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RESEARCH ARTICLE

Magnetic Integration of Circular Pads and LCC-LCC for EV Wireless Charging Tolerant to Misalignment

JUAN C. QUIRÓS[1], ELISEO VILLAGRASA GUERRERO[1], JAMSHID KAVIANPOUR SANGENO[2], AND ALICIA TRIVIÑO[1]
[1]Department of Electrical Engineering, University of Malaga, 29010 Málaga, Spain
[2]Department of Electrical and Computer Engineering, University of Michigan–Dearborn, Ann Arbor, MI 48109, USA
Corresponding author: Alicia Triviño (atc@uma.es)

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ABSTRACT A key component of the magnetic resonant chargers is the coupler, which must be connected to the compensation networks to improve the power transfer. The design of both structures are tightly related since the configuration of one affects the other. Thus, the integration of both structures is convenient to ease the development of other systems of the wireless charger such as the power converters and control. This integration can be optimized if physical aspects are considered. In this paper, we propose a novel physical integration of circular pads and a LCC-LCC compensation. If both systems are connected without any specific consideration, the inclusion of the reactive components in this high-order compensation network derives in a more bulky-structure. Our proposal consists in implementing the inductors of the compensation networks in the same structure of the power coils, leading to a compact system. The position of the compensation coils must be carefully analysed in order to minimise undesired coupling effects. In the proposed integration approach, we have analysed the coupling coefficients between the magnetic components for several positions to identify the optimised configuration. The feasibility of this compact structure has been validated in a prototype, proving that the power transfer levels are suitable. These tests have been carried out for different misalignment conditions, which could model its performance for dynamic charging.

INDEX TERMS LCC-LCC compensation, circular coils, magnetic integration, wireless power transfer, finite elements analysis, electric vehicle, misalignment.

I. INTRODUCTION

Sustainable transport modes are attracting the interest of the industrial and research community. Plug-in Hybrid Electric Vehicles (PHEVs) and pure Electric Vehicles (EVs) constitute a sustainable alternative to fuel-based vehicles. However, there are still some issues to address in order to make them more appealing. In this sense, there are some on-going works trying to improve their charging procedure. The use of Wireless Power Transfer (WPT) technologies will ease this operation and they will also allow dynamic charging, that is, charging the vehicle while it is moving [1].

The interest in EV wireless chargers is growing as they are convenient, reliable, and a less risky charging option than conductive charging. In particular, inductive wireless chargers are the most mature WPT technology applied to EVs [2]. This technology is based on two loosely coupled coils. It employs a coil as a transmitter capable of transferring power through the mutual inductances and a coil as a power receiver with alternating magnetic fields coupled across a relatively large air gap between the coils. The coils are placed in the charging infrastructure and on the vehicle chassis respectively. These magnetic components are connected to

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reactive structures, referred to as the compensation networks. Power converters are also included in these systems in order to generate a kHz-signals.

There are many examples of research in this field with coils design, power converters, control, compensation, and safety as the most popular topics [3]. Two of the main research areas are compensation topologies and coil design. Since the gap between the two coils is large, the coupling coefficient is small, resulting in a large leakage inductance. Therefore, the design of the couplers' geometry is significant in obtaining an acceptable coupling coefficient and a high-quality factor of the coil. It is of special interest that the coupling coefficient remains as stable as possible even with coil misalignment, as a realistic use of wireless chargers may not guarantee that the coils are perfectly aligned.

In WPT systems, the compensation circuit is also necessary, as it helps to maximize the power transfer capability and minimize the VA rating of the power electronics supply [4]. In general, four mono-resonant compensation topologies - SS, SP, PS, and PP - are widely used. In each topology, S stands for series, while P stands for parallel, being the first term associated with the primary side and the second term refers to the connection with the secondary coil. These topologies have some disadvantages, such as sensitivity to the parameter variation and control stability [5]. Thus, a topology called the LCC-LCC topology is introduced because it not only has a resonant frequency independent of coupling coefficients and load conditions, but it is also highly efficient because of working in zero-current switching condition with a stable performance even with misalignment [6]. Several recent works also propose innovative control techniques for this compensation system. In [7] and [8] the authors make a frequency control for a WPT system in order to control efficiency. In [9] the authors propose a control with a DC-DC converter in order to maximize the efficiency.

