

Systematic analysis of wireless energy transmission methods

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Abstract. Wireless energy transfer technology is a new type of power transmission technology that utilizes electric and magnetic fields as mediums. In contemporary society, there are three main methods of wireless energy transfer: magnetic coupling resonance, microwave radiation, and electromagnetic induction. Each of these methods has its unique advantages and limitations, leading to different application scenarios in practical life. This article provides a detailed introduction to the basic structure and principles of magnetic coupling resonance, microwave radiation, and electromagnetic induction wireless energy transfer. Through comparative analysis of the characteristics of these three transmission methods, it explores their specific applications in various industries and life domains. Additionally, the article examines the challenges faced by today's wireless energy transfer technology, such as transmission efficiency, safety, cost, standardization, and technical difficulties. Finally, the article envisions the future development of wireless energy transfer technology, suggesting that as the technology continues to progress and improve, it will see broader application, bringing more convenience to people's lives and promoting integration with other fields to form more efficient and sustainable solutions.

Keywords: Wireless energy transmission; magnetic coupling resonance; microwave radiation; electromagnetic induction; application.

1. Introduction

The origins of wireless power transmission (WPT) technology may be traced back to the late 19th century, when Nikola Tesla introduced the concept of transmitting power wirelessly, making a substantial impact on the field of engineering. Due to advancements in science and technology, wireless energy transfer has transitioned from being a theoretical concept to being implemented in real applications. In recent years, there has been significant progress in the advancement of wireless energy transmission. Various organizations and companies, including Wildcharge, Powercast, SplashPower, and researchers at the University of Tokyo, have successfully developed non-contact chargers. These advancements have effectively showcased the adaptability and usefulness of wireless energy transmission technology. In 2007, MIT achieved the successful illumination of a 60W light bulb utilizing electromagnetic resonance technology known as WiTricity. This breakthrough has significantly propelled the advancement of wireless energy transfer technology [1].

Furthermore, the advancement of wireless energy transmission technology is propelled by space technology, environmental conservation, and the escalating energy requirements. Given humanity's advancements in space technology and growing emphasis on environmental preservation and energy efficiency, wireless energy transmission technology has emerged as a promising solution to overcome the drawbacks associated with conventional cable-based transmission methods. These drawbacks include cable aging, expensive maintenance, and wiring complexities. Wireless energy transmission technology is particularly valued in the field of space technology for its ability to efficiently distribute electricity. It has a broad range of uses, particularly in sectors such as solar power plants and electric vehicle charging.

This study will discuss many ways of radio energy transfer, including magnetic coupling resonance, microwave radiation, and electromagnetic induction. Through an examination of the structure, principle, and transmission efficiency of various methods, the distinctive features of each of the three methods are determined. By comparing and analyzing these features, the methods may be effectively applied in diverse contexts.

2. Analysis and comparison of the basic principles of wireless transmission

2.1. Fundamentals of magnetically coupled resonant wireless energy transmission

2.1.1 Basic structural analysis

The system is composed of a transmitting side, a resonant coil, a receiving side, and external auxiliary circuits. The transmitting side comprises a high-frequency power supply and an inverter circuit, whereas the resonant coil is composed of a transmitting coil, a receiving coil, and a resonant circuit. On the contrary, the receiving side comprises a rectifier circuit to convert AC to DC, a DC/DC circuit for regulating voltage and current, and a load. The transmitting component of the MCR-WPT system comprises a high-frequency power supply and an inverter circuit [2]. The inverter circuit converts the incoming DC signal into a high-frequency AC signal in order to power the resonant coil [2]. Figure 1 shows the basic structure.

