Square Coil Geometry Evaluation on Power Efficiency for Wireless Power Charging Applications

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Abstract—**Wireless power charging includes interesting physics from low frequencies and RF analysis which tends to be complex and tedious to model and simulate. Full wave simulations has been performed in order to evaluate the wireless power efficiency. A square coil was used to perform this analysis and simulations shows pick values of efficiency of 70% around 5 MHz, which is higher than most found at this frequency. The method has been proved, it is simple to implement in a commercial electromagnetic simulator. Then, it can easily be replicated and optimized to find optimal geometries of coil for specific applications such mobile phones, wearable devices or even electric car charging.**

Index Terms—**Wireless Charging, PTE, Quality factor**

I. INTRODUCTION

Wireless power charging systems WPC is becoming one many technologies that tech consumer are adopting quicker in these days. These power transfer technology has the potential to change many other industries as well. It offers many advantages in respect to classical wired power transfer, although efficiency is not one of them. In small scale, it is already visible in the latest handsets from Samsung, Apple, Huawei, etc. In large scale, it could find major applications where it use could become highly profitable such as electric vehicles, Unmanned Aerial Vehicles or inboard electronics on cars, planes or in the office. The feasibility of wireless power transfer for Electric Vehicles by electromagnetic resonance coupling is modelled in [1]. There are applications where WPC is combined with solar energy harvesting to power wireless sensors [2]. All these indicates the growing potential applications of this technology. It has been consistently improving in recent times, mostly because of aspects related to safety and convenience for the user. These systems uses inductive coupling due to the ranges in the near field zone. Magnetic fields travels from one coil to another, introducing inductive coupling currents in the receiver end, that can deliver power to electronic devices.

The principle is to transmit energy from one point to another by means of an electromagnetic field. At first, a proper coil design is indispensable for improving the system performance [3]. For example, in order to have at least 40% of coupling the radius r for the coil must be much lower than λ of the resonant frequency and the optimum separation d between coils. Therefore for a good coupling should be such one that: $r << d << \lambda$, in this way, the coupling is proportional to power 3 of the separation r. On the other side, the relationship between the radius of the coil and the distance present a inverse proportionality to power transfer efficiency.

Usually, three wireless energy transfer mechanisms are involved in these systems: Inductive coupling, self resonant coupling and modified resonant coupling, which leads to two tracks that are followed by researchers in this field to increase efficiency: first, coils with different geometries to increase directivity and consequently in power transfer. Second, using new materials to improve efficiency.

According with [4] the separation effect between the coils on the PTE is inversely proportional to the separation between them, which is tested on [5], where there is a problem with Focault currents that generate a magnetic field H as the coil is near a conducting material. It could be produced in opposition to the phase of the field generated by the transmitting coil, so the ferrite is inserted between the transmitting coil and the conductive material that will prevent these currents.

In this work, a coil design with a rectangular geometry, which is shown in Fig. 2, is analyzed by a FEM electromagnetic simulator software to extract the scattering parameters that can be used to evaluate Wireless Power Transfer WPT.

II. GEOMETRY

The design of the coils was inspired by [8], the dimensions were varied to make it resonate at 6.78 MHz according to the AirFuel standard developed [9] for wireless energy transfer. The dimensions of the design are shown in the Table I. The design is rectangular geometry, the substrate used was ferrite which has a relative permitivity $\epsilon_r = 12$ and relative permeability $\mu_r = 1000$ and copper as conductive material with three turns. The coils are inside a empty cube of edges equal to $\lambda = c/f$, where c is the speed of light and f the operation frecuency.
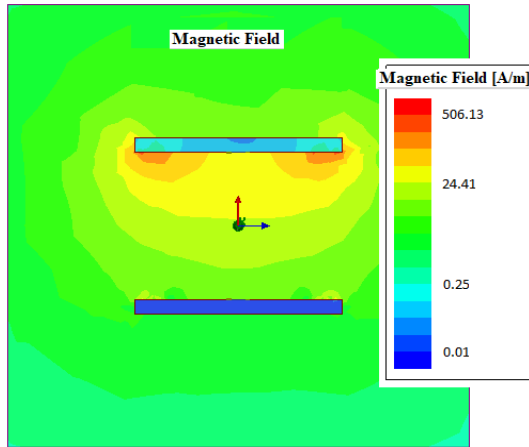
Fig. 1. Magnetic field distribution between two square coils to 20mm of distance at 6.78 MHz

