Smart EV Charginig Infrastructure with Dynamic Load Management

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ABSTRACT: The rapid adoption of electric vehicles (EVs) has increased the need for intelligent charging infrastructure that ensures efficient energy utilization, safety, and reliable monitoring. This paper presents a Smart EV Charging Infrastructure with Dynamic Load Management using an ESP32 microcontroller and Internet of Things (IoT) technology. The system monitors charging voltage, current, battery temperature, and charging status using sensors, transmitting real-time data to Firebase through Wi-Fi. A relay-based protection mechanism disconnects the charging circuit during abnormal conditions, improving safety and protecting battery health. Three charging profiles-Fast, Normal, and Eco-enable flexible charging according to user requirements. Dynamic load management optimizes power distribution and reduces unnecessary energy consumption. Experimental results demonstrate reliable cloud communication, accurate monitoring, and cost-effective implementation. The proposed system provides a scalable solution for residential, commercial, and public EV charging stations, supporting sustainable transportation and future smart-grid development.

Keywords—Electric Vehicle (EV), Smart Charging Infrastructure, Dynamic Load Management, ESP32 Microcontroller, Internet of Things (IoT), Firebase Cloud, Real-Time Monitoring, Battery Protection, Energy Optimization, Wi-Fi Communication.

I. INTRODUCTION

The rapid adoption of electric vehicles has increased the demands for intelligent charging infrastructure that ensures efficient energy utilization, safety, and reliable power distribution. Conventional charging stations often lack real-time monitoring and adaptive control, potentially causing grid overload, energy wastage, and battery damage. This paper proposes an IoT-enabled Smart EV Charging Infrastructure with Dynamic Load Management using an ESP32 microcontroller. The system monitors charging voltage, current, battery temperature, and charging status through sensors and transmits real-time data to Firebase using Wi-Fi connectivity. A relay-based protection mechanism automatically disconnects the charging circuit during abnormal electrical or thermal conditions, enhancing operational safety. Three user-selectable charging modes – Fast, Normal, and Echo – provide flexibility according to energy requirements. Dynamic load management optimizes available power distribution and improves charging efficiency. Experimental evaluation demonstrates reliable cloud communication, effective monitoring, and cost-effective implementation. The proposed architecture offers a scalable solution for residential, commercial, and public charging stations, supporting sustainable transportation and future smart-grid integration.

II. LITERATURE SURVEY

This research explores the use of grid-connected Electric Vehicles (EVs) as mobile energy storage for frequency regulation. The authors propose a multi-layer consensus-based control strategy using an agent-based architecture. By enabling limited communication between charging stations, the system distributes regulation power according to station capabilities while maintaining grid stability and meeting diverse EV charging requirements [1].

This paper optimizes power sharing between the utility grid and EV charging stations to reduce costs and prevent transformer overloading. The researchers propose a distributed consensus-based framework using derivative-free scheduling. This approach enables stations to coordinate power consumption without centralized control. Simulation results demonstrate near-optimal power distribution, lower energy costs, and reliable grid operation during peak demand periods [2].

This paper presents a cybersecurity framework for managing multiple EV charging locations securely and efficiently. It incorporates user authentication and encrypted data transmission between charging stations and central managements system to prevent unauthorized access and cyber-physical attacks. The findings demonstrate improved network security and reduced vulnerability while maintaining real-time charging management efficiency and reliable operational performance [3].

This study addresses uncertain EV arrival times and nonlinear battery charging characteristics. The authors propose an online, prediction-free scheduling method using a deadline-aware charging queue and Lyapunov optimization. The approach accommodates random arrivals and renewable energy fluctuations while respecting battery State-of-Charge (SoC) limits. Results demonstrate reduced energy costs and timely charging demand fulfillment [4].

This paper introduces a menu-based EV charging scheduling approach that simplifies user preference selection. Users choose charging intervals with associated urgency prices upon arrival. An online algorithm assigns completion times while ensuring incentive compatibility. Experimental results demonstrate near-optimal performance compared with theoretical benchmarks, providing a practical solution that improves scheduling efficiency and prevents strategic misreporting of charging requirements [5].

This paper presents an uncertainty-aware Deep Learning (DL) framework for managing large-scale public EV charging stations. The model predicts vehicle arrival rates and energy demand patterns, supporting robust scheduling to meet user deadlines. Results demonstrate improved resilience to arrival fluctuations, more accurate grid power estimation, and reliable charging services despite limited historical data availability [6].

