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Advancements in Wireless Power Transmission: Applications in Biomedical Devices, Space Technology, and Electric Vehicles

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A B S T R A C T

Wireless power transfer (WPT) using magnetic resonance is developing rapidly and is attractive to electric vehicle (EV) charging applications. This paper reviews the technologies in the WPT area applicable to EV wireless charging, which can reduce obstacles of charging time, range, and cost, an overview of theory, design strategy, and practical findings for a two-coil energy transfer system with a connecting coil, metamaterials that can be used to improve the transmission efficiency of a wireless power transfer system using magnetically coupled resonators, software-defined WSNs (SDWSNs) that recently have been realized to maximize resource utilization. Wireless power transfer (WPT) offers a new way to energy acquisition for electric-driven devices, levitating the over-dependence on the battery.

1. Introduction

Here Wireless power transmission, also known as wireless energy transfer or wireless electricity, is a technology that enables the transfer of electrical energy from a power source to an electrical device without the need for physical connections or wires. It utilizes various methods and principles to transmit power over a distance, allowing for the convenient and efficient charging or operation of devices without the constraints of traditional wired connections [1]. The most commonly used method for wireless power transmission is electromagnetic induction. This process involves the use of two coils: a transmitter coil and a receiver coil. The transmitter coil is connected to a power source, which generates an oscillating magnetic field. When the receiver coil is placed within the range of this magnetic field, it induces a current in the coil, which can be used to power a device or charge a battery [2]. Another approach to wireless power transmission is through the use of resonant coupling. This method relies on the principle of resonant frequency, where the transmitter and receiver coils are designed to have the same resonant frequency. By matching the frequencies, power can be efficiently transferred between the two coils, even over longer distances. Wireless power transmission has a wide range of applications. It is commonly used in consumer electronics, such as smartphones, tablets, and wearable, where wireless charging pads or mats are used to charge these devices without the need for physical connectors. It can also be employed in industrial settings to power sensors, monitoring devices, and other equipment that require frequent recharging or have limited access to power sources [3]. One of the key advantages of wireless power transmission is its convenience. It eliminates the need for cables and connectors, reducing clutter and enabling seamless integration into our daily lives. Moreover, it can enhance the safety and reliability of electrical systems by minimizing the risk of electrical shocks and reducing wear and tear on physical connectors. However, wireless power transmission also faces challenges. Efficiency is a significant concern, as power losses can occur during transmission, especially over longer distances. Standards and regulations need to be developed to ensure compatibility and safety across different devices and power sources. Additionally, scalability and cost-effectiveness are important factors to consider when implementing wireless power transmission on a larger scale. Despite these challenges, wireless power transmission holds great potential for the future. As technology continues to advance, we can expect further improvements in efficiency, range, and scalability, paving the way for a world where charging and powering devices wirelessly becomes the norm.

2. Overview of WPT

2.1 Review stage Wireless power transfer different resonating techniques

Transportation electrification has been happening for quite a while, but EVs demand an extremely powerful and large-capacity volume battery pack to function. Subsidies from governments and tax breaks are required to boost market penetration, but the battery is the barrier due to its low energy density, short life span, and high price. EVs require a significant power density, low cost, extended cycle life, safety, and dependability, but lithium-ion batteries tend to be bulky and expensive to compete with a 300-mile range. EV batteries must have a high energy density, a high power density, a low cost, a long cycle lifespan, and a high level of safety and reliability. Lithium-ion batteries are the most cost-effective option, but their lengthy charging process makes them impractical for many drivers, as a single charge can take up to several hours. A wireless EV charger is depicted in Fig. 1 as having disconnected the sending and receiving coils, an offset system, and electric power converters. The coils are made of ferrite and shielding, and the magnetic coupling serves as a representation of the entire system

Figure 1 depicts a typical wireless EV charging system, which includes various steps for wirelessly charging an EV. An ac to dc converter with power factor correction first converts the utility ac power to a dc power source, which is then transformed to a high-frequency ac that powers the coil that broadcasts via a compensation network. For added safety and protection, a high-energy separated transformer can be installed between the dc-ac conversion and the main circuit coil. The high-energy flow in the transmitting coil produces a rotating magnetic field, which causes an alternating voltage on the receiver coil. Finally, the alternating current power is rectified in order to charge the battery [1].

