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Inductive Wireless Charging for Electric Vehicles: Review

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Abstract

Inductive wireless charging technology for electric vehicles (EVs) provides a simple and effective power transmission. Eliminating physical connections, improves user experience and minimizes maintenance. Optimizing system characteristics, including coil alignment, resonance frequency, and coupling factor, is critical for reducing power losses and increasing overall efficiency. This work provides a comprehensive review of an inductive wireless charging system for EVs, including major charging system components as transmitter and receiver coils, and resonant circuits. The inductive power transfer (IPT) model analyzes mutual inductance, coupling coefficient, and resonance frequency. Power transfer efficiency is determined using performance calculations that consider coil misalignment, air gap changes, and core material choices. Actual operating circumstances are used to determine overall power losses and provide optimization options for better system performance. Improved coil design, resonance adjustment, and power electronics optimization can boost system efficiency above 90%. This study offers useful insights into designing and optimizing inductive wireless charging stations for EVs, helping to promote sustainable and efficient charging options.

Keywords: *Inductive Wireless Charging, Electric Vehicles, Power Transfer Efficiency, Resonant Frequency, Power Loss Estimation, Magnetic Coupling.*

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1. Introduction

The global use of electric vehicles (EVs) has led to innovations in charging infrastructure, improving convenience, efficiency, and dependability. Traditional conductive charging techniques use physical connections, which may wear and degrade over time. Inductive power transfer (IPT) using inductive coupling and resonant Inductive coupling is a viable alternative to physical connections, allowing for smooth power transfer. This technology increases user accessibility and safety. It can also minimize maintenance expenses (Patil et al., 2017b).

An inductive coupling-based wireless power transmission (WPT) generates current by mutual induction. A pair of coils conveys electrical power. The main coil functions as an antenna to transmit electricity. The other coil might be considered secondary, acting as the receiving coil. Applying a time-varying voltage to the transmitter side coil leads to a magnetic field. The magnetic flux induces a voltage in the receiver side coil. This is due to mutual induction between the two coils (Bakar et al., 2018). Recent research indicates that A magnetic resonance network may be added to the inductive coupling-based WPT system (Ayisire, 2019), in both the primary and secondary sides. At the resonance frequency, the coupling wave reaches its maximum, resulting in efficient power transmission (Patil et al., 2017a), even when secondary coils are poorly coupled with the primary coil (Sample et al., 2011). Efforts are underway to imitate vehicle behavior and dynamic charging using numerous resonating coils (Baralt, 2011). Moreover, the efficiency of charging systems is strongly dependent on the perfect alignment of the charger and the receiver coil mounted on the vehicle. However, in real-world situations, obtaining precise alignment is a problem, resulting in vertical and horizontal misalignments, severely reducing charging efficiency. (Laksono & Alaydrus, 2019).

These misalignments can result in significant power loss in the output. The scientific research is now focused on minimizing these misalignments by using different coil designs (Kafeel Ahmed et al., 2015). To ensure the vehicle's long-term endurance, energy loss during EV recharging must be minimized. To create an efficient inductive wireless charging system, critical aspects must be taken into consideration, such as coil design(Qiang et al., 2013), coupling coefficient, resonant frequency, and power electronics (Fang Liu et al., 2016). The goal is to optimize power transfer efficiency and minimize losses such as ohmic heating, eddy currents, and core losses. To achieve this equilibrium, materials must be carefully chosen, coil layouts must be optimized, and compensatory topologies should be implemented (Nataraj et al., 2017).

This study provides a complete examination of inductive wireless charging for EVs, including major components such as transmitter and receiver coils, resonant circuits, and power electronics, optimization methodologies and analyzing importanat factors as: mutual inductance, coupling coefficient, and resonance frequency and also Optimizing other factors, including coil alignment and air gap, is essential for efficiency enhancment to improve wireless charging technologies for sustainable EV adoption. As EVs become more popular, there is a growing demand for reliable charging options. Inductive wireless charging, utilizing inductive coupling, removes physical connections and improves accessibility for users.

2. Wireless Charging System Architecture

A Wireless Charging System (WCS) for EVs is composed of many components that work together to transmit power efficiently and smoothly. The device uses IPT to transfer energy from a stationary charging coil to a receiving coil fitted in the EV chassis. This technology removes the need for physical connectors, resulting in less wear and tear and more accessibility (Athira et al., 2022). The system consists of three basic components: the coil with its primary and secondary sides, the resonant circuit, and the power management system, as shown in Figure 1.

