Photovoltaic-inductive wireless charging for electric vehicles

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ABSTRACT

The growing demand for electric vehicles (EVs) necessitates efficient and eco-friendly charging methods. This study presents a photovoltaic-inductive wireless charging (PIWC) system, which integrates solar energy harvesting with inductive power transfer (IPT) to enable seamless operation without physical connectors. The system utilizes solar photovoltaic (PV) panels to generate renewable energy, which is then converted and transmitted wirelessly using resonant inductive coupling. This eliminates the need for physical connections, reducing wear and maintenance while supporting both stationary and dynamic charging applications. To enhance performance, maximum power point tracking (MPPT) controllers optimize solar energy utilization. Power electronics and control strategies regulate the energy transfer, ensuring efficient and stable operation. Additionally, IoT-based monitoring enables real-time system analysis and performance tracking. Through simulations and prototype evaluations, the system's feasibility, efficiency, and environmental impact are assessed. Results indicate that PIWC can minimize grid dependency, providing a sustainable, autonomous, and convenient charging solution for EVs. This innovation contributes to cleaner transportation and the advancement of renewable energy-driven mobility.

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1. INTRODUCTION

Inductive charging, also known as wireless charging, utilizes electromagnetic fields to allow energy transfer between two objects, usually through the use of a charging station. Inductive coupling is used in this process to transfer energy to electrical appliances, allowing them to charge batteries or run without cables. Essentially, it uses inductive coils: one inside the charging base produces an alternating electromagnetic field, and another in the device retrieves this energy and converts it to electric current [1], [2]. Together, these coils function as a transformer. For long distances between the receiver and sender coils, resonant inductive coupling is significant. Advances here involve adjustable receiver coils and sender coils made from materials such as silver-plated copper or aluminum to minimize weight and resistance. Whereas wireless charging attains efficiency rates of about 60-70%, it is less efficient than direct wired connections [3]-[5]. Wired charging is still preferred for booting devices from a powered-off state, but for general use, the convenience of aligning coils and allowing electromagnetic fields to do their magic makes wireless charging an attractive choice [6]-[10]. This innovative method is part of wireless energy concepts, using electromagnetic fields for energy transfer without physical cables. Power reception and transmission coils are set parallel to each other, with ranges usually within 4 to 5 centimeters for proper operation. Prototype versions have low-power transmitters with a narrower range of about 3.5 to 4 centimeters. One important addition to such systems is an LCD screen with real-time feedback on battery condition, including charge percentage, heat levels, and estimated remaining charging time.

The functional advantages are reducing cable mess and setting the stage for developers to integrate inductive pads into surfaces effortlessly. Although the technology tastes futuristic, its roots go back to Nikola Tesla's early experiments more than a century ago. Tesla dreamed of a future in which electrical power would be wirelessly transmitted, and his research formed the foundation for advancements in wireless energy transmission. Modernizations of Tesla's ideas have developed more advanced resonant inductive power transfer systems, particularly for electric vehicles (EVs). The advanced method aims at reducing energy losses while transferring it with maximum efficiency. Resonant coils are pivotal in maximizing the system, even using energy produced by solar panels without any wastage, being in line with green practices. Photovoltaic inductive wireless charging (PIWC) has changed the game of EV charging with quick, environmentally friendly, and hassle-free processes [11]-[15]. Not only does this advanced system promote green mobility, but it also places transportation on a future-oriented path towards lower carbon emissions and intelligent energy solutions.

