Indonesian Journal of Electrical Engineering and Computer Science
Vol. 5, No. 3, March 2017, pp. 599 ~ 605
DOI: 10.11591/ijeecs.v5.i3.pp599-605

Optimum Transmitter Receiver Ratio for Maximum Wireless Energy Transfer

Mohamad Harris Misran*[1], Sharul Kamal Abdul Rahim[2]
[1,2]Wireless Communication Centre (WCC), Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai Johor, Malaysia
[1]Fakulti Kejuruteraan Elektrik dan Kejuruteraan Komputer, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
*Corresponding author, e-mail: harris@utem.edu.my

Abstract

Due to high demand of using cordless mobile device, the interest in wireless energy transfer (WET) has been growth intensively. This paper presented a method to obtained optimum transmitter receiver ratio for maximum performance of WET system using different initial antenna size at various distance. An optimized algorithm has been developed to determine the optimum ratios that yield the highest wireless transfer efficiency (WTE) at near field communication (NFC) frequency, 13.56MHz. 30mm x 30mm single square loop antenna is used as initial size of both transmitter and receiver using FR4 with operating distance = 50mm. Operating distance and initial size of the antenna will be varied and the effect to the WTE will be studied using Matlab, verified using Microsoft Studio CST. At distance = 50mm and initial size of the antenna = 30mm x 30mm, optimum transmitter to receiver ratio equal to 1:3 is obtained. The pattern of optimum transmitter receiver ratio between Matlab and CST has met an agreement. This research limited to integer transmitter receiver ratio used only and no decimal number being involved in magnify the transmitter size.

Keywords: *wireless energy transfer (WET), wireless transfer efficiency (WTE), transmitter receiver ratio, near field communication (NFC)*

1. Introduction

In line with green technology vision, numerous things have use electricity supplied by battery to be functioned. However, this battery is bound with usage time constraint. Later when the battery has been fully drained, charging process will be needed. Using cord in this charging process is very inconvenient, especially when involving with mobile device which expected to be fully mobile. However, wireless energy transfer (WET) system offers a solution for this problem. With a growing demand for WET in this century, countless afford have been done by researcher either from industry or academic field.

In WET, most of the researchers have to deal on how to maximize the wireless transfer efficiency (WTE). All WET systems have some limitation to deal with such as in size, distance, flexibility or bandwidth. Researcher intensively studied on WET system at several operating frequency, from high frequency like 912MHz [1] to low frequency such as 13.56MHz and 115.6 kHz [2-3]. A variety of methods in WET have been investigated, namely inductive coupling [4], resonant coupling [5], capacitive coupling [6] and electromagnetic coupling [7]. For near field WET system, interest in inductive coupling has increase compare to capacitive coupling because of its safety. Researchers have tried various material to be implement in WET system for different purpose like polydimethylsiloxane (PDMS) [8], Kapton polyimide[9], NiZn based substrate[10] and Glass reinforced epoxy laminated sheets (FR4) [11]. Coupled of method to improve the WTE of the WET system have been developed, such as using loaded capacitance [12], antiparallel loop technique [13], higher order coil system [3] and applying metamaterial [14] in the WET system.

One of the methods to maximize the WTE between two antennas is using optimum transmitter receiver ratio size in WET system. Akaa in [15] studied the effects of the size mismatch in near field coupling inductive link antenna. However, there is no optimum size of transmitter receiver ratio being reported in the paper. Benjamin H Walter in [16] investigated the

Received November 30, 2016; Revised February 3, 2017; Accepted February 21, 2017

optimal size ratios for WET application. Still, the paper did not present the effect to the system parameters when the ratios are varied.

This paper determines the optimum size of transmitter receiver ratio to maximize the WET. Several initial sizes of the antennas are used and different operating distances are applied. This research limited to ratio amplification only in integer, and no decimal number being involved. Optimum size of transmitter receiver ratio that yields maximum WTE is expected at the end of the research.

2. Antenna Design

Theoretically, size of the antenna is one of the major factors that will increase the performance of the transfer efficiency. However, when dealing with the size ratio between transmitter and the receiver against their performance, some other factors need to be investigated. Larger antenna will result to higher resistance, *R* and mutual inductance, *m* between both antennas. However, performance of the WET is directly proportional to the *m* of the system but inversely proportional to the *R*. At breakeven point, the optimum size ratio can offer maximum wireless transfer efficiency (WTE) with perfect matching circuit.