The design of a wireless charger entails the definition of the coils (geometry, number of turns, size of the wires, etc.) and the compensation networks (topology and values). For an optimised system, the design of these two systems must be done altogether as the quality factors of the coils and other electrical features of the coils both affect on significant parameters of the wireless charger such as the bifurcation phenomenon, the maximum currents and voltages [10]. Since the coil geometry clearly impacts on the electrical parameters of this component, it is usual to set one design phase where the coils' geometries (and their corresponding electrical parameters) and the compensation networks are defined [11], [12], [13]. In this phase, both systems are studied jointly but the integration is limited to the electrical connection of two separate structures. A novel approach consists in building both systems in a more compact structure, which could reduce the volume of the compensation networks. This is specially suitable for high-order compensation networks. In particular, one of the major drawbacks of LCC-LCC compensation is the volume due to the use of compensation coils.

Despite the benefits of achieving a compact integration, the design is not trivial. It becomes more complex as the coupling coefficients between both structures must be minimised. A careful integration approach must be done in order to obtain a valid solution. There are some previous works oriented to the physical integration of the coils and the compensation networks so that they share the magnetic core and they result in less bulky solutions. For complex coils, we have some proposals in [14], [15], [16], [17], [18], [19], and [20]. In [14] the authors propose an integration between DD power coil and rectangular compensation coils. In this integration, a rotation of the compensation coils is done in order to find the least coupling coefficient. In [15] the authors propose an integration between DD power coils and DD compensation coils. They also study the angle in which the coupling coefficients are minimized. In [16] the authors study the integration of DD compensation coils and rectangular for power transfer coils. An analysis of misalignment and angles are also done in order to find the best solution. Other complex topologies (bipolar and tripolar) for the magnetic integration are proposed in [19] and [20]. Some authors like in [17] only integrate the compensation coil on the secondary side because they do not consider space limitations on the primary side. Finally, in [18] square coils are considered for power and compensation coils. Table 1 summarizes a comparison of the relevant solutions about the integration of power and compensation coils. The comparison about the evaluation of the solutions focuses on: (i) checking if the design was tested under misalignment conditions, (ii) studying if the efficiency was computed, (iii) proving if the integration is valid for different load conditions and (iv) analysing the performance of the system with an integrated and non-integrated solution.

As can be observed, all of works select LCC-LCC except for [18], which uses LCC-S as the compensation network. For the compensation and power coils the most common solutions are DD and square-rectangular coils. Few articles use the circular pad, which is simple but it offers an acceptable performance [6]. Circular coils can be found in e-scooters [21], personal mobility devices [22], drones [23], [24] or e-bikes [25]. The effect of misalignment on the power transfer and on the magnetic integration is a common topic discussed in the related work but the effect of both the magnetic integration and misalignment on the efficiency is a topic only studied in [15], [16], [17], [18], and [20]. How the power level at the output affects the efficiency in this integrated systems is commonly a non studied topic: works in [16], [17], and [20] describe a power analysis and study the effect on efficiency. Finally, the air gap used for different authors is commonly greater than the 100 mm being [17] and [18] the only articles that use an air gap lesser than 100 mm.

TABLE 1. Summary of contributions.

Paper	Compensation	Power coil	Compensation coil	Misalignment	Efficiency analysis	Power variation	Integration effect analysis	Air gap
[14]	LCC-LCC	DD	rectangular	✓	✓	×	×	150 mm
[15]	LCC-LCC	DD	DD	×	×	×	×	150 mm
[16]	LCC-LCC	rectangular	DD	✓	✓	✓	×	200 mm
[17]	LCC-LCC	Circular	Circular (only receiver)	✓	✓	✓	×	50 mm
[18]	LCC-S	Square	Square	✓	✓	×	×	90 mm
[19]	LCC-LCC	DD-Bipolar	Square	✓	×	×	×	150 mm
[20]	LCC-LCC	DD-Tripolar	Square-Tripolar	✓	✓	✓	×	130 mm
Proposal	LCC-LCC	circular	circular	✓	✓	✓	✓	150 mm

This paper addresses the physical and magnetic integration of circular pads and LCC-LCC compensation networks for EV applications. The main contributions of the paper are:

