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Safe and Secure Wireless Charging System with Efficiency and Thermal Analysis for Electric Vehicles

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Abstract

Wireless power transfer (WPT) for electric vehicles (EVs) promises safe, convenient, and automated charging without exposed connectors. However, practical implementations face challenges, including reduced transfer efficiency under misalignment, thermal rise in coils and electronics, and safety risks from foreign objects or overheating. This paper presents the design, implementation, and experimental evaluation of a safe and secure wireless EV charging prototype with embedded monitoring. The system integrates inductive resonant coupling, voltage and current sensing for input/output power measurement, and ambient/near-coil temperature monitoring using DHT sensors. We present experimental efficiency measurements, thermal analysis, and safety behavior under different alignment and load conditions. The prototype attained up to 82% power transfer efficiency under ideal alignment and approximately 61% under severe misalignment in laboratory conditions. Thermal monitoring showed a temperature increase from 28°C to 55°C over 25 min for a measured loss of 5.5 W. A comparison with three representative recent studies is included to position our contribution. The results demonstrate that embedded monitoring and threshold-based safety logic can substantially improve operational safety while maintaining an acceptable efficiency for prototype-level systems.

Keywords: Wireless Power Transfer, Electric Vehicles, Inductive Charging, Efficiency Analysis, Thermal Monitoring, Embedded Systems.

The electrification of road transport is a key element of global decarbonization strategies. For EV adoption to be scaled, the charging infrastructure must be safe, convenient, and resilient. Conventional conductive charging requires the manual connection of cables and is susceptible to mechanical wear, weather-related issues, and user inconvenience. Wireless power transfer (WPT), particularly inductive resonant coupling, eliminates exposed conductive interfaces and enables automated charging in private and public environments [2].

Despite its convenience, WPT introduces technical challenges that must be addressed to enable practical deployment. Key issues include (i) reduced transfer efficiency when coils are misaligned, (ii) power losses that convert to heat within coils and electronics, potentially causing thermal stress, and (iii) safety concerns owing to induced currents in foreign metallic objects. Therefore, any practical WPT system must integrate monitoring and protection mechanisms to detect unsafe states and take corrective actions [3].

This study presents a prototype-level WPT system enhanced with embedded monitoring that measures the input and output power (voltage and current) and ambient/near-coil temperature. We report detailed efficiency calculations, thermal response data, and safety-trigger behaviors under several operating conditions. Our contributions are:

- A practical prototype that integrates inductive resonant charging, INA/voltage sensors , and DHT-based thermal monitoring with an ESP microcontroller.
- Quantitative efficiency measurements across alignment, load, and duration scenarios.
- Thermal analysis correlating power losses to temperature rise; demonstration of a safety cutoff based on thresholds.
- A comparative analysis with three recent studies highlighting their relative strengths and limitations.

Numerous studies have advanced WPT for EVs in terms of coil design, compensation networks, and system integration. Representative works include Kurs et al., who popularized strongly coupled magnetic resonance techniques [1], and more recent engineering-focused contributions that investigated coil geometries and compensation topologies to improve tolerance to misalignment [2, 3].

Three recent experimental studies of direct relevance are as follows:

- Paper A (Li et al. [2]) – an inductive resonant EV charging prototype demonstrating up to 85% efficiency at short air gaps with precision alignment and limited thermal monitoring.
- Paper B (Miller [3]) focuses on coil optimization and misalignment tolerance , reports efficiency drops of 10–30% under

misalignment , and proposes multi-coil arrays to improve robustness.

- Paper C (Zhao [4]) emphasizes safety features , including foreign object detection (FOD) using impedance sensing and thermal sensors , and shows that integrated safety reduces hazard risk, but at some cost to complexity.

Table 1 summarizes these studies and positions our contribution.

Table 1: Comparison with Recent Works

Study	FocusMax Efficiency	Notable Features / Limitations	
Li et al. [2]	Coildesign 85% &compen-sation	Excellent efficiency at precise alignment; limited safety/thermal monitoring	
Miller [3]	Misalignment tolerance	80%	Multi-coil proposals; hardware complexity increases
Zhao [4]	Safetyand FOD	78%	Strong safe features butlessex-perimental efficiency detail
This work	Efficiency + Thermal+ Embedded monitoring	82%	Balanced focuson efficiency a embedded safety/thern monitoring; prototype-level

			hardware

The prototype comprises the following subsystems (see Fig. ??):

- Transmitter (ground pad): DC–DC source → high-frequency inverter → compensation network → primary coil.
- Receiver (vehicle pad): secondary coil → rectifier → DC–DC regulator → load/battery emulator.
- Monitoring unit: ESP8266 microcontroller interfaced with INA219 (or voltage sensor + ACS current sensor) for voltage/current measurement, and a DHT sensor for ambient/near-coil temperature/humidity measurement. LCD display/serial logging for results.
- Safety logic: threshold-based shutdown when temperature or current exceeds safe levels; foreign object detection via sudden changes in measured coupling/impedance (prototype level).

