



AI Enabled Battery Management System for Electric Vehicle with Predictive Maintenance

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Publication History: Received: 25.02.2026; Revised: 20.03.2026; Accepted: 25.03.2026; Published: 28.03.2026.

ABSTRACT: A AI-powered EV battery swapping station that utilizes IoT technology presents a sustainable, quick, and efficient solution compared to conventional charging methods by harnessing energy to pre-charge batteries, enabling users to exchange drained batteries in just a few minutes. These stations, connected through IoT, offer real-time insights into battery condition, state of charge (SoC), and the availability of the station via cloud services. A microcontroller (e.g., Arduino, ESP32) acts as the brain, interfacing with sensors (voltage, temperature) to monitor battery health (SoH), detect faults, and prevent overcharging. If faults detected they will switch primary to secondary through IoT. EV'S decrease reliance on the grid, minimize carbon emissions, and improve convenience for urban electric vehicle drivers.

The primary purpose of a swapping battery is to alleviate "range anxiety," which is the fear of running out of battery charge and getting stranded before reaching a charging station. A range monitor is a secondary onboard power generator that charges an electric car's battery as you drive. It is usually a small powerline engine that kicks on once the car's battery is nearly depleted, providing electricity that flows to recharge the car's battery.

KEYWORDS: Range Monitor, State of Health(SOC), state of charge (SOC), Internet of Things, Artificial Intelligence.

I. INTRODUCTION

1.1. INTRODUCTION:

The rapid growth of the global economy and the industrial revolution has increased the demand for energy resources. Currently, a significant portion of energy resources comes from fossil fuels, which are finite and not environmentally friendly. The use of fossil fuels is also a major contributor to climate change, as it leads to an excessive increase in anthropogenic greenhouse power (GHG) emissions.

The global emissions from fossil fuel combustion increased by 90% since the 1970s, reaching over 36.1 Gt in 2014, an all-time high level of emission. In some countries, reducing GHG emissions has become a national priority. For example, Canada aims to reach a 33% reduction in GHG emissions by 2020 and 80% reduction by 2050 from 2007 levels. One of the largest contributors to emissions is the transportation sector. In Canada, road transportation accounts for 82.5% of national transportation emissions, mainly due to the consumption of fossil fuels by internal combustion engine (ICE) vehicles. Pollution generated from ICE can also negatively impact human health.

A promising alternative to ICE vehicles (ICEVs) is electric vehicles (EVs). In the past, there was resistance toward electrification of vehicles since ICE vehicles had been optimized in performance and costs while EVs had not. However, as time passes by, and with more research and development effort being put into EVs, vehicle electrification is currently considered an inevitable part of the future. EVs use a motor, powered by a lithium-ion (Li-ion) battery pack, to propel the vehicle. Li-ion battery is used due to their long lifespan, high energy density, high power density, and environmental benefits.

EVs have lower environmental and health impacts compared to ICEVs because they do not directly release any emissions or pollutants. NO_x and particulate matters (PMs) are major contributing factors in tail-pipe emissions. From a

well-to-wheel standpoint, utilizing a battery EV can reduce PMs by 4 times and NO_x by 20 times. Therefore, EVs can help prevent climate change and protect public health. EVs also play an important role in the development of smart cities in the future. However, due to the lack of available charging infrastructure, the long charge time, the high cost of long-ranged EVs, and the limited range on affordable EVs, there exists a range anxiety issue that hinders the expansion of EVs. Range-extended EVs (REEVs) are seen as a potential solution to the limited range and high cost of EVs.

A range extender is an auxiliary power unit (APU) that provides the vehicle with additional energy to complement the primary battery in propelling the vehicle. According to the 2012 Amendments to the Zero Emission Vehicle Regulations, a range-extended battery EV should comply, among others, with the following criteria:

The vehicle must have a rated all-electric range of at least 120 km.

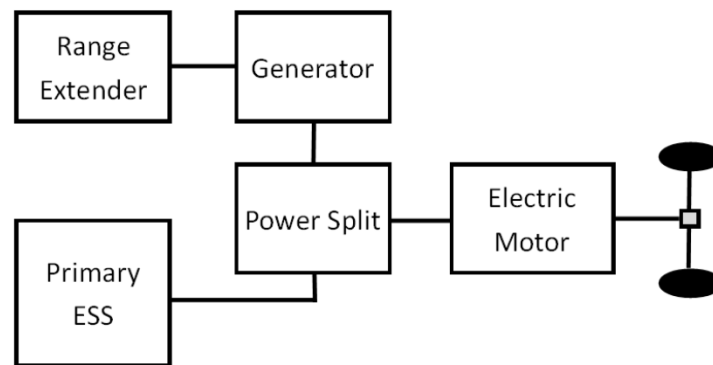
The APU must provide a range less than or equal to the main battery range.

