

# Optimization of Ferrite Core to Reduce the Core Loss in Double-D Pad of Wireless Charging System for Electric Vehicles

Mostak Mohammad

Department of Electrical and Computer  
Engineering, University of Akron, OH, USA  
Email: mm251@zips.uakron.edu

Dr. Seungdeog Choi

Department of Electrical and Computer  
Engineering, University of Akron, OH, USA  
Email: schoi@uakron.edu

**Abstract**—In this paper, an optimized core structure is proposed for the double-D (DD) power pad to reduce its core loss in a wireless charging system for Electric and Plug-in Hybrid Electric Vehicle (EV/PHEV) application. At around 85 kHz operating frequency, the core loss is found to be one of the most significant loss in typical wireless charging system of high power application. The core loss in power ferrite mainly depends on the operating frequency and magnetic field density in the core. The frequency is usually fixed for certain application, therefore, the magnetic field density in the core is to be optimized to reduce the loss. The magnetic field density in core of a double-D (DD) pad has very different pattern compared to unipolar pad; therefore traditional bar or plate core does not provide the optimum performance considering core loss. In this paper, an optimized core structure is proposed to make the flux density uniform in the core and minimize its loss. The proposed optimized model is simulated in finite element analysis (FEA), and compared with traditional flat type core. Finally, the proposed model is verified through a 3.2kW wireless Double-D (DD) type wireless charging pad.

**Index Terms**—Wireless power transfer, inductive charging, ferrite, core loss, eddy loss, shield, bipolar power pad, electric vehicle.

## I. INTRODUCTION

Inductive wireless charging system is becoming a promising way of charging the electric and hybrid vehicles. The application can be range from low power medical devices, cell phones to high power electric and plug-in Electric vehicle (EV/PHEV). In a typical EV/PHEV application, there is usually two charging pads, one is the transmitter, placed on the floor, or just below the ground surface. The other one is the receiver, which is mounted under the car in a suitable position.

Although the technology has showed a significant efficiency and performance enhancement in recent years, it is still facing few major challenges, including misalignment adaptability, electromagnetic field emission, resistive and magnetic losses in the power pad, etc. To enhance misalignment tolerance, high permeability ferrite core is typically used in the pad. It provides a low reluctance path for the magnetic flux and increases the coupling coefficient. However, power ferrite core is a lossy materials and it incurs a significant hysteresis loss at high frequency and high magnetic field density.

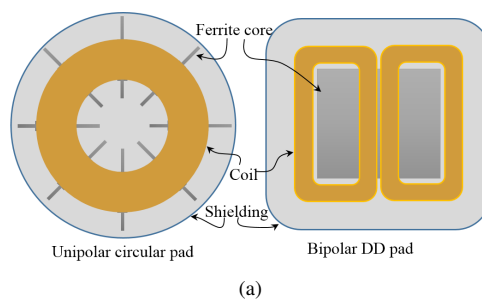


Fig. 1. Comparison of circular and Double-D pad.

Again, different coil topologies has been studied to enhance the coupling coefficient and reduce the electromagnetic field emission. The popular coil types includes the circular pad (CP), rectangular pad (RP), double D (DD), its several modified topologies and bipolar pad (BPP), while DD and CP are the two topologies mostly adopted in EV/PHEV charging system, as shown in Fig. 1(a). A typical wireless charging system having a transmitter and a receiver separated by several hundred millimeter is shown in Fig. 1. Comparatively, the DD charging pad shows higher coupling and better misalignment tolerance than the similar circular pad. Its because the magnetic flux path of the DD coil is quite different, and more concentrated inside the pad than the circular pad. However, recent works shows that core loss in the bipolar power pad is the most significant among all losses [1]. Therefore, this new flux path requires an appropriate core and shield design to guide the flux through minimum flux path as well as to generating minimum magnetic loss. However, very little work has been done to optimize the core structure and reduce this core loss. This paper proposes a core design and optimization for the DD coil topologies considering its unique flux path.

