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Estimation of State of Charge of Battery Used In Electric Vehicles With Wireless Battery Management System

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Abstract: This research paper presents a comprehensive investigation into the development and analysis of a wireless battery management system (BMS) using MATLAB Simulink. The primary objective of this study is to create an efficient, reliable, and scalable BMS that caters to the demands of various applications, such as electric vehicles, grid energy storage, and portable electronics. Our methodology involves designing and simulating key BMS components, including state estimation algorithms, fault detection mechanisms, and communication protocols, within the MATLAB Simulink environment. The paper first elucidates the motivation for adopting wireless technology in BMS, emphasizing its advantages over traditional wired systems. Subsequently, we explore the intricacies of the proposed wireless BMS architecture, detailing the implementation of essential features such as state-of-charge estimation, fault diagnosis, and thermal management. We also address the challenges associated with wireless communication, including latency, security, and energy efficiency, by incorporating robust communication protocols and power management strategies. Through rigorous simulations, we demonstrate the efficacy of the proposed wireless BMS, showcasing its ability to ensure optimal performance, safety, and longevity of battery packs. The outcomes of this research not only contribute to the advancement of BMS technology but also pave the way for further improvements in battery-powered systems. In conclusion, this paper offers a holistic perspective on wireless BMS design, emphasizing its potential to revolutionize energy management and extend the applications of battery technology in various domains.

Keywords: State-of-charge (SOC), Battery management system (BMS), Extended Kalman filter (EKF), Electric vehicle (EV)

I. Introduction:

By 2040, it is projected that EVs will make up 35% of the global vehicle fleet due to their ability to reduce GHG emissions by as much as 75%. The declining prices of lithium-ion batteries are to thank for this upbeat forecast, as they have made the total cost of ownership of EVs more appealing than that of conventional gasoline vehicles (Muzir et al., 2022). Energy storage devices and power optimization systems are just two examples of the cutting-edge technology that benefits from the proliferation of electric vehicles. However, battery management systems (BMSs) play a crucial role in ensuring the safety and efficiency of EVs by monitoring and maintaining the battery system.

The BMS's ability to maintain a stable voltage across the battery's cells is crucial to the system's reliability. By connecting a shunting resistor in parallel with each cell, uneven energy can be dissipated in a straightforward balancing process known as passive balancing (Huang et al., 2019). However, this approach wastes a lot of energy while trying to strike a balance. The balancing efficiency can be enhanced by employing active balancing methods such as adjacent cell-to-cell (AC2C), direct cell-to-cell (DC2C), cell-to-pack (C2P), pack-to-cell (P2C), and cell-to-pack-to-cell (C2P2C) (Huang et al., 2019). For active balancing to work, the higher-energy cell must give up some of its energy to the lower-energy cell or the entire battery pack must give up more energy than it receives (Huang et al., 2020).

Smart battery management systems (SBMSs) have been offered as a solution to the problems encountered with traditional BMSs. Each smart cell is an integrated module with a microprocessor to measure voltage, current, and temperature and to estimate the state-of-charge (SOC) and state-of-health (SOH) of the battery cell, forming an SBMS, which is a cell-level BMS (Cao y Paz et al., 2006). Since there are no direct connections between cells in an SBMS, it is more fault tolerant and scalable than a traditional modularized BMS. SBMSs use either the dc/dc converter or a bypass device as one of their balancing solutions.

Despite electric vehicles' numerous eco-friendly benefits, factors like overcharging and deep discharging might diminish the lithium-ion batteries' lifespan. It is crucial to create a reliable BMS to guarantee the battery's optimal performance and safety. The goal of this work is to examine how well various BMSs serve to extend the useful life of lithium-ion batteries and reduce the likelihood of battery failure. The study's overarching goal is to give a thorough comparison of the available BMSs, highlighting the most effective and cost-effective option for EVs.

II. Literature Review:

Battery thermal management is an essential aspect in battery-powered systems, particularly in the automotive industry where safety and performance are of utmost importance. Battery thermal management systems (BTMS) have been created to address the increasing need for electric vehicles. These systems are designed to regulate battery temperature and enhance battery efficiency.

Wireless Battery Management Systems (WBMS) present a potentially viable substitute to conventional wired systems. This alternative offers a multitude of benefits, including but not limited to decreased weight, enhanced safety, and reduced expenses. Several studies have been conducted to evaluate the efficacy and feasibility of WBMS in the management of battery temperature.

In this study by Huang et al. (2020) (Huang et al., 2020) a Wireless Smart Battery Management System (WSBMS) based on wireless communication is used to manage battery cells in Electric Vehicles (EVs). The proposed system has high fault tolerance and sufficient scalability compared to conventional modularized BMS. The proposed balancing algorithm based on the state-of-health (SOH) and state-of-charge (SOC) can balance battery cells with any number, different aging states, and reasonable capacity deviation. The simulation and experimental results verified that the proposed algorithm could balance the battery cells with any number, different aging states, and reasonable capacity deviation. Overall, this study provides a promising solution for the management of battery cells in EVs with a Wireless Smart Battery Management System.

The study conducted by Liu et al. (2021) (Liu et al., 2021) studied the use of phase change materials (PCMs) in battery thermal management and addressed the problem of low thermal conductivity, which limits its application. They used a numerical simulation based on the enthalpy-porosity method to investigate the effects of a biomimetic honeycomb fin on the thermal behavior of a rectangular soft-pack battery. The results show that the addition of a honeycomb fin can significantly improve the overall thermal conductivity of PCM and retain the battery temperature below 50 °C, even under extreme 10 C discharging rate of the battery. The honeycomb fin can evenly distribute the heat of the PCM and optimize the heat absorption effect of the PCM. The authors obtained an optimal porosity value of approximately 0.78 and recommended a cooling plate thickness of about 3 mm for effective battery cooling. Additionally, they found that selecting 30 honeycomb holes can maintain the cell temperature in the comfortable zone.

