Design and Optimization of Multi 3D Coils System for Wireless Power Transfer

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Abstract. By the application of wireless power transfer technology, our smart phone, mouse or headset can be charged without cable, but there are still some problems with the technology. In this paper, we proposed the possibility to set multi 3D coils system to the electrical device/charger for wireless power transfer, we proposed the mathematical model to calculate the self- and mutual-inductance of the single and series coils, the calculation results are further verified by the simulation (Finite Element Method), the calculation results are always larger than the simulation results with average errors of 1.96% and 2.63% regarding the self- and mutual-inductance. It was concluded that the multi coils can be applied for wireless power system and our mathematical model can guide the design of the coils efficiently.

1. Introduction

Wireless power transfer (WPT) technology had attracted much attention recently, one of the main reason is that products with WPT system has a better user experience[1], e.g., the electrical toothbrushes and vehicles. Generally, the development of wireless power transfer methods can be categorized to radio frequency (RF), inductive power transfer (IPT) and magnetic resonant coupling (MRC). With the WPT techniques, magnetic power can across an air gap by changing electromagnetic fields between the primary and the secondary coils.

Qi [2] and AirFuel Resonant [3] are two typical standards of near field WPT techniques, which utilize inductive power transfer and magnetic resonant coupling, respectively. Wireless Power Consortium (WPC) develop Qi interface standard to ensure a global standard for IPT technology [4]. Typical Qi system consists of a power transmission pad (embeds a flat transmitter coil) and a mobile receiver (equipped with a compatible receiver coil). The mobile device (e.g., the smart phone) can be charged directly when it is placed on top of the charging pad.

Most of the coils for wireless power transfer are 2D, which limits the possibilities of integrating them to more products with 3D shaped shell/charger, e.g. our smart phone, mouse or the laptops, but it is difficult to set a planar coil to some products without large plane. Some researchers try different kinds of methods to solve this problem. Based on the Qi standard Tao et al. [8] proposed a design of 3D coils for wireless power transfer. Kim et al. [9][10] presented a wireless power transfer system using a bowl shaped transmitter coil and its application for charging small electronics devices.

For some products, it is difficult or impossible to find a large enough surface to set one coil to transfer the required magnetic power, which is limited by the geometric and manufacturing constrains [11] of the device. In this paper, we proposed a possible solution to solve the problem above by setting and connecting multiple coils in both sides of the products and the chargers to increase the self-
inductance/mutual-inductance of/between the primary and secondary coils. By this method, we can greatly increase the generated and received magnetic power [12].

In this paper, we proposed the possibility to design multi 3D coils system for wireless power transfer, which can be easily applied into the design of products with 3D out shapes e.g. toothbrushes, headsets or shavers, we also proposed the mathematical model to calculate the self- and mutual-inductance of the coils, it is important to guide our design of the coil’s layout.

The rest of our paper is organized as follows: First, introduction about the wireless power transfer, 3D coils for wireless power transfer and multi coils system are presented. In section 2, we proposed the mathematical model to calculate the self- and mutual-inductance of the coils system. The mathematical are further verified by Finite Element Method (ANSYS™ Maxwell™) [13] in section 3. In section 4, we conclude the paper and highlight the future work.

2. Mathematical Model
The mathematical model in this paper is derived from the Biot-savart law for the calculation of mutual- and self-inductance. The coupling factor means how much of the magnetic field created by the primary coil can be received by the secondary coil, which can be calculated by the self-inductances and mutual-inductance of coils in the system, the self- and mutual-inductances are important to calculate the quality of the coils.

2.1. Mutual inductance
A lot of researchers had proposed frequency dependent formulas [14][15] to calculate of the self-inductance and mutual-inductance of 2D coils. Budnik et al. [16] proposed the mathematical model of 3D coaxial helical current conductors. According to his work and Neumann’s formula, the mutual-inductance between the 3D primary coil and the secondary coil can by calculated as:

\[
M = \frac{\mu_0}{4\pi} \int_{c_1}^{c_2} \frac{\mathbf{dl}_1 \times \mathbf{dl}_2}{D} 
\]

Here \(l_1\) and \(l_2\) are the trace of the primary and secondary coils, and \(D\) is the distance between \(dl_1\) and \(dl_2\). The physical constant \(\mu_0\) denotes the magnetic vacuum permeability(\(4\pi \times 10^{-7}\) H/m).

2.2. Self-inductance
We can calculate the self-inductance of the coil as the sum of the inter inductance and the external inductance [17] as \(L_{self} = L_{external} + L_{internal}\). Where \(L_{external}\) is the external inductance of the coil and \(L_{internal}\) is the internal inductance of the coil. The internal inductance of the coil is (For numerical purposes, we broken the centre line of the coil into n broken lines).

\[
L_{internal} = \frac{\mu_0}{8\pi} l = \frac{\mu_0}{8\pi} \sum_{i=0}^{n} l_{i+1-i} = \frac{\mu_0}{8\pi} \sum_{i=0}^{n} \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2 + (Z_{i+1} - Z_i)^2} 
\]

Where \(l\) is the length of the centre line of the transmitter/receiver coil, which means that the internal inductance is simply calculated as the product of the inter inductance per unit length \(\mu_0 / 8\pi\) and the total length of the coil.