In previous work, the core design was mainly conducted to enhance the coupling coefficient. Consequently, different core shapes were proposed to maximize the coupling coefficient [2]–[12]. However, the consequent core loss was mostly ignored in those works. Therefore, although the design was understood to enhance the mutual coupling, the core

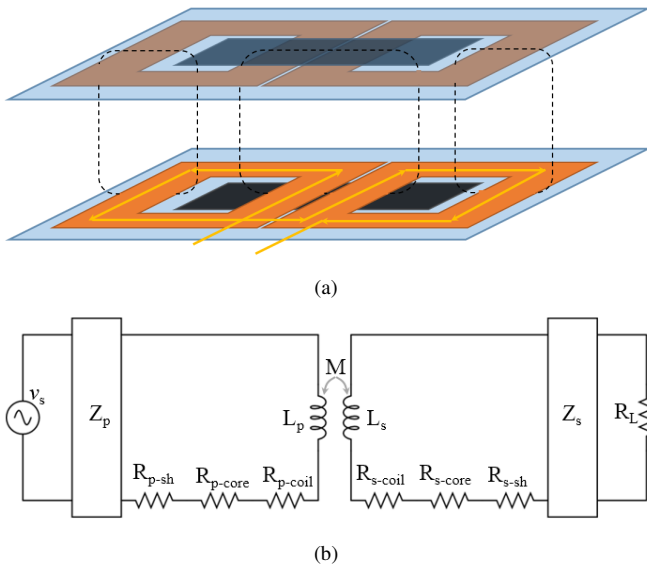


Fig. 2. (a) A typical charging system with both DD Tx-Rx, and (b) equivalent circuit representation considering all the losses.

loss characteristics and their minimization approach was not studied coherently. Again, at the initial stage of high power wireless charging, the unipolar circular pad was the most popular charging pad. Therefore, most of the works found showing the design of core for this unipolar circular pad [13]–[19]. However, none of those works studied the core and shield loss in detail and its consequent effect on efficiency.

Comparatively, the bipolar pads are studied more recently. However, all the major works on bipolar power pad used flat type core with uniform thickness [1]. In [1], it is shown that, the core loss in bipolar power pad for dynamic charging is the most significant (29%) of total loss of the system. Therefore, it is important to minimize the core loss. This work focuses on the minimization of the core loss through optimizing the thickness of the core structure.

For PHEV charging, the Tx and Rx have to be highly efficient as well as comfortably small having minimum weight. Especially, additional core on the receiver side will increase the weight, which needs a serious consideration to minimize. Therefore, the optimization approach needs to consider the core loss, its size and weight.

Section II shows the effect of core on efficiency of a wireless charging system. Section III explains the analytical approach to reduce the core loss obtaining uniform flux density and the proposed design and optimization method. Finally, section IV verifies the performance of the proposed design with an experimental setup of 3.2 kW.

## II. CORE EFFECT ON WIRELESS CHARGING

Figure 2 shows the current flow direction of two magnetically coupled bipolar pads, separated by typically 150 mm air-gap. Though, the gap and the size of the transmitter and receiver may vary for different vehicle size, battery capacity and misalignment pattern.

When the two coils are tuned by the matching impedance  $Z_p$  and  $Z_s$  to operate at same resonant frequency, power can be transferred efficiently between them. The maximum power transfer efficiency  $\eta_{max}$  at an optimum load impedance  $Z_{L_{max}}$  for a series-series compensated core-less wireless charging system can be expressed as [20],

$$\eta_{max} = \frac{1}{1 + \frac{2}{k\sqrt{Q_p Q_s}}} \quad (1)$$

where,  $Q_p$  and  $Q_s$  are the unloaded quality factor of the compensated transmitter and receiver coil and  $k$  is the coupling coefficient between them, given by,

$$k = \frac{M}{\sqrt{L_p L_s}} \quad (2)$$

The quality factors of the unloaded compensated coils are given as,

$$Q_p = \frac{\omega L_p}{R_p}, Q_s = \frac{\omega L_s}{R_s} \quad (3)$$

where  $L_p$  and  $L_s$  are the total inductance of Tx and Rx,  $M$  is the mutual inductance between them and  $\omega$  is the operating frequency.

$R_p$  and  $R_s$  represents the effective parasitic resistance of the transmitter and receiver pad. The resistance of the air-core system mainly includes the resistances due to traditional proximity and skin effect of the coil, and the equivalent shield resistance. However, the incorporation of the ferrite core increases the resistance of the coil significantly [21]. Therefore, the effective resistance of the transmitter and receiver can be expressed as,

$$R_p = R_{p-coil} + R_{p-core} + R_{p-sh} \quad (4)$$

$$R_s = R_{s-coil} + R_{s-core} + R_{s-sh} \quad (5)$$

where,  $R_{core}$  and  $R_{sh}$  are the effective core and shield resistance seen in the respective pad circuit.

The high permeability ferrite core reduces the effective reluctance of the flux path and enhances the coupling coefficient  $k$ , but it also introduces the new resistance component  $R_{core}$ , hence, reduces the quality factor  $Q$ . Therefore, the  $k\sqrt{Q_p Q_s}$  is the figure of merit (FOM), which is to be maximized to enhance coil-to-coil power transfer efficiency through an optimization approach.

