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SIMP-method topology optimization of ferrite structures in inductive power transfer systems

Yao Pei, Lionel Pichon, Yann Le Bihan, Mohamed Bensetti

Abstract— This article demonstrates the interest of topology optimization in designing the ferrite plate used in an inductive power transfer system for electric vehicles. The solid isotropic material with the penalization (SIMP) method is used to optimize the ferrite plate, and it modifies the topology of the ferrite shape iteratively. This SIMP method can lead to novel structures compared to usual existing shapes. In this paper, it is found that a part of the ferrite from the center and the edges of the predefined ferrite plate can be removed to save the ferrite volume while achieving a minimal reduction of transmission efficiency. Moreover, the results from topology optimization are influenced by the aluminum shielding plate near the ferrite plate. Hence, the ferrite on the receiver side has to be larger than the one on the transmitter side. These results give some design guidelines on arranging the ferrite placement for the system, and the approach could be generalized for shielding sheets/walls.

Index Terms—Inductive power transfer system, Topology optimization, Shielding optimization.

I. INTRODUCTION

THE electrification of transportation means has taken importance in recent years, especially in the automotive domain, where the problems of global warming are driving manufacturers to find cleaner solutions that are more respectful of the environment. However, promoting and adopting plug-in electric vehicles (EVs) raises many questions. First, the cost of lithium batteries is high. Second, the batteries are heavy. Third, the charging time for the battery is so long that it requires an expensive infrastructure for charging stations [1-3]. The use of inductive power transfer (IPT) charging systems is a promising solution. In such a system, the energy is transferred wirelessly between two coils (constituting the coupler) through the magnetic field. However, this inevitably causes electromagnetic field (EMF) leakage around the system [1-5].

To mitigate the effects of EMF leakage, shielding is usually added in IPT systems, thus improving the system performance and leading to better efficiency [4-6]. Different types of shielding have been reported in the literature. In [7-9], the extra

coil turns wound in the reverse direction to create a magnetic field in a reverse direction to the original magnetic field created by the coupler to minimize the EMF leakage. Another study by [10] incorporated additional reactive components (e.g., capacitors) and coil turns close to the transmitter coils for the shielding. Reference [11] designed a soft-magnetic-metal-based shield structure to reduce magnetic flux leakage. Recently, a hybrid shielding structure has been proposed by surrounding a reactive LC coil with a ring-based aluminum plate, which weakens EMF leakage around the system [12].

Among the types of shielding mentioned above, ferrite materials are commonly used in IPT systems due to their high permeability and low electrical conductivity [1-6]. Ferrite structures contribute to the shielding effectiveness of the system. The permeability and the losses of the ferrite material determine the magnetic field strength and hence the transmission efficiency of the system. Then, optimizing the ferrite topology can lead to significant improvements in the efficiency of the IPT system.

Recent literature proposes some parameter optimization methods used for the ferrite design of IPT systems [13-17], and for optimizing structural parts in antenna systems [18-21]. Although combining 3D finite element methods (FEM) with optimization algorithms provides a systematic, iterative process, it leads to heavy computations. To reduce the overall cost, a metamodel, such as sparse polynomial chaos expansions (PCE), can be used in the iterative procedure to deal with multiobjective optimization [22-23]. With such an approach, the computational burden can be strongly reduced. However, in these previous parametric optimization works, the general shape of the ferrite structures remains the same and follows some predefined shapes (rectangular, for example). This does not allow innovative ferrite structures. To face such limitations, topology optimization (TO) appears as a powerful computational technique that can be used to optimize the design of ferrite materials in IPT systems [24-27]. It involves iteratively modifying the topology of the ferrite material while ensuring that certain performance criteria are met. The

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performance criteria may include the magnetic field strength, the energy transfer efficiency, or the losses in the ferrite material [28]. The main TO methods are the solid isotropic material with the penalization (SIMP) method [29], the on-off method [30], and others [31]. The main advantage of TO is that it can lead to novel structures, but it is limited by the predefined investigation area.

