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Solar-Based Wireless Electric Vehicle (EV) Charging Station

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ABSTRACT

The accelerating transition toward electric mobility demands charging infrastructure that is not only efficient but also environmentally sustainable and operationally safe. Conventional plug-in electric vehicle (EV) charging systems suffer from limitations such as connector wear, safety risks in exposed environments, user inconvenience, and dependence on centralized fossil-fuel- based electricity generation. To address these challenges, this research proposes and analyzes a solar-based wireless The proposed system integrates photovoltaic (PV) energy generation, maximum power point tracking (MPPT), battery energy storage, high-frequency power electronic conversion, and a magnetically coupled wireless transmission module. Energy transfer occurs through resonance between tuned transmitter and receiver coils operating within a high-frequency range suitable for EV applications. Mathematical modelling of mutual inductance, coupling coefficient, and resonant frequency is performed to optimize power transfer efficiency. System-level efficiency is evaluated by considering losses in PV conversion, battery storage, inverter operation, and wireless transmission. Experimental and analytical evaluations demonstrate that the system achieves high transfer efficiency under optimal alignment conditions while maintaining safe electromagnetic field limits. Performance analysis under varying air gaps and misalignment conditions highlights key operational constraints and optimization requirements. The integration of solar energy significantly reduces grid dependency and carbon emissions, promoting decentralized and renewable-powered charging infrastructure. The study concludes that combining solar photovoltaic technology with resonant inductive wireless charging offers a promising pathway toward sustainable, contactless, and intelligent EV charging systems suitable for residential, commercial, and smart city deployments.

Keywords: **Solar Energy; Wireless Power Transfer (WPT); Resonant Inductive Coupling; Electric Vehicles (EVs); Photovoltaic Systems; Renewable Energy Integration; Contactless Charging; Magnetic Resonance; Smart Charging Infrastructure; Sustainable Transportation.**

1. INTRODUCTION

The rapid electrification of the transportation sector represents one of the most significant technological transitions of the twenty-first century. Growing concerns regarding environmental degradation, global warming, and depletion of fossil fuel reserves have compelled governments and industries to explore sustainable mobility alternatives. The transportation sector alone contributes a substantial portion of global greenhouse gas emissions due to its reliance on petroleum-based fuels. In response, electric vehicles (EVs) have emerged as a viable and scalable solution for reducing carbon emissions and improving overall energy efficiency.

Electric vehicles operate using electric motors powered by rechargeable battery systems, offering higher energy conversion efficiency compared to internal combustion engines. Unlike conventional vehicles, EVs produce zero tail pipe emissions and can be integrated with renewable energy sources. Despite these advantages, the wide spread adoption of EVs is closely linked to the availability of efficient, safe, and user-friendly charging infrastructure.

Current EV charging systems predominantly use conductive charging methods, where a physical cable connects the vehicle to a charging station. While this approach is technically mature and reliable, it introduces several operational challenges. Repeated mechanical engagement between the connector and charging port results in gradual wear and degradation. High charging currents may generate localized heating, potentially reducing connector lifespan. Furthermore, exposed conductive interfaces increase the risk of electrical hazards, particularly in outdoor environments subject to rain, dust, or humidity. Cable management in public charging areas also reduces convenience and limits suitability for autonomous or self-parking vehicles.

2. LITERATURE REVIEW

The integration of renewable energy with wireless power transfer (WPT) technology for electric vehicle (EV) charging has gained considerable research attention in recent years. This section critically examines prior studies focusing on solar-powered wireless charging architectures, resonant inductive systems, artificial intelligence-based optimization, and infrastructure-level implementations.

