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Development of a Polymer-Encapsulated IoT-Based Sensor for Thermal and Electrical Protection of EV Batteries

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Abstract

Electric Vehicles (EVs) mark a critical shift toward sustainable transportation, with Battery Management Systems (BMS) playing a vital role in ensuring battery safety, reliability, and efficiency. The proposed BMS in this project incorporates real-time charge monitoring, temperature sensing, and fire detection capabilities to address safety concerns associated with lithium-ion batteries. Key features include current and voltage tracking, State of Charge (SoC) estimation, fault detection, and a user-friendly LCD interface. By continuously evaluating battery parameters, the system prevents overcharging, overheating, and thermal runaway, helping avoid fire hazards while extending battery life. A significant innovation in this design is the integration of polymer and polymer composite materials in key components. Flame-retardant polymer enclosures are used to insulate high-voltage circuits and protect electronics from thermal damage. Phase change materials (PCMs) and thermally conductive polymer composites support effective heat dissipation around battery modules and Peltier cooling elements. These materials are lightweight, electrically insulating, and capable of withstanding high temperatures ideal for electric vehicle environments. The use of polymer-based solutions strengthens the system's ability to prevent and contain fire incidents, contributing to a safer EV ecosystem. By combining intelligent electronics with materials engineering, the proposed BMS not only improves safety and performance but also promotes broader acceptance of EV technology through enhanced user trust and operational resilience.

Keywords: Electric Vehicle, Battery Management System, Fire Protection, Polymer

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INTRODUCTION

Electric vehicles (EVs) are rapidly emerging as the cornerstone of next-generation sustainable transportation, offering a cleaner alternative to fossil fuel-based mobility. However, the safety-related technologies supporting EV functionality particularly those surrounding battery management are still in their nascent stages. Among the most critical concerns is the incidence of battery-related fires and explosions, which have been documented as the leading cause of fire events in electric vehicles. In fact, recent studies reveal that EVs are involved in up to 50% more fire-related traffic incidents compared to traditional gasoline or diesel-powered vehicles [1–3]. Consequently, improving the operational safety and thermal stability of lithium-ion batteries is of paramount importance within the automotive industry.

In this context, the present research addresses the urgent need for enhanced battery safety through the design and implementation of an IoT-based Battery Management System (BMS). The proposed system integrates several components including sensors for voltage and temperature monitoring, relays for circuit protection, exhaust fans for thermal dissipation, Peltier plates for temperature regulation, a PIC microcontroller for real-time data processing, Bluetooth connectivity, and an LCD interface for user interaction. Together, these elements enable real-time monitoring and proactive intervention to prevent overheating, thermal runaway, and potential fire hazards, thereby contributing to safer and more efficient EV operation. Beyond the electronics and control framework, this study emphasizes the critical role of polymers and polymer composites in advancing EV battery safety. Polymers are extensively employed in battery systems for thermal insulation, electrical isolation, and structural protection. High-performance polymer composites such as epoxy resins, polyimides, and thermoplastic elastomers serve as fire-retardant enclosures, phase change materials (PCMs) for thermal buffering, and lightweight structural barriers that absorb shock and vibration. These materials not only enhance safety during thermal events but also improve mechanical stability and environmental resistance, which are essential for vehicle longevity and passenger safety [4, 5].

This integration of polymeric materials into the BMS framework promoted interdisciplinary research on the development, characterization, and application of polymer-based materials. The incorporating advanced polymer composites into the safety infrastructure of EV batteries, this research contributes to both the field of materials science and the evolving standards of electric vehicle safety, paving the way for safer and more reliable energy storage technologies.

BACKGROUND STUDY

To control the charging and discharging of a lead-acid battery driven by a PV generator, a fully integrated Battery Management System (BMS) prototype was created. The system allows temperature-compensated charging and includes a series solar regulator. To determine the battery's available capacity, it computes the State of Charge (SoC) [6, 7], enabling the implementation of intelligent control techniques. The BMS also features an LCD for real-time feedback to users and acts as a data recorder, capturing key operational variables during testing.