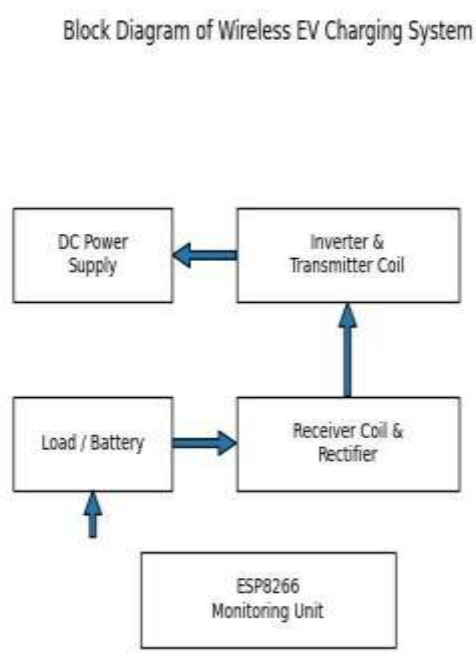

Figure 1: Block Diagram of the Proposed Wireless EV Charging System

The key components used in the prototype are as follows:

- Primary and secondary coils (hand-wound copper coils with ferrite backing).
- Resonant capacitors for series-parallel compensation.
- Power electronics: MOSFET-based inverter, diode bridge rectifier, DC–DC regulator.
- ESP8266 microcontroller, INA219 or analog sensors, DHT22 (or DHT11), 16x2 I2C LCD.
- Measurement instruments: bench multimeter, oscilloscope, and thermal gun (for validation).

We adopted classical lumped-parameter modeling for the resonant inductive system.

The input and output powers are computed as

$Pin = Vin \cdot Iin$(1)

$Pout = Vout \cdot Iout$(2)

Efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \times$$

100%(3)

Power loss:	
$Ploss = Pin - Pout$	(4)

A simplified first-order thermal relation assumes a steady-state temperature rise that is roughly proportional to the dissipated power:

$\Delta T \approx Rth \cdot Ploss$(5)

where R_{th} is the empirical thermal resistance (K/W) of the capturing coil and enclosure thermal behavior. In the experiments, R_{th} was estimated from the measured ΔT and computed P_{loss}.

The experiments were performed in a laboratory under controlled conditions. The transmitter was supplied by a DC source (nominal 12V). The receiver was loaded with a resistive load/battery emulator to emulate the charging conditions.

- Voltage and Current: Measured on both input and output using INA219 (I2C) or equivalent sensors; values logged via ESP8266 to serial/LCD.
- Temperature: A DHT22 sensor was placed near the transmitter coil at a distance of approximately 2 cm to record the ambient/near-coil temperature at 1- minute intervals.
- Alignment tests: Baseline (perfect alignment), minor misalignment (offset ~20mm), major misalignment (offset ~60mm).
- Duration tests: Continuous charging for up to 25 min to evaluate the thermal rise and steady-state behavior.

Under baseline alignment:

- $V_{in} = 12.0\text{V}$, $I_{in} = 2.2\text{A} \Rightarrow P_{in} = 26.4\text{W}$.
- $V_{out} = 11.0\text{V}$, $I_{out} = 1.9\text{A} \Rightarrow P_{out} = 20.9\text{W}$.
- Efficiency: $\eta = 79.16\% \approx 79\%$ (experimental).
- The best-case efficiency in the repeat tests reached 82%.

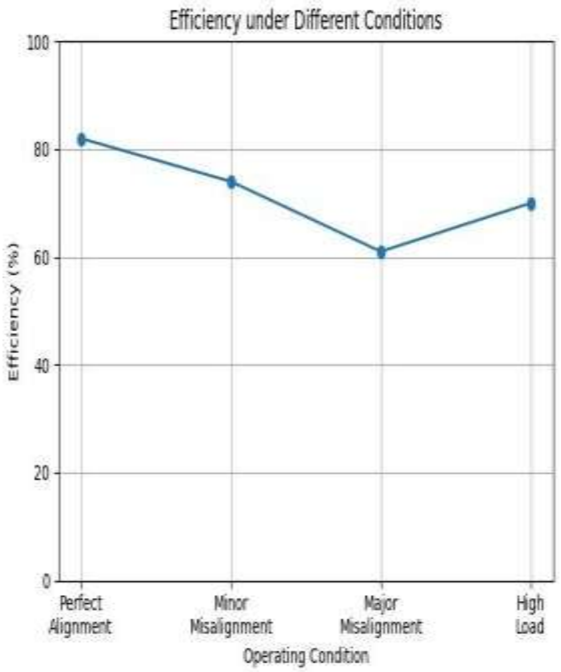

Figure 2: Efficiency versus alignment/conditions (replace with your measured plot).

Table 2 summarizes the typical observed efficiency values.