In [24-25], the coil and magnetic-core shapes are optimized using the on-off method with the aid of a genetic algorithm and 3D FEM so that the coupling coefficient of the IPT system is maximized. Reference [26] proposed a TO method for the IPT system using the geometry projection method to generate the bar-shaped magnetic cores. In [27], TO is applied with the SIMP method to optimize the ferrite structure for circular couplers. Although these papers optimize the ferrite installed on circular/double-D couplers, they do not consider how the ferrite structure varies under different ferrite volume constraints (and then the cost of the system), and they do not give any guidelines to arrange the ferrite placement.

The interest of this work is to find a design guideline for the ferrite distribution that maximizes the transmission efficiency, while constraining the volume of the ferrite plate, obtaining a light and cost effective IPT system. TO with SIMP method is the most commonly used one due to its easy and intuitive implementation [29, 31], and it is adopted to generate different ferrite structures in two situations (without a shielding aluminum plate above the receiver [22], and with a shielding aluminum plate above the receiver [23]). The system has been previously studied in our lab by coupling optimization algorithms with the sparse PCE technique. The results obtained from TO could give some design guidelines for the ferrite arrangement during the design process of the IPT system.

The rest of the paper is organized as follows. Section II provides a general description of IPT systems for EVs and gives some equations about transmission efficiency. Section III presents an overview of topology optimization and how it works with ferrite structures. Some results are presented and discussed. Finally, in Section IV, the main outcomes of the work are summarized.

II. INDUCTIVE POWER TRANSFER SYSTEM

Fig.1 shows the block diagram of an IPT system, which is the most attractive for EVs. The system comprises a transmitter, a receiver, converters, and resonant compensation topologies. It is based on Ampere's and Faraday's laws in a time-harmonic regime [4]. First, the electrical network provides a DC-link voltage through the AC/DC converter to feed the transmitter. Then, the magnetic field produced by the transmitter is coupled with the receiver to induce voltages and currents. The induced power is rectified to charge the EV battery. Compensation topologies (such as series-series, parallel-parallel, series-parallel, and parallel-series) are connected to the transmitter and the receiver to create the resonant case and reduce additional losses [3-5]. The operating parameters of the system considered in this paper are listed in Table 1 [32-33].

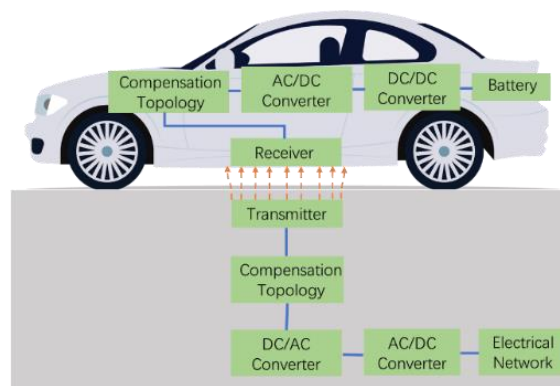
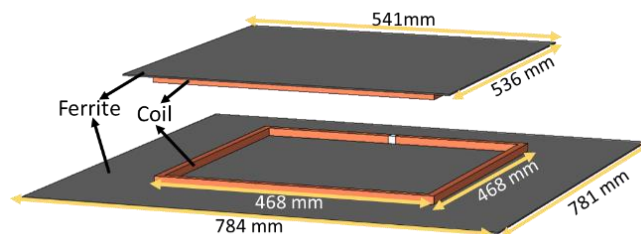


Fig.1. An inductive power transfer system

TABLE I. PARAMETERS AND IPT OPERATING STATUS

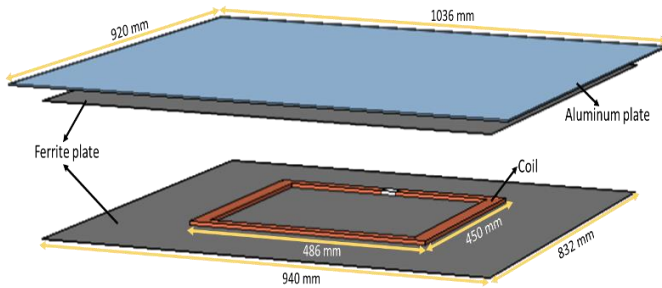
Parameter	Value [Unit]
Transferring power	2.5 [kW]
Operating frequency f_0	85 [kHz]
Transmitting coil current	42 [A RMS]
Air gap between coils	150 [mm]