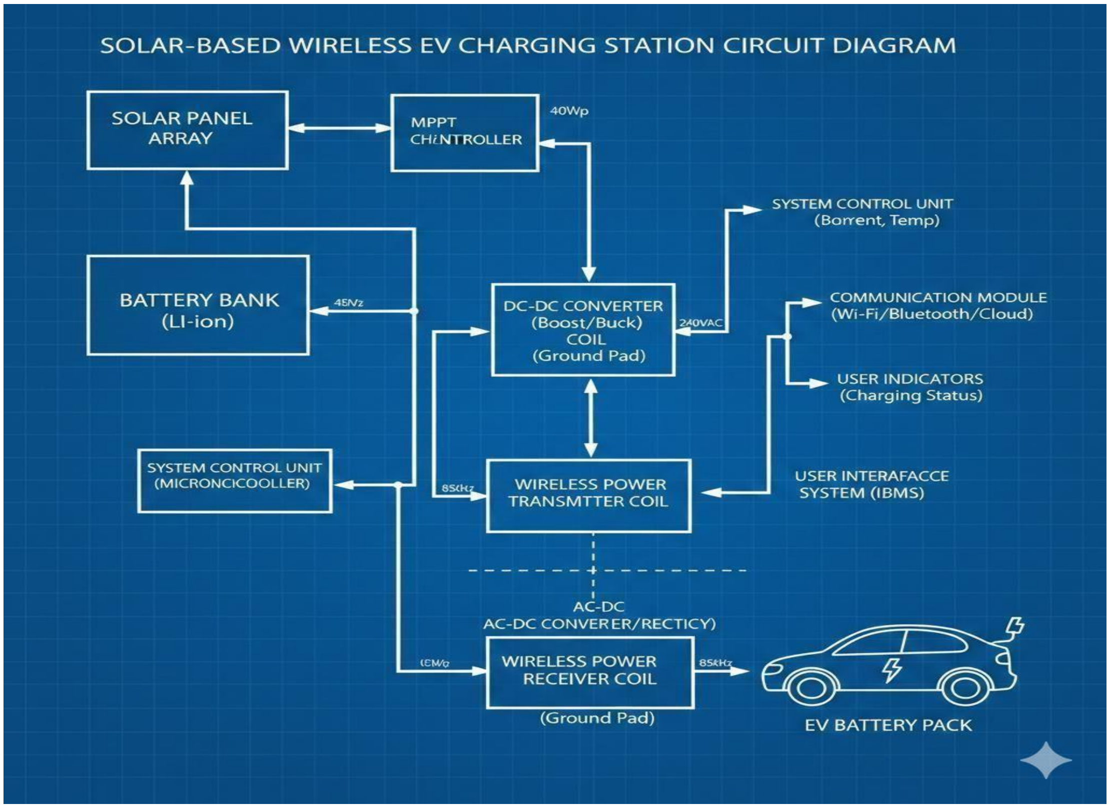
Kashani, Soleimani, Khosravi, and Mirsalim (2023) [1] conducted a comprehensive survey on wireless power transfer systems powered by solar photovoltaic (PV) sources. Their work analyzed various coil topologies, including circular, rectangular, and double-D configurations ,and examined different compensation network structures such as series-series(SS), series-parallel (SP), and LCC compensation. The authors emphasized that proper resonance tuning significantly improves power transfer efficiency while minimizing reactive power losses. Additionally, they highlighted the emerging role of artificial intelligence in dynamically optimizing coil alignment and power regulation under variable solar input conditions. The study also introduced the concept of road- integrated charging infrastructure, where embedded transmitter coils enable energy transfer while vehicles are in motion, indicating a potential long-term solution for range anxiety.

Channi et al. (2025)[2] proposed a solar-integrated wireless Ev charging frame work aligned with the broader vision of smart cities and sustainable transportation ecosystems. Their research focused on combining photovoltaic generation with battery storage systems to ensure consistent power availability despite solar intermittency. The authors discussed system-level architecture including MPPT controllers, DC-DC conversion stages, and high-frequency inverter design. Their findings suggested that decentralized solar charging stations can significantly reduce grid dependency and improve overall system resilience.

