Wireless Power Transfer: An Overview and Challenges

Haitao Luan*
HD-school, Beijing, China
**Corresponding author*

Abstract: Nowadays, individuals have the ability to conveniently place their electric devices on wireless chargers for recharging. What if this same technology could be applied to EVs? This inquiry potentially obviates the need for low power density, high cost, and heavy weight associated with plug-in charging. Wireless power transfer (WPT) represents a power delivery method characterized by high performance, durability, and adaptability, reducing reliance on battery storage. This paper presents an overview of WPT technology by primarily examining the principle and theory of wireless charging, discussing the merits and limitations, and investigating the modes of charging systems, such as stationary and dynamic charging. In conclusion, this paper provides a rational discussion on the future development trajectory of charging in relation to WPT, advocating that this promising renewable energy transmission mechanism holds a significant potential for widespread integration into daily human life.

Keywords: Wireless Power Transfer; Electric Vehicle; Transmission; Coils; Compensations; Challenges

1. Introduction

As an emerging trend in future application, wireless power transfer (WPT) distinguishes itself from conventional vehicles by enabling energy migration in a cordless method, thereby eradicating the potential risks associated with traditional utilization of conventional vehicles. This innovation offers a convenient method for utilizing various applications, including, solar-powered satellites, railway system, medical devices, portable electronic devices, unmanned aerial vehicles (UAVs), and electric vehicles (EVs) [1] [2]. Due to its characteristics of mobility, flexibility, designated position independence, and sustainability potential, the WPT technique is being considered as a viable solution for charging electric-driven devices in specific regions soon. However, WTP have been used in specific domains relevant to everyday life. This is specifically exemplified by the application of WPT for charging electric vehicles (EVs for short). EVs incorporating electric storage technology have not gained significant consumer interest, primarily due to drawbacks such as suboptimal energy density, pressure on power grid, limited lifespan, and high initial battery costs[2]. Taking the long charging duration of EVs as an example, the charging time for electric vehicles is extended. It takes approximately 30-40 minutes to charge from 0% to 80%[3], even with the utilization of rapid charging stations. While standard household charging may require several hours or even an overnight period. These factors present a bottleneck in both advancement of electric storage technology and development of future science and technology. Besides, in the case of power duration, while numerous automobile manufacturers claim that their products can travel over 120-130 km per charge, most electric vehicle (EV) owners tend to limit their driving range to approximately 90-100 km due to concerns about range anxiety[3]. Instead of waiting for a breakthrough in electric storage technology, the WTP technique that eliminates most of the aforementioned charging issues is attracting EV consumers. The current method of charging electric vehicles involves connecting the cable from an AC utility to charge the onboard batteries using an onboard charger (OBC)[11]. However, the WTP technique is designed for comprehensive purposes under diverse conditions. Through the utilization of wireless energy transfer for electric vehicle (EV) charging, the process of recharging becomes a seamless and integral part of daily life. Companies such as WiTricity and Plugless Power have developed residential WPT solutions that eliminate the need for physically plugging in, providing convenience, and reducing wear on charging connectors. These systems are becoming increasingly popular among electric vehicle owners due to their simplicity and user-friendly nature. With a dynamic WPT system (DWPT), EV owners have the capability to continuously charge their vehicles while in motion, thereby facilitating prolonged usage of EVs.

The paper is organized as follows: Section II discusses the fundamental principles of WPT, and its architectural elements required for practical implementation. Section III reviews technology needed in WPT system for EVs, such as the discussion of near-field and far-field transmissions, different magnetic couplers used to transfer power, compensation networks, models & designs, stationary and dynamic WPT charging. Section IV presents an overview of challenges. To encapsulate, this paper reveals the significant technology, current status, accomplishment issues, and a conclusion of WPT charging for EVs.

2. Foundamentals

Due to the increasing requirement for electric vehicle development, scientists have consistently focused on improving the scope, efficiency, and safety of WPT technology. Currently, WPT technology can transfer energy from a power source to a designated target through the air, rather than traditional plug-in charging. This paper will explore WPT system designs and considerations such as standard and limitation. Additionally, we will delve into the theoretical support for WPT technology for EVs[4].

2.1 WPT Architecture for EVs

WPT offers the convenience of charging an EV simply by parking it over a charging pad. The overall architecture of a WPT system for EVs includes several key components and subsystems. Some devices are designed to operate the entire system of electric vehicles independently from the WPT system in order to ensure efficient operation. The main component of EV architecture is the power source, which includes grid connection and power electronics. For example, the grid connection system is typically linked to the electrical grid as its primary energy source. Power electronics, such as AC/DC and DC/AC converters, are used to convert the power into a suitable form for wireless transmission[12]. These converters and systems control power flow, voltage, frequency, and transmission. In addition, the transmitter unit helps regulate the power delivered to the transmitter coil for safe and effective operation. For example, the primary coil (transmitter coil) is either embedded in the ground within a charging pad or placed on the ground surface. When alternating current passes through it, it produces an oscillating magnetic field. The resonance circuit works alongside the transmitter unit to ensure efficient energy transfer at a specific resonant frequency. The resonant circuit consists of the transmitter coil and associated capacitors.