- The analysis of the feasibility of integrating the LCC-LCC compensation in circular planar power transfer coils. A study about the placement of the compensation coil is performed in order to determine the optimised position. In this study the relative position between the power transfer coils and the compensation coils has been analyzed in order to achieve the best results possible in order to obtain the minimum coupling coefficients between both coils.
- The study of the misalignment effects on the coupling factors between compensation and power transfer coils to determine the best configuration of the compact structure. In particular, horizontal misalignment was considered. The nature of the selected coil topology (circular) makes the system to be symmetrical and thus, rotational analysis are not needed because it does not affect on the system performance.
- The evaluation of the compact structure under misalignment and comparison with an equivalent non-integrated structure. With this study, the benefits of the integration can be also analysed in terms of the performance of the system.

The remainder of the paper is structured as follows. Section II describes the proposed compensations networks. Section III describes the integration between the power transfer coils and the compensation coils. Section IV shows the characteristic of the implemented coils and an analysis of the coupling coefficients. Section V shows the results about the performance of the integrated structured in a laboratory test environment. Finally, Section VI outlines the main conclusions of this work.

II. LCC-LCC COMPENSATION TOPOLOGY

Figure 1 shows the basic structure of WPT system with LCC-LCC compensation. As the system works at a higher frequency than the grid, it is necessary to use an inverter. This inverter will transform the DC input voltage (V_s) to high-frequency voltage. The power is transmitted using LCC-LCC compensation to make the system be resonant. Finally, the high-frequency voltage is converted again to DC voltage using a rectifier for this purpose.

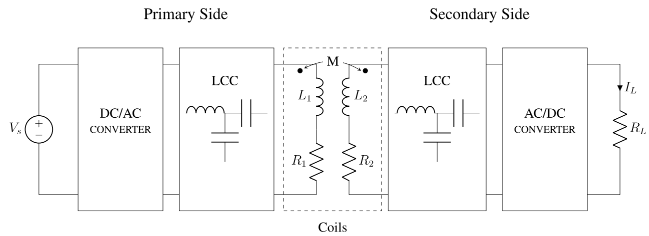

FIGURE 1. Generic WPT system with LCC-LCC compensation.

The LCC-LCC compensation is a compensation method that includes a series inductor and a parallel capacitor compared with the Series-Series (SS) compensation which has only a series capacitor. This compensation behaves as a current source and the transfer power decreases with the decreasing of mutual indutance. The maximum power transfer is achieved when both the primary and secondary coils are aligned. Another characteristic of the LCC-LCC compensation is that the current on the primary side is only determined by the input voltage. This characteristic helps to maintain constant operation independently of load variations being thus perfect for multi-receiver systems or dynamic WPT operations.

Several studies have demonstrated the efficiency of a LCC-LCC compensation topology when used in electrical vehicles and plug-in electric vehicles for WPT applications. With LCC-LCC compensation, the inverter operates at a frequency independent of the load condition and the coupling coefficient, and it is also able to work in a zero current switching condition. By using a LCC-LCC compensation at the secondary side, a unity power factor can be achieved, which leads to a high-power efficiency due to the negligible reflected reactive loading on the transmitter side. On the other hand, the double Sided LCC-LCC compensation has higher number of components, and consequently occupies more space than the other compensation types.

The circuit diagram of the LCC-LCC compensation topology is shown in Fig. 2. L_1 is the self-inductance of the power coil of the primary side, while L_{f1}, C_{f1} and C_1 are the primary compensation components. L_2 is the self-inductance of the secondary side power coil, and L_{f2}, C_{f2}, and C_2 are the components of the associated compensation system. The following equations are used to design the circuit parameters to achieve a constant resonant frequency ω in

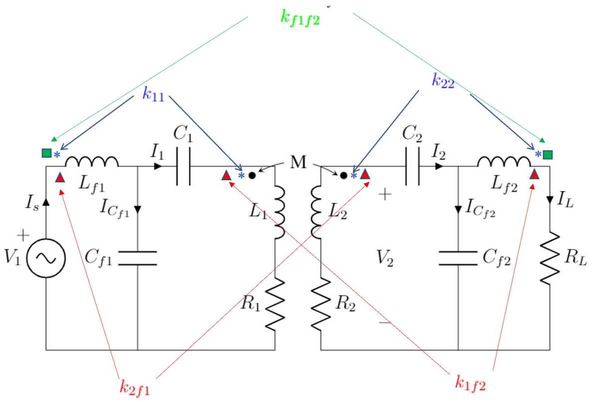

FIGURE 2. LCC-LCC compensation topology and its coupling coefficients.

