Solar PV Powered EV Charging System with MPPT, Battery Backup and Automated Booking and Real-Time Monitoring.

1. Prof. Devika Sahu, 2. Jitesh S. Chimote, 3. Vedant S. Metangle, 4. Dhanshri K. Wasu,

5. Viraj S. Hiwarkar, 6. Sarvesh S. Wabhitkar

A[1] is lecturer at Department of Electrical Engineering in NIT Polytechnic Nagpur & [2 to 6] is a students at Department of Electrical Engineering in NIT Polytechnic Nagpur.

Email: jiteshchimote014@gmail.com

Abstract

The global automotive industry is witnessing a significant paradigm shift from Internal Combustion Engine (ICE) vehicles to Electric Vehicles (EVs) as a primary strategy to mitigate climate change and reduce dependency on fossil fuels. However, the mass adoption of EVs is currently impeded by the lack of convenient, efficient, and sustainable charging infrastructure. Traditional plug-in charging stations suffer from mechanical wear and tear, safety hazards related to exposed connectors, and a reliance on the non-renewable power grid. This research paper proposes the design and development of a **Solar-Powered Wireless EV Charging Station** integrated with a smart **IoT-based Automated Booking System**. The proposed system leverages the principle of **Inductive Power Transfer (IPT)** to charge vehicles wirelessly, thereby eliminating the need for physical cables and connectors.

The system is completely off-grid, powered by a high-efficiency **Solar Photovoltaic (PV) array** coupled with a battery backup and a Buck converter for voltage regulation. The core control logic is executed by an **ESP32 microcontroller**, which facilitates real-time communication between the charging station and the user via the **MQTT protocol**. A custom-built web interface allows users to check availability, book charging slots, and monitor the charging status remotely. The station also incorporates **IR sensors** for precise vehicle detection, ensuring that power transfer is activated only when a valid vehicle is aligned with the transmitter coil. This project demonstrates a scalable, eco-friendly, and user-centric solution for future smart city transportation networks.

Keywords: Wireless Power Transfer (WPT), Electric Vehicles (EV), Internet of Things (IoT), Solar Energy Harvesting, Inductive Coupling, ESP32, MQTT Protocol, Smart City Infrastructure.

1. Introduction

1.1 Background and Motivation

In recent years, the detrimental effects of global warming and the rapid depletion of fossil fuel reserves have necessitated an urgent transition towards sustainable energy and transportation solutions. Electric Vehicles (EVs) have emerged as the most viable alternative to conventional petrol and diesel vehicles. Governments worldwide are incentivizing the adoption of EVs to lower carbon footprints. However, the success of the EV ecosystem is intrinsically linked to the availability and accessibility of charging infrastructure.

Current charging solutions are predominantly wired (plug-in) and grid-dependent. While effective, wired chargers present several operational challenges. Frequent plugging and unplugging lead to the mechanical degradation of ports and connectors. Moreover, in outdoor environments, exposed cables pose electrical safety risks, particularly during monsoon seasons or wet conditions. Furthermore, the environmental impact of EVs is often debated if the electricity used to charge them is generated from coal-fired power plants. Therefore, there is a compelling need for a charging solution that is not only convenient and safe but also environmentally sustainable.

