Chapter 4: Simulation

In many different applications, including wireless power transfer, magnetic resonance imaging, and electromagnetic induction, square and circular coils are often utilised. These two types of coils, however, differ significantly in terms of their geometrical features, electrical characteristics, and magnetic field distributions. Therefore, it's crucial to comprehend and contrast how square and circular coils work in various circumstances and settings. Using MATLAB and COMSOL Multiphysics, and ANSYS we may provide a simulation study of square and circular coils. In this chapter will discuss and present ANSYS simulation and its results in detail. The impact of self-inductance, mutual inductance, coupling coefficient, quality factor, and power transfer efficiency on the size, shape ratio, number of turns, current, and distance of the coils is examined and discuss in chapter. The benefits and drawbacks of square and circular coils for various applications and design requirements are also covered. Experimental measurements utilising a prototype wireless power transfer system will be used to verify the simulation results. This study presents a comparison of the wireless power transfer methods for EVs using square and circular power pads. Based on the SAE J2954 specified physical dimensions, 3D models of both types of power pads have been created using ANSYS Electronics Desktop and Twin Builder. For both the types of power pad, the range of vertical and y-axis misalignment between the transmitting and receiving sides has been considered, from 5 mm to 200 mm. Plots and graphical presentations are made of characteristics including coupling coefficient, mutual inductance, magnetic flux density, and strength of the magnetic field for both kinds of power pads. The simulation results of Ansys Twin Builder circuits are presented and comparative efficient plots have been drawn to compare performance of both types of power pads.

4.1 Coil Misalignment Analysis:

The design obtained is further used for the validation. ANSYS Electronics Desktop 2018.2 is used for the validation of the design. Both the coils are having same 21 turns and are excited with same current of 10 Ampere. The geometry for the coils is selected to be square and circular as shown in Figure 3-12 and Figure 3-14.

A phenomenon known as misalignment occurs when more than two parts or objects are not correctly positioned or aligned with respect to one another. This misalignment can arise in a variety of contexts, including interpersonal connections as well as the fields of engineering, manufacturing, and optics. Depending on the exact circumstances in which it happens, misalignment can result in a variety of challenges and problems, including decreased efficiency, less productivity, wear and tear, and potentially system breakdowns. Misalignment, in its simplest form, denotes an infringement on the planned or ideal alignment, which results in an imbalance or improper synchronization between various components or systems.

In conjunction with experimental sizing, the present research develops a precise comparison with regard to the inductive performances of both coil topologies. However, helix and spiral topologies have been researched in order to identify which set of geometric data delivers the greatest results in terms of coupling coefficient. Several parameters for both of them have been found. Calculations were performed using the industry standard ANSYS Electronics Desktop and ANSYS Twin Builder software simulations.

Initially, coil misalignment has been set to null, and the ANSYS analysis [7] is used to investigate the effect of turn number as well as vertical misalignments on self and mutual inductances, as well as coupling coefficient. The amount of magnetic flux in the lines of a helix coil are plotted in Figure 4-1.

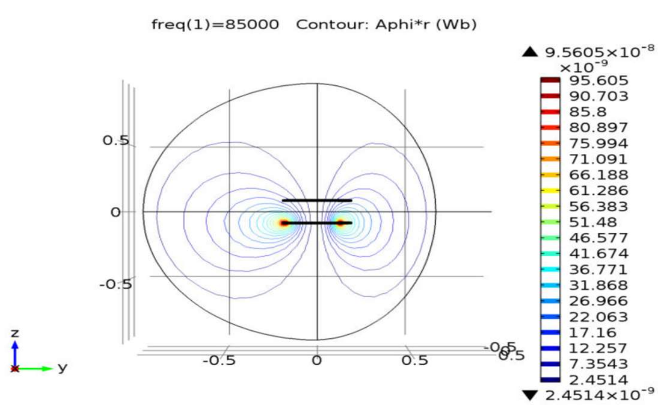

Figure 4-1 Magnetic flux lines of helix coil[7]

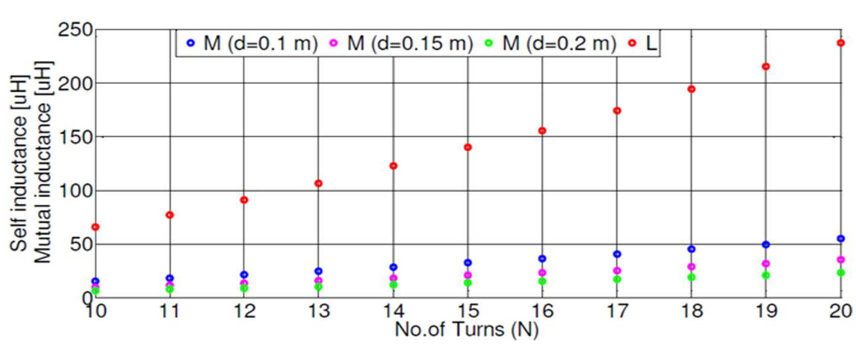

Figure 4-2 Variation of L & M with number of turns for helix coil [7]

Figure 4-2 depicts the self and mutual inductances as a function of coil length, with the number of turns twirling around the value determined by early sizing. The coupling coefficient is shown as a result of the number of turns for a coil distance of 0.15 m and as a function of the coil distance for N = 21 in Figure 4-3 and Figure 4-4. Figure 4-3 and Figure 4-4 represent the key findings of the study.

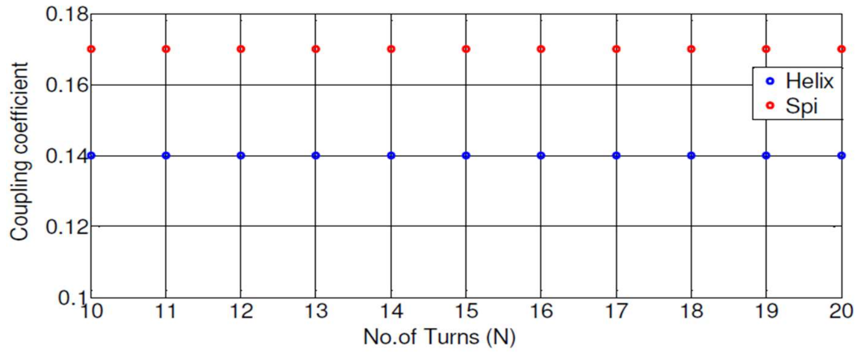

Figure 4-3 Coupling coefficient vs. no. of turns

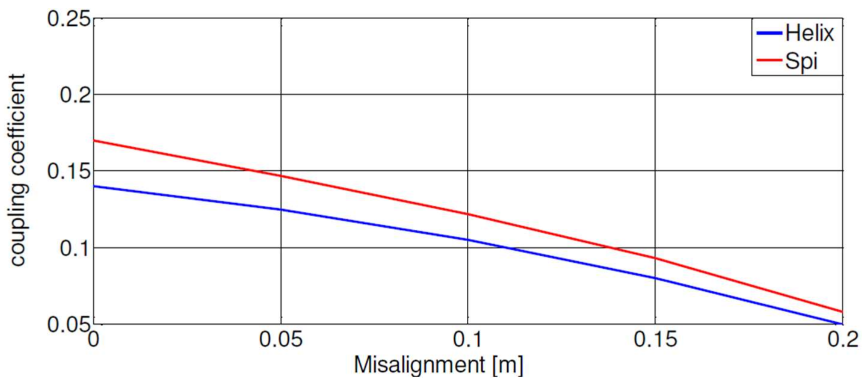

Figure 4-4 Variation of k with z axis misalignment for helix and spiral coils

Evaluation of the Figure 4-3 and Figure 4-4 reveals that:

- The coupling coefficient, like the mutual inductance, decreases as the coil distance increases,
- The self-inductance remains constant with the two-coil distance because the structure has no magnetic core,
- The mutual inductance proportional to the square of the turn number, and
- For coils placed on two planes 0.15 m apart, the effect of coil misalignment with the coupling coefficient is investigated.
- Magnetic field around coils can be presented in visual forms.
- Self and mutual inductance values are obtained for specific misalignments.

Some interesting finding are observed and mentioned below:

- Spiral coils have more coupling coefficient for same no. of turns than helix coils.
- Spiral coils have more coupling coefficients at relatively larger misalignment than helix coils.
- Difference between coupling coefficient of helix and spiral coils unaltered with no. of turns.
- Difference between coupling coefficient reduces as misalignment decreases.

The outcome of the investigation, depicted graphically in Figure 4-4, shows that coil distance has a bigger influence on the coupling coefficient than coil misalignment. A 0.1 m coil misalignment (from 0 to 0.1 m) leads to a 22% drop in k, but a 0.1 m increase in coil distance (from 0.1 to 0.2 m) results in a 94% drop in k as a percentage of its value at 0.15 m.

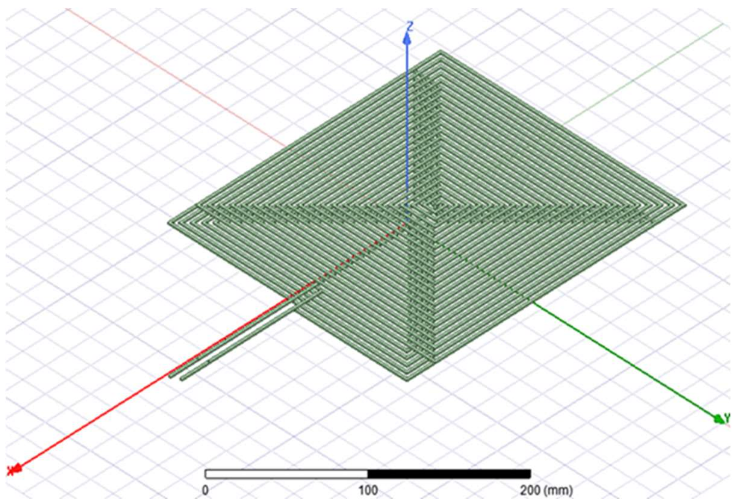

Figure 4-5 Design model of transmitting and receiving coil in ANSYS Electronics Desktop at ZDist of 5 mm

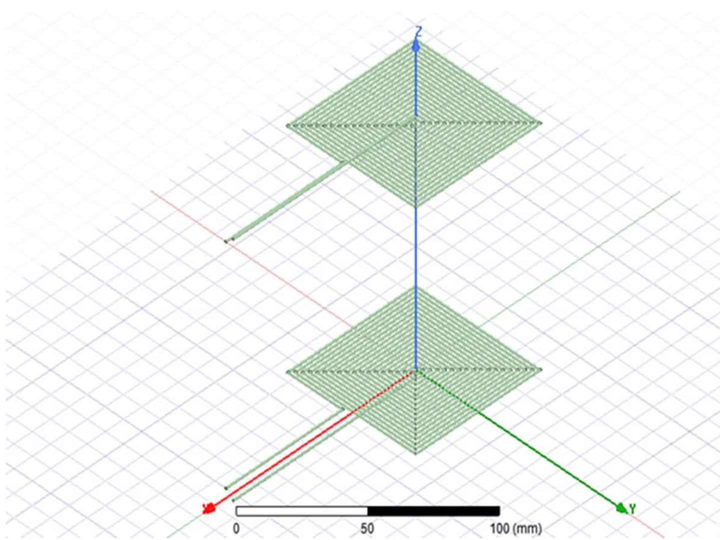

Figure 4-6 Design model of transmitting and receiving coil in ANSYS Electronics Desktop at ZDist of 150 mm

Figure 4-5 illustrates that the z axis misalignmentbetween the coils is at 5 mm, while x axis and y axis misalignments are kept at 0 mm level. Figure 4-6 illustrates that, both x and y axis misalignment are kept at 0 mm while z axis misalignment is kept at 150 mm. though during this study, the limit for x and y axis are test for -100 mm to +100 mm and for z axis this limit is set for 0 to 200 mm.