The APU must not be switched on until the main battery charge has been depleted.

The vehicle must meet the super ultra-low emission vehicle (SULEV) requirements.

The APU and its associated fuel must meet the zero evaporative emissions requirements.

An REEV often uses a simple series hybrid powertrain configuration, as shown in **Figure 1**.



There are several different types of range extenders, including ICE, fuel cell, free-piston linear generator (FPLG), and micro power turbine (MGT). An ICE range extender generates electricity from powerline using a fuel converter. Some examples of ICE range extending EVs include the Chevrolet Volt and the BMW i3. A fuel cell REEV contains a tank of hydrogen fuel, which gets converted into usable electricity using a fuel cell. An FPLG range extender uses a combustion and linear generator to convert chemical energy into electrical energy.

An MGT range extender draws in clean air, compresses it, and passes it through a turbine at extremely high revolutions to generate electricity. In recent years, the concept of a zinc-air (Zn-air) battery as a range extender for EVs has also been investigated.

II. LITERATURE REVIEW

2.1 LITERATURE REVIEW:

Zhenbo Lu *et al* (2020) analyzed the barriers for market penetration of EVs and the technological readiness of different components of battery electric vehicles (BEVs). The authors considered range extenders as the solution to free battery EVs from the 'range anxiety' issue and lower the vehicle weight and capital costs by downsizing the battery.

Friedl *et al.* (2023) presented different solutions for range extender in EVs and explained the priorities and practical use for each application. However, the authors only discussed one type of range extender which was ICE.

Heron *et al.* (2023) conducted a comparison study on four different range extending technologies while considering several criteria including efficiency, vibration, noise, packaging, cost, emissions, and scalability. However, this study was completed almost a decade ago, and since then, there have been significant developments in the field. The lack of a more recent review of REEVs leads to a significant gap in this research field. The contribution of this paper is a comprehensive and up-to-date review and comparison of five range extending technologies as well as some future research goals for REEVs.

Hayes, J.G.(2023), give an research on Stationary inductive charging was successfully used by General Motors for the EV1 in the 1990’s. More recently, inductive charging has been introduced with smart phones and gaming systems, but the majority of consumer portable electronics still rely on wired charging.

Yuan, Tong et al. (2020) conducted a survey that many patents have been published on using an inductive charging system to aid in electric vehicle propulsion, but they fail to actually map out a system and provide a tangible look at the feasibility of the technology. The patents lay out a scenario in which a vehicle would be charged inductively while traveling over roads equipped with conductors.

Bolger, J. C., (1975)- patents point out that the distance between the collector plates on the vehicle and the road conductors is critical to the efficiency of the overall system. However, since the vehicle is moving this presents a challenge. If the plates are too close to the ground a small bump could dislodge the collectors, while too far away the system would not be efficient enough to be justified. Also, the design of the inductive charging system for highways has not been optimized for a specific vehicle or road.

III.PROPOSED SYSTEM

The proposed AI-enabled Battery Management System (BMS) for electric vehicles (EVs) revolutionizes energy oversight by shifting from reactive monitoring to proactive intelligence. At its core, the system utilizes advanced machine learning algorithms—such as Long Short-Term Memory (LSTM) networks—to process high-frequency streaming data from sensors, including voltage, current, and temperature. Unlike traditional rule-based systems, this architecture continuously learns the unique electrochemical "fingerprint" of each battery cell, enabling real-time estimation of State of Charge (SoC) and State of Health (SoH) with unprecedented precision.

A primary innovation of this system is the integration of a **predictive maintenance module**. By identifying subtle deviations in impedance or thermal behavior, the AI can forecast potential degradation or catastrophic failure—such as internal shorts or thermal runaway—long before they occur. This predictive capability allows the vehicle to schedule maintenance interventions or automatically adjust power delivery to prolong battery longevity. Furthermore, the system incorporates cloud-connected digital twins, allowing the BMS to compare individual battery performance against a global fleet dataset. This holistic approach not only maximizes range and safety but also significantly enhances the circular economy of EV batteries by providing accurate data for second-life applications.