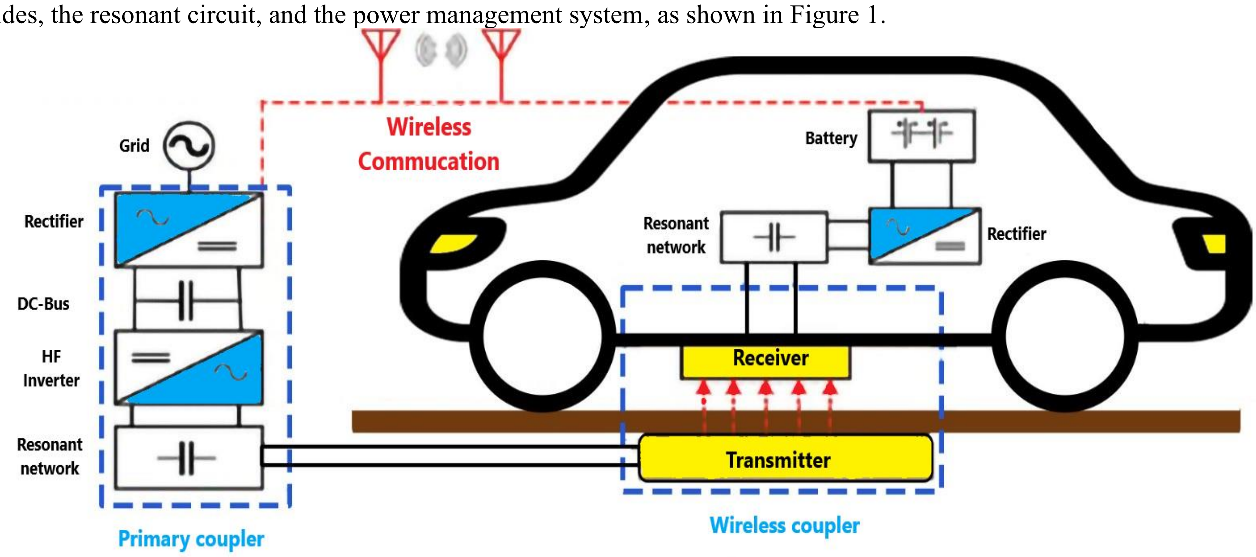

Figure 1: WPT system (Mohamed et al., 2023).

2.1. Coil design

Coil design greatly affects power transmission between the two coils. Circular coil is the most common coil used in literature (Wu et al., 2012; Rui Chen et al., 2014). In (Nataraj et al., 2017), a comparison of circular, square, and rectangular coil geometries is made, and it is concluded that circular coils have the best coupling factor. Another study on wire cross-section found that for the circular coil, the spiral with a planar coil without a core had a greater coupling efficiency than the rounded coil (X. Liu et al., 2018).

Primary side (transmitter coil).

The charging pad is located on the ground in parking lots, garages, dedicated stations, or houses. The coil is connected to an alternating current (AC) source of power and a compensation circuit, converting grid electricity into high-frequency AC. When properly aligned, the transmitter coil's magnetic field induces current in the receiving coil. Coil size, spacing, and alignment are key elements affecting the process's competency.

Secondary Side (receiver coil).

The EV has a coil located below the vehicle in its chassis. Once the vehicle is properly positioned over the charging pad, the receiver coil transforms the magnetic energy from the transmitter coil into electrical energy to recharge the vehicle's battery(Bakar et al., 2018).

2.2. Resonant Circuit.

A resonant circuit is used on both the sending and receiving sides to improve energy transfer efficiency. It can be classified into many types based on the capacitor connection in the compensating circuit. The compensating capacitor can be connected in parallel or series with the coil. Thus, there are four potential combinations. Include parallel-parallel (PP) (Zhang et al., 2013), parallel-series (PS) (F. Liu et al., 2017), series-parallel (SP) (Jegadeesan & Guo, 2012), and series-series (SS) (García et al., 2015), as shown in Figure 2. The primary advantage of the SS topology is that compensating capacitor values are unaffected by resistive load or mutual inductance. It is simply based on the resonance frequency and self-inductance. This benefit enables the system to retain resonance while reducing misalignment sensitivity. In the SS and SP topologies, mutual inductance reduces overall impedance while boosting secondary load, resulting in a greater current pulled from the source. In PS and PP topologies, increasing overall impedance leads to a significant decrease in the current generated from the source of power. In the PP and PS topologies, the main capacitor is calculated using complicated equations, and its value is determined by mutual inductance and load. Compared to the SS topology, the SP structure requires 4.6%, PS needs 30%, and PP requires 24% more copper (Aydin et al., 2022).

