Project Report ECE 423
Efficient wireless non-radiative mid-range energy transfer

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Abstract

A report that provides an attempt of reenactment of simulations and calcutation from a paper, [1] ”Optimization on Three-Coil Long-Range and Dimension-Asymmetric Wireless Power Transfer System. This including a brief introduction to the process or rather steps that have been taken to recreate the graphs and data from the paper. The report will showcase four images in total; using two different softwares three will be using Matlab while the other is captured through Ansys HFSS a high-frequency structure simulator.

Index Terms

Coil current, electromagnetic field (EMF), multiobjective optimization, three-coil structure, wireless power transfer (WPT)

I. Introduction

THE topic of transfering power wirelessly is very important, seeing its broad range in various appliances within our daily lives. Thus wireless power transfer (WPT) is also looked into in getting futher developed, whether it be with its efficency, range, stability or something else. The paper ”Optimization on Three-Coil Long-Range and Dimension-Asymmetric Wireless Power Transfer System” by author Feng Wen and co.[1]; shows exactly how they were able to achieve results in their ventures.

With the further demand for wireless power transfer (WPT), a problem regarding the moment when the WPT system require a long transmission distance. Which in turn casuses the currrent within the transmitter coil to exceed the limit to its overall structure. Since the transmitter coil is taking the overall toll of the defisionsies, the addition of a relay coil is added between the transmitter and reciever to aliviate and reduce the current on the transmitter.

Theoretical

Overall three different compensation topologies were taken into consideration regarding the transmitter coil. Figure. 1 from [1] shows them as an equibalent circuit diagram refered to S-S-S for series, S-S-P for parallel, S-S-LCC for inductor capacitor capacitor.

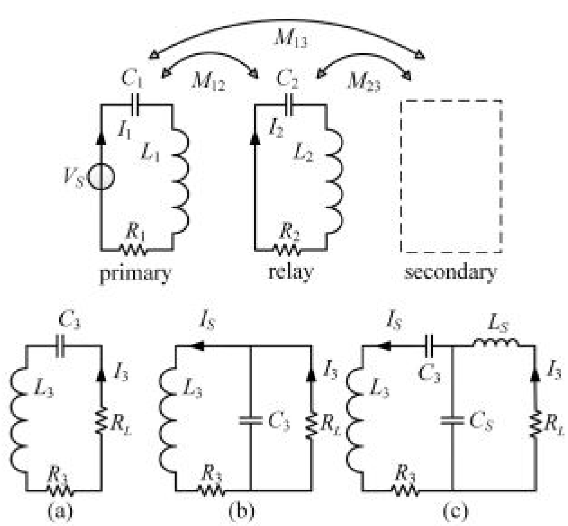

Fig. 1: Equivalent circuit diagrams under different compensation topologies. (a) S-S-S. (b) S-S-P. (c) S-S-LCC. [1]

Through analysis and comparison of these topologies, it was decided to focuse on the S-S-S topology when compared to the other two topologies. From the analysis it was noticed that the topology with a parallel configuation required more current in comparison, while the LCC topology is the smallest amount of current but will require more components thus making it more costly. These constraint mainly cost and the current which is the main purpose of the relay in the first place is what evidently cause the decision in focusing the further analysis and simulation with the S-S-S topology. For more indepth information regarding this descovering go through section II Theoretical Analysis part A. Comparison of different Compensation Toppologies from [1].

Relevant formulas

There are many important formulas that will be necessary during the reproduction part of this paper. This includes the current through the transmitter, relay, and receiver coil. Mutual inductance and the Equivalent Internal Resistance from each coils, theire impedance, the transmission efficiency of the three-coil WPT system. These formulas and the data from Table 1 and the optimized data for the coils from [1] are also taken into account when reproducing the results.

The following formulas can be found in the Appendix B and C from [1] while the current from equation (3) also from [1]; current through coil 1, coil 2, and coil 3 are as follows,

$$\begin{cases} I_1 = \frac{(Z_2 Z_3 + \omega^2 M_{23}^2) V_S}{Z_1 Z_2 Z_3 + \omega^2 (M_{12}^2 Z_3 + M_{23}^2 Z_1)} \\ I_2 = \frac{(\omega M_{12} Z_3) V_S}{Z_1 Z_2 Z_3 + \omega^2 (M_{12}^2 Z_3 + M_{23}^2 Z_1)} \\ I_3 = \frac{(\omega^2 M_{12} M_{23}) V_S}{Z_1 Z_2 Z_3 + \omega^2 (M_{12}^2 Z_3 + M_{23}^2 Z_1)} \end{cases} \tag{1}$$

