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A review of recent trends in wireless power transfer technology and its applications in electric vehicle wireless charging

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ABSTRACT

Recently, electric vehicles (EVs) are becoming increasingly popular, as they decrease reliance on fossil fuels and reduce greenhouse gas emissions. However, there are still many challenges hindering the adoption of EVs. For example, EVs have short driving ranges and long charging times. To overcome these challenges, wireless power transfer (WPT) is emerging as a promising solution. WPT enables the efficient wireless charging of EVs to increase driving range, while simultaneously decreasing battery size and improving convenience. This paper presents a comprehensive overview of recent trends in WPT technologies and applications to wireless charging of EVs. The fundamental principles of WPT are briefly explained. The state-of-the-art technical progress in the field of WPT is explored in detail. The latest applications of WPT to charging EVs are thoroughly investigated, including stationary and dynamic wireless charging. Moreover, the economic feasibility of stationary and dynamic wireless charging of EVs is analyzed. Finally, to address safety issues related to human exposure to electromagnetic fields (EMFs), methods for EMF shielding are proposed.

1. Introduction

Wireless power transfer (WPT) dates back to over two centuries ago. In 1899, Nikola Tesla conducted experiments into the transmission of electrical energy without wires in Colorado Springs, USA [1,2]. In 1961, John Schuder proposed a transcutaneous energy system for implanted devices [3]. By wirelessly powering a model aircraft in 1964, William Brown validated the feasibility of microwave power transmission [4]. In 1968, a solar powered satellite was proposed by Peter Glaser as a new concept for microwave power transmission [5]. In 2007, 60 W of power was wirelessly transferred over a 2-m distance by researchers at MIT [6].

According to the operating principles of WPT, there are three main categories [7,8], i.e., electromagnetic radiation, electric coupling, and magnetic coupling. The electromagnetic radiation mode can achieve long-distance wireless power transmission using microwaves. However, this mode is inefficient and can even be harmful because of the omnidirectional characteristic of radiative energy in the far field. In comparison, the other two modes function in the near field and are nonradiative. In the electric coupling mode, also known as capacitive power transmission, energy is transferred via an electric field between metal plate electrodes. However, this mode has been studied far less than the magnetic coupling mode, because electric fields are more hazardous to living things than magnetic fields. The magnetic coupling mode uses a magnetic field, and can be further divided into inductive power transfer (IPT) and coupled magnetic resonance system (CMRS).

CMRS appears to be different from conventional IPT; CMRS is regarded as an emerging concept and has attracted increasing interest. However, Choi et al. [9] finds that the CMRS is only a special case of IPT with a very large quality factor. By optimizing the two dipole resonators used in an IPT system, 5-m-long wireless power transmission can be efficiently realized [10], which demonstrates that IPT can also achieve long-distance power transmission as CMRS can. Furthermore, Li et al. [11] and Mi et al. [12] demonstrate that CMRS is essentially identical to conventional IPT system. In [13], the authors highlight that WPT is synonymous with IPT and CMRS, where WPT is the recognized term for wireless charging.

Global greenhouse gas emissions have significantly increased in recent years. Among the largest contributors to greenhouse gas emissions is the transportation sector [14]. With increasing concerns about the greenhouse effect, electric vehicles (EVs) are seeing a rise in popularity [15,16]. Unlike fossil fuel powered vehicles, EVs consume electricity, which can be generated by various renewable sources; EVs have zero emissions, and so, can decrease reliance on fossil fuels and reduce greenhouse gas emissions. However, there are still several challenges in EV technology, such as short driving ranges and long

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charging times. To overcome these weaknesses, WPT is emerging as a promising solution for charging of EVs. Because WPT system transfers electrical energy from a power source to a load without using wires, it is more convenient, reliable, and safer than traditional wired chargers. Wireless charging of EVs can be categorized into stationary charging and dynamic charging. In dynamic wireless charging systems, EVs can be continuously charged while in motion, which can decrease battery size, increase driving range, and improve convenience.

In 2009, dynamic wireless charging of EVs was developed by the Korean Advanced Institute of Science and Technology in South Korea. I-type pick-up coils and U-type power supply rails were proposed to increase the transfer distance. A 17-cm transfer distance was realized; the maximum output power was 60 kW with an efficiency of 72%, which successfully demonstrated the feasibility of dynamic wireless power transmission to EVs [17]. Next, upgraded dynamic wireless charging electric buses were deployed on a 48-km-long road in Gumi, South Korea; this project increased the transfer distance and efficiency to 20 cm and 83%, respectively [17]. In 2010, Bombardier developed a wireless charging system for trams in Augsburg, Germany. Because the trams were large vehicles, a three-phase power system was used to achieve a higher charging power level. Moreover, stationary charging and dynamic charging systems have been combined to ensure that the trams could operate continuously; a power transfer level of 250 kW was achieved for wireless charging of the trams [18]. In 2013, Oak Ridge National Laboratory in the USA investigated a WPT system for in-motion EVs [19] in which a series of circular coils formed a power track, and one pick-up coil was installed on the chassis of the EV; when the EV was running, it could obtain a charging power of 2.2 kW with a system efficiency of 74%. In 2014, ZTE Corporation in China developed a stationary wireless charging system; the charging power level was 30 kW at a system efficiency of above 90% at a transfer distance of 20 cm [20]. The early work in [17–20] validates the technical feasibility of stationary and dynamic wireless charging of EVs, and also lays a foundation for succeeding developments.

