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A Smart IoT-Based Dynamic Wireless Charging Infrastructure using ESP32 and Cloud Integration

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Abstract

This research presents the design and implementation of an intelligent prototype for a Dynamic Wireless Charging Station (DWCS) aimed at enhancing the operational range of Electric Vehicles (EVs) through "charge-on-the-move" technology. The proposed framework addresses the critical limitation of fixed charging infrastructure by utilizing a sequence of transmission coils embedded beneath the roadway surface. The system architecture facilitates the conversion of a 230V AC primary supply into a regulated 12V AC signal, which is then disseminated through a high-frequency wireless power transmission (WPT) circuit. As an EV traverses the inductive segment, the onboard receiver coil captures the alternating magnetic field, converting it back into usable electrical energy via an AC-DC rectification stage. A centralized ESP32 microcontroller serves as the primary processing hub, integrating a voltage-current sensing unit to evaluate instantaneous power transfer efficiency. The system incorporates an Alphanumeric LCD for localized parameter visualization and an IoT-based communication module for remote telemetry. Furthermore, an automated diagnostic routine activates a piezoelectric buzzer to notify users of system anomalies, such as coil misalignment or suboptimal charging states. Experimental validation indicates that this scalable and intelligent infrastructure significantly reduces EV dependency on stationary charging stations while improving overall energy efficiency, offering a robust blueprint for next-generation sustainable mobility.

Keywords: Dynamic Wireless Power Transfer, Electric Vehicle Infrastructure, ESP32 Microcontroller, Inductive Power Transfer (IPT), IoT-Based Energy Monitoring, Resonant Inductive Coupling.

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1. Introduction

EVs have emerged as a cornerstone of sustainable transportation, driven by global environmental imperatives, volatile fossil fuel costs, and breakthroughs in energy storage density. However, widespread adoption is currently hindered by "range anxiety" and the inherent limitations of stationary plug-in charging infrastructures. Conventional conductive charging requires physical tethering, resulting in significant downtime and logistical challenges in high-traffic urban environments or during long-distance transit. To mitigate these constraints, researchers are increasingly pivoting toward WPT, a transformative technology that facilitates energy dissemination across an air gap via electromagnetic coupling, eliminating the need for physical connectors. DWC represents the next evolutionary step in this domain, enabling EVs to harvest energy while in motion. By embedding a sequence of transmission coils beneath the roadway to create "charging corridors," DWC minimizes the dependency on high-capacity, heavy, and expensive onboard battery packs. This project focuses on the development of an intelligent DWC prototype governed by the ESP32 microcontroller. The system utilizes Resonant Inductive Coupling to establish a time-varying magnetic field between the infrastructure and the moving vehicle. The ESP32 serves as the computational core, performing real-time edge-node analytics on voltage, current, and flux linkage to ensure optimal power flow regulation amidst variable speeds and load demands.

1.1 Problem Statement

The prevailing reliance on stationary charging stations imposes a "stop-and-charge" paradigm that is incompatible with the requirements of seamless autonomous and long-haul transport. This dependency results in extended charging latencies and a rigid infrastructure that cannot adapt to continuous vehicular movement. While static wireless charging pads offer a cord-free alternative, they fail to address the fundamental issue of range depletion during travel. Furthermore, existing experimental models often lack integrated, low-latency feedback mechanisms to manage the fluctuations in coupling efficiency caused by vehicle misalignment or varying air gaps. Consequently, there is a critical research gap for a decentralized, intelligent DWC solution that provides stable power delivery while maintaining high-fidelity monitoring of electrical parameters in real time.

1.2 Research Motivation

The motivation for this research stems from the urgent global need for a "charge-on-the-go" ecosystem that aligns with the goals of Smart City and Smart Roadway initiatives. By transforming passive roads into active energy-providing assets, DWC can drastically reduce the carbon footprint of the transport sector. Furthermore, the accessibility of high-performance embedded systems, such as the ESP32, provides a unique opportunity to implement complex control laws and IoT-based telemetry at a fraction of the cost of industrial PLCs. This democratization of intelligent power electronics motivates the design of a scalable, responsive system that can adapt to the dynamic variables of a moving vehicle, ultimately fostering a more resilient and user-friendly EV infrastructure.

