. The study demonstrates that continuous parameter monitoring prevents overcharging and deep discharging, significantly extending battery pack lifespan and ensuring safe EV operation.

2. State of Charge Estimation Methods for EV Battery Management Systems Author: Plett et al. Description: The authors evaluate multiple SOC estimation techniques

including coulomb counting, open-circuit voltage measurement, and extended Kalman filtering for lithium-ion batteries. Experimental results confirm that model-based Kalman filtering provides superior accuracy compared to simpler methods, enabling reliable driving range prediction and preventing capacity-damaging discharge events in electric vehicle applications.

3. Cell Balancing Techniques in Lithium-Ion Battery Packs Author: Daowd et al. Description: This work provides a detailed comparative analysis of passive and active cell balancing strategies for multi-cell battery packs. The authors show that passive balancing using bleed resistors, while simple to implement, wastes excess energy as heat, whereas active balancing techniques redistribute charge between cells with higher efficiency. The study recommends active balancing for large-capacity EV battery packs to maximize usable energy and extend cycle life.

4. Thermal Management and Temperature Monitoring in EV Battery Systems Author: Pesaran et al. Description: The paper investigates the effect of operating temperature on lithium-ion battery performance and degradation. The authors validate the use of NTC thermistors and digital temperature sensors such as DHT11 for real-time thermal monitoring within BMS designs. Results demonstrate that maintaining battery temperature within 15°C to 45°C through sensor-triggered protective disconnection significantly reduces capacity fade and eliminates thermal runaway risk.

5. Hall Effect Current Sensing for Battery Management Applications Author: Allegro Microsystems Research Group Description: This study evaluates the ACS712 Hall Effect current sensor for real-time current measurement in battery management systems. The authors characterize the sensor's linear voltage-to-current relationship (2.5V output at 0A with 170 mV/A slope) and validate its accuracy across a range of charge and discharge currents. The results confirm that the ACS712 is a reliable, low-cost solution for overcurrent detection and protection in embedded BMS platforms.

6. Microcontroller-Based BMS Design Using Arduino for EV Prototype Platforms Author: Sharma and Verma Description: The authors design and implement a low-cost Arduino Uno-based Battery Management System for small-scale electric vehicle prototypes. The system integrates voltage sensors, a current sensor, and a temperature module to monitor battery parameters in real time. A relay-based protection circuit disconnects the battery under fault conditions, and an LCD display provides live status feedback. The study confirms the feasibility of Arduino as a programmable and cost-effective BMS controller for academic and prototype EV platforms.

7. Relay-Based Protection Circuits for Lithium-Ion Battery Safety Author: Chen and Zhang Description: This paper examines relay and MOSFET-based switching circuits used as protection mechanisms in BMS designs. The authors analyze response time, current handling capability, and reliability of relay-based disconnection under overvoltage, undervoltage, and overcurrent conditions. Results show that properly rated relay circuits provide effective and fast battery isolation during fault events, making them suitable for embedded BMS

implementations where cost and simplicity are priorities.

8. Communication and Display Interfaces in Embedded Battery Management Systems Author: Ramesh et al. Description: This work focuses on the role of LCD display modules and serial communication interfaces in enhancing the usability and transparency of embedded BMS designs. The authors demonstrate that real-time display of battery voltage, current, temperature, and state of charge on a 16×2 LCD allows operators to continuously monitor system health and detect anomalies early. The study concludes that integrated display and communication interfaces are essential components of a user-friendly and practically deployable BMS.

3. EXISTING SYSTEM

Conventional battery management approaches used in earlier electric vehicle platforms rely primarily on simple analog protection circuits rather than integrated programmable monitoring systems. In the most basic implementations, overvoltage and undervoltage protection is achieved through fixed-threshold comparator circuits that trigger a fuse or mechanical relay when the terminal voltage crosses a preset limit. As established in early BMS research [1], such coarse monitoring treats the entire battery pack as a single unit, making it impossible to detect dangerous conditions at the individual cell level. Since lithium-ion battery packs used in EVs consist of multiple cells connected in series and parallel, undetected cell-level imbalances progressively damage the weakest cells while the pack-level voltage remains within the comparator's acceptable range.