the impedance for each coils, and because the coils satisfy the resonance conditions they can be simplified

$$\begin{cases} Z_1 = R_1 + j(\omega L_1 - \frac{1}{\omega C_1}) = R_1 \\ Z_2 = R_2 + j(\omega L_2 - \frac{1}{\omega C_2}) = R_2 \\ Z_3 = R_L + R_3 + j(\omega L_3 - \frac{1}{\omega C_3} = R_3) \end{cases} \tag{2}$$

the transmission efficiency of the three-coil WPT system,

$$\eta = \frac{(\omega^2 M_{12} M_{23})^2 R_L}{[Z_1 Z_2 Z_3 + \omega^2 (M_{12}^2 Z_3 + M_{23}^2 Z_1)] \cdot (Z_2 Z_3 + \omega^2 M_{23}^2)} \tag{3}$$

and lastly is the mutaul inductance derived from Biot-Savar's Law,

$$\begin{cases} M_{12} = \sum_{j=1}^{n_2} \sum_{i=1}^{n_1} \int_0^{r_2 + (j-1) d_2} \frac{\mu_0 r}{\sqrt{[r + R_1 - (i-1) d_1]^2 + D_{12}^2}} \cdot \\ \left\{ \frac{[R_1 - (i-1) d_1]^2 - r^2 - D_{12}^2}{[R_1 - (i-1) d_1 - r]^2 + D_{12}^2} E(K) + K(k) \right\} \cdot dr \\ E(k) = \int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{4r[R_1 - (i-1) d_1]}{[R_1 - (i-1) d_1 + r]^2 + D_{12}^2} sin^2(\phi)}\, d\phi \\ K(k) = \int_0^{\frac{\pi}{2}} \frac{1}{\sqrt{1 - \frac{4r[R_1 - (i-1) d_1]}{[R_1 - (i-1) d_1 + r]^2 + D_{12}^2} sin^2(\phi)}} d\phi \end{cases} \tag{4}$$

II. Reproducing the results through Matlab

Now due to not having the exact details regarding the wires used, for the following simulations done in Matlab we will used the longer version of the efficiency and not the one shown bellow. Note for the efficiency regarding the three coil WPT can be simplified because the Vs and I from coil 1 are in the same phase making M_{13} negligible[1].

$$\eta = \frac{I_3^2 R_L}{V_S I_1} \tag{5}$$

During the analysis of the parameters regarding the plot graphs for section II. The coil currents are normalized and adjusted by a parameter alpha $\alpha = \frac{I_{3_{ref}}}{I_3}$ and then normalized with the max current respectivly $I_{1*} = \frac{I_1}{I_{1max}}$, this way the current for coil 3 is not necessarily used within the plot since it will be constant through α.

Submit a plot obtained using Matlab that reproduces Fig. 5 of [1]

Regarding the information from the coils, there has been some important information missing from the paper. The paper [1] did not give the gauge or the diameter for the three coil wire, this brings further difficulty in finding the impedance of each coil. With this in mind an arrbitrary number but not unrealistic was chosen to be used as the diameter of the wires, because of this the results from the following plots are not accurate, but they share similarities to be able to derive the same conclusions.