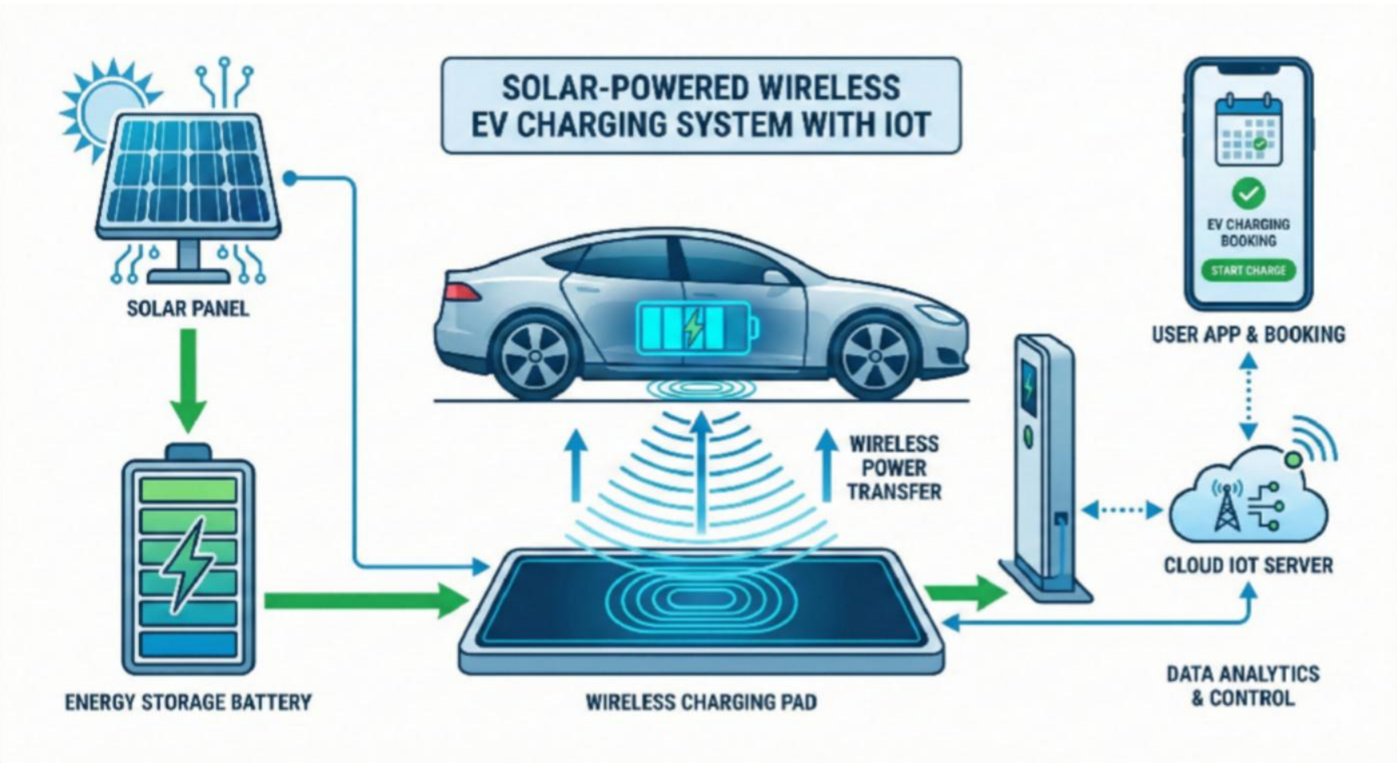
1.2 Problem Statement

Despite the advancements in EV technology, two major hurdles remain: **Range Anxiety** and **Charging Inconvenience**. Drivers often hesitate to switch to EVs due to the fear of running out of charge without finding a station. Additionally, existing public charging stations often lack real-time transparency; a user may arrive at a station only to find it occupied or malfunctioning. On the technical side, integrating renewable energy sources like solar power into charging systems requires efficient energy management, which is often missing in low-cost prototypes.

1.3 Proposed Solution

This paper presents a comprehensive solution by developing a **Solar-Powered Wireless Charging Station**. The system utilizes **Inductive Coupling** to transfer energy across an air gap, removing the need for physical contact. This "Park and Charge" mechanism significantly enhances user convenience. To address the issue of energy sustainability, the station harvests solar energy, storing it in a battery bank to ensure 24/7 operation.

Furthermore, the integration of the **Internet of Things (IoT)** transforms the station into a "Smart" device. By using the ESP32 microcontroller and a cloud-based broker (HiveMQ), the system offers a **Reservation-based Service**. Users can pre-book a slot for a specific duration, ensuring that the station is available upon their arrival. This integration of Renewable Energy, Wireless Power Transfer, and IoT creates a robust ecosystem for modern transportation.



2. Literature Review

To understand the current state of technology and identify the gaps that this project aims to fill, several existing methodologies and research papers were analyzed.