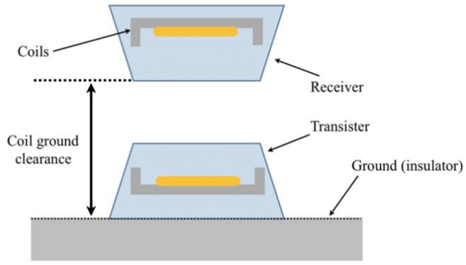

Figure 1. The Sketch of Transmitter and Receiver

2.1.1 WPT Operational Principles: Faraday’s Law and Ampère's Law

The WPT operational principle is directed by Ampère's law and Faraday’s law. Based on Ampère's law and Faraday's law, WPT technology has been successfully utilized in electric vehicles[12]. The introduction of these laws establishes the fundamental working principles of WPT technology. In summary, these laws clarify the following:

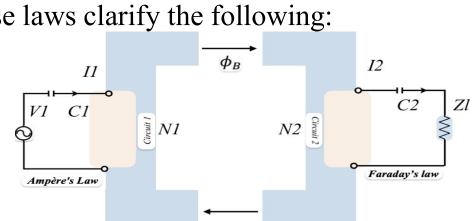

Figure 2. Foundamental Principles for WPT

Faraday’s law is fundamental to the operation of wireless charging systems. It describes how a changing magnetic field induces an electromotive force (EMF) in a conductor. The (1) is mathematically expressed as:

$$\mathcal{E} = -N_2 \frac{d\Phi_B}{dt} \quad (1)$$

Accordingly, (1) involves several physical concepts: where $\mathcal{E}$ is the induced EMF, Φ_B is the magnetic flux through the circuit, N_2 is the number of secondary turns, and t is time.

The elucidation of Faraday’s Law in the context of WPT is important for comprehending the fundamental principles underlying this technique. The vital role played by Faraday’s Law in facilitating WPT can be delineated as follows[12]:

1) Electromagnetic Induction: According to Faraday's law, this changing magnetic field induces an EMF in the secondary coil (receiver), producing an electric current that can be used to charge a device.

2) Magnetic Resonance: This resonance condition increases the magnetic field interaction and, consequently, the induced EMF, allowing more efficient power transfer over greater distances.

3) Energy Conversion Efficiency: By optimizing the coil design, adjusting the operating frequency, and managing the magnetic field variations, the induced EMF can be maximized, improving the overall energy conversion efficiency.

Ampère's Law plays a pivotal role in the realm of wireless charging technology, specifically in the design and optimization of wireless charging systems[12]. The foundation of wireless charging lies in the principle of electromagnetic induction, and Ampère's Law (particularly in its mathematical form, Maxwell-Ampère's Law) depicts the mutuality between current and the resultant magnetic field. This comprehension is indispensable for the development and refinement of wireless charging coils and circuits. The (2) is mathematically expressed as:

$$\sum B_T \Delta l = \mu_o I N_1 \# \quad (2)$$

Accordingly, (2) involves several physical concepts: where B_T is the magnetic flux density in Tesla, Δl is the unit length of the conductor in meters, N_1 is the number of primary turns, and Δl is the current in the primary conductor in amperes (A).

The overall understanding of Ampère's Law in the context of WPT is imperative for comprehending the basic principles. The role played by Ampère's Law in designing WPT can be expressed as follows[12]:

1) Current and Magnetic Field Relationship: Ampère's Law shows that a circulating magnetic field is always created around a current-carrying conductor. In WTP technique, an alternating current in the transmitter coil generates a changing magnetic field, which induces voltage in the receiver coil, enabling successful energy transfer.

2) Electromagnetic Field: In the consideration of both Faraday's Law and Ampère's Law, combination of two laws allow for the analysis of the distribution and strength of electromagnetic fields within the WPT system.

3) Detecting Resonance Frequency: Ampère's Law is crucial for determining the inductive properties of coils and setting the resonance frequency to maximize energy transfer efficiency.

3. Far-field and Near-Field Transmission

WPT for EVs relies on electromagnetic fields to transfer energy from a transmitter which typically embedded in the road or parking space to a receiver which mounted on the vehicle[11]. There are two primary types of WPT systems based on the distance between the transmitter and receiver: near-field and far-field transmission. The utilization of acoustic, optical, and microwave fields as energy carriers enables the understanding of far-field transmission[11]. While near-field transmission, being the predominant approach, predominantly relies on the induction coupling effect of non-radiative electromagnetic fields encompassing both induction and capacitive mechanisms. Therefore, these concepts distinguish between two different modes of charging. Understanding the underlying theory of these two different concepts can set the macro goals for future technological development.

3.1 WPT System: Indutive Poewr Transfer (IPT)

Fig. 4(a) depicts T-model of IPT system. Compared to a circuit model, the equivalent T-model serves as a simplified circuit representation utilized for analyzing the behavior of an IPT system, with particular emphasis on the inductive coupling between the primary and secondary coils. This model helps in understanding the interaction between the coils and the impact of mutual inductance on power transfer[11].