4.1.1 Coupling coefficient variation:

The coupling coefficient (k) of square power pads is not constant. Figure 4-7, Figure 4-8 and Table 4-1 shows how coupling coefficient varies with y axis misalignment (YDist) and z axis misalignment (ZDist). the range of YDist is taken from -100 mm to +100 mm and that of ZDist the range is chosen to be 0 mm to 200 mm for this analysis. Value of the coupling coefficient represents the how both coils are magnetically coupled. For EV wireless charging systems, the strong connection between the transmitting and receiving sides of power pads is indicated by a greater coupling coefficient.

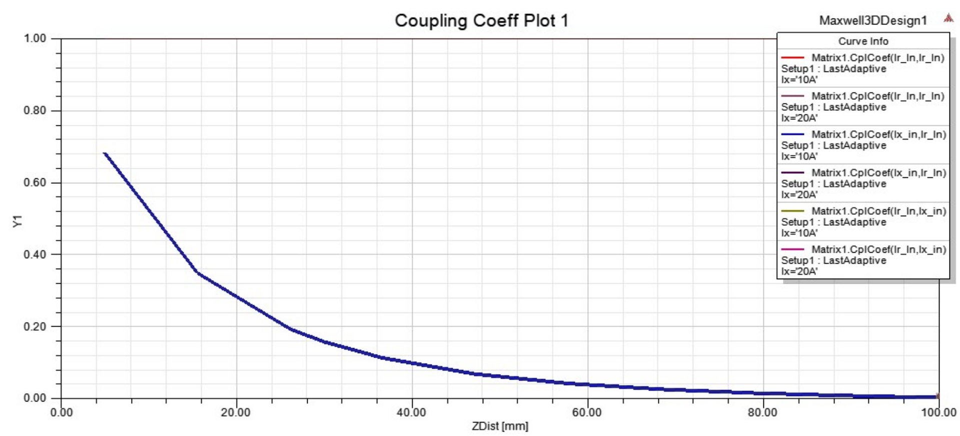

Figure 4-7 2D plot showing variation of k with ZDist (I = 10 & 20 Amps)

Here in this part of the research, simulation results of a square topology power pads are used for getting the results between ZDist (vertical misalignment) and coupling coefficient (k). initially supply (excitation) current of 10 ampere has been given to transmitting coil for having the results of coupling coefficient at various ZDist. Then after excitation current of 10 ampere is given to transmitting coil and 0 ampere current to receiving coil to study the behaviour of coupling coefficient at various ZDist. Figure 4-8 shows that irrespective of excitation current, whether 10 amperes or 20 amperes in this case self-coupling coefficient will remain 1. The blue colour line in the same figure shows the trajectory of variation between ZDist and coupling coefficient. Same things are also represented in tabulation format in Table 4-1.

Figure 4-8 2D plot showing variation of k with ZDist (I = 10 & I induced = 20 Amps)Figure 4-8 represents the result of coupling coefficient (k), when excitation current of 10 ampere is given to transmitting coil and receiving coil induces 20 amperes current. We can analyze this situation as current amplifier circuit.

The coupling coefficient (k) between two coils in a wireless power transfer (WPT) system is a measure of the extent of magnetic coupling between the coils. It quantifies the efficiency of energy transfer from the transmitter coil to the receiver coil. The coupling coefficient is affected by various factors, including the variation of current in the coils.

When the current in one of the coils varies, it affects the magnetic field generated by that coil. This variation in the magnetic field, in turn, affects the flux linkage between the two coils, leading to changes in the coupling coefficient. Here's how current variation in the coils affects the coupling coefficient:

- **Change in Magnetic Field Strength:** The magnetic field strength around a coil is directly proportional to the current flowing through it. When the current in one coil varies, it leads to corresponding changes in the strength of the magnetic field it generates. This change in magnetic field strength alters the amount of magnetic flux that links the two coils.
- **Change in Flux Linkage:** The coupling coefficient is a measure of the magnetic flux that links the two coils. As the magnetic field strength changes due to variations in current, the flux linkage between the coils also changes. This, in turn, affects the efficiency of energy transfer between the coils.
- **Impact on Induced Voltage:** The induced voltage in the receiver coil is directly proportional to the rate of change of magnetic flux linking the coil, as described by Faraday's law of electromagnetic induction. Therefore, any change in the coupling coefficient due to current variation will directly affect the induced voltage in the receiver coil.
- **Efficiency of Energy Transfer:** The coupling coefficient influences the efficiency of energy transfer between the transmitter and receiver coils in a WPT system. A higher coupling coefficient indicates better magnetic coupling and, therefore, higher efficiency in transferring power from the transmitter to the receiver. Conversely, variations in the coupling coefficient due to current changes can impact the overall efficiency of the WPT system.

Coupling Co-efficient at various Y- axis & Z- axis misalignments

	ZDist							
YDist [mm]	**25mm**	**50mm**	**75mm**	**100mm**	**125mm**	**150mm**	**175mm**	**200mm**
-100	0.123609	0.103784	0.082828	0.063273	0.048624	0.037631	0.029364	0.023243
-92	0.163341	0.128562	0.096988	0.072424	0.054504	0.041871	0.031885	0.024911
-83	0.20479	0.154593	0.112765	0.081772	0.060273	0.045148	0.034416	0.026572
-75	0.247819	0.177923	0.127134	0.09113	0.065955	0.048756	0.036635	0.028159
-67	0.291874	0.205118	0.141735	0.099414	0.071271	0.052179	0.038915	0.02955
-58	0.337873	0.227476	0.155901	0.108019	0.076317	0.055318	0.040827	0.030889
-50	0.379372	0.250629	0.168446	0.115549	0.081849	0.058021	0.042673	0.031961
-42	0.42021	0.271433	0.179844	0.122056	0.084868	0.060491	0.044104	0.032921
-33	0.455774	0.290773	0.190279	0.128059	0.088408	0.062576	0.045405	0.033758
-25	0.487674	0.305897	0.198174	0.132582	0.091294	0.0642	0.046389	0.034296
-17	0.511836	0.318359	0.204634	0.135615	0.093934	0.065347	0.047049	0.034669
-8	0.526637	0.32501	0.206901	0.137831	0.094186	0.065719	0.047774	0.034721
0	0.533543	0.325397	0.208718	0.138058	0.093905	0.065737	0.047246	0.034553
8	0.527062	0.323159	0.208047	0.137651	0.094928	0.065749	0.047158	0.03471
17	0.511419	0.315997	0.203565	0.135648	0.092942	0.065176	0.0471	0.034676
25	0.486144	0.304109	0.198434	0.132788	0.090834	0.064072	0.046432	0.034332
33	0.456239	0.289391	0.189377	0.127824	0.088427	0.062363	0.045361	0.033702
42	0.41879	0.273915	0.17976	0.121704	0.084703	0.060561	0.044142	0.032875
50	0.380113	0.249825	0.167945	0.112435	0.080683	0.058006	0.042487	0.031923
58	0.33565	0.228063	0.155215	0.107775	0.076038	0.055226	0.040716	0.030747
67	0.290606	0.201959	0.14109	0.099148	0.070932	0.051968	0.038636	0.029462
75	0.247074	0.179236	0.126754	0.090217	0.065673	0.048493	0.036513	0.027993
83	0.204715	0.151502	0.111651	0.081245	0.060187	0.045006	0.034275	0.026445
92	0.163159	0.127622	0.096015	0.072214	0.054318	0.041683	0.031746	0.024885
100	0.123524	0.103333	0.007836	0.062909	0.048378	0.037404	0.029276	0.023183

Table 4-1 Variation of coupling co-efficient with YDist and ZDist

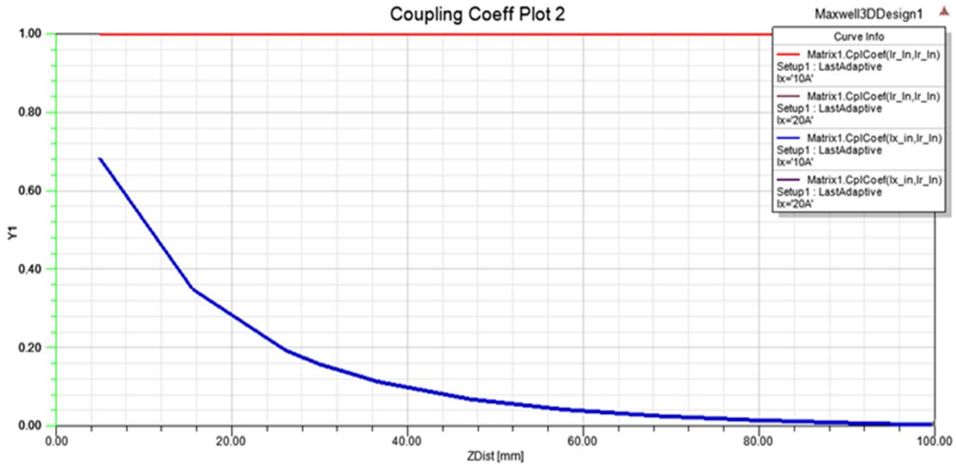

Figure 4-8 2D plot showing variation of k with ZDist (I = 10 & I induced = 20 Amps)