Normally, the transmitter and the receiver consist of copper coils and ferrite plates. However, relying on the ferrite plates for the shielding is not only expensive but also ineffective and heavy for the receiver installed on the EVs [3-4, 23]. Therefore, to solve this problem, several solutions are proposed: one solution [22] is to design the ferrite on the receiver side appropriately in Fig.2 (a), and the other solution [23] is to add an aluminum plate above the receiver to mitigate the magnetic field generated by the transmitter, as shown in Fig.2 (b). It can also help to decrease the power losses in the vehicle chassis. Although the sizes of the coil are different in the figure, the total coil area is the same, and the turns of the coils are both equal to 6. The ferrite thickness is 2 mm, and they are made of 3C95 material from Ferroxcube [34], and its value of the saturation induction (B_s) is around 500 mT.



(a) Without an aluminum plate [22]

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(b) With an aluminum plate [23]

Fig.2. Arrangement of the transmitter and the receiver

For analyzing the IPT system transmission efficiency, circuit models are often used, and the compensation topologies are designed to minimize the reactive component of the electrical circuit. Following [3-5], the series-series compensation topology is considered because the resonance condition in this compensation remains constant, independently of the variations of the mutual inductance and the load. Therefore, the relationship between the maximum transmission efficiency η_{max} and the mutual inductance M between coils can be described in Equation (1) when the transmitter coil and the receiver coil are identical [35].

$$\eta_{max} = 1 - \frac{R_1}{\pi f_0 M} \quad (1)$$

where R_1 is the resistance of the transmitter as same as that of the receiver.

III. TOPOLOGY OPTIMIZATION

Although the dimensions of the ferrite can be easily selected by parametric optimization, however, it is limited to how to arrange the ferrite part in the specified size properly. So, to solve this problem, TO is used to find a ferrite distribution that maximizes the mutual inductance M , while constraining the volume of the ferrite plate, obtaining a light design for the IPT system. The basic idea of TO is to modify the topology of the ferrite shape iteratively. Changing the value of the local relative permeability allows the introduction of holes in the ferrite plate. Although there are several TO methods in the literature, the SIMP method is adopted to arrange the ferrite distribution in this section.

A. Introduction to SIMP-based topology optimization

The SIMP method discretizes a studied domain Ω into numerous elements, for which artificial density values are introduced as design variables ρ_i , as illustrated in Fig. 3. ρ_i is the material density in the i^{th} element. The artificial density value of ρ_i lying between 0 and 1, represents a proportion of solid material or void. It is desired to have either solid material ($\rho_i = 1$), or void ($\rho_i = 0$) as the final material in the element instead of having intermediates (unless intermediates are materials that are available for the users) [27, 31]. The material properties between the solid and void are interpolated with a smooth continuous function which depends on the material density ρ_i .

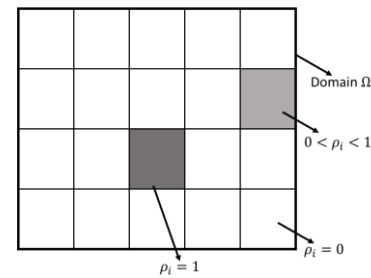
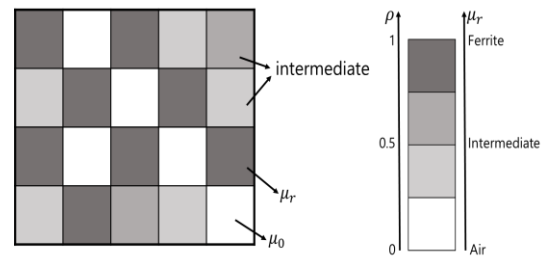