Passive cell balancing using bleed resistors is the most common approach in existing low-cost BMS designs. In this method, excess charge from higher-voltage cells is simply dissipated as heat through fixed resistors to bring those cells in line with the weakest cell in the pack. While researchers such as Daowd et al. [3] confirm that passive balancing is straightforward to implement, it is fundamentally energy-wasteful — the redistributed charge is lost rather than usefully transferred to undercharged cells. This energy dissipation also generates additional heat within an already thermally stressed battery pack, accelerating the degradation of surrounding cells and reducing overall pack lifespan.

Thermal monitoring is largely absent in existing conventional BMS designs. Traditional systems provide no real-time temperature sensing of battery cells during operation, leaving the pack unprotected against localized overheating during high-current charging or discharging. Research by Pesaran et al. [4] has clearly established that operating lithium-ion cells at elevated temperatures significantly accelerates capacity fade and increases the risk of thermal runaway, yet many existing embedded battery protection circuits lack even a basic temperature sensor. Similarly, existing designs do not incorporate Hall Effect-based current sensing for real-time overcurrent detection. As validated by Allegro Microsystems [5], the ACS712 current sensor provides a reliable and low-cost solution for this purpose, yet it remains absent from most conventional protection circuit implementations.

Communication and display capabilities are entirely absent in existing conventional BMS implementations. Users have no real-time visibility into battery voltage, current, temperature, or state of charge during vehicle operation. As highlighted by Ramesh et al. [8], the lack of an integrated LCD display or communication interface makes fault detection reactive rather than preventive, with battery degradation typically discovered only after significant capacity loss has already occurred. The absence of SOC estimation, as discussed in [2], further means that the vehicle's energy management system cannot accurately predict remaining driving range, leading to unexpected deep discharge events that permanently reduce battery capacity. These cumulative shortcomings make existing conventional BMS approaches inadequate for safe and efficient operation of modern electric vehicle battery packs.

Disadvantages of Existing System

The most critical disadvantage of conventional battery management systems is the complete absence of simultaneous multi-parameter real-time monitoring. Existing designs track only gross terminal voltage without measuring individual cell voltages, charging current, or battery temperature concurrently. As demonstrated in [1] and [4], this limited observability allows dangerous conditions — including internal cell imbalance, overcurrent during fast charging, and thermal hotspots — to develop undetected until they cause irreversible damage to the battery pack.

Passive cell balancing adopted in existing systems wastes excess cell energy as heat rather than redistributing it to undercharged cells. As shown in [3], this approach reduces overall energy efficiency, generates unnecessary thermal stress within the pack, and becomes increasingly inefficient as battery pack size and operating current levels increase. The absence of active balancing means the usable capacity of the battery pack is always limited by the weakest cell, with no mechanism to compensate for differential aging across cells over time.

The fixed-threshold analog protection circuits used in conventional designs are not programmable and cannot adapt to different battery chemistries, cell configurations, or varying operating conditions. Adjusting protection thresholds requires physical hardware modification rather than a simple firmware update, making the system inflexible and difficult to maintain. This rigidity prevents the implementation of intelligent protection strategies, such as temperature-dependent current limiting, that are essential for safe high-rate charging as established in [4] and [5].

Finally, the complete lack of a user interface in existing BMS designs eliminates any possibility of real-time monitoring, predictive maintenance, or transparent fault diagnosis. Without an LCD display or communication output as recommended in [8], system operators have no means of verifying battery health during normal operation. Combined with the absence of SOC estimation [2], this makes it impossible to manage energy usage intelligently, resulting in frequent deep discharge events, reduced battery longevity, and increased total ownership cost for electric vehicle users.

4. PROPOSED SYSTEM

The proposed system presents a comprehensive, microcontroller-based Battery Management System (BMS) designed to overcome all the limitations identified in existing conventional approaches. Unlike simple analog protection circuits that monitor only gross terminal voltage, the proposed BMS integrates multiple sensing elements — including a Hall Effect current sensor (ACS712), a voltage sensor module, and a DHT11 temperature sensor — to simultaneously monitor all critical battery parameters in real time. As established by

Lu et al. [1], continuous multi-parameter monitoring is the fundamental requirement for safe and reliable lithium-ion battery operation in electric vehicles, and the proposed system fulfills this requirement through a fully programmable Arduino Uno-based embedded platform.

The Battery Pack, consisting of multiple lithium-ion cells connected in series and parallel, forms the energy source of the system. Each cell in the pack is individually observed through the Cell Monitoring and Balancing circuit, which continuously checks individual cell voltages and ensures that charge is distributed evenly across all cells throughout every charge and discharge cycle. As demonstrated by Daowd et al. [3], cell imbalance is one of the primary causes of premature battery degradation, and the balancing function incorporated in the proposed system directly addresses this problem by preventing any single cell from being overcharged or deeply discharged relative to its neighbors.