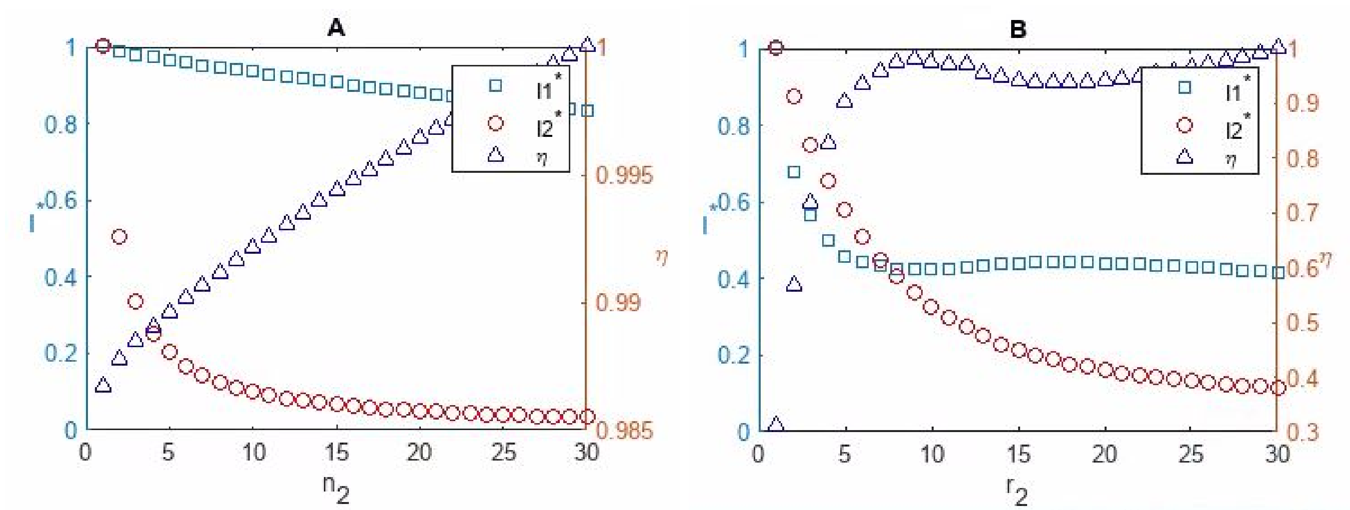

Fig. 2: Normalized coil current and transmission efficiency with respect to relay coil, wrt turn number, inner radius

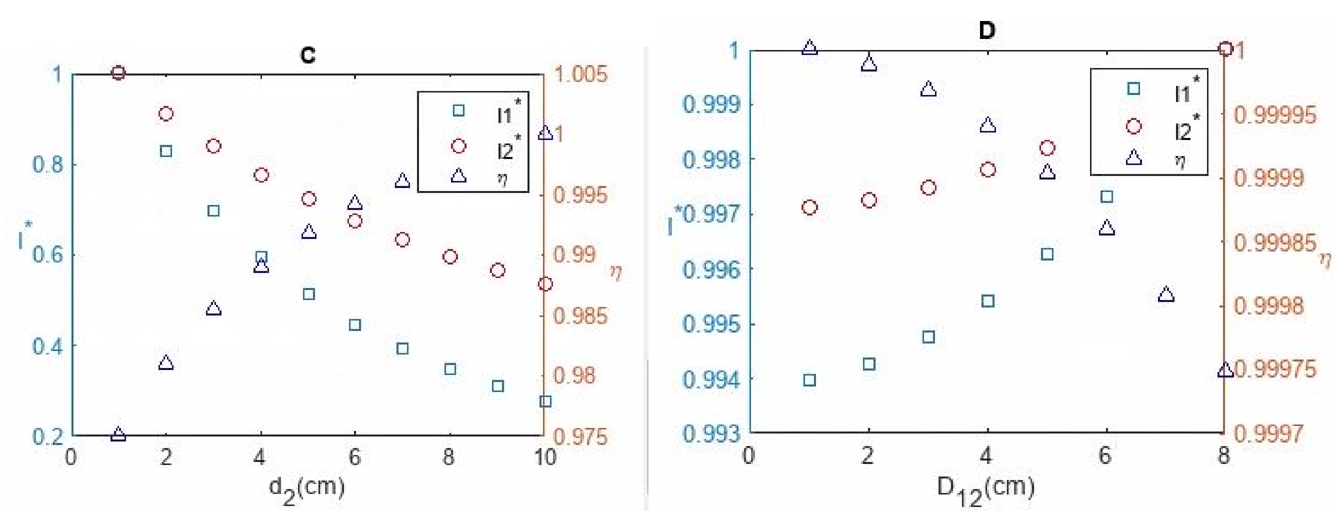

Fig. 3: Normalized coil current and transmission efficiency with respect to relay coil, wrt turn spacing, distance between transmitter and relay coil

Comparing the results from the paper for fig 2 (a) the results are fairly similar. In a different case for (b) at the start the figure was only slightly similar and started to increase in similarity when the resistance for the coils where adhjusted to a very small scale by 0.0008. This is due to reasons stated before as we do not have the information of the exact wires to achieve resonance for all change of variables from the plots shown in Fig. 2 and 3.

Submit a plot obtained using Matlab that reproduces Fig. 8 of [1]

For Fig. 4 some compromises were necessary to achieve results within the limit time. Regarding the data input of n for coil 1, instead of having 300 it was scaled down by 30. While the actual coil turn number is scaled by 10 achieveing the same plot with much smaller divisions and increments. It was decided to change the scale to increase the speed of obtaing resluts, and due to having low quality equipment causing the Matlab program to run at a very slow pace. Thus achieving limited results.

