



Comparison and Commercialization Prospect of Wireless Charging Technology for Electric Vehicles

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Abstract. In the context of global promotion of low-carbon travel and the rise of green energy, electric vehicles can be capable of large-scale production and application. However, the traditional charging technology for electric vehicles has numerous inconveniences. Therefore, the wireless charging technology for electric vehicles gains significant attention in society. At present, although wireless charging technology has achieved certain results in the field of electric vehicle charging, it still faces many challenges. In terms of efficiency, there are problems such as excessive energy consumption and low efficiency; in terms of cost, the equipment is highly expensive and has high maintenance costs; in terms of technological maturity, there are difficulties about lack of research on key technologies. This article will be based on Electromagnetic induction theory, we will compare the principles, efficiency, and applicable scenarios of three wireless charging technologies: Inductive Coupled Power Transfer (ICPT), Magnetic Coupling Resonant Power Transfer (MCRPT), and Capacitive Power Transmission (CPT), and summarize their advantages and disadvantages. Analyzing the aspects of them can be capable of optimizing and improving expansion. The obstacles encountered in the large-scale application of future technology and the commercialization prospects are predicted.

Keywords: Wireless Charging Technology, Electric Vehicles, Commercialization Prospect

1 Introduction

Under the background of the global advocacy for green energy travel, electric vehicles have stood out with their advantages of low energy consumption and zero emission. However, the traditional wired charging of trams has many inconveniences, such as long charging time and uneven distribution of charging piles, affecting the further wide application and popularization of trams [1]. Therefore, wireless charging technology is expected to become a new opportunity to break through the current

technical predicament and promote future development. Based on the current situation, wireless charging technology for electric vehicles has obvious advantages. Its physical structure does not require exposed conductive components, which effectively avoids the risk of leakage and enhances the safety of electric vehicle charging. Different wireless charging technologies have also further expanded the application scenarios of electric vehicles. For example, CPT technology avoids the risk of heat generation caused by metal foreign objects, enabling electric vehicles to be deployed underwater and in dust scenarios [2]; MCRPT can support embedded charging on the road, enhancing the range of electric vehicles and expanding the possibility of long-distance transportation by electric vehicles [3]. However, at present, issues such as excessively high renovation costs and patent monopolies have restricted the popularization of wireless charging technology.

Based on circuit theory knowledge, this article will deeply analyze the working principles of the three mainstream wireless charging technologies, namely inductive coupled power transfer (ICPT), magnetic coupling resonant power transfer (MCRPT), and capacitive power transmission (CPT). It will comprehensively compare their differences in efficiency, applicable scenarios, etc., and summarize their respective advantages and disadvantages. Meanwhile, it will analyze the different advantages of the three technologies in terms of security and the expansion of application scenarios, as well as the current problems that restrict their popularization, such as high transformation costs and patent monopolies. Finally, the possibility of large-scale application and commercial prospects of wireless charging technology for electric vehicles in the future will be predicted.

2 Overview of Technical Principles of Wireless Charging for Electric Vehicles

2.1 Inductive Coupled Power Transfer (ICPT)

ICPT technology is an energy transmission method based on the principle of electromagnetic induction. The core lies in achieving wireless transmission of electrical energy through the magnetic field coupling between the transmitting coil and the receiving coil. If high frequency alternating current passes through the transmitting coil, an alternating magnetic field will be generated around it. This alternating magnetic field will penetrate space and act on the receiving coil. According to Faraday's law of electromagnetic induction, a corresponding electromotive force will be induced in the receiving coil, thereby forming a current in the closed circuit and ultimately transmitting electrical energy to the load end. The principle diagram of ICPT technology is shown in Figure 1, and the system structure diagram is shown in Figure 2.

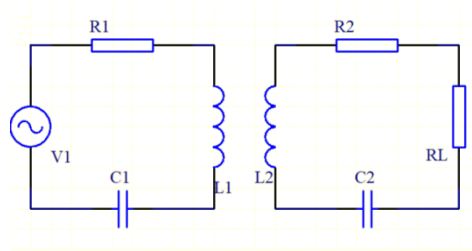


Fig. 1. Principle diagram of ICPT technology and MCRPT technology (Photo/Picture credit: Original).



Fig. 2. System structure diagram of ICPT technology (Photo/Picture credit: Original).