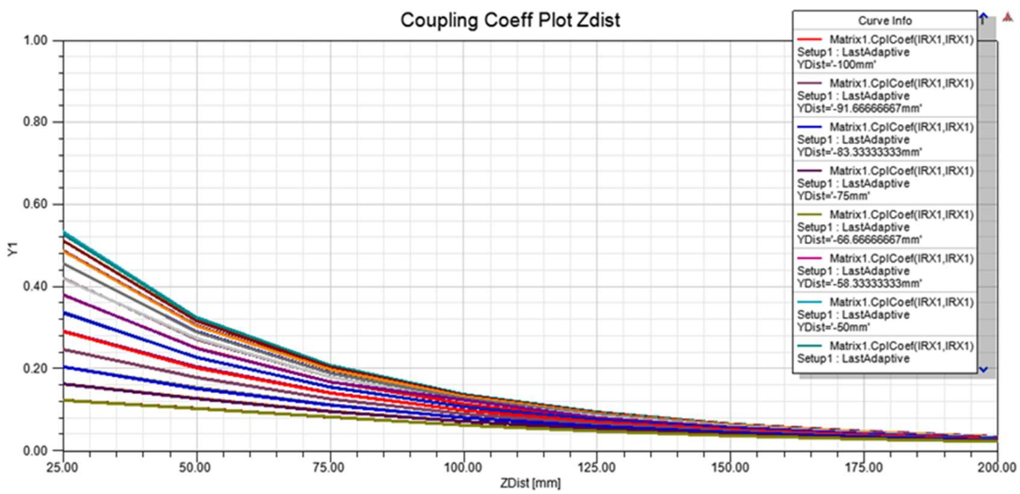

Figure 4-9 Plot showing variation of k with ZDist as a function YDist

Current magnitudes other than 10 A and 20 A are not considered for Wireless Power Transfer (WPT) due to practical limitations and safety concerns, ensuring efficient energy transfer and avoiding overheating or damage to the coils and associated components.

In summary, variations in current in the coils of a WPT system can affect the coupling coefficient by altering the magnetic field strength and flux linkage between the coils. Understanding and controlling these variations are crucial for the efficiency and performance of the WPT system.

Figure 4-9 is showing the relationships between coupling coefficient and ZDist (vertical misalignment) as a function of different YDist (Y-axis misalignment). We can easily predict that when y-axis and z-axis misalignments are very less (ideally zero than only the coupling coefficient is maximum (ideally one). This situation of the coils are also known as tight coupling between coils. Tight coupling is ideal condition and is never possible in practice. Several researchers are doing their work to reduce this misalignment and to achieve near to tight coupling. From Figure 4-9 we can predict that misalignment (in both y-axis and z-axis) should be as minimum as possible. The misalignment should be less than 25 mm to have greater efficient WPT system.

There are many advantages to plot visualizations in three dimensions in the field of electromagnetic modelling and analysis. ANSYS Electronics Desktop is a comprehensive software package that can be used to design and simulate electrical and electromagnetic components and systems. Here are some advantages of using ANSYS Electronics Desktop to create 3D images:

ANSYS Electronics Desktop allows users to see and analyze complex 3D electromagnetic structures such as antennas, RF/microwave components, waveguides, and printed circuit boards (PCBs). When these structures are visualized in 3D, their behaviour, interactions, and possible difficulties become more precise.

4.1.2 Misalignment analysis as a function of receiving coil currents:

The coupling coefficient among two coils for a wireless charging system can be influenced by a number of parameters, including coil shape, alignment, and distance between them. The coupling coefficient is a significant parameter in the context of electric vehicle (EV) charging since it directly impacts the efficiency of power transmission between the charging infrastructure (commonly referred to as the main coil) and a vehicle's reception coil (secondary coil). The coupling coefficient (k) is a measure of how well magnetic energy is exchanged between the main and secondary coils. It has a value between 0 and 1, with 0 representing no coupling and 1 representing complete coupling.

Several aspects must be understood when examining the changing of coupling coefficient with vertical misalignment in a square coil design for EV charging:

- **Coil Geometry:** A square coil has equal-length sides and often has a single turn or numerous rounds of wire. Dimensions of coils will also play very important role.
- **Considerations for Efficiency:** A higher coupling coefficient is preferred for efficient power transmission since it indicates that a greater amount of the magnetic field created by the main coil is caught by the secondary coil. Higher

power losses and worse charging efficiency result from a lower coupling coefficient caused by misalignment.

The coupling coefficient (k) between two coils in a wireless power transfer (WPT) system is directly related to the efficiency of energy transfer between the coils. The coupling coefficient quantifies the extent of magnetic coupling between the transmitter coil and the receiver coil. The relationship between the coupling coefficient and the energy transferred can be understood as follows:

- **Efficiency of Energy Transfer:** The coupling coefficient directly influences the efficiency of energy transfer between the transmitter and receiver coils. A higher coupling coefficient indicates better magnetic coupling between the coils, resulting in more efficient energy transfer.
- **Induced Voltage:** In a WPT system, the voltage induced in the receiver coil is directly proportional to the coupling coefficient. According to Faraday's law of electromagnetic induction, the induced voltage is given by the rate of change of magnetic flux linking the coil. A higher coupling coefficient leads to a higher rate of change of magnetic flux and, consequently, a higher induced voltage in the receiver coil.
- **Power Transfer:** The power transferred from the transmitter coil to the receiver coil is directly proportional to the induced voltage and the current flowing through the receiver coil. Therefore, a higher coupling coefficient not only results in a higher induced voltage but also facilitates the transfer of more power from the transmitter to the receiver.
- **Losses and Efficiency:** Higher coupling coefficients reduce losses in the WPT system, such as resistive losses and leakage losses. As a result, the overall efficiency of the energy transfer process is improved when the coupling coefficient is higher.

In summary, there is a direct relationship between the coupling coefficient and the energy transferred in a WPT system. A higher coupling coefficient leads to more efficient energy transfer, higher induced voltage in the receiver coil, and increased power transfer between the coils. Therefore, maximizing the coupling coefficient is essential for optimizing the performance and efficiency of wireless power transfer systems.

Here in this research coupling coefficient (k) is calculated and presented in the tabular form for various ZDist (vertical misalignment) starting from 0 mm to 105 mm. For calculations of k have been tabulated by carrying out receiving end excitation current values for 0 Ampere and also for 10 Amperes. Results of the study has been presented in tabulation form in Table 4-2.

ZDist (mm)	**mag(CplCoef) Ir='0A'**	**mag(CplCoef) Ir='10A'**
5	0.683244122	0.683323243
15	0.360811543	0.360823453
25	0.205821675	0.205923443
30	0.158444031	0.158663201
35	0.123250979	0.123485769
45	0.076523188	0.076677544
55	0.0487278	0.048921856
65	0.031514447	0.021534568
75	0.020309469	0.020456475
80	0.016273645	0.016316834
85	0.012749914	0.012752347
95	0.007293759	0.007298747
100	0.005069423	0.00512418
105	0.002998475	0.003007173

Table 4-2 Variation of k with Z Dist at Ir=0 A &10A.

Plotting in 3D allows us to visualise the distribution of electromagnetic fields (electric and magnetic) in complicated structures. This can assist users in identifying areas of high or low field strength, identifying possibilities for interference or interaction, and optimising the design for improved performance.

- Wireless Radiation Patterns: When modelling devices, charting in three dimensions allows the user to see the distribution of radiation in all three dimensions. Understanding how the element radiates energy in different structural integrity and thermal impacts of electronic components and systems in addition to electromagnetic fields.
- Simulation Validation: Validating simulation accuracy requires comparing simulation findings to experimental data. 3D visualisation aids in the validation

	Mutual Inductance between transmitting and receiving coils (micro Henrry) ZDist [mm]							
YDist [mm]	**25mm**	**50mm**	**75mm**	**100mm**	**125mm**	**150mm**	**175mm**	**200mm**
-100	5.694506	4.82085	3.853374	2.934254	2.257223	1.747516	1.36422	1.073571
-92	7.52512	5.954284	4.49267	3.370942	2.530338	1.919726	1.480027	1.152238
-83	9.450005	7.097382	5.254859	3.786152	2.792646	2.093511	1.590893	1.227977
-75	11.46181	8.293882	5.932914	4.204504	3.056543	2.260453	1.701514	1.299325
-67	13.51455	9.449528	6.620632	4.614769	3.310973	2.421877	1.798602	1.366073
-58	15.54951	10.60778	7.261702	5.016178	3.544259	2.565139	1.899584	1.426029
-50	17.52699	11.6876	7.863091	5.355861	3.754386	2.697868	1.979528	1.479564
-42	19.39833	12.66704	8.397571	5.671417	3.943539	2.811422	2.047293	1.523864
-33	21.05912	13.51692	8.883294	5.938155	4.100783	2.903507	2.106082	1.559933
-25	22.48589	14.22152	9.220868	6.150366	4.22248	2.979989	2.148838	1.586089
-17	23.59237	14.72352	9.47682	6.30527	4.307741	3.025079	2.183057	1.601953
-8	24.28877	15.05203	9.668884	6.391889	4.355461	3.050577	2.187994	1.606396
0	24.52172	15.14355	9.724662	6.433312	4.363421	3.049385	2.187159	1.600264
8	24.26528	15.04974	9.684682	6.39002	4.353572	3.048862	2.189167	1.605504
17	23.56931	14.73533	9.495355	6.301591	4.305236	3.023066	2.183961	1.600202
25	22.45484	14.19945	9.211587	6.139601	4.219695	2.974492	2.148631	1.584873
33	21.02772	13.49904	8.842473	5.927847	4.091169	2.899665	2.105822	1.557288
42	19.33388	12.62267	8.390842	5.660986	3.934494	2.80137	2.044177	1.520897
50	17.47153	11.6452	7.820083	5.433432	3.747707	2.688938	1.971035	1.476292
58	15.48508	10.55289	7.245118	4.99881	3.533436	2.554739	1.889034	1.421859
67	13.43192	9.429085	6.583765	4.612446	3.300072	2.408715	1.797101	1.361425
75	11.38405	8.230991	5.906688	4.184624	3.042477	2.251271	1.688767	1.294435
83	9.376355	7.066922	5.208748	3.780467	2.779693	2.083816	1.586199	1.222637
92	7.440745	5.912258	4.462214	3.337293	2.510786	1.909638	1.47418	1.146493
100	5.624982	4.810278	3.657842	2.914367	2.243284	1.730842	1.353896	1.067338

Table 4-3 Variation of mutual inductance with YDist and ZDis

process and builds trust in the simulation model by visually comparing simulated and measured outcomes.

- Design Optimisation: Visualising 3D simulations helps us more effectively spot design problems and potential for optimisation. Based on the insights gathered from the 3D plots, you can iteratively adapt and enhance your design.