Nevertheless the plot has shown similar results, as we can see that the Mutual inductance between the transmitter and receiver coil is increaseing as the number of turns for the transmitter coil is also increaseing. The difference in data regarding the mutual inductance is a result from having potentialy different variable compared to the paper [1].

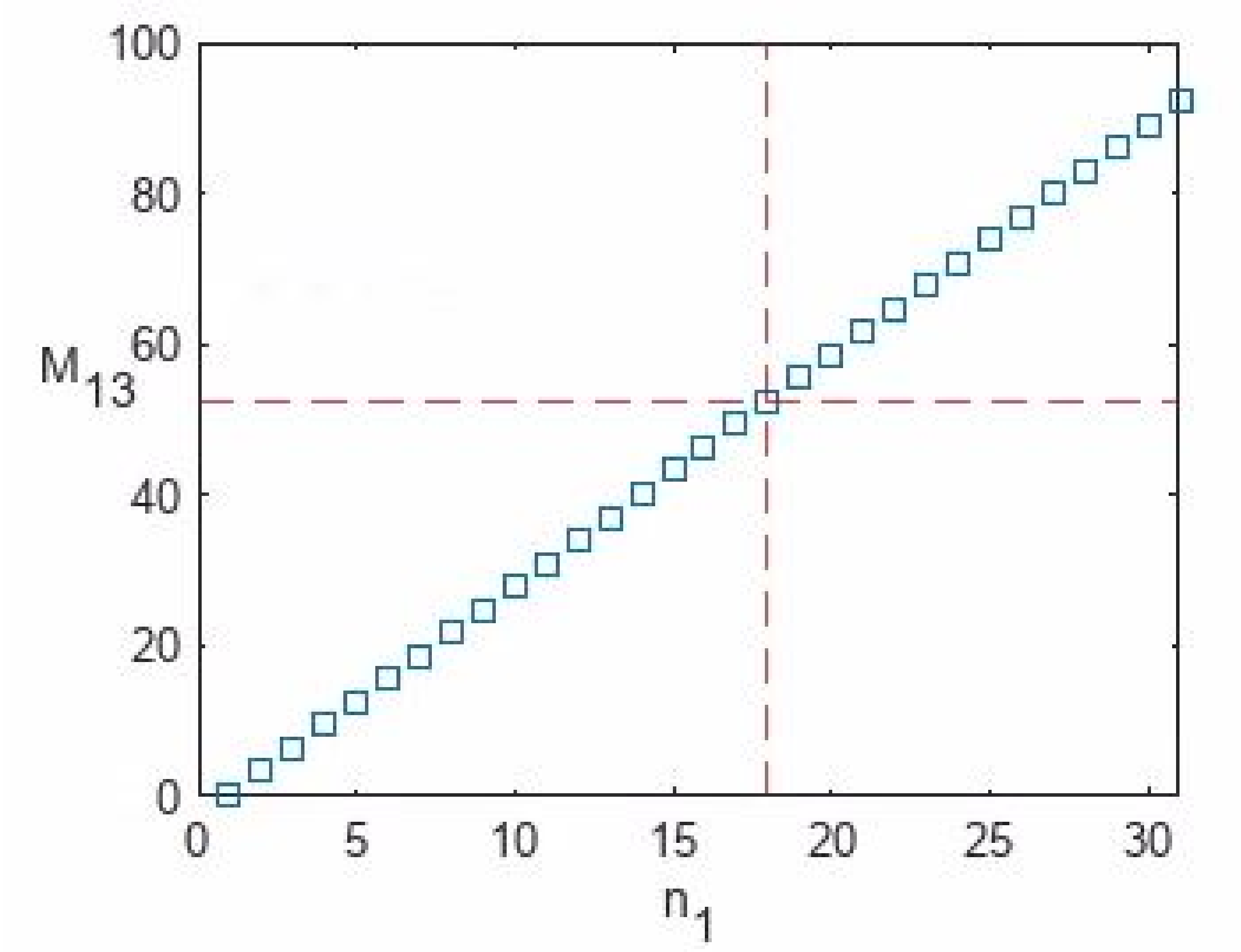

Fig. 4: Mutual inductance between transmitter and receiver coil M13 with respect to transmitter coil turn number n1.

