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Smart grid integrated wireless EV charging system using machine learning

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Abstract -

The rapid growth of electric vehicles (EVs) demands intelligent, efficient, and sustainable charging infrastructure integrated with smart grid technologies. This project presents a Smart Grid Integrated EV Charging System with Machine Learning and Power Flow Analysis, designed to enable wireless EV charging, real-time power monitoring, and intelligent decision-making. The proposed system uses wireless power transmission coils for contactless charging, where IR sensors detect vehicle presence and activate relays to initiate charging. Electrical parameters such as voltage and current are continuously monitored using sensors and transmitted to a Python-based platform for analysis. A Random Forest machine learning algorithm is employed to analyze sensor data and predict charging behavior, efficiency, and abnormal conditions. The system also integrates IoT functionality using NodeMCU, allowing real-time data upload to cloud platforms for remote monitoring. A solar-powered charging station charges a battery to support green energy utilization, while a robotic vehicle chassis represents the EV, controlled via Bluetooth. LED indicators display charging status and system states. The proposed solution demonstrates an intelligent, scalable, and eco-friendly EV charging system suitable for future smart grid applications.

***Key Words*:** Electric Vehicles (EVs), Wireless Power Transmission (WPT), Wireless EV Charging, Smart Grid Integration Inductive Coupling (Implied by wireless coils)

1. INTRODUCTION

The rapid global transition toward sustainable transportation has established electric vehicles (EVs) as a primary solution for reducing carbon emissions and dependency on fossil fuels. However, the large-scale adoption of EVs depends heavily on the development of a charging infrastructure that is not only efficient and scalable but also integrated seamlessly into modern smart grids. Current conventional charging methods often rely on physical wired connections, which can be inconvenient, prone to mechanical wear, and limited in their ability to provide real-time data and intelligent energy management.

This project introduces an innovative approach: a Smart Grid Integrated EV Charging System that leverages wireless power transfer and advanced machine learning. Unlike traditional systems, this model utilizes inductive power transfer (IPT), where energy is exchanged between ground-based and vehicle-mounted coils via magnetic fields. This contactless method significantly enhances user convenience and safety, particularly in varied environmental conditions where exposed electrical components could pose risks.

A critical challenge in wireless charging is maintaining high power transfer efficiency, which is often sensitive to precise coil alignment. To address this, the system incorporates intelligent sensing and automation. Infrared (IR) sensors are deployed to detect vehicle presence, triggering relays that initiate the charging process only when an EV is correctly positioned. This automated activation minimizes idle energy loss and ensures that power is transferred effectively.

Furthermore, the system integrates a Random Forest machine learning algorithm to transition from reactive to proactive energy management. By continuously monitoring electrical parameters such as voltage and current through a Python-based module, the algorithm can predict charging status, analyse power flow efficiency, and identify potential anomalies or abnormal conditions in real time. This data-driven intelligence allows for more reliable grid integration and prevents issues such as grid overloading during peak demand periods.

To complement these technologies, the project employs Internet of Things (IoT) capabilities through NodeMCU. This enables the seamless transmission of charging data to cloud-based platforms for remote monitoring and visualization, providing both users and grid operators with transparent, up-to-date information on energy consumption. Sustainability is further enhanced by incorporating a solar-powered charging station, which utilizes green energy to charge buffer batteries, thereby reducing the overall carbon footprint and dependency on the conventional electrical grid.

In summary, this smart grid integrated system provides a comprehensive solution for future transportation needs. By combining wireless power transfer with machine learning, solar energy utilization, and IoT-based monitoring, it addresses the fundamental limitations of existing EV charging technology while promoting a more sustainable and intelligent energy ecosystem.