Technological advancements pertaining to the thermal safety of lithium-ion batteries (LIBs) have been extensively explored in recent research. For LIB packs, detailed studies have focused on (a) thermal behavior, modeling, and testing; (b) thermal runaway mechanisms; and (c) active and passive safety management strategies. These batteries are now integral to a wide range of applications from handheld electronics to large-scale electric vehicle systems. Despite their efficiency and energy density, LIBs present significant safety hazards, including susceptibility to thermal runaway and fire. A number of high-profile incidents have highlighted the urgency of developing safer, more resilient energy storage systems [8, 9].

To address these challenges, increasing attention has been directed toward the integration of polymeric materials and polymer composites for thermal management and safety enhancement. For instance, flame-retardant polymers such as polyimides and polyvinylidene fluoride (PVDF) are commonly employed as separators and coatings within battery cells to inhibit thermal propagation. Phase change polymer composites (PCMs), which absorb and dissipate heat during operation, are also used to passively regulate battery temperature. Epoxy-based composite enclosures and silicone-based thermal interface materials (TIMs) provide mechanical protection while ensuring effective heat conduction away from battery modules. Recent studies have further demonstrated that polymer nanocomposites, reinforced with ceramic or carbon-based fillers, can dramatically improve thermal conductivity without compromising electrical insulation key for safe battery pack design in electric vehicles. These polymeric solutions not only enhance fire suppression and thermal regulation but also support the trend toward lightweight, compact, and scalable battery system designs [10, 11].

The Table 1 shown comparative analysis of EV battery management system.

Table 1. Comparative Analysis of EV Battery Management.

Technology	**Description**	**Advantages**	**Disadvantages**	**References**
Thermal Management	Systems that use liquid cooling, air cooling, or phase-change materials to regulate battery temperature during charging.	- Prevents overheating and thermal runaway. - Prolongs battery life- Enhances charging efficiency.	- Increases system complexity and cost. - Requires regular maintenance- Additional weight in the vehicle.	[12]
Battery Management (BMS)	Monitors and controls cell voltage, temperature, and state of charge (SOC) during charging to ensure safety and efficiency.	- Protects against overcharging and deep discharge. - Enhances overall battery performance. - Facilitates fault detection.	- May fail under extreme conditions without redundancy- Adds cost to the battery pack. - Requires periodic updates.	[13]
Overcurrent Protection	Fuses and circuit breakers prevent excessive current during fast charging.	- Prevents short circuits and battery damage- Simple and reliable- Essential for safety compliance.	- Requires replacement after activation (fuses). - Limited ability to prevent other types of failures (e.g., thermal issues).	[14]
Voltage Regulation Circuits	Circuits ensure the battery is charged within a safe voltage range, protecting cells from overvoltage.	- Prevents battery degradation due to overvoltage- Improves charging efficiency- Reduces risk of thermal runaway.	- Additional hardware increases cost. - Limited to voltage-related protection.	[15]
Fire Suppression Systems	Integrated fire suppression mechanisms, such as foam, gas, or aerosol-based systems, in charging stations or vehicles.	- Immediate response to battery fires. - Increases safety during emergencies. - Limits damage to surrounding areas.	- High installation and maintenance costs. - Requires proper training for handling.	[16]
Insulation and Encapsulation	Use of materials to insulate battery cells and modules, preventing short circuits and reducing risk of thermal propagation.	- Minimizes risk of external electrical faults- Protects battery from environmental conditions- Reduces vibration damage.	Increases weight and material costs. May complicate repair and recycling of battery packs.	[19]
Solid-State Battery Designs	Use of solid electrolytes that are inherently safer compared to liquid electrolytes.	- Reduces risk of leakage and fire. - Improves thermal stability- Enables higher energy density.	- Still in development and expensive- Limited scalability for mass production- Compatibility with current EVs is limited.	[20]