This paper provides a comprehensive overview of recent advances in WPT technologies and their applications to wireless charging of EVs. The objectives of this paper include: (1) presenting the recent technical progress in WPT; (2) investigating the latest applications of stationary and dynamic wireless charging for EVs; (3) evaluating the economic feasibility of stationary and dynamic wireless charging of EVs; and (4) exploring methods for electromagnetic field (EMF) shielding.

In this paper, a model of a WPT system is presented; then, the transmitting/receiving coil design and system architecture are discussed. Various popular research topics, including (1) maximum efficiency tacking, (2) comparative analysis of 2-coil and 3-coil WPT, (3) mutual inductance and load estimation, (4) multi-frequency WPT, (5) 2-dimensional and 3-dimensional WPT, and (6) bidirectional WPT, are being actively investigated. Additionally, the latest advances in the field of wireless charging for EVs are thoroughly explored, including stationary and dynamic wireless charging of EVs. Furthermore, economic feasibility studies of stationary and dynamic wireless charging of EVs are presented. Finally, safety issues concerning human exposure to electromagnetic fields (EMFs) are addressed and solutions for EMF shielding are proposed.

2. Basic principles of WPT

2.1. Modeling of WPT system

WPT systems are governed by Maxwell's equations; the operation of WPT can be explained as follows [17,21]: A transmitting coil, which is driven by a high-frequency alternating current, generates a time-varying magnetic field. Via inductive coupling between the transmitting and receiving coils, the voltage induced in the receiving coil supplies power to the load, thus realizing wireless power transmission. In addition, a distributed capacitance or external capacitor is utilized to create a resonant topology for increased efficiency.

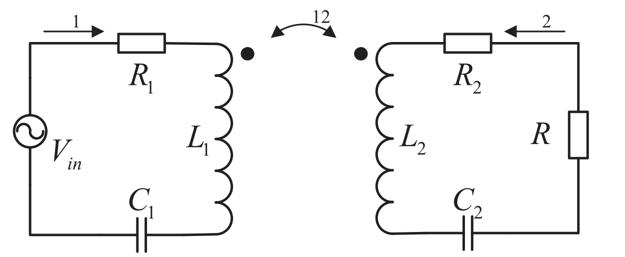

Fig. 1. Equivalent circuit of a two-coil WPT system.

Using circuit theory [17,22], a two-coil WPT system can be modeled as shown in Fig. 1. A high-frequency voltage source V_{in} provides the input power. The parameters L_1, C_1, and R_1 are the inductance, capacitance, and equivalent resistance of the transmitter, respectively; the parameters L_2, C_2, and R_2 are the corresponding parameters of the receiver. The inductive coupling between the transmitter and receiver is represented by mutual inductance M_{12}; R_L denotes the load.

2.2. Transmitting/receiving coil design and system architecture

To efficiently transmit power over a long distance, the equivalent resistances of the transmitting and receiving coils should be as small as possible when operating at a high frequency. However, a high operating frequency will increase the coils' equivalent resistance due to the proximity effect and skin effect. To enhance the magnetic field between the transmitter and receiver, and to suppress leakage flux, ferrite bars or plates are usually used. Because the material of the coil, coil geometry, and ferrite have a profound impact on system efficiency, various design schemes are presented in [23–25] to optimize the WPT system performance.

In the two-coil WPT system, the efficiency significantly decreases with increasing transmission distance. To avoid this disadvantage, a relay resonator (also referred to as an intermediate coil or a repeater) is placed between the transmitter and receiver; this resonator is evaluated to improve both the transmission distance and the efficiency [26–28]. As addressed in [29] and [30], a four-coil WPT [6,31] or a domino-coil WPT [32,33] can also be applied to more efficiently control the wireless power flow. One of the merits of the WPT system is its ability to manage the power flow from multiple transmitters to a single receiver or vice versa; multi-transmitter WPT systems [34–36] or multi-receiver WPT systems [37–39] can be developed for these purposes.

3. Recent research on WPT

3.1. Maximum efficiency tacking

In practical situations, inevitable uncertainties affect the parameters of WPT systems. Taking a wireless charging EV system as an example, the mutual inductance depends on the EV's position; the equivalent impedance of batteries also changes throughout the charging process. Because of these changes, the efficiency of the WPT system will significantly change. Therefore, novel techniques for tracking the operating point of maximum efficiency must be exploited.

With varying axial displacement, relative angle, and air gap between the receiver and transmitter, Na et al. [40] puts forward an adaptive technique to maximize the transfer efficiency. With variations in transfer distance, a parallel/serial capacitor matrix is proposed in [41] for increased efficiency. By altering the switching configuration of the capacitances in this matrix, the optimal impedance-matching can be tracked. Another approach proposed in [42], which applies a cascaded boost-buck converter to the WPT system, can maintain an optimum impedance against loading variations, thus obtaining a high efficiency. However, Hui et al. [29] points out that the analytical expression of