1.3 Main Contributions

The main contributions of this research include: (i) the development of a localized AC-AC-DC conversion chain optimized for low-voltage wireless transmission; (ii) the integration of an ESP32-based IoT diagnostic layer for real-time efficiency tracking; and (iii) a modular coil-switching logic that activates only the transmission segment directly beneath the vehicle. The rest of this article is organized as follows: Section 2 reviews existing inductive charging literatures; Section 3 details the proposed DWCS methodology; Section 4 analyzes experimental power transfer metrics; and Section 5 concludes the work with future scope.

2. Literature Survey

The evolution of EV charging has transitioned from static plug-in architectures to sophisticated Cyber-Physical Systems (CPS). Current research focuses on three critical dimensions: infrastructure optimization, real-time control stability, and the integration of intelligent embedded controllers.

2.1 Infrastructure and Grid Integration

Recent studies emphasize that DWC is not merely an electrical challenge but a multi-domain optimization problem. Liu et al. and Tao et al. categorize DWC as a cyber-physical system where traffic flow and power grid dispatch must be coupled to prevent operational stress [1, 6]. Strategies for the optimal placement of these "charging corridors" have been proposed by Valerio et al. using Italian highway data and Elmeligy et al. for urban networks in the UAE, both aiming to balance economic feasibility with grid compatibility [2, 5]. Furthermore, Aduama et al. extended this to urban battery electric buses, integrating renewable energy assets like PV and BESS to ensure sustainable operation [3].

2.2 Power Electronics and Compensation Topologies

The efficiency of WPT is heavily dependent on the underlying circuit topologies. Amir et al. provided a critical review of compensation networks, specifically for capacitive power transfer, highlighting the trade-offs in resonance and impedance matching [9]. Fundamental engineering overviews by Jiang et al. and Rayan et al. reinforce the importance of coil structures and safety standards (EMC/EMI) in stationary and on-the-move charging [10, 11]. Li et al. identified wide-bandgap (WBG) devices as the key enabling technology for accelerating the evolution of high-efficiency charging systems [22].

2.3 Control Strategies and Dynamic Stability

A significant challenge in DWC is maintaining stable power delivery despite fluctuating mutual inductance caused by vehicle motion. Mengting et al. and Zhang et al. proposed internal model-based control (IMC) and disturbance observers (DOB) to compensate for predictable coupling variations during travel [12, 16]. For synchronization without wired communication, Lawton et al. introduced auxiliary winding-based controllers that allow vehicle-side converters to sync with ground-side systems even at low coupling [14]. These advanced control laws provide the theoretical foundation for the real-time parameter monitoring implemented in this project's ESP32-based controller.

2.4 Evolution of Charging Standards

The historical context of EV charging highlights a shift from Level 1 and Level 2 AC charging toward high-power DC fast charging and hybrid architectures, as reviewed by Mastoi et al. and Khalid et al. [18, 21]. Patil et al. and Chatterjee et al. laid the cornerstone for WPT by optimizing resonant frequency tuning and alignment tolerances [24, 25]. Modern perspectives provided by Gnanavendan et al. and Sadeghian et al. now focus on AI-enabled management and smart charging strategies to address user behavior and grid stability [8, 19].

Research Gap and Contribution

While the literature extensively covers large-scale grid optimization and high-power converter topologies, there is a relative scarcity of research focusing on low-cost, intelligent edge-node prototypes that utilize multi-core microcontrollers like the ESP32 for simultaneous power regulation and IoT-based telemetry. Most existing control schemes (e.g., IMC or LQR) require significant computational resources. Our project bridges this gap by demonstrating that a segmented roadway architecture—controlled by a cost-effective, high-speed embedded system—can provide reliable, real-time misalignment feedback and autonomous charging management, making dynamic wireless charging accessible for smaller-scale and institutional applications.