2.2 Magnetic coupling resonant power transfer (MCRPT)

MCRPT, like ICPT, is based on the principle of electromagnetic induction. The two essentially represent two different manifestations of the same technology. The difference lies in that when the resonant frequencies of the receiving coil and the transmitting coil are the same, the receiving coil will efficiently capture the magnetic field energy through magnetic resonance coupling and induce an electromotive force inside it, ultimately transmitting the electrical energy to the load end. The principle diagram of MCPRT technology is shown in Figure 3, and the system structure diagram is shown in Figure.

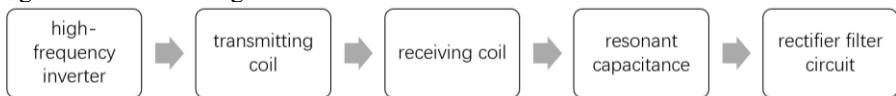


Fig. 3. System structure diagram of MCRPT technology (Photo/Picture credit: Original).

2.3 Capacitive Power Transmission (CPT)

CPT technology is based on the principle of electric field coupling. Its core lies in achieving wireless transmission of electrical energy through the electric field coupling between the transmitting plate and the receiving plate. If high-frequency alternating current passes through the transmitting plate, an alternating electric field will be generated around it. This alternating electric field will penetrate the space and act on the receiving plates. According to the principle of electric field induction, the corresponding electromotive force will be induced in the receiving plates, and eventually the electrical energy will be transmitted to the load end. The system structure diagram of the CPT system is shown in Figure 4.

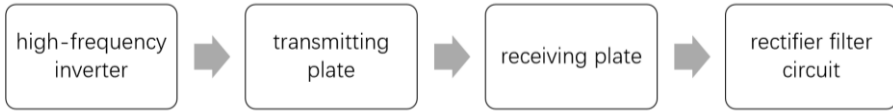


Fig. 4. System structure diagram of CPT technology (Photo/Picture credit: Original).

3 Comparison of Advantages and Disadvantages

3.1 Inductive coupled power transfer (ICPT)

Inductive coupled power transfer technology is relatively mature, with a high efficiency of over 80%, which is suitable for charging under static conditions and can quickly replenish the energy of electric vehicles parked for a long time. Although CPT can reach at a high efficiency of over 80%, its Transmission power has some lacks. And it uses high-frequency magnetic fields for energy transmission, reducing electromagnetic radiation to the human body. CPT's energy lost is mainly due to the resistance consumption. According to the energy transformation equation $\eta = P_{out}/P_{in} * 100\%$, It still has many shortcomings. It relies on coupled coils for transmission, resulting in a shorter transmission distance. Compared with MCRPT, it has weaker anti-offset ability. The stability and controllability of the system are not ideal, especially when the working frequency is inconsistent with the system's resonant frequency, the transmission efficiency of the ICPT method will drop sharply, so it has strict requirements for the charging position [4]. So, it is not suitable for dynamic wireless charging. High-frequency magnetic materials and high-precision coil manufacturing both increase its cost. Figure 5 is a Circuit composed of coil-magnetic core-aluminum plate

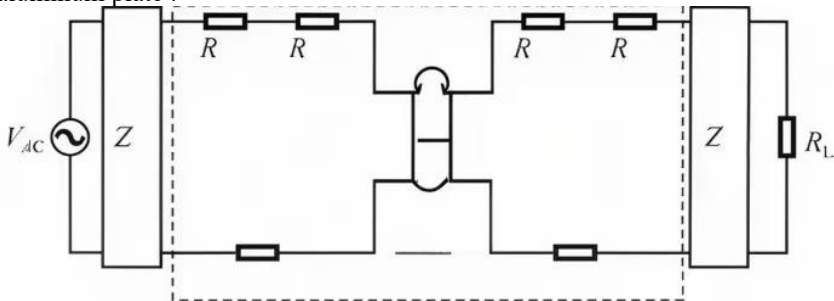


Fig. 5. Circuit composed of coil-magnetic core-aluminum plate (Photo/Picture credit: Original).

3.2 Magnetic Coupling Resonant Power Transfer (MCRPT)

MCRPT has numerous advantages that adapt to the reality environment. It's energy transmission is achieved by matching the resonant frequency of the transmitting coil with that of the receiving coil, which makes it less susceptible to distance and position deviations, has strong anti-offset capability, and is suitable for charging in dynamic

environments (such as when a vehicle is in motion). But it will consume additional energy due to its complex structure. When the current flows through resistors R_1 and R_2 , some energy is consumed. The change in load resistance has a significant impact on the system's output power and transmission efficiency. When the load resistance is small, the system's output power will increase as the load resistance increases. However, if the load resistance continues to increase, the transmission efficiency will gradually decrease, and the output power will also decrease rapidly [5].