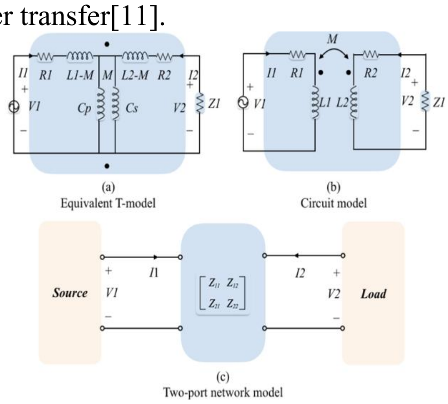

Figure 3. Inductive Power Transfer[9] [11].

According to the Fig. 4, the inductive coupling between the primary and secondary coils is represented by an equivalent circuit consisting of: Leakage inductances L_1M and L_2M, primary inductance L_1, secondary inductance L_2, Mutual inductance M, load Z_L, series resistances R_1 and R_2 representing the inherent resistances (Ω) of the coils, current I_1 and I_2, and AC power source V_1. Specifically, L_{lp} and L_{ls} show the shares of the inductance that do not contribute to mutual coupling. (3) and (4) are two equations about the primary and secondary circuit impedance:

The impedance seen by the source in the primary circuit Z_{in} is primary circuit impedance, which can be written as[11]:

$$Z_{in} = R_1 + j\omega L_1 + \frac{(j\omega M)^2}{R_2 + j\omega L_1 + \frac{1}{j\omega C_s} + Z_L} \# \quad (3)$$

The secondary circuit's impedance Z_s includes the effects of the load and the secondary coil's parameters can be written as following (4):

$$Z_s = R_2 + j\omega L_2 + \frac{1}{j\omega C_s} + \frac{Z_L}{1 + j\omega Z_L C_s} \# \quad (4)$$

The mutual inductance M is reflected into the secondary circuit as a voltage source with an induced voltage V_m. Where I_p (I_1 and I_2) is the current in the primary coil:

$$V_m = j\omega M j I_p \# \quad (5)$$

The power delivered to the load P_{load} can be expressed as:

$$P_{load} = \frac{(j\omega M I_p)^2}{Z_s} \# \quad (6)$$

Substituting the expression for Z_s which presents at (6). (7)is utilized to calculate the power transfer to the load:

$$P_{load} = \frac{(j\omega M I_p)^2}{R_2 + j\omega L_2 + \frac{1}{j\omega C_s} + \frac{Z_L}{1 + j\omega Z_L C_s}} \# (7)$$

Accordingly, the load power will significantly decrease as the transmission distance increases in IPT systems. This limitation is why IPT systems are only suitable for near-field energy transmission.

Fig. 4(a) depicts the equivalent T-model of 2-coils IPT system. The efficiency (η) can be calculated as:

$$\eta = \frac{P_{load}}{P_{in}} \# \quad (8)$$

$$\eta = \frac{\left(\frac{\omega M}{Z_{in}}\right)^2}{Z_L + j\omega L_1 \left(\frac{M}{L_2}\right)^2 Z_s} \# \quad (9)$$

The following (10) is an expansion of the calculation of efficiency (η):

$$\eta = \frac{\left(\frac{\omega M}{Z_{in}}\right)^2}{Z_L + j\omega L_1 \left(\frac{M}{L_2}\right)^2 \left(R_2 + j\omega L_2 + \frac{1}{j\omega C_s} + \frac{Z_L}{1 + j\omega Z_L C_s}\right)} \# \quad (10)$$

In addition, various compensation networks, a more user-friendly technology, are required to enhance the overall system efficiency[11]. To optimize the entire IPT system and improve its efficiency, technical enhancements from various perspectives are necessary[11]. The primary purpose of the compensation network is to enhance the efficiency of power transfer between the transmitter and receiver coils, ultimately leading to improved overall system performance. Capacitors are utilized in these networks to counterbalance the reactive power produced by the sensing elements, thereby enhancing power transmission efficiency. Various types of compensation networks exist, such as series-series (SS), parallel-parallel (PP), series-parallel (SP), and parallel-series (PS) [11]. TABLE II shows a specific information of different capacitive compensation networks in order to categorizing mentioned equations and principles.

Table 1. Equation of Different Capacitive Compensation Network[11]

Topology	Reflected quality factor	Secondary quality factor	Primary capacitance
SS	$\frac{\omega_0 L_s}{R}$	$\frac{\omega_0{}^2 M^2}{R}$	$\frac{C_s L_s}{L_p}$
PP	$\frac{R}{\omega_0 L_s}$	$\frac{M^2 R}{L_s}$	$\frac{C_s L_s{}^2}{L_p L_s - M^2}$
SP	$\frac{R}{\omega_0 L_s}$	$\frac{\omega_0{}^2 M^2}{R}$	$\frac{C_s L_s}{\frac{M^4}{L_p C_s L_s R} L_p}$
PS	$\frac{\omega_0 L_s}{R}$	$\frac{M^2 R}{L_s}$	$\frac{C_s L_s}{\frac{M^4 C_s R}{L_s}(L_p L_s - M^2)}$

3.2 Capacitive Power Transfer

An alternative to the traditional IPT system, Capacitive Coupling Power Transfer (CCPT) is a more advanced option compared to inductive coupling[11]. Fig. 5 shows a bock diagram of CCPT. CCPT uses an electric field instead of a magnetic field to transfer power between two or more capacitor plates. Although CCPT systems may have lower efficiency than IPT systems over longer distances due to challenges in maintaining a stable electric field, they can achieve high power density under suitable conditions, especially when capacitive plates are close together. Furthermore, the CCPT system has been effectively employed in a range of uses, including electric vehicles, synchronous electric motors, and consumer electronics.