the topology [26]:

$$C_1 = 1/(\omega^2(L_1 - L_{f1})) \quad (1)$$

$$C_2 = 1/(\omega^2(L_2 - L_{f2})) \quad (2)$$

$$C_{f1} = 1/(\omega^2 L_{f1}) \quad (3)$$

$$C_{f2} = 1/(\omega^2 L_{f2}) \quad (4)$$

The power transfer is related to the mutual inductance M between the primary and the secondary coils, being $M = K_{12}\sqrt{(L_1 L_2)}$.

III. INTEGRATION OF COMPENSATION AND POWER COILS

The physical integration of the power pads and the coils of the compensation networks leads to undesirable additional coupling coefficients. In particular, extra couplings such as K_{1f1}, K_{2f2}, K_{1f2}, and K_{2f1} are produced. M is the main mutual inductance, with an associated coupling coefficient equal to K_{12}. In WPT, the main coupling K_{12} plays a principal role to transfer power from one side to another, and the other extra couplings are redundant. Moreover, they could lead to unexpected problems (overvoltages, overcurrents, bifurcation) if they are not considered properly. The inclusion of these additional coupling coefficient in the theoretical analysis is complex so the strategy to follow is to maximize the main coupling and eliminate the four extra couplings or minimize their coupling effects to a negligible level. This is an issue that must be carefully considered in the integration approach.

In our case, we are integrating a circular pad and the LCC-LCC compensation network as shown in Fig. 3. The design criterion is to place the compensated coil in the region with weaker magnetic field densities in order to further lower coupling effects between the power coil and the coils of the compensation networks. By means of simulations in Ansys Maxwell, we have observed that the best position to place the coil is in the middle of the circular coupler. The dimensions have been optimized in order to obtain maximum coupling coefficient K_{12} which should be more than 0.18, and

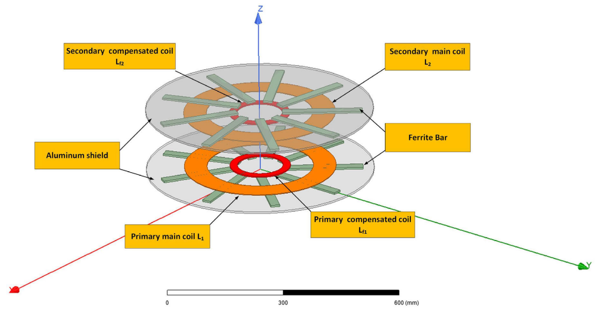

FIGURE 3. Structure of the integrated magnetic coupler structure.

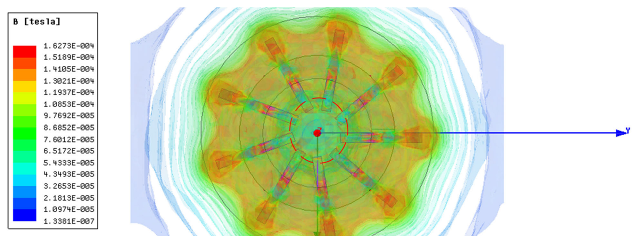

FIGURE 4. Magnetic field densities of the primary side.

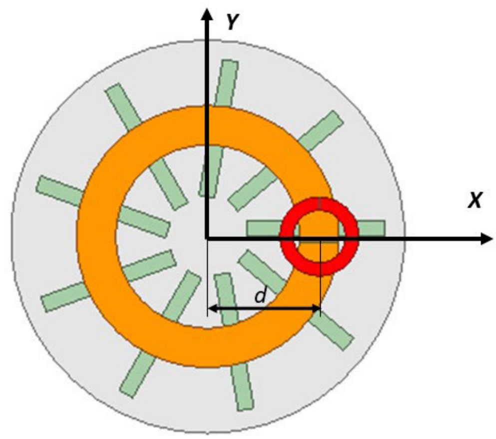

FIGURE 5. Displacement between compensation and power transfer coils.

minimum same-side coupling coefficient K_{1f1}, K_{2f2} which should be less than 0.1. Our proposal is illustrated in Fig. 3. In order to illustrate the areas with less presence of magnetic field Fig. 4 is used. This Figure is an example of the distribution of the magnetic fields under a current of 1 A in the primary coil.

