Unveiling The Magic of Wireless Energy Transfer: Technologies and Applications

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Abstract. Wireless energy transfer technology, often heralded as the harbinger of future advancements, revolutionizes the landscape of electricity transmission by offering unparalleled flexibility, convenience, and safety. It eliminates the cumbersome need for frequent physical connections, promising a paradigm shift in energy distribution. This paper delves into the evolutionary trajectory of wireless energy transmission, elucidating various methodologies such as magnetic fields, electric fields, microwaves, lasers, and ultrasound. By harnessing electromagnetic waves and microwaves, these technologies facilitate the seamless transmission of power, akin to a wireless network, thereby transcending conventional wired setups. The discussion extends to the current applications and potential future avenues of wireless energy transmission, highlighting its pivotal role in diverse sectors including electronics, automotive, medical, aerospace, and beyond. However, amidst its promising prospects, the technology also confronts multifaceted challenges encompassing transmission efficiency, distance limitations, cost considerations, and safety concerns. As research endeavors continue to unfold, the trajectory of wireless energy transmission is anticipated to evolve towards greater efficiency, extended transmission ranges, and heightened applicability, ushering in a new era of energy distribution and utilization.

Keywords: Wireless Energy Transmission; Magnetic Fields; Electric Fields; Microwaves; Lasers; Ultrasound.

1. Introduction

As scientific progress unfolds, and myriad wireless devices become commonplace, wireless energy transmission technology has garnered increasing interest [1-3]. Wireless energy transmission technology is very cool, allowing electricity to transmit from power sources to electrical appliances without the need for physical wiring. This technology utilizes electromagnetic waves and microwaves to transfer energy, much like a wireless network, except that it transfers power instead of data. Because it does not require physical connections, it is safer to use, eliminates the need for cumbersome wires, and offers greater ease and efficiency [4]. Consequently, it holds vast potential for application in various fields such as electronic devices, electric vehicles, and aerospace. Since the time of Tesla, often regarded as the father of alternating current, human research on wireless energy transmission has persisted. Researchers have faced numerous challenges and difficulties but have continuously propelled significant progress in related technologies.

2. Several Modes of Wireless Energy Transmission

Wireless energy transfer technology is akin to a superpower that enables electricity to travel from one location to another without the need for wires. The concept originated with Nikola Tesla in the distant past, and since then, it has persisted, evolving into a formidable force over time. Today, this technology encompasses several main types: magnetic field coupling, electric field coupling, microwaves, lasers, and ultrasound. Each of these types of functions like a different kind of magic, capable of transmitting energy over varying distances and requiring different types of electrical mechanisms [5].

2.1. Magnetic field coupling type

The integration of magnetic fields in wireless power transmission is truly fascinating; it resembles an intangible energy thread that can effectively harness electricity from one location to another, eliminating the need for any physical connections. This technology is akin to having a superhero whose superpower is to transmit electricity without direct contact. Magnetic fields can transmit electricity over long distances, as if they possess a super long energy rope stretching from one point to another. Another remarkable aspect of magnetic fields is their versatility; they can operate in various environments, whether sunny or rainy, ensuring stable energy transmission. Consequently, magnetic fields find application in numerous exciting endeavors, such as powering electric cars without the need for physical plugs and enabling drones to inspect power lines safely over extended distances.

Over the years, magnetic fields have become increasingly potent; they initially could only transmit short distances and small amounts of power, akin to pushing small rocks [6]. However, they have evolved to transmit medium distances and power, comparable to hurling large rocks over significant distances. This advancement means that magnetic fields can transmit more energy over greater distances, meeting many of the requirements for wireless energy transmission. Nonetheless, magnetic fields have their limitations; they are more reliant on their surroundings and space, requiring assistance to transmit energy if clutter obstructs their path. Additionally, their ability to penetrate walls could be improved, as dense obstacles might impede transmission [7]. Therefore, scientists must continue to enhance magnetic field technology to enable energy transmission in a broader range of scenarios. Achieving ubiquitous energy transmission via magnetic fields would significantly enhance convenience and uniqueness in our lives.

Concerning the enhancement of coil couplers, the novel structure initially facilitates the optimization of magnetic circuit layouts, minimizing energy conversion losses and enhancing coupling coefficients and transmission effectiveness. Secondly, the material composition of couplers can undergo optimization; for instance, the exchange loss of superconducting material coils is significantly lower than that of traditional coils, and employing electromagnetic material coils notably enhances the efficiency of wireless power transmission systems. Notably, these coils possess superior focusing abilities, contributing to increased coupling coefficients among resonant coils, thus optimizing energy conversion efficacy and extending transmission ranges.