METHODOLOGY AND APPROACH

Developing an IoT-based sensor for EV battery protection requires a number of hardware components, each playing a key role in ensuring system functionality, efficiency, and safety. Figure 1 illustrates the interconnection of these components to form a fire prevention and monitoring system. A fundamental component is the transformer, which utilizes electromagnetic induction to transfer energy between circuits. Typically composed of two or more coils wound around a magnetic core, the transformer supports voltage conversion and electrical isolation. In high-voltage environments like EVs, polymeric insulating materials such as epoxy resins, polyethylene terephthalate (PET), and polyimide films are used to encapsulate transformer cores and windings, providing thermal resistance, dielectric stability, and protection against environmental stressors. The system operates efficiently on a low power supply (up to 10 V DC), ensuring dependable functionality of the IoT sensor array. A 12 V AC step-down converter is used to transform the 230 V AC input into 12 V AC, as illustrated in Figure 2.

This component too is often encased in flame-retardant polymer housings to prevent electric shock and suppress fire propagation during faults. For wireless communication, the system incorporates the HC-05 Bluetooth module, widely used for its ease of integration and support for the Bluetooth 2.0 protocol. The device is housed in durable polymer casings, offering mechanical protection and resistance to high-frequency electromagnetic interference. It can operate as either a master or slave, connecting seamlessly with Bluetooth-enabled devices, as shown in Figure 1. Maintaining battery temperature within safe operational limits is critical for both performance and longevity. This is achieved using the L293D motor driver IC to control DC or stepper motors that drive ventilators or cooling fans. Here, thermally conductive polymer composites, such as polycarbonate or polyamide filled with boron nitride or aluminium oxide, are employed to fabricate fan housings and motor enclosures. These materials dissipate heat efficiently while offering electrical insulation and structural stability. The IoT-based system triggers motor activation based on real-time feedback from temperature and current sensors, thereby automatically responding to thermal anomalies. All circuit elements, including the motor driver, are mounted on polymer-based printed circuit boards (PCBs) typically using FR-4 substrates (flame-retardant epoxy reinforced with glass fibers), which offer excellent dielectric properties and thermal performance. A 12V DC motor is included for mechanical actuation, converting DC power into rotational energy. Polymer materials are commonly used in its outer casing and shaft insulation, offering resistance to vibration and temperature fluctuations. As shown in Figure 1(d), these materials contribute to lightweight design and improved system efficiency.

At the core of the system is the PIC16F866 microcontroller (MCU), which reads data from sensors monitoring battery temperature, voltage, and current. It converts analog inputs to digital using its internal ADC, processes the information, and responds to abnormal conditions such as overcharging, over-discharging, or overheating. The MCU can execute algorithms for cell balancing and battery health optimization as part of a broader Battery Management System (BMS). In safety-focused designs, polymeric conformal coatings are often applied to microcontroller boards to protect them from moisture, dust, and corrosive elements, thereby increasing longevity and reliability. For display and user interaction, the system includes a 16x2 alphanumeric LCD. This low-power device is suitable for microcontroller-based systems and is often integrated into polycarbonate bezels or acrylic enclosures for visibility and physical protection.