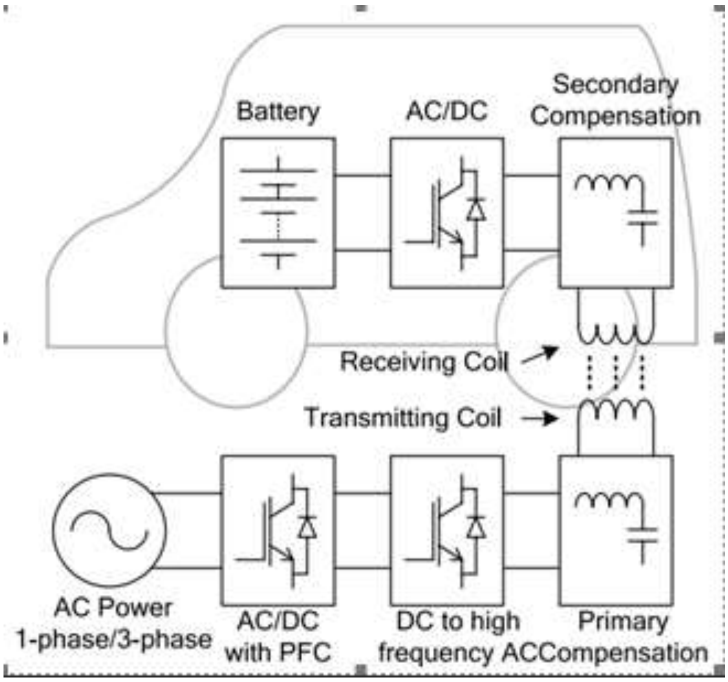

Fig.1. Typical wireless EV charging system [1]

Inductive coupling is a wireless power transfer method used for passive RFID powering, which is smaller than mobile phone charging. Inductive WPT transfers power between two perfectly aligned transmitter/receiver coils using Ampere's and Faraday's laws, but it requires close proximity and precise positioning to attain high power transfer efficiency. The inductively coupled system uses a primary and secondary coil for wireless power transfer, with a power supply and resonant circuit. Figure2 shows the schematic of it [2]. Inductive coupling is a near-field WPT method that uses a magnetic field to transfer power between two properly aligned transmitter/receiver coils. It is governed by Ampere's law and Faraday's law of induction. It is possible to reach up to 90% power transfer efficiency, but it demands close contact and precise position, making it undesirable for charging numerous devices at the same time [3]. New power transmission methods for electronic devices like sensor networks are needed to enhance daily security, safety, and convenience. Inductive coupling and MEMS technology have been used for large-area wireless systems. However, inductive coupling is effective only for short distances. Wireless power transmission involves inductive coupling for short distances, maintaining distances within 50mm, and resonant coupling for long distances, allowing distances up to 2m between the send and receive coils [4]. The inductively linked WPT approach is a frequently utilized technology in converters with air gaps that operate at frequencies lower than MHz. When compared to magnetic resonance, it has a better efficiency with a few mm air gap. Due to low coil mutual connection and higher leakage inductance, efficiency declines with misaligned or greater air gap distance [5]

2.2 Wireless power transfer in data communication and biomedical researches

The distributed BMI architecture consists of small, independent, free-floating, and wireless implants. The main challenges for these implants are their size and the need for sufficient wireless power to support functionality. Various methods, such as energy harvesting and electromagnetic fields, are being explored to power these implants. Resonance-based near-field electromagnetic wireless power transmission is a promising solution. Designing a robust and safe method for power transmission and communication with these implants is still an open question. The weak coupling between the embedded receiver coil and the external transmitter coil can be improved by adding a resonator at the receiver plane. This enhances power transfer efficiency and extends the coverage area [6]. Resonant soft-switching converters like Class E and Class EF2 inverters are commonly used in high-power inductive wireless power transfer systems due to their efficiency and simplicity. However, these converters are designed for optimal switching conditions at a fixed load, making them less tolerant to load variations. Attempts to tune the Class E inverter using saturable reactors and varactors have been made, but they require manual tuning or control loops and can limit the inverter's power levels. A design using finite-DC inductors has been proposed to achieve zero-voltage switching and constant output voltage as the load resistance varies. However, this design is not suitable for inductive WPT systems where the coil distance changes, leading to varying load resistance as shown in Figure 2 [7].