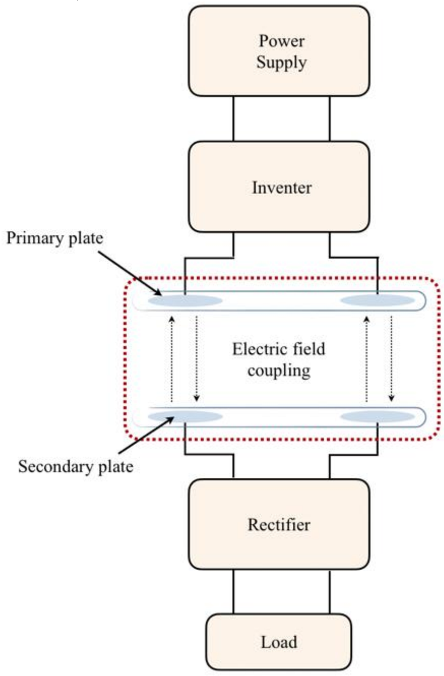

Figure 4. A Block Diagram of Typical CCPT System

3.3 Coupling Pad

The coupling pads work based on the principle of magnetic resonance and coupling coefficient. Magnetic resonance altered the primary and secondary pads to resonate at the same frequency[11]. This resonance enhances the efficiency of energy transfer, especially over larger air gaps. Coupling coefficient (k) is a measure of how effectively the primary pad's magnetic field links with the secondary pad. A higher coupling coefficient indicates better efficiency, which is influenced by pad design, alignment, and distance between the pads. Hence, the desired characteristics for coupling pads are the high coefficient of coupling k, quality factor Q, and high misalignment tolerance. A high-quality factor Q, a high coupling coefficient k and high misalignment tolerance involves a combination of optimized geometry, advanced materials, and adaptive control mechanisms. These factors work together to ensure an efficient WPT systems for EVs.

The quality factor Q of a resonant circuit is the geometric mean of primary and secondary quality. This factor which is a measure of its efficiency is defined for a single coil as[11]:

$$Q = \sqrt{Q_1 Q_2} \# \quad (11)$$

$$where\ Q_1 = \frac{\omega_0 L_1}{R_1} \text{ and } Q_2 = \frac{\omega_0 L_2}{R_2} \# \quad (12)$$

Both primary and secondary coils have their own quality factors Q_1 and Q_2, respectively. Constant $\omega_0 = 2\pi f_0$ is the angular resonant frequency, with resonant frequency f_0, L_1 and L_2 are the inductances of the coil, R_1 and R_2 are the resistances of the coil.

Quality factors Q_1 and Q_2 are independent in both primary and secondary coils. The general efficiency of the system is influenced by the product of quality factors:

$$Q_{total} = \frac{Q_1 \cdot Q_2}{Q_1 + Q_2} \# \quad (13)$$

Accordingly, both Q_1 and Q_2 should be high to maintain a high efficiency, which means low resistive losses and a well-tuned resonant circuit. Furthermore, coupling coefficient (k) between two inductive coils (primary and secondary) is given by (14):

$$k = \frac{M}{\sqrt{L_1 \cdot L_2}} \# \quad (14)$$

In (14), M is mutual inductance between the coils, L_1 is the self-inductance of the primary coil, L_2 is the self-inductance of the secondary coil. In accordance with practical examples, for closely coupled coils with optimal alignment, k approaches 1, indicating strong coupling. Contrastively, kdecreases as the gap increases or the alignment deteriorates.

The power transmission efficiency can be expressed in terms of k, Q_1, and Q_2. This power transfer maximization is given by:

$$\eta = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2} \# \quad (15)$$

Significantly, achieving high k and Q values to maximize the efficiency of the power transmission.

Many scholars have advocated various coil configurations in order to enhance the coupling coefficient and uphold a high-quality factor. The addition of insulating material, such as ferrite bars or plates, can enhance the coupling coefficient and enhance the inductance, quality factor, and mutual inductance of a decoupling pad. Nevertheless, the inclusion of ferrite bars also results in increased core losses and copper losses due to field modification in the conductors.

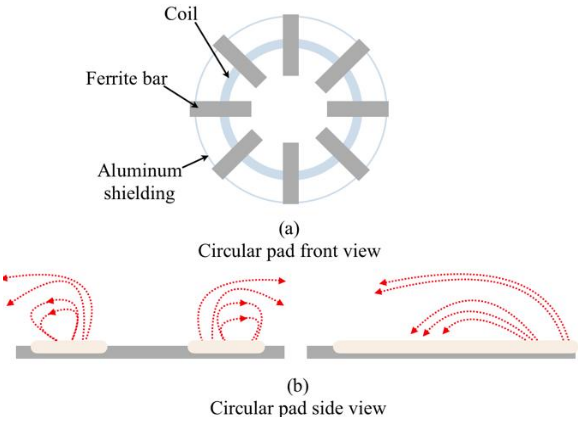

Figure 5. [12] (a) Circular Pad Front View and (b) Flux Lines of Circular Pad Side View