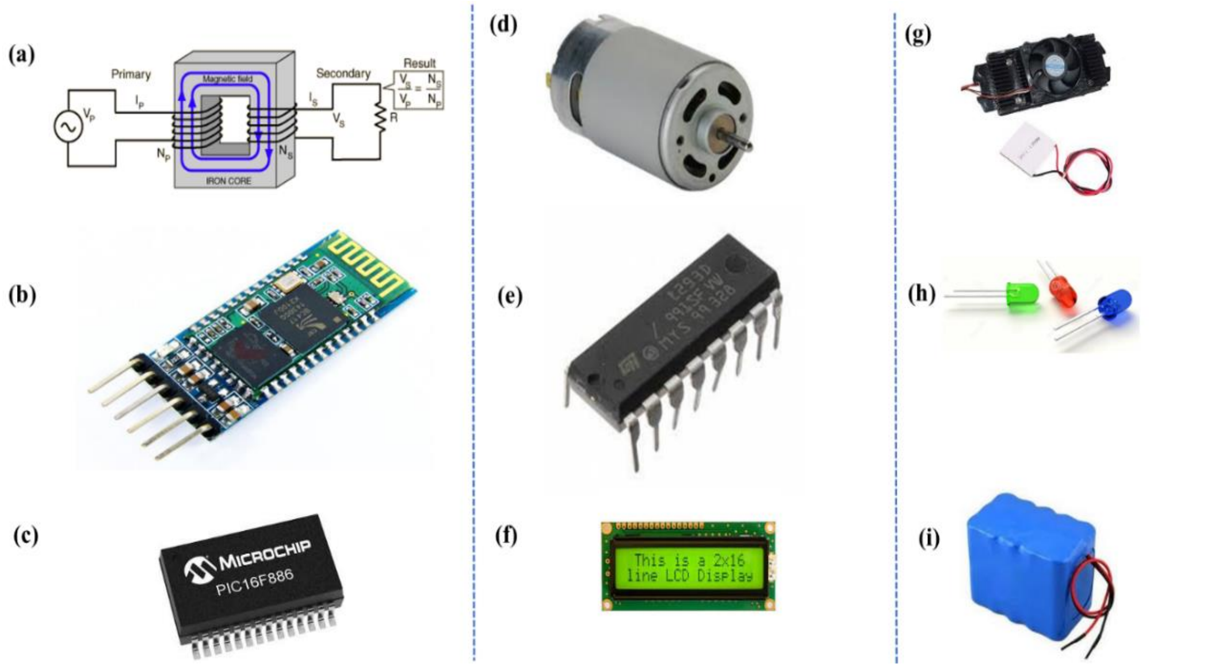


Figure 1. Hardware Components of IoT Sensor Protection of EV Battery.

The electrically isolate and switch high-current loads, relays are used, ensuring motors are separated from low-power control circuits. These electromechanical switches often rely on polymer encapsulants and glass-filled thermoplastics to maintain arc resistance and thermal durability. Light-Emitting Diodes (LEDs), widely used for visual feedback, are similarly embedded in transparent polymer lenses or epoxy domes that enhance light focus and provide environmental protection. Their compact, rugged design makes them ideal for harsh automotive conditions. A 12V rechargeable battery is the primary power source for the system. Battery modules are often encased in high-performance polymer housings, such as polypropylene or nylon, which offer impact resistance, chemical inertness, and thermal insulation. Fire-retardant polymers help contain potential thermal runaway events. Finally, thermal management is reinforced by integrating a Peltier plate (thermoelectric cooler), which provides active cooling based on temperature readings. When paired with a fan, this setup becomes an efficient cooling mechanism. The heat sinks and fan housings used with the Peltier module are increasingly made from thermally conductive polymers, which reduce weight and offer electrical isolation ideal for compact automotive applications [21].

IOT SENSOR FOR PROTECTING EV BATTERY BLOCK DIAGRAM

The block diagram of project is shown in Figure 2, which shown various hardware connected with the PIC microcontroller 16 f 866. The block diagram represents in overview of connection of hardware to run or execute the program. The AC Power (230V) is converted to DC using the step-down transformer and bridge rectifier. The microcontroller, powered by this DC supply, controls various components: LCD display, motors (through L293D motor drivers), and Peltier/Exhaust systems (via relay circuits). The relay circuits and motor drivers act as intermediaries to safely manage high-power devices using the microcontroller's low-power control signals. The battery bank may provide backup power in case of external power failure or when the system needs to operate in remote or portable conditions. This system likely manages a mix of environmental control (via the Peltier plate and exhaust fans), displays information, and controls various motors, possibly for an automotive or industrial application.