By the mathematical model proposed by Tominaka [18], we can calculate the external inductance of the coil obtained as the mean of two mutual-inductance as:

\[
L_{external} = (M_{mid-inn} + M_{mid-out})/2
\]

\(M_{mid-inn}\) is the mutual-inductance between the center filament and inner edge of the coil, and \(M_{mid-out}\) is the mutual inductance between the center filament and the outer edge of the coil. Take advantage of the loop model[19] and decomposing the 3D coils into N loops, N is the number of turns of the coil. According the loop model, we can calculate the mutual-inductance between two coils as:

\[
M_{line1-line2} = \sum_{i=1}^{N} Q_{j=1}^{N} M_{coil1, coil2} = \sum_{i=1}^{N} (M_{coil1, coil2})
\]
Where $M_{coil1,coil2}$ means the mutual-inductance between the $i^{th}$ turn of the primary coil and $j^{th}$ turn of the secondly coil. $M_{coil1,coil2}$ means the mutual inductance between the $i^{th}$ turn of primary coil and the whole secondly coil, which means how much the magnetic flux generated by the secondly coil crosses the area encircled by the $i^{th}$ turn of the primary coil.

Take Eq.4 into Eq.3 the external inductance of the coil can be calculated as:

$$L_{external} = (\sum_{i=1}^{N} (M_{center1,i,inner-edge}) + \sum_{i=1}^{N} (M_{center1,i,outer-edge}))/2$$

(5)

2.3. Inductance of the Multi coils

Due to the effect of the mutual-inductance between the series coils [20]. The self-inductance of each individual coil, the total inductance value induced into the cumulatively coupled coils is given as

$$L_{series} = \sum_{i=1}^{n} L_i + 2 \sum_{i=1}^{n+1} (M_{ij})$$

where $L_i$ means the self-inductance of the $i^{th}$ small coil, and $M_{ij}$ means the mutual-inductance between the $i^{th}$ small coil and the $j^{th}$ small coil of the series coils.

The mutual inductance between the primary and secondly multi 3D coils can be calculated as

$$M_{mimo} = \sum_{i=1}^{n} \sum_{j=1}^{n} (M_{ij})$$

Where $M_{ij}$ is the mutual-inductance between the $i^{th}$ small coil of the primary series coils and the $j^{th}$ small coil of the secondly series coils.

(a) Charging by the $1^{th}$ small transmitter coil
(b) Charging by the $2^{nd}$ small transmitter coil
(c) Mutual inductance between the $1^{th}$ and $2^{nd}$ small transmitter coils
(d) Charging by the series transmitter coils

Figure 1. Simulation about the 3D multi coils charging system

3. Simulation

The calculation results of the proposed mathematical model about the 3D coils are verified by simulation. In this paper, ANSYS™ Maxwell™ are used to simulate the performance of the coils. Figure 1 presents simulation of our design model, we simulated the $1^{th}$ and $2^{nd}$ small transmitter coil (green) with large receiver coil (red) separately as Fig.1(a) and Fig.1(b) shows, we also do the simulation between the two transmitter coils in Fig.1(c), the induce relationship between the receiver coil (with green colour) and the series transmitter coils (with red colour) are simulated as Fig.1(d) shows. According to the Qi standard[21], we used the magnetostatics analysis with a 2A current at 100 KHZ as the input of the WPT system. During the simulation process, it took about 15 minutes for every setup, the computer used for simulation is powered by an Intel™ Core i7™ 2.6 GHZ processor. The time cost for simulation is about 900 times longer than the time for the mathematical model (30 seconds for all 4 sets).
Table.1 The comparison between the calculation and simulation results

| Results             | 1st small coil | 2nd small coil | Series coils | Receiver coil |
|---------------------|----------------|----------------|--------------|---------------|
| Self-inductance (μH) |                |                |              |               |
| Calculation         | 5.18           | 3.16           | 8.03         | 9.05          |
| Simulation          | 5.05           | 3.09           | 7.88         | 8.95          |
| Error               | 2.57%          | 2.26%          | 1.90%        | 1.12%         |
| Mutual inductance (μH) |                |                |              |               |
| Calculation         | 2.25           | 3.38           | 5.45         |               |
| Simulation          | 2.17           | 3.22           | 5.39         |               |
| Error               | 3.68%          | 3.11%          | 1.11%        |               |

The calculation results are further verified by the simulation. From Table.1 we can find that the calculation results are always larger than the simulation results with average errors of 1.96% and 2.63% (below 3%) regarding the self- and mutual- inductance. This is partly because the following reason, the ANSYS™ Maxwell™ [13] take the skin effect into consideration during the simulation process, but in the calculation model we calculated the self- and mutual- inductance according to the center filament of the coils. Actually, the current density is largest near the surface of the coil.

