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An optimization model for wireless power transfer system based on circuit simulation

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HIGHLIGHTS

- An optimization approach for coupler based on circuit simulation is proposed.
- A secondary capacitor is further optimized to make system perfect resonant.
- Nonlinear effects and requirements of circuit elements are considered in the optimization.
- The algorithm of optimization method is designed.

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ABSTRACT

Recently, the market promotion of wireless power transfer (WPT) products has generated great expectations for systematic design and optimization of practical WPT system (especially the coupler). The existing optimization methods usually employ the Finite Element Analysis (FEA) to simulate the magnetic field, where the effects and requirements of overall circuit are neglected. To address this issue, an optimization approach for the coupler based on circuit simulation is proposed in this paper, and the secondary compensation capacitor is further optimized to improve the system performance. The simulation model is embedded into Simulink and the calculation part is embedded into MATLAB, where the objective is to achieve the maximum efficiency by searching three variables under adequate constraints. The numerical results imply that the proposed method is more effective and accurate than the traditional trial-and-error way, and that it suits the practical WPT system design excellently.

1. Introduction

Over the last decades, the aspiration for clean and efficient transportation has raised great public attention of electric vehicles (EVs) which can help to reduce the dependence on fossil fuels and decrease greenhouse gas emissions. However, range anxiety, high cost, and inconvenient charging are hindering the overall acceptance of EVs. A wireless power transfer (WPT) system with high efficiency, convenient and safe operation, high reliability, robustness can solve this problem since no physical contact between the transmitter and receiver is involved [1–3]. Moreover, dynamic charging can be realized to reduce the requirements of on-board battery greatly [4].

Numerous in-depth researches for WPT system including coil geometry [5,6] and system parameters design [7,8], compensation topologies [9,10], electronics [11,12], control strategy [13,14], analytical model [15–17], electromagnetic field (EMF) [18], even the energy logistics cost analysis [19,20] and charging station locating strategy [21–23] have been carried

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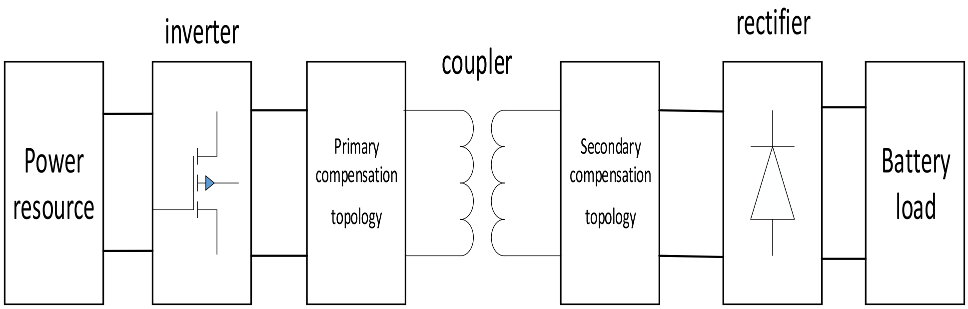

Fig. 1. Schematic diagram of inductive WPT system.

out worldwide. In addition, with the development of dynamic charging technology, the related researches, such as track design [24–26], charging lanes' location [27], traffic flow model [28–34], and switching strategy [35,36] along the segmental tracks, are hot currently. When WPT products get promoted in the market nowadays, systemic design and optimization for practical WPT system is under great demand to substitute the traditional trial-and-error method. Korea advanced institute of science and technology (KAIST) proposes a simulation-based optimization framework to investigate the feasibility of ferrite-less railway, which is primarily composed of a FEA model (ANSYS Maxwell) to simulate the magnetic field and an optimization module (in-house code) with the objective to minimize the mass of the coil and ferrite in secondary module. However, 15 variables and 23 constraints contained in the algorithm mean it is quite involved [37]. In a similar manner, Utah State University research team combines the FEA model and optimization algorithm to complete optimization of circular pad with ferrite core and aluminum shielding [16]. As detailed description in Ref. [16], the optimization process first applies multi-objective hybrid particle swarm optimization (MOHPSO) algorithm to explore the parameter dependence and identify critical optimization parameters, based on which a simpler algorithm, multi-objective real-numbered particle swarm optimization (MORPSO) algorithm, is executed twice to optimize two different pair of parameters of the circular coupler configuration separately. Later, the effectiveness of this optimization method is validated through experiment. Despite the accuracy, the models above are both computationally expensive and time-consuming due to complexity of FEA simulation. To address this issue, an integrated analytical mathematical model that takes the effect of magnetic core and shielding layer into account is developed by Florida International University to optimize the circular pads, which is aimed toward reducing running time of searching process for the optimum solution [15]. All the optimization approaches mentioned focus on the decoupled coupler optimization through magnetic field simulation, whereas the compensation capacitance, system efficiency and power transfer capability are simply calculated by an equivalent circuit model which inevitably neglects or simplifies some nonlinear elements (e.g., the battery load, the filter capacitor, etc.). From that point on, these methods are not suitable for coupler design considering the requirements of whole WPT system in a specific project.

In order to conquer the above limitations of the existing methods, we, in this paper, developed an optimization model based on circuit simulation in Simulink, and an iteration calculating function coded in MATLAB to realize the coupler and compensation capacitance optimization to achieve the highest efficiency. This paper is organized as follows: the circuit simulation model is proposed in Section 2, the iteration calculating method and procedure are formulated in Section 3, the experimental tests are carried out to testify whether the proposed model is reasonable in Section 4, and some conclusions are summarized in Section 5.

2. Circuit simulation model

Fig. 1 shows that a typical Inductive WPT system is composed of six functional parts, and they are power resource, inverter, coupler, compensation circuit, rectifier and battery load respectively. The H-bridge inverter and full-bridge rectifier are fully developed and commonly used by the WPT system for EV applications. Besides, the power resource and battery load are given in a specific project problem. Thus, the coupler and compensation circuit parameters are the design focus. Fig. 2 outlines the structure of a typical circular coupler consisting of aluminum shield, magnetic core and coil winded by Litz wire. Apart from the circular pad, researchers have proposed considerable alternative coupler shapes with better misalignment tolerance, which are analyzed with single-turn in Ref. [38] to get conclusions that the coil size is of dominant effect on coupling than extract shape, and circular shape has slight superior performance over the others. Moreover, isotropic characteristic and small geometry dimensions contribute to the popularity of circular pad for EV WPT system applications. Therefore, we choose the circular pad as the optimization objective. The effect of the ferrite core and aluminum shield is omitted herein for the sake of simplifying the model, where the nonlinear behavior in magnetic field will be studied by FEA model in the future. The inductance of coreless coil can be acquired through numerical calculation, where the procedure is coded in MATLAB [39].

The geometry dimensions of a coreless coil are given in Fig. 3, where r_1 is the inner radius, r_2 is the outer radius, and $r_0 = (r_1 + r_2)/2$ is the average radius of the coil. Thus, the coil self-inductance can be formulated as follows.

$$L = L_e + L_i, \qquad (1)$$