2.3. Rectifier and Battery Management System (BMS)

To charge the EV battery, at the secondary coil side, AC must be converted to direct current (DC) through a high-frequency rectifier circuit, while a BMS controls the charging process. The BMS monitors important factors, including voltage and current, to guarantee safe and structured charging. Advanced BMS technology can connect with the vehicle's control unit to optimize charging rates and prevent battery overcharging and overheating. Table 1 shows previous states of the art of stationary wireless inductive charging research (Challoob et al., 2024).

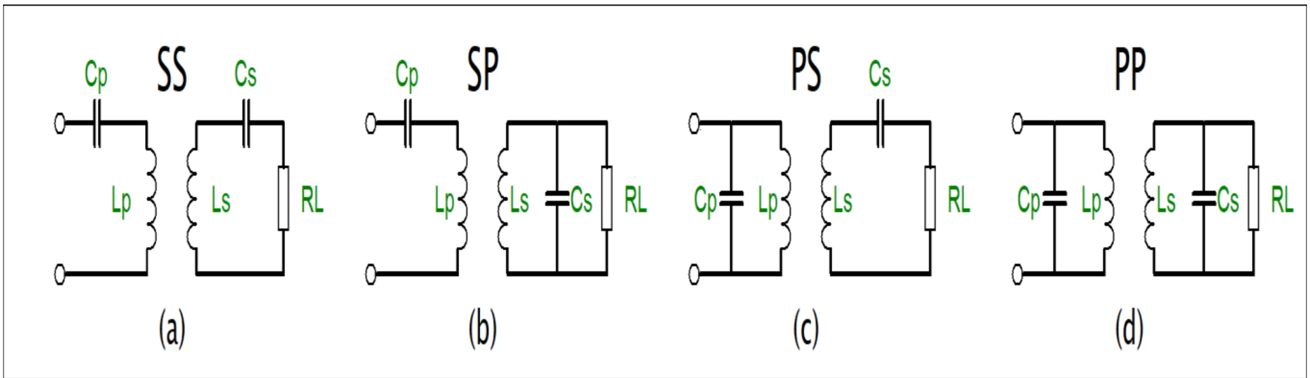

Figure 2 Classical compensation circuits topologies (Shevchenko et al., 2019).

Table 1. State of the art for stationary wireless inductive charging

Ref.	Year	Coil Shape	No. of Coils	Frequency (KHz)	Power (W)	Distance Between Coils (cm)	Software Used	Application
(Wu et al., 2012)	2012	Circular	2	20	5000	17.5:26.5	Simulation Technology for Electromagnetic Design (JMAG Designer)	EVs charging
(Budhia et al., 2013)	2013	DD, DDQ	2	20	2000	20	JMAG Designer	Tiny electronic devices, automatic guided vehicles, and EVs
(Rui Chen et al., 2014)	2014	Circular	2	80	4000	4	Finite element analysis software	Mobile phone, EVs charging
(Diekhans & De Doncker, 2015)	2015	Circular	2	35	3000	10	Finite-element method JMAG Designer	Contactless vehicle charger
(Park et al., 2015)	2015	Square	2	20	1403 471 209	3 4 5	ANSYS Maxwell	Transportation applications
(Nataraj et al., 2017)	2017	Square Circular Rectangular	2	-	-	2	ANSYS Maxwell 3D	EVs, sensor devices, and biomedical implantable devices
(Chayapas Sritongon et al., 2018)	2018	Circular	6	65	100	5	-	Biomedical implants, portable devices, and EVs
(Pearce et al., 2019)	2019	DD	2	85	3700	17.5	JMAG Designer	Biomedical, cellphone charging, stationary EVs, wireless charging
(Nutwong et al., 2019)	2019	Circular	5	60	500	10	-	Static WPT applications
(Yan et al., 2020)	2020	Square	3	90	500	5	ANSYS Maxwell	Vehicles, railways, medical implants, handheld electronic and cellphones devices
(Nie et al., 2021)	2021	Rectangular	4	85	3300	20	ANSYS Maxwell	EVs charging
(Tan et al., 2021)	2021	Hexagonal	4	85	200	10	ANSYS Maxwell	Electronics, medical implants, EVs charging
(Athira et al., 2022)	2022	Circular	4	50	1.84	-	MATLAB Simulink	Wide variety of applications
(Le et al., 2023)	2023	Circular	8	85	300	6.5	COMSOL Multiphysics simulation	Automatic vehicle applications
(Bouanou et al., 2023)	2023	Circular	2	85	3700	12	ANSYS Maxwell	EVs charging

3. System Efficiency and Optimization

Wireless charging system performance is affected by several parameters, including coil misalignment, air gap, frequency, and coil geometry, as shown in Figure 3. Advanced recompense topologies, such as SS and SP resonant circuits, can increase power factor correction and reduce energy losses. Intelligent positioning devices can help drivers align their vehicles correctly with the charging pad, improving coupling efficiency. Wireless charging systems may reach great efficiency and dependability, making them a viable alternative to traditional plug-in charging methods for EVs (Aydin et al., 2022).