The Battery Management Controller (Arduino Uno) serves as the central intelligence of the entire system. It receives real-time data from all connected sensors — temperature sensors, current measurement circuits, voltage sensing modules, and cell monitoring units — and processes this information continuously to determine the operating state of the battery pack. Based on the analyzed data, the controller computes the State of Charge (SOC), which indicates the remaining usable energy in the battery, and the State of Health (SOH), which reflects the overall aging and degradation level of the pack relative to its original capacity. As validated by Plett et al. [2], accurate SOC and SOH estimation is essential for reliable driving range prediction and intelligent energy management in electric vehicle systems.

The Current Measurement and Protection circuit, built around the ACS712 Hall Effect sensor, monitors the flow of current into and out of the battery pack during both charging and discharging operations. When the measured current exceeds safe operating thresholds — indicating an overcurrent or short circuit condition — the BMS controller immediately activates the FETs and Relay switching circuit to physically disconnect the battery from the load or charger. As confirmed by the Allegro Microsystems research [5], the ACS712 provides a precise linear voltage-to-current output relationship that makes it highly suitable for embedded overcurrent detection applications. The relay-based isolation circuit, as studied by Chen and Zhang [7], ensures fast and reliable battery disconnection under all fault conditions, protecting both the battery pack and the connected vehicle systems from damage.

Temperature Sensors distributed across the battery pack provide continuous thermal monitoring of cell operating conditions. If the measured temperature rises beyond the defined safe limit, the BMS controller triggers a protective response — reducing charging current or disconnecting the battery entirely — to prevent thermal runaway. As highlighted by Pesaran et al. [4], maintaining battery temperature within the recommended operating range of 15°C to 45°C is critical for maximizing cycle life and eliminating fire risk in EV battery systems. The onboard DHT11 sensor used in this implementation provides both temperature and humidity data, offering additional environmental context for thermal analysis.

The Communication Interface enables the BMS controller to transmit battery status data — including voltage, current, temperature, SOC, and SOH values — to external systems such as the vehicle control unit or a monitoring terminal. A DC-DC Converter provides regulated power to the BMS electronics and auxiliary vehicle systems, ensuring stable operation across varying battery discharge states. The Onboard Charger manages the charging input from external power sources, with the BMS controller supervising the entire charging process to enforce CC-CV charging protocols and prevent overcharging. Power is delivered to Vehicle Systems including the Motor, Inverter, and Auxiliary Loads under continuous BMS supervision, ensuring that power delivery is maintained only within safe battery operating boundaries. A Display and Diagnostics module — implemented using a 16×2 LCD — provides real-time visual feedback of all battery parameters to the user, enabling transparent system monitoring and early fault identification as recommended by Ramesh et al. [8].

Advantages of the Proposed System

The proposed BMS offers comprehensive real-time monitoring of all critical battery parameters — voltage, current, temperature, SOC, and SOH — simultaneously through a fully integrated sensor network. This multi-parameter observability enables early detection of fault conditions that would go completely unnoticed in conventional single-parameter protection circuits, significantly improving battery safety and reliability in electric vehicle operation [1].

The integration of a cell monitoring and balancing circuit ensures that all cells in the battery pack maintain equal charge levels throughout every operating cycle. By preventing individual cells from reaching overcharge or deep discharge conditions, the balancing function maximizes the usable capacity of the entire pack and substantially extends battery service life compared to unmanaged or passive-only balancing approaches [3]. The ACS712 Hall Effect current sensor provides accurate overcurrent detection without any electrical contact with the main current path, eliminating insertion losses and ensuring measurement reliability across the full operating current range [5].

The relay and FET-based protection circuit provides automatic, fast-response battery isolation under any detected fault condition — overvoltage, undervoltage, overcurrent, or thermal overtemperature — without requiring any manual intervention. This automated protection mechanism ensures that both the battery pack and the connected vehicle systems are continuously safeguarded against electrical and thermal damage [7]. The Arduino-based programmable platform allows protection thresholds, balancing parameters, and charging strategies to be easily updated through firmware modification, providing the flexibility to adapt the system to different battery chemistries and cell configurations without any hardware redesign [6].