2. Related works

The integration of a **Smart Grid Integrated EV Charging System** using **Machine Learning** represents a significant leap toward efficient and sustainable infrastructure for electric vehicles. Conventional charging faces hurdles like grid overloading and inefficient energy use, which this system overcomes by combining **wireless power transfer**, real-time monitoring, and **IoT technologies**. The physical setup utilizes **wireless power transmission coils** for contactless energy

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delivery, with **IR sensors** detecting vehicle presence to automatically trigger the charging process via **relays**. To ensure safety and performance, **ACS712 current sensors** and **voltage sensors** continuously monitor electrical parameters, transmitting this data to a **Python-based platform**. Here, a **Random Forest algorithm** analyses the sensor data to predict charging behaviour, evaluate efficiency, and proactively detect abnormal conditions.

Managed by an **Arduino Mega** and integrated with **NodeMCU** for cloud-based remote monitoring, the system provides a transparent and scalable energy management solution. Sustainability is prioritized through a **solar-powered charging station** that charges a **12V battery**, promoting green energy utilization and reducing grid dependency. The entire operation, featuring an EV represented by a **robotic chassis** controlled via **Bluetooth**, demonstrates a reliable and intelligent ecosystem. By aligning with smart grid concepts, this automated framework—developed by G. Amrutha Sri Pradha, P. Dhanunjai, T. Ravi Teja, and V. Joshyam—paves the way for an eco-friendly future in sustainable transportation

3. Methodology

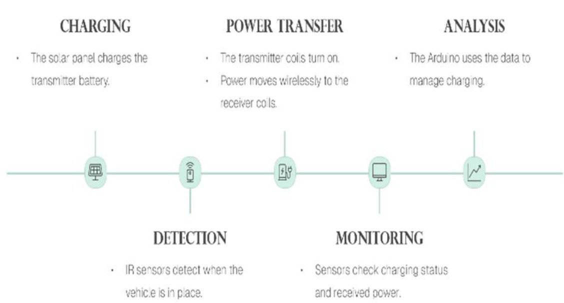


Fig -1: Framework

Figure 1 shows the conceptual framework of the system where the input, process, and output are shown. This Solar-Powered Wireless Charging System represents a sophisticated, five-stage integration of renewable energy and automated hardware management. The process begins with **Charging**, where solar panels harvest photovoltaic energy to replenish a transmitter battery, providing a sustainable power reservoir. To ensure the system remains energy-efficient, the **Detection** phase utilizes IR sensors to identify when a vehicle is correctly positioned over the charging pad. Only after successful detection does the **Power Transfer** stage activate; here, transmitter coils generate a magnetic field to move electricity wirelessly to the receiver coils via inductive coupling

As energy flows, the system enters a continuous **Monitoring** loop, where specialized sensors track the received power levels and real-time charging status to maintain safety and peak efficiency. Finally, the **Analysis** phase serves as the system's "brain." Utilizing an Arduino microcontroller, the system processes the collected sensor data to intelligently manage the charging cycle, adjusting parameters to prevent overcharging or energy waste. By combining solar harvesting with automated detection and microcontroller-based analysis, the system creates a seamless, autonomous bridge between green energy production and wireless consumption, optimizing the entire lifecycle of power delivery for modern electric transport.

B. System Block diagram

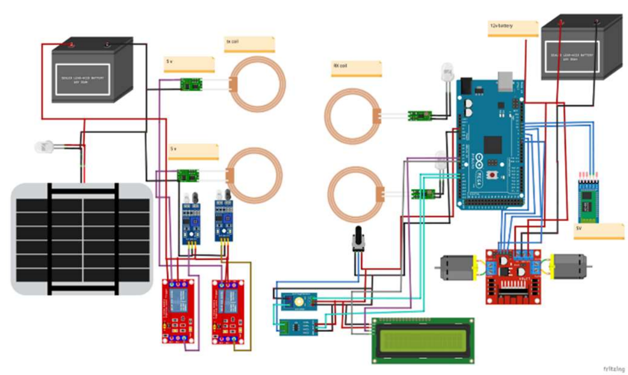
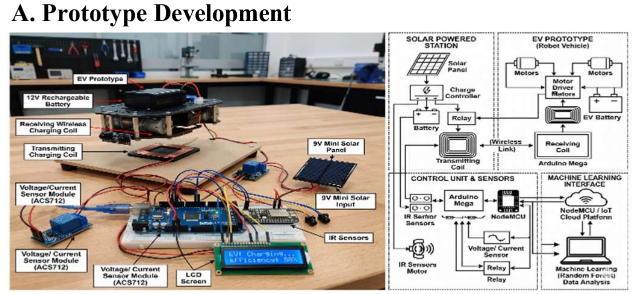


