

Finite Element Analysis of a Contactless Power Transformer with Metamaterial

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Abstract

Wireless power transfer technologies enable power transfer to loads through air. The contactless power transformer is a key element of it. In this work, a new transformer with metamaterial is proposed, through which the power transfer distance increases. The electromagnetic properties about metamaterial are discussed at first. Then, the finite element analyses of this transformer are presented as well. The magnetic field distributions and the computational results show that this type of transformer can enlarge the power transfer range of a wireless power transfer system.

Keywords: wireless power transfer, metamaterial, finite element analysis

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1. Introduction

With the increasing demands in applications, the WPT (wireless power transfer) technology has been a hot topic for researchers [1, 2]. WPT based applications range from implanted medical devices to electric and mobile electric products with different power levels from milliwatts to a few kilowatts. Although there are a large number of WPT applications existing, most of them are based on the following fundamental concepts: microwave power transmission, inductive coupling, and resonant coupling [3]. In short-range WPT applications, inductive coupling and resonant coupling are two major technologies. And inductive coupling technology employs magnetic coupling between transmitting and receiving coils to transfer power and this technology transfer higher level power than others with higher efficiency at the same time. This technology is called inductive coupled power transfer (ICPT). Because of its advantages, ICPT based applications are used in special occasions. First, ICPT-applications are employed in high level voltage equipments to avoid electric shocks because there is no need for user to handle the plugs and cables [1]. Second, the lifetime of this system will be extended in under-water, under-mine and corrosive environments. Then, in implanted medical applications, the battery inner body can be recharged directly [4]. So far numerous efforts are underway to seek to increase the efficiency and enlarge transfer range of ICPT applications as much as possible. An energy transmission system for an artificial heart using leakage inductance compensation of transformer was proposed by Gyu in [5]. A contactless electrical energy transmission system for portable telephone is discussed in [1]. In addition, Shinya [2] presented his work about a design method of wireless power transfer system based inductive coupling. A bidirectional ICPT system is discussed; the mathematic model and controller design are presented in [6]. Besides, an optimization model of a wireless power transfer system for medical implanted devices is presented in [7]. Nevertheless above mentions are mainly based on circuit topologies, and not focused on the contactless power transformer (CPT), which is a key element of an ICPT system.

The mutual coupling strength of the CPT is a main factor which determines the transfer efficiency of ICPT system. An obvious means of increasing the mutual coupling is through the use of a material of high permeability magnetic material which guide magnetic flux in the specific way. Moreover, to design a special CPT with high coupling is a good method to improve efficiency of ICPT system. CPT models based on finite element analysis (FEA) are presented in

[8, 9]. A homogenization method and three dimensional FEA have been used to estimate the losses of a two-winding transformer with large air gap [10, 11]. However, methods mentioned above cannot break out the bottleneck of short distance of ICPT because of its inherent mechanism.

In this paper, a CPT with metamaterial is proposed. With a slab of metamaterial between the primary coils and secondary coils of CPT, the near-field coupling between two resonant coils can be enhanced; the coupling coefficient of CPT increases as well [12-14]. Metamaterials are artificial electromagnetic structures with the negative permittivity and the negative permeability in a specific frequency band simultaneously. They are also called left-hand materials because their electric field, magnetic field, and propagation vector are related by a left-handed rule [15-18]. Chung analyzed the wireless power transmission between two metamaterial-inspired loops employing a generalized equivalent circuit [19]. Reference [20] proposed the use of metamaterials to enhance the evanescent wave coupling and improve the transfer efficiency of a wireless power transfer system based on coupled resonators. They show with measurement results that the power transfer efficiency of the system can be improved significantly by the metamaterial. Da huang investigate numerically the use of a negative-permeability perfect lens for enhancing wireless power transfer between two current carrying coils [21]. The negative permeability of metamaterial serves to focus its fluxes generated in the primary side to secondary side, thereby increasing the mutual inductive coupling between the coils. However, above works about are focused on resonant coupling method of WPT system, while at presented the work about the application of metamaterial of ICPT systems presented seldom.