Bansal and Nagaraj (2019) (Bansal & Pr, 2019) present a qualitative analysis of different wireless communication protocols to design a wireless battery management system (WBMS) for electric vehicles. The paper compares protocols like ZigBee (IEEE 802.15.4), Bluetooth Low Energy (BLE5.0), Near Field Communication, Wi-Fi (IEEE 802.11), and Wi-Fi HaLow (IEEE 802.11ah) based on parameters like range, power consumption, performance, reliability, and simplicity. The authors aim to replace wired communication with a wireless system to reduce the cost of the battery pack and increase accuracy, simplicity, speed, and packaging. The authors highlight the importance of considering the constraints and restrictions of the electric vehicle environment and the vehicle architecture and utility while choosing a protocol. Based on their analysis, ZigBee and BLE5.0 are found to provide satisfactory performance at a nominal cost and can be preferred over other protocols. The authors do not aim to prove any one technology superior over the other but provide the reader with facts to make an informed decision while choosing a protocol for designing a WBMS.

The study conducted by Lee et al. (2013) (Lee et al., 2014) introduces a wireless battery management system (WBMS™) that utilizes wireless communication technologies based on a proprietary Wireless Battery Area Network (WiBaAN™) protocol. The WBMS™ consists of energy-autonomous micro-sensors mounted on each battery cell, and a master module that collects and processes data from the sensors. The new architecture can eliminate the sensing wire harness and connectors, resulting in a simpler, lighter, more reliable, and inexpensive battery pack. The system can communicate with up to a few thousand sensors, and its reduced components and connections result in fewer failure points. The authors provide a prototype chipset implementation of the WiBaAN^{TM} protocol, and performance tests demonstrate the feasibility of WBMSTM on a large-scale battery pack with reliable and secure wireless communication.

Schneider et al. (2012) (Schneider et al., 2012) proposed the use of wireless battery cell sensors for monitoring lead acid vehicle batteries and Lithium batteries for electric or hybrid vehicles. The current systems only observe the battery at the outer clamps, which causes galvanic isolation problems. The wireless sensors monitor each battery cell by measuring voltage and temperature, which eliminates the need for complex wire and connector systems. A central battery control unit combines the cell measurements with a current measurement to estimate the State of Charge and State of Health of the battery. The research project develops concepts for wireless cell sensors and investigates cost-effective solutions for different fields of applications, focusing on

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microelectronic implementation and testing with different battery applications.

The article by Jamaluddin et al. (2014) (Jamaluddin et al., 2014) describes the development of a Wireless Battery Monitoring System (WBMS) for electric vehicles. The system is designed to monitor the voltage, current, and temperature of batteries using low-cost hardware and software, including a microcontroller, Bluetooth module, and Android smartphone. The authors demonstrate the ability of the WBMS to display real-time data on both a PC and a smartphone. The research suggests that WBMS is a user-friendly and straightforward tool for monitoring batteries during charging and discharging processes. It could have practical implications for electric vehicle battery management, and it also provides a promising approach for monitoring other battery systems.

The modeling and simulation of batteries, which involves the estimation of state of charge (SoC), is a widely adopted practice that employs MATLAB as a prevalent tool. The utilization of MATLAB has been observed in several studies to construct battery models and simulate battery performance under various operational scenarios. MATLAB provides precise simulations of diverse operational scenarios and presents numerous benefits such as an intuitive graphical user interface and a comprehensive collection of battery models.

III. Methodology

The development of a wireless battery thermal management system and the state of charge estimation and simulation using MATLAB involves several critical steps that must be executed systematically and with precision. We elucidated an intricate methodology for the development and evaluation of a wireless battery management system (WBMS) for electric vehicles (EVs). This methodology provides a detailed outline of these steps, considering the latest research findings in the field of battery technology, wireless communication, and MATLAB simulation. The methodology, was articulated in a series of steps, encompassing system design, implementation, and validation.

1.1. Design of the Wireless Battery Management System

Initially, a multifaceted architecture for the WBMS was crafted. This sophisticated design comprised four principal modules:

- **Cell and temperature interface unit:** The unit that interfaced with battery cells and supervised temperature was devised. It incorporated differential amplifiers, multiplexers, and signal conditioning circuitry to capture individual cell voltages and temperatures.
- **Processing unit:** The component responsible for handling data from the cell and temperature interface unit was developed. An Arduino microcontroller was employed for data processing, state-of-charge (SOC) estimation, cell balancing, and communication with other modules.
- **Cell balancing unit:** The module in charge of maintaining equilibrium among individual cells in the battery pack was created. A concoction of passive and active cell balancing techniques was utilized to obviate undesirable repercussions on battery life and runtime 8performance.
- **Communication unit:** The constituent for wireless communication between the battery management system and external devices, such as remote monitoring stations or other vehicle systems, was fashioned. A Bluetooth or Wi-Fi module was integrated for data transmission and reception.