Fig.3. Domain Ω discretization with SIMP method [27, 31]

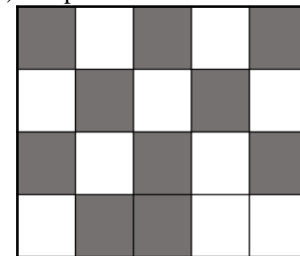
Then, as it is desired here to optimize the topology of the ferromagnetic materials, the adequate choice is to consider only permeability as the material property. So, the function of the ferrite's relative permeability μ_r is achieved in the following equation [27, 29, 31, 36-37]:

$$\mu_{r_i} = \mu_{r0} + (\mu_r - \mu_{r0})\rho_i^n \quad (2)$$

where μ_r is the relative permeability of ferrite, equal to 3000; μ_{r0} is the relative permeability of air, equal to 1, and $0 \leq \rho_i \leq 1$. The penalization coefficient n , (usually set between 2 and 5) is used to change the interpolation behavior with $n \geq 1$, and it works on the design variable ρ_i . The gradient-based optimization solver is used to find a good solution, and each variable is allowed to take the relative permeability of either ferrite (μ_r) or air (μ_{r0}) so as to maximize the objective function [27, 31, 36-37]. Fig.4 (a) shows the initial domain to be optimized, where each discretization represents a variable of the problem, and the color legend for the materials, with the corresponding ρ and μ_r . The TO result should be composed of ferrite and air, as shown in Fig.4 (b).



(a) TO process on SIMP method



(b) TO result

Fig.4. Ferrite placement with TO on SIMP method

In this section, the objective function of the ferrite placement optimization, under the defined ferrite volume constraint, is to minimize the ratio α :

$$\alpha = \frac{M_{initial\ ferrite\ domain}}{M_{\mu_{r_i}\ optimized\ ferrite\ domain}} \quad (3)$$

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where $M_{initial\ ferrite\ domain}$ represents the mutual inductance with the initial ferrite design domain, and $M_{\mu_r_i\ optimized\ ferrite\ domain}$ represents the i^{th} mutual inductance with the i^{th} ferrite structure. The optimization process is based on the assumption that the ferrite is not in the saturation state [27, 29].

The process for the TO on the ferrite placement is presented in Fig.5.

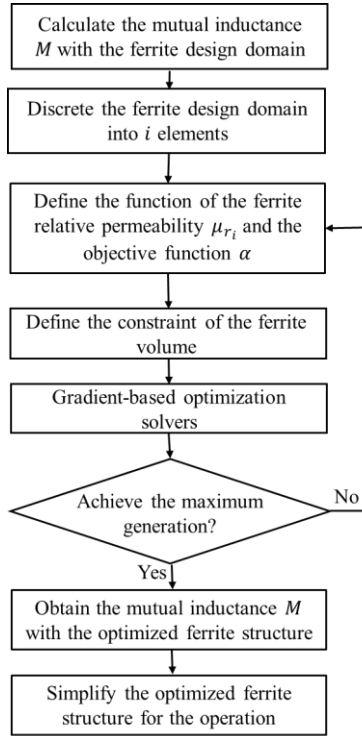


Fig.5. Flowchart of TO in the ferrite placement

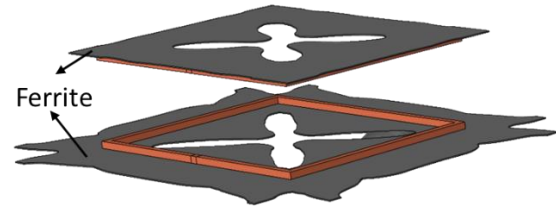
The constraint of ferrite volume can be defined manually, but the optimization of the ferrite placement aims at minimizing the reduction in the value of the mutual inductance M compared to M with the initial ferrite domain. The TO result allows some ferrite parts to be removed. The penalization coefficient n is set to 4, which is suggested by some authors in order to produce no intermediate values for μ_r [27, 31].