3.1 LAYOUT OF THE PROPOSED BLOCK DIAGRAM:

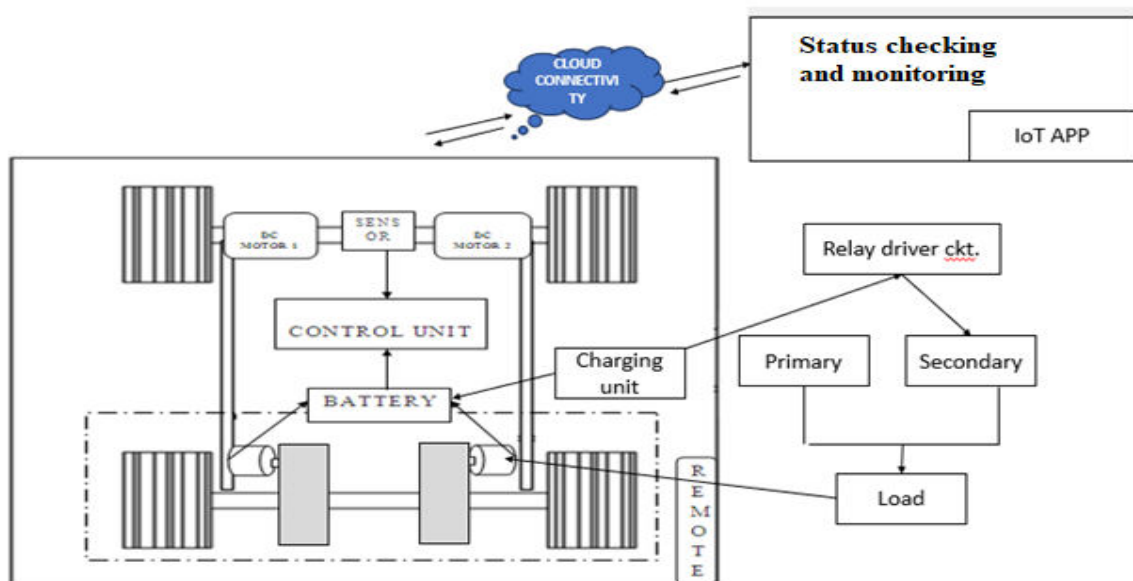


Fig 3.1. LAYOUT OF THE PROPOSED BLOCK DIAGRAM



The proposed AI-enabled Battery Management System (BMS) offers several transformative advantages for Electric Vehicle (EV) operations:

Proactive Predictive Maintenance: Unlike traditional systems that react only after a fault occurs, this AI-driven approach identifies degradation patterns and thermal anomalies in advance, significantly reducing the risk of catastrophic battery failure and costly repairs.

Enhanced State Estimation Accuracy: By utilizing deep learning models like LSTMs to analyze complex electrochemical data, the system achieves far higher precision in calculating the State of Charge (SoC) and State of Health (SoH) than standard, simplified mathematical algorithms.

Extended Battery Longevity: Through real-time monitoring and intelligent power management, the system dynamically adjusts discharge rates to minimize cell stress, effectively slowing the rate of capacity degradation and extending the overall lifespan of the battery pack.

Optimized Energy Efficiency and Range: The AI continuously adapts to driving behavior and environmental conditions, optimizing energy distribution to maximize vehicle range and ensure the battery operates within its most efficient performance window at all times.

Scalable Cloud-Based Fleet Analytics: Integration with "digital twin" technology allows the system to compare an individual vehicle's battery data against fleet-wide performance benchmarks, enabling continuous model improvement and refined maintenance strategies based on diverse real-world usage.

Improved Safety and Reliability: By constant, high-fidelity monitoring of cell temperatures and voltages, the system can detect and isolate early signs of thermal runaway or short circuits, providing a critical layer of safety for both passengers and the vehicle infrastructure.

IV HARD WARE REQUIREMENTS

4.1. ARDUINO CONTROLLER:

Arduino ESP 32 is a microcontroller board based on the ATmega. ESP32 is the name of the chip that was developed by Espressif Systems. This provides Wi-Fi (and in some models) dual-mode Cloud connectivity to embedded devices. While ESP32 is technically just the chip, modules and development boards that contain this chip are often also referred to as "ESP32" by the manufacturer.

It provides you with a faster processor and good memory size, which allow considerable larger projects to be designed on only one SOC. ESP32 provides us with reliable and hi-tech security. The strong security feature is a speciality of ESP32. There is 520 KB of available SRAM (320 KB of DRAM and 200 KB of IRAM) on the ESP32. However, due to a technical limitation, the maximum statically allocated DRAM usage is 160 KB.

ESP32 has a few hundred kilobytes of internal RAM, residing on the same die as the rest of the chip components. It can be insufficient for some purposes, so ESP32 has the ability to also use up to 4 MB of external SPI RAM memory. Our preferred method to program the ESP32 is with C/C++ "Arduino programming language".

4.2 ESP32 FEATURES

Processors – As previously mentioned, the ESP32 uses a Tensilica Xtensa 32-bit LX6 microprocessor. This uses 1 or 2 cores (*all chips in the series are dual-core, except the ESP32-S0WD). The clock frequency reaches up to 240MHz and it performs up to 600 DMIPS (Dhrystone Million Instructions Per Second). Moreover, its low power consumption allows for ADC conversions, computation, and level thresholds, all while in deep sleep mode.

- **Wireless connectivity** – The ESP32 enables connectivity to integrated Wi-Fi through the 802.11 b/g/n/e/i/. Moreover, dual-mode Cloud is made possible with the v4.2 BR/EDR and features Cloud Low Energy (BLE).