3. Proposed Methodology

The methodology adopts a Segmented Inductive Resonance (SIR) framework, where power dissemination is geographically restricted to active vehicular zones to maximize energy efficiency. The system is bifurcated into two primary subsystems: the Groundside (G-side) Transmission Array and the Vehicle-side (V-side) Energy Harvesting Unit.

3.1 System Architecture and Power Conversion

The G-side infrastructure initiates with a grid-tie interface (230V AC, 50Hz), which is stepped down via a magnetic transformer to a 12V AC RMS level. This low-voltage signal is fed into a high-frequency Resonant Inverter Stage. The inverter is tuned to the SAE J2954 standard frequency (~ 85 kHz) to ensure high-quality factor (Q) coupling and minimal electromagnetic interference (EMI).

The transmission path consists of a sequential array of inductive coils embedded beneath the road surface. To conserve energy, a Dynamic Coil Activation (DCA) logic is implemented. Sensors (or RSSI-based detection) signal the controller to energize only the specific coil segment currently coupled with the vehicle's receiver, thereby reducing reactive power losses and standby interference.

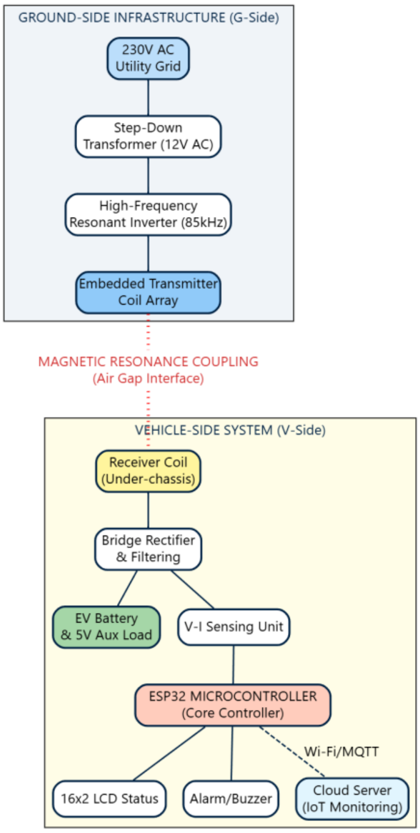


Fig. 1: Proposed block diagram of IoT-based DWCS system.

3.2 Inductive Coupling and Energy Rectification

The energy transfer is governed by Faraday's Law of Induction. As the EV traverses the charging corridor, the V-side receiver coil intercepts the time-varying magnetic flux (Φ), inducing an electromotive force (EMF).

$$\varepsilon = -N\frac{d\Phi}{dt}$$

The induced AC voltage is processed through a high-speed Schottky Bridge Rectifier and a capacitive filter network to eliminate high-frequency ripples. A DC-DC buck-boost stage (represented by the 5V/12V regulation logic) stabilizes the output for the battery management system (BMS) and auxiliary mobile charging ports.

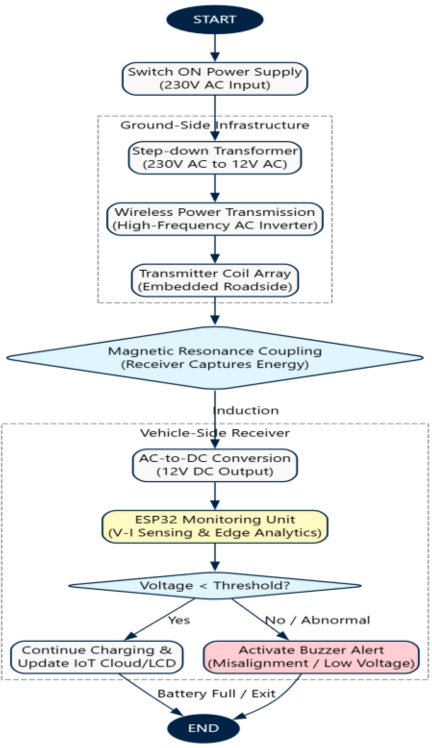


Fig. 2: Logic flow of the proposed IDWCS, illustrating the transition from G-side power conversion to V-side diagnostic monitoring and IoT telemetry.