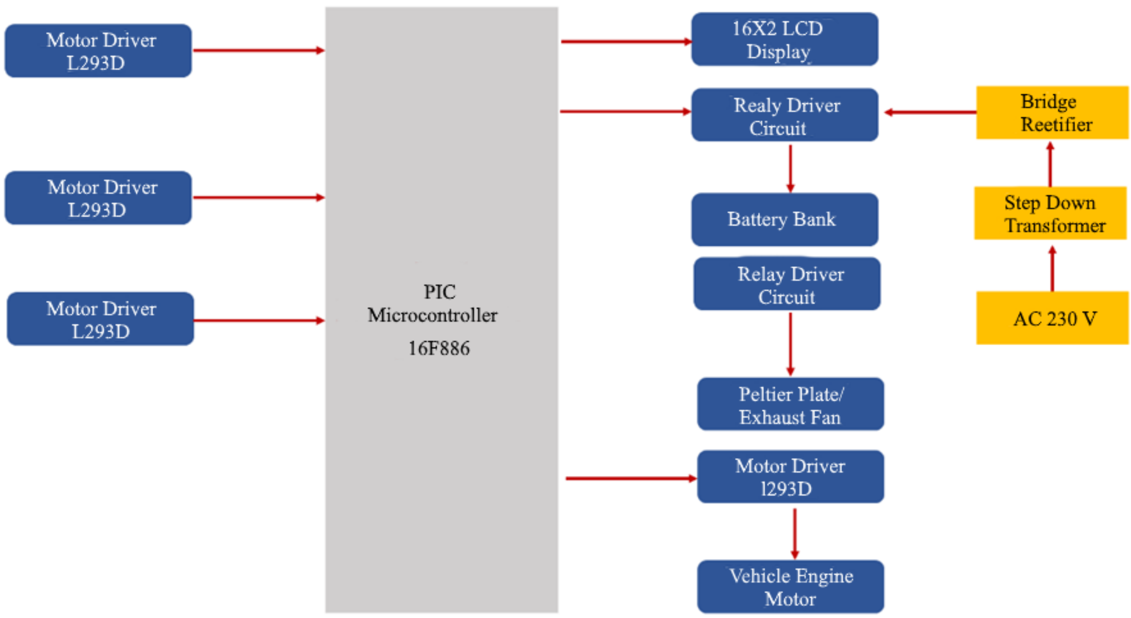


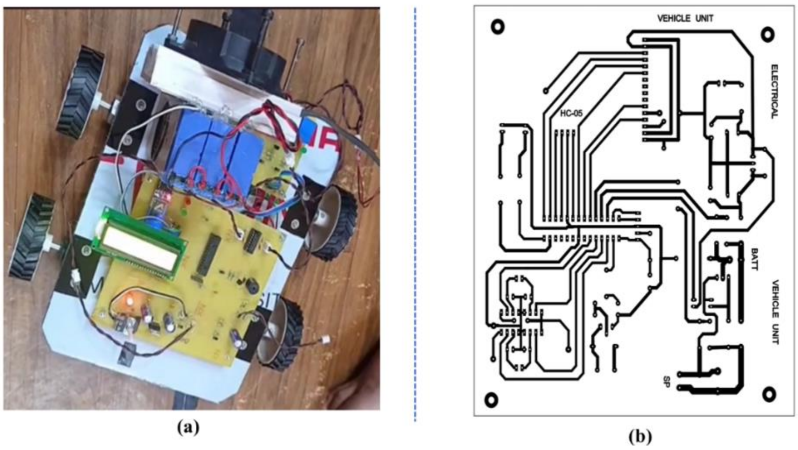
Figure 2. Block Diagram of IoT Sensor Protection of EV Battery.

IOT SENSOR WORKING AND PRINCIPLE

The Battery Management System (BMS) with fire protection is designed to monitor and regulate a battery's operation, ensuring safety, performance, and longevity. It continuously tracks critical parameters such as voltage, current, and temperature to prevent overcharging, deep discharging, and overheating. The BMS maintains all battery cells within safe operating limits, balances charge across cells, and disconnects power in the event of hazardous conditions. A key part of the safety architecture includes provisions for thermal runaway prevention, cooling mechanisms, fire suppression systems, and structural isolation all integrated into a comprehensive protection strategy. The support these functions, advanced polymeric materials are used throughout the BMS architecture. Flame-retardant polymers, such as polyimides and polyvinylidene fluoride (PVDF), are employed as separators within the battery cells, providing critical barriers to prevent electrical shorting and limit the spread of thermal events. Polymer-based thermal interface materials (TIMs) and phase change materials (PCMs) are used to absorb and dissipate excess heat, maintaining optimal cell temperatures during operation and mitigating the risk of overheating.

