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Overview of Inductive Wireless Charging

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Abstract: Electric transportation is gaining popularity due to its cost-effectiveness and convenience compared to traditional fuel cars. Electric vehicles (EVs) offer the advantage of reducing greenhouse gas emissions, making them more environmentally friendly. To promote widespread adoption of EVs, it is essential to establish a large number of charging stations in an EV-friendly environment. However, the current challenge lies in the daily battery charging difficulty for EV owners. Wireless charging technology provides a promising solution as it is both eco-friendly and convenient without the need for plug-ins. This alternative technology can replace traditional plug-in charging stations with wireless charging systems using wire power transfer (WPT). Although WPT may result in some power wastage compared to wired methods, it presents new opportunities for more convenient EV charging.

Keywords: Wireless Charging; Electrical Vehicles; Compensation Typology; Inductive Power Transfer; Magnetic Coupler.

1. Introduction

The increasing significance of greenhouse gases, toxic emissions, and particulate matter from the utilization of fossil fuels has a detrimental impact on both the environment and human health. It is crucial to take prompt measures in replacing conventional fuel cars with electric vehicles that run on sustainable energy sources [1,2]. However, electric vehicles have limitations such as a lack of infrastructure and limited charging range. The current rate at which charging infrastructure is being developed is not keeping up with the growing demand for electric vehicles. As the number of electric vehicles on the road continues to rise, finding effective and efficient charging solutions remains a challenge that significantly affects power grids.

Wireless power transfer (WPT) technology can be categorized into four groups based on transmission distance and working principle: far-field transfer, near-field transfer, mechanical interaction with permanent magnets, and acoustic methods [3]. There are two main types of WPT technologies for time-varying electromagnetic fields: Near-field and Far-field. The near-field scenario involves non-radiative power transfer with limited transmission distance within one wavelength, using inductive or capacitive methods. Far-field transfer technologies operate between 300MHz and 300GHz such as laser, microwave and radio-wave, enabling high efficiency power transmission over long distances but requiring large antennas and complex tracking strategies [3]. Magnetic gear is a type of mechanical WPT technology that utilizes the mutual attraction between synchronized permanent magnets to replace conventional connected gears [3]. Acoustic WPT involves converting electric power into compressed sound waves and then transforming the movement generated by sound waves back into electrical power using a transducer.

Therefore, the manuscript focuses on inductive power transfer (IPT) technology that is well capable for EVs charging. Taking into account factors such as power transfer capacity, distance of transfer, effectiveness, and feasibility, IPT demonstrates encouraging outcomes for the use in electric vehicles. The following section explored the IPT technology from the aspect of IPT pad configuration and compensation networks. Additionally, the article addresses challenges with wireless transfer systems and discusses future trends before concluding.

2. Inductive Power Transfer System

IPT is a well-established technology that wirelessly transmits power by utilizing magnetic fields with the use of coupling coils. This technology is utilized not only in the field of electric vehicles, but also in biomedical devices and consumer electronics such as cell phones and smart watches. The working principle of IPT technology can be explained by Ampere and Faraday's laws, as shown in Figure 1. According to Ampere's law, the flow of current through the transmitter coils generates a magnetic field, which can be represented by Equation (1). This equation states that the flow current in the closed path is equal to the line integral of the magnitude of magnetic fields (H). When it comes to the receiver coils, an induced voltage potential (V) can be generated when the generated magnetic field cutting the receiver coils, where the number of turns can be represented in N_r. In the Equation (2), this process can be illustrated in mathematic format, where ϕ represents the magnetic flux of receiver coils.