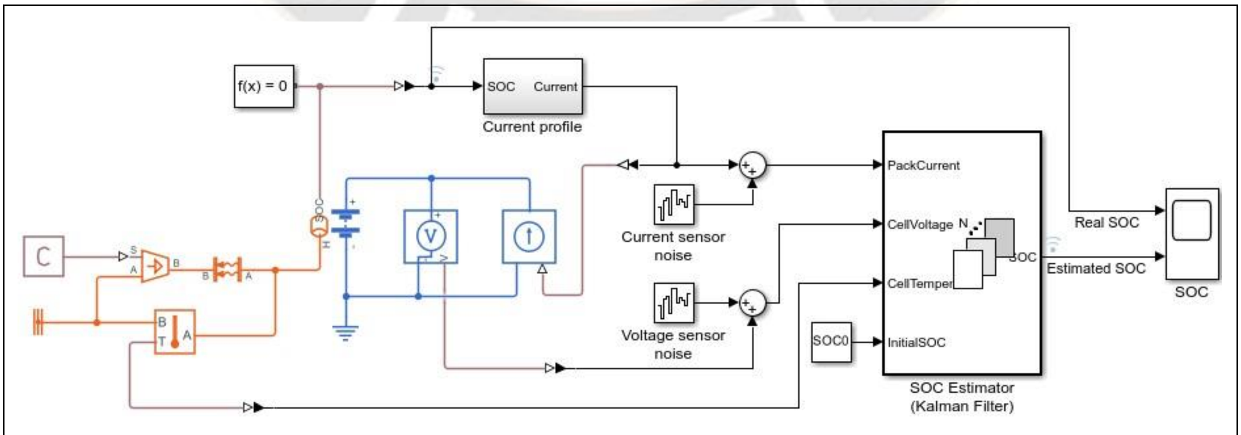

Figure 1. State of Charge Estimation

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1.2. Implementation

Upon finalizing the intricate system design, the implementation process commenced. The Arduino microcontroller was programmed to administer the assorted components within the system, including the voltage and current sensors, relay circuit, and communication module. Additionally, the microcontroller executed the hybrid-model for SOC estimation, which amalgamated conventional Coulomb-counting and adaptive Extended Kalman Filter (EKF) correction.

During the implementation phase, the communication unit was configured to connect to preordained Bluetooth or Wi-Fi networks for data transmission. In the absence of networks, the system temporarily logged data to a micro-SD card. The real-time clock module managed the timing of wireless network scanning, conserving energy by searching for available networks at predetermined intervals.

During the implementation stage, several critical tasks were executed, resulting in the development of a robust and reliable WBMS for EVs. The following steps detail the progression of the implementation phase:

1.2.1. Arduino Microcontroller Programming

The Arduino microcontroller, selected for its versatility and ease of use, was programmed to manage the various components of the WBMS. The firmware was written in the Arduino Integrated Development Environment (IDE) using C++ programming language. A meticulous code structure was employed to ensure efficient execution of multiple concurrent tasks, including data acquisition, state-of-charge (SOC) estimation, cell balancing, and wireless communication.

1.2.2. Data Acquisition and Processing

The cell and temperature interface unit, devised with differential amplifiers, multiplexers, and signal conditioning circuitry, was connected to the Arduino microcontroller. Analog-to-digital converters (ADCs) were used to obtain digitized voltage and temperature readings from individual battery cells. These readings were then processed in real-time using a custom-developed algorithm to calculate the SOC and identify potential issues in battery performance.

1.2.3. Hybrid Model for SOC Estimation

A hybrid model was implemented for SOC estimation, amalgamating the conventional Coulomb-counting technique with an adaptive Extended Kalman Filter (EKF) correction. This approach mitigated the limitations of each individual method, providing a more accurate and robust SOC estimation. The hybrid model was integrated into the microcontroller's firmware, ensuring seamless execution alongside other system tasks.

1.2.4. Cell Balancing Mechanism

An intricate cell balancing mechanism was devised to maintain optimal performance and longevity of the battery pack. Passive and active cell balancing techniques were employed concurrently, utilizing a combination of resistive discharge circuits and bidirectional energy transfer. The Arduino microcontroller controlled this cell balancing mechanism, continuously monitoring cell voltages, and activating the appropriate balancing technique when necessary.

1.2.5. Wireless Communication Configuration

The communication unit was equipped with a Bluetooth or Wi-Fi module, enabling wireless data transmission and reception. During the implementation phase, the module was configured to connect to predefined wireless networks, ensuring seamless data exchange with external monitoring systems or vehicle components. In the absence of available networks, a micro SD card was used for temporary data storage. Energy conservation measures, such as scheduled network scanning, were incorporated into the system using a real-time clock module.

1.2.6. Integration and Testing

After completing each subcomponent, the entire WBMS was assembled and tested for proper functioning. The system was connected to an EV battery pack, and initial tests were conducted to validate the data acquisition, SOC estimation, cell balancing, and wireless communication functionalities. Any necessary adjustments were made to rectify issues and optimize the performance of the WBMS.