Regarding the optimization of foreign body detection technology, a method based on fifth-order harmonic current monitoring was proposed in 2022, enabling accurate detection of metal foreign bodies even with significant coil shifts. However, further improvements are necessary to enhance detection accuracy in diverse application scenarios. Combining relevant design and control elements can create a comprehensive, intelligent foreign body detection and management system.

2.2. Electric Field Coupling Type

In 1962, Paul, an American electrical engineer, devoted himself to underwater communication and proposed an electric field-coupled wireless energy transmission scheme [8]. Subsequently, researchers began to explore and experiment with it.

The electrostatic field interaction method employs the influence of electric fields for the wireless transfer of electrical energy. Its fundamental concept entails installing electrodes at both the transmitting and receiving ends, facilitating energy conveyance via capacitive coupling between metallic plates [9]. Electric field-coupled wireless energy transmission can transmit over metal obstacles, with the characteristics of low electromagnetic interference and high security [10,11]. This has led to the development of electric field coupling modes in ultra-short-distance transmission applications, especially in household equipment, mobile phone charging, and other consumer electronics. However, some limitations and challenges exist in electric field-coupled wireless energy transmission, which transmits relatively little power and may require assistance with the charging requirements of some high-power devices [12].

While exploring enhancing capacitive coupling efficiency, researchers introduced a mutual coupling model pertaining to a multipoint coupling system. They have also developed a decoupling circuit that employs shared inductance along with a complementary compensation network. Nevertheless, there remains a necessity for continued investigation and refinement of capacitive coupling methodologies and associated loss models.

Regarding security enhancement, the system's coupling electrode is encapsulated with insulation and protective covering to avert electrical shocks. A novel equivalent circuit model is introduced for solitary capacitive wireless power transmission, utilizing resonant coils in a distributed configuration. This strategy aims to innovate and propel the progression of wireless power transmission technology that harnesses electric fields.

2.3. Microwave

Wireless energy conveyance through microwave technology constitutes a method of transmitting electrical power utilizing microwave frequencies [13]. In the context of electrical energy transmission utilizing microwaves, the process involves transforming electrical energy into microwave radiation at the transmitter, which is then emitted via an antenna. On the receiving end, the antenna captures this microwave energy and subsequently translates it back into electrical energy. Microwave radio energy transmission distance, high efficiency, good stability, etc., for remote mountainous areas, sparsely populated, dispersed residences, lack of conventional energy sources, can be effectively solved by microwave power transmission technology in the blind area of the power grid, making the occasion of long-distance transmission widely used [14,15]. However, the transmitting antenna requires high directionality, which also restricts its promotion and application in practical applications.

The quest to enhance high-power microwave sources' performance involves the progressive integration of third-generation comprehensive bandgap semiconductor technologies. These advancements promise substantial improvements in power output, operational efficiency, and the quality of microwave beams generated by solid-state devices, thereby unlocking untapped developmental prospects.

In terms of optimizing the highly directional transmitting antenna, to improve the uniform distribution of microwaves in the target area, in addition to beam focusing, it is also necessary to have the function of flat-top beamforming.

2.4. Laser

NASA first proposed laser-based wireless energy transmission to achieve the solar satellite plan. However, due to the low efficiency of lasers and photovoltaic batteries, the development of this technology progressed slowly, and it wasn't easily applicable in practice until the end of the 20th century and the beginning of the 21st century. With the development of high-power lasers and high-efficiency photovoltaic cell technology, laser wireless energy transmission technology has once again garnered attention.

Laser-guided electrical energy transmission is a mode of wireless energy transmission using lasers for guidance [16,17]. In laser-guided electrical energy transmission, the transmitting end converts electrical energy into laser light and transfers the energy to the receiving end through the guidance of the light beam. This method of transmission is akin to using FTL magic to send energy super far and super-fast. However, we still need to find a better way to make the laser more focused, turning it into a super-powerful energy beam. Additionally, we must make the conversion between the laser and electricity more efficient to avoid energy waste. Moreover, controlling the temperature of the laser is crucial to prevent overheating, which could pose safety concerns. Therefore, scientists must continue working to improve these technologies for better efficiency and safety [18-20].