1) Submit a plot obtained using Matlab that reproduces Fig. 9 of [1]: For the following plot regarding the coil current and tranmission efficency wrt the load resistance. We can see that both the currents follow similar path lines as from the paper. The current from coil 3 is decreasing from a higher point, while the coil 1 is decreasing slighty from a lower point and coil3 apears constant. Although the efficiency is different while using the formula it shows taht it is not incorrect, unless the wrong formula was used in this case.

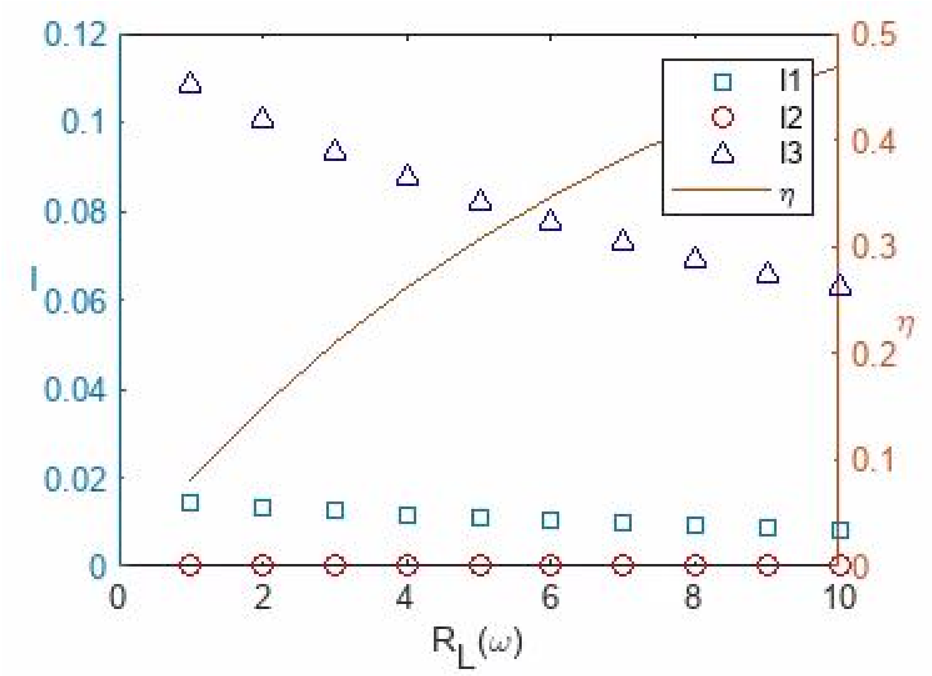

Fig. 5: Coil current and transmission efficiency with respect to load resistance

III. Reproducing plot and models through Ansys HFSS

Submit a plot obtained using Ansys HFSS that reproduces Fig. 11 of [1]

In the process of creating the simulation model, many aspects from the paper [1] where taken into consideration while building the model for the simulation. In the process of recreating the coils, the function of creating a radial helix with radial of 0, from Draw¿User Defined Primitive¿Syslib¿SegmentedHelix¿Radhelix. With this the coils where created by adding the parameters from the paper [1] and enough segments to make the coils circular.

