HOMOGENEOUS COIL DESIGN FOR WIRELESS CHARGING ELECTRIC VEHICLES

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ABSTRACT

Electric vehicles are slowly becoming the first option for the consumers as by the time goes the challenges that are limiting the chances of its existence are being reduced due to the efforts of all the researchers on the idea of having a green world as much as possible by eliminating any source of pollution that found a green replacement. However, the performance of the electric vehicles is not enough to make an industrial change while there are challenges that are yet to be solved additionally the main problem is the time taken to have the battery fully charged in both ways static and dynamic charging. However, for the static charging the time is rapidly being enhanced due to the enhancement in the fast charging cable improvements but for the dynamically charging it's all about the efficiency of the connection during the power transmission. In this paper, a homogenous coil has been designed and tested under different conditions in order to obtain the best record of the efficiency. lastly an enhanced method has been produced to wirelessly charge the electric vehicle with the help of the homogeneous pads.

Keyword: *Wireless Power Transfer, Coils Design, Electric vehicle (EV), Inductive Power Transfer (IPT); Dynamic Charging System*

1. INTRODUCTION

Wireless power transmission is the transmission of electrical energy without using any conductor or wire. It is useful to transfer electrical energy to those places where it is hard to transmit energy using conventional wires [1][2][3]. Nowadays , wireless power transfer is taking a big step in our daily life as how it has been used for charging cell phones wirelessly although the efficiency of the power transferred is not like the wired but good enough to charge a phone on the other hand , we had the concept implemented in the TV remote control and Air conditioning Remote control as well which carrying the same concept that is transferring the signal wirelessly and lastly the most recent and also the bigger implementation of the concept of Wireless Power Transfer was in the Electric vehicles charging system which was taking a place in the wireless charging and in many different ways as we will be discussing most of them later on. Wireless Power Transfer for electric vehicles can be implemented with many different theories and in all the research regarding the matter the major problem was the rate of the received signal efficiency [4][5] as shown in fig.1.

2. COIL DESIGNS FOR WIRELESS CHARGING

Electric vehicle market is trending in the past years since the studies of how the petrol cars effecting the environment so the whole production is leaning to the green approaches as shown in fig.2. The technology is becoming more the favourable since its considered to be supported by wireless charging. The coil design is the key factor for having the best performance [5][6][7][8][9].

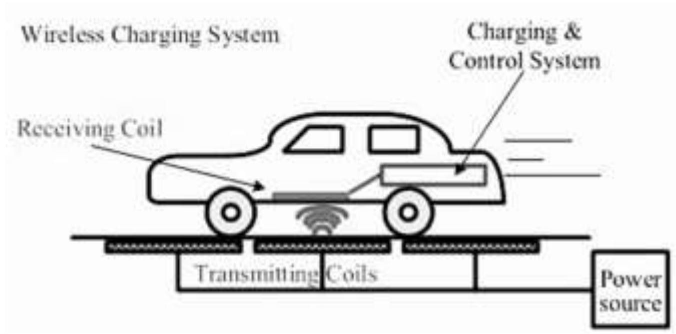

Fig. 1. Components of the WPT [4]

The coil designs that have been used and has shown a good results were the Circular Rectangular pad (CRP), Circular pad (CP), homogeneous pad (HP), double-D pad (DDP), double-D quadrature pad (DDQP) and bipolar pad (BP). The below figure shows the CRP [5].

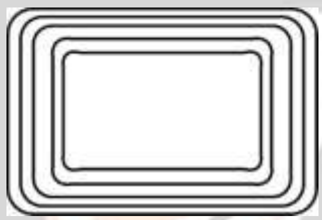

Fig. 2. Circular rectangular pad.[4]

2.1. Circular/Rectangular Pad (CRP/CP)

In the early development of WPT, the circular rectangular pad was proposed for many years, which consists of four fillets as shown in fig.3. This topology mainly improves the flux area; and the flux leakage in edge can be reduced. However, the low efficiency which is a result of poor coupling, and the large total flux leakage are indispensable. Thus, it is normally accepted for the transmitting coil design according to the specific requirement. With all these issues the researchers went to produce the CP to overcome all these draw backs with almost identical specifications when it comes to the transferable power, The design of the pads along with their weights, the cost of material and the applicable distance for the transmission to happen. The figure below shows the CP. [6]