2.1 Wireless Power Transfer Technologies

Wireless charging is primarily based on the principle of electromagnetic induction, discovered by Michael Faraday. Early research focused on **Inductive Power Transfer (IPT)** for small appliances. Modern studies, such as those by *Tesla et al.* and recent IEEE publications, demonstrate that **Resonant Inductive Coupling** can achieve efficiencies of up to 90% over short distances. However, a common limitation identified in existing literature is the lack of intelligent control systems; most transmitters transmit power continuously, leading to energy wastage when no receiver is present. Our project addresses this by implementing an IR-based detection feedback loop.

2.2 Solar Energy Integration in EVs

Research by *Kumar and Singh (2022)* highlights the feasibility of solar-powered charging stations in tropical regions. Their study concludes that while solar panels are effective, the intermittent nature of sunlight requires a robust **Battery Management System (BMS)** and efficient DC-DC conversion. Standard PWM controllers often result in power loss. This project incorporates a Buck converter and regulated power supply design to maximize the utility of the harvested solar energy for the specific requirements of the wireless transmitter circuit.

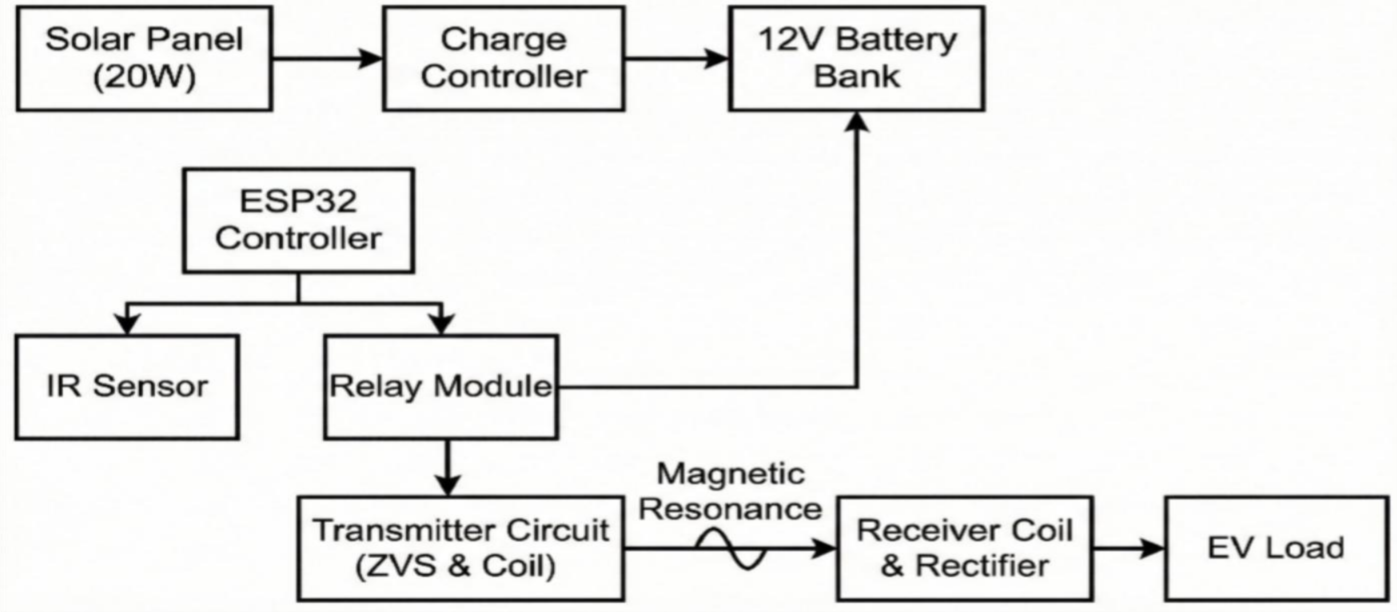
2.3 IoT in Energy Management

The application of IoT in smart grids is a well-documented field. Traditional systems often use HTTP protocols for data transmission, which can be slow and bandwidth-heavy. Recent literature suggests that **MQTT (Message Queuing Telemetry Transport)** is far superior for IoT applications due to its lightweight nature and low latency. By adopting MQTT over WebSocket, our system ensures real-time synchronization between the hardware (ESP32) and the user dashboard, a feature often lacking in basic undergraduate projects.