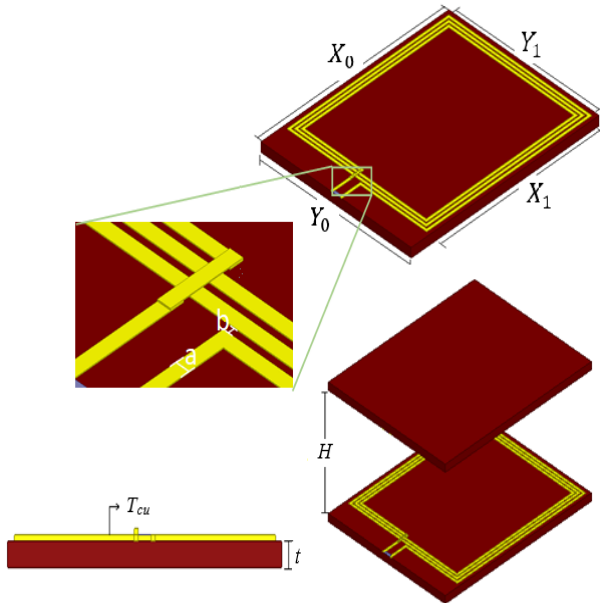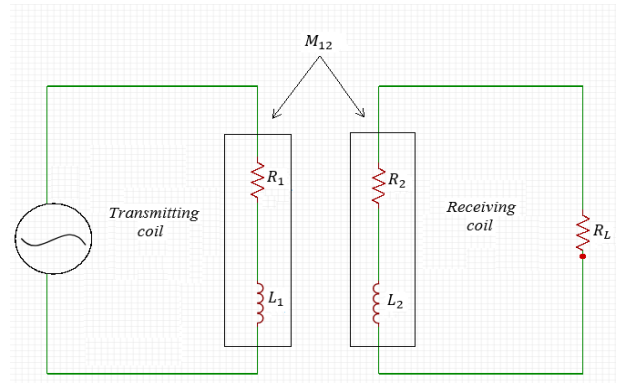| Variable	Values (mm)
X_0	37
Y_0	27
X_1	31
Y_1	25
a	0.6
b	0.3
H	10,20,30,40
t	0.5
T_{cu}	0.036

Fig. 2. Coil design with dimensions.

Fig. 3. Equivalent circuit of the coils

III. METHODS

In [7] a mixed method is described for the analysis of the wireless transfer power, which includes capacitive and inductive components. In the following section, a full description of a simple methodology to analyse magnetic coupling between square coils is presented and discussed. A full wave simulation is performed to obtain Magnetic field distribution as depicted in Fig. 1 which is measured at 20mm of distance at 6.78MHz and the magnitud is expresed in a color scale in amperes per meter (A/m). The dispersion parameters are extrated to continue with the procedure to describe the behavior of the wireless power transfer and how inductive coupling is key in this technology.

A. Equivalent circuit

The equivalent circuit for the coils is shown in Fig. 3 where V_1 is the voltage delivered to the transmit coil. R_1 and R_2 represent the parasitic resistance of the transmit and receive coil respectively, L_1 and L_2 represent the self inductance of the transmitter and receiver respectively and R_L the resistance of the load.

The capacitances coming from the imaginary part of the impedance matrix [Z] have been neglected because those capacities are calculated from circuit models as in [6] that have to be adapted for the particular geometry presented.

It is possible to obtain the required parameters following (1) to (5) equations, using the values of the discrete components of the circuit:

$$Q_1 = \frac{\omega L_1}{R_1} \tag{1}$$

$$Q_2 = \frac{\omega L_2}{R_2} \tag{2}$$

$$Q_{2L} = \frac{\omega L_2}{R_2 + R_L} \tag{3}$$

$$M = K\sqrt{L_1 L_2} \tag{4}$$

$$PTE = \frac{K^2 Q_1 Q_{2L}}{1 + K^2 Q_1 Q_{2L}} \cdot \frac{R_L}{R_L + R_2} \tag{5}$$

Where:

$$\omega = \text{Angular frequency}$$
$$K = \text{Coupling coefficient}$$

Q_1 y Q_2 represents the quality factor of the transmitter and receiver coil respectively, Q_{2L} represents the quality factor of the receiving coil and load. M is the mutual inductance and PTE the power transfer efficiency.

B. Analysis of wireless power transfer

As shown in Fig. 4, the steps for the wireless power transfer analysis for different geometries of coil are as follows:

- The first step is, using a full wave electromagnetic simulator, the geometry of the coils is analyzed with Maxwell Equations solver in the frequency domain. This allows to extract S parameters by exciting the coils through two lumped ports.
- Once S parameters are obtained, then a standard mathematical routine is used to transform it into Z parameters.
- Therefore, from impedance it is possible to determine the self-inductances dividing the imaginary part to Z_{11} with ω for L_1 and Z_{22} with ω for L_2.
- Following, the quality factor is obtained for each coil by dividing imaginary part of Z_{11} with the real part of Z_{11} to find the quality factor of coil 1, Q_1, and the process is repeated for Q_2.
- Thus, the mutual inductance, M, is determined from a division of the imaginary part of Z_{12} or Z_{21} with the angular frequency ω.
- The coupling coefficient K is obtained by clearing equation (4)
- Finally, PTE is obtained using equation (5).