3.3.1 Circular Coils

Due to simplicity, circular coils are the most commonly configuration as shown in Fig. 8. Circular coils well informed and improved in. Specifically, circular coils are easy to manufacture, making them a cost-effective option for many applications. Their straightforward geometry simplifies the design process and allows for efficient mass production. Furthermore, circular coils are often utilized in applications where EV's alignment can be controlled. The circular nature of the coil is commonly used in WPT systems because the single-sided magnetic field enters and leaves the coil from the front of the coil, which is in line with the basic idea of WPT. Design parameters, includes coil diameter, number of turns, wire gauge, and spacing between turns and core material, are essential to develop an efficient circular pad. Take coil diameter as an example, the diameter of the circular coil significantly impacts the magnetic field strength and the area of coverage. Larger diameters result in a more extensive magnetic field. Similarly, number of turns in the coil affects the inductance. More turns increase inductance, capacitance, and magnetic field strength. However, more turns increase resistance (Ω), which can reduce the quality factor (Q).

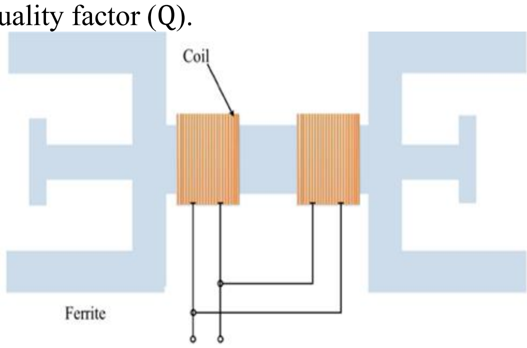

Figure 6. [12]Flux Pipe

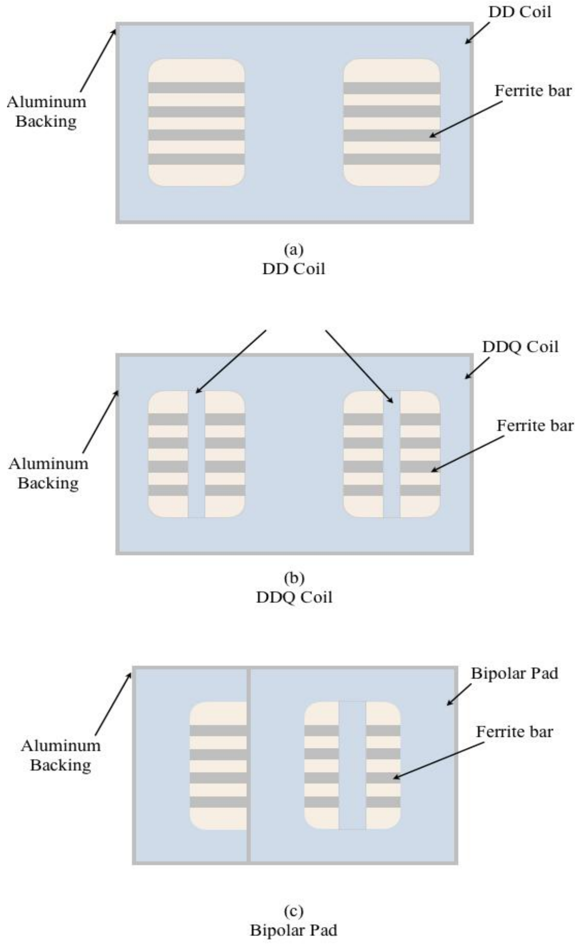

Figure 7. Different Coil Structures[12]: (a) DD Coil, (b) DD-Q Coil, and (c) Bipolar Pad

3.3.2 Flux Pipes

In WPT systems, the concept of flux pipes pertains to a structural component utilized for the purpose of guiding, concentrating, and augmenting the flux between the transmitter (primary coil) and the receiver (secondary coil). Various coil shapes enhance coupling, with Fig. 7 depicting a rectangular ferrite bar that achieves similar effects. The function of the flux pipes is to focus and direct the flux produced by the primary coil toward the secondary coil. The two coils shown in Fig. 7 are connected by a wire, resulting in an energy-guided effect. This effect increases the mutual inductance M between the coils, thereby increasing the coupling coefficient k and improving the efficiency of power transmission. However, shielding reduces the quality factor and consequently decreases EV charging efficiency. The concept of flux pipes ensures that power transmission is optimized even if the vehicle is not precisely aligned with the pad.

3.3.3 DD Coils

The Double-D (DD) coils consist of two

D-shaped coils positioned next to each other, which shown in Fig. 8 (primary coil and secondary coil)[12]. They offer better tolerance for misalignment compared to single circular or rectangular coils. Additionally, they provide a more even distribution of the magnetic field across the area, which can improve the stability of power transfer. However, Double-D coils have a complex design that increases manufacturing complexity and requires careful tuning to optimize resonant frequency and efficiency.

3.3.4 DDQ Coils

Double-D Quadrature (DD-Q) Coils builds on the DD design by adding another pair of D-shaped coils perpendicular to the first pair[12]. As shown in Fig. 8, this design creates a quadrature arrangement. Specifically, the coil is located at the center of the DD coil, and due to the overlapping magnetic fields of multiple coils, it has a high degree of tolerance for misalignment. Besides, DDQ coils coil construction improves power transmission efficiency across different arrangements and directions, largely compensating for misalignment.