Square shape antenna is chosen to optimize the most available area in common smartphone. Single square loop antenna as shown in Figure 1 is used to obtain WTE pattern at different transmitter receiver ratio. Hence optimum ratios that offer highest performance can be determined. Different initial size of 1:1 transmitter receiver ratio will be studied.

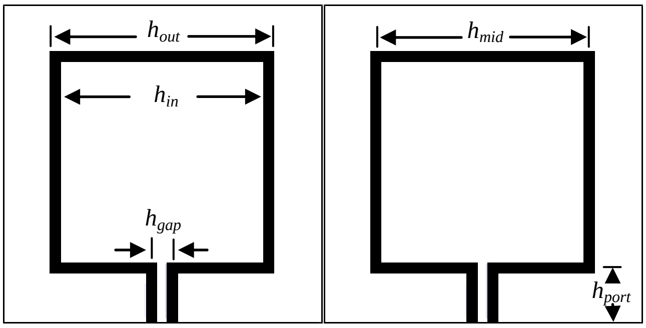


Figure 1. Single Square Loop Antenna (30mm x 30mm Transmitter and Receiver)

WET system that consist a pair of single turn square planar loop antennas (PLAs) can be illustrated into an equivalent circuit as shown in Figure 2. In consideration of loop antenna will be used in the WET system, overall system will become more inductive rather than capacitive. Therefore, reactance component in the system can be eliminated using external matching circuit with two parallel capacitors to make the system resonant at chosen operating frequency, 13.56MHz for maximum WTE.

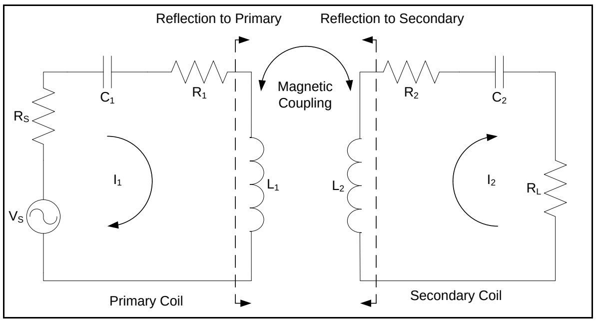


Figure 2. Equivalent circuit for antenna

For single square loop antenna, the inductance of each square PLA can be calculated using [17].

$$L = \frac{\mu n^2 h_{avg} c_1}{2}\left[\ln\left(\frac{c_2}{\rho}\right) + c_3\rho + c_4\rho^2\right] \tag{1}$$

Where μ is the conductor permeability, which is copper and n is number of turns of the PLA. c_1, c_2, c_3, and c_4 denote 1.27, 2.07, 0.18 and 0.13 respectively. The fill ratio, ρ and average side length of the PLAs are given by:

$$\rho = \frac{h_{out} - h_{in}}{h_{out} + h_{in}}, \qquad h_{avg} = \frac{h_{out} + h_{in}}{2} \tag{2}$$

The resistance of the antenna will increased due to the skin effect at higher frequencies. Taking this into consideration, total AC resistance, R_{ac} of the antenna at f = 13.56MHz can be calculated as:

$$R_{dc} = \frac{\rho_c l}{w t_c}, \quad R_{ac} = \frac{R_{dc}}{\delta}\left(\frac{t_c}{1 - e^{-\frac{t_c}{\delta}}}\right), \delta = \frac{\sqrt{\rho_c}}{\sqrt{\pi f \mu}}, \quad \mu = \mu_o \mu_r \tag{3}$$

where ρ_c is resistivity of copper (1.7 × 10^{-8} Wm), l is the total length of the PLA, μ_o is the vacuum permeability and μ_r is the relative permeability of the copper. t_c and w denote the thickness of the conductor and width of the conductor respectively. l can be determined by using:

$$l = 4h_{mid} - h_{gap} + 2h_{port} \tag{4}$$

Two loop antennas close to each other will induce mutual inductance, m caused by magnetic field activity. This mutual inductance, m can be calculated using [15].