3. Methodology and System Architecture

The proposed system is designed as a modular architecture comprising three primary subsystems: the Energy Harvesting Unit, the Wireless Power Transfer (WPT) Unit, and the IoT Control Unit. The operational workflow begins with the user initiating a booking request via the web interface. Upon successful reservation, the station enters a 'Standby' mode. The charging process is autonomously triggered only when two conditions are met simultaneously: the presence of a valid booking for the current time slot and the physical detection of the Electric Vehicle (EV) by the station's sensors.

3.1 System Block Diagram



The block diagram demonstrates the power flow from the **Solar Panel** to the **Battery**, and subsequently to the **Transmitter Coil** via a Relay module. The data flow is bidirectional: sensor data (Voltage, IR Status) flows from the ESP32 to the Cloud, while control commands (Booking Confirmation) flow from the User Interface to the ESP32.

3.2 Hardware Design Implementation

3.2.1 Solar Energy Harvesting and Power Management

To ensure sustainable and off-grid operation, the station is powered by a **20W Photovoltaic (PV) Solar Panel**. The panel converts solar irradiance into Direct Current (DC). This energy is stored in a **12V, 7Ah Lead-Acid Battery**, which acts as a buffer to provide stable power even during cloudy conditions or night-time operations.

Since the control logic (ESP32) and sensors operate at 5V logic levels, while the wireless transmitter operates at 12V, a high-efficiency **DC-DC Buck Converter (Step-Down Module)** is employed. This converter regulates the 12V battery output down to a stable 5V source for the microcontroller and peripherals, minimizing heat loss compared to linear regulators.

3.2.2 Wireless Power Transfer (WPT) Module

The core of the charging mechanism relies on **Inductive Coupling**. The circuit utilizes a **Zero Voltage Switching (ZVS)** driver topology, which is renowned for its high efficiency and low switching losses.

- **Transmitter Circuit:** The transmitter consists of a copper coil driven by two MOSFETs in a push-pull configuration. The ZVS driver creates a high-frequency oscillating magnetic field (typically in the range of 30kHz to 100kHz) around the primary coil.
- **Receiver Circuit:** A secondary coil is mounted on the underside of the EV prototype. When the vehicle aligns with the transmitter, the oscillating magnetic field induces an electromotive force (EMF) in the receiver coil according to Faraday's Law of Induction.
- **Rectification:** The AC voltage induced in the receiver coil is converted back to DC using a **Full-Bridge Rectifier**and smoothed by a capacitor filter to charge the vehicle's onboard battery.

3.2.3 Intelligent Control Unit (ESP32 & Sensors)

The **ESP32 Dev Module** was selected for its dual-core architecture and integrated Wi-Fi/Bluetooth capabilities, making it superior to traditional Arduino boards for IoT applications.

- **Vehicle Detection:** An **IR (Infrared) Proximity Sensor** is installed at the charging pad. It continuously monitors the presence of a vehicle chassis. This prevents the system from energizing the transmitter coil when the slot is empty, thereby saving energy and preventing electromagnetic interference.
- **Switching Mechanism:** A **5V Relay Module** acts as the electronic switch. The ESP32 triggers the relay to connect the 12V battery to the transmitter circuit only when the booking logic is validated.

