A Novel Honeycomb-DD Multi Coil Design for Wireless Power Transfer Systems

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Abstract*—Wireless power transfer (WPT) technology has received significant attention recently as an alternative charging method for batteries in a wide range of power levels. In the literature, many types of coil structures have been well-studied. Honeycomb coil arrays, which have been used mostly for low-power applications, have not been well-studied for high-power-level applications. In this paper, a novel honeycomb-DD coil design is proposed for high-power wireless battery charging systems. The proposed coil design with step by step design process is given and Finite Element Analysis (FEA) was performed to observe the full performance characteristics of the system for a 100 kW system. In addition, the misalignment tolerance of the proposed system was observed by shifting the secondary side charging pad at different misalignment positions, and the electromagnetic compatibility to the standards was investigated. The core and strand losses were obtained. The results show that the honeycomb coil array provides high coupling coefficient and better misalignment tolerance, making it a potential coil topology for WPT applications.

Keywords— Wireless power transfer, coil design, finite element analysis, electromagnetic compatibility

I. INTRODUCTION

WPT technology is widely used in a wide power range for different type of battery-powered applications such as UAVs, electric vehicles (EVs), portable electronics and space applications. WPT is a safe, flexible, and convenient method for charging of batteries since there is no physical connection between primary and secondary coils. The primary and secondary coils are magnetically coupled and an efficient power transfer is possible with strong coupling. All over the world, EVs are getting more popular and automotive companies switching to EVs from conventional motor vehicles. However, still people have concerns because of the limited range and long charging durations. Extreme Fast Charging (XFC) is the most recent solution for taking away these concerns. XFC is commercial for conventional plug-in charging of EVs but not for WPT systems yet.

In the literature, there are high-power applications of WPT systems with high efficiencies. A 4-coil array design was proposed for a WPT system that can be powered up to 300 kW [1]. For wireless charging of an electric bus, a 200 kW system design was proposed to extend the range and the results show that even operating at 150 kW power level is enough to have a long range which can even be considered as unlimited-range. By using the impedance plane method, an evaluation of a 50 kW was given in [2]. The thermal design of a 50 kW WPT system by considering the public exposure limits was investigated [3]. Multi-objective optimization of a 50 kW WPT system was done and a 95.8% efficiency was achieved [4].

Coil design is the most important part of a WPT system since its geometry, structure, and materials determine the magnetic coupling between the primary and secondary. Different coil designs have been proposed to obtain better coupling under perfect and misaligned conditions. These coils are circular, rectangular, and hexagonal as conventional where poly-phase, DD, DDQ, and BPP coils are examples of more advanced and recent designs [5]-[10]. DD coil design has a main flux path in the middle and allows a strong coupling with a similarly shaped secondary side coil and is one of the most preferred designs for WPT applications in different power levels. However, for several types of applications, multiple primary and secondary coils may be needed for more flexibility, modularity, misalignment tolerance, and reaching higher power levels. Recently, a poly-phase coil design was proposed for high-power applications with different tuning topologies [11-16]. For these power levels due to the high-frequency inverter voltage level limitations, the current values are considerably high. Therefore, the magnetic flux density levels are increasing which needs to be within the limits of standards [17,18]. For multi-coil array designs, the hexagonal coil has the advantage of effectively using total area since the other couplers will have dead flux regions between each other. However, the hexagonal coil array, which can be called a honeycomb, has cancellation parts due to opposite current flow directions and these parts weaken the coupling. As a solution, separately excited coils can be used for a honeycomb, where, each coil needs to be excited separately and a complicated switching control is needed [19].

This paper not only aims to overcome these challenges of conventional honeycomb design with proper wiring but also proposes a novel honeycomb model including DD points. In section II, the lumped structure and basics for WPT systems and

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a novel honeycomb-DD coil design for a 100 kW WPT system proposed in this paper are given. In section III, FEA analysis are performed and the results are given and discussed to evaluate the performance of the proposed honeycomb-DD coil by considering the magnetic coupling variation for different positioning of the secondary side, electromagnetic compatibility, and losses.

II. WPT and Coil Design

A. System Description

In WPT systems, the voltage is induced on the secondary side by the high-frequency current flowing through the primary coil. High power transfer efficiency can be obtained by using a compensation topology to eliminate the reactive power and choosing the correct compensation topology is important in terms of efficiency and misalignment tolerance. In addition to basic topologies, different hybrid compensation topologies have been proposed and studied in the literature. However, the Series-Series (SS) compensation is still one of the most common topologies for different power-level applications. The lumped structure of a SS compensated WPT system is given in Fig.1.