To ensure that the position with less coupling factor between the compensation and the power transfer coil is the center, an analysis has been done. In Figure 5 compensation and power transfer coils are represented (red and orange circles respectively), with a displacement of d. The analysis consists in moving the compensation coil along the x-axis in order to find the position with less coupling coefficient between them while maximizing the coupling associated to the power transfer (K_{12}). Figure 6 shows how the coupling

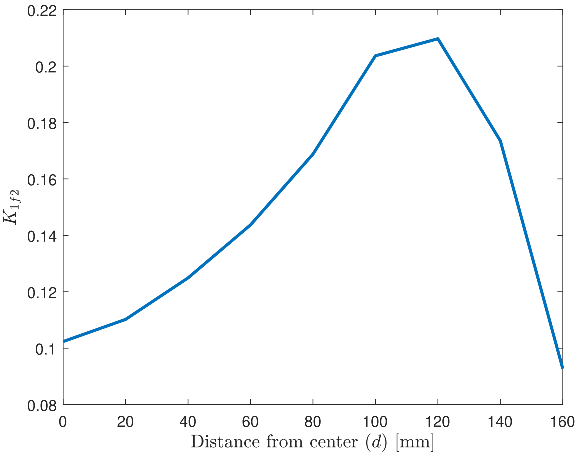

FIGURE 6. Coupling coefficient between compensation and power transfer coil analysis.

coefficient between a power transfer and a compensation coil changes depending of the relative distance between them. It can be observed that as the compensation coil gets further from the power transfer coil the coupling coefficient between them gets higher until the maximum is reached. For positions further than this maximum the compensation coil is above the external diameter of the power transfer coil so that the integration of both coils is no longer existent. Regarding the coupling coefficient K_{12}, an analysis has been done as well. Results show that the position of compensation coils does not affect the coupling coefficient K_{12} being this one constant for every position.

In conclusion, the optimal solution for this topology is to place the compensation coil and the power transfer coil aligned.

IV. MISALIGNMENT EFFECTS

An additional step of the design is the validation of the performance of the structure under misalignment conditions, which may be present in conventional EV wireless charging. To do so, the integrated magnetic structure is evaluated for a specific implementation in Ansys Maxwell. The features are detailed in Table 2. To mitigate the effects of the extra couplings, the coupling coefficients K_{1f2}, K_{2f1}, K_{1f1}, and K_{2f2} must be reduced during the magnetic coupler design. Taking into account the magnetic fields of the power coils and the compensation coils, the closer the magnetic flux of the outflow is to the inflow, the lower the extra coupling coefficient, which includes all cross-side and same-side couplings. Furthermore, since the magnetic field of the power coils is unequal, the coupling would be affected by the various locations of compensation coils. To determine the results of various misalignments, Fig. 7 is used to explain the misalignment in a horizontal plane between the power coil and the compensated coil on the same side. Ansys Maxwell is used for simulating compensation inductances from a misalignment of 0 mm to 450 mm, and the result is shown in Fig. 8.

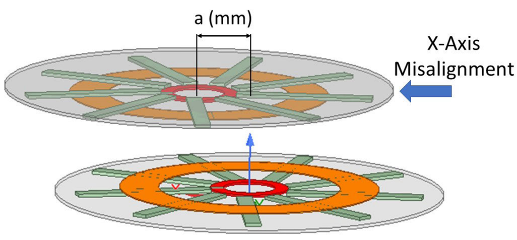

FIGURE 7. Misalignment between coils.

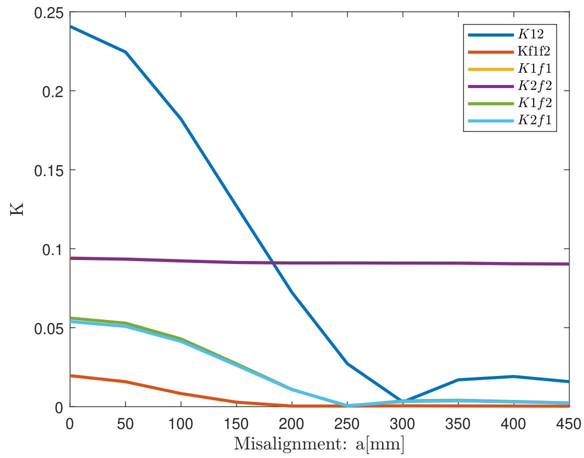

FIGURE 8. Coupling coefficients for compensation and power coils.