Including the uniform thickness plate type core, the coupling coefficient can be enhanced up to a certain maximum ratio compared to the air-core system, [22]. But, the core loss, and subsequent equivalent ac resistance varies with the geometry and structure of the core. Therefore, the quality factor can be degraded up to its lowest region if the core thickness and geometry is not well designed. Under the alignment of the transmitter and receiver, the coupling coefficient of a typical WCS for EV can be enhanced by  $x$  times compared to only coil-coil system. The trade off between these coupling coefficient and quality factor with core loss is shown in Fig. 3.

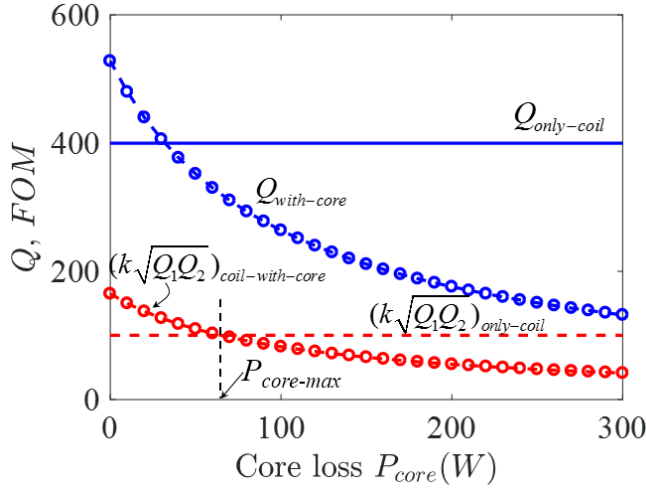


Fig. 3. Trade off of quality factor and coupling coefficient under core loss variation at fixed frequency.

It indicates that for a particular system, while the main purpose is to minimize the core loss, it must be lower than a certain threshold, marked as  $P_{core-max}$ .

### III. CORE DESIGN FOR LOSS REDUCTION

The core design is focused on the minimization of the core loss, shield loss as well as the core weight. Therefore, the characteristics of the core loss with system parameter needs to be understood thoroughly for the optimization. The loss of the high power ferrite core for can be expressed as [23],

$$P_{core} = C_m f^\alpha B_{max}^\beta \quad (6)$$

where  $C_m$ ,  $\alpha$ , and  $\beta$  are the constant which depends on the core properties. It indicates that, the core loss for ac magnetic field at any point in the ferrite is directly related with the frequency of the magnetic field and the peak flux density. The total core loss is the volume integral of this loss in the transmitter and receiver core, given as follows:

$$P_{core,total} = C_m f^\alpha \left[ \int_{Tx} B_{max}^\beta dV + \int_{Rx} B_{max}^\beta dV \right] \quad (7)$$

As mentioned earlier, the operating frequency is fixed at 85 kHz, the only parameter left for optimization is the flux density distribution in the core. The flux density at any point in the core, given in (8), depends on the current through the coil, number of turn, position and span of the coil as well as the permeability, geometry and most importantly the thickness of the core.

$$B_{core}(x, y, z) = f(I_p, I_s, w_{coil}, N_p, N_s, d, \Delta, \mu_r, l_{core}, t_{core}, x, y) \quad (8)$$

where,  $I_p$ =current through transmitter coil,  $I_s$ = current through receiver coil,

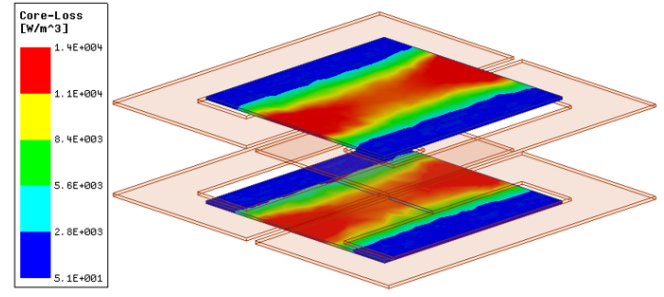


Fig. 4. Core loss distribution in a DD coil.

$w_{coil}$ =total width of the coil,  
 $N_p$ =number of turn in primary coil,  
 $N_s$ =number of turn in secondary coil,  
 $d$ = air-gap between Tx and Rx,  
 $\Delta$ =lateral misalignment,  
 $\mu_r$ =relative permeability of ferrite core,  
 $l_{core}$ =total length of the core,  
 $t_{core}$ =thickness of the core.