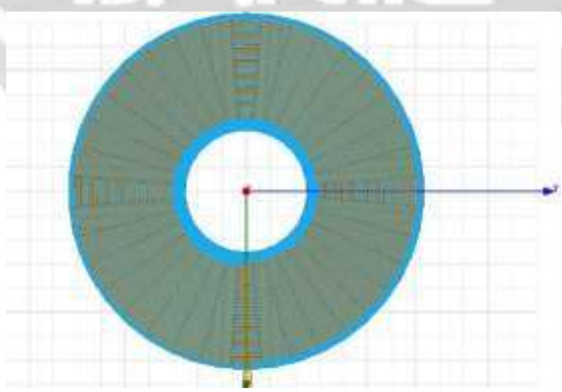

Fig. 3. Circular pad CP [5]

In [7], the coil design that was designed had the symmetric double-sided flux path height, fig. 4 shows the proposed design.

$$\Delta P_z \,\alpha\, \frac{1}{4} P_u \qquad (1)$$

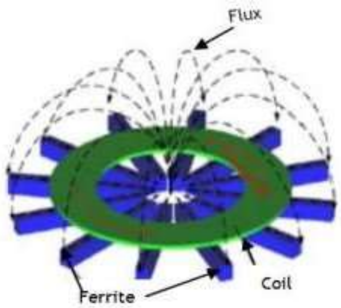

Fig. 4. Symmetric double-sided flux [6]

In this design the path of the fundamental flux which has a height that is proportional to around 0.25 of the pad Diameter cannot be used for dynamic wireless charging.

In [8], the proposed design was carried in 3 different ways with varying the coil diameter size for the primary and secondary coil and recording the readings of the power transfer with a comparison with the Misalignment and Magnetic flux. An important observation that the best recorded results were in the case of having the outer diameter of the secondary and primary coils were the same as for the other two cases has recorded lower values of magnetic flux between the coils which determines low power transfer.

In [9], the design was using rectangular coil and spiral windings with the aim to have an organised magnetic field and a better result regarding the misalignment However the design coil is having low distance range in order for the transmission system to work and also has a poor interoperability characteristic. Furthermore the results In[9] regarding the testing on the dynamically charging using CRP and CP coil designs it gave the same concluded results in[10].

2.2. Homogeneous Pad (HP)

One of the main issues that was the reason for the homogeneous pads to be introduced in the field was that the inductive power is limited to only on the surface to be having a high efficiency and also the ability of having a lateral displacement between the receiver and transmitter coils its most likely going to cause an effect on the coupling factor and for that The author describes an approach for determining the turn distribution in order to ensure homogenous coupling between coils of different diameters. However, an array of transmitter coils can also be employed to create lateral displacement across a broader region. The receiver coil is chosen in such a way that it always covers the whole transmitter coil. With homogeneous magnetic coupling, the power transmission area can be arbitrarily big if only the covered transmitter coil is triggered by a proper sensing circuit.[11]

This coil design is one of the keys to having the ability to charge the electric vehicle while moving as its circuit design contains multiple primary coils, However, this design comes with some challenges like its known with its low of power transfer and its high material cost while its transmission distance comes in a medium range. The HP circuit is as shown blow in the fig.5.

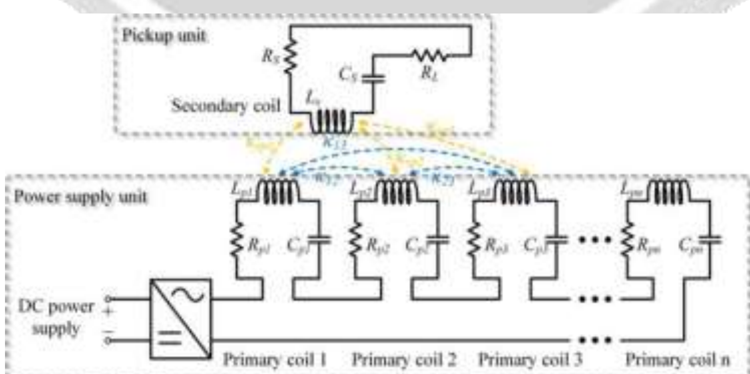

Fig. 5. Basic circuit for dynamic charging circuit

The fundamental structure of a wireless charging mechanism for move-and-charge systems is depicted in the diagram, in which the power supply unit uses several series linked primary coils arranged along the charging target's moving trace.