The core function of the BMS is to control rechargeable batteries so they operate within safe electrical and thermal boundaries. It continuously assesses battery conditions, calculates secondary performance metrics, and communicates key data such as the State of Health (SoH) and State of Charge (SoC) to external systems. These parameters are essential for estimating battery capacity and predicting remaining service life. To safeguard the battery, the BMS implements automatic disconnection protocols when voltage, current, or temperature exceed safe thresholds. Cell balancing, another vital function of the BMS, is used to correct inconsistencies in charge levels across cells. The system may either redistribute charge or dissipate excess energy, often using thermally stable polymer enclosures that withstand prolonged heat exposure without deformation or degradation. In high-risk scenarios, where thermal runaway could occur an uncontrollable self-heating reaction the BMS plays a critical role. It utilizes polymer-based heat shielding barriers to contain localized heating and minimize the chance of fire propagation between cells. Active cooling systems are also implemented, often using polymer composite fan blades or ducts that are both heat-resistant and lightweight, enabling efficient thermal regulation without adding unnecessary bulk.

If a fire incident does occur, the BMS triggers integrated fire suppression systems that deploy non-conductive agents, such as inert gases or aerosolized chemicals, to extinguish flames. These agents are often released from polymer-encased pressurized vessels, which are designed to withstand thermal stress and mechanical shock. Moreover, the battery module itself is typically encased in fire-resistant polymer composite housings, such as glass fiber-reinforced epoxy or flame-retardant polypropylene, which act as structural barriers to confine the incident and prevent it from affecting nearby systems. Through this multi-layered safety approach enabled in part by specialized polymer materials—the BMS ensures secure and reliable performance of electric vehicle battery packs, effectively addressing both operational risks and fire hazards in demanding automotive environments. The Figure 3 is shown the prototype of IoT Sensor Protection of EV Battery with PCB design.



(a) (b)

Figure 3. Development Board of IoT Sensor Protection of EV Battery (a) Project Model of IoT Sensor Protection of EV Battery (b) PCB Design of IoT Sensor Protection of EV Battery.

FLOW CHART OF PROJECT

The flow chart of IoT Senor for protection of EV Battery is shown in Figure 4. The flow chart shown the process of execution of system or device from battery start charging to battery cooling process. The flowchart represents the sequence of operations for an Electric Vehicle (EV) battery protection system. The process begins with system initialization, during which the battery management system (BMS) and related components are powered on. A 16x2 LCD controller is used to display critical system parameters. Sensors then measure essential parameters, including the voltage, current, and temperature of the battery. These values are continuously sent to the controller and displayed on the LCD for real-time monitoring. If the temperature exceeds safe limits, a thermal management system activates, utilizing either a Peltier plate or an exhaust fan to cool the battery. This ensures the battery operates within its optimal temperature range, enhancing its safety and longevity.