The energy consumed by the resistor can be calculated by Joule's law and the phase difference of the circuits. However, the transmission efficiency of CPT is not affected by the load resistors. It is clear that MCRPT is not as stable as CPT in output power. Moreover, the coils L_1 and L_2 will produce eddy current loss due to the interaction of the current. Capacitance also generates a lot of energy loss, resulting in low circuit efficiency. Therefore, MCRPT's structure is more complex, and energy consumption is larger than CPT's. C_1 and C_2 in the figure can be calculated by equivalent electric circuit calculation. In a word, it is highly resistant to shifting and can adapt to more flexible life scenarios, but there are disadvantages of inefficiency and high cost. Figure 6 is the comparison of different topologies.

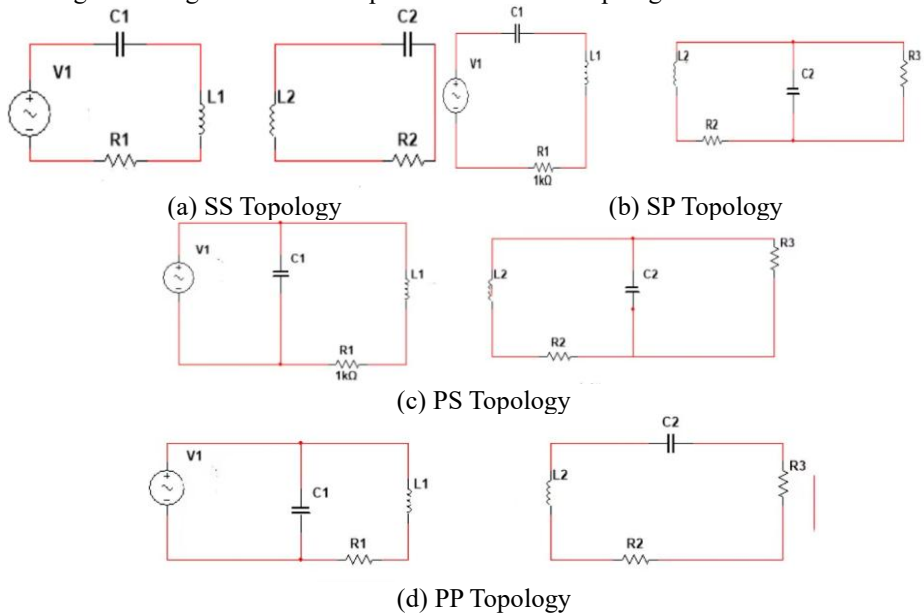


Fig. 6. Comparison of different topologies (Photo/Picture credit: Original).

3.3 Capacitive power transmission (CPT)

CPT transfers energy by the capacitance between metal plates. Thus it is adopted to various situations and environment, such as under water and dust. What's more, CPT will not be affected by any other magnetic field. It's high transmission efficiency (more than 90%) makes it have great potential. Compared with ICPT and MCRPT, the simple structure of CPT is also it's unique advantage. It mainly consists of emitter

plate, receiver plate and related receiving circuit. There is no complex core structure, which is easy to produce and manufacture. It is likely to be widely used in the future. While CPT's transmission efficiency is lower than the other two (usually less than 1kW), only be suitable for some small-scale situation. Transmission efficiency is mainly affected by the distance between the plates. According to the formula of capacitance $C = KS/D$ (k is the dielectric constant), the greater the distance between the plates, the greater the power loss, which will reduce its efficiency. Compared with ICPT and MCRPT, it's lower transformation efficiency limits its development. It is difficult to apply to high-power equipment, and its applicability is not as extensive as ICPT and MCRPT.

In summarily, the three different Wireless Charging Technology for Electric Vehicles have its own advantages and disadvantages, table 1 below.