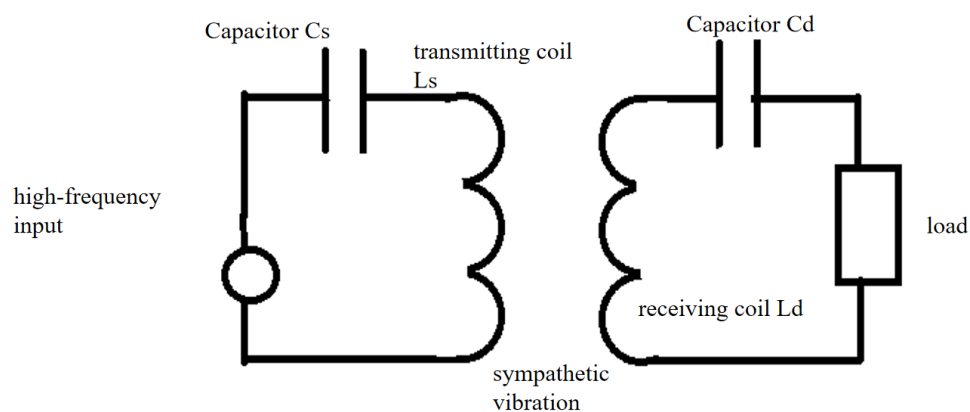


Figure 1 Basic structure of magnetically coupled resonant wireless energy transmission

2.1.2 Fundamental principle

Wireless energy transmission through magnetic fields involves two methods: electromagnetic induction and magnetic coupled resonance. Both technologies employ electromagnetic phenomena to facilitate the wireless transfer of energy. Magnetic coupling resonant wireless power transmission is a particular example of wireless energy transmission that belongs to the magnetic field coupling category. Electromagnetic induction is a distinctive form of wireless energy transfer that involves two transceiver coils in the system, both operating at the same inherent frequency. Unlike electromagnetic induction, the key characteristic of this system is that its two transceiver coils have the same inherent frequencies. Resonance occurs when the frequency of the driving signal aligns with the frequency of the coils, resulting in a connection between the two transceiver coils. Resonance occurs when the frequency of the drive signal aligns with the natural frequency of the coil. This causes the two transceiver coils to vibrate in harmony, leading to the lowest resistance in the resonant coupling circuit. Resonant coupling enables the efficient transmission of energy from the transmitting end to the load, ensuring maximal energy transfer. The impedance of the resonant coupling loop is minimized, facilitating efficient transmission of the transmitter's energy to the load through the resonant coupling [3].

The system's energy conversion process entails the transformation of electric field energy into magnetic field energy, followed by its reconversion back into electric field energy. This is accomplished by producing a high-frequency input signal using a high-frequency power source. The resonant capacitor transforms the electromagnetic energy derived from the transmitting coil by utilising the medium and high-frequency magnetic field. The transceiver coils thereafter resonate, ultimately leading to the resonance circuit of the receiving coil. Transmission of data or signals between two or more locations.

The underlying principle of the system is as follows: The high-frequency power supply produces an input signal characterised by a high frequency. Resonance occurs when the frequency of the input signal matches the inherent frequency of the resonator, which is composed of the transmitting coil LS and the capacitor CS. Consequently, the power supplied by the power source is transformed into energy in the form of magnetic and electric fields in the resonant transmission circuit. The energy is subsequently stored in the inductance and capacitance of the coil. Both the coil inductor LS and the compensating capacitor CS store energy, and this energy undergoes repeated oscillations at a frequency that is twice the operational frequency. Presently, when a receiving resonator Ld Cd, which has the same inherent frequency, is placed in the magnetic field close to the emitter LS CS, the transceiver coil generates an inductive current of the identical frequency in the receiving coil by mutual inductive coupling. This is comparable to the receiving resonator being stimulated by an applied excitation source with the same inherent frequency, thereby enabling the transfer of the magnetic field and electric field in the surrounding space. Oscillation is the repeating motion or fluctuation of an object or system, characterised by a back-and-forth movement. There are three energy transfers in the power transmission system: the exchange of magnetic field energy between the two resonant coil circuits, the exchange of magnetic field energy with the electric field in the resonant coil circuit at the transmitting end, and the exchange of magnetic field energy with the electric field in the resonant coil circuit at the receiving end. In summary, magnetic coupling and resonance are the fundamental prerequisites for accomplishing magnetically connected resonant wireless energy transmission [3].