The advent of electric vehicles not only transformed the notion of mobility but also made it necessary for a developed and robust charging infrastructure. In contrast to conventional fuel stations, which are accessible and deeply rooted in our transport networks, charging stations for EVs are in the midst of scaling up and fine-tuning. For electric cars to become a common means of transport, the supporting charging system needs to be developed to equal the convenience and size of traditional refueling infrastructure. EV charging systems are generally classified into three categories: Level 1, Level 2, and DC fast charge. Level 1 chargers are the most elementary and are typically located in domestic environments, and they are compatible with standard power outlets. Though they charge slowly, they are easy to use in overnight domestic applications [16], [17]. Level 2 chargers charge more quickly and tend to be mounted in public spaces like workplaces, shopping centers, and car parks. There are also DC fast chargers, which charge quickly at high speeds in much less time and are suitable for use on long trips and for rapid refueling. Nonetheless, their expensive installation and maintenance costs render them less common [18]. In spite of the advances in technology, one of the biggest challenges is still the uneven distribution of charging points. Urban areas tend to enjoy more access to chargers, while rural and developing areas have little or no access. This disparity adds to what is generally known as "range anxiety" a driver's fear of exhausting his battery before arriving at the next charging station. This apprehension dissuades potential users, especially those who live in or are traveling through rural areas. In addition, the growing population of electric vehicles has started to exert pressure on current power grids, particularly at peak usage times. Meeting this expanding demand requires creative solutions beyond conventional models of infrastructure. A smart way to improve charging stations is by using renewable energy sources like solar and wind to power them. Not only does this alleviate the load on the primary power grid, but it also fosters environmental sustainability. Smart grid technology also offers a promising avenue by enabling real-time communication between the grid and EVs [19]. This system allows for better load management, optimized charging schedules, and efficient energy distribution, ensuring that power is delivered where and when it is needed most. It can also help shift charging to off-peak hours, reducing stress on the grid and lowering costs for consumers. Apart from innovation in technology, there needs to be policy intervention and fiscal incentives for the establishment of infrastructure. The role of governments is pivotal in facilitating the expansion of EV networks through the provision of subsidies for the installation of stations, investment promotion by private firms, and regulations that provide equal access and environmental protection. Public-private collaborations have the potential to accelerate this process by marrying state funds with business creativity and capital. In short, having a reliable EV charging network is essential if we want to move toward a greener future in transportation. Although existing constraints like high costs, technical issues, and uneven availability continue to exist, continued technology, policy, and planning efforts are slowly overcoming these obstacles. As infrastructure expands and evolves, fear of range anxiety will fade and electric vehicles will shift from a substitute option to a mainstream answer in the transition to cleaner energy globally [20].

2. PROPOSED CIRCUIT DIAGRAM

2.1. Solar panel

Figure 1 shows the circuit diagram of solar-powered inductive charging for an electric vehicle. A photovoltaic (PV) system is a machine that converts sunlight directly into electricity through PV cells. The cells are usually constructed from silicon, a semiconductor material that produces electric current when exposed to sunlight. Solar panels, composed of several PV cells, are a common method of generating clean and renewable energy. They reduce our reliance on fossil fuels and carbon emissions. The efficiency of a solar panel is based on the amount of sunlight it absorbs, or irradiance. Temperature also comes into play, with excessive heat degrading efficiency [21]-[25]. PV panels are capable of generating a lot of electricity under optimum conditions. They are thus applicable for powering domestic homes, electric cars, and even industrial machinery. Solar energy is becoming cheaper and more widespread as technology continues to improve. It's an important step towards a more sustainable and greener future.