EMI/EMC study: 3D plots can depict how electromagnetic radiation propagates and interacts inside a system, assisting in identifying potential interference sources and vulnerable locations for electromagnetic compatibility (EMC) and electromagnetic interference (EMI) studies.

In a broader sense, using ANSYS Electronics Desktop to create 3D visualisations strengthens the ability to analyse, optimise, and visualise complicated electromagnetic systems and components. In the realm of electronics and electromagnetics, this can lead to better designs, increased performance, and more efficient problem-solving.

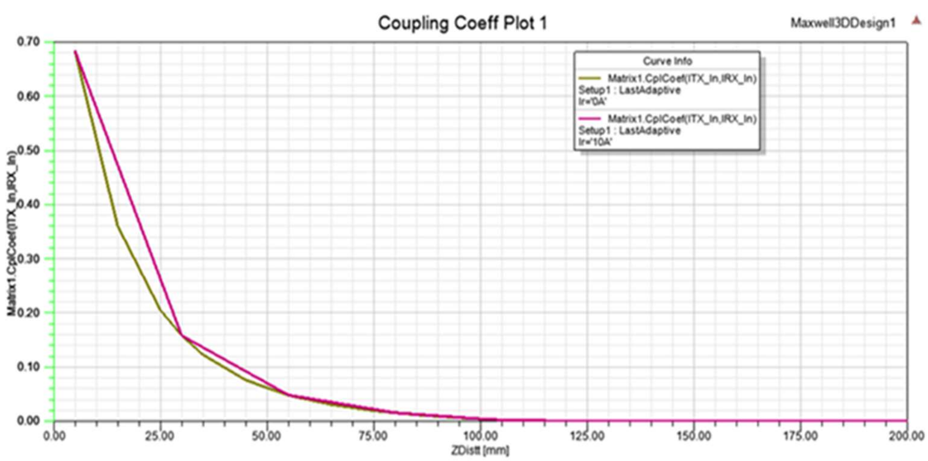

Figure 4-10 ZDist v/s k for 0 & 10 A.

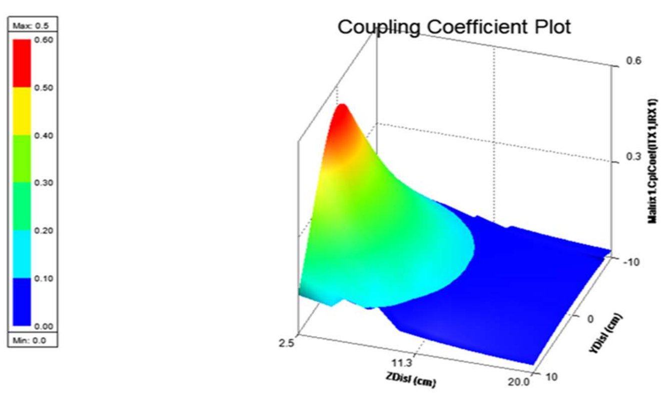

Figure 4-11 3D image showing variation of coupling co-efficient v/s YDist and v/s ZDist.

Here in this part of research, 3D plots of y-axis misalignment (YDist), z-axis misalignment (ZDist) with magnitude of coupling coefficients has been presented. The data sets of Table 4-3 is taken for three-dimensional plot. With the help of ANSYS Electronics Desktops and the simulated results obtained from above Table 4-3 we can easily get 3D rectangular plot. We can easily conclude from this graphical representation that, which y-axis and z-axis misalignment can give optimum coupling coefficient. Here, from Figure 4-11 it can be predicted that maximum coupling coefficient value (tight coupling) is from 1 mm and for optimal results of 0.5 coupling coefficient upto 33 mm in both the y-axis and z-axis misalignment required.

4.1.3 Self and mutual inductance variation:

The square coil type is deemed appropriate for this study, as illustrated in Figure 4-5 and Figure 4-6. ANSYS Electronics is used for 3D modelling. FEA is used to estimate the coil inductance values. The coils are designed in ANSYS Electronics and are simulated for vertical misalignment from 0 mm to 200 mm. The excitation to both the coils are first given as 10 Amperes to transmitting coil and 0Amperes to secondary coil. For second time it has been predicted that excitation on both the coils are having same current of 10Amperes.In both the conditions self-inductances (L_1& L_2) and mutual inductance between the two coils has been measured. Self-inductance (L_1) and (L_2) and mutual inductance (M_{12}) for various misalignment has also been obtained and tabulated in Table 4-4 and Table 4-5.

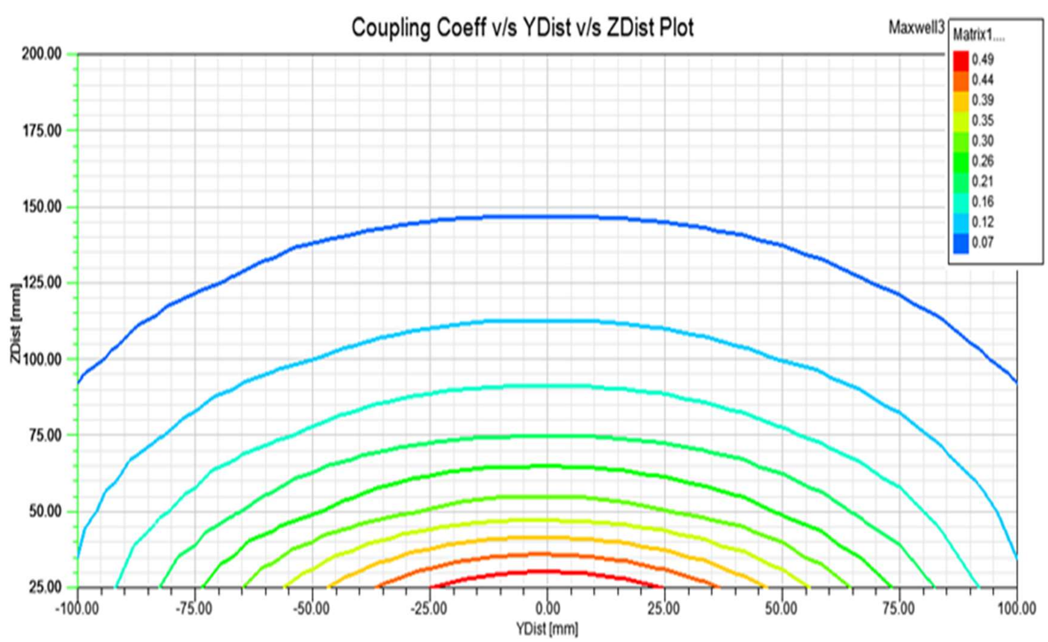

Figure 4-12 Contour of coupling co-efficient for YDist and ZDist

ZDist (mm)	L1 (µH)	L2 (µH)	M12 (µH)
5	9.032131	9.030705	6.171378
30	9.032064	9.026632	1.432625
55	9.033617	8.985861	0.440772
80	9.033991	8.673104	0.144432
100	9.031701	6.583477	0.039513
105	9.032825	4.594961	0.019374
130	9.028852	0.000019	0.000000
155	9.029584	0.000025	0.000000
180	9.027949	0.000028	0.000000
200	9.030039	0.000029	0.000000

Table 4-4 Self & mutual inductance variation with Ir=10A.

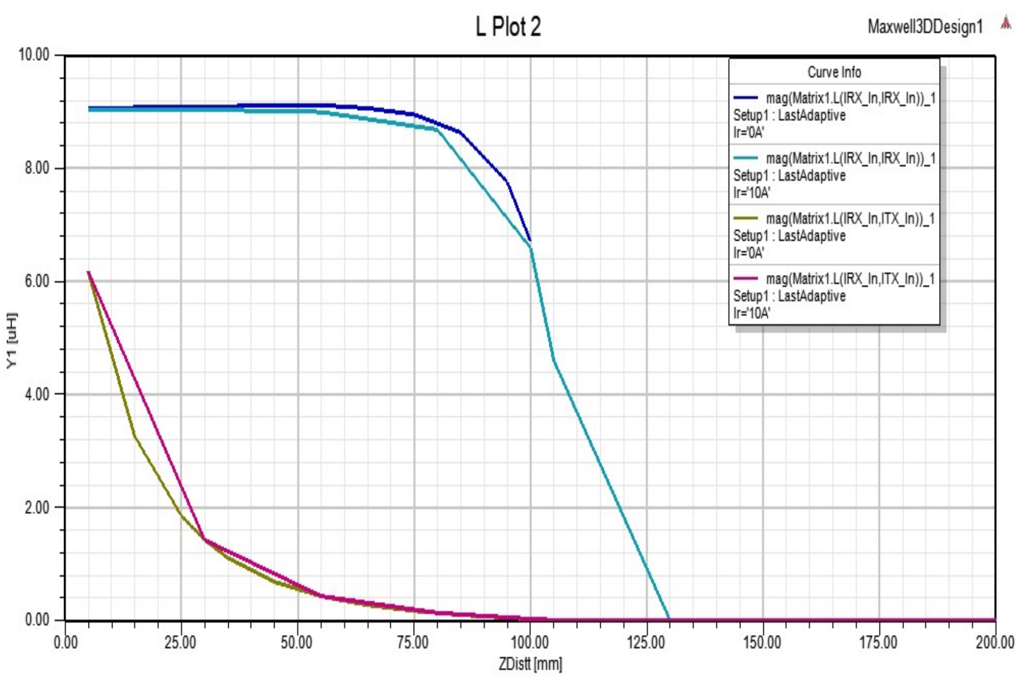

Figure 4-13 Plot of L_1 v/s ZDist, L_2 v/s ZDist & M_{12} v/s ZDist (0 Amp & 10 Amps)

The simulation results are represented and compared in, Figure 4-11 and Figure 4-12. By close observation of Figure 4-14, blue lines are indication of lowest coupling, green lines are for lower coupling, orange lines are for moderate coupling and dark red lines are represented as most coupling (tight coupling).

Z Dist (mm)	L1 (µH)	L2 (µH)	M12 (µH)
5	9.026371	9.043653	6.173116
15	9.023328	9.063831	3.263020
25	9.022116	9.074749	1.862356
30	9.023332	9.078181	1.434032
35	9.022567	9.084136	1.115828
45	9.022801	9.107483	0.693686
55	9.023427	9.105403	0.441684
65	9.023177	9.051156	0.284801
75	9.023009	8.941905	0.182427
85	9.022533	8.620888	0.112447
85	9.022533	8.620888	0.112447
95	9.023571	7.747405	0.060984
100	9.022143	6.699515	0.039413

Table 4-5 Self & mutual inductance variation with I = 0 A.

