Novel Computational Approaches to Suppress Magnetic Field Leakage in Inductive Power Transfer Systems

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ABSTRACT: Inductive power transfer (IPT) has been extensively studied as a promising technology for charging electric vehicles and mobile devices. This study focuses on novel computational approaches that help suppress magnetic field leakage in IPT systems. In particular, this manuscript presents an overview of (1) techniques for canceling magnetic field leakage, (2) Z-matrix estimation using phase retrieval, and (3) an automatic coil design algorithm. These approaches aim to suppress magnetic field leakage while reducing the cost of IPT systems and enhancing their transfer efficiency.

KEY WORDS: inductive power transfer, magnetic field leakage, coil design

1. INTRODUCTION

Inductive power transfer (IPT) is becoming a key technology for powering electric vehicles (EVs) and Internet of Things devices. The obsolescence of power supply cables will dramatically alter the way we use electrical equipment and provide us with greater safety.

Transmission power is one of the most important performance metrics in IPT because it shortens charging time. However, increasing the transmission power is a crucial challenge because it leads to an increase in the intensity of the magnetic field leakage generated by IPT systems, which causes interference. Considering electromagnetic compatibility, further magnetic field strength reduction measures are needed to accommodate the trend of increase in transmission power.

The magnetic field leakage generated by IPT systems comprises fundamental and harmonic components. The fundamental component undergoes greater magnetic field leakage than the harmonic components because it is the operating frequency of the power transmission. It may induce malfunctions in surrounding electronic devices, even when the frequency bands of wireless communication systems and IPT systems do not overlap [1]. Although the strength of the harmonic components is less than that of the fundamental components, the harmonic components interfere with existing wireless communication systems because their frequency bands overlap with those of the wireless systems [2]. To further develop high-power IPT systems, it is necessary to reduce both the fundamental and harmonic components of magnetic field leakage.

Several methods have been proposed to reduce the fundamental and harmonic components of magnetic field leakage. For example, shielding and coil structures with reverse-phase currents have been studied for the suppression of magnetic field intensity [3-5]. Another method dithers the transmission frequency; however, the amount of reduction is limited by the frequency bandwidth that is stipulated by radio law [6].

We have studied computational approaches that help suppress magnetic field leakage in IPT systems. Specifically, the current study presents an overview of: 1) techniques for canceling magnetic field leakage; 2) Z-matrix estimation using phase retrieval; and 3) an automatic coil design algorithm. These approaches aim to suppress magnetic field leakage while reducing the cost of IPT systems and enhancing their transfer efficiency.

2. CANCELING MAGNETIC FIELD LEAKAGE

To cancel magnetic field leakage while enhancing transmission efficiency, we studied two techniques: one cancels the fundamental component of the magnetic field leakage, while the other cancels the harmonic components [7,8].

The former, which is used with a transmitting coil array because a single transmitter cannot cancel leakage, optimizes the currents input into the transmitter array and the load impedance at the receiver based on the Z-matrix to minimize the magnetic leakage while enhancing the power transfer efficiency (PTE). Optimization is achieved by solving a quadratic programming problem that considers the conditions of the magnetic field leakage cancellation. The latter cancels magnetic field leakage in the harmonic components of IPT systems. This technique involves designing an input voltage waveform for the transmitter to cancels out the multiple low-order harmonics in the leakage from both the transmitter and the receiver. This is achieved by analyzing the harmonic components in the input voltage to the full-bridge rectifier.

Our experiments and simulations confirmed that both techniques could reduce the fundamental and harmonic components of the magnetic field leakage with only a slight reduction in the PTE. In addition, simulations carried out in a recent study verified that the combination of the two techniques could simultaneously cancel the fundamental and harmonic components of the magnetic field leakage from the transmitter and receiver, as shown in Fig. 1 (a) [9].

3. PHASE-RETRIEVAL-BASED Z-MATRIX ESTIMATION

An accurate Z-matrix estimation of the IPT circuit is necessary for maximizing the PTE but also for applying the cancellation techniques described above. We have previously proposed a novel Z-matrix estimation mechanism in multiple-input multiple-output wireless power transfer systems, as shown in Fig.1 (b) [10].

Traditional approaches often rely on precise receiver positioning or complicated mechanisms that synchronize time between transmitters and receivers, which can be costly and impractical. The proposed technique overcomes these limitations using a phase-retrieval approach to estimate the Z-matrix without requiring synchronization. It successfully estimates the Z-matrix by retrieving phase information using measurements of the AC voltages and currents at the transmitters and the DC currents at the output of the full-bridge rectifiers on the receivers.