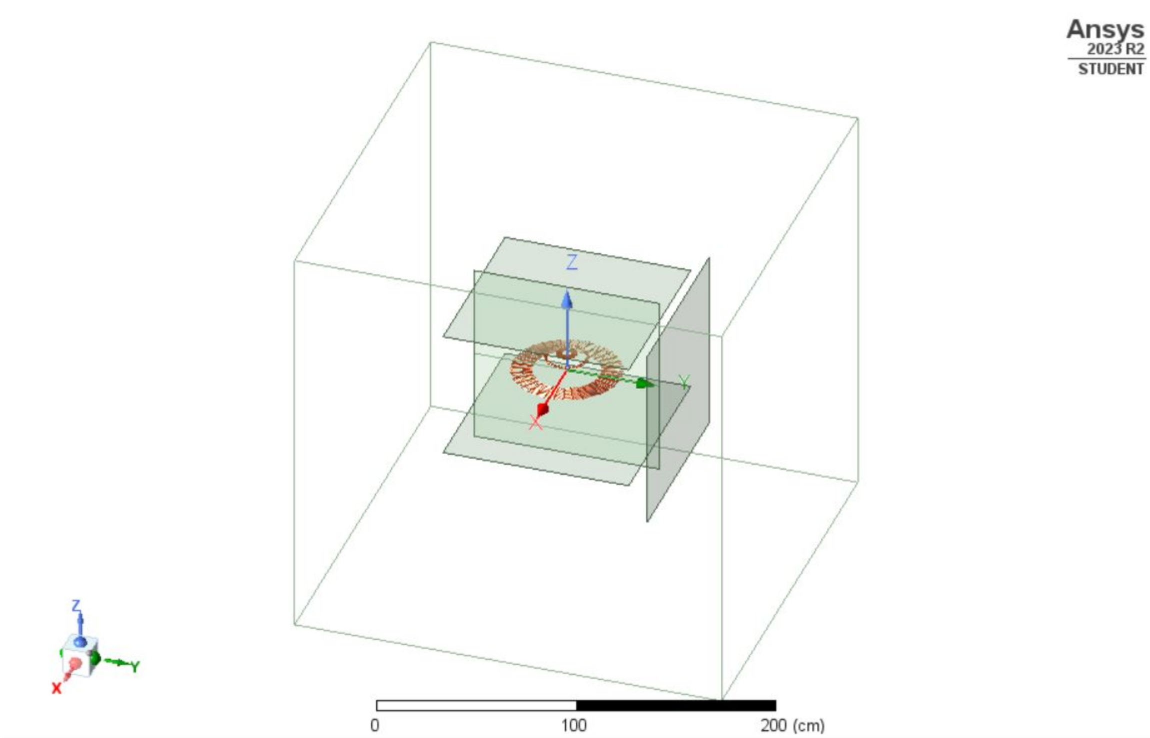

Fig. 6: Model of the region, transmitter, relay, and reciever coil

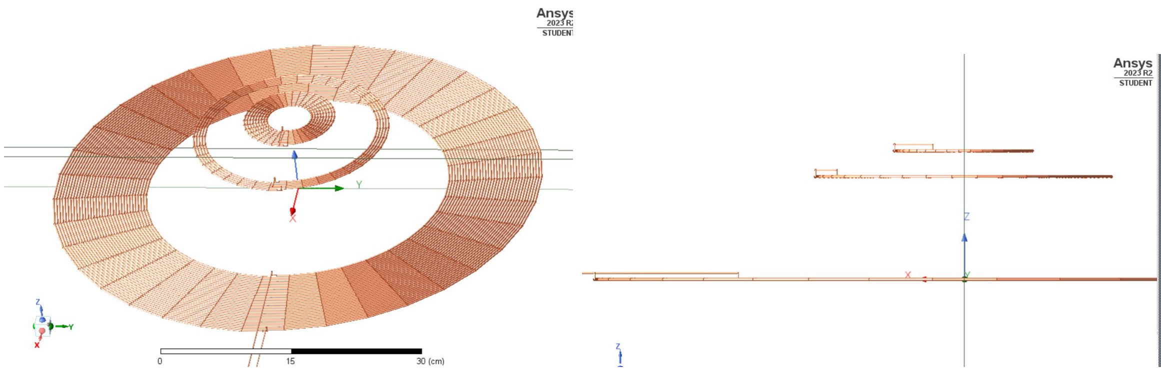

Fig. 7: Design of the physical copper, transmitter, relay, and reciever coil

As it is shown in Fig.7 the coils 2 and 3 are connected to complete the their loop respectfully, while coil 1 is extended to the border of the boundary for adding excitations. In Fig.6 we have the boundary of radiation shown as a box around the WPT, and four rectangular planes for the plot of the B field with polylines for the plots regarding change in distance.