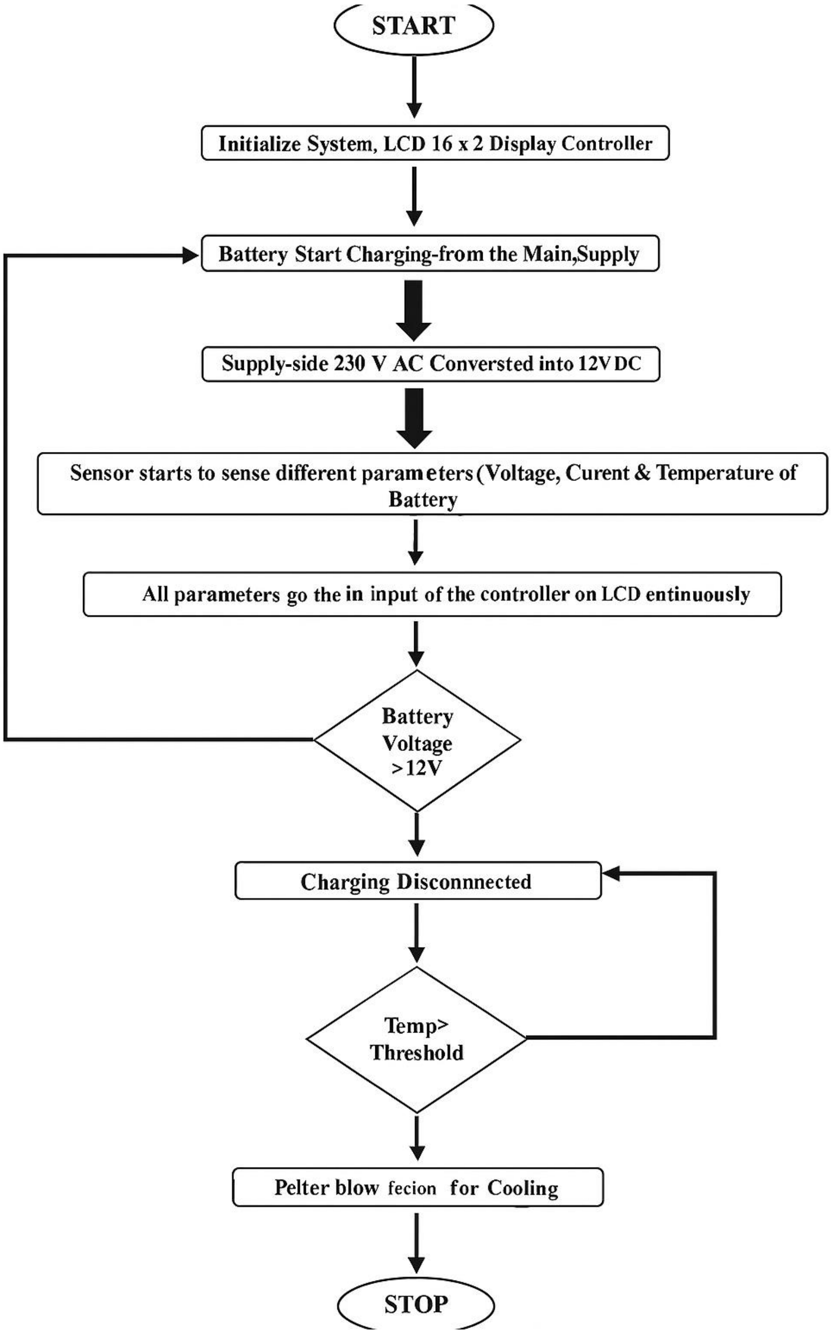


Figure 4 Flow Chart of IoT Sensor Protection of EVs Battery.

RESULT ANALYSIS

The battery management system for the research project, which uses a PIC Controller 16F866, was successfully designed and implemented as shown Figure 5. The system effectively maintained the battery temperature within a safe range of 37 to 40 degrees Celsius at 12.5 volts as shown in Table 2. When the temperature exceeded 40 degrees, an overheating alarm was triggered, and a warning notification was sent to the user via the HC-05 Bluetooth terminal, ensuring real-time awareness and response. The incorporation of polymer-based thermal interface materials (TIMs) and phase change materials (PCMs) significantly contributed to stabilizing the thermal environment of the battery pack. These polymer composites facilitated efficient heat dissipation and delayed temperature escalation, allowing for more controlled and consistent operation. Additionally, the use of flame-retardant polymer enclosures around key circuit components including the controller, relays, and motor driver provided added insulation and fire protection, reducing the likelihood of thermal propagation during abnormal conditions. This integration of advanced polymers not only improved thermal reliability but also enhanced the overall safety and efficiency of the system, validating their importance in next-generation EV battery management solutions. The Table 3 is represented key for execute different operation.