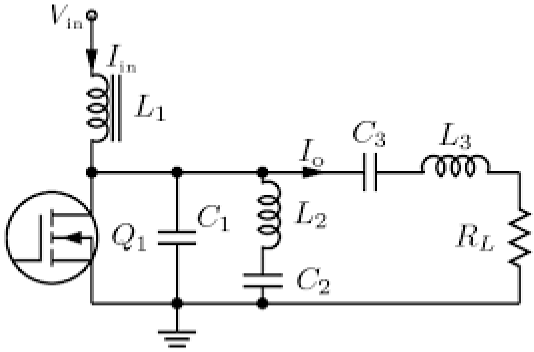

Fig. 2. The Class EF inverter [7]

Research has focused on rectennas for space, satellite, and wireless embedded sensor applications. A circularly polarized microstrip patch antenna was designed for a rectenna prototype operating at 5.5 GHz. The rectenna circuit diagram and components are shown in Figure 6, and a photograph of the fabricated prototype is shown in Figure 7. The rectenna's performance characteristics were measured using a test setup depicted in output power amplifier and a four-element linearly polarized microstrip array antenna was used. A high-efficiency detector diode was employed for rectification, with the microstrip transmission line dimensions chosen for impedance matching. A capacitor and a load resistor were used to maximize the dc voltage output [8].

Numerous studies have aimed to enhance the performance of wireless power transfer systems. An important aspect of WPT optimization is the design of the WPT coils, which significantly impacts system performance. Some studies have focused on improving coupling and coil quality factor, but they vary in design conditions and conclusions. While electromagnetic coupling, quality factor, and AC resistance are vital for performance improvement, they may not be ideal for all design scenarios. This paper proposes guidelines for WPT system design using miniature receiver (Rx) and significantly larger transmitter (Tx) coils. Empirical formulas are introduced to approximate generalized design principles, offering a time-saving alternative to optimization algorithms. existing literature has extensively discussed the optimization of quality factor (Q factor) in WPT coils. Qualitative design recommendations have been proposed, considering factors like coil winding, pitch between turns, and loop radii. However, these recommendations lack a generalized guideline for high Q coil design, necessitating specific simulations or numerical optimizations. This paper addresses this issue by using curve-fitting techniques to obtain a generalized design guideline. The proposed guidelines, based on varied wire and coil radii, can be applied to a wide range of applications, including biomedical implants and consumer electronics [9] Metamaterials are artificial structures with unique properties like negative refraction. Their electromagnetic characteristics are derived from smaller elemental structures rather than composite materials. Macroscopic parameters such as electric permittivity and magnetic permeability describe these properties. Negative-index metamaterials (NIMs) are significant examples. This paper explores a wireless power transfer system utilizing magnetic resonant coupling. Coupled resonant coils transfer power through inductive coupling. Optimal coupling and highest efficiency require adjusting the distances between the power loop and source coil, as well as between the sink coil and load loop [10].

2.3 Wireless power transmission using software networking electronic files.

Software-defined networking has been extended to wireless sensor networks to simplify network management. Several studies in the literature explore the feasibility and technical challenges of SDN in WSNs. One paper introduces SDWSN, which aims to reduce information exchange between sensor nodes and controllers while enabling programmability. The benefits of SDWSNs over traditional WSNs are highlighted, and a prototype implementation is presented. Another study proposes Tennyson for WSNs, allowing multiple controllers. Energy-efficient sensor activation, task, mapping and sensing scheduling are investigated to achieve high-quality sensing in SDWSNs. A distributed information extraction approach utilizing multiple software agents with dynamic itineraries. Recent studies have focused on energy harvesting for wireless sensor networks. Reviews of energy harvesting schemes for WSNs are provided and the feasibility of RF energy harvesting is explored, presenting measurements of RF power density. Wireless power transfer and its impact on WSNs are analyzed. Medium access control (MAC) protocols, overlaid wireless sensor transmission, and cross-layer optimization schemes are investigated for energy optimization Mission-aware placement and optimization of energy transmitters are studied However, realistic scenarios and wireless power transfer in software-defined wireless sensor networks have not been extensively addressed in existing literature [11].