3.3.5 Bipolar Pad Coils

The Bipolar Pad (BP) Coils must be specifically tailored to align with the receiving coil of the vehicle. Bipolar pads create a magnetic field with two opposing poles (north and south), while single pole designs typically only have one magnetic pole. Bipolar plates aid in generating a more even distribution of the magnetic field between the transmitter and receiver coils, which can effectively maintain peak efficiency and power transmission[12].

3.4 SWPT and DWPT

Charging power increases for efficient charging. DC fast charging needs bigger cables, which adds weight and makes things more complicated. The system can leak and have hazards because of managing heat with the cable. SWPT is a big step forward in transferring electrical energy through the air, offering many benefits like safety and convenience. The emergence of SWPT eliminates the need for plugging and unplugging devices, reduces electric shock risk, and minimizes wear and tear. However, cost and health concerns are obstacles to fully utilizing this technology. Stationary WPT for EV charging is more widely accepted with lower implementation costs compared to dynamic WPT systems. DWPT wirelessly charges electric vehicles while they are moving, extending their driving range and reducing the need for frequent recharging stops. To improve efficiency, it is important to focus on the design and alignment of coils, inverters, rectifiers, and system management. Common coil configurations include circular, rectangular, and DD-Q coils [12].

4. Challenges

Nowadays, an increasing number of academic researchers are principally focused on improving the transmission performance of energy, emphasizing efficiency, power loss, range, material safety and health issues, regulatory and legal issues, consumer acceptance, cost, and additional. Previous presentations have temporarily touched on these issues from a technical standpoint[11]. This paper delves into the primary technical obstacles faced by WPT systems and their impact on system operation and development, which is the main focus of discussion in this paper. Addressing these challenges, on the other hand, is critical to making WPT a viable alternative to wired charging, especially in terms of energy consumption, operating costs, and environmental impact. In the future, solving these technical problems will lay the foundation for the development of future WPT technology and drive the development of more advanced WPT.

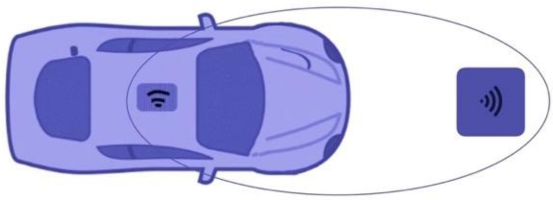

Figure 8. Illustration of Transmitter and Receiver of WPT System

4.1 Efficiency and Power Losses

One of the main challenges confronting wireless charging technology is the dissipation of energy during the transmission process. Depending on the charging speed and the device used, traditional wired EV charging systems can achieve 90-95% efficiency [5][6]. WPT systems typically have lower efficiency. For example, early WPT systems operating at low power (3.3 kW) had an efficiency of about 85 to 90% at optimal alignment [7], but this dropped to below

70% as the distance between the transmitter and receiver increased or if there was misalignment. WPT systems demonstrate a certain deficiency in energy transmission efficiency, particularly for long-distance charging. The inefficient transfer of energy not only results in increased energy consumption, but also leads to prolonged charging times for devices, causing inconvenience for long-term users. Furthermore, if an electric car requires 30 kWh for a full charge, then with an efficiency of 95%, a wired system will draw approximately 31.6 kWh from the grid. However, a WPT system with an efficiency of 85% would require 35.3 kWh of charge, resulting in an additional energy demand of 3.7 kWh or nearly 12% increase in energy consumption[8]. Therefore, additional research and enhancements are necessary to improve the efficiency of wireless charging technology and meet people's demand for rapid and convenient charging.

4.1.1 Coils Design Optimization

The optimization of coil geometry, material, and configuration is crucial for enhancing performance. Current advancements encompass the utilization of multi-layer coil designs and circular coils to attain optimal power transmission and impedance matching, thereby minimizing losses. By using multi-layer coils as an example, the arrangement of stacking multiple turns of wires is designed to increase inductance and magnetic field strength. This enhances the coupling between the transmitter and receiver, leading to a more secure connection between devices and improved efficiency. These layered coils are commonly found in numerous WPT systems due to their symmetrical magnetic fields, making them effective for various applications. In practical use, these solutions are regularly combined to achieve maximum efficiency in WPT systems. A WPT system may utilize resonant frequency matching for optimal power transfer, impedance matching to minimize losses, and optimized coil design for enhanced magnetic coupling. Furthermore, WPT uses an intermediate coil to enhance the apparent self-inductance and magnetization of the host group near the resonant frequency, effectively compensating for the apparent coupling coefficient. Additionally, advanced control systems can dynamically adjust these parameters to maintain optimal performance under different conditions. Moreover, in order to ensure the extreme efficiency of the WPT system, the quality factor Q is crucial in coil design. Q can be increased through the concepts mentioned above, and an improved scheme for hollow flat spiral winding can increase Q by using a non-uniform width-to-radius ratio geometry and increasing the internal radius of the winding.