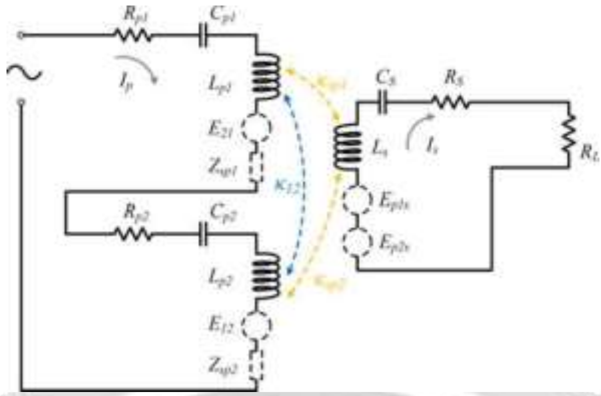

Fig. 6 The equivalent circuit modal

In fig. 6, the equivalent circuit shows hoe the mechanism of the dynamic charging is processed, when the transmission is happening from the first primary coil to when between the two primary coils and so on. The mutual inductance can be calculated from the following:

$$L_{12} = K_{12}\sqrt{L_{p1}L_{p2}} \quad (2)$$

$$L_{sp1} = K_{sp1}\sqrt{L_{p1}L_{p2}} \quad (3)$$

$$L_{sp2} = K_{sp2}\sqrt{L_{p2}L_{s}} \quad (4)$$

In [11], HP was designed to attempt and have the system to be continuously energized also enhancing the magnetic flux however the misalignment is a major issue when it comes to HP but the main course was to continuously have the transmission between the main and secondary coil. Moreover in [12], the issues and the drawbacks of this coil design raised again in such the power transfer was low and transmission distance was fairly acceptable with an effected efficiency of the transmission.

2.3. Bipolar And Double-D Pads (BP and DDP)

Few of the topologies has two couplers which is in the design for the WPT in specific with the BPP and DD circuit design furthermore this kind comes with a topology of a Parallel-Parallel compensation. For the BP and DDP coil designs they are mostly used together as the BP for the receiver side and the DDP for the transmitter side as shown in fig. 7 that shows the circuit for the primary side and the secondary side [13]

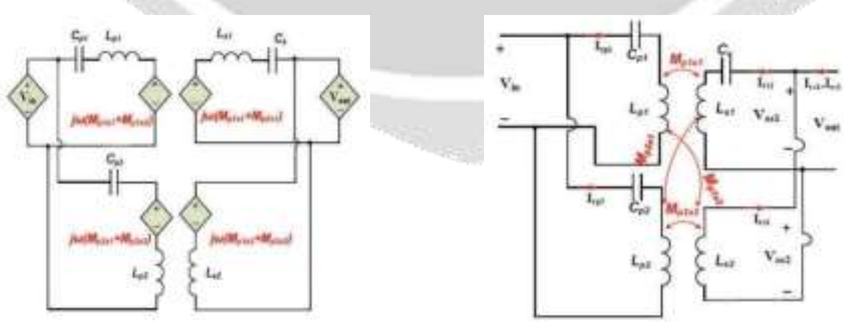

Fig. 7. (a) Simplified IPT circuit for double couplers configuration
(b) IPT systems consists of two primary couplers and two secondary couplers.

The following formula can be used to calculate the output power of an inductive power transfer system.[13]

$$P_{out} = w_r \frac{M^2}{L_2} I_{rp}^2 Q_2 \quad (5)$$

2.4. Double-D Quadrature Pad (DDQP)

Double-D Quadrature topology was designed to overcome the lack which was experienced with the DDP and CP when it comes to poor interoperability characteristic. So, the DDQ-pad is solving this drawback by a design that have the parallel and perpendicular magnetic field together. Moreover, this topology is being able to produce the polarized and non-polarized filed by organizing the current flowing in the coil and the flexibility is the highest compared to the other topologies however the disadvantage in this design is the cost as it requires a greater number of coils.

In [14], The design of the DDP in a way the current flowing in opposite direction in the double coils. And the flux path is being created accordingly with the ferrite bars however it has the poor interoperability characteristic issue so in the [15], the design changed for that matter, and it was the DDQ pad design the issue was solved However that comes with a cost of more material and the cost of rectifier is higher. Furthermore, for the DDQ and BP coil designs they can achieve almost identical power transmission as the design can be adjusted to fit the given sized structure whereas the primary has no effect whether its polarized or non-polarized as showed in fig. 8. A comparison showd in Table 1.