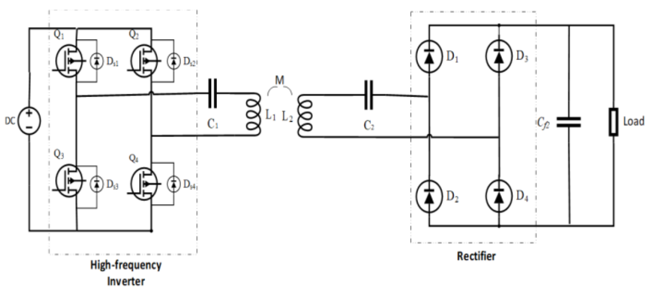


Fig. 1. SS compensated WPT system

In Fig. 1, L_1 and L_2 are the primary and the secondary coil self-inductances, C_1 and C_2 are the compensation capacitors and M shows the mutual inductance.

The target output power for the proposed system in this paper is 100 kW and the relationship of current, voltage and desired power is given in equation (1).

$$P=\frac{4}{\sqrt{2}\pi}V_{dc}I \quad (1)$$

V_{dc} shows the DC-link voltage and is set as 700 V. The required current value is calculated from equation (1) and it is $159A_{rms}$ for the primary and secondary sides since the coils are considered identical on both sides. The transferred power equation is given in equation (2) and the required mutual inductance value is calculated as M=7.4 µH.

$$P=\omega MI^2 \quad (2)$$

The currents are equal for primary and secondary coils since they are identical. The operating frequency was selected as 85 kHz which is most commonly used frequency for this type of application.

B. Proposed Coil Design

The magnetic design of WPT systems is the most important part to achieve high power efficiencies. The coil and core geometries can be in different shapes and types. In recent years, multi–coil designs are getting the attention of researchers to achieve high-power and highly efficient WPT systems. A conventional multi-coil honeycomb coil design has one cancellation part as it is shown in Fig. 2. This cancellation weakens the magnetic coupling and decreases the misalignment tolerance of the system. To overcome this problem, this paper proposes a novel Honeycomb-DD coupling structure that addresses the shortcomings of the conventional honeycomb coil array and gathers the advantage of DD and honeycomb designs

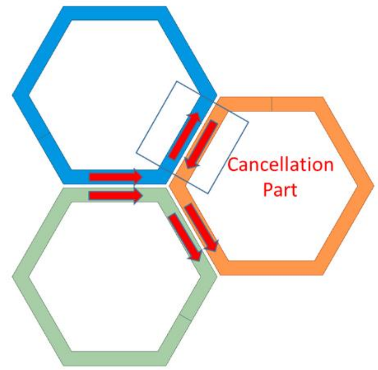
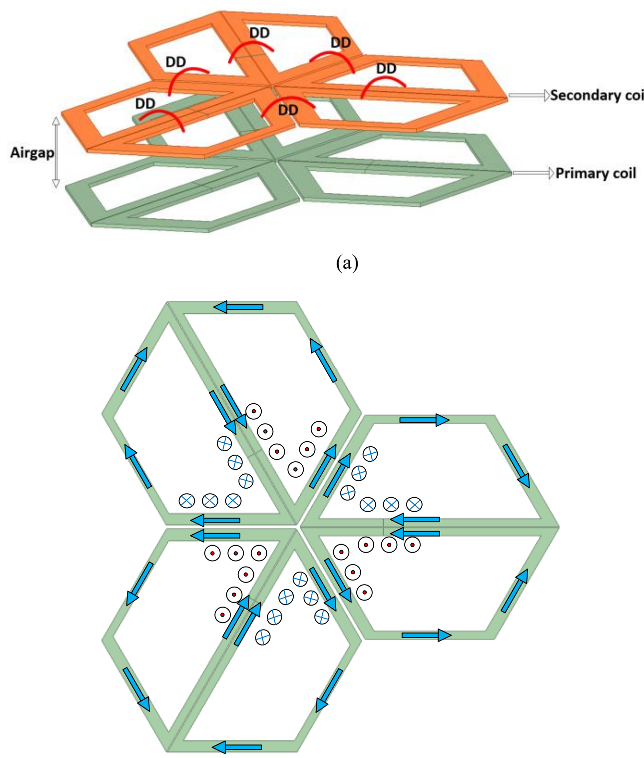


Figure 2. A conventional honeycomb coil array.

advantages in a single design. By using only a single wire and winding it by considering the current directions, the proposed coil can be created without any flux cancellations.



(a)

(b)

Fig. 3. Honeycomb-DD coil design, a) DD parts, b) current and magnetic vector point directions

This coil design can generate concentrated magnetic flux at six points where only one concentrated magnetic flux occurs in a conventional DD coil. The six points of DD flux concentrations, current directions, and vector magnetic directions for each point of the proposed design are presented in Fig. 3.

