The Application and Development of Wireless Power Transfer Technology

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Abstract. The power transmission issue is a hot topic now. With the development of technology, traditional power transfer methods like battery and wired power transfer cannot meet the demand for highly efficient, low-cost, and flexible power transfer anymore. Thus, the wireless power transfer (WPT) technique has steadily grown in importance. It provides a completely new approach to powering electric devices. This kind of new approach is more convenient and flexible. This paper provides an overview of WPT technology. It mainly focused on the physical principles of WPT. This paper also introduces its applications in daily life and provides some efficient ways to optimize them by analysing and summarizing previous research and experiences about WPT. It will also talk about the future development trend of WPT and provide some advice about it. This new energy transmission method has important implications for the widespread use of renewable energy sources in our daily lives.

INTRODUCTION

With the rapid development of modern society, various electronic devices are becoming increasingly widespread, making the issue of charging these devices an important topic. These devices include mobile phones, electric vehicles, and medical implant devices... With the increasing popularity of electric devices, the demand for efficient and convenient power supply solutions is also increasing. Traditional power supply methods mainly include wired power transfer and battery power. These methods have shown many problems in various aspects. Battery power has issues such as high costs, limited lifespans, and environmental pollution. And though wired power transfer is reliable, they are very inconvenient in usage, and it often leads to cable clutter. To solve these problems, wireless power transfer technology has gradually emerged. WPT offers many advantages that traditional methods do not have, such as convenience and flexibility. And the main difference between WPT and traditional power supply is that it allows charging to no longer be limited to fixed locations. Such a difference can significantly improve production efficiency in certain industries such as robot manipulation, automated underwater vehicles, and induction generators [1]. Therefore, wireless charging technology plays a crucial role in driving social progress and improving production efficiency. As we know, wireless power transfer technology has only become popular in recent years, but the concept of WPT was first suggested by Nicola Tesla as early as the late 19th century. However, this technology has not been widely used in life during the following century because of the limitations of facilities and costs. But the proposal of such a significant concept laid the solid theoretical foundation for recent widespread applications of WPT. When external sources interrupt electrical circuits through electromagnetic induction, conduction, or electrostatic coupling, it is referred to as electromagnetic interference (EMI). It enables compatibility and interoperability among devices of different brands and types. Nowadays, the applications of WPT are everywhere in our lives, such as wireless charging of mobile phones, dynamic wireless charging, and industrial applications. This paper's goal is to examine the application and optimization of electromagnetism and circuit theory in wireless charging systems. This paper will first introduce several main wireless charging principles, then carry out a deep analysis of the key components of wireless power transfer technology, followed by examples of important applications of wireless charging technology in daily life.

THE PRINCIPLES OF SEVERAL TYPES OF WIRELESS POWER TRANSFER

Over the more than one hundred years, especially the past two decades, many principles of WPT have been discovered. The majority of these ideas are predicated on Faraday's Law of Electromagnetic Induction. Three of the most common principles are as follows.

Magnetic Field-coupled Wireless Power Transfer

Magnetic field-coupled WPT includes magnetic induction type and magnetic resonance type. The magnetic induction charging system is composed of two induction coils, which are the transmitter (TX) and receiver (RX). According to Faraday, a fluctuating magnetic field will be created around the near field as an alternating current passes through the TX coil. This changing magnetic field will spread to the RX coil and excite the induced electromotive force in the RX coil because the magnetic field is dynamic. Electrical energy can be obtained by connecting the device to the RX coil, enabling wireless charging. However, the charging efficiency will drop rapidly when RX and TX are separated by more than a few centimetres. For this reason, magnetic resonance charging can be proposed. Compared with the former, the magnetic resonance charging system adds capacitors. In this way, an energy channel is formed between the two coils by using the frequency resonance between the TX end and RX end, and wireless charging, no matter the distance. However, magnetic field-coupled wireless charging systems still face the problem of low efficiency and safety [2]. In 2022, Maryam Saeedi Fard and her team found the method of cost-effective dynamic wireless power transfer (DWPT), which greatly improved the efficiency and safety of electromagnetic induction charging [3].

Electric Field-coupled Wireless Power Transfer

Electric field-coupled WPT is another common technology of WPT. Electric-field coupled WPT (EC-WPT) technology generates high-frequency, high-voltage alternating current from a DC input through a high-frequency inverter circuit and the transmitting end of a resonance compensation circuit. The metal plate coupling mechanism creates an equivalent coupling capacitance for the EC-WPT system to provide a complete electrical circuit. After the receiving end's rectifier filter circuit and resonance compensation circuit, it is converted into the electrical energy needed by the load and eventually achieves wireless electrical energy transfer. In 2024, YuHong MO and her team found that good anti-misalignment and load-independent constant-current output characteristics are possible with the EC-WPT system based on bilateral LC and LCLC [4].