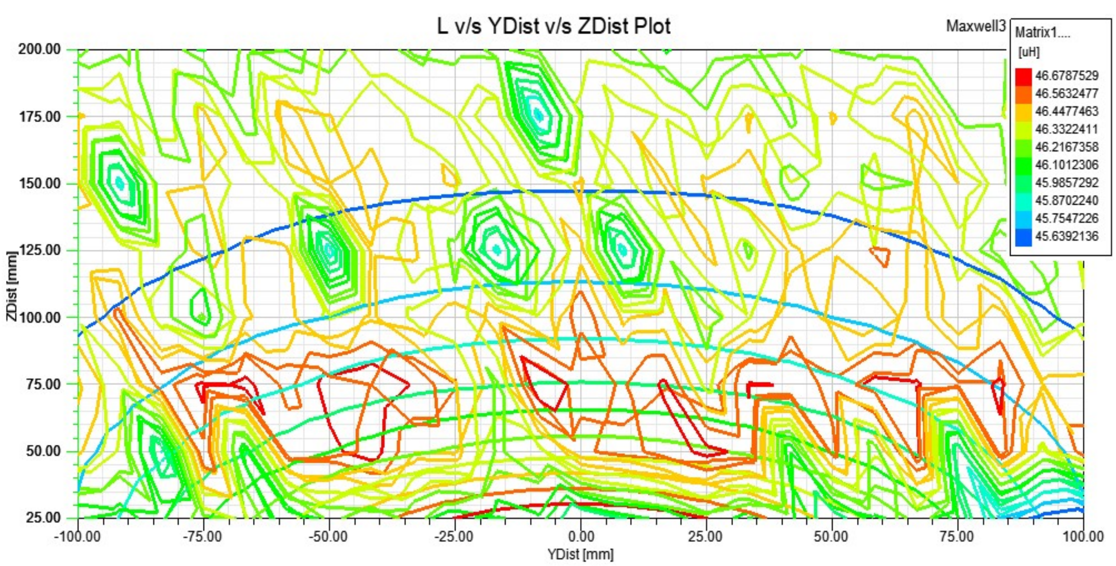

Figure 4-14 2D contour of variation between mutual inductance, YDist and ZDist

Figure 4-14 shows that mutual inductance between transmitting and receiving coils as a function of YDist and ZDist. Close observation of the contour plot reveals that YDist (y axis misalignment) is less susceptible to mutual inductance than ZDist (z axis misalignment). Hexagon like shapes of the contour plot with dark blue colour represents lowest values of mutual inductance and that of dark red colour contour lines of hexagon like shapes highest values of mutual inductance.

It is observed and concluded that as vertical misalignment increases, self-inductance of receiving coil (L_2) reduces and mutual inductance between the two coils (M_{12}) decreases. As reluctance between the two coils increases, it is obvious that the coupling coefficient (k) reduces.

4.1.4 Flux density distribution:

A 3D visualization of the flux density distribution performed with ANSYS Maxwell demonstrates how magnetic flux density is distributed throughout a three-dimensional element or structure. This visualization aids in understanding the magnetic field's intensity and direction at various positions inside the analyzed geometry. The following points are discussed to understand the above 3D visualization:

- **Colour Mapping:** Colour is extensively utilized in a 3D flux density distribution conceptualization to show the magnitude or intensity of the magnetic flux density (B-field) at different positions within the geometry. A colour scale is typically used to map different flux density values to specific colours. For example, blue may indicate low flux density, green moderate flux density, and red high flux density.
- **Geometry Representation:** The graphic reflects the real 3D geometry of the structure you examined. This might be a graphic representation of a gadget, component, or any other thing where the magnetic flux density distribution is of interest.
- **Vector arrows or field lines:** Vector arrows or field lines may be added to the picture to represent the direction of the magnetic field. These vectors represent the magnetic field's orientation at various positions inside the geometry. The length of the vector is proportional to the size of the magnetic flux density at that position, and the arrow indicates the field's orientation.
- **Contour plots:** Contour plots are another technique to depict the flux density distribution. Contour lines are used to represent regions of similar flux density magnitude in these figures. The contour line spacing corresponds to variations in flux density intensity.

- **Isosurfaces:** Isosurfaces are surfaces that indicate a certain magnetic flux density value. You may see the locations inside the geometry where the flux density meets specific thresholds by constructing isosurfaces at varying values.
- **Annotations:** Annotations or labels may be added to the picture to offer more information about specific regions of interest or critical values within the distribution.
- **Interaction:** We may be permitted to interact with the 3D picture, depending on the programme. Rotate, zoom, and pan to see the flux density distribution from various angles and viewpoints.

Overall, the 3D flux density distribution picture gives a detailed visual depiction of how the magnetism is distributed throughout the analyzed structure. This visualization assists in comprehending electromagnetic field behaviour, identifying regions of concern or interest, and optimizing designs for certain performance requirements.

The flux density vector and other magnetic field parameters are frequently visualised via the ANSYS Electronics Desktop post-processing environment. It may be possible to produce arrow plots and vector plots that display the magnitude and direction of flux density at various locations throughout space. Figure 4-15 illustrates flux density at 30 mm vertical misalignment. The centre region with red colour of the plate situated at 15 mm shows maximum flux density, while that of blue region shows least flux density.

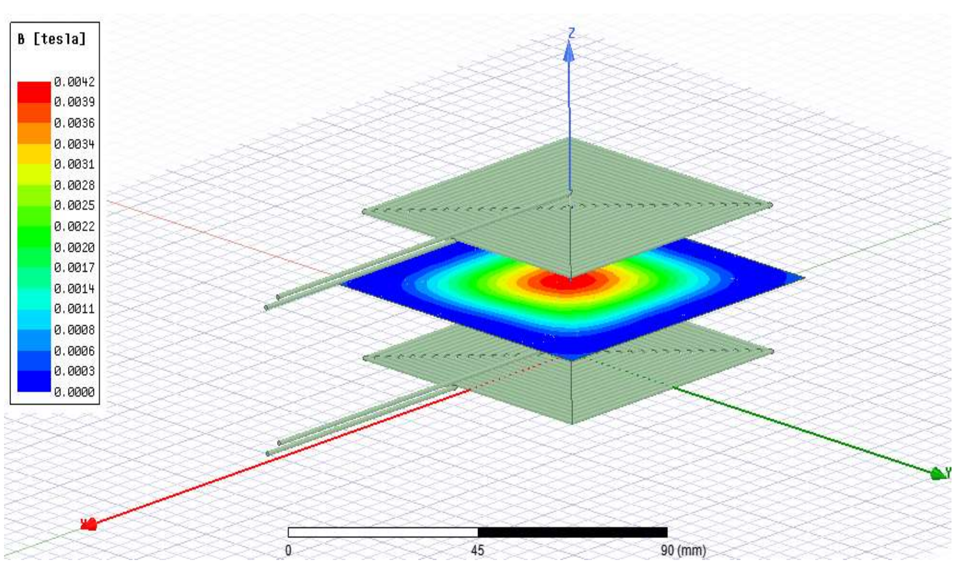

Figure 4-15 Flux density at ZDist = 30 mm.

Select flux density as a field quantity that will be visualised to create an arrow plot. Then, utilising the tools of the programme, you may create arrow vectors at specific points in your shape of coils. The amount and direction of the flux density at those locations will be shown by these arrows. Figure 4-15 shows that flux density vector at 30 mm vertical misalignment and horizontal plate placed at the centre of vertical misalignment (i.e. at 15 mm vertical distance).

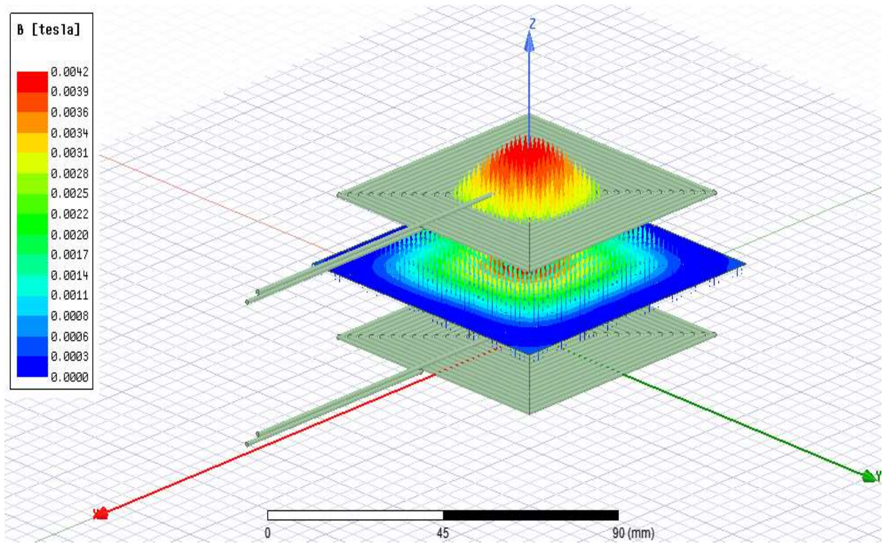

Figure 4-16 Flux density vector at ZDist=30mm.

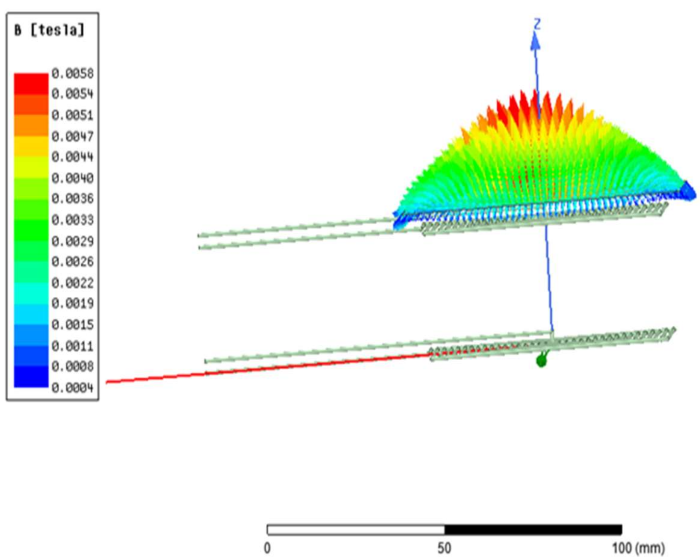

Figure 4-17 Flux density vector ZDist=30 mm and plate at 35 mm

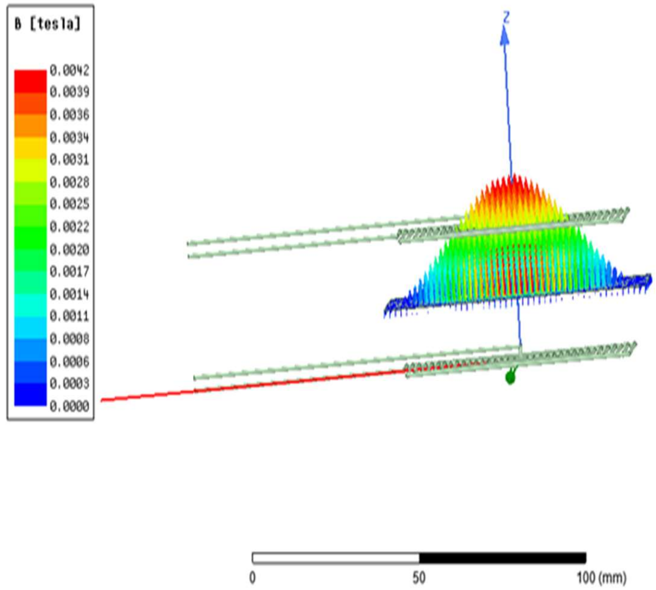

Figure 4-18 Flux density vector ZDist=30 mm and plate at 15 mm.