To obtain the required mutual inductance value, a parametric optimization was done by changing the dimensions of the side length of each hexagon and the number of turns. The 2 AWG litz wire was selected for coils to have a less than J =5 A/mm^2 current density. A 5 mm thickness core material is used for both sides and the dimensions of this core are the same as the outer dimensions of the coil pads.

III. FEA Results

After the design procedure which was given in Section II, the 3D model of the proposed design was created in ANSYS, Maxwell and the FEA analysis was performed. According to the results, the outer dimensions of each pad obtained as 750 mm× 750 mm and the 3D of the design is given in Fig. 4.

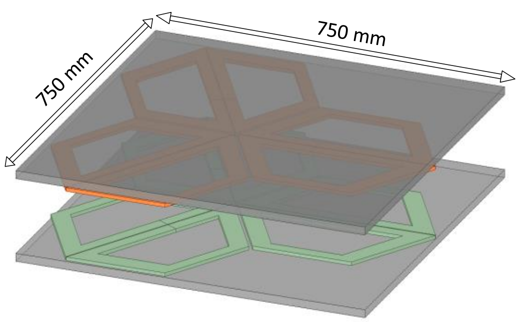


Fig. 4. The created 3D model and its dimensions.

Eddy current simulations were performed and the magnetic field density distribution on the secondary side core material is given in Fig.5. It can be seen from Fig. 5., six DD points are formed as expected which help to have magnetically strong coupled pads. The magnetic field density is higher at the long DD paths than at the short DD paths. The self and mutual inductance values are given in Table I.

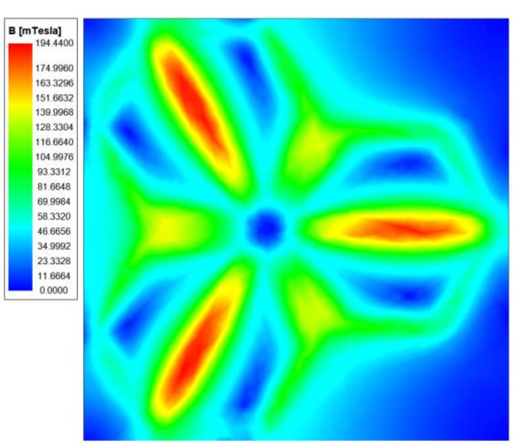


Fig. 5. Magnetic field distribution of the proposed design on the secondary side core material

TABLE I. Inductance Results and Design Parameters

Parameter	Value
L_p (μH)	49.7
L_s (μH)	49.7
M (μH)	7.57
k	0.152
N_p	3
N_s	3
Airgap (mm)	125

In Table I, L_p, L_s, M, k, N_p *and* N_s show the self-inductance of the primary coil, secondary coil self-inductance, mutual inductance, coupling coefficient, primary coil number of turns and secondary coil number of turns respectively. For the core material, TDK PC95 was selected from the ANSYS, Maxwell material library.

One of the most important challenges for WPT systems is misalignment tolerance as mentioned in the introduction. The coupling coefficient value given in Table I is for the perfectly aligned coils and k= 0.152. To understand the proposed design performance for different positioning of the secondary side, a parametric analysis was performed. The secondary charging pad shifted on the x- and y-axis from 0 cm to 10 cm and the coupling coefficient variation according to this is given in Fig. 6.

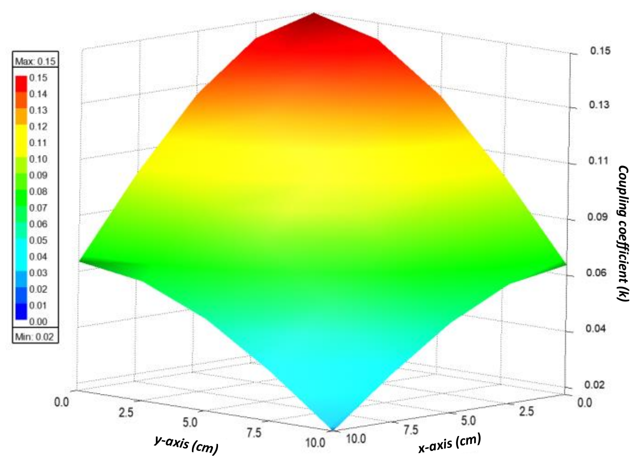


Fig. 6. The variation of coupling coefficient versus different positioning on the x- and y-axes.