In (8), the flux density in the core,  $B$  shows a significant dependency on both the electrical and geometrical configuration of the system. In a typical charging pad, the coil turns are planer spiral and mostly circular or rectangular, with a minimum inter-turn gap and the core is fully or partially covering one side of the coil. The other side of the core is back-covered by the Aluminum shield to limit the magnetic field emission. Therefore, the shield is fully or partially overlapping with the core. This configuration is important, because it will eventually affect the eddy current distribution in the shield and subsequent shield loss.

Based on the coil span and total ampere-turn in it, the flux density in the core will have a certain pattern. The typical pattern is the highest flux density at the center of the core, near the central legs on the coil and then next to it, a slowly decreasing flux density region.

In traditional DD coil, the typical coil pattern and turn direction is such that the current flow direction is as shown in Fig. 2(a). Unlike the circular pad, the core shape can be significantly varied in a DD pad considering its shape, position and relative size with respect to the shield and coil. Typically, either the uniform thickness ferrite plate or ferrite bar is used. However, those core structure are highly underutilized and generates high core loss. Figure 4 shows the flux density and core loss distribution in a typical DD wireless charging system for a typical system with configuration shown in Table I . It shows that, the flux density and the loss distribution in the core are highly nonuniform and maximum around the central core region. Hence the core loss is also found mostly concentrated at the central region of the core.

#### A. Uniform flux density vs uniform thickness of core

In the traditional uniform thickness core of DD pad, the flux density varies both in  $x$  and  $y$  direction. The pattern of this variation depends on the coil design, and the total ampere-

TABLE I  
NOMINAL VALUE OF THE INITIAL DESIGN PARAMETERS.

Parameter	value
Central core thickness, $t_1$	5mm
Outer edge core thickness, $t_2$	2mm
Core section lengths, $l_1, l_2$	300mm, 100mm
Maximum flux density, $B_{max}$	200mT

turn flowing through the coil. Usually the variation is much higher along its width than along its length. Therefore, the similar pattern will be observed for core loss too. The total core loss at a particular frequency in a power pad with uniform thickness core, let be in the transmitter, can be given as,

$$P_{core-ut} = C_m f^\alpha \int_{Tx} B_{max}^\beta dV \quad (9)$$

where,  $C_m$ ,  $\alpha$ ,  $\beta$  are the core material specific constant. For the core studied in this analysis,  $C_m = 2.0312$ ,  $\alpha = 1.418$  and  $\beta = 2.755$ .

In the proposed core, the flux density will be made uniform through the core thickness optimization. Therefore, the thickness of the core will be varying along its length and height and considering the uniform flux density, the total core loss equation of the optimized core can be simplified as,

$$P_{core-uf} = C_m f^\alpha B_{max}^\beta \int_{Tx} dV \quad (10)$$

The ratio,  $P_{core-uf}/P_{core-ut}$  is always less than 1, as  $\beta$  is typically between 2 to 2.5 and  $B \propto t$ . Therefore, as the flux density become more uniform in the equivalent core structures, the core loss reduces.

From the core design standpoint, it is required to ensure that, the flux density become uniform t, as well as it remains below saturation, to achieve minimum loss and better utilization of the core.

To achieve the desired uniform flux density in the core, the two most affecting design parameters are the total width of the coil,  $w_{coil}$  and the thickness of the core,  $t_{core}$ . However, the coil design is mainly focused on the self and mutual inductance, of the pad. Therefore, for a particular coil, the thickness of the core has to be modified such that the flux density become uniform through the core.

### B. Proposed core structure

The variation of the flux density in along the  $y$  direction in the transmitter core is shown in Fig. 5(a). A more detailed flux density in the transmitter core along the  $y$  direction shows an almost uniform flux density region around the central area fo the core and a slowly decreasing flux density area outside that region. Therefore, for the simplicity of the design and optimization, the entire core can be divided into two regions along its width. First one is the approximately uniform flux density region near the center and second is the two decreasing flux density region outside the first region.