2.1.3 Transmission efficiency analysis

The MCR-WPT system primarily consists of transmitter and receiver circuits. The transmitter, connected to the power supply, is comprised of a voltage regulator and filter module, a high-frequency inverter module, a resonance compensation network, and a transmitter coil. On the other hand, the receiver of the MCR-WPT system supplies power to the load and is made up of a receiver coil, a resonance compensation network, and a power regulation module. Currently, the MCR-WPT system without relays may be categorized into four fundamental topologies: series-parallel, series-parallel, parallel-parallel, and series-parallel, based on the transmitter and receiver's series-parallel resonance compensation [4].

For the series-series structure and the series-parallel structure, in order to achieve maximum efficiency, it is necessary to ensure that the system is in a resonant state. This criterion applies to the four basic topologies. Nevertheless, the parallel-serial and parallel-parallel topologies do not achieve maximal efficiency at the resonance point [4]. At resonance, the system achieves maximum transmission efficiency when there is a load present. However, the optimal transmission efficiency varies at different distances [5]. The transmission efficiency of the MCR-WPT system with a series-string structure is affected by the coil spacing. When the spacing between two coils exceeds a certain distance, the system's transmission efficiency decreases significantly. On the other hand, the transmission efficiency of the other three topologies decreases at a faster rate as the coil spacing increases [5].

Upon analyzing and comparing the factors that affect efficiency in the four basic topologies, it is evident that the series-string structure achieves the highest transmission efficiency when the system parameters are fixed and the system resonates. Furthermore, the analysis reveals that the optimal efficiency of the series-string structure consistently occurs at the intrinsic resonance frequency point. Therefore, it is only necessary to track the resonance frequency point in order to attain the optimum efficiency of the system [5].

2.2. Microwave radiated wireless energy transmission

2.2.1 Basic structural analysis

The microwave radiated wireless power transfer (WPT) system primarily consists of three primary components: the microwave power source, the transmitting antenna, and the rectifying antenna. The

microwave power source consists of a DC power supply and a DC-RF converter. The rectifier antenna comprises a receiving antenna, a low-pass filter, a rectifier diode, and a DC filter. The transmitting antenna is categorized into a phased array antenna and a directional antenna array with directional control methods. Typically, a parabolic antenna structure is employed to achieve its high focussing capability. The microwave radiating wireless power transfer (WPT) operates by converting direct current (DC) into microwave energy using a microwave power generator. This microwave energy is then efficiently emitted to the rectifier antenna after being focused by the transmitting antenna. Through free space propagation, the microwave energy reaches the rectifier antenna and is converted into DC power by the rectifier antenna's rectifier filter circuit. This DC power is then used to supply power to the load [6]. Figure 2 shows the basic structure.

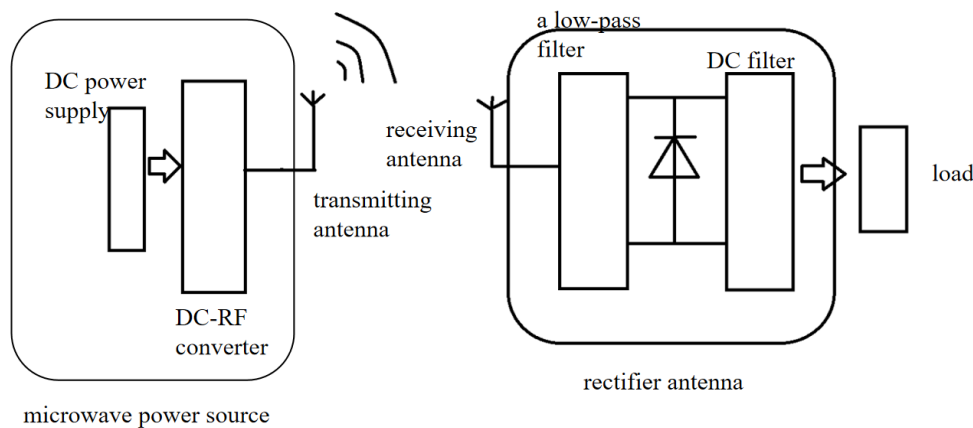


Figure 2 Basic structure of microwave radiated wireless energy transmission

2.2.2 Fundamental principle

The microwave radiating wireless power transfer (WPT) operates by converting direct current (DC) into microwave energy using a power generator. This microwave energy is then concentrated by a transmitting antenna and transmitted to a rectifying antenna with high efficiency. The microwave energy travels through free space to reach the rectifying antenna, it is transformed into direct current (DC) electricity using a rectifying filtering circuit. This DC power is then used to supply power to the load [6].