We demonstrate our work here about a new CPT using metamaterial to enhance the power transfer efficient of the ICPT systems. This paper is organized as follows. In section 2 the operation principle of ICPT system is reviewed at first. In section 3, the proposed CPT is shown. At first, the refractive properties of metamaterial are discussed with the help of finite element analysis. Then, the magnetic field distributions of proposed CPT and traditional CPT are compared by the aid of software ANSOFT MAXWELL; the results show that with this new CPT, the power efficient of ICPT system will increase its power efficient at different gaps of transformer. At last, the conclusions are given in section 4.

2. Review of ICPT System

Figure 1 shows a typical ICPT system which consists of high frequency inverter, compensated net, rectifier and loads. The inverter, contactless transformer and compensated net form a resonant converter [3].

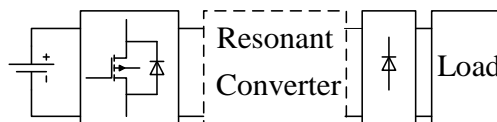


Figure 1. Typical structure of ICPT system.

Figure 2 is the Schematic of an ICPT system based on a half-bridge inverter. As seen from figure 2, by driving switches Q_1 and Q_2 alternately with a 50% duty cycle, the half-bridge generates a square voltage at the mid-node. Then, the square voltage drives the resonant converter to transfer power to loads. Because there is a wide gap between the primary coils and the secondary coils, the coupling coefficient of CPT is relatively low. Thus the power transferred to loads is also very low. To compensate this, the capacitor C_p and C_s are connected in series with the primary coils and secondary coils, respectively. These capacitors and CPT form a resonant circuit. When system operates in its native resonant frequency, the resonant converter is like a filter, and just the fundamental wave can pass through which. In addition, the equivalent load of the resonant converter becomes a resistor at resonant frequency. Therefore, the

equivalent impedance is the minimum at resonant frequency. Thus, the power is transferred to loads efficiently.

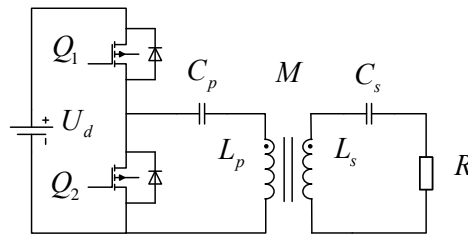


Figure 2. Schematic of half-bridge ICPT system.

3. Structure of CPT System

In this section, a CPT with a metamaterial slab is proposed shown in figure 3. The transformer core is EE type and its material is ferrite with the 1000 of relative permeability. The metamaterial slab placed between the EE cores is close to the primary side to enhance the coupling coefficient of the CPT. As discussed above section, the relative permeability of metamaterial is -1. The dimension values are shown in table 1. And the coils of primary side and secondary sides are the same which is 10 turns.

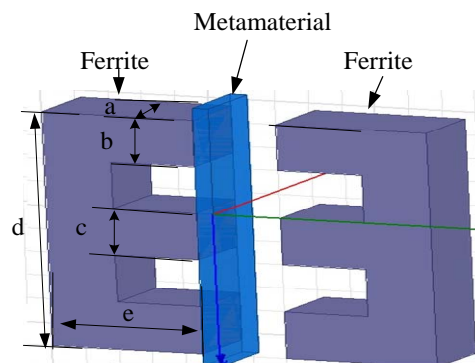


Figure 3. EE type ferrite core

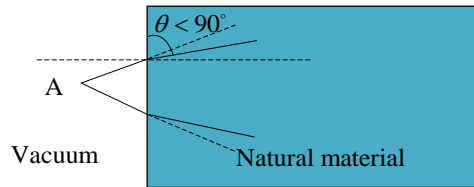
Table 1. Dimension of EE core

Parameters	Values(mm)
a	20
b	8
c	8
d	40
e	40

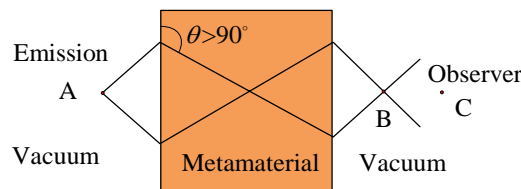
3.1. Refractive Property of Metamaterial

Metamaterial is a new class of artificial material composed of man-made structures. The blocks of the metamaterial are much smaller in size than its working wavelength. Like other electromagnetic material, the electromagnetic properties of metamaterials are described by macroscopic parameters such as permittivity ϵ and permeability μ . When evanescent waves propagate in air or other dielectric media, they can be enhanced [22]. It was showed that with a slab of material with $\epsilon=-1$ and $\mu=-1$, both far-field propagating waves and near-field evanescent waves of an object can be restored [23, 24].