Fig -2: System Circuit Diagram

Figure 2 shows the Systems block diagram. This circuit diagram illustrates the technical implementation of the solar-powered wireless charging system. On the **transmitter side**, a solar panel charges a 12V lead-acid battery, which powers two wireless TX coils via voltage regulators and relay modules. IR sensors are integrated to trigger these relays only when a vehicle is detected.

The **receiver side** features an **Arduino Mega** as the central controller. It captures energy through RX coils, monitors voltage levels, and displays data on an LCD screen. The system also includes an L298N motor driver for vehicle movement and a Bluetooth module for remote data transmission and control.

A. Prototype Development



The prototype development for the **Smart Grid Integrated EV Charging System** involved building a functional model using a **robot chassis** to represent the EV. Controlled via **Bluetooth**, the vehicle is detected by **IR sensors** that trigger **wireless power transmission coils** through **relays** to initiate charging. The system incorporates an **Arduino Mega** for control and **sensors** to monitor voltage and current. **Machine learning** via a **Random Forest algorithm** analyzes this data, while a **NodeMCU** enables **IoT** cloud connectivity for remote monitoring. A **solar-powered station** charges the battery, ensuring sustainable energy management.

2) Software Development

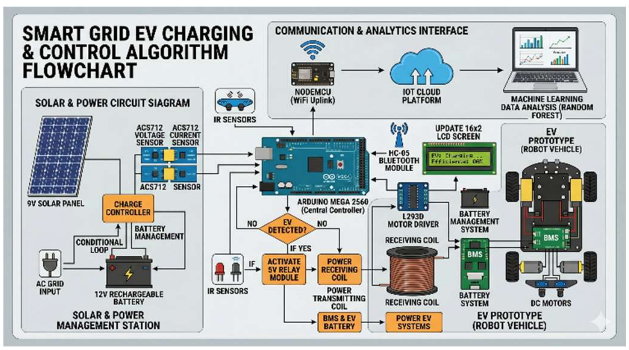


Fig. 4. The Algorithm Flow Chart

Figure 4 shows the flow chart of the algorithm used in this study. The **Smart Grid Integrated EV Charging System** is an intelligent infrastructure that unifies wireless power transfer, real-time monitoring, and machine learning into a single platform. When the prototype robot vehicle approaches the station, **IR sensors** detect its presence and trigger a **5V relay** to activate the **wireless power transmission coils**. This contactless method initiates charging while minimizing mechanical wear.

Electrical parameters are continuously measured by ACS712 voltage and current sensors. This data is processed through a Random Forest machine learning algorithm to predict charging behavior, efficiency, and abnormal conditions. For remote transparency, a NodeMCU module uploads real-time data to a cloud platform. Additionally, the station incorporates a solar panel and a 12V battery to promote sustainable, green energy utilization while reducing grid dependency. Ultimately, this system demonstrates a scalable and reliable solution for future smart city transportation.

4. Results and Discussion

Figure 5 The implementation of the Smart Grid Integrated EV Charging System yielded several significant outcomes regarding automated wireless power transfer and real-time system intelligence. The system successfully achieved contactless energy transfer using inductive coupling between the transmitter and receiver coils, where an alternating current in the transmitter coil created an oscillating magnetic field to induce voltage in the receiver. The IR sensors demonstrated high reliability in vehicle detection, consistently triggering the 5V relay to initiate the charging process only when the EV prototype was properly aligned. This automated approach ensures that power is transmitted only when needed, enhancing overall system safety.

