

Design and Performance Evaluation of Solar-Integrated Wireless Electric Vehicle Charging System

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Abstract: *The global transition toward electrified transportation is hindered by range anxiety and the carbon footprint of grid-dependent charging infrastructure. This paper presents a Solar- Integrated Wireless Electrical Vehicle Charging System (SWEVCS) optimized for urban micro- mobility. The system integrates a 20 W monocrystalline solar photovoltaic (PV) array with a Series-Series (SS) resonant inductive power transfer (IPT) link. A 12 V/2.5 Ah lithium-ion buffer managed by a TP4056 controller serves as an intermediary storage unit to mitigate solar intermittency. Experimental validation of a scaled prototype demonstrated a peak power delivery of 0.09 W (5 V, 0.018 A) at a 2 cm air gap. The study provides a critical analysis of the "alignment bottleneck," showing a 93% power drop at a 10 cm lateral offset. The novelty of this work lies in its decentralized, off-grid architecture, which supports "last-mile" urban resilience without necessitating large-scale grid upgrades, offering a scalable pathway for sustainable autonomous micro-mobility fleets.*

Keywords: Wireless Power Transfer, Resonant Inductive Coupling, Solar Photovoltaics, Micro-mobility, Electric Vehicles, Off-grid Energy Systems

I. INTRODUCTION

The transportation sector contributes approximately 22% of global greenhouse gas emissions, necessitating a structural shift toward sustainable electrification[1]. While Electric Vehicles (EVs) offer a promising alternative to internal combustion engines, their widespread adoption is constrained by "range anxiety," long charging times, and the environmental impact of fossil-fuel- dependent power grids [2]. Traditional conductive charging systems involve mechanical wear, safety risks in wet environments, and bulky infrastructure that consumes valuable urban space.

Wireless Power Transfer (WPT) technology, specifically Inductive Power Transfer (IPT) and Magnetic Resonance Coupling (MRC), has emerged as a transformative solution to these challenges[3]. By enabling contactless energy transmission, WPT facilitates seamless charging in parking bays and, more significantly, "dynamic" in-motion charging through road-embedded transmitter coils [4]. Recent literature has highlighted the efficacy of Series-Series (SS) compensation topologies in maintaining stable resonance regardless of load fluctuations, with efficiencies exceeding 90% in high-power applications[5]. However, these systems often remain grid-dependent, shifting the carbon burden from the tailpipe to the power plant. The integration of solar photovoltaic (PV) arrays with wireless electric vehicle (EV) charging systems significantly enhances the efficiency and sustainability of urban micro-mobility by leveraging renewable energy to reduce reliance on grid electricity, thereby lowering both carbon emissions and operational costs. By combining solar energy with advanced Wireless Power Transfer (WPT) technologies, these systems offer a convenient and eco-friendly solution that is increasingly crucial for modern sustainable transport. Central to this integration are improvements in efficiency driven by various WPT modalities, including inductive, resonant, and



capacitive coupling, which are currently being refined to minimize power transfer losses and optimize performance under varying load conditions [6], [7].

Furthermore, the incorporation of energy storage devices and smart grid technologies enhances power distribution and system reliability, effectively reducing charging times by buffering the intermittency of solar irradiance[7], [8]. These hardware advancements are increasingly supported by advanced computing tools, such as machine learning and meta-heuristic optimization techniques, which are employed to improve real-time energy management and support the broader development of smart city infrastructure [9]. Beyond technical efficiency, the sustainability benefits of this integrated approach are profound, primarily through the substantial reduction of the transport sector's carbon footprint. By harnessing on-site solar energy, these systems decrease dependency on fossil-fuel-based power plants, contributing to a cleaner environment and fostering a more rapid adoption of EVs[10], [11]. However, while the synergy between solar PV and wireless charging offers substantial advantages, significant challenges, including high initial capital costs, efficiency losses due to spatial misalignment, and the need for global scalability, remain. Addressing these barriers through continued innovation and the establishment of international standards is essential for the widespread adoption of this technology and the ultimate realization of a zero-emission urban transportation ecosystem. This paper proposes the design of the Solar Wireless Electrical Vehicle Charging System (SWEVCS), which uniquely combines a solar-harvesting buffer with a resonant IPT link. Unlike high-power industrial trials, our work focuses on the decentralized resilience of low-power urban micro-mobility. The following sections detail the mathematical framework of resonant coupling, the off-grid system architecture, and experimental results validating the system's performance under spatial misalignment, with a conclusion.