2.2.3 Transmission efficiency analysis

Efficiency is a vital consideration when quantitatively analyzing microwave radiative wireless power transfer systems. Equation (3) demonstrates the overall transmission efficiency of a WPT system that utilizes microwave radiation [6].

$$\eta_g \eta_t \eta_s \eta_r \eta_d = \eta \tag{1}$$

The variables η_g , η_t , η_s , η_r , and η_d represent the turning productivity of the DC-RF converter, the transmission effectiveness of the microwave transmitting antenna, the transmission efficiency of the microwave from the transmitting end to the receiving end in free space, the reception efficiency of the microwave receiving antenna, and the rectification conversion efficiency of the rectifier circuit, respectively [6]. The efficiency η_t and η_r of the microwave transmitting/receiving antenna in Eq. (3) depend on the best shape of the antenna, particularly the distribution of the aperture field. Furthermore, it is important to mention that the transmission efficiency of microwaves in unobstructed space can achieve a maximum of 100%. The conversion efficiency η_g and η_d mostly depend on the efficacy of the DC-RF converter and rectifier circuits [6].

The design of microwave transmitter/receiver antennas can be determined using the Friis transmission formula. Initially, compute the output power of the microwave power source. Next,

calculate the gain of the transmitting/receiving antenna by considering the microwave wavelength, transmission distance, and receiving power. This will enable us to obtain the utmost receiving capability [6].

$$P = \left(\frac{\lambda}{4\pi d} \right)^2 G_r G_t P_t = \frac{A_t A_r}{\lambda^2 d^2} P_t \quad (2)$$

Where P_t represents the power of the transmitting antenna. The gains of the transmitting and receiving antennas are denoted as G_t and G_r , respectively. The effective areas of the transmitting and receiving antennas are denoted by A_t and A_r , respectively. The transmission distance is represented by d , while the working wavelength is symbolized by λ [6].

2.3. Electromagnetic induction wireless energy

2.3.1 Basic structural analysis

Figure 3 depicts the schematic diagram of a typical magnetic inductively coupled wireless energy transfer system. The entire system primarily comprises a transmitting circuit on the primary side and a receiving circuit on the secondary side. The primary circuit comprises three main components: the high-frequency inverter, the resonant network, and the transmitting coil. On the other hand, the secondary circuit consists of the receiving coil, the resonant network, and the rectifier circuit. In contrast to traditional transformers, the primary and secondary coils are linked by means of a substantial air gap. In this scenario, the system's power is transmitted without the need of wires. However, both the primary and secondary coils have a significant amount of leakage inductance. To address this issue, a compensation network must be added to the circuit in order to offset the reactive power [7].

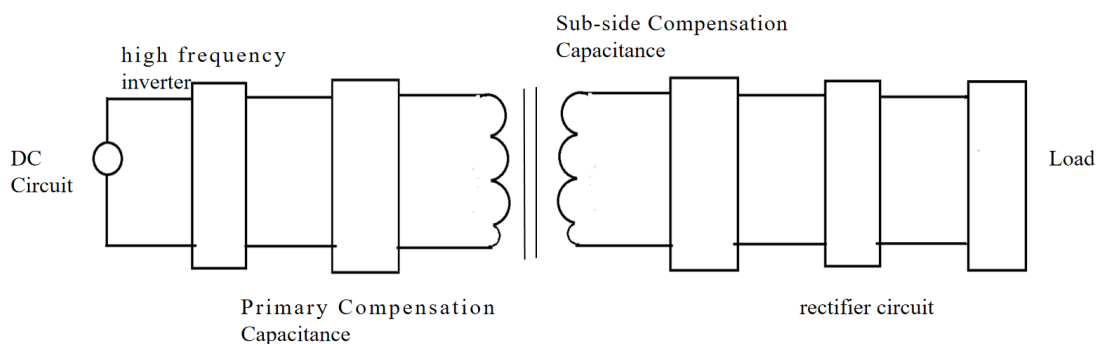


Figure 3 Basic structure of electromagnetic induction wireless energy transmission

Practically, the quantity of secondary coils can be decided based on the desired number of energy sections received. Consequently, the system can be categorized as either single-loaded or multi-loaded, depending on number of loads [7].