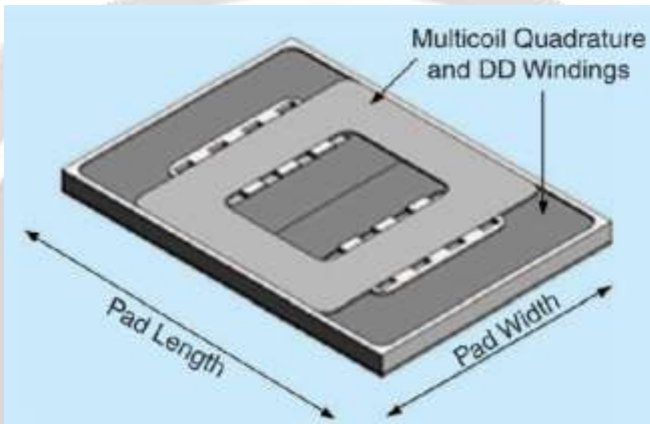

Fig. 8 The DDQ [15]

Table 1 Shows a Comparison between the coil pads features

Type	CRP/CP	HP	DDP	DDQP	BPP
Factors	• Cost and size constraints • System weight • Electric Vehicle Types • Power Level • Distance Between Primary and Secondary Batteries • Chassis Structure	• High misalignment need • Size design of each cell coil • Secondary size and direction design • Small system cost and size • System weight	• Ferrite bar length and thickness • Unwanted flux leakage • Low system cost and size • System weight • Power level • Coupled flux direction need	• Ferrite bar length and thickness • Control methods • System cost and size limitations • System weight • Electric vehicle types • Power level • Chassis structure	• Ferrite bar length and thickness • System costs and size are kept to a minimum. • The central area is overlapping. • Amount of power • The distance between primary and secondary schools • Structure of the chassis

Features	•Flux is symmetric around the centre of the CP. •Pattern of nonpolarized perpendicular field by CP •It is most commonly utilised in primary and secondary schools. •Inadequate interoperability Characteristics •Create perpendicular flux and couple it • Applications that are adaptable	•Inadequate interoperability Characteristics •Create and link polarised parallel flux along the length of the pads. • It's a term that's commonly used in primary schools. •Cost effectiveness • Magnetic field distribution that is homogeneous • High misalignment potential	• Generation of a single-sided flux • Improve performance and interoperability with a variety of secondary topologies • It's a term that's commonly used in primary schools. •At high power rates, ferrite bars are easily saturated. •There is no reverse flux to remove the undesirable back flux.	• As a secondary, giving three times the z charge zone of DDP •Improved performance with various secondary topologies • It's a term that's commonly used in secondary schools. •Excitation Modes with Variable Excitation •Inefficient material utilisation • Flexible central coil design to accommodate the airgap	•Partially overlapping coil structure that is mutually disconnected •DDQP utilised as a secondary has about the same performance as DDQP used as a primary. • DDQP uses less copper than this. •Improved performance with various secondary topologies •It's a term that's commonly used in secondary schools.

3. WPT TOPOLOGIES

In wireless power transfer there are 4 topologies that can be used in order to have the connection between the two circuits the primary and the secondary coils and it may be a parallel, series or combined. Fig. 9 shows the to the topologies. SS is having a series - series connection, SP is having a series parallel connection, PS is having a parallel series connection and lastly PP is having a parallel series connection [15][16][17][18][19][20][21]. Table 2 summarize the pro and con of different topology.

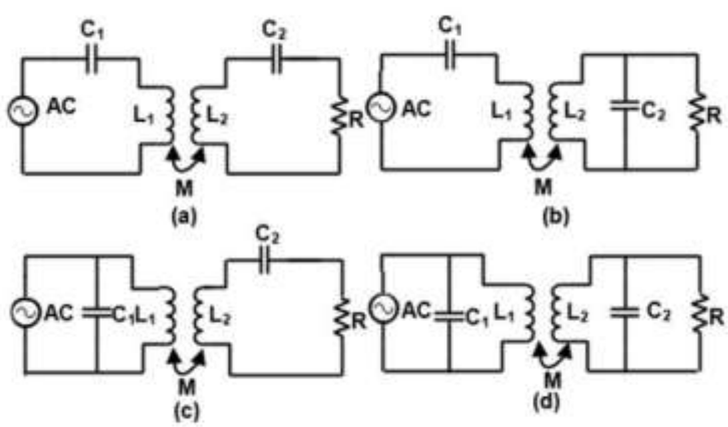

Fig.9. WPT Topologies; (a) SS, (b) SP, (c) PS, and (d) PP [16,17,18,19]