$$P_{out} = V_{out} \times I_{out} \quad (1)$$

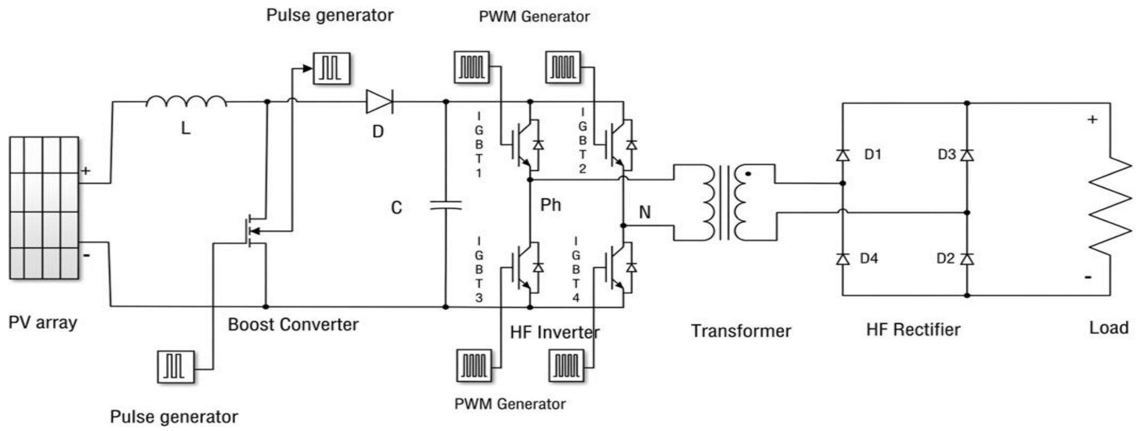

Figure 1. Circuit diagram for solar-powered inductive charging for an electric vehicle

2.2. Inverter

Figure 2 shows the inverter circuit in a solar EV wireless charging system that uses high-frequency switching to convert DC to AC power. A PWM DC-DC converter feeds a steady voltage to the inverter, stabilizing the variable output from the solar panel. Control signals [A] and [B], created with help from a NOT gate, ensure proper timing for switching IGBT transistors in an H-bridge. This H-bridge, made of four transistors (H1–H4), converts 13.1V DC into 13.1V high-frequency AC. The AC output generates a magnetic field that transfers energy wirelessly to the EV. When the car parks over the charging pad, a coil in the car picks up the magnetic field, inducing current without any contact. This AC is then turned back into DC to charge the battery. The core principle is mutual induction, where energy transfers between coils using a changing magnetic field.

$$Vs = M * \frac{dIp}{dt} \quad (2)$$

Where, V_s is the induced voltage in the subordinate coil, M is the mutual inductance, and $\frac{dIp}{dt}$ is the rate of alteration of current in the primary coil.

2.3. Rectifier

The vehicle’s rectifier circuit, shown in Figure 3, plays a crucial role in converting high-frequency AC power into usable DC for charging an EV battery. This is especially important in wireless charging, where energy is transferred magnetically. The setup uses four diodes (D1–D4) in a bridge layout to allow current to pass in only one direction. As AC power enters, two diodes conduct during one half of the cycle and the other two during the second half, turning the AC into steady DC. After passing through the transformer from the HF inverter, the AC is rectified into 13.1 V DC. A capacitor (C2F) is placed at the output to smooth out voltage ripples, providing clean and stable power for the battery.

Figure 4 shows the vehicle on the road. In a photovoltaic-inductive wireless charging system for electric vehicles, the transmitter is typically embedded in the ground, such as in a driveway or parking space. It is powered by electricity generated from photovoltaic (solar) panels. This solar energy, originally in DC form, is converted into high-frequency AC power. The AC flows through a coil in the transmitter, producing an oscillating magnetic field. This magnetic field extends across a small air gap and carries energy wirelessly. The system is activated when a vehicle is parked correctly above it. Once active, the transmitter continuously emits the magnetic field. Its main function is to transfer energy without any physical connection. The receiver, on the other hand, is installed on the underside of the electric vehicle. It contains a coil that is aligned with the magnetic field coming from the transmitter. When the vehicle is in position, the receiver coil picks up the magnetic energy through electromagnetic induction. This energy, now in the form of AC, is converted back into DC power using rectifying circuits within the receiver. The DC power is then delivered to the vehicle's battery to charge it. The receiver operates only when within range of the transmitter. It allows for seamless, contactless power transfer. Overall, it enables convenient and sustainable EV charging, especially when paired with solar energy. Table 1 shows a comparative table of conventional and wireless chargers.