Figure 4 demonstrates the refractive property of man-made material (metamaterial) and natural material. When waves pass through a natural material, the refraction angle is less than 90° in figure 4 (a), while the refraction angle through metamaterial is more than 90° in figure 4 (b). As shown in figure 4 (b), when waves emit from position A through a slab of metamaterial, the waves will focus on position B because of its special refraction feature. So from the view of observer C, the waves emit from position B equivalently. Therefore, with a slab of metamaterial the distance between the emission source and observer decreases equivalently.



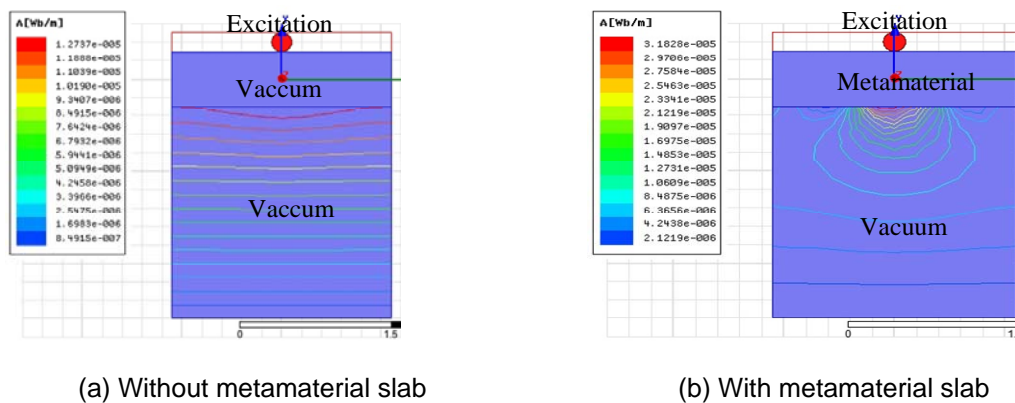
(a) Refraction of nature material



(b) Refraction of metamaterial

Figure 4. Refractive properties display

By using simulation software ANSOFT MAXWELL, the finite element analysis results are shown in figure 5. Compared figure 5 (a) without metamaterial and (b) with metamaterial, it is clearly shown that when using metamaterial the fluxes focus on the edge of the metamaterial. These are consistent with the theory analysis.



(a) Without metamaterial slab

(b) With metamaterial slab

Figure 5. Fluxes distribution of metamaterial and vacuum.

3.2. Finite Element Analyses of CPT

In this section, the finite element results of CPT with metamaterial slab and without metamaterial are compared. Figure 6 (a) is the plot of magnetic flux distributions of the CPT with metamaterial slab while figure 6 (b) shows the flux distribution without metamaterial slab.

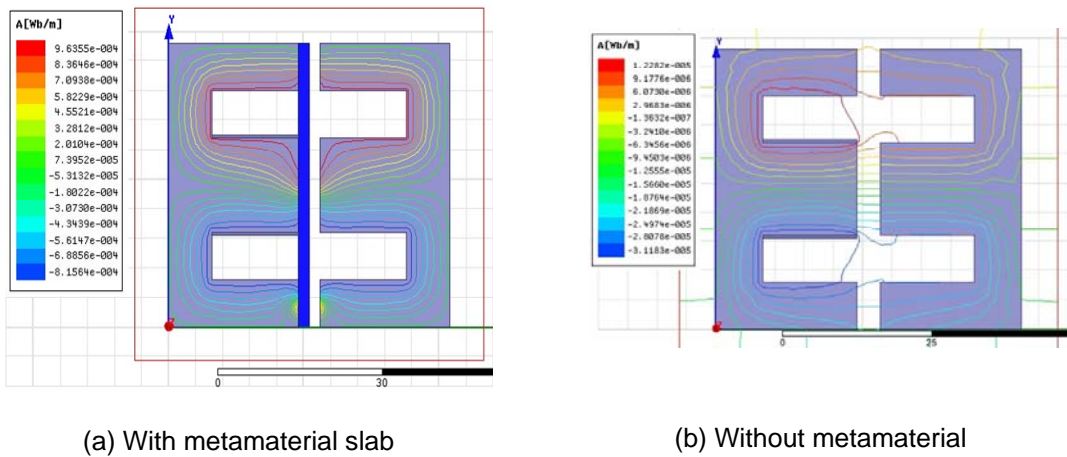


Figure 6. Fluxes distribution of CPT.