B. Topology optimization applied to the ferrite plate

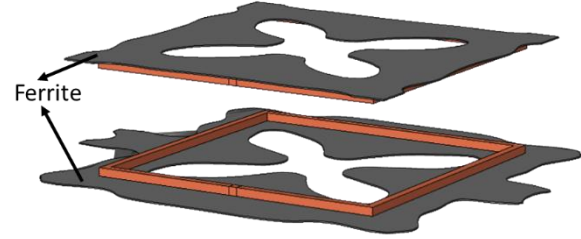
Here, the ferrite structure is discussed in two situations: without an aluminum plate above the receiver (in Fig.2 (a)) and with an aluminum plate above the receiver (in Fig.2 (b)). The TO process works with the optimization module [38] from COMSOL 5.6 on an Intel Xeon W-2125 processor.

1) Without an aluminum plate

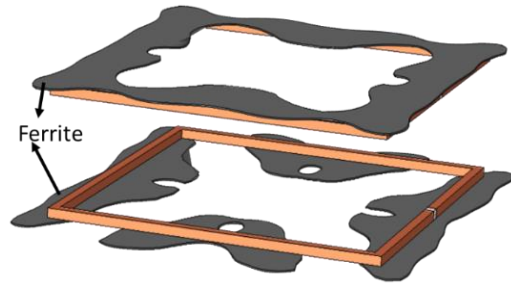
In order to further save ferrite volume and keep nearly the same mutual inductance, TO with SIMP method is used to find an efficient arrangement of ferrite. The initial dimension of the ferrite plate from Fig.2 (a) and the ferrite structure resulting from the TO optimization under different volume constraints are shown separately in Fig.6.



(a) Structure from TO under 70% of the ferrite volume



(b) Structure from TO under 50% of the ferrite volume



(c) Structure from TO under 30% of the ferrite volume

Fig.6. Ferrite placement without an aluminum plate

The relationship between the ferrite volume and the mutual inductance is shown in Fig. 7.

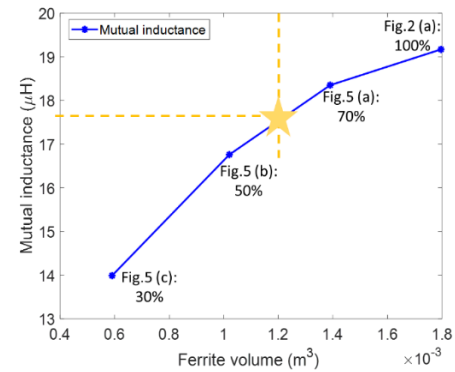


Fig.7. Relationship between the ferrite volume and the mutual inductance

Then, it can be observed that during the TO process, removing a part of the ferrite from the center and the edges of the ferrite plates is recommended, no matter the constraint of the ferrite volume ratio. Arranging the ferrite plates with this tip can facilitate a 40% reduction of the ferrite volume, as labeled by the yellow star in Fig.7. Besides, it also has an approximate 10% reduction in the mutual inductance.

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2) With an aluminum plate

Even in the case of an aluminum plate above the receiver, the previous optimization procedure can also provide an appropriate arrangement of ferrite for saving ferrite volume and keeping nearly the same mutual inductance. The initial dimension of the ferrite plate from Fig.2 (b) and the ferrite structure under different volume constraints are presented separately in Fig.8.

It shows that during the TO process, a part of the ferrite from the center and the edges of the ferrite plates should be removed no matter the constraint of the ferrite volume ratio. However, due to the effect of the aluminum plate, the ferrite on the receiver side has to be larger than that on the transmitter side.