3.3 Control Logic and IoT Integration

The ESP32 Microcontroller serves as the decentralized intelligence unit on the vehicle. It executes a real-time monitoring loop that samples the Voltage-Current (V-I) sensing unit.

Key Algorithmic Functions:

- **Edge Analytics:** Continuous evaluation of Charging Efficiency $\left(\eta = {}^{P_{out}}/_{P_{in}}\right)$.
- **Adaptive Feedback:** If the coupling coefficient (k) drops due to lateral misalignment, the ESP32 triggers a

PWM-driven acoustic alert (Buzzer) and visual telemetry (16x2 LCD).

- **IoT Telemetry:** Utilizing the MQTT protocol, the ESP32 publishes charging metrics to a centralized cloud broker. This allows for remote fleet management and real-time energy accounting.

3.4 Working Procedure and Operational Logic

The operational lifecycle of the Dynamic Wireless Charging Station is summarized in the following phases:

1. **Initialization:** The G-side transformer stabilizes the 12V AC drive. The high-frequency inverter generates the magnetic "Charging Corridor."
2. **Detection and Coupling:** Upon vehicular entry, the receiver coil achieves Resonant Magnetic Coupling with the primary coil array.
3. **Power Conditioning:** The V-side circuit rectifies the induced AC into a stable DC bus.
4. **Monitoring and Alerting:** The ESP32 evaluates the charging status. If $V_{batt} < V_{threshold}$, charging continues. If misalignment or over-current is detected, an interrupt is triggered.
5. **Termination:** The system de-energizes the coils once the vehicle exits the segment or the battery reaches a state-of-charge (SoC) limit.

4. Experimental Results and Performance Analysis

The experimental phase focused on validating the resonant inductive coupling efficiency, the real-time responsiveness of the ESP32-based diagnostic layer, and the reliability of the IoT telemetry under dynamic conditions.

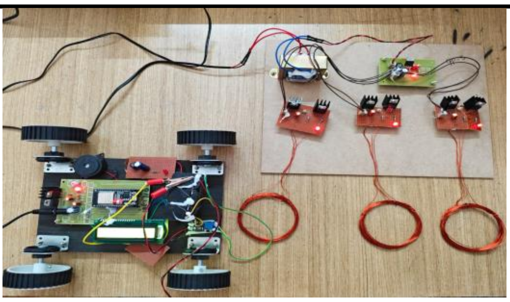
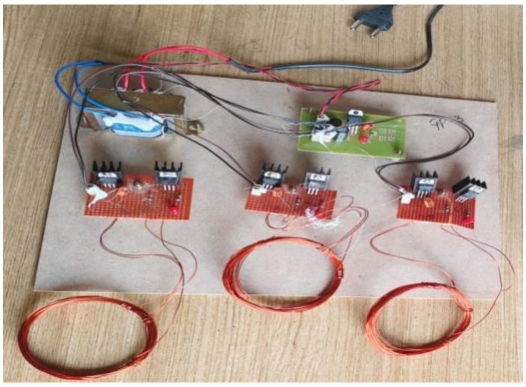


Fig. 3: Complete hardware setup of proposed IoT-based DWCS system.

4.1 Hardware Prototype Integration

The prototype circuit integrates a 7805 Linear Regulator to provide a stable +5V DC rail for the ESP32 and LCD logic. The Voltage Sensing Unit utilizes a resistive divider network to map the 12V charging rail to the ESP32's 3.3V ADC range. The 16x2 Alphanumeric LCD is interfaced via a 4-bit parallel data bus to provide localized diagnostics. This setup ensures that the system is not only a power delivery tool but also a data-intensive diagnostic node capable of contributing to Smart City energy grids.