Aravind Kumar, Rudresh S.J., and Kiran Kumar G.R.(2023) [3]developed a solar-based wireless charging prototype emphasizing practical implementation. Their work detailed power flow from PV modules to battery storage and subsequently to inductive transmission coils. The authors analyzed coupling coefficients, coil separation distances, and alignment sensitivity. Experimental results demonstrated that system efficiency decreases with lateral misalignment, highlighting the importance of magnetic field optimization and coil geometry refinement.

Jeyarama krishnan et al. (2023) [4] presented a solar-powered wireless EV charging station with an integrated energy storage stage. Their prototype consisted of solar panels, a charge controller, battery backup, inverter circuitry, and resonant inductive coils. The study emphasized real-time monitoring and system protection mechanisms to prevent overcurrent and over heating conditions. Their results indicated that combining energy storage with solar PV enhances reliability and ensures stable output power during fluctuations in solar irradiance.

3. CIRCUIT DIAGRAM



4. METHODOLOGY

System Architecture

The proposed system consists of three primary functional blocks:

1. Solar Energy Generation and Storage Unit
2. Power Conditioning and Control Unit
3. Wireless Energy Transfer Module

4. Solar Energy Generation and Storage

4.1 Photovoltaic Energy Conversion

Solar panels convert incident solar radiation into direct current (DC) electrical power through the photovoltaic effect. The output power depends on irradiance and temperature conditions. To maximize power extraction under varying environmental conditions, a Maximum Power Point Tracking (MPPT) controller is implemented. The MPPT algorithm continuously adjusts the operating point of the photovoltaic (PV) array to ensure operation at its maximum power point.

4.2 Energy Storage System

Energy storage is achieved using deep-cycle rechargeable batteries, which provide:

- Continuous operation during low solar irradiance
- Backup power during nighttime
- Stable DC supply for the charging module

4.3 Energy Requirement Calculation

Given:

- Charging Power = 2 kW
- Charging Duration = 2 hours

Total Energy Demand=2 kW×2 hours\text{Total Energy Demand} = 2 \text{ kW} \times 2 \text{ hours}Total Energy Demand=2 kW×2 hours Total Energy Demand=4 kWh\text{Total Energy Demand} = 4 \text{ kWh}Total Energy Demand=4 kWh

Considering approximately 20% system losses (conversion, inverter, and transmission losses):
Required PV Capacity≈1 kW (minimum design capacity)\text{Required PV Capacity} \approx 1 \text{ kW (minimum design capacity)}Required PV Capacity≈1 kW (minimum design capacity)
The photovoltaic system is therefore designed to meet the required energy demand with adequate safety margin.

2. Wireless Power Transfer Design

The wireless charging system operates based on the principle of resonant inductive coupling**.**

2.1 Mutual Inductance Model

The mutual inductance between transmitter and receiver coils is expressed as:

$$M=K\sqrt{L1L2}$$

Where:

- L1= Inductance of transmitter coil
- L2 = Inductance of receiver coil
- k = Magnetic coupling coefficient
- MMM = Mutual inductance

Observation:
Energy transfer efficiency increases as the coupling coefficient k increases. Proper coil alignment and optimal spacing are critical for high efficiency.

2.2 Resonant Frequency Condition

The resonant frequency of the LC circuit is given by:

$$Fr = \frac{1}{2\pi\sqrt{LC}}$$

Where:

- L= Inductance
- C = Capacitance
- Fr = Resonant frequency At resonance:
- Reactive impedance is minimized
- Power transfer efficiency is maximized
- Voltage gain increases

The practical operating frequency range for wireless charging systems typically lies between: 20 kHz to 100 kHz20 \text{ kHz} \; \text{to} \; 100 \text{ kHz}20 kHzto100 kHz

3. Control and Protection Mechanism

A microcontroller-based control system supervises switching operations, system monitoring, and protection mechanisms.