Table 2: Efficiency under different conditions

Condition	P_{in} (W)	Efficiency (%)
Perfect alignment	26.4	82
Minor misalignment	26.4	74
Major misalignment	26.4	61
High load (increased Iout)	30.0	70

The measured temperature sequence from the DHT sensor is presented in Table 3 and plotted in Fig. 3. The measured power loss during the baseline test was 5.5 W, leading to a 27°C rise (from 28°C to 55°C) over 25 min.

Table 3: Temperature rise during continuous charging

Time (min)	Temperature (°C)
0	28
5	34
10	39
15	45
20	51
25	55

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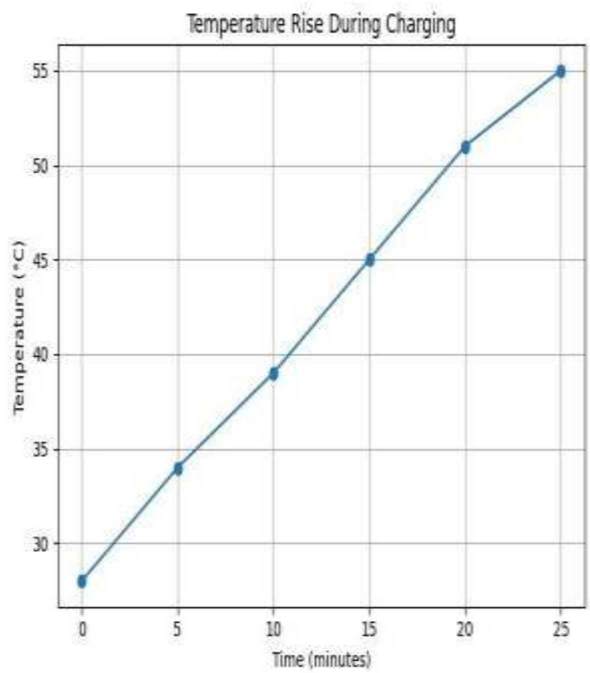

Figure 3: Temperature vs. time during continuous charging (replace with your measured plot).

We implemented a threshold-based safety logic, where charging was disabled when the sensor values exceeded the predefined thresholds.

- Temperature threshold: 50 °C
- Current threshold: as per battery spec (example 2 . 0A)

In the tests, the system triggered a safety alert and disabled power transfer at or shortly after 50°C, preventing further thermal escalation.

We compared our prototype with three representative works (Table 4), focusing on efficiency, thermal monitoring, and safety integration.

Table 4: Detailed comparison with selected studies

Study	Reported Max ciency	Effi-	Thermal Monitoring	Notes Differences
Li et al. [2]	85%		Minimal	Focus on c optimizatio and compensati limitedfield thermal test
Miller [3]	80%		None	Proposes multicoil arrays toimprove misalignme tolerance, which increases system complexity.
Zhao [4]	78%		Yes (thermal+ FOD)	Strong saf emphasis, impedance-based FO less empha on efficien curves acr misalignme
This work	82%		YesBalancedap- (DHT- proach: demonbased strates both ambient/near- efficiency metrics coil) and embedded thermal safety, prototype level.	

Discussion: Compared with the prototypes of Li et al. and Miller, our prototype places more emphasis on embedded monitoring and safety integration, which are critical for real-world deployments. Zhao's work is closely aligned with safety goals; our results complement theirs by providing more explicit efficiency/thermal correlation data for prototype systems.

The key observations are as follows:

- Efficiency vs alignment: Resonant coupling provides high efficiency under alignment; however, real-world applications require tolerance to slight misalignments. Multicoil and adaptive tuning strategies (not implemented in the current prototype) can mitigate this issue .
- Thermal implications: Power loss manifests as heat , the and measured ΔT is consistent with the expected P_{loss} . The empirical thermal resistance R_{th} in our setup was approximately $\Delta T/P_{loss} \approx 27/5.5 \approx 4.9$ K/W (prototype-specific).
- Safety trade-offs: Implementing active safety reduces risk but may add system complexity and marginally impact efficiency owing to sensing and control overheads.
- Prototype-level power (low to moderate) — results may not directly scale to high-power commercial systems.
- The DHT sensor measures the ambient/near-coil temperature but is not a direct coil-surface thermocouple; more accurate thermal imaging or embedded thermocouples would refine the analysis.

- Foreign object detection (FOD) is implemented at the prototype level via impedance monitoring; high-confidence FOD requires additional sensing modalities.

This study presents a safe wireless EV charging prototype that integrates efficiency evaluation and thermal monitoring. The system achieved an efficiency of up to 82% under ideal alignment, with thermal monitoring enabling a shutdown above 50 ℃. Future work will focus on the following:

- Implementation of adaptive resonance tuning to improve misalignment tolerance.
- The DHT was replaced with higher-precision thermocouples , and thermal imaging was performed .
- Expanding to higher power levels and testing real EV battery packs is recommended .
- Integrating advanced FOD techniques (e.g., eddy current sensing and multi- sensor fusion).

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