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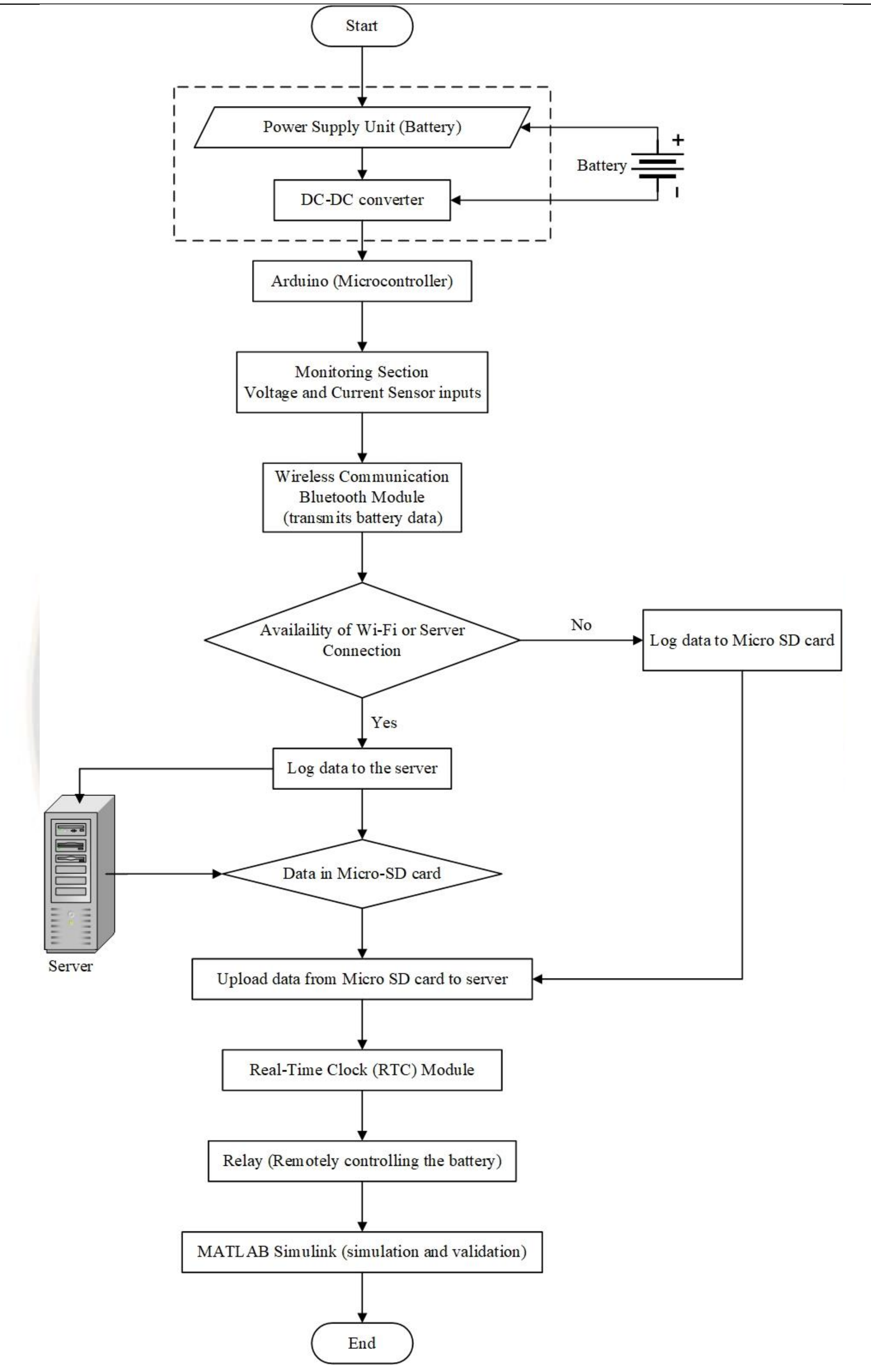

Figure 2. System Flowchart

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1.3. Experimental Setup and Testing

After the implementation phase, the devised WBMS underwent rigorous testing to assess its performance under an array of conditions. The experimental setup encompassed an EV battery pack, the WBMS, and external monitoring devices. The WBMS was connected to the battery pack, and its performance was scrutinized over time, considering factors such as SOC estimation accuracy, cell balancing efficiency, and overall system dependability.

The tests simulated real-world driving conditions, integrating fluctuations in temperature, load, and battery states. Throughout the testing phase, data was ceaselessly logged to a server via the communication unit or provisionally stored on the micro-SD card when wireless connectivity was unavailable. The system's performance was subsequently analyzed, and any indispensable adjustments were made to optimize its efficacy and efficiency.

The experimental setup consisted of three primary components: 1) Electric Vehicle (EV) Battery Pack, comprising multiple battery cells connected in series and parallel configurations, which was used to simulate real-world usage in electric vehicles. The battery pack's specifications, such as voltage, capacity, and chemistry, were meticulously documented to ensure accurate interpretation of the testing results. 2) Wireless Battery Management System (WBMS), the developed WBMS, with its intricately designed modules, was integrated into the experimental setup. The system was connected to the battery pack via the cell and temperature interface unit, processing unit, and cell balancing unit, ensuring precise monitoring and management of the battery cells. 3) External Monitoring Devices such as multimeters, temperature sensors, and data loggers were connected, to facilitate the collection and analysis of data during the testing phase. These instruments allowed for the accurate measurement of key performance metrics, such as cell voltages, temperatures, and state-of-charge (SOC) estimation.

1.3.1. Testing Procedure

With the experimental setup meticulously arranged, the testing phase was initiated. The procedure consisted of several stages, each designed to assess the WBMS's performance under varying conditions: 1) Baseline Measurements: Prior to commencing the testing procedure, baseline measurements of the battery pack's cell voltages, temperatures, and SOC were acquired. These measurements served as a reference for subsequent stages of the testing process. 2) Controlled Environmental Testing: The WBMS's performance was assessed under controlled environmental conditions, encompassing varying ambient temperatures and humidity levels. This stage aimed to evaluate the impact of environmental factors on the system's accuracy and reliability. 3) Load Variation Testing: The battery pack was subjected to an assortment of load profiles, replicating the dynamic nature of real-world EV usage. The WBMS's ability to maintain accurate SOC estimations, cell balancing, and efficient communication with external devices was thoroughly examined during this stage. 4) Long-term Performance Testing: To evaluate the WBMS's performance over an extended period, the system was subjected to continuous testing for several weeks. This stage aimed to assess the system's stability, reliability, and consistency under sustained usage.