Microwave Wireless Power Transfer

Electromagnetic radiation is the main principle of far-field WPT, and microwave wireless power transfer technology is its core. It is mainly based on the principle of microwave far-field transmission to achieve the conversion between electrical signals and microwave signals. The benefits of microwave wireless charging technology include the ability to charge products close to the charging device, a transmission range of several meters or even thousands of meters, and a more flexible and convenient use position than electromagnetic induction [5].

KEY COMPONENTS OF WIRELESS POWER TRANSFER TECHNOLOGY

Key components of wireless charging technology have a great impact on the operation of WPT. How each component influences WPT and the optimizations are as follows.

Design of Transmitter and Receiver Coils

The design of the transmitter and receiver coils is of great importance. Here are some influences and optimizations.

The Influence of Coil Structure on Electromagnetic Field Distribution

In WPT technology, the coil structure's impact on the distribution of electromagnetic field is of great significance because it directly determines the efficiency, range, and stability of energy transmission. One significant problem that affects wireless charging systems' transmission efficiency is non-alignment. The steady magnetic field in a multi-load wireless charging system can ensure stable charging power, extend battery life, and increase the charging area available to the loads [6]. Cun Zhang and his colleagues suggested a type of arrangement of circular WPT coils with a compensatory mechanism in 2021 [6]. By examining the magnetic field trajectory of the array coils' elementary, this coil structure can be found.

Optimization of Coil Self-Inductance and Mutual Inductance

Variations in coil mutual inductance in a WPT system can impact its efficiency and generated power [7]. Therefore, Coil Self-Inductance and Mutual Inductance need to be optimized. In 2022, a new method was proposed by Mehran Mirzaei for calculating the self-inductance and mutual inductance of thin-wire loop coils [8]. This method is called mutual inductance calculation of racetrack and circular coils, and it optimizes the typical coil self-inductance and mutual inductance system. It can be used in WPT and wireless charging applications.

Efficiency Enhancement Techniques

There is no denying that the charging efficiency is a hot topic in WPT at present. Here are some ways to improve efficiency.

Methods to Enhance the Coupling Coefficient

There are many ways to enhance the coupling coefficient. And these methods are mainly focused on these aspects: coil design, alignment and positioning, and operating frequency. For example, we can optimize coil design by increasing coil size to capture more magnetic flux, improving coupling efficiency.

Power Factor Correction in Wireless Charging

Power Factor Correction (PFC) in Wireless Charging aims to improve efficiency by aligning the input voltage and current phases, reducing reactive power and losses. Main methods include active PFC circuits, passive PFC, and harmonic filtering [9]. So, PFC is a necessary part of WPT.

Electromagnetic Compatibility and Safety

Electromagnetic compatibility and safety a long-standing topics in the field of electromagnetism.

The Impact of Electromagnetic Interference (EMI) on Electronic Devices

EMI is the term for the disruption caused by outside sources that interfere with electrical circuits by conduction, electrostatic coupling, or electromagnetic induction. EMI has a significant impact on electronic devices' performance, reliability, and longevity, which includes performance degradation, malfunction or failure, and safety risks [10].

Electromagnetic Shielding and Safety Standards for Wireless Power Transfer Systems

Wireless charging systems must comply with international safety standards to ensure they do not pose risks to users, other devices, or the environment. The Federal Communications Commission (FCC) Regulations, Institute of Electrical and Electronics Engineers (IEEE) Standards, and International Electrotechnical Commission (IEC) Standards are important standards. These standards are all proposed to ensure the safe use of WPT.

APPLICATIONS OF WIRELESS POWER TRANSFER IN REAL LIFE

WPT technology has a wide use in various territories in our daily lives, especially in Portable Electronic Device Charging, Electric Vehicle Wireless Charging, and Industrial and Medical areas.

Portable Electronic Device Charging

In recent years, portable electronic devices have grown, so the usage of WPT in this area is very significant.

Smartphone Wireless Charging

Up to now, smartphone wireless charging technology has achieved great success, there is an increasing number of smartphones supporting wireless charging [11]. The physical principle of wireless charging for mobile phones is mainly based on MC-WPT. The system works through electromagnetic induction, where an alternating current in the transmitter coil creates a magnetic field, inducing a current in the receiver coil (inside the phone), which is then converted to DC power to charge the battery. This method requires proximity (typically within a few millimetres) and proper alignment for efficient energy transfer, as standardized by Qi to ensure compatibility across devices. Recently, many kinds of wireless charging devices have appeared on the market, and the most popular device among them is the magnetic suction power bank. You just need to stick it on the back of the phone, and it will automatically attach to the phone and start to charge, which brings a great deal of convenience. But smartphone wireless charging still faces some problems, like low efficiency. In 2022, Xiao Huihui and her team proposed a WPT system based on double-layer orthogonal DD coils, and this system can ensure the charging system operates continuously at higher power levels [12]. Overall, this technology is relatively mature, but there is still room for improvement.