4.1.2 Power Control

A control scheme for tracking the maximum efficiency point by evaluating the efficiency of closed-loop WPT systems. This is done in order to maximize energy efficiency as the load and coupling effects modify when adjusting the output voltage. By controlling the amplitude of the output voltage and the phase shift of the active rectifier, we can modify the equivalent load impedance to maximize energy transfer efficiency. Additionally, adjusting the output voltage while ensuring maximum efficiency tracking can be effectively achieved with a series resonant tank. Cascaded boost-buck DC-DC converters are designed for various loads to ensure optimal impedance matching of WPT systems.

4.2 Range and Alignment

When the distance between the transmitter and receiver of WPT system increases, the efficiency will significantly decrease. For example, it is usually between 10 and 20 cm[9]. As the distance increases between the transmitter (charging pad) and receiver (vehicle), the efficiency of these systems decreases significantly. In real life, vehicles are typically parked in the same position. The vehicle cannot align perfectly with the charging pad, so the charging efficiency may drop to 60-65%[10]. Additionally, 3.3 kW WPT system may achieve around 90% efficiency with a 10 cm gap, but if the gap increases to 20 cm, the efficiency may drop to around 70%[10]. Therefore, vehicles and charging pads need to maintain a short and precise distance.

4.3 Optimizing Positions

Some WPT systems are exploring adaptive positioning technologies that can automatically adjust the position of the charging pad or the vehicle to optimize the distance between the coils. For example, robotic charging arms or movable pads can adjust to ensure optimal alignment, though these solutions add complexity and cost.

4.4 Resonant Coupling Enhancement

Another approach is to enhance resonant coupling between the transmitter and receiver. By tuning the resonant frequency of the coils more precisely, WPT systems can maintain higher efficiency even at slightly greater distances or with slight misalignments. Research into metamaterials and advanced coil designs is ongoing to push these boundaries further. More progressive resolutions being investigated include inductive dynamic charging. This system is less sensitive to alignment since the vehicle can be charged over a longer distance, though it is currently in the experimental stage and involves high infrastructure costs.

4.5 Displacement Flexibility

In a WPT system, the position between the transmit coil and the receive coil determines the transmission power. This means that transmission performance can be reduced due to angle or lateral misalignment, which may affect final efficiency. The output power of the IPT system can be calculated using the formula[11]:

$$P_{out} \approx \eta P_{in} = \frac{\eta U_1{}^2 Re(Z_r)}{Z_r} \# \qquad (16)$$

Therefore, there are two ways to increase the tolerance for position errors: 1) compensating for the capacitance when the reflected impedance occurs; 2) Optimizing the coil to mitigate the attenuation of the coupling effect.

4.6 Materials

In accordance with the fundamental criteria for WPT systems, researchers must carefully consider a range of material factors when designing the system. Material selection and utilization are subject to certain limitations, including compatibility, environmental impact, and cost. Considering the longevity, dependability, and influence on electromagnetic signals are meaningful when choosing materials for the WPT system in order to guarantee its stable operation over an extended period[11]. As a result, multiple aspects of electric vehicles, materials must be able to withstand temperature, humidity, chemicals etc., without damage. The following examples, includes magnetic materials, conductive materials, and shielding materials are an overview of materials and the confronts associated with them:

4.7 Magnetic Materials

Ferrites serve as a typical illustration of magnetic materials. They are frequently utilized in the iron cores of transformers and inductors to improve the magnetic connection between the sender and receiver, thus reducing eddy current losses.

Copper is widely considered the best conductive material for electric vehicles. Due to its excellent electrical conductivity, copper is commonly used in coils and wiring in WPT systems. Relevant materials, including mu-metal and other magnetic shielding substances, are employed to confine and guide magnetic fields, minimizing disruption and enhancing safety.

4.8 Safety and Health Concerns

WPT systems, especially those running at high power levels, can produce electromagnetic fields (EMI) that might disrupt nearby electronic devices or even present health risks to humans and animals if not adequately shielded. Additionally, the security of transmitted energy in multi-objective WPT systems is getting more attention. A wireless charger needs to encrypt the energy to ensure authorized receptors get the power they need and prevent unauthorized ones from stealing it.

4.9 Dynamic Wireless Power Transfer (DWPT)

DWPT involves the transmission of power to vehicles while in motion, which requires careful consideration of infrastructural requirements, cost estimates, and technical challenges. The integration of roadway systems involves the incorporation of inductive coils and alignment technologies. This process necessitates the embedding of coils into road surfaces, requiring extensive civil engineering to seamlessly integrate them without disrupting existing infrastructure. The cost of embedding coils can range from $1 million to $5 million per mile, depending on the technology and conditions of the roadway[13]. Additionally, the infrastructure for power supply and control systems is of equal importance. On-road power stations or substations are necessary for converting electrical energy for transmission, requiring high-capacity transformers and converters. Furthermore, reliable communication technology between vehicles and road infrastructure is essential for real-time monitoring and control of power transfer. Research indicates that regular maintenance of embedded systems is necessary, estimated to cost 5-10% of installation costs annually[13].

4.10 Cost's Drawbacks and Potential Benefits

The installation of WPT infrastructure, including the associated power electronics and the necessary parking spaces, is expensive. Without widespread industrialization, this could be a barrier to widespread adoption, increasing the cost of production. Manufacturers and policymakers need to carefully consider how to make WPT technology more affordable and accessible in order to encourage widespread adoption of EVs.