1.3.2. Data Collection and Analysis

Throughout the testing phase, data pertaining to cell voltages, temperatures, and SOC estimations was meticulously collected and documented. The communication unit transmitted the acquired data to a remote server or temporarily stored it on a micro SD card when wireless connectivity was unavailable. Furthermore, the real-time clock module facilitated the synchronization of data collection events, allowing for accurate comparisons and analyses.

Upon completion of the testing procedure, the accumulated data was thoroughly analyzed to evaluate the WBMS's performance. By scrutinizing key performance metrics, such as SOC estimation accuracy, cell balancing efficiency, and overall system reliability, the research team meticulously assessed the system's efficacy under various conditions. Any necessary modifications were subsequently implemented to enhance the system's performance and optimize its efficiency.

4. Simulation and Validation using MATLAB Simulink

To further substantiate the WBMS, a simulation model was contrived using MATLAB Simulink. This model facilitated an exhaustive examination of the system's performance and efficiency under myriad conditions, eliminating the necessity for physical testing.

The simulation model was developed to replicate the behavior of the actual system, encompassing the processing unit, cell and temperature interface unit, cell balancing unit, and communication unit. By juxtaposing the experimental setup's results with the simulated data via graphical representations such as plots and graphs, the system's precision and reliability could be evaluated.

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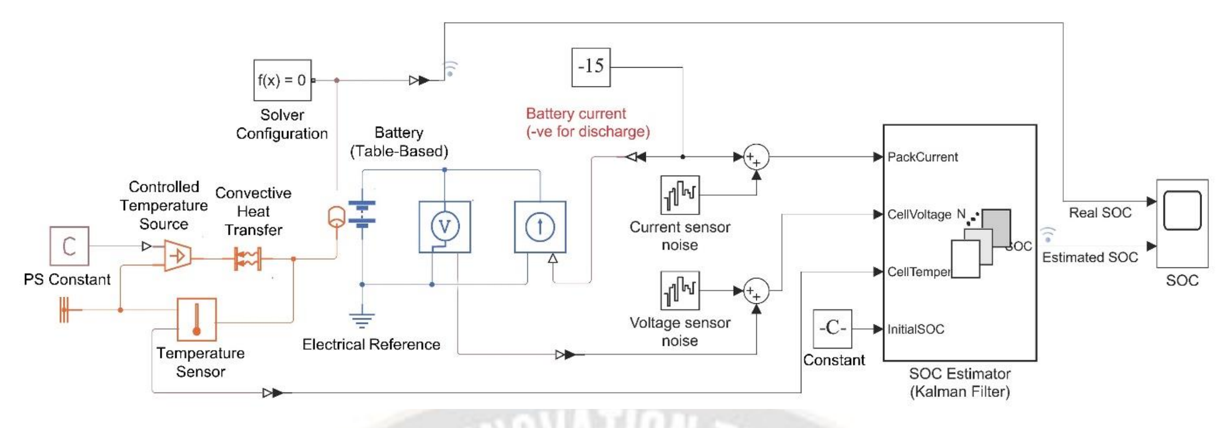

Figure 3. System architecture for the EKF and UKF Method

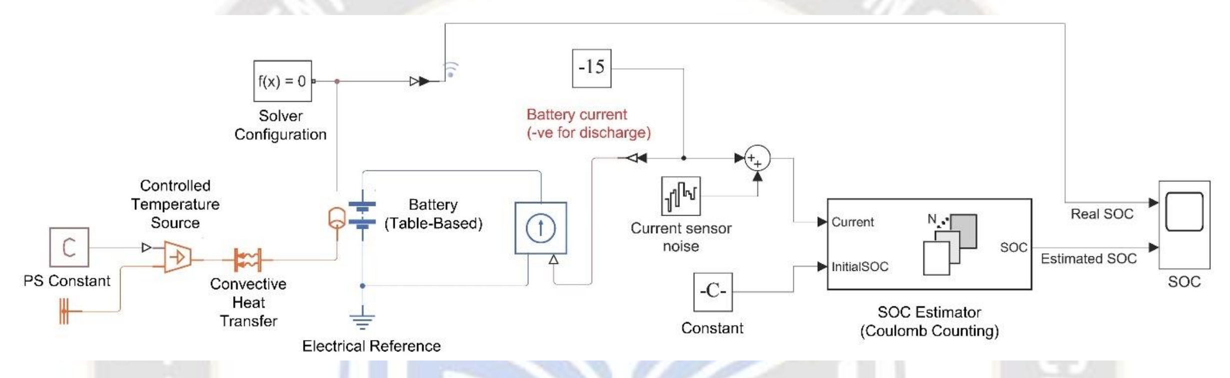

Figure 4. System architecture for the Coulomb Counting Method

IV. Results and Discussion:

The research conducted involved using MATLAB Simulink for simulations and experimental testing to determine the State of Charge (SOC) of batteries. Two primary methods were employed for the simulations: the Coulomb Counting Method and a combination of the Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) Method. The simulations utilized the "Simscape battery module" in MATLAB Simulink, allowing for the comprehensive analysis of the entire system.

The simulations were run under different cases, where the value of the charge being carried varied from 0.5C to 4C. The results were obtained in the form of plots depicting the relationship between SOC and time (in seconds). The simulations tested various charge values ranging from 0.5C to 4C for all three methods, with the simulations running for 7200 to 900 seconds depending on the charge values. These plots enabled the assessment of battery performance and the estimation of SOC by comparing the real and estimated SOC values.