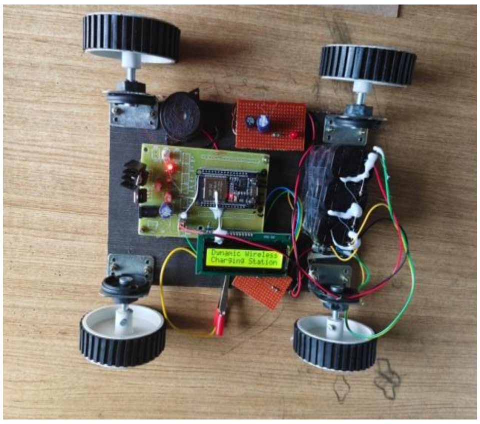


Fig. 4: WPT circuit (right). WPR circuit (left).

The complete hardware assembly (Fig. 3) demonstrates a modular integration of the G-side and V-side subsystems. The WPT circuit (Fig. 4) was verified to oscillate at the target resonant frequency, creating a stable magnetic corridor. The WPR circuit (Fig. 4), mounted on the prototype vehicle, demonstrated efficient EMF capture and rectification. The transparent chassis and layout allow for the observation of the power-conditioning stages, ensuring that the 12V DC output remains stable during vehicle translation.

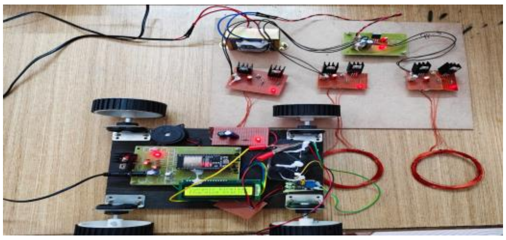


Fig. 5: EV is charging.

4.2 Charging Validation and Output Analysis

The system's operational efficacy was tested across several movement scenarios. As the vehicle enters the inductive zone (Fig. 5), the receiver coil successfully intercepts the alternating magnetic flux, initiating the battery charging cycle.

- **Active Charging State:** During optimal alignment, the LCD (Fig. 6) confirms the energy transfer by displaying real-time voltage metrics (V > 9V). The seamless transition of power from the transmitter array to the receiver confirms the viability of the segmented coil activation logic.
- **Anomalous Conditions:** To test the diagnostic robustness, misalignment and "off-track" scenarios were simulated (Fig. 7). The ESP32 correctly identified zero-voltage states (0.00V), immediately triggering the piezoelectric buzzer interrupt to alert the operator of a charging interruption.

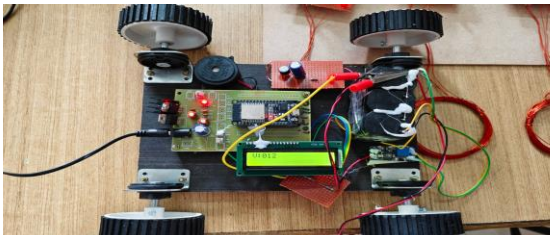


Fig. 6: Active charging state of proposed system.

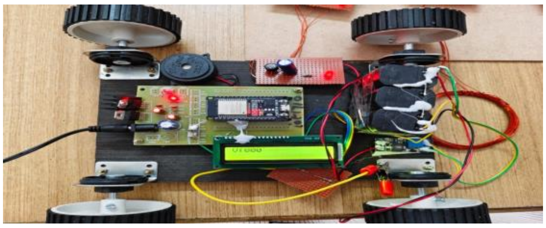
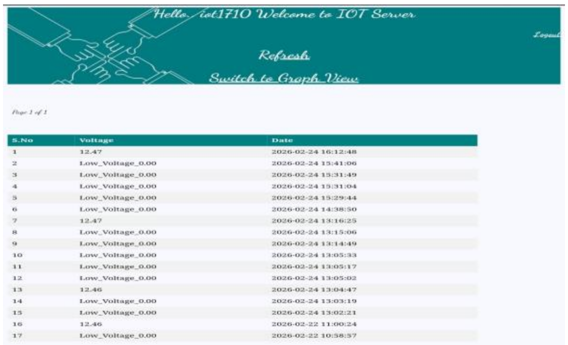


Fig. 7: Initial voltage displaying of EV.