IV. RESULTS

Fig. 5 shows the results of the Quality Factor for the transmitter coil Q_1 measured at 6.78MHZ are observed in three different distances, 10, 20, 30 and 40 mm between the transmitter and receiver coils. When the coils are located at 10mm the quality factor value is 35.06, at 20 mm of distance the quality factor is 31.74, for 30 mm of separation it is 29.69 and for 40mm the corresponding value is 29.64. Then, we can deduce that quality factor tends to decrease with the increased separation between the coils.

The curve of mutual inductance is shown in Fig. 6 and was calculated by one of the two equations described in the analysis that shown in Fig. 4. The values for the mutual inductance of Fig. 6 correspond to micro Henries. It can be seen that the value of the mutual inductance increases when the separation distance decreases, so it can be deduced that the closer the coils are, the greater the mutual inductance produced.

The coupling coefficient indicates the fraction of magnetic flux produced between both coils. The coupling coefficient module for this work is shown in Fig. 7. It can be seen that the value for the coupling coefficient along the frequency axis
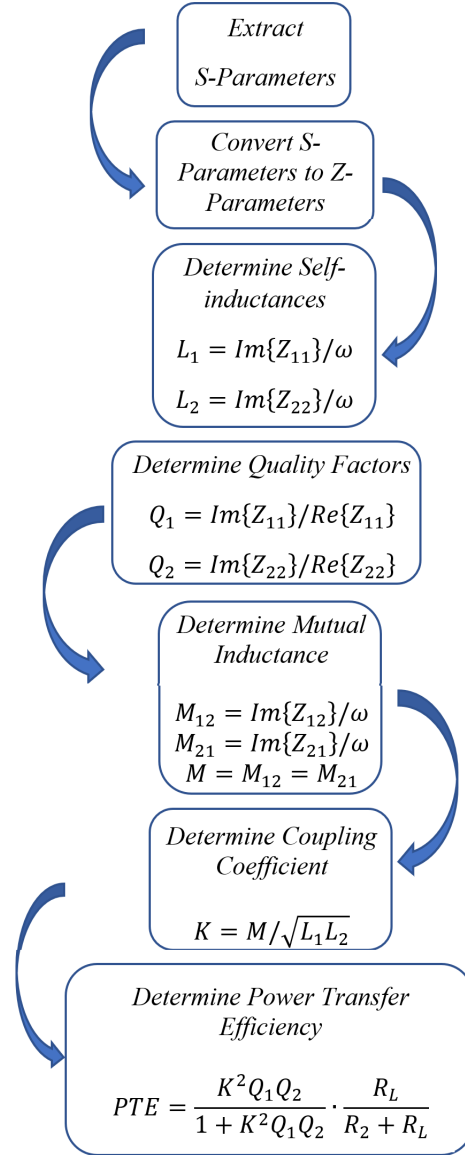

Extract S-Parameters

Convert S-Parameters to Z-Parameters

Determine Self-inductances
$$L_1 = Im\{Z_{11}\}/\omega$$
$$L_2 = Im\{Z_{22}\}/\omega$$

Determine Quality Factors
$$Q_1 = Im\{Z_{11}\}/Re\{Z_{11}\}$$
$$Q_2 = Im\{Z_{22}\}/Re\{Z_{22}\}$$

Determine Mutual Inductance
$$M_{12} = Im\{Z_{12}\}/\omega$$
$$M_{21} = Im\{Z_{21}\}/\omega$$
$$M = M_{12} = M_{21}$$

Determine Coupling Coefficient
$$K = M/\sqrt{L_1 L_2}$$

Determine Power Transfer Efficiency
$$PTE = \frac{K^2 Q_1 Q_2}{1 + K^2 Q_1 Q_2} \cdot \frac{R_L}{R_2 + R_L}$$
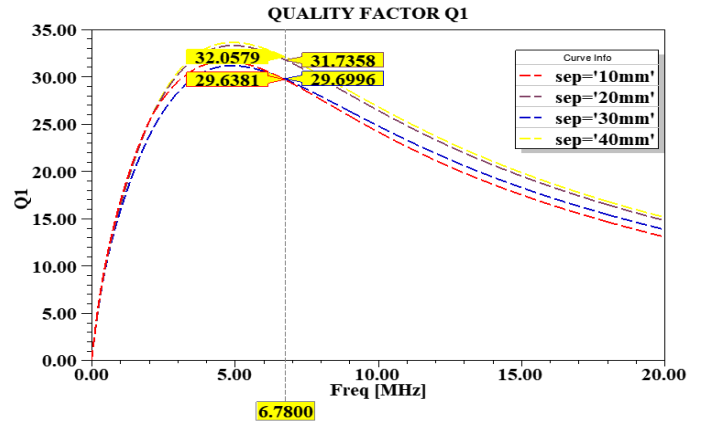
Fig. 4. Analysis of wireless power transfer.