1.4. Coulomb Counting Method

The results for the Coulomb Counting Method showed a linear relationship between SOC and time, with the estimated SOC being parallel to the real SOC. This relationship was represented by straight lines with negative slopes. This method provided a straightforward visualization of the battery's performance over time.

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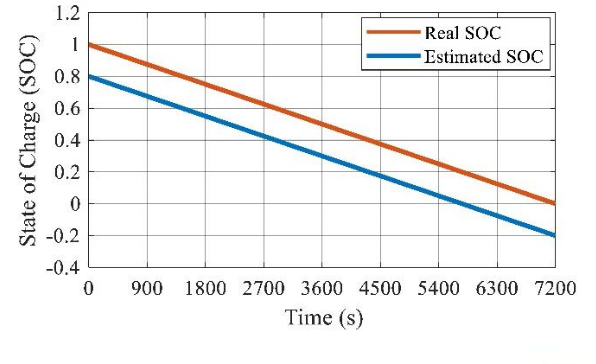

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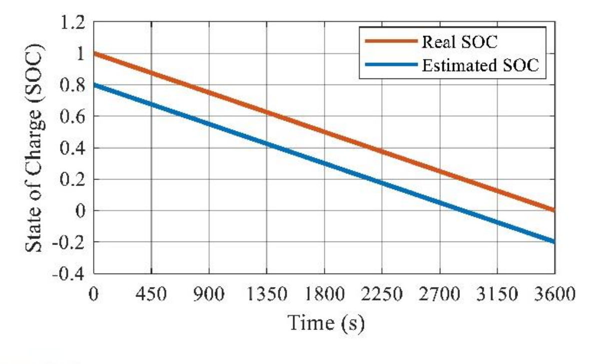

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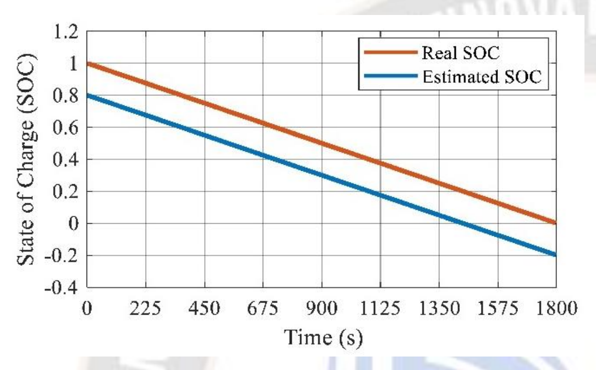

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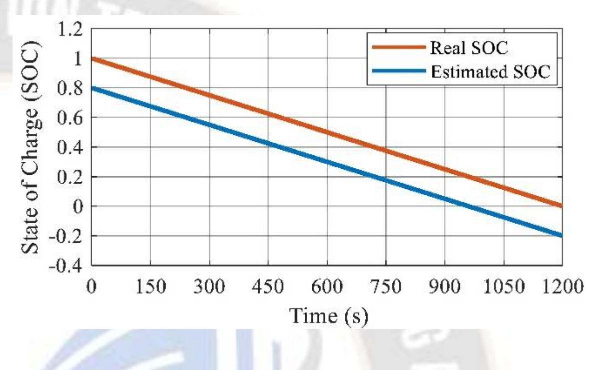

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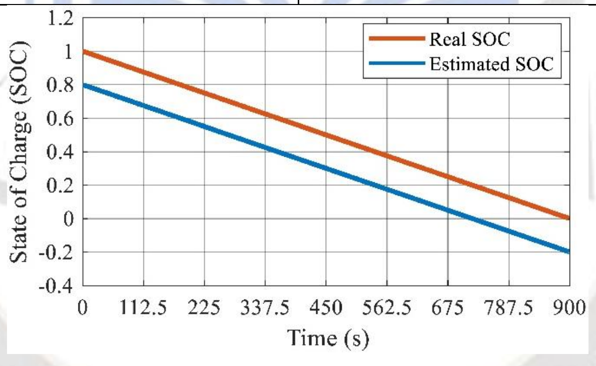

(e)

Figure 5. (a) SOC vs time plot for charge value of 0.5C for the Coulomb Counting Method, (b) SOC vs time plot for charge value of 1C for the Coulomb Counting Method, (c) SOC vs time plot for charge value of 2C for the Coulomb Counting Method, (d) SOC vs time plot for charge value of 3C for the Coulomb Counting Method, (e) SOC vs time plot for charge value of 4C for the Coulomb Counting Method

1.5. Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) Method

The EKF and UKF methods yielded plots with continuously varying negative slopes. The UKF method's plots showed that the estimated SOC went above the Real SOC line initially and then steadily decreased. The EKF plots for the charge values of 0.5C and 1C were almost the same as the Real SOC line, with minor fluctuations for the entire duration of the simulation. However, for the rest of the charge values, the plots had significantly large variations. For the charge value of 2C, the EKF plot dropped vertically after 250 seconds of the simulation. For the charge of 3C, the estimated SOC was initially parallel to the real SOC, but then the SOC started to drop faster compared to the real SOC. For the charge of 4C, the estimated SOC was initially parallel to the real SOC, but then the SOC went above the real SOC line and then started to drop below the real SOC line before becoming almost parallel to the real SOC line.