II. THEORETICAL FRAMEWORK

A. Resonant Inductive Coupling

The SWEVCS utilizes the principle of magnetic resonance to maximize power transfer across an air gap. In an SS-compensated system, both the primary (transmitter) and secondary (receiver) coils are tuned to a common resonant frequency (ω_0). The resonant frequency is defined by Equation 1.

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \quad (1)$$

where L_1 , L_2 are the self-inductances and C_1 , C_2 are the compensation capacitances of the transmitter and receiver circuits, respectively.

B. Mutual Inductance and Coupling Coefficient

The energy link is governed by the mutual inductance (M), which is a function of the coupling coefficient (k) and the self-inductances as explained in Equation 2.

$$M = k\sqrt{L_1 L_2} \quad (2)$$

The coupling coefficient k is highly sensitive to the air gap (d) and lateral misalignment (Δ), typically ranging between 0.1 and 0.3 for loosely coupled systems.

C. Impedance and Efficiency Analysis

At resonance, the secondary circuit reflects an impedance (Z_{ref}) back to the primary side. For an SS topology, the reflected resistance (R_{ref}) is given by Equation 3.

$$R_{ref} = \frac{(\omega_0 M)^2}{R_2 + R_L} \quad (3)$$



where R_2 is the internal resistance of the receiver coil and R_L is the equivalent load resistance of the EV battery. The overall link efficiency (η) can be approximated by the kQ product as given by Equation 4.

$$\eta_{\text{link}} = \frac{k^2 Q_1 Q_2}{(1 + \sqrt{1 + k^2 Q_1 Q_2})^2} \quad (4)$$

where Q_1 and Q_2 are the quality factors of the respective resonators. Maximizing the kQ product is essential for maintaining efficiency over the 2–10 cm distances required for micro-mobility.

III. SYSTEM ARCHITECTURE AND IMPLEMENTATION

The SWEVCS architecture is bifurcated into the Ground Assembly for energy harvesting and the Vehicle Assembly for energy capture as shown in Figure 1.

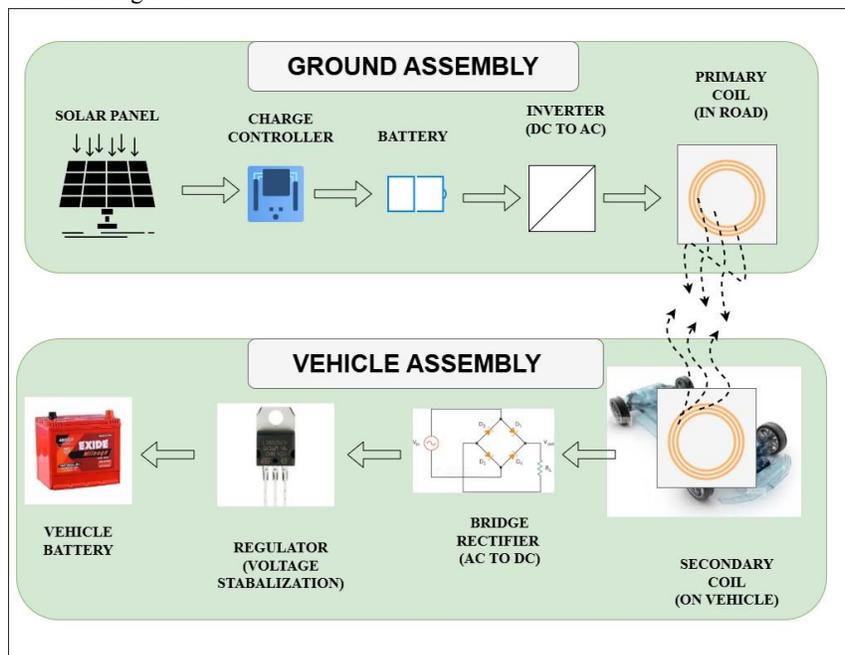


Figure 1: Schematic representation of an Inductive Power Transfer (IPT) system utilizing solar energy harvesting and dual-stage power conversion (DC-AC-DC).