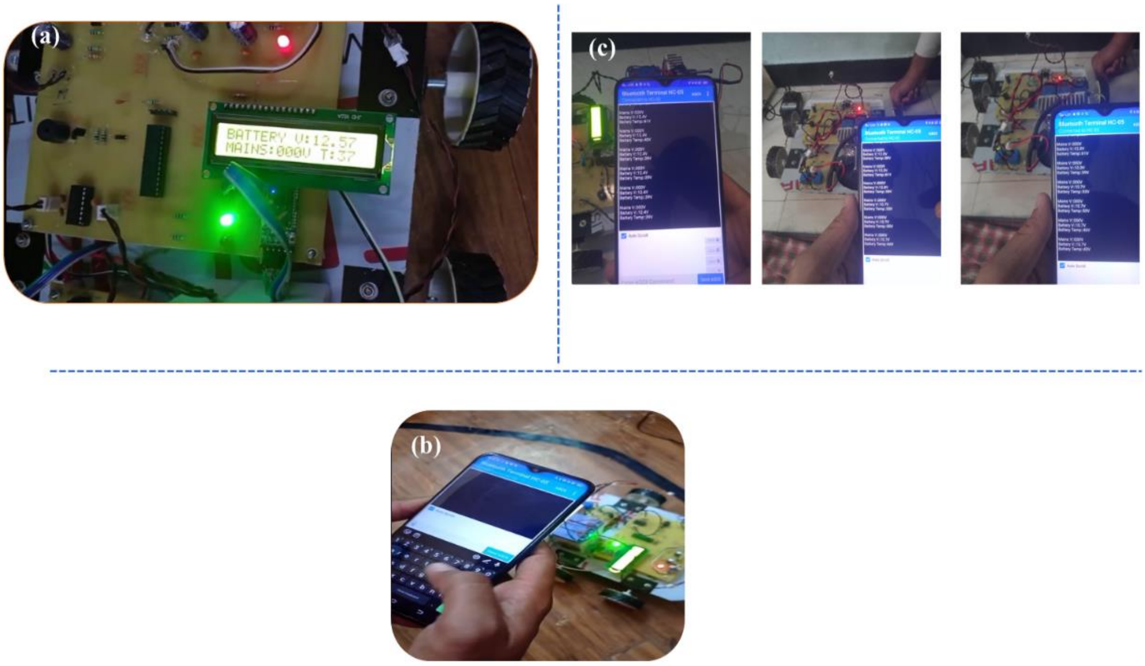


Figure 5. Execution of the Project IoT Sensor for Protection of EV Battery.

Table 2. Battery Parameter with Output Battery Voltage.

Battery Parameter	**Voltage Value**
Battery Voltage	12.5 v
Battery fix temperature	37 to 40 v
Battery above heat temperature	Above 41 v

Table 3. Parameter Using in keypad for Operation.

Parameter of command	**Command value**
Forward	A
Reverse	B
Turn Left	C
Turn Right	D
Vehicle Stop	0

SUMMARY AND CONCLUSION

The project proposed device that significantly advances safety and reliability of electric vehicle (EV) battery systems. By implementing a proactive IoT-based Battery Management System (BMS) that monitors voltage, temperature, and current conditions in real-time, the design effectively prevents fire hazards and promotes early detection of abnormal events. This approach not only enhances user safety and confidence but also establishes a new benchmark for industry-wide EV safety protocols. A key innovation in this work lies in the integration of polymer and polymer composite materials throughout the system. The use of flame-retardant polymer enclosures, thermal interface materials (TIMs), and phase change composites (PCMs) plays a vital role in improving thermal insulation, structural integrity, and fire suppression. These materials ensure electrical isolation, resist environmental degradation, and contribute to the lightweight, compact design of the overall system. Their incorporation reinforces the multifunctional safety envelope of the BMS, offering a scalable solution for EVs and other high-performance battery-powered applications. The project demonstrates how multidisciplinary engineering blending electronics, embedded systems, and polymer science can lead to safer, smarter, and more sustainable transportation technologies. The success of this integrated solution not only benefits vehicle occupants but also supports broader environmental and industrial goals by encouraging EV adoption and reducing risks associated with battery failures.

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