In optimizing photovoltaic reception technology, it is necessary to consider the selection of photovoltaic materials, improving light energy utilization, understanding the temperature characteristics of the device, implementing receiving tracking technology, and incorporating anti-interference measures.

When optimizing the energy management system, it must be designed to accommodate the expanding power demand. An energy management system is essential for optimal laser energy reception, ensuring that the energy received by the laser wireless energy transmission system is detected, managed, and controlled to achieve efficient and stable energy output.

2.5. Ultrasonic

Ultrasonic wireless energy transmission is a technology that uses ultrasound as a carrier to transmit energy [21]. This technique has garnered attention due to its advantages, including low attenuation, high spatial resolution, and safety in specific application scenarios, particularly in medical implants, microelectronic devices, and wireless charging, which have extensive applications [22,23].

Ultrasonic wireless energy transfer technology offers advantages that traditional electromagnetic coupling technology does not have, but as scientists conduct further research and technology upgrades, it may become commercially available in several areas. However, to achieve widespread application, there is still a need to address challenges such as energy transfer efficiency, device compatibility, and cost-effectiveness.

Regarding optimizing the energy transfer mechanism, finite element analysis is an effective method to study the characteristics of ultrasonic transducers and the transmission performance of the system. Combining other methods to establish a more complete analysis model can lay a practical foundation for developing and applying ultrasonic wireless energy transfer technology. Concerning optimizing acoustic wave transmission technology, studying the gradient matching layer scheme in depth can smooth the acoustic impedance transition between the transducer and the transmission medium, increasing the transmittance of acoustic wave radiation and improving overall system efficiency. Regarding optimizing phased focusing technology, utilizing phased focusing technology can improve the system's receiving efficiency and enable control over the transmission direction.

3. Prospect of Wireless Energy Transmission Technology Application

3.1. Electric Vehicles

Adopting wireless charging technology provides a new solution to electric vehicle charging [24,25]. By parking the electric vehicle near the wireless charging equipment, it can be charged automatically, greatly simplifying the charging process and improving convenience. Simultaneously, it addresses safety concerns associated with wired charging, avoiding potential hazards such as electric shock and fire caused by cable aging and breakage. Through optimizing the power and efficiency of the wireless charging equipment, intelligent management can achieve automatic adjustment of the charging power according to the vehicle's power demand. Users can monitor the charging status and control the process through mobile phone apps, in-vehicle systems, etc., ensuring highly efficient and stable charging [26].

However, this technology also faces challenges in practical applications [27,28]. Wireless energy transmission is typically less efficient than wired transmission, resulting in greater energy loss, especially over longer distances. Infrastructure development requires the construction of specific roads or charging stations to realize dynamic wireless charging, necessitating significant investment and urban planning. Cost issues arise as wireless energy transmission systems are expensive to build and maintain, particularly on a large scale. Concerning electromagnetic compatibility and safety, wireless energy transmission systems may generate electromagnetic interference, affecting the normal operation of surrounding electronic equipment.

Future wireless charging for electric vehicles aims to improve transmission efficiency by optimizing coil design, using more efficient materials, and enhancing coupling techniques and control strategies [29,30]. Infrastructure compatibility and standardization efforts involve developing uniform technical and safety standards to ensure compatibility with existing transport infrastructure. Cost reduction initiatives focus on lowering system costs through large-scale production and technological innovation to make it more economical. To enhance system stability and safety, advanced monitoring and control technologies should be developed to ensure stable operation under various conditions and reduce electromagnetic interference.

3.2. Mobile Devices

Wireless energy transmission technology provides convenience for charging mobile devices such as mobile phones, tablet PCs, and laptops. Users do not need to plug in or unplug the charger but simply place the device on a charging mat or charging station to charge it. This approach avoids the constraints of traditional wired charging, simplifies the charging process, improves charging convenience, and makes charging these devices more diverse and flexible.

However, it still faces some challenges and limitations. For example, efficiency can be affected by distance and obstacles, leading to slower or incomplete charging. Additionally, the cost of wireless charging devices is relatively high, which limits their application in some fields [31].

In the future, research will focus on developing more efficient and stable transmission methods to increase transmission distance, thereby enhancing the efficiency and stability of power transmission. Consideration also needs to be given to the compatibility and expandability of the system so that new equipment or functions can be easily added.