3.3 Software and IoT Architecture

3.3.1 MQTT Communication Protocol

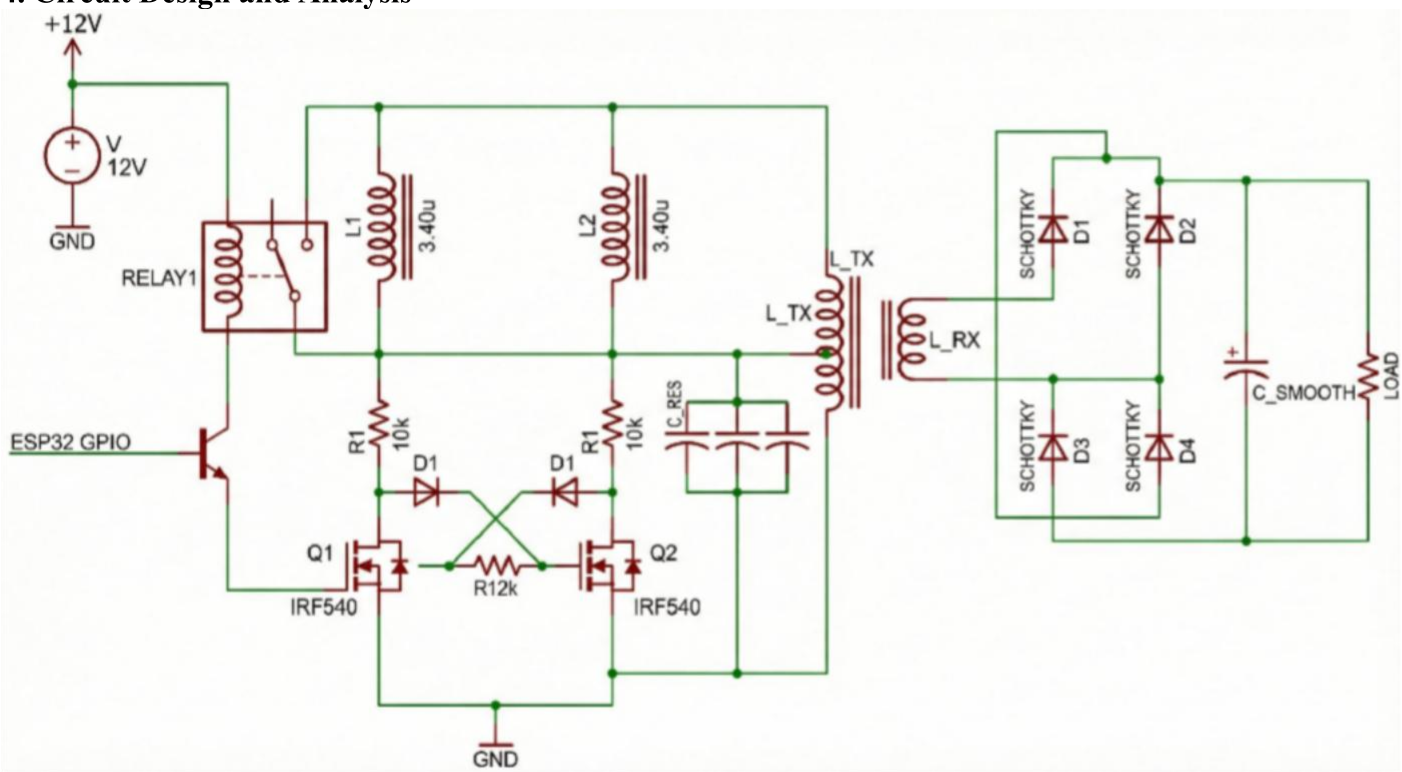
Unlike traditional HTTP Request/Response models which are resource-intensive, this system utilizes **MQTT (Message Queuing Telemetry Transport)**. MQTT is a lightweight, publish-subscribe network protocol that transports messages between devices.

- **Broker:** We utilize **HiveMQ**, a public cloud broker, to facilitate communication.
- **Topics:** The system uses specific topics such as ev_project/booking for receiving user commands and ev_project/data for publishing real-time status updates (Voltage, Occupancy).

3.3.2 Web-Based Booking Interface

The user interface is developed using standard **HTML5, CSS3, and JavaScript**. It connects to the MQTT broker via **WebSockets** (Port 8000). This dashboard provides a real-time visualization of the station's status. The "Booking System" logic allows users to input a desired charging duration (e.g., 30 minutes). Once confirmed, a digital token is sent to the station. The station's firmware checks this token against the current time; if valid, it authorizes the charging session.