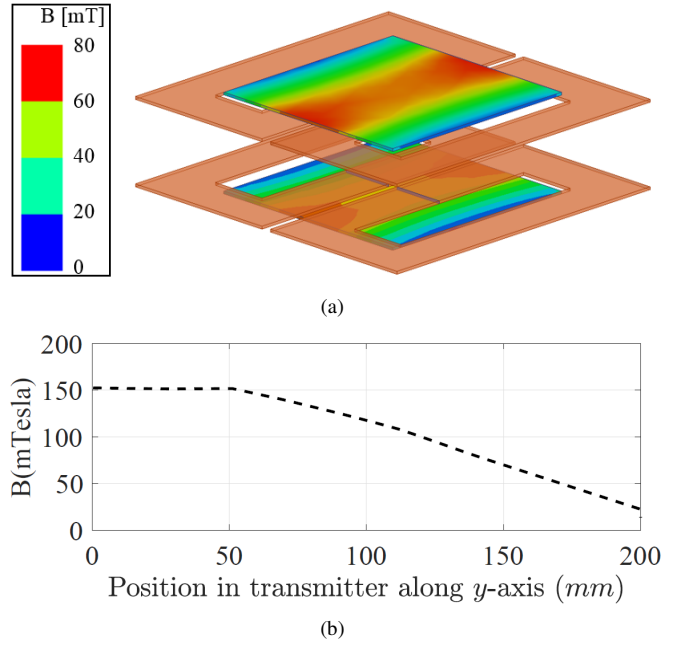


Fig. 5. (a) Flux density distribution in the core and (b) flux density along the  $y$  direction in the transmitter core.

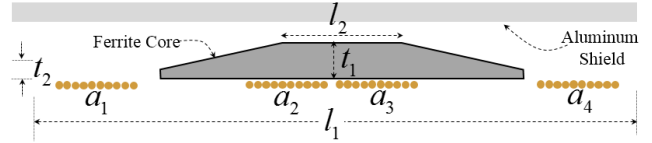


Fig. 6. Cross section of the proposed core on  $yz$  plane.

The flux density in the core at any point is inversely proportional to the thickness, expressed as,

$$B \propto 1/t_{core} \quad (11)$$

Therefore, to attain a uniform flux density, a core is required with higher thickness around  $y = 0$  and linearly decreasing thickness along  $y$  direction. The cross sectional area of proposed core structure is shown in Fig. 6. Where, the thickness,  $t_i$  and the length,  $l_i$  are the subject to optimize. The position and the width of the coils,  $a_i$  will also have an effect on the concerned flux density distribution. However, that is beyond the scope of this paper.

### C. Optimization Process

The proposed optimization method to tune the thickness profile of the core is set to attain the following two target,

- uniformity of the flux density in the core.
- minimization of core loss,

An objective function  $\Phi$  is proposed in (12), completely focusing on uniform flux density, to minimize the core loss at certain core weight, while maximizing the magnetic coupling and efficiency under certain constraint of weight and efficiency.

TABLE II  
GENERAL SYSTEM CONSTRAINS

Parameter	Physical Constrains	Constrains
$W$	Maximum additional weight allowed for Tx and Rx	$W < W_{max}$
$k$	Minimum $k$ for threshold transmission efficiency	$k > k_{th}$
$P_{core}$	Maximum allowed core loss	$P_{core} < P_{core_{max}}$
$P_{eddy}$	Maximum allowed shield loss	$P_{eddy} < P_{eddy_{max}}$
$t_i$	Mechanical stability and pad thickness	$t_{i_{min}} < t_i < t_{i_{max}}$
$l_i$	The maximum length allowed for sections	$l_{i_{min}} < l_i < l_{i_{max}}$
$B_{max}$	Maximum allowed flux density in the core	$B_{core} < B_{max} < B_{saturation}$

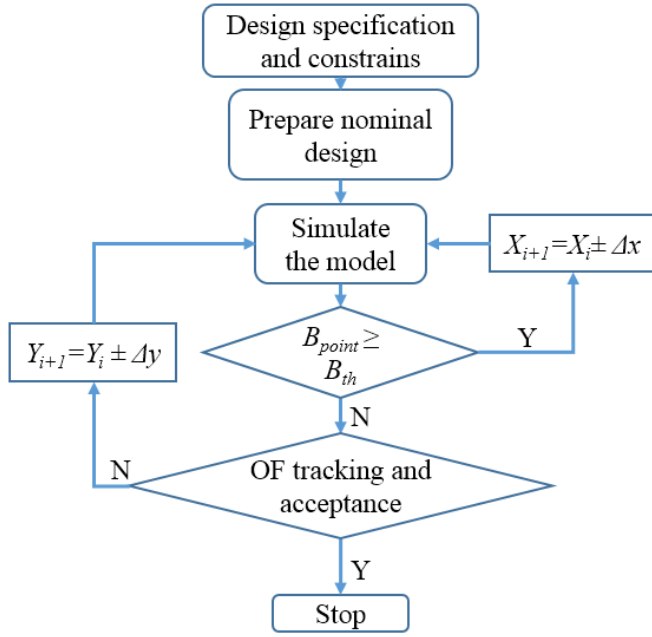


Fig. 7. flowchart of the optimization process.

$$\Phi^2 = (\delta B_y / B_y) \quad (12)$$

where,

$\Phi$ = Objective Function,

$P_{core}$ = hysteresis loss in core,

$W_{core}$  = total core weight,

$\delta B_y$ = variance of flux density along  $y$  axis,

$B_y$ =average flux density along  $y$  axis.

and,  $c_1, c_2, c_3$  are the weighting factor for core loss, shield loss and flux density variance. However, those optimization process must be run under certain constrains, determined by the target application. Table I shows the constrains of the proposed optimization method for a typical EV system.