$$I = \oint \vec{H} \cdot \mathrm{d}\vec{l} \tag{1}$$

$$V = -N_r \frac{\mathrm{d}\phi}{\mathrm{d}t} \tag{2}$$

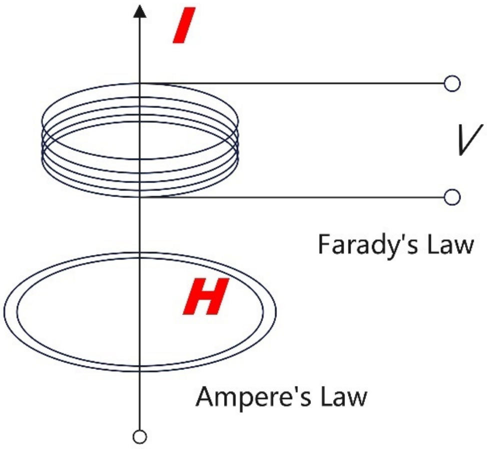


Figure 1. Ampere and Faraday's laws

IPT is a highly favorable option for the charging of electric vehicles due to its numerous advantages, including: (1) Complete electrical isolation of each component to enhance the safety of human charging [4]. (2) The system operates automatically and does not need any intervention from the user [5, 6]. (3) Eliminating the issue of plug and outlet compatibility to ensure seamless integration [3]. (4) Enhance the efficiency and reliability of the EVs' operation under the extreme environment such as storm, pooling rain and snowfall [3]. (5) Without moving or rotating components, benefits to reduce noise level and the cost of maintenance requirements.

A commercial and exemplary IPT system for EVs, is commonly composed of two electrically isolated parts: transmitted side (ground side) and receiver side (vehicle side). For transmitted side, it usually be integrated of PFC boost AC-DC converter (rectifier), high frequency DC-AC converter (inverter) and resonant circuit (compensation network). For the receiver side, it commonly be composed of battery group, filter network, AC-DC converter and compensation network. Between the two electrically isolated sides, the wireless communication channel such as Bluetooth and Wi-Fi protocol exists for offering payment processing services, ensuring correct alignment, and notifying about battery status. The IPT system structure chart is illustrated in Figure 2.

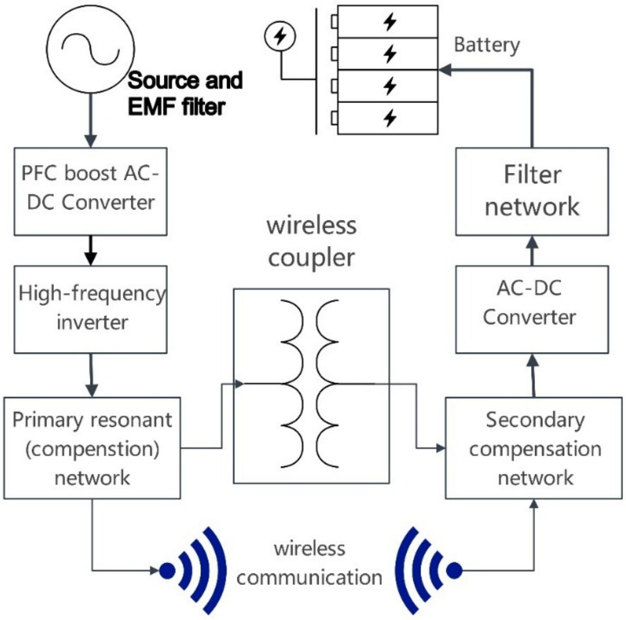


Figure 2. The IPT system structure chart

The transmitting pad is powered by a high-frequency AC voltage generated by the high-frequency inverter using rectified AC power. Instead of a direct connection to the transmitting pad, the high-frequency AC voltage is passed through a compensation network in order to boost the transmission voltage at the transmitted pad, thereby improving transmission efficiency [4]. The transmitting coil resonates and converts magnetic field energy into electrical energy to supply power to the load, achieving wireless energy transmission through magnetic coupling. According to SAE J2954 standard, the IPT system operates within a frequency range of 79 kHz to 90 kHz, allowing for smaller size of both transmitting and receiving pads. The next section of this exploration on IPT system will focus on magnetic coupling architectures and compensation network.

2.1. Magnetic Coupling Architecture

The magnetic coupling architecture plays an essential and significant role in the process of wireless power transmission, which is composed of three essential components in one pad: conductive coils, magnetic materials and EMF shield [3]. Magnetic coupling architecture is the most sensitive component of the whole IPT system desired primary focus during designing. The architecture arrangement is shown in Figure 3.