Table 2 Summary of advantages and disadvantages of these topologies

Specifications	SS	SP	PS	PP
sensitivity with relation Over distance	low	low	medium	medium
the value of the impedance at resonant	low	low	high	high
compatibility with EV	High	High	Medium	Medium
PT capability	High	High	Low	Low
tolerance of the alignment	High	High	Medium	Low
tolerance of frequency with relation to the efficiency	Low	High	Low	High

4. Coil Design

With the rapid growth of the electric vehicle (EV) market, the new wireless EV charging technology has gotten a lot of attention in recent years. The coil design is critical for increasing the performance of a wireless charging system for electric vehicles. The main parts to be taken under consideration when designing the coil after determining which type it will be the parameter calculations which will affect the maximum efficiency of the coil. In this paper ££ coli has been chosen [22][23][24[25]. From [R], The parameters are: Outer radius ($R_{\mathrm{Tx,Rx}}$), Wire radius (r_o) and number of turns ($N_{\mathrm{Tx,Rx}}$) Power transfer efficiency (PTE), transfer distance, transferred power,and misalignment tolerance are the most important WPT performance parameters. PTE is calculated using the following formula:

$$PTE_{\max}= \frac{k^2\ Q_{Tx}\ Q_{Rx}}{(\ 1+\sqrt{1+k^2 Q_{Tx}\ Q_{Rx}}\ )^2} \quad (1)$$

- **Coil radius effect**

The radius of the coil has the ability to control the amount of the power which will be received and for that the following testing has been conducted to double check and ensure about the radius of the coil that will be used in this paper to produce the Hemo coil will have the best results. The testing coil was created with n = 17 as shown in fig. 10.

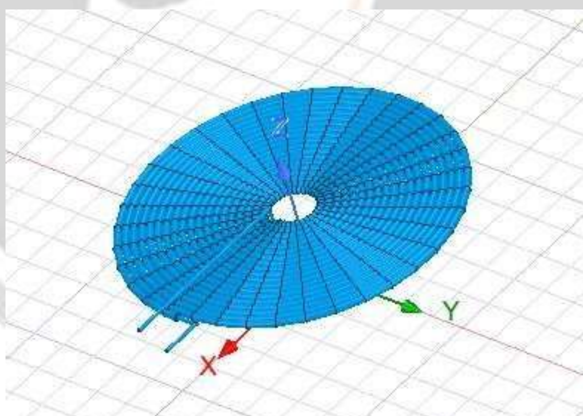

Fig. 10. Testing coil

The design has been tested on the Ansys Maxwell software with a value of 15A for the current. And 6.87 Hz as the resonance frequency. The coil radius was examined with different values and compared on both coils. The comparison between all the test results is as carried based on the plotted efficiency. The first coil was constructed with starting radius of 3mm for the transmission side and 3mm for the receiver side. The way Ansys software works in a way that the coils must be connected to terminals and the terminals must be in contact with the region that must be created to simulate the surroundings as if the process is in a room as the region has been assigned with air material and the coils are assigned with a copper material as shown in fig. 11.