Here height and colour of arrows shows the flux density. Red colour with longer arrows shows highest value of flux density, while blue coloured arrows with smaller height shows least values of flux density. So, near the central point of coils, the region is having highest values of flux density and shown by red coloured arrows, while outer border of the coils having least value of flux density and arrows are shown by blue coloured little arrows. Similar to that Figure 4-15 to Figure 4-22 shows flux density distribution at various ZDist.

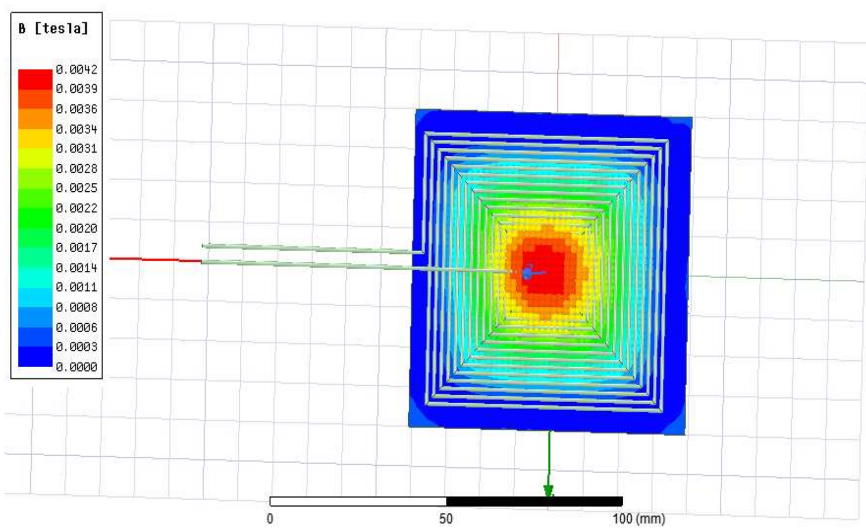

Figure 4-19 Flux density vector ZDist = 30 mm and plate at 15 mm top view.

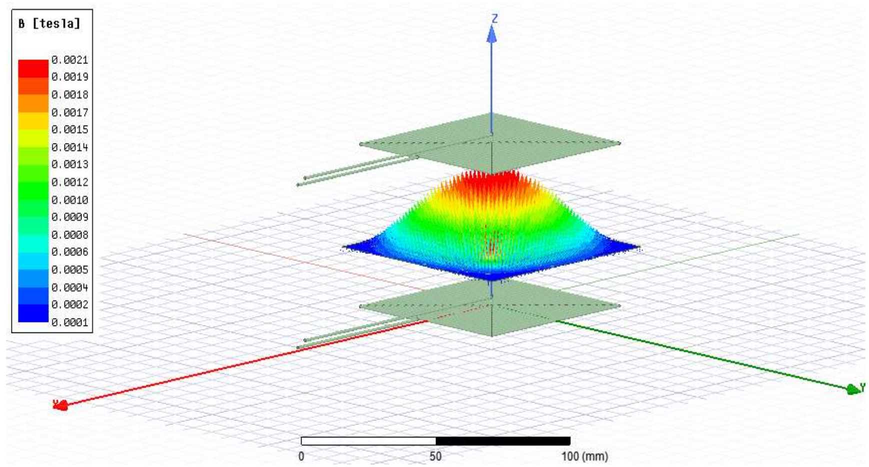

Figure 4-20 Flux density distribution at ZDist = 55 mm & plate 20 mm.

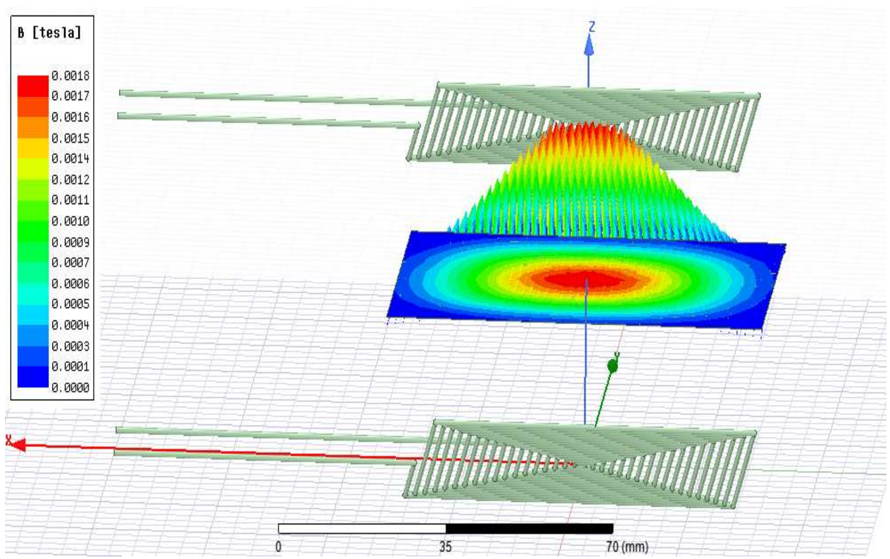

Figure 4-21 Flux density distribution at ZDist = 55 mm & plate 30 mm.

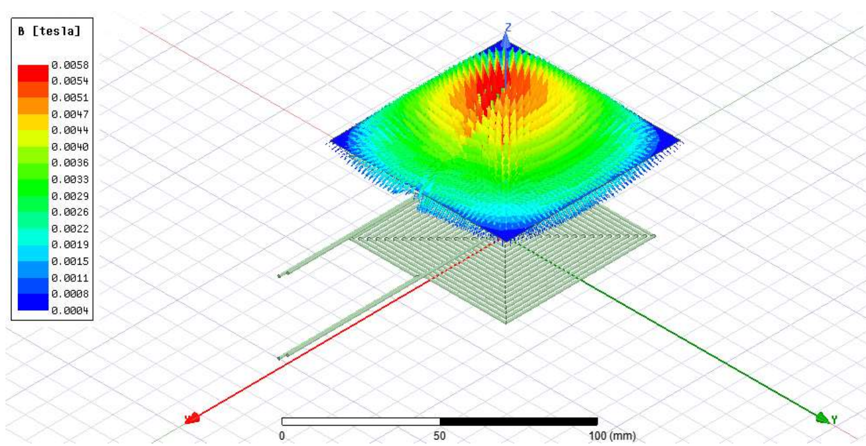

Figure 4-22 Flux density distribution at ZDist = 55 mm & plate 55 mm.

Research on wireless power charging must include flux density distribution analysis with various misalignments for a of optimization of alignment reasons.

Optimization of Alignment: In real-world wireless power transfer applications, misalignment between the transmitter (charging pad) and the receiver (the device being charged) is frequently encountered. By examining the flux density distribution under different misalignment conditions, charging devices can be designed to transfer power efficiently even in cases where alignment is not ideal.

Flux density distribution analysis presents that around 30 mm misalignment the coil structure presents optimal results both in the case of circular and square coils in the present research work. It can be observe from Figure 4-16 to 4-22.

4.2 Circular coil:

Similar to square topology of coils, many other configurations are possible. Here in this research planner circular coil has been used. Figure 4-23 shows circular configuration with planner coils simulated in ANSYS Electronics Desktop. Bottom coil is known as transmitting coil while upper coil is known as receiving end coil. Simulation parameters are tabulated in Table 4-6.

Excitation current (I) Amperes	**Frequency (f) kHz**	**Turns N**	**Start helix radius mm**	**Radius change mm**
10	53.1	21	5	8

Table 4-6 Circular coil simulation parameters

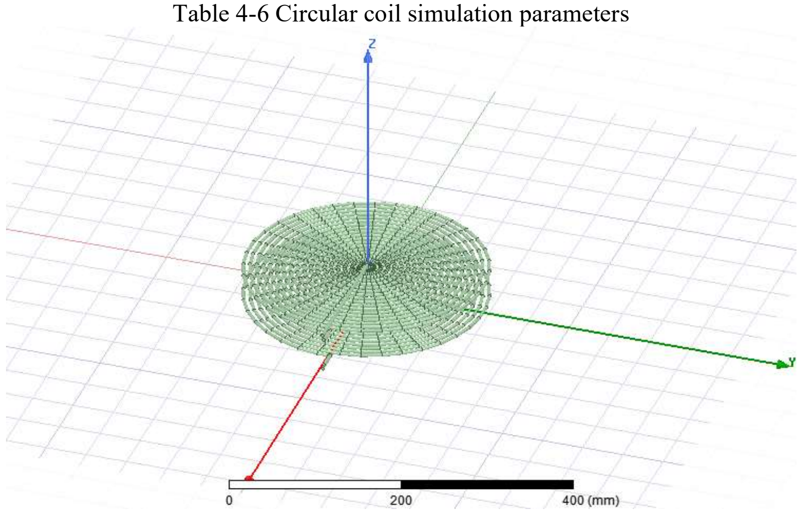

Figure 4-23 Circular coil configuration at ZDist = 5 mm

4.2.1 Coupling coefficient:

Similar to square configuration of coils, coupling coefficient values have been obtained from ANSYS Electronics Desktop. It is also tabulated in Table 4-7.

From Table 4-7 it is observed that both self-coupling coefficients having value equal to 1, while mutual coupling coefficient (coupling coefficient of one coil to that of other coil) having different values lying between 0.0045662554 to 0.834986118.