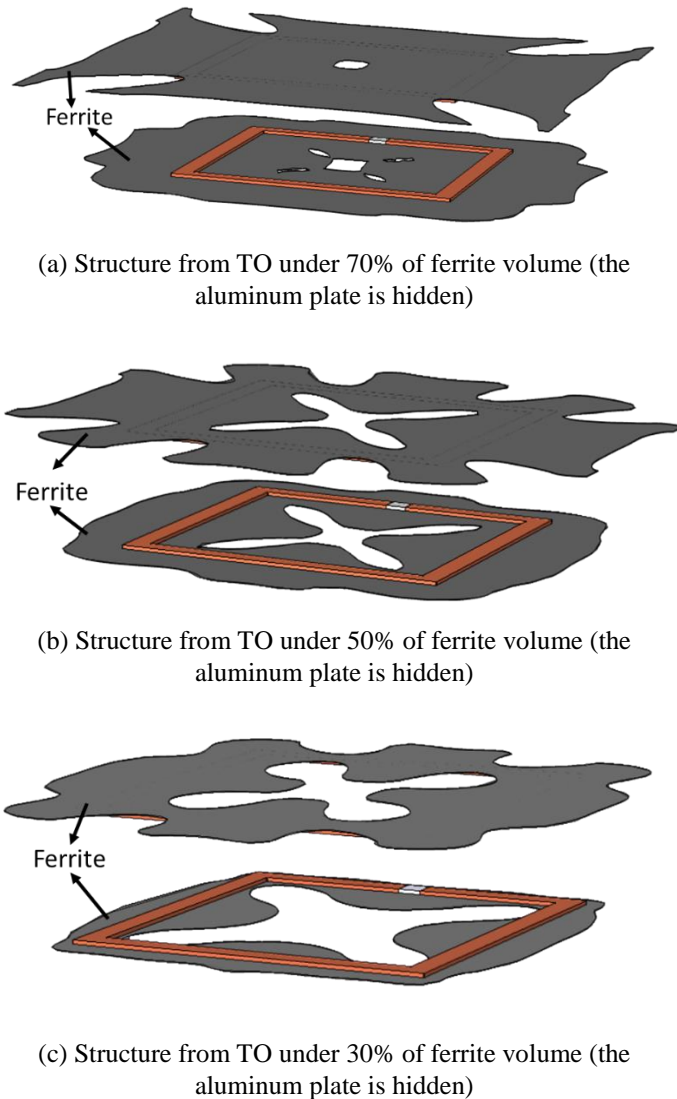


Fig.8. Ferrite placement with an aluminum plate

Then, the relationship between the ferrite volume and the mutual inductance is summarized in Fig. 9.

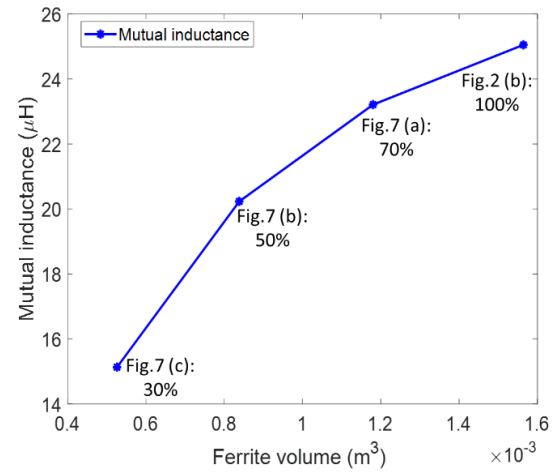


Fig.9. Relationship between ferrite volume and mutual inductance

Compared to Fig.2 (b), Ferrite structure Fig.7 (a) saves almost 30% of ferrite, but the mutual inductance decreases by around 10%.

C. Discussion

TO, with the SIMP method, provides a quite original ferrite placement. A part of the ferrite from the center and the edges of the ferrite design domain can be removed to decrease the volume and keep a minimal reduction of the mutual inductance (compared to the one calculated with the initial ferrite design domain) when the transmitter and the receiver are aligned. However, the results from TO are influenced by the aluminum plate near the ferrite design domain. With the existence of the aluminum plate, the ferrite on the receiver side has to be larger than that on the transmitter side.

