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State-of-the-art literature review of WPT: Current limitations and solutions on IPT

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ABSTRACT

N. Tesla, the prospector of the power delivery in free space, suggested a huge amount of power can be transferred through the earth while G. Marconi concentrated on inventing wireless communication system over the ocean a hundred years ago. Whereas the telecommunication technology has been developed successfully, the development of wireless power transfer (WPT) system had been stagnant over decades as large devices were required to create the resonant oscillation in a safety manner and the system indicated low efficiency. Due to the development of power devices and the day-by-day increase of mobile products, electric vehicles and wireless sensors in smart grids, WPT technology is expected to undergo substantial advancement and significant power systems applications in the near future. This paper is aimed at introducing a state-of-the-art review for existing WPT technologies with detailed comparison. The paper also presents the limitation of inductive power transfer system through simulation and practical analyses. Finally, recommendations and future perspective to overcome these limitations are provided with four main themes: design, efficiency, stability, and safety.

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1. Introduction

Since electromagnetism was defined by the association of M. Faraday and J. C. Maxwell in the nineteenth century [1], it was clarified that the electromagnetic radiation behaves as light and hence it was proposed that electric energy is able to be transmitted without wire [2]. Nikola Tesla proposed energy transmission through air in 1897 [3]. He elevated an AC voltage up to 100 MV at the top of a transmitting sphere where a 300 kW power at 150 kHz resonant frequency was radiated to the far end of the coil [4]. He believed that power energy can be transmitted and collected at any place through the ground by oscillating standing wave. However, practical measurements indicated low efficiency as the research was conducted on a large scale with the application of relatively low frequency [5]. In addition, this research was suspended due to the lack of financial support. Consequently, the research on wireless electric energy transmission was shelved over decades [6]. With the rapid advancement in mobile devices, electric vehicles and the global trend to adopt smart grids that call for millions of low power-based sensors, wireless technology has come back to the picture. Unlike information and communication technology (ICT) which utilizes small amount of power to carry valid data, the aim of WPT is to send a large amount of electric energy to the load over a particular distance safely. For the last decades, a usage of battery-powered devices such as mobile phones, electric vehicles, and medical implants has significantly increased worldwide in which WPT can find significant applications. WPT can be also implemented in various industrial and robotic applications such as conveying electric power through a bent joint without physical contact [6] and a robotic device that performs duty such as disaster relief at non-accessible or dangerous area [7]. For these reasons, it is necessary to develop more efficient and safer design of WPT technology. This paper is aimed at presenting a state-of-the-art review for current WPT topologies and highlighting the limitations of the mostly used technique, inductive power transfer system, through simulation and practical analyses. While some WPT review papers can be found in the literature, the fast advancement of capacitive power transfer (CPT) systems was not adequately covered [8–10]. Moreover, the current state of IPT, CPT, and the microwave WPT technologies are not covered in the recent publications. The key contribution of this paper is summarised below:

- providing a review of the state of the art for IPT, CPT and microwave current technologies along with a brief comparison of these techniques,
- presenting a case study for IPT system through analytical calculations, finite element simulation and experimental measurements,
- introducing a new application for frequency response analyser in WPT,
- providing recommendations and future perspective to overcome current WPT limitations in four main themes: design, efficiency, stability, and safety.

This paper is organised as below:

Section 2 introduces a detailed classification and comparison of current WPT technologies. In Section 3, the limitations of IPT system are presented through analytical and experimental circuit analyses on two-coil series–series topology. The practical measurements in this section introduces a novel application for the frequency response analyser that is conventionally used to detect windings and core deformations within power transformers to observe the variation of the wireless power transfer level over a wide frequency range. Perspective recommendations with four categories: efficiency, design, stability, and safety, to enhance the performance of WPT technology are highlighted in Section 4.

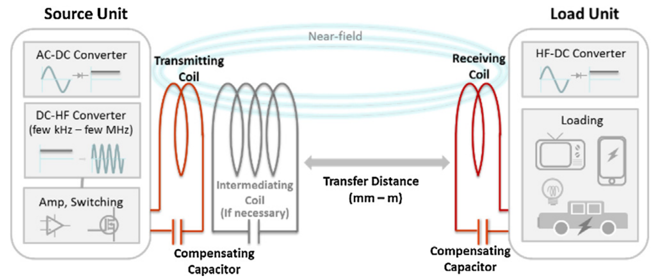

Fig. 1. Inductive power transfer with compensating capacitors in series.

2. Classification of WPT systems

WPT has been found feasible under two main categories: radiative and non-radiative methods as shown in Table 1. The non-radiative application is classified into two approaches: inductive power transfer (IPT) and capacitive power transfer (CPT). An innovative IPT-CPT combined system transferring electric power of 2.84 kW at 1 MHz frequency with 94.5% efficiency for a distance of 150 mm was demonstrated in 2016 [11].

2.1. Inductive power transfer (IPT)

The first demonstration of WPT which is analogous to the present IPT topology was performed by Tesla in 1898 [13]. He clarified that the resonant system allows for the electromagnetic coupling in near-field between transmitter and receiver. Afterward, further research was continued to enhance the technology of IPT in the field of biological engineering [14–16]. The development of Litz wire consisting of several stranded-wires to reduce skin and proximity effect losses at high-frequency (HF) and the advancement of HF power electronic switches contributed to the enhancement of IPT in the mid of 19th century. A commercial inductively coupled WPT was introduced by J. Boys in 1994 [17] and an intermediate coil at the transmitting device to increase the transfer distance was proposed in 1998 [18]. The intermediate coil, also known as a relay coil, can enhance the efficiency over the transferring distance, however it requires further considerations such as cost-effectiveness and the difficulty of tuning the frequency due to the additional unit [19]. The magnetic resonant coupling (MRC) system introduced by the Massachusetts Institute of Technology (MIT) in 2007 proposed auxiliary coils with compensating capacitors at both transmitter and receiver [20]. The transfer distance of this four-coil system was enhanced by inserting additional sending and receiving coils [21]. This system could achieve 60 W of wireless power transfer at 2 m distance. While system efficiency between the transmitter and the receiver was only 15% at 10 MHz, this achievement has motivated researches to advance the WPT at mid-range distance.

It is convenient to think of inductively coupled power transfer as an air core transformer. When the current flowing in the source coil it produces magnetic flux that links within the load coil and induces electric energy into it based on Faraday's law as shown in Fig. 1. When the compensating capacitor cancels out the leakage inductance of the winding, the energy conversion takes place between the two coils wirelessly without significant radiation. The operation mechanism of both IPT and MRC system is based on the same principle [19]. Although with four-coils the system can achieve larger distance than the two-coil system [22], it was pointed out that the system efficiency and amount of power delivered are mainly affected by the volume of copper (or number of turns) not by the number of coils [23].