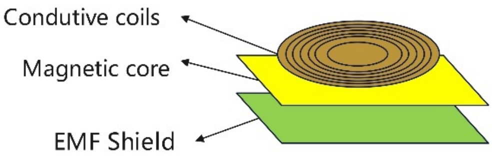


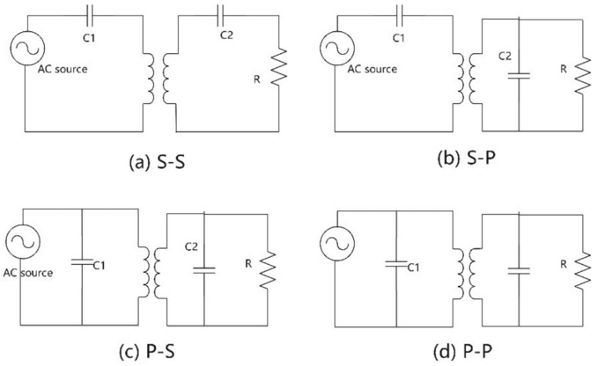
Figure 3. The architecture arrangement

The positioning of the wireless coupling pad plays a crucial role in assessing the effectiveness of an inductive power transfer system, particularly with regards to EMFs safety, transmission efficiency, coupling factor, and ability to withstand misalignment scenarios. Initially, U-cores, E-cores, and pot cores were the traditional architectures used for transformers and were also initially considered for IPT systems [5]. These structures are commonly used in the transformer industry. Nevertheless, their performance for stationary EV charging is suboptimal because of their considerable size, rigid configuration, substantial weight, high expense, and limited ability to tolerate lateral misalignments. To tackle these issues, planar coils have been suggested. In this type of architecture, the coil core and shield have been optimized to minimize the weight dimensions and thickness of the coupling pad in IPT system. Additionally, they have been improved to enhance its ability to withstand misalignment whether it be lateral or rotational. For commercial application it allows any charger regardless of electric vehicle or manufacturer restrictions.

EMF components can be classified into three types based on their materials and structure: non-polarized pads, polarized pads, and a third category consisting of multiple coils such as bipolar and tripolar pads. Non-polarized pads such as circular type and rectangular type of coupling pads, are capable of producing a magnetic field with perpendicular components. Polarized coupling pads, such as DD and DDQ charging pads, can generate a magnetic field with horizontal components. Coupling pads composed of multiple coils can produce both perpendicular and horizontal magnetic fields. It has been shown that the DDQ coupling pad architecture and bipolar architecture have higher transmission efficiency at the vehicle side compared to most other architectures [7,8]. However, most pad architectures are more suitable for use on the transmitted side of the IPT system, such as DD, multi-coil homogeneous, circular, and rectangular pad architectures. Furthermore, these designs prioritize compatibility by allowing any electric vehicle to be charged from any inductive charger without restrictions set by EV or charger manufacturers.

2.2. Compensation Networks

Compensation network is one of most significant components in inductive power transfer system, which can greatly improve the transmission efficiency of the overall system by compensating the leakage inductance due to a significant airgap distance [9]. Furthermore, it can reduce the apparent power needs by providing reactive power, achieve unity power factor control with a phase angle of zero in order to prevent the need for bifurcation analysis, and allow for soft switching in electronic devices. In IPT, the purpose of the compensation network is making the overall system work in a resonant state. There are four types of single-order compensation networks as followed: (1)S-S (2)S-P (3)P-S (4)P-P. In the diagram shown in Figure 4, S is used to denote the capacitor connected in series, while P is used to denote the capacitor connected in parallel.