This paper proposes temperature-controlled smart EV charging to improve battery lifespan and charging efficiency, particularly in cold climates. The method analyzes battery thermal dynamics to optimize heating schedules and energy allocation while considering charging rates and battery health. Simulation results show charging cost reductions of up to 18.4%, reduced heating overhead, and improved renewable energy utilization [7].

This paper reviews global EV charging infrastructure, highlighting challenges such as inconsistent standards, grid limitations, and high implementation costs. It examines charging technologies, communication protocols, smart charging, and Vehicle-to-Grid(V2G) systems. The study emphasizes scalable, secure, and low-cost charging solutions with dynamic load management and monitoring to improve accessibility, reliability, and sustainable electric mobility [8].

III. PROPOSED SYSTEM

The proposed Smart EV Charging Infrastructure is designed to provide an intelligent, low-cost, and scalable charging solution by integrating embedded hardware, IoT communication, cloud-based monitoring, and dynamic load management. The system is centered around the ESP32 microcontroller, which continuously acquires charging parameters from multiple sensors and executes real-time control decisions to ensure safe and efficient battery charging.

Dynamic Load Management (DLM) is the primary contribution of the proposed charging infrastructure. Unlike conventional chargers that operate at a fixed charging rate, the proposed controller dynamically adjusts power allocation according to the electrical operating conditions. The controller continuously evaluates the following parameters:

- Battery voltage
- Charging current
- Battery temperature
- User-selected charging mode
- Available charging power

If abnormal operating conditions are detected, the relay immediately disconnects the charging circuit to prevent battery damage and electrical hazards. Three charging profiles are implemented:

Fast Mode

- Maximum charging current
- Minimum charging time
- Suitable during emergencies
- Higher thermal monitoring frequency

Normal Mode

- Balanced charging current
- Improved battery health
- Recommended for daily charging

Eco Mode

- Reduced charging current
- Lowest power consumption
- Maximum battery lifespan
- Reduced grid loading

The charging mode can be changed dynamically through the user interface without interrupting the charging session.

The electrical power delivered to the battery is calculated as

$$P = V \times I$$

Where P is the charging power (W), V is the battery voltage (V), and I is the charging current (A).

The total energy delivered during charging is

$$E = \int_0^T P(t)dt$$

Where E is the delivered energy (W) and T represents the charging duration.

Battery State-of-Charge (SoC) is estimated using

$$SoC = \frac{Q_{current}}{Q_{rated}} \times 100$$

Where $Q_{current}$ is the present battery capacity and Q_{rated} is the rated battery capacity.

Temperature protection is implemented using

$$T < T_{critical}$$

If

$$T \geq T_{critical}$$

The controller immediately opens the relay and terminates charging.

Charging efficiency is calculated by

$$\eta = \frac{P_{Battery}}{P_{input}} \times 100\%$$

Where η is the charging efficiency, $P_{Battery}$ is the useful battery power, and P_{input} is the input power.

The proposed methodology offers several advantages over conventional EV charging systems:

- Real-time monitoring of charging parameters.
- Cloud-based remote accessibility.
- Dynamic load balancing for efficient power utilization.
- Automatic battery protection against overheating and overcurrent.
- User-selectable charging modes.
- Low-cost hardware implementation.
- Easy scalability for multi-station deployments.



FIGURE1: PROPOSED SMART EV CHARGING INFRASTRUCTURE

The FIGURE1 shows the proposed Smart EV Charging Infrastructure that uses voltage, current, and temperature sensors to monitor charging conditions. The ESP32 processes sensor data and controls charging through a relay driver and relay. Wi-Fi enables communication with Firebase Realtime Database for cloud storage. A

web dashboard allows users to monitor charging parameters, manage charging operations, track energy consumption, and support efficient, reliable EV charging.