As can be observed, misalignment affects the same-side coupling coefficients. This value is not actually zero, but can be minimized. Fig. 8 verifies that the pad center is the most convenient place to add compensation coils because the coupling coefficient K_{1f1} and K_{2f2} are reduced to its minimum level. Additionally, the simulation results of coupling coefficients K_{12}, K_{1f2} and K_{2f1} as a function of horizontal coil misalignment are also shown in Fig. 8. K_{12} is kept in an acceptable range up to 50 mm of horizontal coil. Since the cross-side coupling coefficients K_{1f2} and K_{2f1} have insignificant amount in 0 mm misalignment, therefore, they are negligible.

Finally, Fig.8 shows the coupling coefficient between the compensation coils (K_{f1f2}) under misalignment conditions. It can be seen that this coupling value is insignificant, as it decreases heavily with misalignment, reaching a maximum of 0.02. This analysis let us consider this result as negligible for the rest of the implementation and theoretical analysis.

V. EXPERIMENTAL RESULTS

In order to verify the correct functioning and design of the proposed system, an experimental implementation has been realized. In these experiments the coupling coefficients are tested in order to ensure values near to zero and thus, validating the design process. The efficiency of the system and its electrical parameters are also measured in order to check a right functioning.

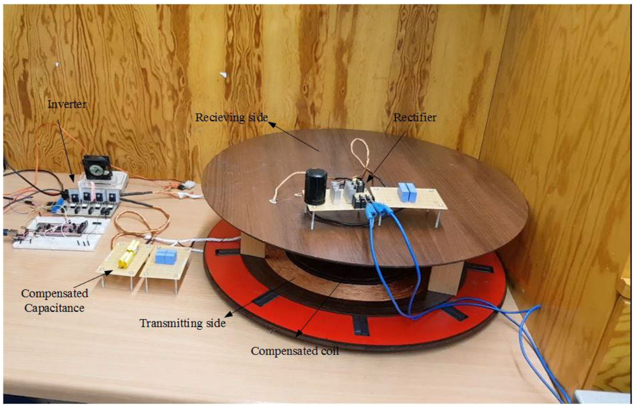

FIGURE 9. The experimental setup.

TABLE 2. Wireless power system specifications.

Parameters	value
Input DC voltage	80 V
Air-gap	150 mm
Coupling coefficient	0.22
Primary self-inductance	311 μ H
Secondary self-inductance	312.2 μ H
Primary compensation inductance	68 μ H
Secondary compensation inductance	69.5 μ H
Power coils diameter	40 cm
Number of turns of the power coils	20
Compensation coils diameter	12 cm
Number of turns of the compensation coils	21
C_1	14 nF
C_2	14 nF
C_{f1}	59 nF
C_{f2}	59 nF
Switching frequency	50 kHz
Maximum power	500 W
Efficiency	91.25%

The implemented power transfer coils have 40 cm of external diameter, 28 cm of internal diameter and 20 turns of Litz wire. The compensation coils have an external diameter of 12 cm and 8 cm of internal diameter with 21 turns of Litz wire. Ferrite tiles are used for this implementation. They have been positioned in a radial disposition. Their dimensions are 21 × 2.4 × 0.5 cm and both power transfer coils have 9 of them. Finally, an aluminum plate shielding is placed for both power transfer coils. These plates have a diameter of 60 cm.

Fig. 9 displays the experimental set-up for the integrated LCC-LCC compensation with the circular pad. The specifications of the coils and circuit parameters are given in Table 2. Fig. 10 presents the proposed coil configuration showing the compensation inductance integrated into the power coils. The coils are made of AWG-38 Litz wires for a system resonant frequency of 50 kHz to minimize the skin effect. The current density is about 6 A/mm2. Apparently, the compensation coils and the power coils are decoupled since K_{1f2}, K_{2f1}, K_{1f1}, and K_{2f2} are all nearly zero.