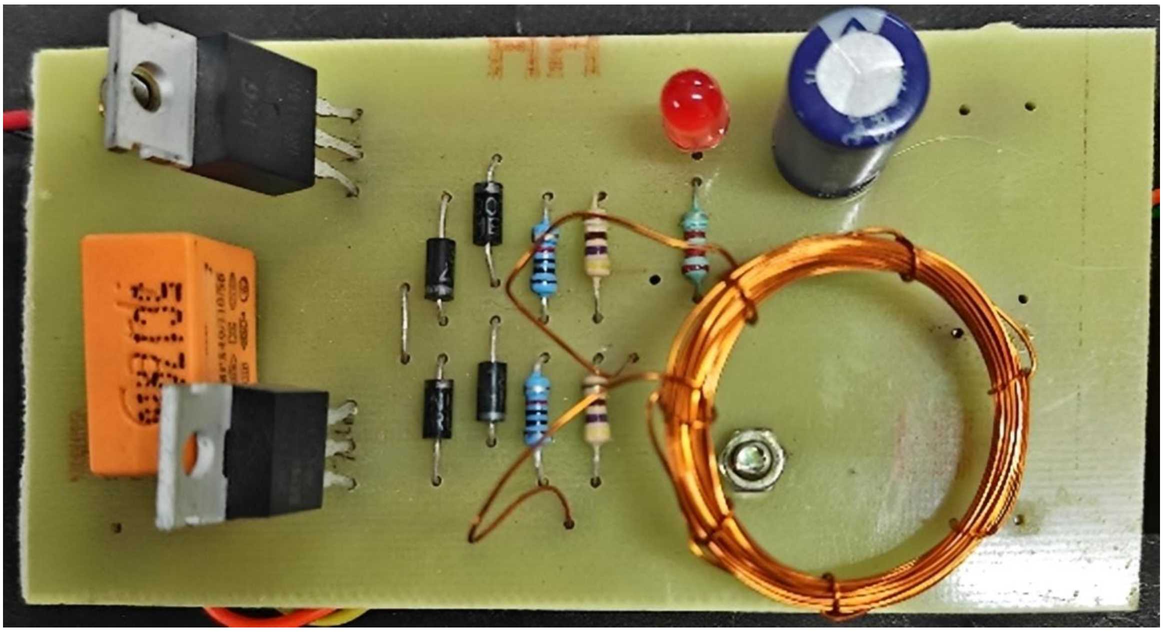

Figure 2. High-frequency inverter

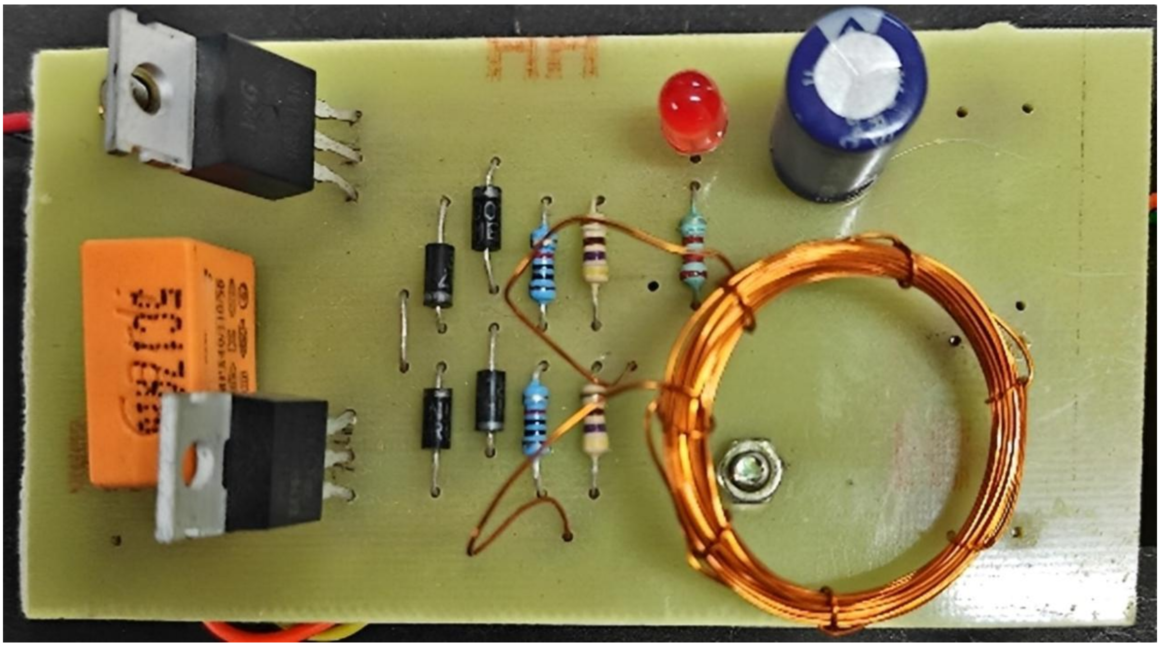

Figure 3. High-frequency rectifier

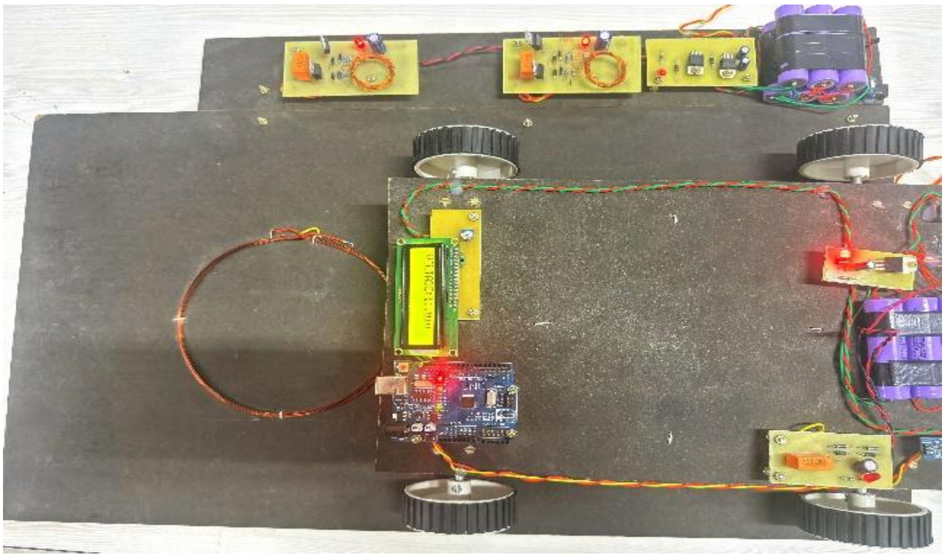

Figure 4. Vehicle on the road

Table 1. Comparative table: conventional and wireless charger

Aspect	Conventional wired charging	Wireless (inductive/resonant) charging
Working principle	Electricity flows via a cable/plug connection from the charger to the vehicle. Usually, AC to DC conversion or direct DC in fast chargers.	Power is transferred by magnetic fields from a primary coil to a secondary coil through an air gap.
Power levels	Power levels from low (<3-7 kW) to high (DC fast chargers up to several hundred kW).	Wireless charging power levels WPT1 (~3.7 kW), WPT2 (~7.7 kW), WPT3 (~11 kW) for static charging. (psecommunity.org) Higher power wireless (e.g. ~200 kW) under R&D.
Efficiency (grid → battery)	Typically, very high. Losses due to cable resistance, conversion (AC→DC), and heat. Efficiency often in the ~90-98% range depending on charger type, power level, and cable length.	Slightly lower, but improving. Many wireless systems report end-to-end efficiency of ~85-94% under good conditions (good alignment, short air gap) for static use. (EnergySage) Misalignment or larger gaps reduce efficiency. (MDPI)
Cost of Infrastructure & Components	Lower cost per unit power at scale (manufacture of plugs, cables is mature). Existing infrastructure widespread. Installation simpler.	Higher initial cost: coils, pads, control electronics, alignment/sensors, and additional safety mechanisms. Civil works for pad embedding. Also, a less mature supply chain. Maintenance for alignment, pad surfaces, and thermal management.
Future trends	Higher power DC fast charging, more efficient power electronics, standardization (e.g. plug types). More pervasive infrastructure.	Increasing wireless power levels; better misalignment tolerance; improved efficiency; dynamic wireless (while moving); mass adoption of standards (SAE J2954, IEC), reducing cost; integration into roads, and parking. Projects aiming for 90-94% efficiency at high power.