The flowchart of the optimization method is shown in Fig. 7, where the OF is minimized through an iterative differential parameter tuning.

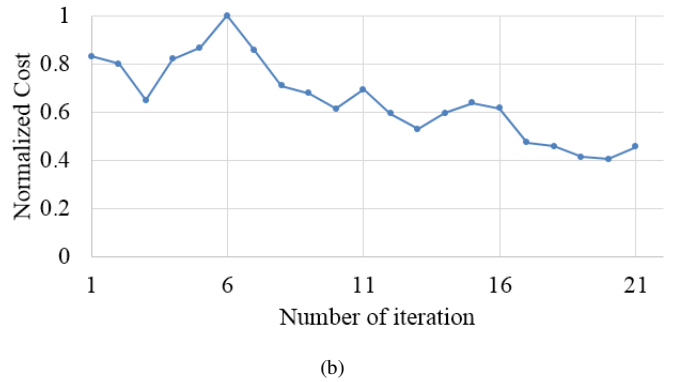
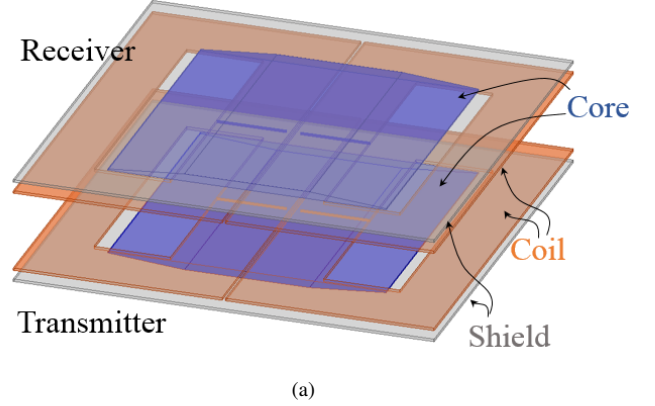


Fig. 8. (a) 3D model of FEA model, and (b) the iterative cost of the proposed objective function, found from the FEA based optimization.

Where,  $X_i$  are the parameter that affect the EMI and  $Y_i$  are the parameter affecting the core and shield loss.

The initial parameter and specific constrains are given in Table II. The proposed optimization method is implemented for a 3D FEA model in Ansys, as shown in Fig. 8(a) and the normalized cost found from the objective function is shown in Fig. 8(b).

#### IV. EXPERIMENTAL SETUP

A 3.2 kW wireless charging system is implemented to verify the proposed method as shown in the Fig. 9 and the design constrains and implemented system parameters are shown in Table II. The coils are made of AWG38x800 litz

TABLE III  
CONSTRAINTS FOR FEA ANALYSIS

Parameter	Constraints
$W$	$W < 5kg$
$k$ at $\Delta = 0$	$k > .1$
$P_{core}$	$P_{core} < 1.5\%$ of $P_{load}$
$P_{eddy}$	$P_{eddy} < 0.3\%$ of $P_{load}$
$t_i$	$1mm < t_i < 15mm$
$l_i$	$l_{i\_min} < l_i < l_{i\_max}$
$B_{max}$	$B_{core} < 200mT$

TABLE IV  
EXPERIMENTAL PARAMETER

Parameter	Value
Power	3.2 kW
Gap	150 mm
Uniform core thickness	5 mm
Tx and Rx pad width	600 mm
Tx and Rx pad length	600 mm
Number of turn	10

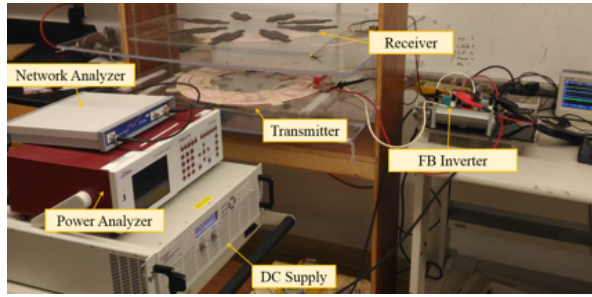


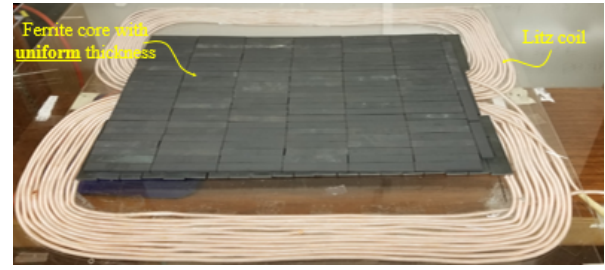
Fig. 9. Experimental setup of a 3.2 kW WCS for EV.