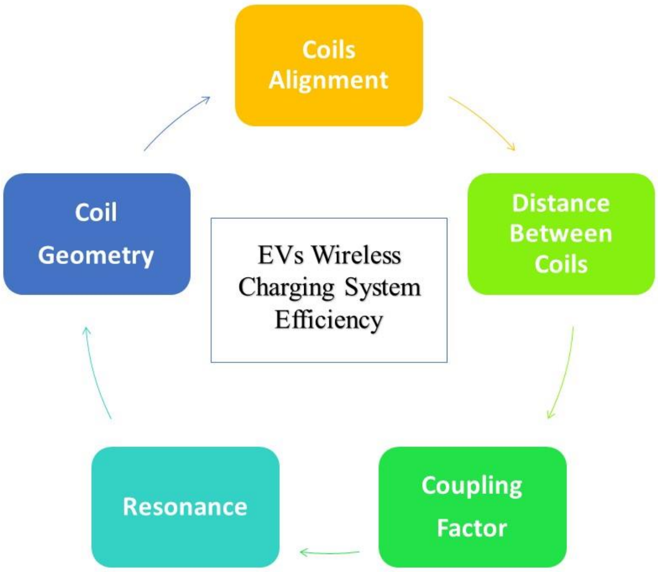

Figure 3: Factors affecting EV charging efficiency (Bhattacharya & Tan, 2012).

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A theoretical study of an inductive wireless charging system for EVs is essential for determining its efficiency, performance, and limits. This section addresses the fundamental concepts of IPT, the mathematical modeling of power transmission, the impact of link coefficient and resonance frequency, and estimating power transfer efficiency (E.Abdelhamid et al., 2014).

The IPT model is based on Faraday's law of electromagnetic, which states that a variable magnetic field induces a nearby conductor. Wireless charging uses an AC in the main coil to produce a fluctuating magnetic field, which induces a voltage in the secondary coil and allows for power transfer. The power transmitted (P_T) may be represented as follows:

$$P_T = V_P I_P \tag{1}$$

$$V_p = (R_P + J X_P) I_p - j \omega_S M I_s \tag{2}$$

$$j \omega_S M I_s = (R_S + j X_S + R_e) I_s \tag{3}$$

Where, V_p is the primary side voltage, I_P is the transmitting side current, I_s is the receiving side current, R_P is the primary resistance, X_P is the primary reactance, R_S is the secondary resistance, X_S is the secondary reactance. R_e is the equivalent resistance of the primary. For Mutual inductance and coupling coefficient: IPT efficiency relies heavily on mutual inductance (M) between the transmitter and receiving coils. The mutual inductance is calculated as:

$$M = K\sqrt{L_P L_S} \tag{4}$$

In this equation, K represents the coupling coefficient, whereas Lp and Ls represent the self-inductances of the main and secondary coils, respectively. The coupling coefficient (K), a dimensionless quantity ranging from 0 to 1, determines how efficiently power is exchanged between coils. A higher K value suggests a stronger magnetic connection and better efficiency. To improve power transfer efficiency, the system is adjusted to run at the resonant frequency. The resonant frequency is defined by the inductance L and capacitance C:

$$F_r = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

Operating at resonance improves energy transmission by reducing resistance and increasing voltage gain. The wireless charging system efficiency (η) is calculated by comparing the conventional power from the receiving coil to the power transferred by the sending coil (Premkumar et al., 2020).

$$\eta = \frac{P_R}{P_T} = \frac{|R_e I_S^2|}{|V_P I_P| \, Cos(<V_P - <I_P)} \quad (6)$$

$$\eta = \frac{P_R}{P_T} = \frac{|R_e I_S^2|}{R_P \, I_P^2 + (R_S + R_e) I_S^2} \quad (7)$$