$$m = \frac{\mu_o \pi h_{tx}^2 h_{rx}^2}{2\left(h_{tx}^2 + h_{rx}^2 + z^2\right)^{\frac{3}{2}}}\left(1 + \frac{15}{32}\beta^2 + \frac{315}{1024}\beta^4\right)\left(\frac{4}{\pi}\right)^{1+\frac{h_{in}}{h_{out}}}, \quad where\ \beta = \frac{2h_{tx}^2 h_{rx}^2}{h_{tx}^2 + h_{rx}^2 + z^2} \tag{5}$$

h_{tx} and h_{rx} are corresponding to the side length of the transmitter and receiver respectively, while z denotes the distance of the transmitter and receiver. The wireless transfer efficiency (WTE) of the established link is calculated as [13]:

$$\eta = \frac{k^2 Q_{tx} Q_{rx}}{\left(1 + \sqrt{1 + k^2 Q_{tx} Q_{rx}}\right)^2} \tag{6}$$

where Q_{tx} and Q_{rx} are the quality factors of the transmitting and receiving antenna respectively. k present the coupling coefficient of the system between transmitter and receiver. k can be obtained using:

$$k = \frac{m}{\sqrt{L_{tx} L_{rx}}}, \quad Q_{RX} = \frac{\omega L_{rx}}{R_{rx}}, \quad Q_{TX} = \frac{\omega L_{tx}}{R_{tx}} \tag{7}$$

The S-parameter for the antenna system is obtained by running full wave electromagnetic simulation using CST Microwave Studio to obtain the preliminary pattern on the transmitter receiver ratio effect. Based on [18], WTE from simulation can be determined using $|S_{21}|^2$.

3. Results and Analysis

Simulated antennas are matched using Mini Match matching technique in CST. Two parallel capacitors are used at each antenna to get a resonant at 13.56MHz, as shown in Figure 3.

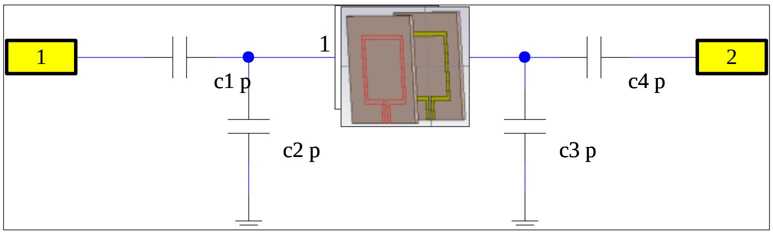
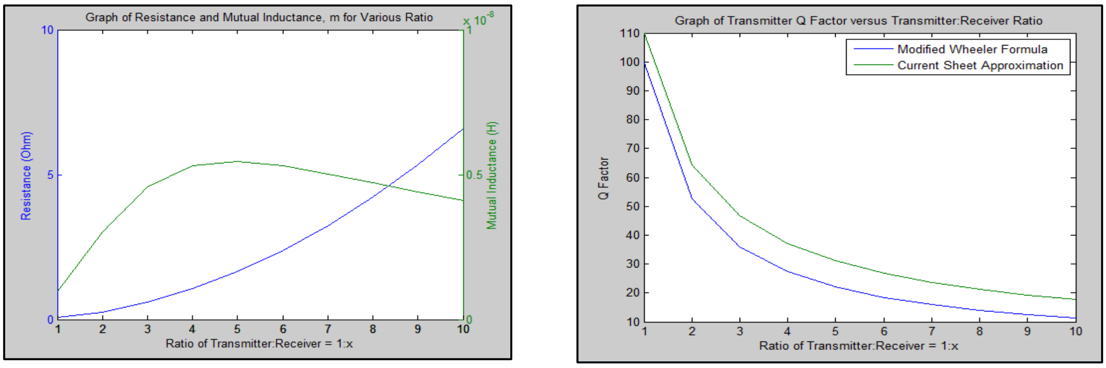


Figure 3. Matching Circuit of the Antenna

In first scenario, 30mm x 30mm antenna is used as a transmitter with transmitter:receiver ratio 1:1. Antennas are separated at 50mm operating distance and perfectly matched with 50Ω SMA connector at operating frequency. While transmitter being magnifide by two times until 10 times of receiver, performance of the system is monitored and analyzed.

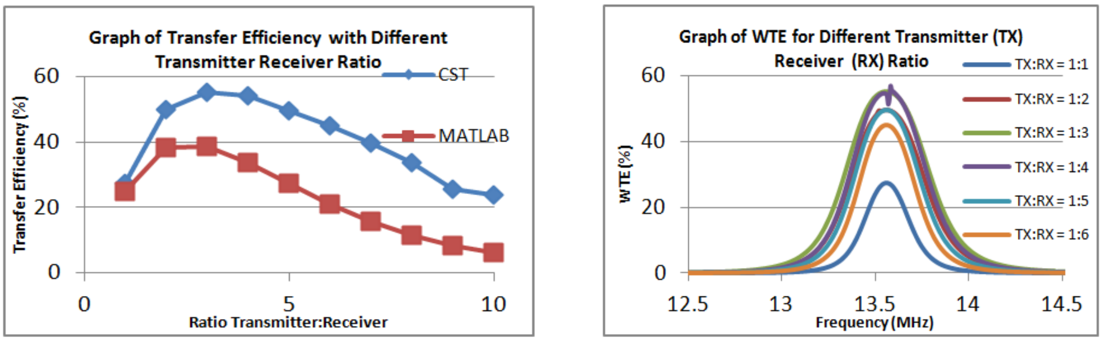


(a) (b)