wire, which is suitable for 50 kHz to 100 kHz operation. A 2.0 mm Aluminum 6101 sheet is used for shielding. The uniform thickness and the proposed optimized core structure are realized by arranging block shape core with two different dimensions, 3mm20mm100mm and 4mm10mm60mm. The experimental setup of the uniform thickness core is shown in Fig. 10(a). The optimized core is partially implemented in three sections of three different thickness as shown in Fig. 10(b), where the thickness of the center section is  $t_1=11$  mm.

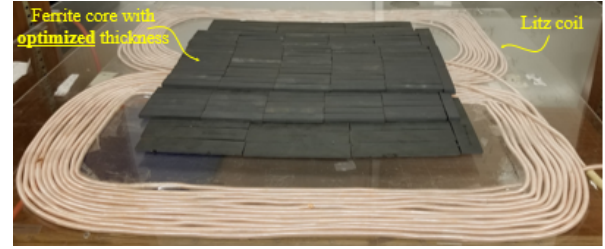
The core loss in both the uniform thickness and optimized core structure are measured for different current through the coil and shown in Fig. 11. The core loss of the optimized core has shown a significant reduction. The equivalent core resistance is also found to be varying with the current through the coil.

## V. CONCLUSION

The core loss is one of the most significant loss of the DD pad of the wireless charging system. The uniform thickness flat type core has shown widely varying flux density in it,



(a)



(b)

Fig. 10. (a) Uniform thickness core, and (b) Optimized core with thickness variation.

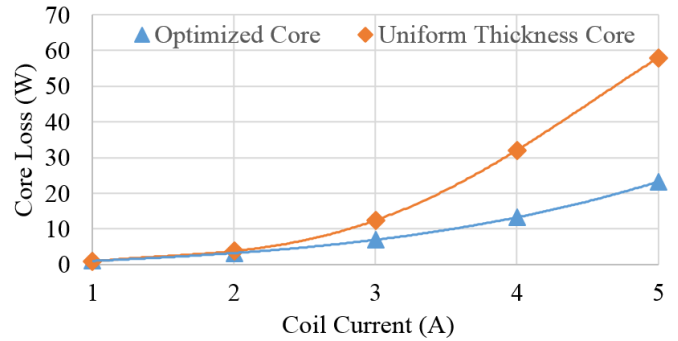


Fig. 11. The core loss comparison of the uniform thickness and optimized core structure.

resulting uneven core utilization as well as significant core loss. The proposed structure with optimized thickness and core structure reduces the core loss significantly. The core loss in the optimized core has been reduced by up to 60% with respect to a comparable uniform thickness core. The maximum allowed core loss is identified for a particular system considering the coupling coefficient and quality factor for both the uniform thickness and the proposed optimized core. Unlike the constant equivalent shield and coil loss resistance, the equivalent resistance of the core loss is found varying with the coil current.

## REFERENCES

- [1] F. Lu, H. Zhang, H. Hofmann, and C. C. Mi, "A dynamic charging system with reduced output power pulsation for electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 10, pp. 6580–6590, Oct 2016.
- [2] H. Kim, C. Song, D. H. Kim, D. H. Jung, I. M. Kim, Y. I. Kim, J. Kim, S. Ahn, and J. Kim, "Coil design and measurements of automotive magnetic resonant wireless charging system for high-efficiency and low magnetic field leakage," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 2, pp. 383–400, Feb 2016.