Compromises made to obtain some results

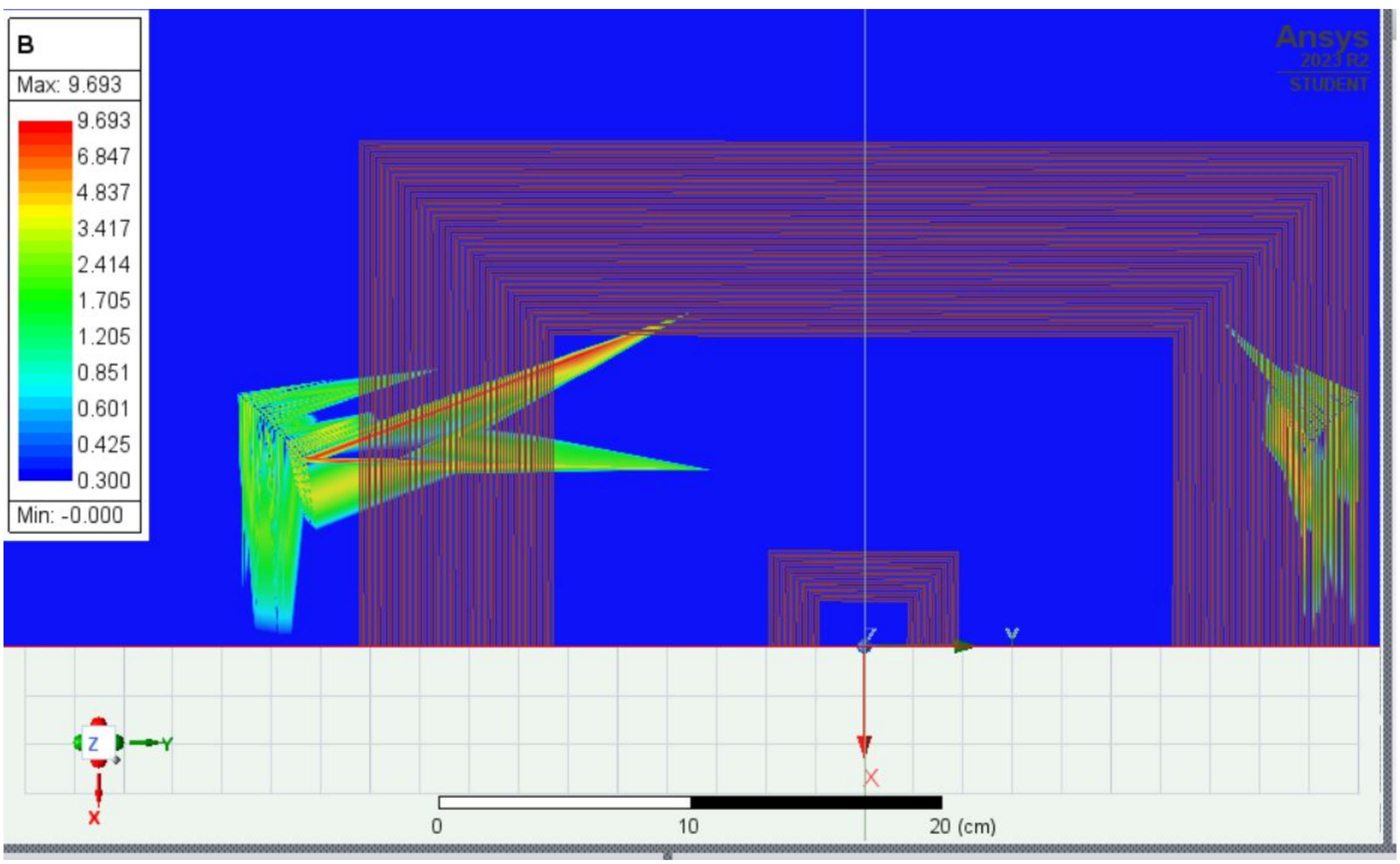

Fig. 8: Plot of Magnetc Field Density B log scale, transmitter, and reciever coil

As it can be seen from Fig 7 and Fig 8 the results is lacking to be desired. The reason for this is due to have a student license for ansyss HFSS, which only allows 500k total mesh elements. Although for some reason while attempting the simulation the limits are even less, this made the model getting drastically changed. For starters to decrease the total mesh elements the mesh resolution was decreased as much as possible, and the total segments per rotation of the coils where made to 4 instead of around 30 which made it into the circular coil that was needed. Even the wire itself is no longer a circular wire but a squared one for the same reason.

Even with these changes it still was not able to simulate, so the model was split in half and simulated the 2 coil version of the model which worked succesfully as seen from Fig 8.. Granted the results are rather unusable.