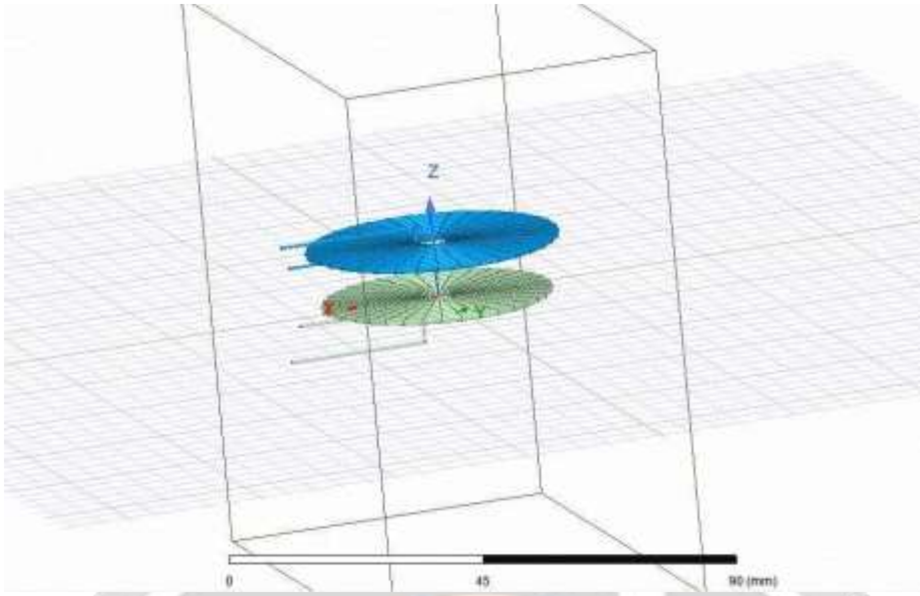

Fig. 11 Primary and Secondary Coil for the radius testing.

The process started by assigning excitations to the terminals connected to the primary coil with 15A current and for the receiver coil 0A as it will be excited later by the magnetic field generated from the primary coil. This step is very important as it tells the software where exactly in the created structure the current will be flowing. Secondly assigning mesh to both the coils and the region, mesh analysis is basically an attempt for the betterness of the simulations, the higher the mesh values the more time will be taken the more realistic the results are. Lastly assigning the testing parameters and in this project the assignation was about the offset in the X-axis and the Y-axis. This process has been done in 4 different variations as shown in table 3.

Table 3 Radius testing variations.

Primary coil radius(mm)	Secondary coil radius(mm)
3	3
3	5
5	3
5	5

The problem that this paper is looking to solve is to have the connecting roads to be dynamic charging supported to a certain extend that the owner of an electric car will be less concerned with the idea of whether their car is being able to reach the destination or not. So far it has been included in may researches that for the vehicle to charge in the move there will be a speed limit. Only one side of the road will be for charging to ensure that the other drivers with full battery or gas supported to have the chance to drive in a higher speed. The consideration in terms of the coupling coefficient in the design was in having more than one transmitter coil as in a Single coil structure designs that has been tested there wear a large leakage flux and for that reason the segmented or in other words the multiple transmitters are better as they provide a better coupling which it effects the efficiency of transmission and also the leakage is reduced.

Fig. 12 shows the Homogeneous coil structure that has been created for testing and as the figure shows every transmitter is having two terminals however the inner structure of the circuit has all the coils being connected in twin builder, this specific step is to be able to obtain the values of inductance and coupling coefficients and other results that are coil based.

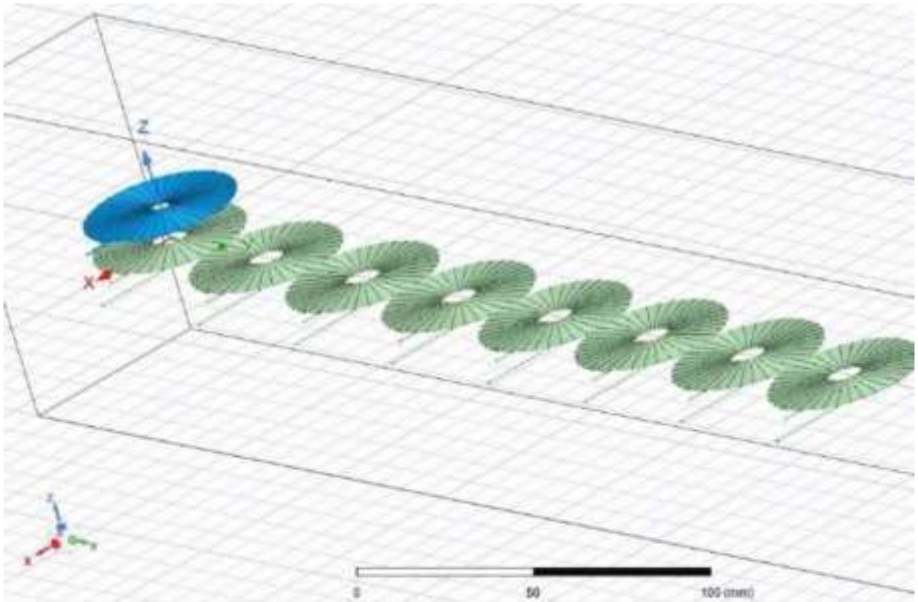

Fig. 12., Homogeneous coil structure.