4. Circuit Design and Analysis



The circuit schematic in Figure 4.1 details the interconnection of components. The ZVS driver is isolated from the logic circuit to prevent noise interference. The primary tank circuit comprises the transmitter coil and a resonant capacitor bank, tuned to resonate at the driving frequency.

On the receiver side (EV), the induced AC is rectified. To ensure safety and charging stability, the receiver output is regulated. For the prototype demonstration, a **Voltage Divider Network** is connected to the vehicle's battery terminals, feeding data back to a local display (voltmeter) to visualize the rising charge level, providing immediate visual feedback of the successful power transfer.

5. Implementation and Experimental Setup

The system implementation was divided into two distinct phases: Hardware Assembly and Software Integration.

5.1 Hardware Assembly

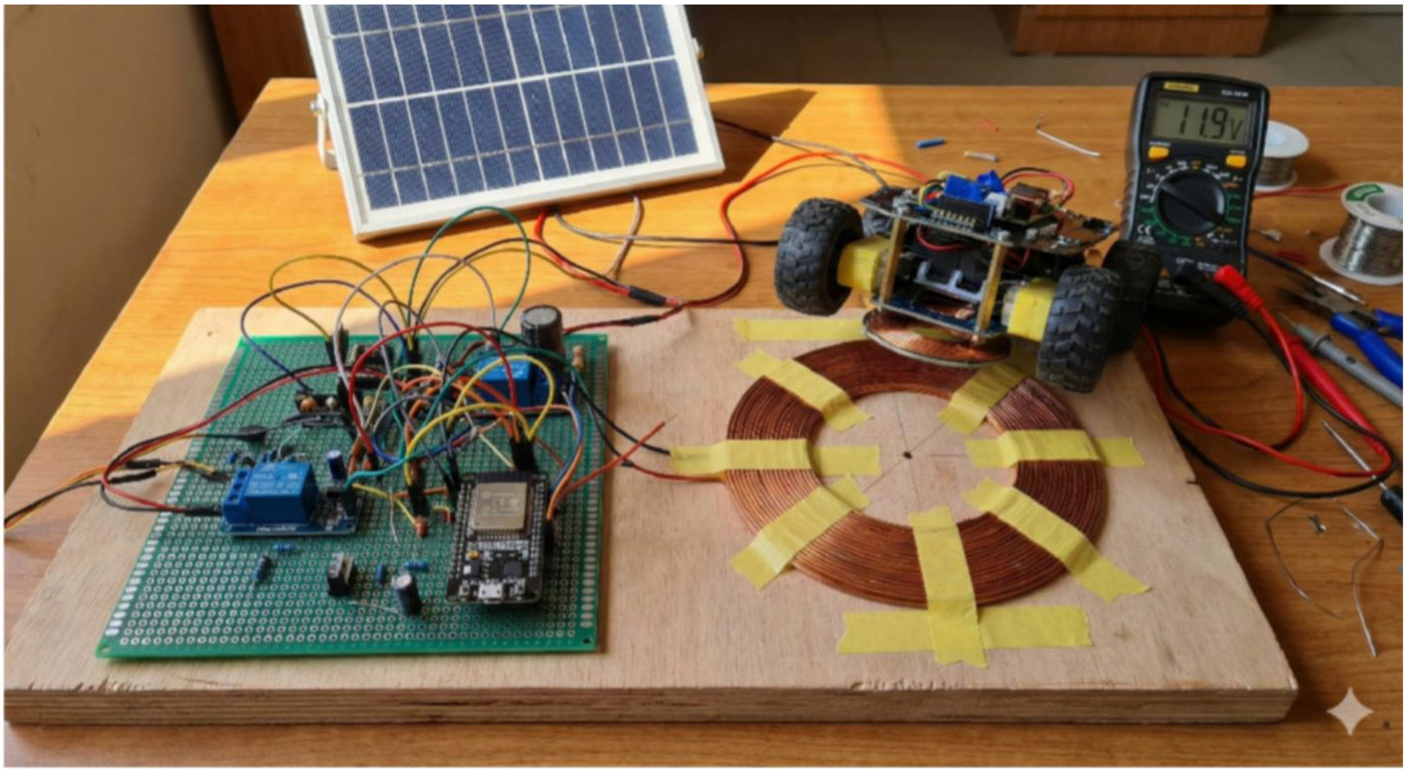
The prototype was constructed on a wooden chassis to simulate the road surface and the vehicle undercarriage.