Although the initial investment in WPT systems can be high, their long-term advantages, including improved efficiency, shorter charging times, and positive environmental effects, make them a compelling choice for investment. First, WPT systems enable continuous charging while vehicles are in operation, leading to less downtime compared to traditional plug-in charging methods. Second, it improves infrastructure efficiency by reducing the need for extensive charging stations and minimizing real estate and associated infrastructure costs. Third, it helps reduce greenhouse gas emissions by promoting increased usage of EVs, which contributes to creating cleaner urban environments. Additionally, as WPT technology advances, the potential for substantial cost reductions through mass production becomes increasingly feasible, with the possibility of lowering costs by 20-30%[13]. This could greatly enhance the practicality of widespread adoption. Eventually, anticipated future developments in technology and the increased scale of production are likely to further improve the affordability and practicality of WPT systems.

5. Conclusion

This paper presents a comprehensive overview of wireless power transfer (WPT) technology, with a focus on its fundamental principles and technical challenges. Regarding the basic principles, this paper initially introduces the overall structure, standards, principles, and fundamental formulas of WPT. Moreover, comparing the advantages and disadvantages of two basic laws and elucidates the fundamental operating principle of WPT. Furthermore, this paper offers an overview of the evolution of WPT technology by examining its progress and current position in recent decades. In the subsequent section, this paper delves into the operational mechanism of inductive power transfer (IPT) systems as a near-field transmission system through models and formulas. . After conducting comprehensive research on the fundamental principles and associated models of WPT, it has been discerned that near-field charging holds significant importance for electric vehicles in the current stage. Furthermore, dynamic charging is anticipated to emerge as a predominant trend in the future. Nevertheless, the development and research of WPT technology is still in the early stages. Researching improved coil designs (such as multi-layer and 3D configurations, as well as dynamic alignment technologies) and exploring new materials (including superconductors and advanced ferrite materials) are potential directions for significantly enhancing the efficiency, reliability, and adoption of WPT technologies. This could make them a crucial element in future transportation systems.

References

[1] U.S. Energy Information Administration, "International energy outlook 2023," U.S. EIA, Washington, DC, 2023. [Online]. Available: https://www.eia.gov/outlooks/ieo/.

[2] M. J. Bradley and S. Associates, "Transportation energy use and emissions: Trends in 2023," ICCT Working Paper, 2023. [Online]. Available: https://theicct.org.

[3] J. P. Thomas and R. S. Schock, "Electric vehicle fast charging: A review of current technology and future directions," IEEE Transactions on Power Electronics, vol. 31, no. 2, pp. 1105-1116, Feb. 2016, doi: 10.1109/TPEL.2015.2453465.

[4] SAE International, "SAE J2954: Wireless Power Transfer for Electric Vehicles," SAE International, 2022. [Online]. Available: https://www.sae.org/standards/content/j2954_202208/.

[5] ISO/IEC, "ISO 19363: Electric Vehicles Wireless Power Transfer (WPT) – System Efficiency and Interoperability," International Organization for Standardization, 2020. [Online]. Available: https://www.iso.org/standard/77957.html.M a Kunlong. Short term distributed load forecasting method based on big data. Changsha: Hunan University, 2014.

[6] A. Khaligh and S. Dusmez, "Comprehensive Topological Analysis of Conductive and Inductive Charging Solutions for Plug-In Electric Vehicles," IEEE Transactions on Vehicular Technology, vol. 61, no. 8, pp. 3470-3484, Oct. 2012, doi: 10.1109/TVT.2012.2206294.

[7] S. Y. Choi, B. W. Gu, S. Y. Jeong, and C. T. Rim, "Advances in Wireless Power Transfer Systems for Roadway-Powered Electric Vehicles," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 3, no. 1, pp. 18-36, Mar. 2015, doi: 10.1109/JESTPE.2014.2304477.

[8] H. H. Wu, A. Gilchrist, K. D. Sealy, and D. Bronson, "A High Efficiency 5 kW Inductive Charger for EVs Using Dual Side Control," IEEE Transactions on Industrial Informatics, vol. 8, no. 3, pp. 585-595, Aug. 2012, doi: 10.1109/TII.2012.2189225.

[9] K. Lee, S. Kang, D. Lee, and Y. Cho, "A control scheme for maximum efficiency tracking in closed-loop wireless power transfer systems," IEEE Transactions on Industrial Electronics, vol. 64, no. 11, pp. 8890-8898, Nov. 2017, doi: 10.1109/TIE.2017.2711536.

[10] H. Jang, S. Lee, and G. A. Rincon-Mora, "Load-aware inductive power transmission efficiency optimization for mid-range wireless power transfer," IEEE Transactions on Power Electronics, vol. 34, no. 4, pp. 3286-3294, April 2019, doi: 10.1109/TPEL.2018.2858738.

[11] Zhang, Zhen, et al. "Wireless power transfer—An overview." IEEE transactions on industrial electronics 66.2 (2018): 1044-1058.

[12] Patil, Devendra, et al. "Wireless power transfer for vehicular applications: Overview and challenges." IEEE Transactions on Transportation Electrification 4.1 (2017): 3-37.

[13] Tian, Y., & Zhao, H. (2021). "Dynamic Wireless Power Transfer: Technical and Economic Analysis." IEEE Transactions on Power Electronics, 36(6), 6765-6778.