4. Conclusion

In this paper, we designed the 3D multi coils system for wireless power transfer. We proposed the mathematical model for the calculation of the self- and mutual- inductance. Verified by the simulation, our mathematical model is quite accurate with the results. It was concluded that our mathematical model can guide the design of the coils efficiently and the multi coils can be applied for the wireless power system.

References

[1] H. Lakhal, M. Dhieb, H. Ghariani, and M. Lahiani, “Wireless power transmission, technology, and applications,” Sci. Tech. Autom. Control Comput. Eng., vol. 101, no. 6, pp. 1271–1275, 2013.
[2] Wireless Power Consortium, “WHAT IS WIRELESS CHARGING,” 2018. [Online]. Available: https://www.wirelesspowerconsortium.com. [Accessed: 19-Jun-2019].
[3] “AirFuel Resonant,” 2018. [Online]. Available: https://www.airfuel.org/what-is-airfuel/airfuel-resonant/. [Accessed: 19-Jun-2019].
[4] A. Agbaeze, S. Kamal, A. Rahim, C. Yen, and S. Jayaprakasam, “Low-power near-field magnetic wireless energy transfer links : A review of architectures and design approaches,” Renew. Sustain. Energy Rev., vol. 77, no. April, pp. 486–505, May. 2017.
[5] A. E. Rendon-nava, J. A. Diaz-méndez, L. Nino-de-rivera, W. Calleja-arriaga, F. Gil-carrasco, and D. Diaz-alonso, “Study of the Effect of Distance and Misalignment between Magnetically Coupled Coils for Wireless Power Transfer in Intraocular Pressure Measurement,” Sci. World J., vol. 2014, p. 11, Jun. 2014.
[6] D. Van Wageningen and T. Staring, “The Qi wireless power standard,” Proc. EPE-PEMC 2010 - 14th Int. Power Electron. Motion Control Conf., pp. 25–32, Feb. 2010.
[7] E. Waffenschmidt, “Homogeneous magnetic coupling for free positioning in an inductive wireless power system,” IEEE J. Emerg. Sel. Top. Power Electron., vol. 3, no. 1, pp. 226–233, July. 2015.
[8] T. Hou, Y. Song, W. S. Elkhuizen, J. Jiang, and J. M. P. Geraedts, “3D wireless power transfer based on 3D printed electronics,” in 2018 14th IEEE Conference on Automation Science and Engineering (CASE), 2018, pp. 499–505.
[9] J. Kim, D. H. Kim, J. Choi, K. H. Kim, and Y. J. Park, “Free-positioning wireless charging system for hearing aids using a bowl-shaped transmitting coil,” IEEE Trans. Microw. Theory Tech., vol. 63, no. 3, pp. 60–63, 2014.
[10] J. Kim, D. H. Kim, J. Choi, K. H. Kim, and Y. J. Park, “Free-positioning wireless charging system for small electronic devices using a bowl-shaped transmitting coil,” *IEEE Trans. Microw. Theory Tech.*, vol. 63, no. 3, pp. 791–800, 2015.

[11] M. Q. Nguyen, D. Plesa, S. Rao, and J.-C. Chiao, “A multi-input and multi-output wireless energy transfer system,” *2014 IEEE MTT-S Int. Microw. Symp.*, no. 7, pp. 1–3, 2014.

[12] D. Zhao, E. J. Ding, and H. Xue, “Multiple-Input Single-Output Wireless Power Transmission System for Coal Mine Application,” *Appl. Mech. Mater.*, vol. 462–463, no. 6, pp. 900–904, 2013.

[13] ANSYS, “ANSYS Maxwell Capabilities Low Frequency Electromagnetic Field Simulation,” 2019. [Online]. Available: https://www.ansys.com/products/electronics/ansys-maxwell/maxwell-capabilities. [Accessed: 25-Jun-2019].

[14] M. I. Shloimys, “basic knowledge-Sources of Magnetic Fields,” *Fizika?*, pp. 1–69, 1974.

[15] H. Sanchez Lopez, M. Poole, and S. Crozier, “Eddy current simulation in thick cylinders of finite length induced by coils of arbitrary geometry,” *J. Magn. Reson.*, vol. 207, no. 2, pp. 251–261, 2010.

[16] E. Zeszyt et al., “Analytical Magnetic Field Calculation of Helical current conductors,” vol. 4, no. 216, 2010.

[17] Frederick W Grover, *Inductance Calculations*. 2013.

[18] T. Tominaka, “Self- and mutual inductances of long coaxial helical conductors,” *Supercond. Sci. Technol.*, vol. 21, no. 1, 2007.

[19] F. W. Grover, “working formulas and tables,” in *Inductance Calculations*, 2009.

[20] G.-Q. Zhou, “The Equivalent Self-Inductance of N Coupled Parallel Coils,” *Prog. Electromagn. Res. Lett.*, vol. 46, no. May, pp. 59–66, 2014.

[21] K. S. Bill Johns, Tony Antonacci, “Designing a Qi-compliant Qi receiver coil for wireless power systems, Part 1,” *Texas instruments Inc.*, vol. 1, pp. 8–14, 2012.