Smart Wearable Device Wireless Power Supply

The wireless power supply of a smart wearable device is also a common application of portable electronic device charging. This is typically achieved by MC-WPT and EC-WPT. And just as smartphone wireless charging, smart wearable device wireless charging also faces the problem of efficiency and safety [13].

Electric Vehicle Wireless Charging

WPT technology has achieved great success in smartphone wireless charging and smart wearable device wireless power supply. It also has a wide application in electric vehicles (EVs). The applications of WPT in electric vehicles focus on In-vehicle wireless charging and dynamic wireless charging.

Challenges and Optimization Solutions for In-Vehicle Wireless Charging

Nowadays, In-vehicle wireless charging is widely used in various kinds of cars. It is more convenient than the traditional wired charging technology. However, it still faces challenges and needs to be optimized. Low efficiency is still the most significant challenge. The distance between the device and the charging source is recognized as the most significant factor affecting the charging efficiency. Based on the theorem of electromagnetic induction, in 2024, Han Dajiang optimized WPT and desired a high-efficiency in-vehicle system [14]. Through electromagnetic and circuit simulation, he analysed and designed the system's impact parameters [14].

Dynamic Wireless Charging Technology

One type of in-motion EV charging system is a dynamic wireless charging system (DWC). Power modulators, a compensation network, and power transfer pads make up its main components. The physical principle of DWC is also like MC-WPT. AC/DC and DC/AC converters transform the grid's AC mains power into AC with high frequency so that electrical energy can move from the transmission end to the receiving end. Both the transmitting and receiving sides have compensation topologies based on series as well as parallel combinations to increase charging efficiency [15].

Industrial and Medical Application

WPT technology is also widely applied in Industrial and medical areas, which has greatly accelerated the development of these two areas.

Application of Wireless Power Transfer in Medical Implant Devices

WPT technology also has a significant application in medical implant devices, especially for cardiovascular implantable devices (clMDs). Typical clMDs are mostly powered by batteries. However, long-term use and comfortable deployment are hampered by the battery's limited capacity and large volume in the implants [11]. WPT technology can solve these problems well by offering power continuously. This actively adjustable power approach can control the input voltage to give the load steady and sufficient support. This method has a bright future. It supports a variety of wearable and implantable devices without the need for batteries or percutaneous connections by using electromagnetic energy between the external transmitter and internal receiver. Nowadays, scientists are committed to advanced power methods and the future development of inexhaustible sources [16].

Wireless Functional Systems in Industrial Automation

WPT technology is crucial in industrial automation. In the framework of the fourth industrial revolution, industrial automation is one system that is receiving more attention. Operations in a hard real-time manufacturing system have to be finished by a certain date. To support the deterministic transmission, researchers have devoted themselves to time-sensitive networking (TSN) [17]. Typical wired TSN has no flexibility or scalability, so wireless TSN was proposed. This technology has greatly improved industrial automation and is expected to be more advanced in the future.

CONCLUSION

This paper provides an overview of WPT technology. It mainly focuses on physical principles, key components, and applications of WPT technology. Regarding the physical principles, it introduces about 3 main types of work theorems. These 3 theorems are MC-WPT, EC-WPT, and microwave WPT, and such theorems have their advantages and disadvantages. They are used in different areas. For key components, this paper focuses on the design of transmitter and receiver coils, efficiency enhancement techniques, and PFC in wireless charging. Based on key components, it also provides some optimizations. After that, this paper also analyses the present applications in various territories, like electric vehicles and portable electronic devices. Then it proposes some ways to improve WPT technology in these areas. This paper found that the technology of WPT has developed well during the past decades, and it has wide applications in various areas. But such technology still faces some problems, especially as low efficiency and safety. At present, many researchers are committed to improving the applications of WPT in daily life. And this paper is based on previous experiences. By analysing the fundamental physical principle of WPT technology, this paper proposes some methods to improve the present WPT technology. These methods include methods to enhance the coupling coefficient, ways to improve the charging efficiency of electric vehicles, and optimization of coil self-inductance and mutual inductance. By reviewing the development and current state of WPT technology, this paper is expected to offer convenience for readers to learn about the present development of WPT technology more comprehensively. However, current research still cannot solve the efficiency and safety issues thoroughly. WPT is a significant and hot technology now, its improvement can greatly promote the progress of society. So, future research is supposed to focus on the basic principle of WPT technology and try to perfect WPT technology.

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