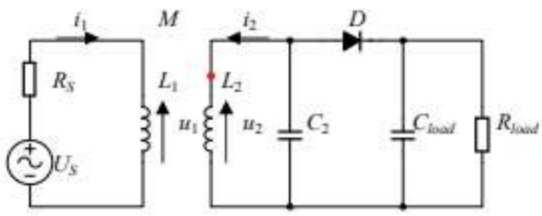

Figure 3. Wireless power transfer system [12].

Cell phone chargers are standardized with USB connectors for their power capabilities. New phones are compatible with 5V USB power, enabling universal chargers. Wireless charging options exist, including inductive coupling, which is preferred for its safety and efficiency. Successful tests have demonstrated 60W transfer over 2m using inductive coupling. Inductive coupling is a wireless power transfer method that utilizes an air-core transformer. Unlike a typical transformer, the primary and secondary coils are not fixed together. This method is commonly used for passive RFID powering, where power requirements are lower compared to mobile phone charging as shown in Figure 3. The system consists of a primary side with a power supply and coil, and a secondary side with a resonant circuit, rectifier, and resistive load representing the mobile phone battery charger [12]. Wireless Power Transfer technologies offer advantages and disadvantages. Research focuses on improving transmission efficiency and distance, as well as designing multiple transmitters/receivers. However, there are open research challenges that hinder the widespread acceptance of WPT. Addressing these challenges is crucial for the future development and application of WPT technologies. Improving power transfer efficiency is crucial in wireless power transfer technology. The investigation of a strong directional and energy-concentrated laser beam, similar to a microwave beam, is deemed valuable. The electromagnetic radiation approach involves a microwave source, waveguide, transmitting antenna, and receiving antenna, with energy transferred through electromagnetic waves. This approach offers high PTE over long distances but faces radiation concerns and requires line-of-sight transmission. A summary of advantages and disadvantages of various WPT technologies [13]. Wireless Power Transfer enables electrical energy transmission without physical connections. It offers benefits such as flexibility, user-friendliness, and durability, making it ideal for applications where traditional wiring is impractical or impossible. WPT technology has evolved from theory to commercial products, with a projected market value of $15 billion by 2020. WPT development focuses on near-field (capacitive and inductive) and far-field (microwave and laser) techniques, each with advantages and limitations. Near-field WPT is suitable for consumer electronics, EVs, robots, and biomedical devices, while far-field WPT, particularly laser-based systems, can transmit kilowatts of power over long distances, opening possibilities for applications like UAVs, satellites, and lunar habitats. The pursuit of high-intensity laser power beaming (HILPB) systems holds promise for expanding WPT capabilities and creating flexible virtual power grids [14]. The optimization of Quality Factor (Q) for Wireless Power Transfer coils has been extensively discussed in the literature. Qualitative design recommendations have been proposed but lack a generalized guideline for high Q coil design. A curve fitting technique to derive design guidelines for high Q coils is proposed here. The optimum pitch and number of turns are approximated as coil radius and wire radius functions, providing practical design equations for high-Q spiral coils in various applications such as biomedical implants and consumer electronics [15].

2.4 Wireless transmission for solar power satellite and software-designed sensor

The global issue of energy and the environment is crucial for sustaining our society. With 80% of our energy coming from fossil fuels, their depletion within 100-150 years and the resulting environmental concerns necessitate a paradigm shift. Space solar power systems (SPS) offer a solution by tapping into constant solar energy in space and transmitting it to the ground using microwave or laser beams as shown in Figure 4. SPS has the potential to replace fossil fuel plants with a large-scale clean energy system. Various SPS models have been proposed, with most utilizing microwave technology for efficient power transmission and reception.