4. Improving Power Transfer Efficiency

4.1. Improved Coil Design

The design of coils is a key aspect in determining the effectiveness of a WPT system. High-frequency operation in traditional wire designs can result in considerable eddy current losses owing to skin and proximity effects. Litz wire is a useful tool for reducing losses. Litz wire is constructed of copper and has thin, separated strands. Each strand acts as a single wire, minimizing the skin effect by lowering the cross-sectional area. The strands are twisted in specific patterns and might have numerous layers. The winding design equalizes the length of all strands at the end conductor, dispersing the current and lowering the equivalent resistance while reducing internal proximity effect losses by adjusting the thickness of the insulation layer (Ahmed A.Shaier et al., 2020). When adjoining conductors transmit alternating current (AC) in a single direction, the current in the conductor focuses on the side opposite the other conductor. In conductors transporting AC in opposing directions, this causes the current to concentrate on the side closest to the neighboring conductor. Litz wire's low AC resistance makes it ideal for high-frequency applications such as IPT systems. The wire AC resistance consists of R_{dc}, R_{skin} , and $R_{proximity}$. Further illustrations of skin and proximity resistances in litz wire were published (Rossmanith et al., 2011). Selecting a high-frequency value reduces coil diameters. In order to avoid audible noise and to account for power electronics switch capabilities and losses, the majority of experiments used an operating frequency of 20 kHz. WPT systems can function at hundreds of kilohertz if the right switches are used. With 85 kHz as the standard resonant frequency for certain charging power levels, the WPT operating frequency was ultimately standardized for car EV charging. This design improves power transfer efficiency, lowers AC resistance, and lessens the skin effect. Optimizing coil shapes with more turns, spacing, and high-quality conductive materials enhances magnetic field coupling and decreases energy dissipation.
(*IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3kHz to 300 GHz*, 1992)
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4.2. Higher coupling coefficient

The coupling coefficient (K) indicates how efficiently electricity is transferred between transmitting and receiving coils. A low coupling coefficient leads to high power loss, lowering overall organizational efficiency. To improve K, suitable coil alignment mechanisms are needed. Dynamic positioning approaches, such as sensor-based alignment or adaptive coil designs, should be used to enable optimal placement during power transmission. The use of ferrite cores concentrates magnetic flux and reduces stray field losses (Haruko Nawada et al., 2019).

4.3. Resonant Compensation

To perform successfully, wireless power transfer devices require an ideal resonant frequency. Resonant compensation minimizes energy losses and maximizes power transmission by operating the transmitter and receiver at a frequency that cancels out inductive reactance. Various compensation topologies, such as series, parallel, and hybrid resonant circuits, aim to enhance efficiency under varying loads. By carefully selecting resonance characteristics like capacitance and inductance, designers may increase voltage gain, power delivery, and system range. Maintaining zero-phase angle operation reduces reactive power losses and improves overall system performance(Shevchenko et al., 2019).

5. Conclusion and Recommendations

This study provides a full examination of inductive wireless charging for EVs, including system design, theoretical modeling, power loss, and optimization methodologies for IPT efficiency enhancement. Efficiency issues occur from coil misalignment, air gaps, and electromagnetic losses. Moreover, mutual inductance, coupling coefficient, and resonant frequency have a considerable influence on power transmission efficiency. Optimizing coil design and adopting high-quality materials, such as litz wire in the charging coils, as well as the use of ferrite sheets below and above the coils, concentrates magnetic flux and reduces stray field losses, which are the main causes of efficiency decrease during power transmission. By adjusting these factors, efficiency increases of over 90%.This results in more interest in the adoption of IPT for wireless charging for EVs. Advancements in wireless charging address the demand for quick, dependable, and efficient EV charging options.

There are numerous deficiencies in technology and suggestions for additional research:

- High-power transfer systems with smaller coils and compensating topologies are lighter and less expensive.
- Dynamic WPT systems provide high-speed charging for EVs, reducing charging time.
- Developed grid management with static and dynamic WPT technologies and V2G for wireless EV charging.
- Scalable systems with low to high power outputs are gaining popularity in WPT applications.
- Electrifying highways is a potential use being studied in international trials and is likely to become commercially available shortly.
- EVs are more environmentally sustainable than traditional means of transportation.
- Integrating energy storage devices like batteries into WPT systems enhances energy efficiency and balances energy flows.
- Using eco-friendly materials, enhancing manufacturing, and reducing prices may benefit both the environment and the economy while expanding the market for WPT systems.
- Methods to identify and reduce the influence of foreign chemicals that may enter the coils.
- Wireless charging provides immediate and long-term financial benefits for EVs compared to traditional modes of transportation.

6. Declaration

- Availability of data and materials
  Data will be made available upon reasonable request
- Funding
  Not applicable
- Competing interest
  The author has no competing interests

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