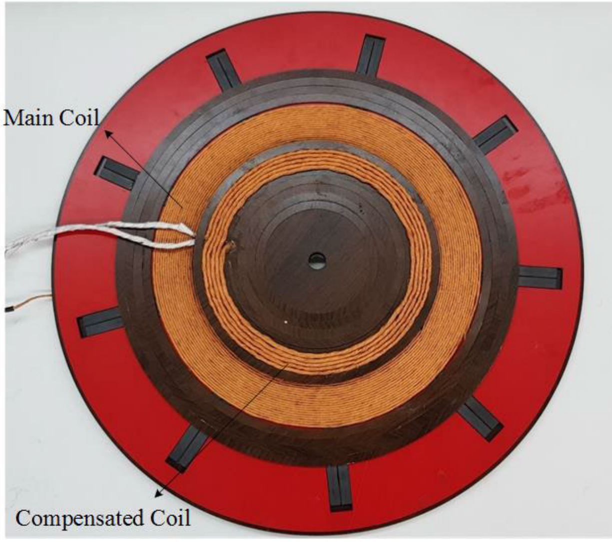

FIGURE 10. The experimental coil structure.

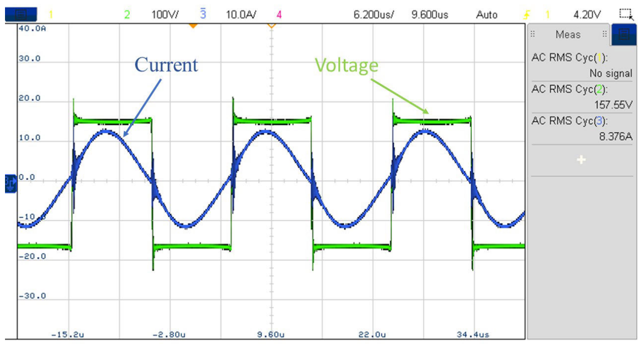

FIGURE 11. Voltage and current on the primary side.

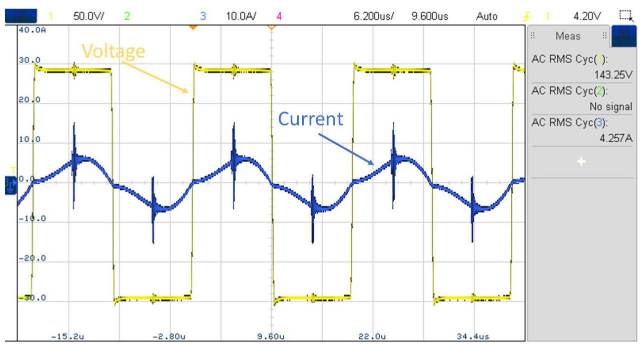

FIGURE 12. Voltage and current on the secondary side.

The waveforms of the input and output voltages and currents of the LCC-LCC compensation are shown in Figs. 11 and 12. In fully aligned, the system delivers 500 W power from DC resource to the load with the efficiency of 91.25%.

Other several experiments have been carried out in order to test the viability of the proposal. The effect of misalignment

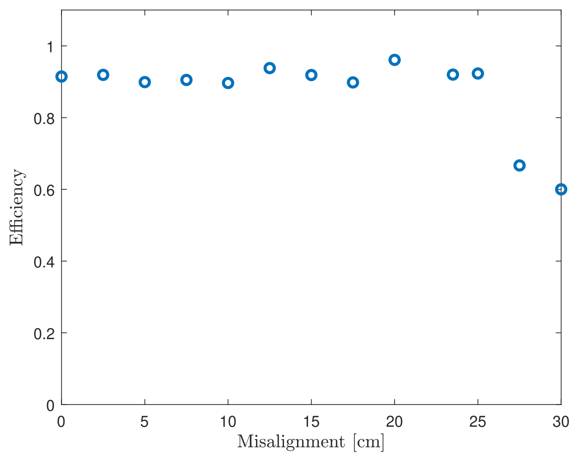

FIGURE 13. Effect of misaligment in efficiency.