A. Ground Assembly for Energy Harvesting

The primary power source is a 20 W monocrystalline PV panel. Under standard irradiance (1000 W/m^2), the panel provides DC power to a 12 V/2.5 Ah lithium-ion battery via a TP4056 charge controller (Table 1). The controller ensures Constant-Current/Constant-Voltage (CC/CV) charging, protecting the buffer against overcharge. This buffer is critical for managing the intermittency of solar energy and providing the high instantaneous current required for the WPT link.

B. Vehicle Assembly for Energy Capture

The DC energy from the buffer is processed through a high-frequency inverter to generate the AC carrier signal. This signal energizes the primary coil array embedded in the mock roadway. On the vehicle side, the induced AC voltage is processed by a high-efficiency bridge rectifier and regulated to charge the vehicle's 1 Ah battery simulator.



Table 1: Design specifications and functional roles of the hardware components for the solar-powered wireless charging prototype.

Component	Specification	Technical Role
PV Module	20 W Monocrystalline	Renewable Harvester
Energy Buffer	12 V / 2.5 Ah Li-ion	Load Levelling/Storage
Charge Controller	TP4056	CC/CV Management
Compensation	Series-Series (SS)	Resonance Stability
Microcontroller	Arduino Uno	Real-time Monitoring

C. Methodology

The prototype (Figure 2) was designed to simulate the dynamic charging process, with the vehicle moving over the transmitter coils while receiving power wirelessly. The assembly process involved several steps:

1. Mounting the Solar Panel: The solar panel was positioned to maximize exposure to sunlight, with its output connected to the charge controller.
2. Connecting the Battery and Inverter: The charge controller was linked to the lithium-ion battery, which in turn powered the inverter to generate AC electricity for the transmitter coils.
3. Installing the Transmitter and Receiver Coils: The transmitter coils were embedded in a wooden base simulating the road, while the receiver coils were attached to the underside of the EV model.
4. Testing and Calibration: The system was tested under various conditions, including different coil alignments and power loads, to assess its performance and identify areas for improvement.