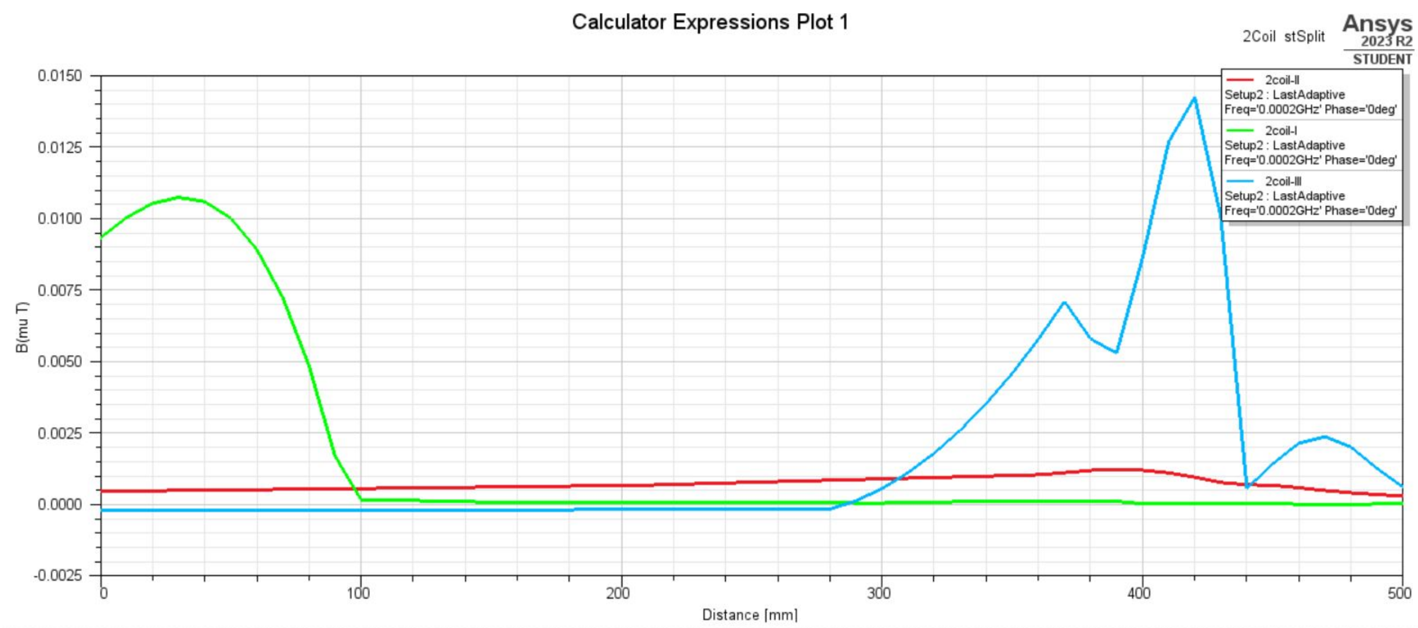

Fig. 9: Magnetic flux density with variation wrt distance from measuring pos. at 200kHz, transmitter,and reciever coil

Calculating Flux density

Overall the simulation and the analysis from the HFSS software was succesful. At this point the only problem was that the flux density that was needed for the plots was not availabe. So I had to create the parameter for the results to be ploted, this was done with the use of the Fields Calculator located within the field overlay. It was found that the Magnetic field was available from the named expressions, so some variables where added that where missing such as the permeability and permitivity

$$B = \mu H \quad \mu : magnetic\, permeability$$

$$\mu = \mu_r \mu_0 \quad \mu_r : relative\, permeability \quad \mu_0 : permeability\, of\, vacuum$$

$$\mu_r = 1H/m(for\, copper) \quad \mu_0 = 1.25663706 \times 10^{-6} H/m$$

IV. Conclusion

This report shows that the results from paper [1] are viable and reproducable when done correctly. The Matlab portion shows how the WPT coils efficiency change with the specific adjustment regarding the relay coil for the larger portion changes. Other changes are with respect to the number of turns from the transmitter coil this changes the mutual inductance from the transmitter to the receiver coil, and the size of the resistance of the load resistor attached to the reciever coil. While the HFSS simulation could be improved with better model design and mostly a better equipment and software to run the simulation, the software is due to the student version nothing more.

Because of the Ansyss HFSS version type the simulation was not able to provide us with, adequate results. Especially with regards to the field report of the Magnetic Flux density seeing as only one plane showed result, thus the rest of the three planes where ignored and not added in the report.

List of Figures

REFERENCES

[1] F. Wen, X. Chu, Q. Li, R. Li, L. Liu, and F. Jing, *"Optimization on three-coil long-range and dimension-asymmetric wireless power transfer system,"* IEEE Transactions on Electromagnetic Compatibility, vol. 62, no. 5, pp. 1859-1868, 2020.

[2] A. Karalis, J. D. Joannopoulos, and M. Soljacic, *"Efficient wireless nonradiative mid-range energy transfer,"* Ann. Phys., vol. 323, no. 1, pp. 34-48, 2008.