(a) S-S (b) S-P

(c) P-S (d) P-P

Figure 4. Four types of single-order compensation networks

Most research studies primarily focus on the four fundamental compensation networks, while others aim to optimize hybrid compensation techniques such as LCL and LCC compensation networks. Among the four basic compensation networks, the S-S type is widely utilized due to its constant current output characteristic and independent compensation capacitance value from mutual inductance and load. This enables the overall system to maintain a resonant state even when there are coil offsets or changes in load. The S-S type compensation circuit is commonly employed for cases of coil drifting. Reference [9] suggests that both S-S and S-P types can enhance the transmission efficiency of an IPT system with asymmetric coils. However, it has been found that the S-P type is more susceptible to mutual inductance and therefore more suitable for significant load changes. Both S-S and S-P compensation networks demonstrate high energy transfer efficiency, often surpassing 90% in the majority of use cases. On the other hand, P-P and P-S compensation networks are significantly affected by mutual inductance of coupling coils and load changes, limiting their use to cases where coil offset is minimal and load changes are slight. Additionally, these two types of networks require high operating voltage for sufficient power due to their significant input impedance. The advantages of these two types of compensations circuits include: (1) high power-factor (2) long transmission distance (3) wide range of load change (4) high transmission efficiency at low mutual inductance (5) ability to work at the same frequency (6) low operating power. A comparison is shown in Table 1 as followed.

Table 1. Comparison for four basic topologies

Topologies		S-S	S-P	P-S	P-P
Total impedance		Decreases with misalignment	Decreases with misalignment	Increases with misalignment	Increases with misalignment
Sensitivity to misalignment		Low	Slightly higher than S-S type	High	High
Total chopper mass at 200kW system		Least chopper mass of others	4.6% higher than S-S	30% higher than S-S	24% higher than S-S
Zero coupling allowance		Not allowed	Allowed	Allowed	Allowed
Transmission efficiency		Very high	Low	Low	High
Independence on coupling factor and load impedance	Transmitter side	√	√	×	×
	Vehicle side	√	×	√	×
Output power		High	High	High	Low
Power level		High	Low or medium	High	High
Other features		Low- independent output current; high power and efficiency than S-P when the frequency larger than 1 MHz	Less receiver self-inductance than S-S; Stable current because of the parallel compensation in receiver side	Optimal transmission efficiency and power factor achieved with minimal mutual inductance and significant load variation	High-power current transmission for long distance
Application		WPT system for EVs (both dynamic and stationary)	Biomedical field and low-power application	Application of high power (EVs)	Application of high power (EVs)

When it comes to mixed (composite) compensation techniques, through combining capacitor (C) and inductors (L), hybrid compensation networks can be obtained, such as LCL-LCL, LCC-S, LCC-LCC, CCL-LC, LC-LC and others, which are shown in Figure 5. In these topologies, a greater number of passive elements are employed to harness the benefits of both series and parallel connections while mitigating the limitations inherent in the fundamental topologies.