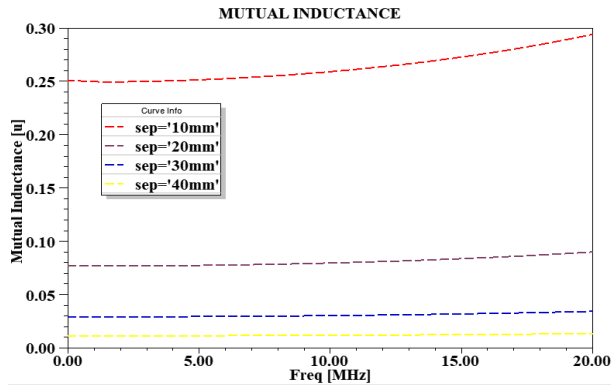Fig. 5. Quality factor of Q_1 at different distances

Fig. 6. Mutual inductance at different distances.

is constant except for the 10mm separation whose curve varies slightly and that on average its value is 0.25. Furthermore, it can be deduced that the coupling coefficient is inversely proportional to the separation between the coils, that is to say that coupling coefficient decreases when the separation between the coils increases.
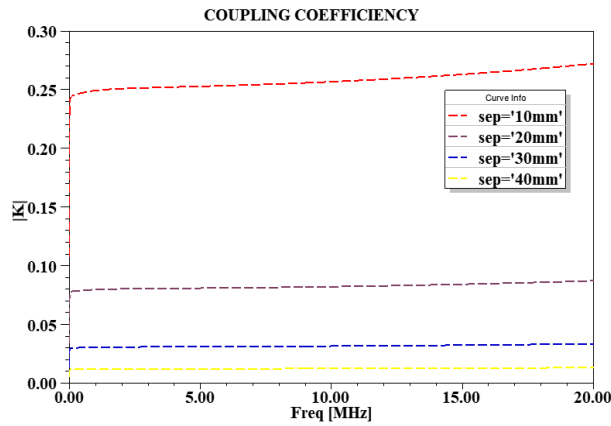

Fig. 7. Coupling coefficient module

In Fig. 8 shows the power transfer efficiency at 6.78MHz. For a separation of 40mm between the coils, 13.45% efficiency was obtained, for a 30mm separation 42.88%, for a 20mm separation 69.97% and 75.64% for 10mm.

We present a comparison with other works as you can see on Table II. The first work didn't show the distance of operation, but we can asume that they work on the near field where they obtain 65% of efficiency. The second work have the smallest size of coils in this comparison and 65.9% of efficiency. However, on this work the efficiency reach 75.64% on the near field and we calculated the PTE at different distances.

V. CONCLUSIONS

An effective method was described for the calculation of the step-by-step power transfer efficiency based on the dispersion parameters or S parameters on square coil geometry. This method is available to calculated any other array of coupling coils where the capacitivies can be obviated. A next step in the
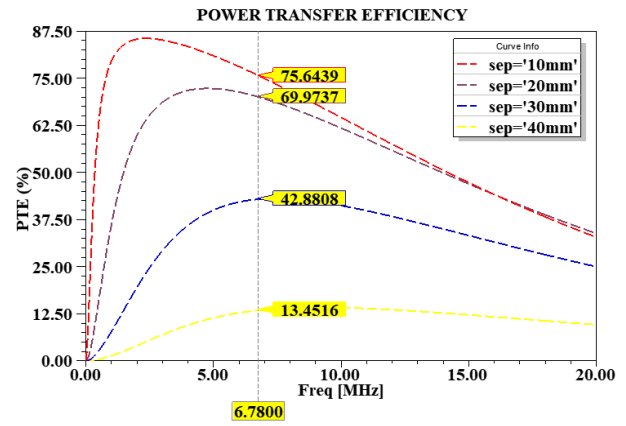

Fig. 8. Power transfer efficiency at different distances

TABLE II
COMPARISON OF PTE

Work	Tx Size	Rx Size	Distance	Frecuency	PTE
[10]	70mm	35mm	No defined	5MHz	65%
[11]	30mm	20mm	12mm	8.1MHz	65.9%
This work	37mm	37mm	10mm	6.78MHz	75.64%

present work is to extract this circuit model for the geometry that is currently being used. Other means of controlling permeability, such as metamaterials, are going to be explored as well.

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