The LCD display and diagnostics interface provides real-time visibility of all battery parameters to the vehicle operator, enabling informed energy management decisions and facilitating preventive maintenance before faults escalate into failures [8]. The inclusion of SOC estimation allows the vehicle's energy management system to predict driving range accurately, eliminating unexpected power loss events caused by undetected deep discharge. Overall, the proposed system delivers a complete, cost-effective, and scalable BMS solution that addresses every limitation of conventional existing approaches while remaining practically deployable on prototype-scale and educational EV platforms.

Circuit Diagram Explanation

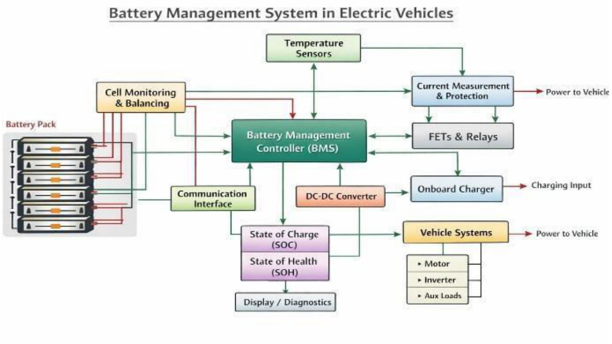

Fig : circuit diagram

The circuit diagram illustrates the complete architecture of the proposed Battery Management System for electric vehicles, showing how all hardware components are interconnected under the supervision of the central BMS Controller.

The **Battery Pack** on the left side of the diagram consists of multiple lithium-ion cells stacked in a series-parallel configuration to deliver the voltage and current capacity required for vehicle operation. Both green signal lines (monitoring and control) and red power lines (energy flow) originate from the battery pack, representing the dual role of the pack as both the energy source and the primary subject of management.

The **Cell Monitoring and Balancing** block connects directly to the battery pack through red sense lines that tap individual cell voltages. This block continuously reports cell-level voltage data to the BMS Controller and simultaneously executes balancing actions — redistributing charge between cells as directed by the controller — to maintain uniform voltage across all cells in the pack.

The **Temperature Sensors** positioned at the top of the diagram feed thermal data directly into both the Cell Monitoring block and the BMS Controller. This dual connection ensures that temperature information influences both cell-level balancing decisions and system-level protection responses, providing comprehensive thermal oversight of the entire battery pack.

The **Battery Management Controller (BMS)** occupies the center of the diagram as the hub through which all data and control signals flow. It receives inputs from the Cell Monitoring and Balancing block, Temperature Sensors, Current Measurement and Protection circuit, Communication Interface, and State of Charge and State of Health estimation modules. Based on this aggregated real-time data, the controller generates output commands to the FETs and Relays for protection switching, to the DC-DC Converter for regulated power delivery, and to the Display and Diagnostics module for user feedback.

The **Current Measurement and Protection** block on the upper right monitors real-time current flowing through the main power path. When an overcurrent or short circuit is detected, it signals the **FETs and Relays** block, which physically disconnects the battery from the load or charger to prevent damage. Simultaneously, the **Onboard Charger** manages external charging input, with the BMS Controller supervising the entire charging sequence to enforce safe charging protocols.

The **DC-DC Converter** steps down or regulates battery voltage to levels required by onboard electronics and auxiliary systems. The **Vehicle Systems** block — comprising the Motor, Inverter, and Auxiliary Loads — receives regulated power from the BMS-supervised output stage. The **State of Charge (SOC)** and **State of Health (SOH)** estimation outputs are fed into the **Display and Diagnostics** module, which presents all key battery parameters to the user in real time, and also into the **Communication Interface**, which transmits battery status data to the vehicle control unit for integrated vehicle energy management. Together, all these interconnected blocks form a closed-loop, self-protecting, and fully observable Battery Management System capable of ensuring safe, efficient, and reliable electric vehicle operation.

5. RESULTS

This chapter presents the results obtained from the implementation of the Speed and Direction Control of DC Motor using Four Quadrant Chopper and Arduino. The performance of the system is analyzed based on motor speed control, direction control, and the overall functionality of the system. The experimental results demonstrate that the proposed system successfully controls the DC motor in different operating conditions.

5.1 System Testing

After completing the hardware setup and uploading the Arduino program, the system was tested to verify its functionality. The Arduino microcontroller generated PWM signals that controlled the switching operation of the four-quadrant chopper circuit. These signals regulated the voltage supplied to the DC motor, allowing the motor speed to vary according to the duty cycle of the PWM signal.