- [3] S. Santalunai, C. Thongsopa, and T. Thosdeekoraphat, "An increasing the power transmission efficiency of flat spiral coils by using ferrite materials for wireless power transfer applications," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2014 11th International Conference on*, May 2014, pp. 1–4.
- [4] C. C. Hou, Y. H. Teng, W. P. Chang, and K. Y. Chang, "Analysis and comparison of ee-type and cc-type cores for wireless power transfer systems," in *2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, June 2015, pp. 1950–1954.
- [5] T. C. Y. Ho, B. Gomersall, and L. Ran, "Contactless charging for electric vehicles with a large air gap," in *Power Electronics and Applications (EPE 2011), Proceedings of the 2011-14th European Conference on*, Aug 2011, pp. 1–10.
- [6] T. Maruyama, K. Yamamoto, S. Kitazawa, K. Kondo, and T. Kashiwagi, "A study on the design method of the light weight coils for a high power contactless power transfer systems," in *Electrical Machines and Systems (ICEMS), 2012 15th International Conference on*, Oct 2012, pp. 1–6.
- [7] M. Chigira, Y. Nagatsuka, Y. Kaneko, S. Abe, T. Yasuda, and A. Suzuki, "Small-size light-weight transformer with new core structure for contactless electric vehicle power transfer system," in *2011 IEEE Energy Conversion Congress and Exposition*, Sept 2011, pp. 260–266.
- [8] K. Aditya and S. S. Williamson, "Design considerations for loosely coupled inductive power transfer (ipt) system for electric vehicle battery charging - a comprehensive review," in *Transportation Electrification Conference and Expo (ITEC), 2014 IEEE*, June 2014, pp. 1–6.
- [9] S. Y. Choi, B. W. Gu, S. Y. Jeong, and C. T. Rim, "Advances in wireless power transfer systems for roadway-powered electric vehicles," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 1, pp. 18–36, March 2015.
- [10] C. Park, S. Lee, S. Y. Jeong, G. H. Cho, and C. T. Rim, "Uniform power i-type inductive power transfer system with dq-power supply rails for on-line electric vehicles," *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6446–6455, Nov 2015.
- [11] Y. H. Sohn, B. H. Choi, E. S. Lee, and C. T. Rim, "Comparisons of magnetic field shaping methods for ubiquitous wireless power transfer," in *Emerging Technologies: Wireless Power (WoW), 2015 IEEE PELS Workshop on*, June 2015, pp. 1–6.
- [12] Y. Tang, F. Zhu, Y. Wang, and H. Ma, "Design and optimizations of solenoid magnetic structure for inductive power transfer in ev applications," in *Industrial Electronics Society, IECON 2015 - 41st Annual Conference of the IEEE*, Nov 2015, pp. 001 459–001 464.
- [13] M. Budhia, G. A. Covic, and J. T. Boys, "Design and optimization of circular magnetic structures for lumped inductive power transfer systems," *IEEE Transactions on Power Electronics*, vol. 26, no. 11, pp. 3096–3108, Nov 2011.
- [14] A. Zaheer, M. Budhia, D. Kacprzak, and G. A. Covic, "Magnetic design of a 300 w under-floor contactless power transfer system," in *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, Nov 2011, pp. 1408–1413.
- [15] T. Diekhans and R. W. D. Doncker, "A dual-side controlled inductive power transfer system optimized for large coupling factor variations and partial load," *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6320–6328, Nov 2015.
- [16] S. Santalunai, C. Thongsopa, and T. Thosdeekoraphat, "An increasing the power transmission efficiency of flat spiral coils by using ferrite materials for wireless power transfer applications," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2014 11th International Conference on*, May 2014, pp. 1–4.
- [17] O. H. Stielau and G. A. Covic, "Design of loosely coupled inductive power transfer systems," in *Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on*, vol. 1, 2000, pp. 85–90 vol.1.
- [18] H. R. Ahn, M. S. Kim, and Y. J. Kim, "Inductor array for minimising transfer efficiency decrease of wireless power transmission components at misalignment," *Electronics Letters*, vol. 50, no. 5, pp. 393–394, Feb 2014.
- [19] W. Ding and X. Wang, "Magnetically coupled resonant using mn-zn ferrite for wireless power transfer," in *Electronic Packaging Technology (ICEPT), 2014 15th International Conference on*, Aug 2014, pp. 1561–1564.
- [20] H. Takahashi, Y. Sato, Y. Kaneko, S. Abe, and T. Yasuda, "A large air gap 3 kw wireless power transfer system for electric vehicles," in *2012 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sept 2012, pp. 269–274.
- [21] M. Mohammad, S. Kwak, and S. Choi, "Core design for better misalignment tolerance and higher range of wireless charging for hev," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2016, pp. 1748–1755.
- [22] M. Mohammad, S. Choi, Z. Islam, S. Kwak, and J. Baek, "Core design and optimization for better misalignment tolerance and higher range of wireless charging of phev," *IEEE Transactions on Transportation Electrification*, vol. 3, no. 2, pp. 445–453, June 2017.
- [23] J. Muhlethaler, J. Biela, J. W. Kolar, and A. Ecklebe, "Core losses under the dc bias condition based on steinmetz parameters," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 953–963, Feb 2012.