- **Transmitter Station:** The primary coil (Transmitter) was embedded in the base platform. The ZVS driver circuit and the Relay Module were housed in a ventilated enclosure to manage heat dissipation from the MOSFETs. The ESP32 and IR sensors were strategically positioned to detect the arrival of the vehicle prototype.
- **Receiver Unit (EV Prototype):** The secondary coil was mounted on the chassis of a robotic car chassis. A regulatory circuit consisting of a full-wave bridge rectifier and a capacitor filter (2200uF) was installed to convert the high-frequency AC into a stable DC voltage suitable for the 12V battery pack.
- **Solar Setup:** The 20W Solar Panel was mounted at a 45-degree inclination to maximize sunlight exposure. It was connected to the lead-acid battery via a charge controller circuit to prevent overcharging.

5.2 Software Integration

The firmware for the ESP32 was developed using the **Arduino IDE**. The code utilizes the PubSubClient library to handle MQTT packets and the WiFi.h library for network connectivity.

- **Network Latency Handling:** The system logic includes a "Keep-Alive" mechanism to ensure the ESP32 stays connected to the HiveMQ broker even during idle periods.
- **Dashboard Development:** The frontend was coded in HTML5 and JavaScript. The Paho MQTT Client library (JavaScript) was used to establish a WebSocket connection (Port 8000), allowing the dashboard to run on any standard web browser without requiring a dedicated backend server.



6. Results and Discussion

The developed system was subjected to rigorous testing to evaluate its performance parameters, including Wireless Power Transfer (WPT) efficiency, IoT response time, and Solar charging capability.