Table 1. Comparison of the advantages and disadvantages of three wireless charging methods

Wireless charging technology	advantages	disadvantages
ICPT	Maturely technology, high efficiency (80%-92%), suitable for static charging	Short transmission distance, strict position alignment requirements
MCRPT	Strong anti-offset capability, supports dynamic charging	High cost and consumption
CPT	adapt to various environments (such as underwater and dust), no magnetic interference.	Low transformation efficiency (usually less than 1kW)

4 Challenges and Future Trends

4.1 Current challenges

For the three wireless charging types mentioned above, there are bottlenecks from the perspective of technological practicality: ICPT class charging device has the technical problem of low fault tolerance, and the coil offset fault tolerance requires less than 5cm to realize efficient charging; MCRPT class charging efficiency decreases at high speeds; CPT class charging device is limited by the charging power, BYD company, for example, has a maximum charging power of 7kw [6], and an ordinary tram needs at least 8h to reach full charge status, which is difficult to meet the mainstream fast charging demand.

Wireless charging technology for electric vehicles is facing rollout challenges, with high infrastructure costs slowing construction progress. The comparison is shown in the following table 2 [7-10].

Table 2. Differences in initial investment structure and typical costs among the four charging technologies

Technology type	Components of initial investment cost	Typical cost data (USD)
Wired charging	Cable laying, charging post hardware - Grid expansion costs Interfaces maintenance equipment	Conventional contact power supply has lower hardware costs because it does not require high-frequency circuitry
CPT	High-frequency inverters, electromagnetic emitters Power network modifications (need to accommodate non-contact coupling)	CPT requires a full-bridge inverter and a phase-shift control strategy at a lower cost than ICPT.
ICPT	Embedded coils (road/rail) Resonance Compensation Capacitor Battery Management System	Total investment in monorail system: 1,125,725 (including 3.24kWh battery)
MCRPT	High Precision Resonators (MHz Class) Broadband semiconductors (GaN/SiC) thermal management system	High-frequency resonant circuits cost 30%-50% more than ICPT (requires high-frequency capacitors and high-temperature-resistant materials)

Comparatively, it is observed that the cost of wireless charging devices is much higher than that of wired fast charging stations, and a huge capital investment is required to build a wireless charging infrastructure. On the other hand, the user side is highly sensitive to cost, and about 46% of the respondents are usually willing to pay extra for wireless charging [11]. This also makes it difficult for wireless charging to enter consumers' lives.

Wireless charging technology currently has certain safety concerns. For example, there are difficulties in the thermal management of wireless charging technology for trams. Wireless charging technology energy transmission loss is easy to cause equipment heating, there are relevant safety measures (such as radiation shielding) can reduce the risk. Trams rely on high-power wireless charging device charging, which makes the car's thermal management difficulty increase steeply.

4.2 Future trends in wireless charging for trams

Technology optimization may become the future trend of wireless charging for trams. Currently, it is possible to improve the transmission efficiency to a level close to that of wired charging by improving the magnetic coupling mechanism (e.g., optimizing

the coil design, adopting new magnetic materials), and dynamic power regulation technology (e.g., ZVS-IPT topology). Further improving the performance of wireless charging devices can further enhance the incentive for consumers to purchase and use them, thus promoting the positive cycle of the industry.

Mass production to reduce costs may become a trend in the trolley industry. The key components required for wireless charging have not been mass-produced, such as coils and capacitors, which are expensive. Mass production of related components can further reduce costs and increase the popularity of wireless charging.

The integration of intelligence and the Internet of Things (IoT) is also a potential future trend. In view of the safety risks of wireless charging of trams, the fusion of intelligence and the Internet of Things for dynamic monitoring can effectively reduce the risks. Use intelligent means to realize charging reservation, dynamic load balancing, remote monitoring and other functions. Further enhance user experience and safety.

5 Conclusion

With the global pursuit of green mobility, electric vehicle (EV) wireless charging technology, as a convenient and fast charging method, has become an important means of realizing the convenience of tram charging. This paper presents a comparative analysis of three wireless charging technologies - capacitive (CPT), inductive (ICPT) and magnetically coupled resonant (MCRPT) - each with different advantages and challenges. Each technology has different advantages and challenges: CPT adapts to complex environments, but the power is difficult to meet the requirements of wireless charging for trolley buses; ICPT is a mature technology, but it is only suitable for static wireless charging and has a short transmission distance; MCRPT adapts to dynamic wireless charging and has a strong anti-offset capability, but its efficiency is low. Although wireless charging technology has a broad market prospect, but high cost, technical bottlenecks and other issues remain to be solved. In the future, the development of wireless charging technology for trams may focus on improving charging efficiency and reducing the cost of the device and other aspects. With the policy support and the concept of green travel continues to be promoted, wireless charging technology may reach a popularization degree, promoting the development of tram industry technology.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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