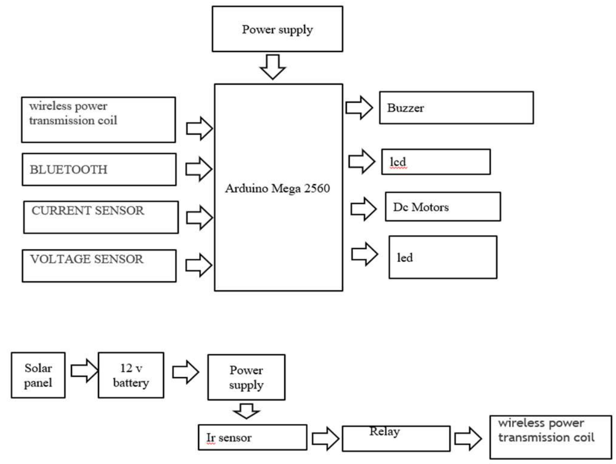


Fig. 5. Block Diagram

Electrical monitoring results showed that the **ACS712 sensors** and voltage sensors provided accurate, continuous measurements of the system's electrical parameters. These real-time values were successfully processed by a **Random Forest machine learning algorithm**, which accurately predicted charging status and load conditions while identifying potential anomalies. Furthermore, the **NodeMCU** integration enabled the seamless upload of this data to a cloud platform, allowing for transparent remote visualization. Finally, the hardware successfully demonstrated green energy utilization, as the **9V solar panel** effectively charged the **12V battery**, proving that the system can operate with reduced dependency on the conventional power grid.

The results of this project indicate that integrating smart grid concepts with machine learning significantly overcomes the limitations of conventional wired charging systems. Traditional methods often lack real-time monitoring and predictive capabilities, making them reactive rather than proactive. By contrast, the proposed model's use of a **Random Forest algorithm** provides an intelligent decision-making layer that anticipates charging behavior and identifies faults before they lead to system failure. This transition to data-driven management is essential for the reliability of future smart grid applications

The discussion also highlights the sustainability and scalability of the prototype. The successful use of **solar energy** to power the charging station confirms that renewable sources can be effectively integrated into EV infrastructure to promote eco-friendly transportation. While conventional stations operate as standalone units, this project's use of **IoT via NodeMCU** ensures that the system is part of a larger, connected network suitable for urban environments like parking lots and highways. Although the current prototype uses a robotic vehicle chassis,

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the underlying principles of inductive power transfer and distributed control are highly adaptable for full-scale electric vehicles. Ultimately, the system demonstrates a reliable and eco-friendly charging solution that aligns with the evolving demands of modern energy management.

Conclusions and Recommendations

The project successfully demonstrates the design and implementation of a Smart Grid Integrated EV Charging System that effectively addresses the rising demand for sustainable and efficient infrastructure. By unifying wireless power transfer, real-time monitoring, machine learning, and IoT technologies into a single platform, the system achieves a high level of automated and intelligent decision-making. The integration of IR sensors for vehicle detection and relays for wireless power transmission allows for a contactless charging process that minimizes mechanical wear and enhances user convenience. Furthermore, the application of a Random Forest machine learning algorithm enables the system to proactively predict charging behavior and identify abnormal conditions, while the use of solar energy promotes eco-friendly operation by reducing dependency on the conventional grid. Ultimately, this model provides a scalable and reliable solution for future smart city energy management.

To further advance this research, it is recommended that future developments focus on more sophisticated distributed charging control algorithms to better manage grid reliability and prevent overloading during peak demand periods. Expanding the scope of machine learning beyond the Random Forest algorithm could also improve forecasting accuracy for energy demands and further optimize grid integration. There is a significant opportunity to investigate vehicle-to-grid (V2G) interactions, which would allow electric vehicles to serve as active components of the smart grid by supplying energy back during emergencies. Additionally, aligning hardware design with evolving Qi standards and enhancing the mechanical durability of wireless coils through improved ferrite shielding and waterproofing will be essential for successful commercial and industrial applications. Future work should also address research gaps in load-balancing techniques to ensure the system remains user-friendly and operationally efficient at a larger scale.

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