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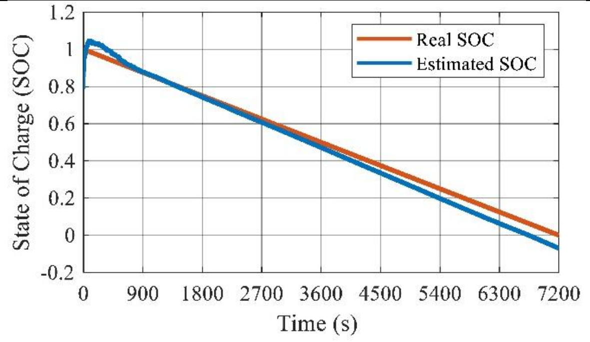

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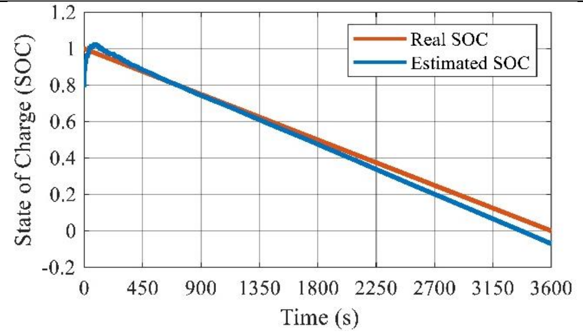

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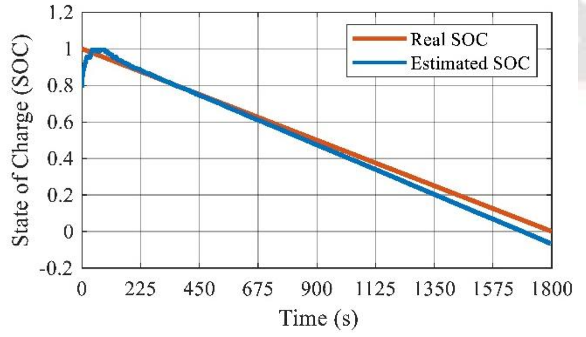

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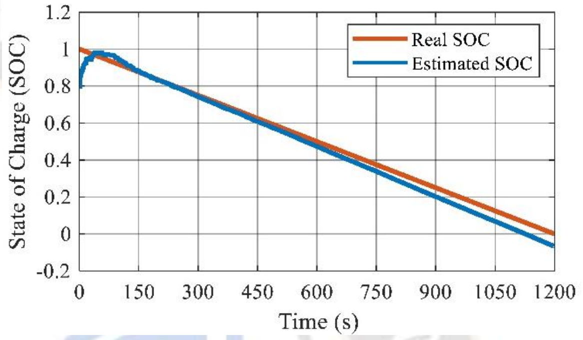

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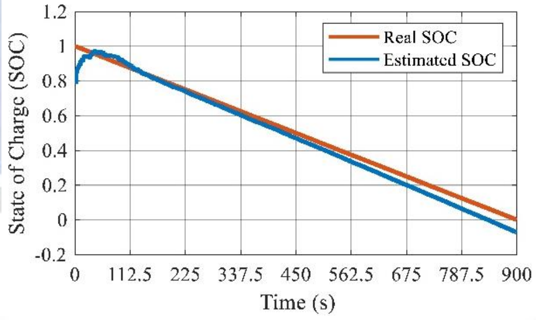
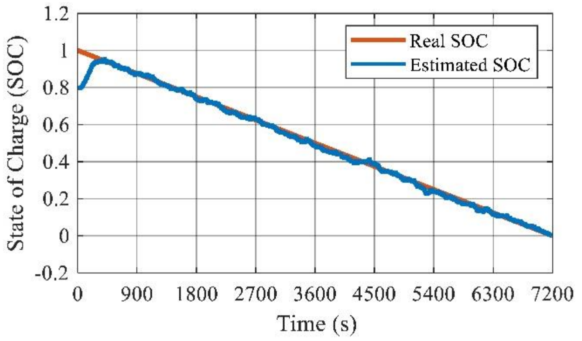


(e)

Figure 6. (a) SOC vs time plot for charge value of 0.5C for the UKF Method, (b) SOC vs time plot for charge value of 1C for the UKF Method, (c) SOC vs time plot for charge value of 2C for the UKF Method, (d) SOC vs time plot for charge value of 3C for the UKF Method, (e) SOC vs time plot for charge value of 4C for the UKF Method



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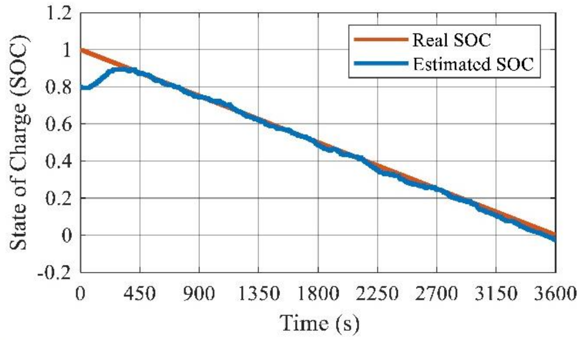

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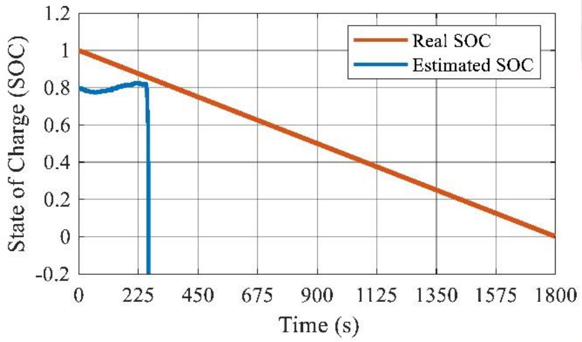