IV. HARDWARE AND SOFTWARE IMPLEMENTATION

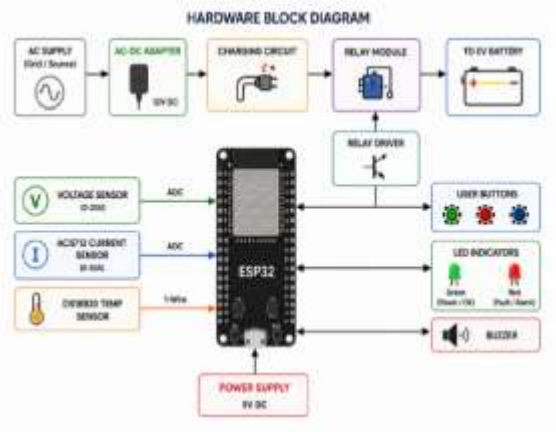


FIGURE2: HARDWARE BLOCK DIAGRAM

The FIGURE2 illustrates the complete hardware architecture of the charging station. The proposed Smart EV Charging Infrastructure uses affordable embedded components, making it economical, scalable, and practical. The ESP32 microcontroller serves as the central controller, managing sensing, processing, communication, and charging control. Voltage, ACS712 current, and DS18B20 temperature sensors collect electrical and thermal data. The processed information is transmitted through Wi-Fi to Firebase for real-time monitoring and management.

The charging control unit regulates the power supply using a relay mechanism based on the system's operating conditions. Wi-Fi connectivity enables continuous data transfer to Firebase Realtime Database, where charging parameters are stored and updated. A web-based dashboard provides users with real-time access to voltage, current, temperature, and energy consumption data. Additionally, energy usage prediction, automatic billing, and user authentication improve operational efficiency, transparency, and charging management.



FIGURE3: SOFTWARE ARCHITECTURE

The software architecture consists of three main layers: embedded firmware, cloud backend, and web dashboard. The ESP32 initializes sensors, collects and filters data, manages dynamic loads, controls relays, and communicates through Wi-Fi. Sensor readings are securely transmitted using HTTPS to Firebase Realtime Database, which stores voltage, current, temperature, charging mode, and session details. The web dashboard synchronizes with Firebase, enabling real-time monitoring, charging status updates, historical analysis, user management, alerts, and administrative control.

The architecture also supports efficient energy utilization and reliable charging operations through continuous data exchange between the ESP32 and Firebase. Dynamic load management helps regulate charging according to system conditions, while stored session information supports energy consumption analysis and automatic billing. The dashboard provides alerts and notifications to inform users about charging conditions. This integrated design improves system scalability, accessibility, operational efficiency, and remote management of EV charging infrastructure.

The proposed system provides a cost-effective and scalable solution by integrating embedded hardware, Wi-Fi communication, cloud storage, and intelligent control. Its key advantages include enhanced operational safety, real-time monitoring, adaptive charging modes, and dynamic load management. Furthermore, Firebase integration enables remote access to charging data and efficient energy management. The system can be further enhanced for large-scale deployment in smart cities and smart-grid environments.

V. RESULTS

The proposed Smart EV Charging Infrastructure was implemented and experimentally validated using an ESP32-based embedded platform integrated with voltage, current, and temperature sensing modules. The prototype was assembled on a solderless breadboard to facilitate rapid prototyping and testing. A 12 V DC power supply was used to emulate the charging source, while a rechargeable battery represented the electric vehicle battery pack.

The ESP32 continuously acquired measurements from the sensing modules and executed the Dynamic Load Management (DLM) algorithm. The processed data were transmitted through the onboard Wi-Fi interface to the Firebase Realtime Database, enabling real-time visualization and monitoring through a web-based dashboard.



FIGURE3:HARDWARE PROTOTYPE

The hardware setup shown in the FIGURE3 represents the prototype of a Smart EV Charging Infrastructure with Dynamic Load Management system in connected and disconnected states. The kit consists of a microcontroller development board (ESP-based), a breadboard for circuit connections, voltage and current sensing modules, LED indicators, a relay module, and a rechargeable battery pack for power supply. The components are interconnected using jumper wires to form the complete hardware prototype.



FIGURE4: SERIAL MONITOR OUTPUT

The FIGURE4, shows the Arduino Serial Monitor output of the system. The serial monitor displays real-time data received from the voltage and current sensors connected to the microcontroller.

When the hardware kit is powered using the adapter, the sensors begin measuring electrical parameters such as voltage and current from the charging circuit. These values are processed by the ESP-based microcontroller and continuously printed on the serial monitor. The serial output helps in verifying that the sensors and circuit connections are functioning correctly.