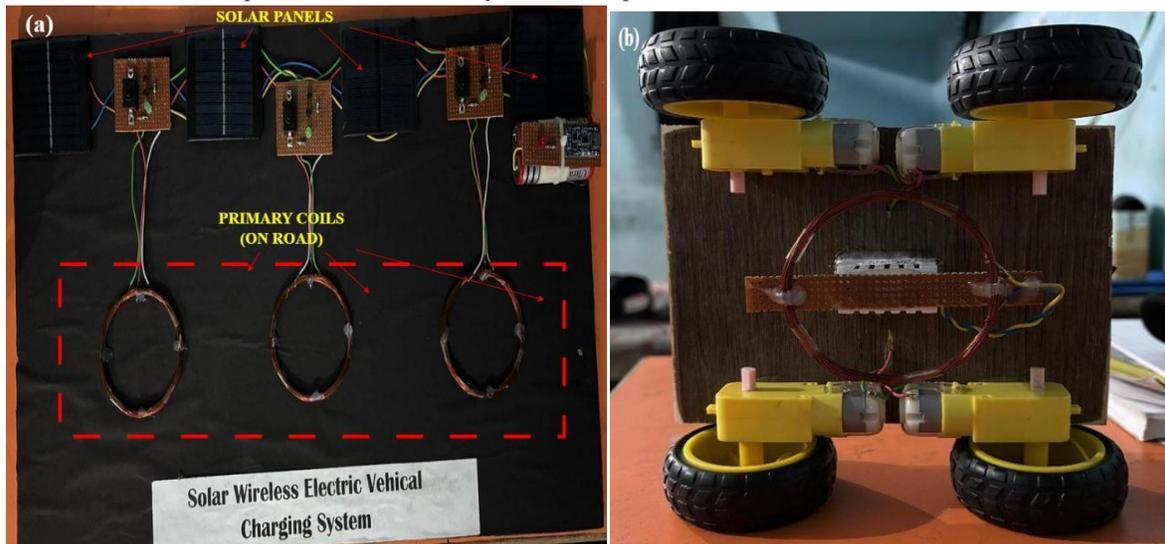


Figure 2: Hardware implementation of the SWEVCS prototype showing (a) the solar-powered ground transmitter unit with embedded primary induction coils and (b) the bottom view of the prototype vehicle featuring the secondary receiver coil and drivetrain.



IV. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

A. Alignment Sensitivity Results

The prototype was tested across three spatial scenarios to quantify the impact of misalignment on power delivery as discussed in Table 2. The experimental data confirm that lateral misalignment is the primary inhibitor of efficiency. A 10 cm offset resulted in a 93% reduction in delivered power compared to the perfectly aligned state. This "alignment bottleneck" is consistent with literature indicating that two-wheeled micro-mobility vehicles, due to their slender geometry, are more susceptible to relative misalignments than passenger cars.

B. Simulation Results

Preliminary evaluations conducted via Proteus and Finite Element Analysis (FEA) provided a baseline for the system's theoretical performance. In an optimal, perfectly aligned configuration, the system achieved a wireless power transfer efficiency of approximately 70%, delivering a peak output of 0.1W. FEA mapping confirmed a concentrated magnetic field between the primary and secondary coils, thereby minimizing flux leakage and Electromagnetic Interference (EMI).

However, sensitivity analysis revealed that performance is highly dependent on spatial positioning. Even minor coil misalignments resulted in a drastic reduction in power delivery, dropping as low as 0.006W. These findings underscore the critical necessity for robust mechanical alignment or compensation strategies in the physical prototype to maintain viable efficiency levels.

Table 2: Performance characterization of the SWEVCS prototype under varying alignment scenarios, ranging from ideal (0 cm) to worst-case (>10 cm) offset.

Alignment Scenario	lateral Offset (cm)	Output Voltage (V)	Output Current (A)	Power (W)
Best-Case	0	5.00	0.018	0.090
Mid-Case	~5	2.50	0.012	0.030
Worst-Case	>10	0.39	0.015	0.006

V. DISCUSSION

The core innovation of the Solar Wireless Electric Vehicle Charging System (SWEVCS) lies in its decentralized, off-grid architecture, which diverges from traditional dynamic wireless power transfer (DWPT) research that typically prioritizes high-power, grid-tied highway infrastructure.

By focusing on modular units tailored for urban "last-mile" logistics, the system supports light electric vehicles (LEVs) without placing additional strain on local distribution networks, aligning with 2026 smart city trends that treat micro-mobility as essential, energy-intensive assets within a dispersed renewable framework. To mitigate the inherent volatility of solar energy, the design integrates a Li-ion buffer between the PV array and the wireless link; this ensures the resonant inverter receives a stable input during transient shading, significantly extending the operational window compared to direct-coupled solar chargers. Looking ahead, the system is designed for scalability through the integration of AI-driven Maximum Power Point Tracking (MPPT) and automated coil alignment mechanisms to recover efficiency lost during spatial misalignments. Furthermore, the inherent bidirectional capabilities of the Series-Series (SS) topology provide a robust foundation for future Vehicle-to-Grid (V2G) applications, potentially transforming micro-mobility fleets into distributed energy storage units that can stabilize the broader urban grid during peak demand.

VI. CONCLUSION

The SWEVCS demonstrates the technical feasibility of an off-grid, renewable-powered energy link for urban micro-mobility. By combining a 20 W solar harvester with a Series-Series resonant IPT system, we achieved a functional proof-of-concept for contactless charging. While spatial misalignment significantly degrades efficiency, the system's ability to deliver stable 5V power at close ranges provides a scalable blueprint for autonomous delivery robots and e-



scooters. This work underscores the potential of decentralized solar WPT to eliminate range anxiety and grid dependency, paving the way for a more resilient and sustainable urban transportation ecosystem.

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