A robust wireless research instrument, the EnerCage-HC2 system, has been developed for behavioural research on small freely behaving animals. It is fully compatible with standard home cages and allows wireless energization and communication with sensors and electronic devices attached to or implanted in animals. The system incorporates optimized Rx and Tx coils for power harvesting and transmission, a robust communication network, and a stable power delivery mechanism. In vivo testing on freely behaving rats demonstrated successful wireless deep brain stimulation, resulting in consistent and quantifiable behavioral responses while recording stimulus current and power measurements [17]. Microwave power transmission (MPT) is an efficient technique that enables power transmission over long distances, using frequencies ranging from 1GHz to 1000GHz. MPT systems shape the reception area through high-directivity antennas or laser beams. Resonant magnetic coupling allows significant power transfer over distances multiple times the size of the transmitter coil. Inductive coupling, based on mutual induction, is suitable for short-range power transfer, but efficiency decreases with distance. Inductive coupling is commonly used in applications like electric toothbrushes, providing the advantages of wireless recharging and safety in wet environments [18]. Non-radiative techniques, such as inductive and capacitive coupling, enable power transfer over short distances using magnetic or electric fields. Inductive coupling is widely used in wireless technology for various applications. Near-field transfer allows energy transfer between two coils close, with minimal interference and potential health risks. Magnetic fields used in these techniques are generally safe for humans within the transfer range [19]. Recent studies have focused on energy harvesting from ambient sources for wireless sensor networks. RF energy harvesting feasibility and energy storage using supercapacitors for WSNs are investigated. Wireless power transfer is explored as an alternative for controlled energy harvesting. Medium access control protocols, cross-layer optimization, and directional energy transmission/reception models are proposed to optimize energy charging and data communication. Placement optimization of energy transmitters and chargers is examined to maximize network lifetime and energy harvesting. Greedy algorithms are utilized for optimal deployment of wireless chargers in rechargeable sensor networks [20].

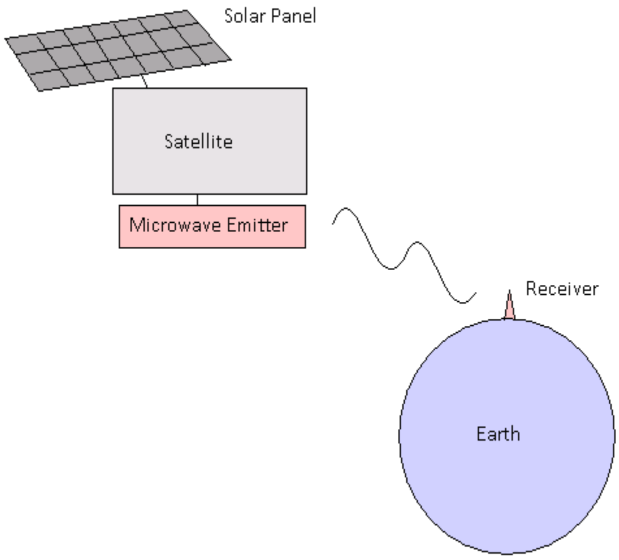

Figure 4. Configuration of space solar power systems, consisting of solar power satellite and ground segments.[16]

3. Conclusion

In conclusion, wireless power transmission has shown great potential for various applications. It offers benefits such as increased device mobility, elimination of wiring hazards, improved reliability for electric vehicles, and cost savings. Different methodologies for WPT have been investigated, including inductive coupling, microwave power transmission, and laser technology. Magnetic resonance WPT has emerged as a promising technique for powering devices wirelessly with high efficiency, while microwave power transmission is being explored for long-distance high-power transmission. The Qi wireless power transfer standard has demonstrated its potential for charging high-power devices. However, health and safety considerations remain important, and further research is needed in this area. Overall, WPT holds promise as a convenient and efficient solution for powering a wide range of devices wirelessly in the future.

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