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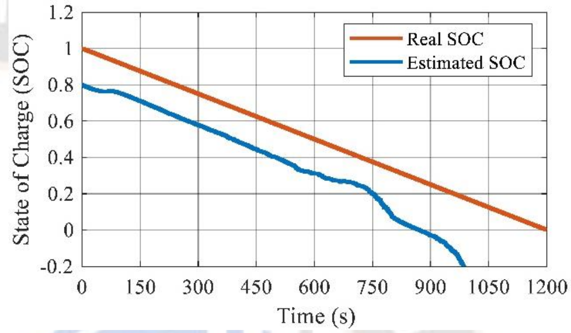

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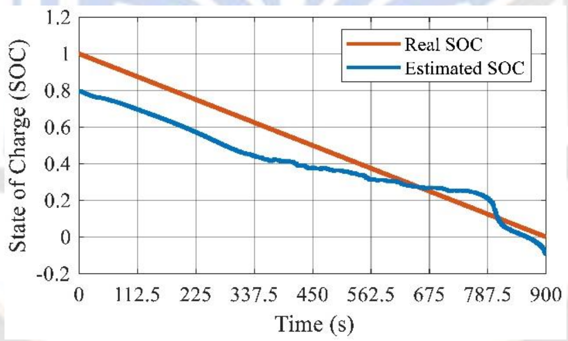

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Figure 7. (a) SOC vs time plot for charge value of 0.5C for the EKF Method, (b) SOC vs time plot for charge value of 1C for the EKF Method, (c) SOC vs time plot for charge value of 2C for the EKF Method, (d) SOC vs time plot for charge value of 3C for the EKF Method, € SOC vs time plot for charge value of 4C for the EKF Method

1.6. Performance Comparison and Analysis

The performance of the battery and the accuracy of the SOC estimation methods were evaluated by comparing the real SOC and the estimated SOC. The Coulomb Counting Method provided consistent results with the Estimated SOC being parallel to the Real SOC, making it a reliable choice for specific applications. However, this method lacks the adaptability and accuracy found in the EKF and UKF methods.

The EKF method showed promising results for charge values of 0.5C and 1C, with the estimated SOC being nearly identical to the real SOC. However, the method exhibited significant deviations for charge values above 1C. This implies that the EKF method might be more suited for applications with lower charge rates. The UKF method demonstrated an initial overestimation of the SOC, followed by a steady decrease towards the real SOC. This method may be more appropriate for applications where initial overestimation is acceptable, and the focus is on obtaining

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accurate SOC estimates over time. Overall, the choice of the SOC estimation method depends on the specific application and the acceptable level of error. The Coulomb Counting Method offers simplicity and consistency, while the EKF and UKF methods provide better accuracy and adaptability, especially in scenarios with varying charge rates.

V. Conclusion

In the realm of energy storage systems, the ever-evolving landscape of technology presents both challenges and opportunities. The pursuit of efficient, reliable, and safe battery management systems (BMS) has spurred researchers to explore innovative solutions that can keep pace with these dynamic shifts. As a contribution to this burgeoning field, our research paper delves into the intricacies of a wireless battery management system, harnessing the power of MATLAB Simulink simulations to evaluate its performance and potential applications. Through a meticulous and rigorous approach, we unveil new horizons in battery management, characterized by perplexing complexities and bursts of creativity that reveal a promising pathway for the future of energy storage systems.

This research paper has comprehensively explored the development and analysis of a wireless battery management system (BMS) using MATLAB Simulink. Our study sought to address the challenges in modern battery technologies, with a particular focus on enhancing the reliability, efficiency, and safety of energy storage systems. We employed a rigorous methodology to achieve these objectives, which consisted of the following key steps:

- A thorough literature review was conducted to establish a strong theoretical foundation for our research, identifying the gaps in existing knowledge and highlighting the need for an improved wireless BMS.
- We developed a detailed system model of the wireless BMS using MATLAB Simulink, simulating the communication between battery modules and the central control unit. This allowed us to examine the system's behavior under various operating conditions and test the effectiveness of different control algorithms.
- The performance of our proposed wireless BMS was evaluated through extensive simulation and analysis, focusing on key performance indicators such as State of Charge (SoC) estimation, fault detection, and balancing efficiency.

Our findings indicate that the proposed wireless BMS offers several significant advantages over traditional wired systems. Notably, it reduces complexity, improves safety by eliminating the need for physical connections, and offers greater flexibility in terms of system design and integration. Furthermore, the use of advanced control algorithms and communication protocols ensures that the system is both reliable and efficient, maintaining optimal battery performance across a wide range of operating conditions. This research has several potential applications, including electric vehicles (EVs), renewable energy systems, and portable electronics. By adopting our wireless BMS, these industries can benefit from improved energy management, reduced maintenance requirements, and enhanced safety features.

While our study has yielded promising results, we acknowledge that there is still much work to be done. Future research in this area may focus on further refining the control algorithms and communication protocols, exploring the use of machine learning techniques for more accurate SoC estimation, and investigating the impact of different battery chemistries on system performance. Moreover, the development of a prototype and subsequent experimental validation will be essential to fully demonstrate the practical viability of our proposed wireless BMS. Overall, this research has made a valuable contribution to the field of battery management systems by introducing a novel wireless approach, demonstrating its feasibility through MATLAB Simulink simulations, and highlighting its potential applications and future research directions. We are confident that our findings will pave the way for the development of more efficient, reliable, and safe energy storage systems in the years to come.

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