5. RESULT ANALYSIS

In this work, we started with the behaviour of the coil. The coil radius was examined with different values and compared on both coils. The comparison between all the test results is as carried based on the plotted efficiency. The radius of the Primary side is 3mm and for the secondary side is 3mm, results are as follows:

Table 4, 3mm

Distance(mm)	Efficiency(%)
5	92.66
10	78.35
15	66.2

And the coupling coefficient showed in Table 5, coupling coefficient.

Distance(mm)	Coupling coefficient
5	0.5
10	0.3
15	0.18

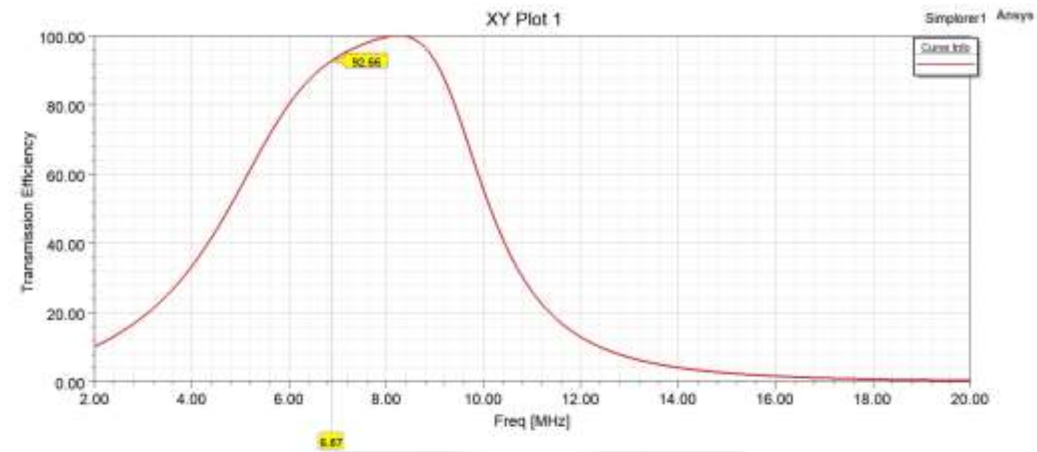

Figure 4.1 shows the Transmission Efficiency in a 5mm distance gab.

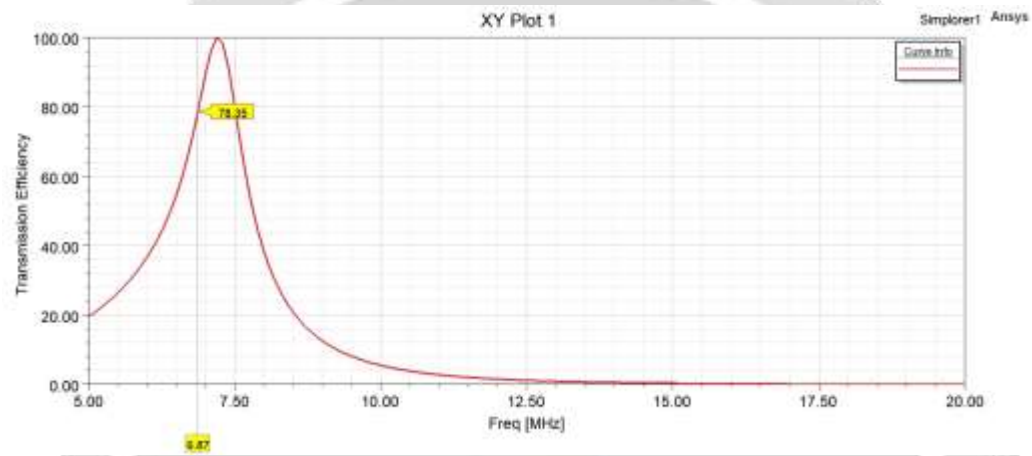

Figure 4.2 shows the Transmission Efficiency in a 10mm distance gab.