- **Memory** – Internal memory for the ESP32 is as follows – ROM: 448 KiB (for booting/core functions), SRAM: 520 KiB (for data/instructions), RTC fast SRAM: 8 KiB (for data storage/main CPU during boot from sleep mode), RTC slow SRAM: 8 KiB (for co-processor access during sleep mode), and eFuse: 1 KiBit (256 bits used for the system (MAC address and chip configuration) and 768 bits reserved for customer applications). Moreover, two of the ESP32 chips – ESP32-D2WD and ESP32-PICO-D4 – have internally connected flash. The others are as follows: 0 MiB



(ESP32-D0WDQ6, ESP32-D0WD, and ESP32-S0WD chips), 2 MiB (ESP32-D2WD chip), and 4 MiB (ESP32-PICO-D4 SiP module).

- **External Flash and SRAM** – ESP32 supports up to four 16 MiB external QSPI flashes and SRAMs with hardware encryption based on AES to protect developers' programs and data. It accesses the external QSPI flash and SRAM through high-speed caches.
- **Security** – IEEE 802.11 standard security features are all supported, including WPA, WPA/WPA2 and WAPI. Moreover, ESP32 has a secure boot and flash encryption.

4.3 ESP32 Functions

ESP32 has many applications when it comes to the Internet of Things (IoT). Here are just some of the IoT functions the chip is used for:

- **Networking:** The module's Wi-Fi Antenna and dual-core enables embedded devices to connect to routers and transmit data.
- **Data Processing:** Includes processing basic inputs from analog and digital sensors to far more complex calculations with an RTOS or Non-OS SDK.
- **P2P Connectivity:** Creates direct communication between different ESPs and other devices using IoT P2P connectivity.
- **Web Server:** Access pages written in HTML or development language

4.4 ESP32 Applications

The ESP32 modules are commonly found in the following IoT devices:

- Smart industrial devices, including Programmable Logic Controllers (PLCs)
- Smart medical devices, including wearable health monitors
- Smart energy devices, including HVAC and thermostats
- Smart security devices, including surveillance cameras and smart locks

4.5 Disadvantages of ESP32: support only Wi-Fi networks with a frequency range of 2.4 GHz – they will not connect to a modern 5 GHz network

V.SOFTWARE DESCRIPTION

5.1 Safety-Critical Real-Time Operating System (RTOS): The system must run on a deterministic RTOS to ensure that safety-critical tasks—such as overcurrent protection, cell balancing, and temperature cutoff—are executed with fixed, predictable timing regardless of the computational load from AI modules.

5.2 Model Inference & Optimization: Because onboard compute is limited, AI models (e.g., LSTMs or GRUs) must be optimized using **quantization** and **pruning**. This reduces the memory footprint and latency, allowing the model to make predictions (like detecting a short circuit) within milliseconds of the raw sensor input.

5.3 Predictive Maintenance Algorithms: The software implements hybrid models:

5.4 Physics-Informed Models: Using mathematical equivalents (e.g., Equivalent Circuit Models) to handle baseline behavior.

5.5 Data-Driven Models: Deep learning architectures that capture non-linear degradation trends (SoH/RUL) that traditional physics models often miss.

5.6 Digital Twin Synchronization: The software must manage a "digital shadow" in the cloud. It periodically synchronizes compressed battery health snapshots to the cloud. This allows the system to compare the vehicle's real-time performance against a high-fidelity digital twin that runs more complex, non-real-time simulations for deep analysis.

5.7 Cybersecurity & OTA Frameworks: Given the connectivity, the software must be **ISO/SAE 21434** compliant. This includes secure Over-the-Air (OTA) update mechanisms that allow for safe, authenticated model updates to be pushed to the vehicle as the battery ages and the AI needs retraining.



VI. CONCLUSION

The integration of AI-enabled Battery Management Systems (BMS) with predictive maintenance represents a fundamental shift in electric vehicle technology—moving from reactive, failure-based maintenance to a proactive, data-driven reliability model. By leveraging machine learning for real-time State of Health (SoH) and State of Charge (SoC) estimation, this project addresses the core challenges of battery degradation, safety, and operational uncertainty. The ability to predict anomalies like thermal runaway or internal cell shorts before they escalate ensures passenger safety and protects valuable assets. Through intelligent management, the system directly extends the usable life of battery packs, reducing the frequency of replacements and lowering the total cost of ownership. By combining edge-computing for immediate safety responses with cloud-based digital twins for long-term health tracking, the proposed architecture provides a scalable and robust solution for modern, interconnected transport ecosystems. This research confirms that embedding AI at the edge is not merely an enhancement but a requirement for the next generation of high-performance, long-range electric vehicles.

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