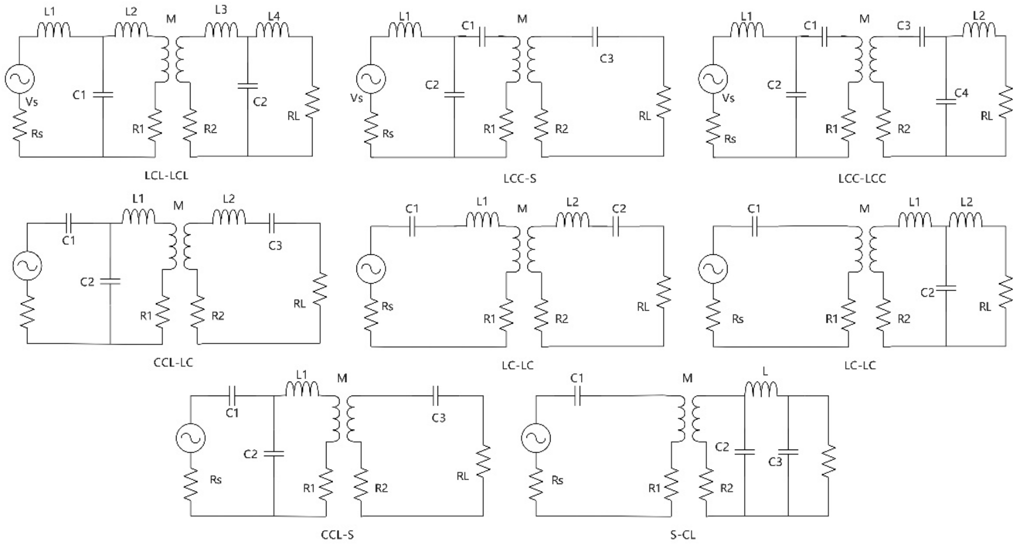


Figure 5. Hybrid compensation networks

The typologies of LCC-LCC and LCL-LCL, two kinds of hybrid compensation circuits, can enhance the effectiveness of IPT systems across the entire coupling and load range. However, the additional leakage resistance in capacitors and inductors results in higher copper losses compared to the S-S type. Two-side LCL and LCC technologies are well-suited for EV battery charging because they enable the vehicle-side current source to collaborate with the transmitter's voltage source inverter. Reference [6] examined two-sided LCC compensation technology and determined that adjusting the LCC circuit could achieve zero current switching while maintaining a constant root mean square (RMS) of the output current. The use of LCC typology architecture compensates for reactive power on the receiving side, achieving unit power factor operation without being affected by loading conditions or coupling factors. LLC compensation technology is implemented on the transmitter side with an operating frequency exceeding 1 MHz, resulting in high transmission efficiency despite a small rated voltage. Table 2 presents a comparison between basic and hybrid compensation techniques, taking into account different metrics such as operating frequency, output power, coupling coefficient (k), transmission efficiency (η), air gap distance, and coupler configuration [9].

Table 2. Comparison between basic and hybrid compensation techniques

Topology	Operating frequency (kHz)	Output Power (kW)	Coupling coefficient (k)	Transmission efficiency (η)	Airgap distance (mm)	Coupler
S-S and LCC-LCC	85	1	0.135	95% for S-S 93% for LCC	200	Core: circular-circular
	79	7.7	0.188-0.311	96% for LCC	200	Core: DD-DD
S-S and LCL-LCL	85	3.3	0.1	93.1% for S-S 89.5 for LCL	100	Coreless: rectangle-rectangle
LCC-LCC	79	7.7	0.18-0.32	96%	200	Core: rectangle-rectangle
	95	5.6	0.14-0.3	95.36%	150	Core: DD-DD
	85	3.3	0.153	92.6%	150	Coreless: circular-circular
	85	3	0.1877	95.5%	150	Core: DD-DD
	85	1.4	0.13	89.78%	150	Core: rectangle-rectangle
LCL-S and LCC-S	140	1	0.18-0.32	93%	100	Core: circular-circular
LCL	58	5	0.37-0.54	-	240	Core: DD-DD or bipolar-bipolar
S-P	23	2	-	92%	100	Core: circular-circular
S-S	85	20	0.4	80%	100	Coreless: rectangle-rectangle
	85	-	-	97.6%	200	Core: rectangle-rectangle

3. Conclusion

The article aims to offer a comprehensive review of current research on inductive power transfer (IPT) systems for electric vehicles (EVs) and their applications in transportation. It presents the developmental status of both EVs and wireless power transfer (WPT) technology, comparing various categories to determine the most appropriate system for current-stage EVs research. Additionally, it examines IPT system components for wirelessly charging EVs with a focus on magnetic coupling architecture and compensation networks. The discussion regarding magnetic coupling architecture encompasses coil materials, electromagnetic field (EMF) shielding, as well as inductive pad design.

Furthermore, the article discusses the current challenges of the WPT system and explores future development trends. The use of power transmission frequency and safety considerations necessitates a set of standard constraints. Although the existing interoperability standards are generally comprehensive, further clarification is needed for higher power levels. Safety concerns require governments and institutions to establish a standardized framework, which can attract attention and promote WPT technology in global markets. Challenges and opportunities still exist in implementing WPT systems for EVs. Dynamic wireless charging has the potential to sustain battery charge while driving, potentially reducing the need for large battery packs and alleviating range anxiety in electric vehicles. The real-world deployment of dynamic WPT electric vehicles requires careful consideration of environmental, economic, and sociological impacts, as well as infrastructure performance in terms of energy efficiency, durability, and reliability.

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