ZDist [mm]	Matrix1. CplCoef (IRX1,IRX1)	Matrix1. CplCoef (ITX1,IRX1)	Matrix1. CplCoef (IRX1,ITX1)	Matrix1. CplCoef (ITX1,ITX1)
5	1	0.834986118	0.834986118	1
25	1	0.542614255	0.542614255	1
30	1	0.499370331	0.499370331	1
35	1	0.460837395	0.460837395	1
50	1	0.365366091	0.365366091	1
55	1	0.338690722	0.338690722	1
80	1	0.233786628	0.233786628	1
105	1	0.163085578	0.163085578	1
130	1	0.114945914	0.114945914	1
155	1	0.081905697	0.081905697	1
180	1	0.05897233	0.05897233	1
200	1	0.045662554	0.045662554	1

Table 4-7 Coupling coefficient at various ZDist for circular coil

Similar to square coil, here in the case of circular coil also we have calculated self and mutual inductance values at different ZDist (z – axis misalignment). Value of ZDist is as of the case of square type of coil and its value varies from 5 mm to 200 mm. excitation current for the coils are kept at 10 Ampere. Values obtained are presented in the tabular form in Table 4-8. By close observation, we can conclude that self-inductance of both coils (transmitting and receiving) is having same values and mutual inductances of both the coils (transmitting and receiving) are also having approximately same values.

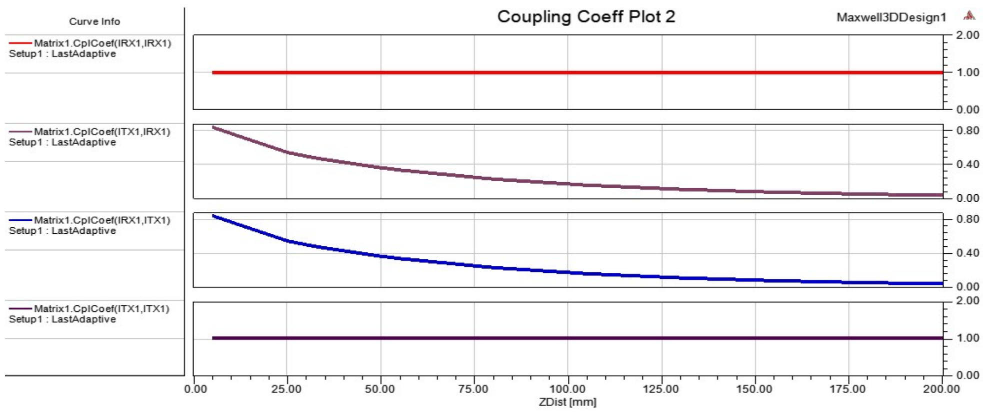

Figure 4-24 Variation of coupling coefficient with respect to ZDist for circular coil

ZDistt [mm]	**Matrix1.L (IRX_In,IRX_In) [uH] - Ir='10A'**	**Matrix1.L (ITX_In,IRX_In) [uH] - Ir='10A'**	**Matrix1.L (IRX_In,ITX_In) [uH] - Ir='10A'**	**Matrix1.L (ITX_In,ITX_In) [uH] - Ir='10A'**
5	17.5248307	14.63309	14.63309	17.52508
25	25.89517094	14.05134	14.05134	25.8961
30	27.16368801	13.56421	13.56421	27.16155
35	28.21453091	13.00272	13.00272	28.21632
50	30.44206811	11.12263	11.12263	30.44276
55	30.96831233	10.48786	10.48786	30.9635
80	32.59905136	7.621124	7.621124	32.59821
105	33.36397251	5.441489	5.441489	33.36772
130	33.75509417	3.880187	3.880187	33.75818
155	33.95523791	2.781075	2.781075	33.95396
180	34.06079598	2.008655	2.008655	34.06115
200	34.11774795	1.557855	1.557855	34.11562

Table 4-8 Self and mutual inductance at various ZDist for circular coil

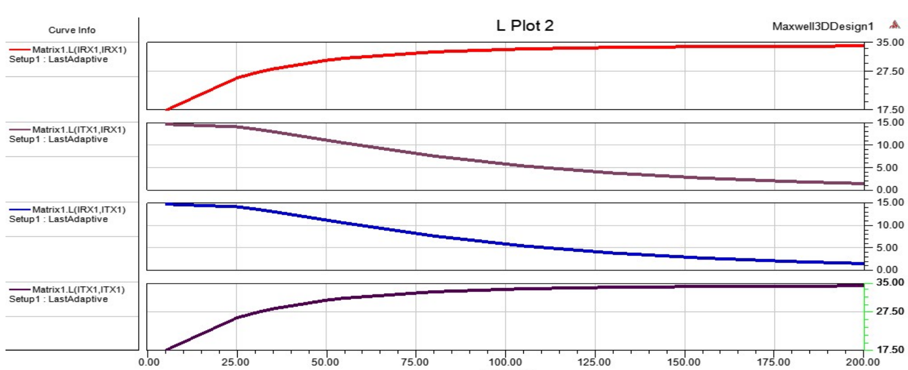

Figure 4-25 Variation between self and mutual inductance with ZDist for Circular coil

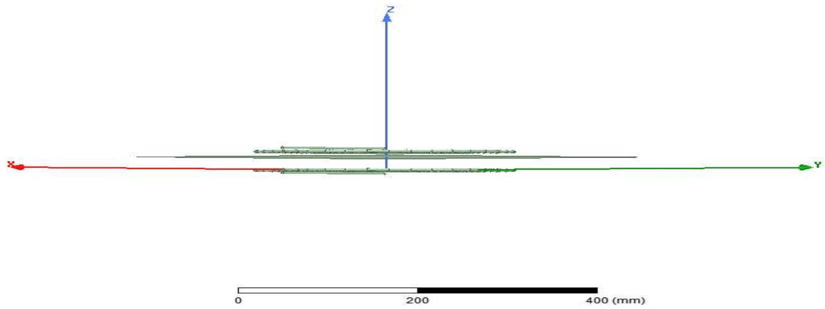

Figure 4-26 Vertical misalignment of 5 mm and y axis misalignment of 0 mm

The values obtained are also presented in graphical form for better understanding in Figure 4-25.

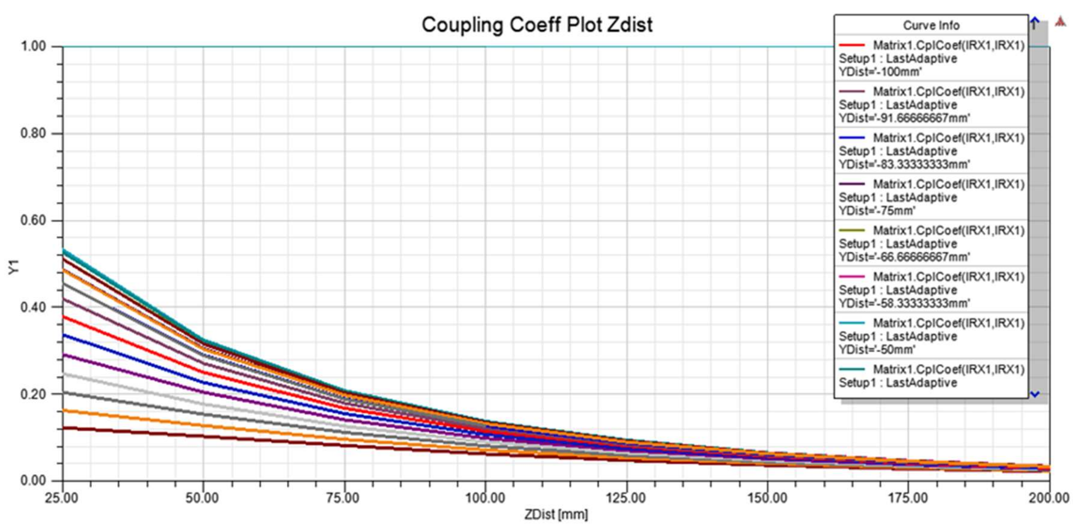

Figure 4-27 Plot showing variation of k with ZDist as a function YDist

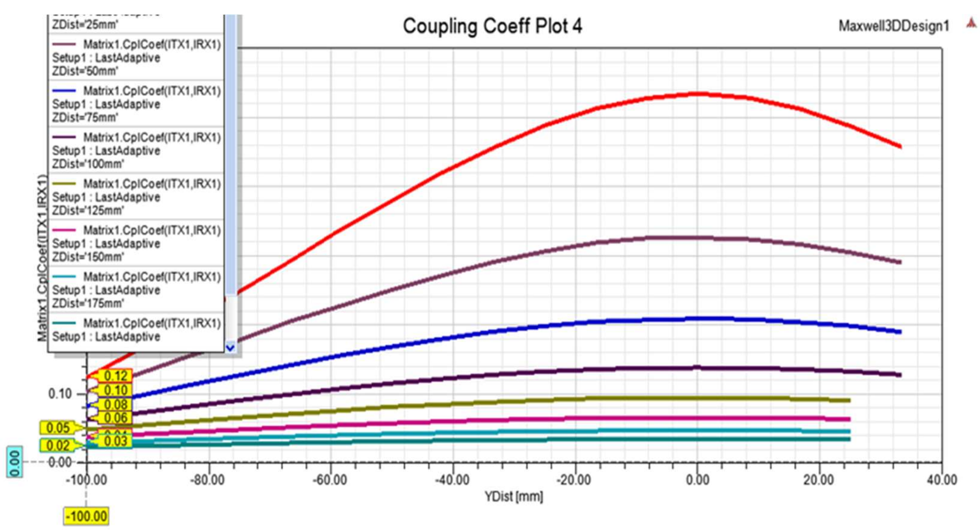

Figure 4-28 Value of k v/s YDist as a function of ZDist.

To study misalignment in y axis as well as z axis, this receiving end circular coil has been analysed with y axis misalignment of -100 mm to +100 mm and simultaneously z axis misalignment from 0 mm to 200 mm. Side view of 3D image of the circular coil simulated in ANSYS Electronics Desktop software is shown in Figure 4-26. In this Figure 4-26 vertical misalignment of 5 mm and y axis misalignment of 0 mm is shown as an example. Other similar diagrams are not presented here in figure forms, but results are presented in graphical forms in Figure 4-27 and in Figure 4-28.

4.2.2 Self and mutual inductance variation:

Figure 4-29 depicts, variation of mutual inductance with YDist as a function of ZDist. It is also predicted that when ZDist and YDist are minimum mutual inductance having maximum value. This is because of lower reluctance offered to flux creation. This situation is called magnetically tight coupling. When ZDist and YDist are maximum, mutual inductance values will be lowest due to higher magnetic reluctance.