Figure 4. Graph of (a) Transmitter Resistance, *R* and Mutual Inductance, *m* of the WET system and (b) Q Factor of the Transmitter for Different Transmitter Receiver Ratio

The total resistance, *R* of the antenna is increased exponentially when the antenna being magnify as shown in Figure 4(a). The increment of the total length contributes to the accretion of the *R*. This factor will affect the performance of the WET system because *R* value will dragged down the Q-factor of the antenna. However, this problem is countered by the increment of antenna's mutual inductance, *m*. Figure 4(b) shows the changing of the antenna's Q-factor when the ratios is varied. Two methods are being used to estimate the value of antenna's inductance, *L* which is Modified Wheeler Formula and Expression Based on Current Sheet Approximation Another [19] which result in different Q-factor. Q-factor of the antenna is directly proportional to the *L* but inversely proportional to *R*. At breakeven point, optimum ratio of transmitter receiver will result in highest WTE.

Figure 5(a) shows the WTE for initial antenna size = 30mm x 30mm at operating distance = 50mm for various ratios. Graph shows that the maximum WTE occur when the transmitter receiver ratio is equal to 1:3. Even though there is different between CST simulation and Matlab calculation as shown in Figure 5(b), the pattern of the WTE versus transmitter receiver ratio is acceptable. This different is contributed by the parasitic effect of the substrate, which cannot be calculated using Matlab and approximation formula to calculate *L* value. Different operating distance will require different transmitter receiver ratio to yield maximum WTE. For example, transmitter:receiver = 1:1 produce maximum WTE at 20mm operating distance. However at 40mm operating distance, optimum ratio of transmitter:receiver that give highest WTE is 1:2. This is true for single square loop antenna regardless of the microstrip line width.



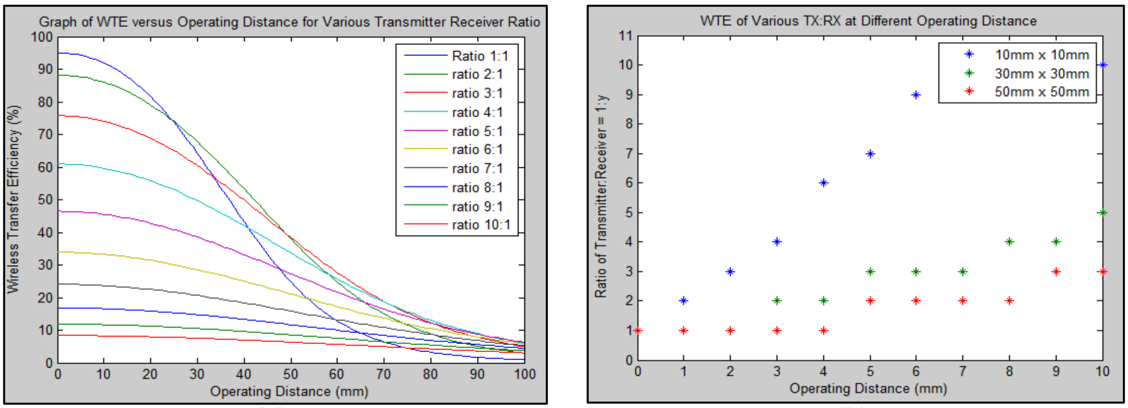
(a) (b)

Figure 5. The (a) WTE of the System and (b) Pattern of WTE for Different Transmitter Receiver Ratio

Table 1. WTE at Different Operating Distance for Various Transmitter Receiver Ratios