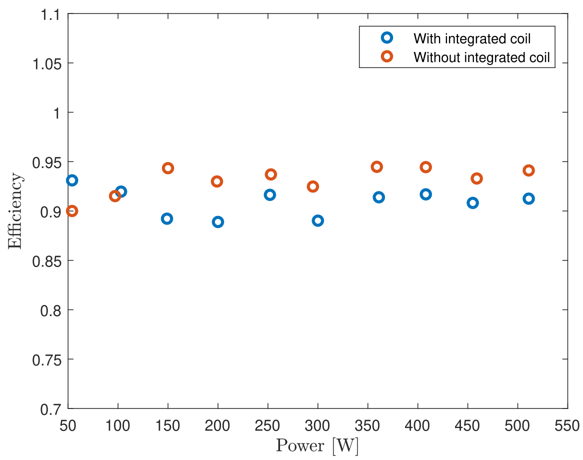

FIGURE 14. Variation of efficiency as a function of power.

is shown in Fig. 13. In this Figure the efficiency has been measured for different positions with horizontal misalignment. The experiment shows that the efficiency is maintained above 90% in most part of the range. The efficiency only goes down when the misalignment is near the power coil radius length.

In Fig. 14, we show the comparative analysis of an integrated and non-integration solution in terms of the system performance. Two sets of experiments have been carried out for this. In these experiments the effect of the output power on the efficiency is shown, with and without the compensation coil integrated on the power coils. Without the integration of the compensation coil, it can be seen that the efficiency is higher than without the integration. This is due to the coupling between the compensation and the power coils, which leads to a reduction of the magnetic field crossing the power coils. Anyway, in both cases the efficiency is above 90% in the range tested. We can conclude that the integration of the compact and the power coils is feasible as it achieves acceptable efficiency levels (almost the same that without the integration) but reducing the space needed.

VI. CONCLUSION

This paper proposes a compact structure that physically integrates the coupled circular coils and the compensation coils in an LCC-LCC wireless charger. The proposal is based on a careful design in which the potential placement of the compensation coils is studied. The results demonstrate that the main coupling coefficient is kept in an acceptable horizontal variation whereas the additional coupling coefficients are lower than 0.12 for 50 mm of misalignment. Finally, a magnetic coupler with minimized extra couplings is designed, fabricated, and tested. The 700mm-diameter magnetic coupler can transfer 500 W with 91.25% efficiency to the load with a 150-mm gap when fully aligned. The benefits of the compact structure are not only studied in terms of space reduction but the system performance is evaluated with different power levels and misalignment conditions. The proposed structured can lead to reasonable efficiency levels (slightly lower than those achieved with a non-compact charger) but with a very convenient reduction of the dimensions.

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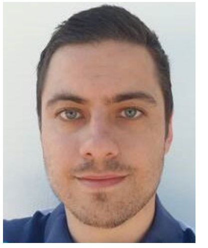
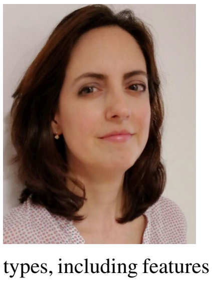
JUAN C. QUIRÓS was born in Estepona, Spain. He received the B.Sc. degree in electrical engineering and the M.Sc. degree in mechatronics engineering from the University of Malaga, in 2021 and 2022, respectively, where he is currently pursuing the Ph.D. degree in wireless power transfer in electric vehicles, with a focus on the integration with conductive chargers. He was a recipient of the Best Student of the Year Award for the B.Sc. degree.



ELISEO VILLAGRASA GUERRERO was born in Málaga, Spain. He received the B.Sc. degree in industrial technologies from the University of Malaga, Spain, in 2020, where he is currently pursuing the double master's degree in industrial and mechatronics engineering.

JAMSHID KAVIANPOUR SANGENO was born in Mazandaran, Iran, in 1991. He received the master's degree in electrical engineering from the Amirkabir University of Technology. He is currently pursuing the Ph.D. degree in power electronics converters with the University of Michigan–Dearborn, Ann Arbor, MI, USA. His research interests include wireless power transfer and dc–dc converters for electric vehicles.



ALICIA TRIVIÑO received the dual master's degrees in telecommunication engineering and computer science engineering from the University of Malaga, Spain, in 2002 and 2008, respectively. Her thesis, which she defended in 2007, with a focus on wireless networks.

She is currently an Associate Professor with the University of Malaga. In the field of electric vehicle wireless chargers, she has played an active role in designing and developing several prototypes, including features such as bi-directionality and dynamic charging. Her research interest includes wireless power transfer.