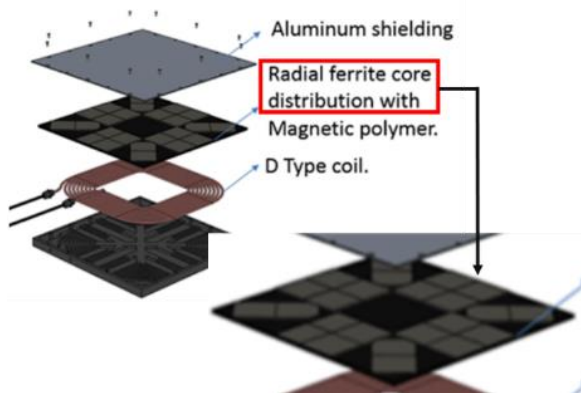
Obviously, the structures from the optimization procedure have to be further simplified because the TO results cannot be easily manufactured in reality. Then, there are some features that can be deduced from how ferrite should be placed in a manufacturing form [24-27, 31]:

- The optimized ferrite structures are similar but not entirely symmetrical plates. This is due to the optimization randomness. In practice, the placement of the ferrite should be symmetrical, as the coils are rectangular and identical. Therefore, the ferrite should be simplified as symmetrical.
- The appearance of curves is inevitable in topology optimization. Therefore, curves will be approximated by straight lines or stair-case lines for simplification and operability. Ferrites are commercially available as small tiles and bars. The curved boundaries of the shapes obtained as theoretical results have to be approximated according to the size of the tile/bar.

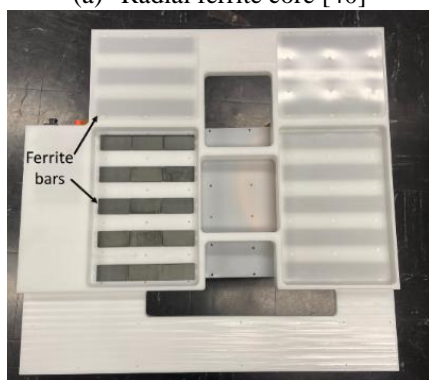
The present work shows an interest in the distribution of ferrite for IPT systems. Some researchers propose using ferrite bars instead of the ferrite plate for the IPT systems [3-5, 39]. In [40], the radial ferrite core is distributed on the receiver side, as shown in Fig. 9 (a). The center and the edges of the ferrite

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corner are removed, and they are made from tiles of ferrite material, which satisfies the manufacturing rules. In our GeePs laboratory, for example, the ferrite bars are distributed as illustrated in Fig.9 (b). The ferrite's center is empty, and two sides of the plate are arranged by ferrite bars. Fig.9 (a) and (b) have an arrangement of ferrite bars similar to the TO results. Our optimization procedure gives a possible theoretical explanation of the ferrite shapes used in practice.



(a) Radial ferrite core [40]



(b) Ferrite bars

Fig.10. Ferrite placement for IPT systems

IV. CONCLUSION

This paper shows that topology optimization of ferrite materials in IPT systems is a promising approach for improving the efficiency of these systems. By optimizing the design of the ferrite material, it is possible to keep nearly the same power transmission efficiency and reduce the overall size, weight, and cost of the system compared to those obtained with traditional approaches. By discussing the ferrite structures of the IPT system without an aluminum plate and with an aluminum plate, decreasing 30% of the ferrite volume leads to only a 10% reduction of the mutual inductance. It is also found that a part of the ferrite from the center and the edges of the predefined ferrite plate can be removed to save the ferrite volume while achieving a minimal reduction of the mutual inductance value. Moreover, the results from TO are influenced by the aluminum plate near the ferrite design domain, so the ferrite on the receiver side has to be bigger than the one on the transmitter side. However, if the TO results are planned to be used in reality, they need to be further simplified for the manufacture. Current ferrite structures

can be explained as resulting from topology optimization. Finally, the approach described in this work can be applied to the design of any shielding plate. Furthermore, for high-power IPT systems, additional constraints, such as magnetic flux density distribution, can be added to the optimization process.

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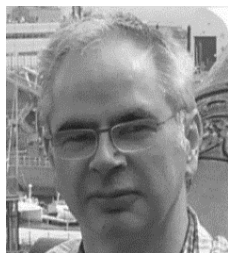
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