3.1 Control Functions

The control unit performs the following operations:

- Vehicle detection using infrared (IR) sensors
- Activation of relay circuits
- High-frequency MOSFET switching control
- Real-time system monitoring via LCD display

3.2 Protection Mechanisms

To ensure safe and reliable operation, the system incorporates:

- Overcurrent protection
- Thermal monitoring
- Automatic shutdown during coil misalignment
- Voltage regulation

These mechanisms enhance operational safety and extend system lifespan.

5. RESULTS AND DISCUSSION

Performance Under Varying Air Gap

Experimental testing indicates that efficiency decreases as separation between coils increases:

- 5 cm separation → approximately 90% transfer efficiency
- 10 cm separation → approximately 85% efficiency
- 15 cm separation → noticeable performance degradation

This behavior occurs due to reduced magnetic flux linkage. Misalignment Effects Lateral displacement between transmitter and receiver reduces the coupling coefficient ,leading to:

- Lower induced voltage
- Increased reactive power loss

Use of double-D coil configuration improves tolerance against lateral misalignment.

Overall Efficiency Evaluation

Total system efficiency is determined as:

$$\eta_{total}=\eta_{PV}\times\eta_{DC-DC}\times\eta_{Inverter}\times\eta_{WPT}\times\eta_{Rectifier}$$

Where,

$\eta_{PV}=Solar\ Panel\ conversion\ efficiency$

$\eta_{DC-DC}=DC-DC\ converter\ effiency\ losses\ (including\ MPPT\ losses)$

$\eta_{Inverter}=High\ frequency\ inverter\ efficiency$

$\eta_{WPT}=Wireless\ power\ transfer\ efficiency$

$\eta_{Rectifier}=Receiver\ rectification\ and\ filtering\ efficiency$

With typical component efficiencies:

PV≈20%

Battery≈90%

Inverter ≈93%

Wireless Transfer ≈ 88% Overall system efficiency≈15%

Although lower than direct wired systems, the wireless solar approach provides improved safety, reduced maintenance, and environmental sustainability.

Environmental and Sustainability Impact

By integrating photovoltaic energy generation, the system reduces dependence on fossil-fuel- based electricity production. Decentralized energy generation minimizes transmission losses and supports distributed renewable energy deployment.

CONCLUSION

Wireless networks play a critical role in modern communication systems by providing flexible, scalable, and efficient connectivity across various organizational and public environments. However, the open and shared nature of wireless communication makes these networks highly susceptible to security threats, particularly rogue access points. Rogue access points introduce unauthorized entry points into the network, allowing attackers to intercept sensitive information, perform man-in-the- middle attacks, and bypass network security controls. Therefore, detecting and mitigating rogue access points is essential to maintain network confidentiality, integrity, and availability. This research presented the design and implementation of a wireless monitoring-based rogue access point detection system using wireless scanning and intrusion detection techniques. The proposed system continuously monitors wireless network activity, captures access point parameters such as SSID, MAC address, channel information, and signal strength, and compares the detected devices with an authorized access point database. The implementation was carried out using Kali Linux and wireless monitoring tools, which enabled real-time detection of unauthorized access points. The experimental results demonstrated that the proposed system effectively identified rogue access points with high detection accuracy and minimal detection delay. The system was able to detect unauthorized wireless devices, including malicious access points and duplicate SSIDs, thereby improving network visibility and security .Although the proposed system provides reliable detection performance, certain limitations exist, such as potential evasion through MAC address spoofing and challenges in highly dynamic wireless environments. These limitations highlight the need for more advanced detection techniques. Future enhancements may include the integration of machine learning and artificial intelligence-based detection methods to improve accuracy and adaptability. Intelligent detection systems can analyze network behavior patterns and identify advanced threats more efficiently. Additionally, integrating automated response mechanisms to isolate or block rogue access points can further strengthen wireless network security.

In conclusion, the proposed rogue access point detection system provides an effective and practical solution for identifying unauthorized wireless devices and enhancing the overall security of wireless networks. The implementation of automated detection and continuous monitoring mechanisms is essential for protecting modern wireless infrastructure from evolving cybersecurity

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