3.3. Drones

In order to solve the problem of drones, radio transmission technology allows drones to charge during flight, thereby extending the flight time and operating scope. However, there are some drawbacks to this technology in practical applications. In terms of system resistance to offset, the charging efficiency of existing wireless charging systems decreases dramatically when the UAV moves, or its position is offset. Wireless charging is usually less efficient than wired charging due to technological limitations, resulting in energy loss during transmission, especially over long distances [32].

In the future, to enhance offset resistance, new technologies and algorithms will be researched and developed to improve the system's tolerance to changes in the UAV's position. This is to ensure that high charging efficiency can be maintained under different flight conditions. In terms of system complexity, the system design tends to become more intricate and requires more sophisticated control strategies and regulation mechanisms [33].

3.4. Medical Field

Wireless power technology can be applied to implantable medical devices (e.g., pacemakers) to provide continuous power supply, effectively avoiding the need to replace batteries, reducing patients' medical costs, mitigating risks, and improving quality of life. It can also enable remote monitoring and diagnosis of equipment, addressing the timeliness and regional limitations of medical services, and providing convenience for remote areas or locations with scarce medical resources.

However, there are challenges such as attenuation and dissipation in transmission efficiency, energy loss, and potential risks posed by electromagnetic radiation and heat generated during the transmission process, which hinder the improvement of wireless power technology in the medical field.

Currently, this application is primarily used in specific medical equipment, and its scope is expected to expand in the future to include prostheses, hearing aids, etc., providing power supply during surgeries to further enhance the efficiency and quality of medical services.

3.5. Aviation

Regarding aviation radio navigation systems, wireless power technology provides accurate target orientation, position, and other information, helping aircraft achieve automatic driving and safe landing, thus effectively improving the safety and accuracy of flights. In terms of aeronautical radio communication systems, internal dispatching and command, and ground-air liaison can be realized, ensuring unimpeded information exchange between aircraft and the ground and enhancing flight coordination and efficiency. With regards to aviation radio monitoring systems, they can accurately determine the speed, position, and other vital data of aircraft to ensure that each aircraft can fly along the correct route.

However, the simultaneous use of a large number of radio equipment may lead to interference among them, causing a severe impact on the normal operation of aircraft. Additionally, issues such as reducing energy consumption and heat during transmission also affect a wide range of applications in the aviation field.

In the future, wireless power transfer technology can be combined with solar technology to provide a more environmentally friendly and sustainable energy supply for aircraft. Through wireless transmission, the electrical energy generated by the solar panels can be transmitted directly to the aircraft's power system, achieving the goal of green aviation.

3.6. Underwater Robots

In order to enhance the operational endurance of underwater robots, scientists have conducted research on wireless power transmission technology for supplying power to these robots. In 1994, the University of Wisconsin in the United States developed a resonant underwater system. Additionally, the 5-kW rail-rail wireless charging device developed by Professor Zhu Chunbo's team at Harbin Institute of Technology in China has a transmission power of up to 10 kW and a transmission efficiency of 91%, making it one of the highest-powered underwater wireless charging systems currently available [34].

However, the aquatic wireless energy transmission system relying on magnetic coupling encounters constraints due to the dimensions of the transmitter coil, thereby restricting its operational range. When the radius of the transmitting coil exceeds that of the receiving coil, the system efficiency will sharply decline. Therefore, scholars believe that electric field-coupled wireless energy transfer technology holds promise in underwater wireless energy transfer scenarios. However, under seawater conditions, the coupling capacitor will experience dielectric resistance, and conductive seawater will introduce additional power loss. Hence, it is necessary to further study the loss problem of electric field-coupled underwater wireless energy transfer systems in the future.

Currently, there are very few research studies on the application of underwater ultrasonic wireless energy transmission systems. The primary challenge limiting its efficiency is that the piezoelectric transducer does not match the acoustic impedance of seawater, resulting in multiple reflections of sound waves in seawater and attenuation. Once this problem is addressed, the efficiency of the wireless energy transmission system will be effectively improved, leading to enhanced working time and reliability of underwater robots, which is of great significance to underwater exploration.

4. Conclusion

Despite the great potential of wireless energy transmission technology, it still faces numerous challenges, including transmission efficiency, distance, cost, safety, and others. Wireless transmission technology is expected to evolve towards higher efficiency, longer distances, and higher frequencies. In summary, wireless energy transmission, as an emerging field, offers significant comprehensive benefits and vast application prospects. With ongoing advancements and enhancements in the technology, breakthroughs in transmission efficiency, distance, and cost are anticipated, enabling a wider range of applications.

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