	Operating Distance (mm)									
TX: RX	10	20	30	40	50	60	70	80	90	100
1:1	**91.894**	**81.568**	64.185	43.241	24.840	12.791	6.3650	3.2304	1.7113	0.9510
1:2	85.940	79.054	**67.751**	**53.258**	37.982	24.680	14.969	8.7763	5.1288	3.0455
1:3	73.964	68.739	60.425	49.861	**38.401**	**27.621**	**18.743**	12.220	7.8131	4.9830
1:4	59.638	55.744	49.651	41.997	33.660	25.602	18.594	**13.037**	**8.9409**	6.0715
1:5	45.511	42.750	38.468	33.124	27.295	21.571	16.429	12.150	8.8015	**6.2990**
1:6	33.273	31.422	28.560	24.990	21.076	17.176	13.582	10.477	7.9341	5.9340
1:7	23.659	22.474	20.640	18.343	15.800	13.225	10.793	8.6239	6.7771	5.2618
1:8	16.614	15.879	14.735	13.291	11.672	10.003	8.3888	6.9064	5.6012	4.4903
1:9	11.671	11.220	10.514	9.6145	8.5912	7.5164	6.4532	5.4506	4.5413	3.7421
1:10	8.2753	7.9979	7.5606	6.9973	6.3479	5.6539	4.9529	4.2759	3.6454	3.0757

TX = Transmitter **RX = Receiver** **Bold: Maximum WTE**



(a) (b)

Figure 6. (a) WTE versus Operating Distance for Various Transmitter Receiver Ratios (b) Optimum Transmitter Receiver Ratio for Various Initial Size of the Transmitter

From Table 1, the WTE at different operating distance for various transmitter receiver ratios is shown. At 50mm, transmitter: receiver equal to 1:3 give the best WTE. This condition mostly affected by changing value of *R*, *k* and *m* when the ratio is varied. However, this result is valid only for 30mm x 30mm transmitter at initial side length. If the initial side length of the antenna is different from 30mm x 30mm, the pattern of the optimum transmitter receiver ratio versus WTE at specific operating distance will be different. For instance, Figure 6(b) shows the optimum transmitter receiver ratio that yield maximum WTE for various operating distance. From the graph, it shows that initial size of transmitter 10mm x 10mm, 30mm x 30mm and 50mm x 50mm has maximum WTE at operating distance 50mm when the transmitter receiver ratio is 1:2, 1:3 and 1:10 respectively.

From the simulation, it is concluded that changing size of the antenna will change the value of *R*, *L*, Q-factor and *m* value. However, based on equation (11), even though high Q-factor can increase the WTE of the system, it seem that increasing or decreasing value of *L* solely will not effects WTE at all. WTE highly depends on value of *R*, *Q* and *m*, which can be manipulated to improve the WET system performance.

$$\eta = \frac{k^2 Q_{tx} Q_{rx}}{\left(1+\sqrt{1+k^2 Q_{tx} Q_{rx}}\right)^2} = \frac{\left(\frac{m}{\sqrt{L_{tx} L_{rx}}}\right)^2 \frac{\omega\, L_{rx}}{R_{rx}} \frac{\omega\, L_{tx}}{R_{tx}}}{\left(1+\sqrt{1+\left(\frac{m}{\sqrt{L_{tx} L_{rx}}}\right)^2 \frac{\omega\, L_{rx}}{R_{rx}} \frac{\omega\, L_{tx}}{R_{tx}}}\right)^2}$$

$$\eta = \frac{\frac{m^2 \omega^2}{R_{rx} R_{tx}}}{\left(1+\sqrt{1+\frac{m^2 \omega^2}{R_{rx} R_{tx}}}\right)^2} \qquad (8)$$

In short, the optimum transmitter receiver ratio is obtained. Different initial size of transmitter will result to different pattern of optimum transmitter receiver ratio over various operating distance. Even though magnification the size of transmitter will increase the value of *R*, it does not necessary mean that the WTE will be reduced. The increment of *m* and the changed in Q-factor value should be consider and at breakeven point, an optimum transmitter receiver ratio that produces maximum WTE can be determined.

4. Conclusion

As a conclusion, the optimum transmitter receiver ratio can be calculated for known specific initial size of antenna at any operating distance. The changed in antenna size will result to different value of R, L, Q-factor and m, hence will alter the WTE of the system. However, the maximum WTE can be achieved with optimum transmitter receiver ratio at breakeven point.

Acknowledgements

This research was supported by the Ministry of Higher Education (FRGS Grant 4F901), Universiti Teknikal Malaysia Melaka and Universiti Teknologi Malaysia.

References

[1] J Choo, J Ryoo, I Park, J Hong, K Park, J Lee. *A novel multi-loop tag for near field communication in UHF band.* Proceedings of Asia-Pacific Microwave Conference 2007. 2007.