3. EXPERIMENTAL RESULTS

Figure 5 shows the output voltage of the receiving side when self-induction due to a single coil to demonstrate self-induction. As the current in the coil changed, it created a varying magnetic field that induced a voltage within the same coil. This configuration resulted in a slightly lower voltage of 8.66 V. The small difference in readings between the two setups reflects the nature of self-inductance compared to mutual inductance. Again, the Arduino and LCD worked together to measure and present the voltage accurately.

Figure 6 shows that mutual induction was demonstrated using two coils. When the magnetic field in the primary coil changed, it induced a voltage in the secondary coil. This interaction led to a voltage reading of 11.01 V, which was shown on an LCD screen connected to an Arduino Uno. The setup effectively highlighted how energy can transfer between two coils through mutual inductance, with the Arduino capturing and displaying the induced voltage in real time.

Wired tends to be more efficient; wireless gives more ease of use. The loss in efficiency must be weighed against convenience, behavior, and cost over time. Wired charging infrastructure is more standardized and cheaper per kW installed. Wireless is catching up, but still higher in cost, especially at larger power levels. For fast charging, wired is ahead. Wireless needs good alignment, minimal air gap, solid thermal design to approach comparable speed. Wireless reduces the mechanical wear of connectors but brings other issues.

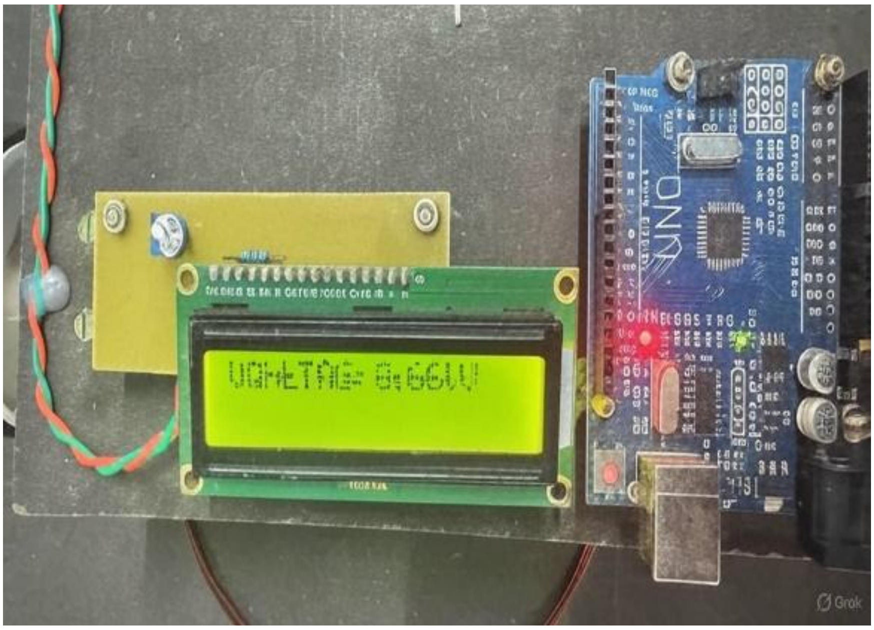

Figure 5. Output voltage due to a single coil

Figure 6. Output voltage due to mutual induction

4. CONCLUSION

Solar-powered inductive charging is making waves in the EV world, combining clean energy from the sun with the convenience of wireless charging. Instead of relying heavily on traditional electricity, this technology uses solar panels to generate power, helping cut down on harmful emissions and supporting the shift toward greener transportation. One of the biggest perks for EV owners is how effortless it is just park over a charging pad, and the car starts charging without any need for cables or plugging in. But it's not just about convenience; it's also a smart, energy-conscious solution. With the help of energy storage systems, these solar charging stations can store excess power to keep things running smoothly even when the sun isn't shining. That makes them perfect for cities, parking lots, and even private driveways anywhere people want a balance of sustainability and simplicity. As more people switch to EVs, there's a growing demand for cleaner, easier ways to keep them charged. Solar-powered inductive charging helps reduce the pressure on the power grid and makes EV ownership more appealing. It's a step toward a cleaner, more sustainable future, where energy, land, and transportation all work together in a smarter way.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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