Observed from figure 6, we know that the magnetic fluxes concentrate at the edge of metamaterial slab, and the magnetic field intensity of secondary side core increased with the metamaterial slab. Compared with figure 6 (a) and figure 6 (b), it is clear that the magnetic flux in the core of secondary side with a metamaterial slab are denser than the one without metamaterial. Figure 7 (a) and (b) is the microscope of figure 6. Observed from figure 7 (a), the magnetic fluxes focused at the point A. Looking from the secondary side, it is just like that the fluxes emit at the point A. Compared with figure 7 (a) and (b), it is equivalent that the distance between primary side and secondary side decreases from the view of magnetic field.

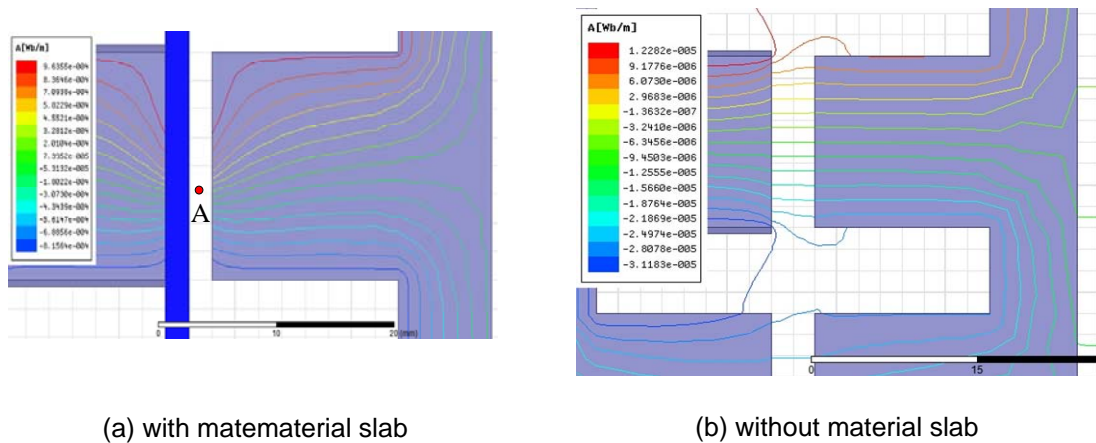


Figure 7. Fluxes distribution of CPT.

Different distances of primary side and secondary are simulated by software ANSOFT MAXWELL; the results are list in table 2. Figure 8 shows the trend of coupling coefficient of CPT with metamaterial and traditional CPT at different distances. The results show that the coupling of proposed CPT are strong than traditional one at different distances.

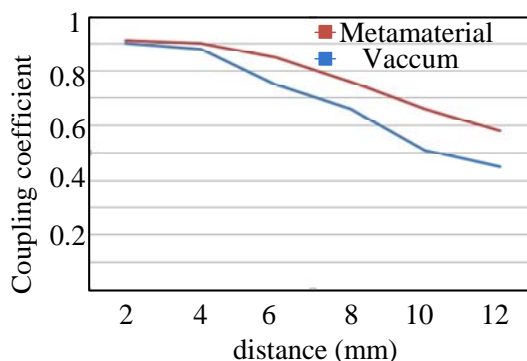


Figure 8. Coupling coefficient with different distance.

Table 2. Coupling coefficient of CPT with metamaterial

Distance (mm)	Coupling coefficient with metamaterial	Coupling coefficient with vacuum
2	0.91	0.86
4	0.89	0.88
6	0.86	0.75
8	0.76	0.67
10	0.65	0.5
12	0.58	0.44

4. Conclusion

In this paper, a novel concept of CPT is proposed. With a slab of metamaterial between the primary side and secondary side, the coupling coefficient of CPT increases. The FEA approach based on the Maxwell Equations show that with this metamaterial, the fluxes generated in the primary side focus at secondary side, thus the coupling of CPT strengthens. The proposed CPT is analyzed by FEA, and the simulation results show that the coupling coefficient increases with different gaps.

Acknowledgments

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