[2] Teck Chuan Beh, Masaki Kato, Takehiro Imura, Sehoon Oh, Yoichi Hori. Automated impedance matching system for robust wireless power transfer via magnetic resonance coupling. *IEEE Transactions on Industrial Electronics*. 2013; 60(9): 3689-3698.

[3] WX Zhong, C Zhang, X Liu, et al. A Methodology for Making a 3-Coil Wireless Power Transfer System More Energy Efficient Than a 2-Coil Counterpart for Extended Transmission Distance. *IEEE Transactions on Power Electronics.* 2014; 30(2): 933-942.

[4] R Jegadeesan, YX Guo. Topology selection and efficiency im- provement of inductive power links. *IEEE Trans. Antennas Propagation*. 2012; 60(10): 4846-4854.

[5] JS Ho, AJ Yeh, E Neofytou, S Kim, Y Tanabe, B Patlolla, RE Beygui, ASY Poon. *Wireless power transfer to deep-tissue microimplants.* Proc. Nat. Acad. Sci. USA. 2014; 111(22): 7974-7979.

[6] A Sodagar, P Amiri. *Capacitive coupling for power and data teleme- try to implantable biomedical Microsystems.* In Proc. IEEE/EMBS 4th Int. Conf. Neural Eng. 2009: 411-414.

[7] C Liu, YX Guo, H Sun, S Xiao. Design and safety considerations of an implantable rectenna for far-field wireless power transfer. *IEEE Trans. Antennas Propagation.* 2014; 62(11): 5798-5806.

[8] Rangarajan Jegadeesan, Sudip Nag, Kush Agarwal, Nitish V Thakor, Yong-Xin Guo. Enabling Wireless Powering and Telemetry for Peripheral Nerve Implants. *IEEE Journal of Biomedical and Health Informatics.* 2015; 19(3): 958-970.

[9] Haider R Khaleel, Hussain M Al-Rizzo, Daniel G Rucker. Compact polyimide-based antennas for flexible displays. *Journal of Display Technology*. 2012; 8(2): 91-97.

[10] Szymon Tankiewicz, Joshua Schaefer, Andrew DeHennis. *A co-planar, near field communication telemetry link for a fully-implantable glucose sensor using high permeability ferrites.* 2013 IEEE SENSORS Conference. 2013: 1-4.

[11] David Jugieu, Guillaume Vigneau, Mohamed Cheikh, Sebastien Kessler, Rachid Benbouhout, Alexandru Takacs. *Design and simulation of printed winding inductors for inductive wireless power charging applications.* 2015 IEEE Wireless Power Transfer Conference (WPTC). 2015: 1-4.

[12] W Lee, K Oh, J Yu. Distance-insensitive wireless power transfer and near-field communication using a current-controlled loop with a loaded capacitance. *IEEE Transactions on Antennas and Propagation.* 2014; 62(2): 936-940.

[13] W Lee, W Son, K Oh, et al. Contactless energy transfer systems using antiparallel resonant loops. *IEEE Transactions on Industrial Electronics.* 2013; 60(1): 350-359.

[14] Gunyoung Kim, Bomson Lee. *Effects of Metamaterial Slabs Applied to Wireless Power Transfer at 13 . 56 MHz.* 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting. 2015: 113-114.

[15] Akaa Eteng, Sharul Kamal A Rahim, Chee Yen Leow. *Effects of Size Mismatch in Dual-function Near-Field Antennas.* 2014 IEEE Asia Pacific Conference on Wireless and Mobile. 2014: 260-263.

[16] Benjamin H Waters, Brody J Mahoney, Gunbok Lee, Joshua R Smith. *Optimal coil size ratios for wireless power transfer applications.* 2014 IEEE International Symposium on Circuits and Systems (ISCAS). 2014: 2015-2048.

[17] Raju S, Rongxiang Wu, Mansun Chan, Yue CP. Modeling of Mutual Coupling Between Planar Inductors in Wireless Power Applications. *IEEE Transactions on Power Electronics.* 2013; 29(1): 481-490.

[18] Inagaki N. Theory of Image Impedance Matching for Inductively Coupled Power Transfer Systems. *IEEE Transactions on Microwave Theory and Techniques*. 2014; 62(4): 901-908.

[19] SS Mohan, M del Mar Hershenson, SP Boyd, TH Lee. Simple accurate expressions for planar spiral inductances. *IEEE Journal of Solid-State Circuits*. 1999; 34(10): 1419-1424.