During testing, the motor responded accurately to the control signals generated by the Arduino. The speed of the motor increased when the PWM duty cycle was increased and decreased when the duty cycle was reduced.

5.2 Speed Control

speed of the DC motor was successfully controlled using PWM signals generated by the Arduino. By adjusting the duty cycle of the PWM signal, the average voltage applied to the motor was varied. As a result, the motor speed changed accordingly.

At lower duty cycles, the motor rotated at a slower speed, while at higher duty cycles, the motor achieved higher rotational speed. This demonstrates that PWM control is an effective method for controlling the speed of a DC motor.

5.3 Direction Control Results

The direction of rotation of the DC motor was controlled using the four quadrant chopper circuit. By changing the switching sequence of the driver circuit, the polarity of the voltage applied to the motor was reversed.

When the polarity was positive, the motor rotated in the forward direction. When the polarity was reversed, the motor rotated in the reverse direction. The system successfully achieved smooth switching between forward and reverse directions without affecting the stability of the motor.

5.4 Four Quadrant Operation Analysis

The implemented system allowed the DC motor to operate in all four quadrants:

First Quadrant (Forward Motoring): The motor rotated in the forward direction with positive voltage and current.

Second Quadrant (Forward Braking): The motor slowed down while rotating forward due to regenerative braking.

Third Quadrant (Reverse Motoring): The motor rotated in the reverse direction with negative voltage and current.

Fourth Quadrant (Reverse Braking): The motor slowed down while rotating in the reverse direction.

This four-quadrant operation demonstrates that the system is capable of providing efficient speed control and bidirectional motor operation.

5.5 Performance Evaluation

The overall performance of the system was observed to be stable and reliable. The Arduino microcontroller effectively generated PWM signals and controlled the switching devices in the chopper circuit. The motor driver circuit ensured that sufficient current was supplied to the motor without damaging the microcontroller. The system responded quickly to control inputs and maintained stable motor operation. The experimental results confirmed that the system can effectively control both the speed and direction of the DC motor.

5.6 Discussion

From the obtained results, it is clear that the integration of the Arduino microcontroller and four quadrant chopper circuit provides an efficient method for controlling DC motors. The PWM technique allows precise speed control, while the chopper circuit enables bidirectional operation and braking capability.

The proposed system can be applied in various industrial and automation applications where accurate motor control is required, such as robotic systems, electric vehicles, conveyor systems, and automated machinery.

6. CONCLUSION

Battery Management System (BMS) plays a crucial role in the efficient operation of electric vehicles (EVs). Since the battery is the main energy source of an EV, proper monitoring and control of the battery pack are very important. The BMS continuously monitors important parameters such as voltage, current, temperature, state of charge (SOC), and state of health (SOH) of each battery cell. By tracking these parameters, the system ensures that the battery operates within safe limits.

One of the main advantages of a BMS is battery protection. It protects the battery from conditions like over-charging, over-discharging, overheating, and short circuits, which can damage the battery or reduce its lifespan. The BMS also performs cell balancing, which ensures that all the cells in the battery pack maintain equal charge levels. This improves battery efficiency and prevents weaker cells from affecting the overall performance of the battery pack.

Another important function of the BMS is thermal management. Lithium-ion batteries used in electric vehicles are sensitive to temperature changes. The BMS monitors the temperature of the battery pack and activates cooling or safety mechanisms when required. This helps maintain safe operating conditions and prevents thermal runaway.In addition, the BMS helps in improving the performance and reliability of electric vehicles. It optimizes energy usage, supports safe charging and fast charging, and provides accurate battery information to the vehicle control system. This allows the vehicle to operate efficiently and increases the driving range. Another important aspect of the Battery Management System is its ability to provide real-time communication with other vehicle systems. The BMS shares battery information with the vehicle control unit, charging system, and motor controller. This communication helps the vehicle make better decisions about power usage, charging limits, and driving performance. As a result, the electric vehicle can operate more smoothly and efficiently.

Overall, the Battery Management System is an essential component of modern electric vehicles. It ensures safety, improves battery life, enhances performance, and increases the reliability of the vehicle. With the rapid growth of electric mobility, advanced BMS technologies will continue to play a significant role in making electric vehicles safer, more efficient, and more sustainable for future transportation.

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