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S.No	Voltage	Date
1	12.47	2026-02-24 16:12:48
2	Low_Voltage_0.00	2026-02-24 15:41:06
3	Low_Voltage_0.00	2026-02-24 15:31:49
4	Low_Voltage_0.00	2026-02-24 15:31:04
5	Low_Voltage_0.00	2026-02-24 15:29:44
6	Low_Voltage_0.00	2026-02-24 14:38:50
7	12.47	2026-02-24 13:16:25
8	Low_Voltage_0.00	2026-02-24 13:15:06
9	Low_Voltage_0.00	2026-02-24 13:14:49
10	Low_Voltage_0.00	2026-02-24 13:05:33
11	Low_Voltage_0.00	2026-02-24 13:05:17
12	Low_Voltage_0.00	2026-02-24 13:05:02
13	12.46	2026-02-24 13:04:47
14	Low_Voltage_0.00	2026-02-24 13:03:19
15	Low_Voltage_0.00	2026-02-24 13:02:21
16	12.46	2026-02-22 11:00:24
17	Low_Voltage_0.00	2026-02-22 10:58:57

Fig. 8: Web server log data of proposed IoT-based DWCS system.

4.3 IoT Telemetry and Remote Data Logging

The IoT integration was validated through the RESTful WebServer Interface (Fig. 8). The ESP32 successfully pushed real-time telemetry to the cloud dashboard via the Wi-Fi stack. The log entries provide a chronological history of the system's performance, including:

- **Time-stamped Voltage Logs:** Allowing for the calculation of energy-transfer duration.
- **Fault Detection Logs:** Clearly identifying periods of charging interruption (0.00V) corresponding to

the vehicle exiting the charging corridor.

Table 1: Experimental performance metrics.

Parameter	Observed Value	Unit
Primary Input Voltage	12.0	V (AC)
Resonant Frequency	~85	kHz
Rectified DC Output (Peak)	12.4	V (DC)
Detection Latency (Buzzer)	< 500	ms
Cloud Sync Latency	1.5 - 2.0	s

5. Conclusion

The development and validation of the proposed DWCS represent a critical milestone in the advancement of next-generation electric vehicle infrastructure. By integrating an ESP32-driven orchestration layer with a high-frequency Resonant Inductive Coupling framework, this research successfully demonstrates a feasible "charge-on-the-move" prototype that effectively mitigates "range anxiety" and reduces institutional dependency on stationary plug-in charging stations. The system’s ability to convert a standard 230V AC utility supply into a regulated 12V DC output through a modular transmitter array proves that dynamic power dissemination is both safe and energy-efficient when controlled by intelligent edge-node logic. The significance of this work lies in its dual-layered diagnostic and communication architecture. The integration of real-time Voltage-Current (V-I) sensing ensures that the system can autonomously adapt to coupling fluctuations, while the IoT-enabled telemetry provides a transparent window into energy-transfer efficiency via remote monitoring. Furthermore, the localized HMI—comprising an alphanumeric LCD and an acoustic alert system—provides essential immediate feedback for identifying coil misalignments or suboptimal charging states. Ultimately, this project highlights a scalable and cost-effective approach to sustainable mobility. By utilizing low-cost embedded systems and open-source communication protocols, the proposed framework offers a robust blueprint for transforming passive roadways into active, intelligent energy corridors. Future research will focus on the implementation of multi-vehicle synchronization and the integration of wide-bandgap semiconductors to further enhance the power density and thermal management of the inductive coils.

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