2.3.2 Fundamental principle

The successful implementation of a magnetic induction wireless power transfer (WPT) system depends on the careful design of the coupler and the utilization of power electronics. The coupler's design necessitates a sufficient coupling coefficient, denoted as k , and a high-quality factor, represented as Q . The utilization of power electronics primarily relies on inverter circuits, inverters, and power electronics 错误!未找到引用源。 [7]. The primary use of power electronics is in the utilization of inverter circuits, rectifier circuits, and DC/DC circuits such as Buck/Boost circuits [8]. The primary utilization of power electronics technology is around the implementation of DC/DC circuits, including inverting circuits, rectifier circuits, and Buck/Boost circuits. These circuits are combined with related driving circuits and control algorithms to accomplish various forms of output control [8].

The magnetic induction wireless power transfer (WPT) system operates by rectifying and inverting the transmitter's signal to generate a higher frequency current. This current is then used to induce voltage on the receiving side through electromagnetic induction using a coupler. The induced voltage on the receiving side is subsequently rectified and regulated to provide energy to the load. The analysis of the magnetic induction wireless power transfer (WPT) system typically involves the application of circuit theory. The equivalent circuit model is established by creating a mutual inductance coupled circuit model and employing the sinusoidal AC analysis method [8].

2.3.3 Transmission efficiency analysis

To achieve high transmission efficiency and power in the magnetic induction WPT system at the same transmission distance, and to enhance the power factor of the system, it is common practice to perform resonance compensation at both the transmitter and receiver ends of the system. There are four fundamental types of compensation circuits based on how the compensation capacitors are connected at the transmitting and receiving ends: SS, SP, PS, and PP (S in series and P in parallel). Nevertheless, the traditional methods of compensation have certain constraints, as the resonant frequency of the SP, PS, and PP systems is influenced by the load and the coupling coefficient. Consequently, the SS type is commonly employed for applications that involve variable load and coupling coefficient. However, the SS-type architecture is plagued by the issue of rigidity when it comes to configuring system settings. Thus, we suggest the topologies of LCL, LCC, and their combination [8].

2.4. Comparison of wireless energy transmission methods

In summary, each of the three methods of wireless energy transmission has its own differences, as well as different environments of use. This is shown in the table 1 below.

Table 1. Characteristics of the three types of wireless energy transmission

Method	Specificities
Resonant wireless energy transfer by magnetic coupling	High transmission power and efficiency for a wide range of applications, especially in applications requiring efficient energy transfer
microwave radiated wireless energy transmission	Suitable for specific application scenarios, e.g. energy transfer via ultrasound, possible applications in medical, industrial inspection, etc.
Electromagnetic induction wireless energy	Capable of transmitting over long distances, but requires precise alignment for specific high-power long-distance transmission applications, such as solar power satellites

3. Applications of wireless energy transmission

3.1. Unmanned aerial vehicle

When compared to traditional wired power supply technology, autonomous charging of UAVs through wireless energy transmission technology offers several unique advantages. These include electrical isolation safety, convenient non-contact charging, and excellent adaptability to harsh environments. As a result, UAVs can achieve a more efficient and safer flight experience [9].

Wireless power transmission (WPT) is a non-contact technique of transmitting electricity that eliminates the need for electric lines. It offers greater flexibility, safety, and dependability, allowing for the wireless transmission of electric energy within a specific range. Implementing Wireless Power Transfer (WPT) technology in manned aircraft reduces the need for wired charging interfaces, hence enhancing the autonomy of unmanned aerial vehicles (UAVs) and expanding their operational range and flexibility [9].