FIGURE5: REALTIME DATABASE OF FIREBASE

The FIGURE5 shows the Firebase Realtime Database dashboard of the system. The database displays live data that is transmitted from the hardware kit through the ESP-based microcontroller using Arduino code and Wi-Fi connectivity. When the hardware system is powered on, the voltage and current sensors measure electrical parameters from the charging circuit. The Arduino program processes these values and sends them to the Firebase Realtime Database in real time. The dashboard shown in the image confirms that the connection between the hardware system and Firebase has been successfully established. In the database, the charging station data is stored under the node charging_station_1.



FIGURE6: HOST VIEW

The Host View in the figure 4.6 is characterized by the "System Admin" profile in the top right. It provides a high-level overview of the entire network. The interface is designed with a user-friendly layout to ensure easy navigation and quick access for users. Input validation is implemented to verify correct email format and password requirements before allowing login. Security features such as password masking and basic authentication checks are incorporated to protect user credentials.

Main Dashboard consists of Active sessions, Vehicle status, Network load, Charging Mode Toggle.

Recent charging sessions is a tabular log showing historical data across the network. It tracks Session ID, User Name, Duration, Energy consumed in kWh, total Cost, and Session Status.

Registered User directory is a management table listing all authorized users. It includes User IDs, Email Addresses, their specific EV Model, and their current connectivity status.

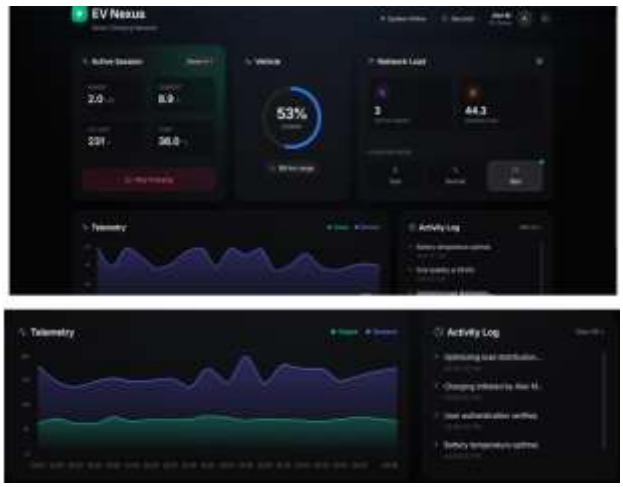


FIGURE7: USER VIEW

When logged in as a user (e.g., Alex M.), the view becomes more focused on the individual's specific charging experience as shown in FIGURE7. It consists of Personalized charging interface, Active session monitoring, Vehicle Metrics, Simplified network load.

Hence the EV Nexus dashboard is a professional, dark-mode management interface designed for a smart EV charging network. It functions as a dual-role platform that caters to both network administrators and individual vehicle owners.

The Host view serves as a command centre for infrastructure oversight. Administrators have access to global network metrics, including the total number of charging sessions, real-time grid demand, and the status of all active charging nodes. They can manage the user directory tracking individual drivers and their associated vehicle models and view a comprehensive log of all charging sessions, complete with financial breakdowns and session statuses (e.g., "Completed" or "Interrupted").

The User view transitions the interface into a personalized assistant. It strips away the network-wide management tools and focuses exclusively on the user's specific vehicle status. The dashboard provides clear, actionable information such as battery percentage, remaining driving range, and current power draw. It includes a user-friendly interface for initiating or stopping charging sessions and allows the owner to toggle between charging modes Fast, Normal, or Eco to optimize for their personal needs.

Both views share a sophisticated telemetry and monitoring system that bridges the gap between infrastructure health and individual performance.

VI. CONCLUSION

This paper presents a Smart EV Charging Infrastructure with Dynamic Load Management using an ESP32 microcontroller integrated with IoT-based cloud monitoring. The proposed system addresses several limitations of conventional EV charging stations by combining embedded sensing, intelligent charging control, real-time communication, and cloud-based supervision within a unified and cost-effective architecture.

Experimental validation demonstrated reliable operation across Fast, Normal, and Eco charging modes. The integrated relay protection mechanism successfully isolated the charging circuit under abnormal thermal and electrical conditions, thereby enhancing battery safety and operational reliability. Continuous synchronization with the cloud platform enabled efficient remote monitoring and supervision with minimal communication latency.

Therefore, the proposed system offers a practical, economical, and intelligent solution for next-generation electric vehicle charging stations. Its modular design supports deployment across residential, commercial, institutional, and public charging environments while providing a strong foundation for future smart-grid integration.

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