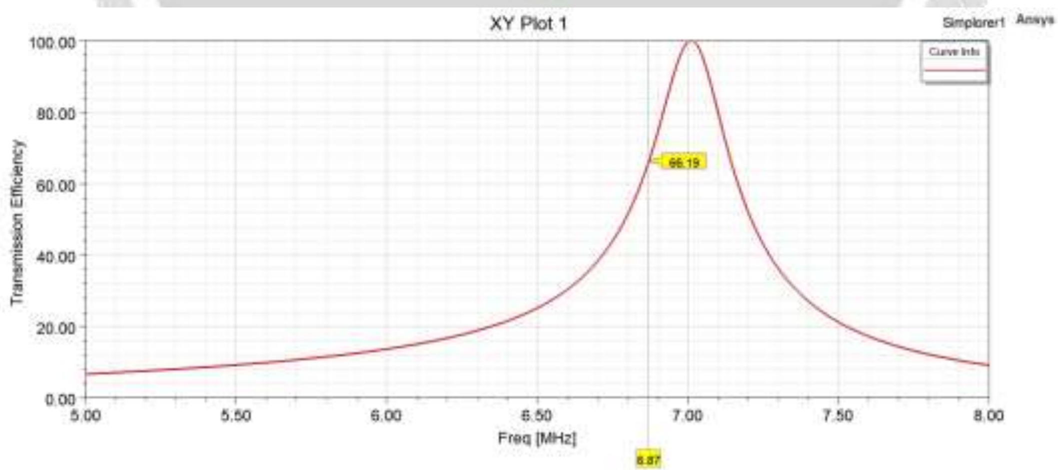

Figure 4.3 shows the Transmission Efficiency in a 15mm distance gab.

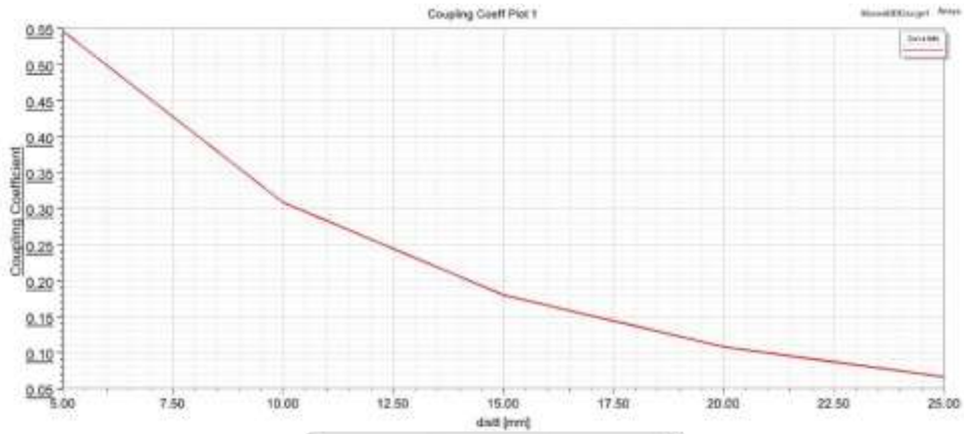

Figure 4.4 coupling coefficient.

The radius of the Primary side is 3mm and for the secondary side is 5mm, results are as follows:
Table 6, Efficiency.

Distance(mm)	Efficiency (%)
5	84.8
10	70.28
15	67.9

And the coupling coefficient is shown Table 7, Coupling coefficient.

Distance(mm)	Coupling coefficient
5	0.54
10	0.31
15	0.18

6. CONCLUSIONS

In this paper, a homogenous coil design was proposed and it was found that the radius of the transmitter coil can have a greater impact on the efficiency of the process and why does port transfer in which when the radius of the transmitter is bigger than the radius of the receiver coil then the power transfer system will have a higher efficiency of transmission would respect too distance (gab in Y-axis) in other words the coupling coefficient of this kind is better and that's because degenerated magnetic field is greater so it covers higher spaces. In the coil design section, the simulation was carried out on Ansys maxwell and Ansys twin builder with the equivalent circuit of the parallel-Parallel LC circuit as shown in the following figure ##. Regarding the coil design the results obtained was recorded to differentiate between when the transmission coil has a bigger or smaller inner radius with the greater effect on the efficiency of the wireless power transmission, on the other hand the receiver coil has recorded an effect of causing a loss and the more the gap between the coils the more power loss and that can be seen in the recorded efficiency however in the case of 5mm and 5mm the system maintained a good connection and the power efficiency recorded was resonating in (80%+) but as soon as the gab increased a little bit the efficiency reduced to less than 65% which means it's not consistent and for that reason the coil radius that has been chosen for the Homogeneous system are with the configuration of the transmission coil radius bigger than the receiver coil.

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