3.2. Metro

In 2015, the Korea Railway Research Institute (KRRI) achieved the development of a wireless charging system for rail trains. The transmitter track, measuring 128 m in length, is capable of transmitting 1 MW of power with an efficiency of 82.7%. The Japan Railway Technology Research Institute has developed a non-contact power supply system for rail vehicles. The coil structure utilises an octagonal coil, which efficiently minimizes the eddy current loss on the track and ensures consistent power transmission for the train while it is in motion. The year is 2021. On January 7th, Professor He Zhengyou's team from Southwest Jiaotong University achieved a significant breakthrough by successfully researching and developing a novel wireless power supply system for urban rail vehicles. This system is based on magnetic field coupling and was successfully implemented in the Tangshan plant of China Railway. This marks the first instance of transitioning from a 'wired' to a 'wireless' power supply system for urban rail vehicles in the country. A groundbreaking advancement has been made in the transition from wired to wireless power delivery. The wireless charging system used for urban rail vehicles has a transmission power of 500 kW and a transmission efficiency of over 90% when the space between the charging system and the car is 15 cm [10].

3.3. Smart home

Wireless energy transmission technology plays a crucial role in the smart home industry, enabling the intelligentization of products. It revolutionizes the conventional method of using electricity by eliminating the need for plugging and unplugging wires. This technology enhances the spatial environment and user experience by primarily utilizing static inductive coupling to achieve wireless charging [11].

Haier Group, a frontrunner in the advancement of wireless energy transmission technology in the smart home sector at a moderate power level, has consistently introduced numerous industrialised products in recent years. For instance, in 2010, the world witnessed the introduction of the first television without a tail. In 2012, kitchen equipment without tails were also introduced. Then, in 2016, the WeiXi tailless smart toilet seat, which can be wirelessly charged and operated by a mobile phone application, was unveiled. In March 2019, the Wireless Power Consortium announced its development of a new wireless power standard called Qi specifically designed for kitchen appliances. This advancement in wireless power transmission has significant potential for enhancing smart homes. Furthermore, scientists are currently developing technologies to provide wireless power to household gadgets simultaneously, including wireless mice, mobile phones, laptops, lamps, and humidifiers. This is achieved through the utilization of microwave wireless power. Furthermore, scientists are currently developing technologies that utilize microwave radio power to wirelessly energise many household appliances, including wireless mice, mobile phones, laptops, lamps, and humidifiers [11].

3.4. Wireless charging of AUVs from submarine base stations or mother ships

To address the issue of charging Autonomous Underwater Vehicles (AUVs) in underwater environments, researchers have explored the implementation of wireless energy transfer technology. This approach aims to enhance the charging system's dependability and safety [12].

In 2001, Bradley and Feezor pioneered a system for recharging Autonomous Underwater Vehicles (AUVs) using an undersea observation network. This system was capable of delivering 200W of power to AUVs located 2,000m below the surface of the ocean, with a gearbox efficiency of 79%. In 2004, Tohoku University and NEC Corporation enhanced the design of a loosely-coupled transformer by utilizing a uniquely shaped ferrite core and conical coils. This modification led to the development of a system capable of delivering 500W of power to Autonomous Underwater Vehicles (AUVs). In 2004, Tohoku University and NEC enhanced the loose-coupled transformer by utilising a uniquely shaped ferrite core and tapered coils. This optimisation resulted in an underwater wireless charging system that successfully transmitted 500W of power to the AUV, achieving a transfer efficiency of 90% [12].

4. Conclusion

Due to the advancement of time and the growth of scientific and technological advancements, the study and utilization of WPT technology is expanding significantly. WPT technology holds immense potential for future development. This study initially outlines the fundamental framework, underlying concept, and transmission efficiency of three types of Wireless Power Transfer (WPT) technology. Subsequently, it evaluates and compares the distinctive features of these three WPT technologies. Subsequently, it examines and contrasts the attributes of the three wireless power transfer (WPT) technologies, provides instances of the utilization of these technologies in daily life, and ultimately deliberates on the future prospects of WPT technology. The summary and analysis of this study are expected to offer valuable guidance for the research and implementation of WPT technology. There are also some challenges for wireless power transmission technologies such as Transmission efficiency issues, security, cost issues, standardization issues and technical issues.

The development of wireless energy transmission technology is promising and is expected to be more widely used in the future. The continuous improvement and popularization of wireless charging technology will bring more convenience and comfort to people's lives. At the same time, technological advances will also promote the combination of wireless energy transmission technology with other fields to form a more efficient and sustainable solution. We are looking forward to the future of wireless energy transmission technology.

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