The experiments and simulations demonstrated reliability and effectiveness and showed that the difference in the PTE was less than 0.4% when the PTE is optimized with the estimated Z-matrix and ground truth Z-matrix.

4. AUTOMATIC COIL DESIGN ALGORITHM

Coil design is crucial to enhancing PTE and suppressing magnetic field leakage. Traditional coil designs often rely on trial-and-error adjustments, which are time-consuming and inefficient, especially when the operating environment of the coil (e.g., nearby metal structures) affects its performance.

To realize a low-cost design system for IPT coils, we developed an automatic coil design algorithm, as shown in Fig. 1 (c) [11,12]. The proposed technique consists of two main steps: optimal current distribution analysis and coil geometry design using

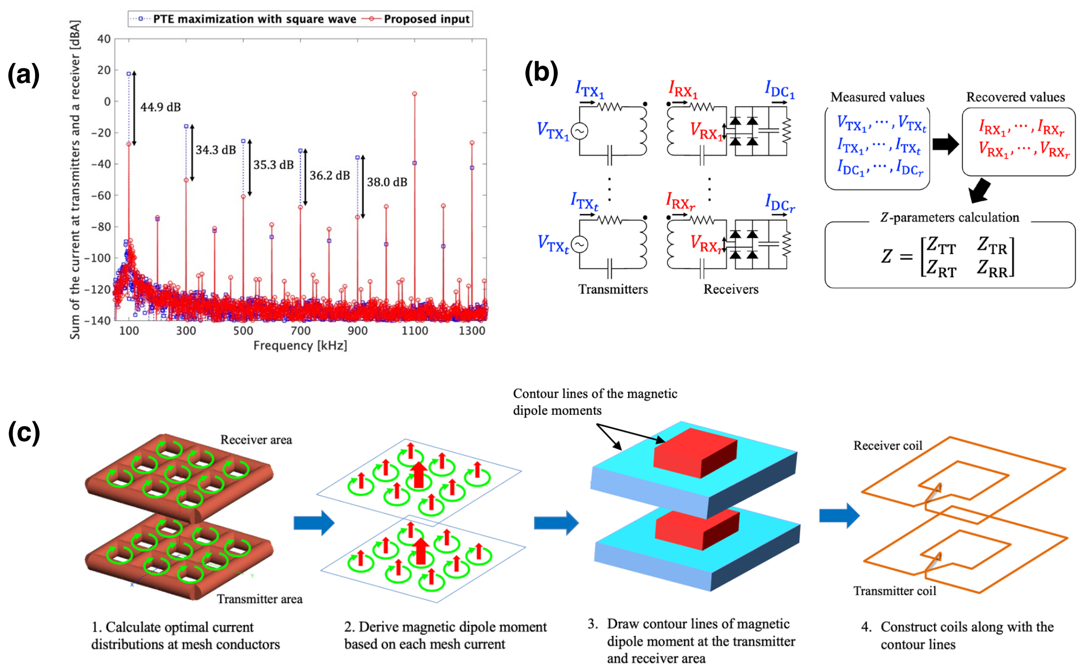

Fig. 3 Overview of computational approaches to suppress magnetic field leakage in IPT systems: (a) Comparison of the PTE maximization method and the proposed method for canceling both the fundamental and harmonic components; (b) Flowchart of phase retrieval-based Z-matrix estimation; and (c) Flowchart of an automatic coil design algorithm.

magnetic dipole moments. This method calculates the optimal current distribution using the Z-matrix obtained from the electromagnetic simulations. This optimization enables the generation of coil geometries that enhance PTE and/or reduce unwanted magnetic field leakage. The coils are designed by creating contour lines based on the distribution of the magnetic dipole moments, which are calculated using the optimal current distribution.

The effectiveness of this technique was validated through simulations and experiments, as well as by demonstrating the practical implementation of metal 3D printing.

5. CONCLUSIONS

This study presented three computational approaches for addressing the issue of magnetic field leakage in IPT systems. These techniques focus on suppressing magnetic field leakage while maintaining high PTE. The cancellation methods, which include optimized coil design and Z-matrix estimation via phase retrieval, were shown to effectively suppress magnetic field leakage without significantly compromising performance. The experimental and simulation results validated the efficacy of these methods, which achieved substantial reductions in magnetic field leakage and will provide a foundation for future improvements in IPT systems. Furthermore, the proposed automatic coil design algorithm offers a practical approach to developing cost-effective and efficient coils that support these goals. These advances contribute to safer, more efficient, and more scalable IPT systems, thereby paving the way for their broader adoption in EVs and other applications. This work was supported by JSPS KAKENHI, Grant Numbers JP24K00879 and JP23H01408.

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