In Fig. 6, it can be seen that there is not a significant decrease in the magnetic coupling of the coils in the red area. The misalignment tolerance of the system for 2.5 and 5 cm changes along both axes x and y seems great. The coupling coefficient decreased from 0.152 to 0.11 for a misalignment of 5 cm on both axes. This shows the proposed coil has an excellent misalignment tolerance since the produced magnetic fields are not canceling each other as shown in Section II.

In order to investigate the electromagnetic compatibility of the proposed design with ICNIRP standards, four measurement points are created on the 80 cm side from the center of the charging pads. The maximum value of the magnetic flux density in the scale set as 27 μT according to the maximum allowable exposure value given in the standard and the distribution of the magnetic field at these points are given in Fig. 7.

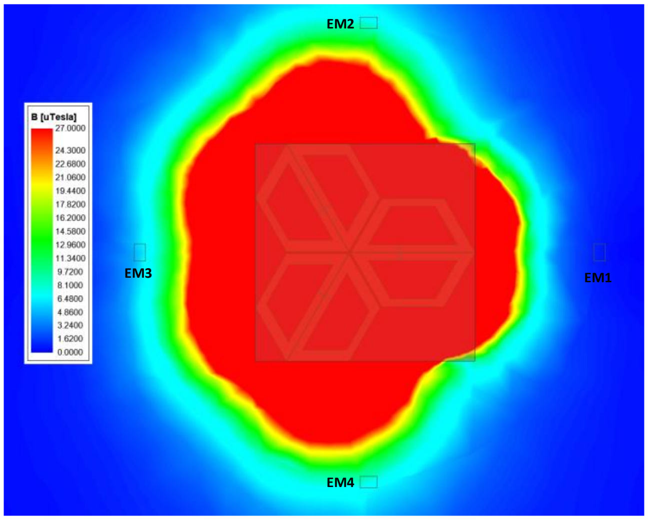


Fig. 7. Magnetic field distribution for each EMI point around the charging pad

In Fig. 7, it can be seen that the magnetic field emission values are lower than 27 μT and these values are given in Table II. These results show that, if the charging pad is located under the vehicle chassis towards to low EMI direction, the field values will be extremely low and safe charging can be achieved.

TABLE II. MAXIMUM MAGNETIC FIELD DENSITY VALUES ON THE MEASUREMENT POINTS

Measurement Points	**EMI values (μT)**
EM1	0.87
EM2	9.66
EM3	6.17
EM4	9.66

The core material provides a low reluctance path for the magnetic flux and a better magnetic coupling. However, it adds core loss and additional parasitic series resistances to the primary and secondary coils. All these consequences depend on the selection of the core geometry, core material, frequency and flux distribution. The total core loss is 120.64 W and strand losses are 105.68 W for the system. The core loss distribution on the secondary side core material is given in Fig. 8. As expected, the losses are higher on the DD paths than on the other parts. Because of the design symmetry, the losses are distributed on the core material well and they are not concentrated in only one portion of it. This helps to prevent heating-up problems in terms of thermal design consideration.

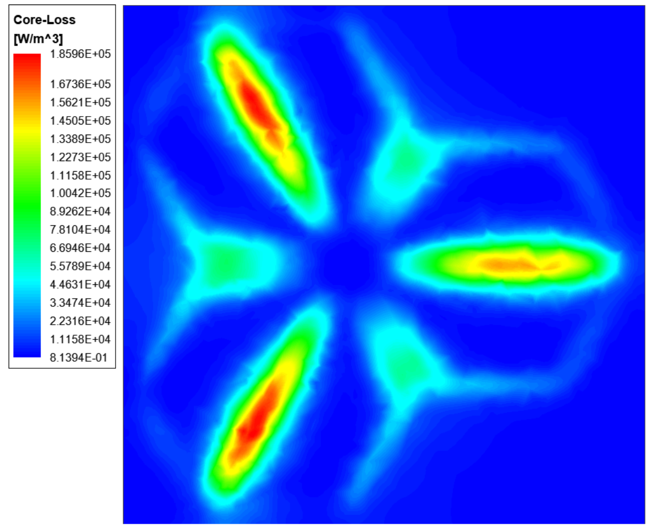


Fig. 8. Core loss distribution on the secondary side core material

IV. CONCLUSION

In this paper, a Novel Honeycomb-DD coil design for a 100 kW WPT system was proposed. The results show that, the proposed design has a good misalignment tolerance and an extremely low magnetic field at the measurement points. The highest field value is 9.66 μT and the lowest one is just 0.87 μT. Creating 6-DD points in the design not only helps to have a better coupling but also helps to distribute the field density over the core material which is important for thermal design considerations.

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