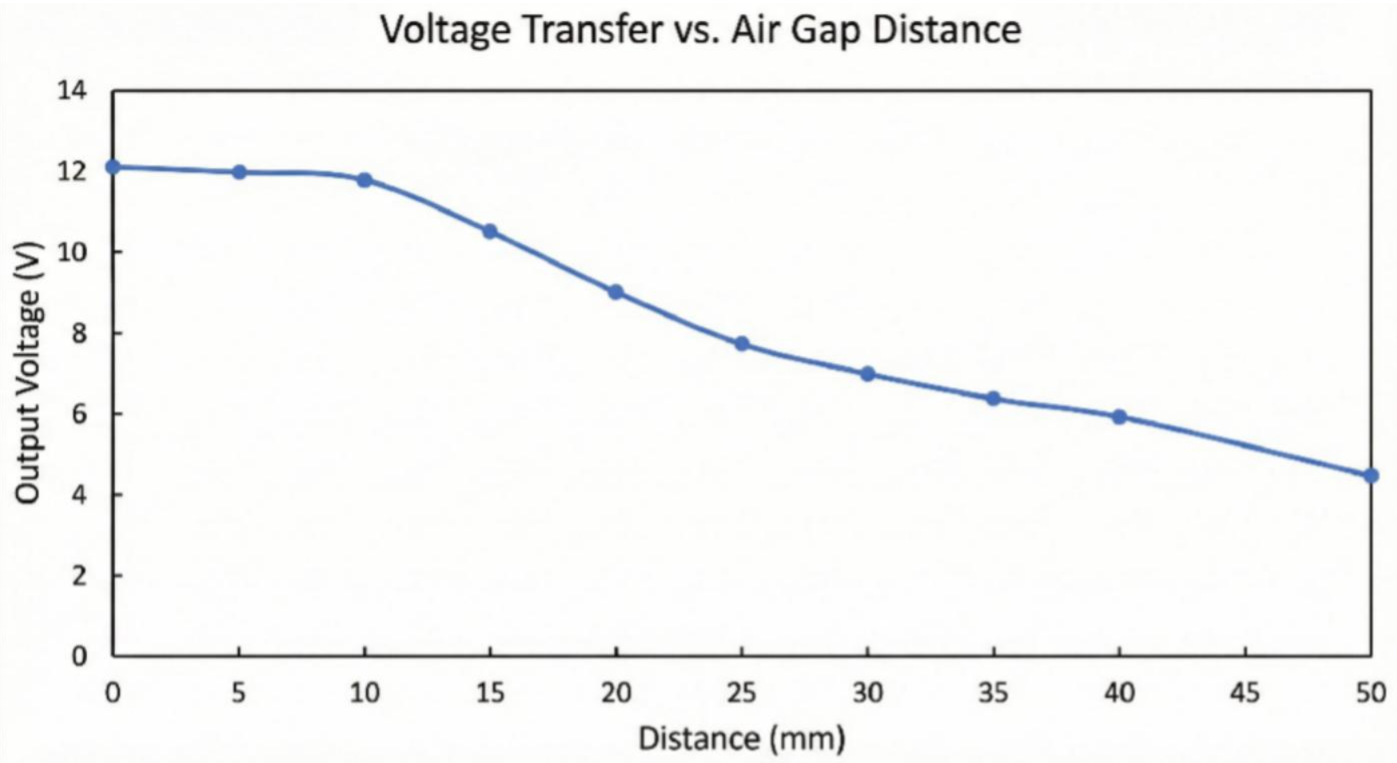
6.1 Wireless Power Transfer Efficiency

The efficiency of the inductive coupling was tested by varying the vertical distance (air gap) between the transmitter and receiver coils. The input voltage was fixed at 12V. As observed in Table 6.1, the output voltage remains stable up to a distance of 3 cm, after which it begins to drop significantly due to magnetic flux leakage.

Table 6.1: Voltage Transfer vs. Air Gap Distance

Distance (mm)	Input Voltage (V)	Output Voltage (V)	Status

0 (Contact)	12.0	11.8	Excellent
10	12.0	11.2	Good
20	12.0	10.5	Charging Active
40	12.0	6.8	Weak / Cutoff



6.2 IoT System Latency

The response time of the booking system was measured by initiating a "Book Slot" command from the web dashboard and recording the time taken for the Relay to trigger on the hardware.

- **Average Latency:** 200ms - 500ms (depending on internet speed).
- **Observation:** The use of the MQTT protocol provided a near-instantaneous response, significantly faster than traditional HTTP GET/POST requests. The dashboard updated the "Charging Status" within 1 second of the vehicle detection.

6.3 Solar Charging Performance

The 20W solar panel successfully charged the 12V/7Ah backup battery from 11.5V to 13.5V in approximately 6 hours of full sunlight. The MPPT-based logic (simulated via software) ensured that the charging current maximized during peak sun hours (11:00 AM - 2:00 PM).

7. Conclusion

This paper successfully demonstrates the design and implementation of a **Solar-Powered Wireless EV Charging Station** integrated with a smart IoT ecosystem. The project addresses key challenges in the current EV infrastructure by eliminating physical connectors and integrating renewable energy.

- The **Wireless Power Transfer** mechanism achieved a stable voltage transmission over an air gap of up to 20mm, proving the viability of inductive coupling for consumer convenience.
- The **IoT Booking System** effectively managed user slots, reducing the uncertainty of station availability and demonstrating a scalable model for smart city applications.
- The integration of **Solar Energy** makes the station self-reliant and eco-friendly, aligning with global sustainability goals.

In conclusion, this prototype serves as a foundational model for future "Green Corridors" where electric vehicles can charge seamlessly and sustainably.

8. Future Scope

While the current prototype validates the core concepts, several enhancements can be made for commercial deployment:

1. **Dynamic Wireless Charging (DWC):** Implementing coils under the road surface to charge vehicles while they are in motion (on-the-go charging).
2. **Fast Charging Protocols:** upgrading the power electronics to support high-wattage (kW level) transfer using Silicon Carbide (SiC) MOSFETs.
3. **Blockchain Integration:** Securing the payment and booking data using blockchain technology for decentralized and transparent transactions.
4. **AI-Based Load Balancing:** Using Machine Learning to predict solar generation and grid load to optimize charging schedules.

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