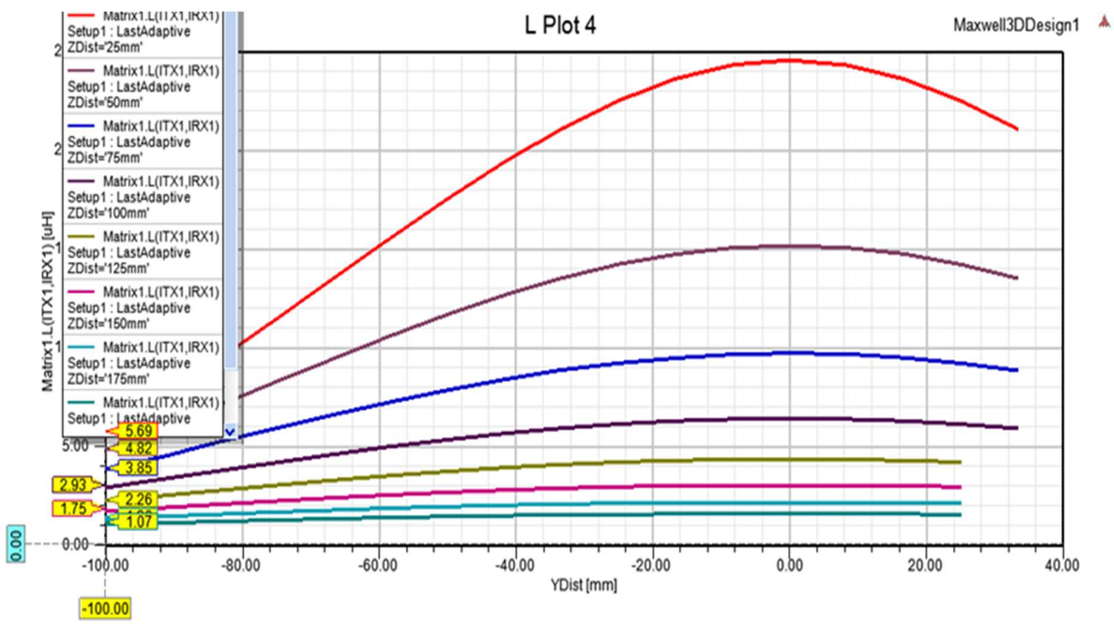

Figure 4-29 Value of M v/s YDist as a function of ZDist.

4.2.3 Flux density distribution around coils:

Figure 4-30 and Figure 4-31 both represents flux density around the space between two coils. Both of these figures are having little change in the setting of ANSYS Electronics Desktop, flux density though having same value but looks slightly different. Both the figures are arranged 35 mm apart from each other vertically and y axis misalignment is considered at zero value.

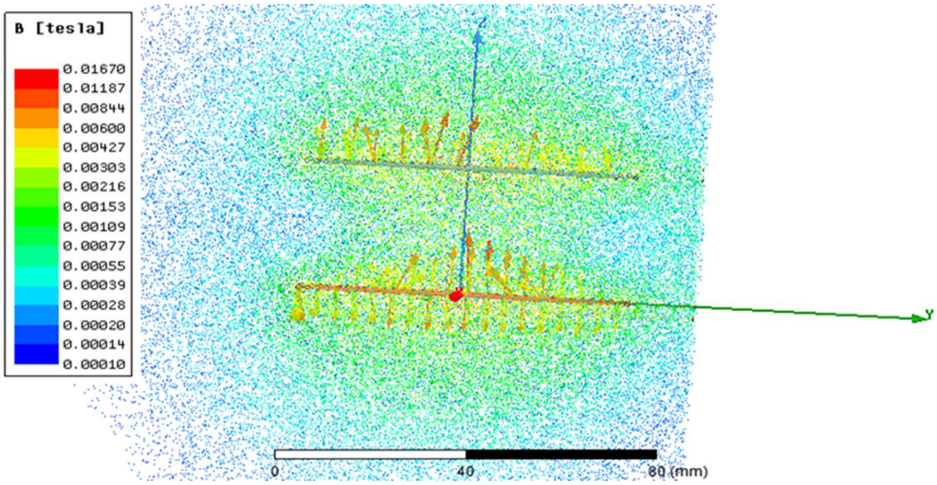

Figure 4-30 Flux density distribution around circular coils.

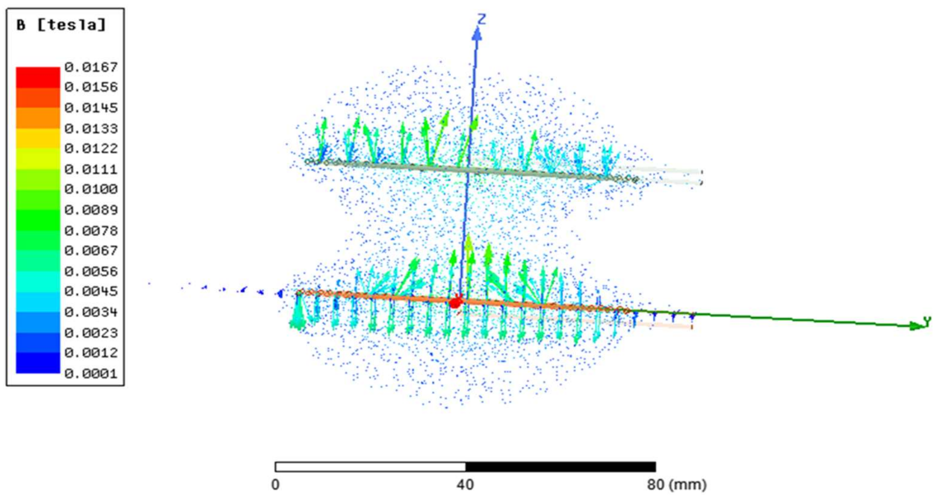

Figure 4-31 Flux density distribution around circular coils with less density setting.

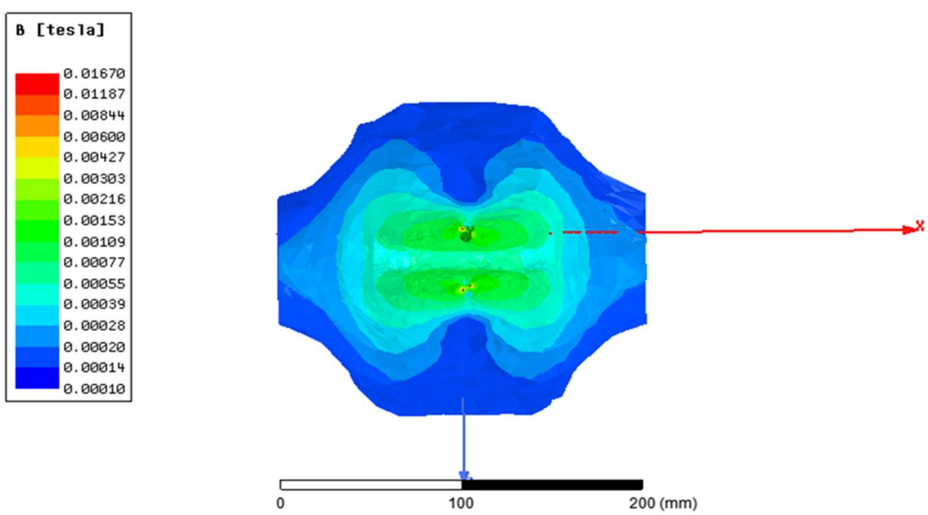

Figure 4-32 Flux density distribution around circular coils in cloud form.

Figure 4-32 represents flux density distribution around coils in the form of clouds. In this figure various colour code have been used to represent flux density around coil and in the air medium. It can be observed from Figure 4-29 to Figure 4-32 that, at 35 mm vertical misalignment flux density around coils are maximum compared to farther from the centre of the coils.

4.3 3D plot for resonance frequency:

Resonance frequency for WPT can be found by analytical method as well as graphical method. Analytical equations for finding the value of resonance frequency have been given in Chapeter:2. In this part of chapter, we are presenting graphical method to find resonance frequency. ANSYS Electronics Desktop can plot 3D graph with frequency on x- axis, ZDist on y- axis and electrical power on z- axis. We can easily find resonance frequency by observing the 3D plot, as magnitude will be maximum at resonance point. Figure 4-33 shows that resonance occurs at 53.1 kHz frequency.

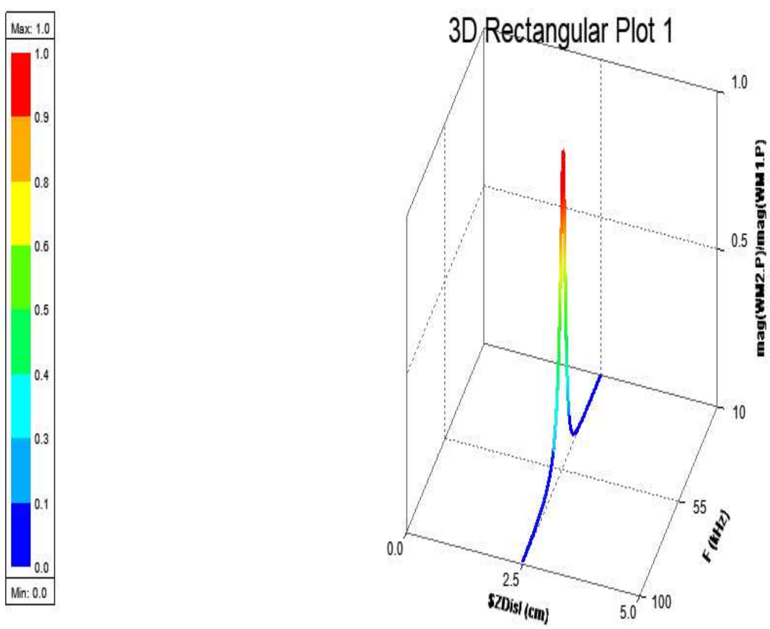

Figure 4-33 3D plot between f, ZDist and amplitude.

4.4 Comparison of parameters for square and circular coils:

When the vertical misalignment (ZDist) is kept at 5 mm for both configure of power pads, the coupling coefficient seems to be the maximum, the values are equal to 0.683323243 & 0.834986118 for circular and square pads respectively. With increasing vertical misalignment, coupling coefficient steadily diminishes.

Misalignment [mm]	Square "k"	Circular "k"
5	0.834986118	0.683323243
25	0.542614255	0.3776
30	0.499370331	0.158663201
55	0.338690722	0.048921856
80	0.233786628	0.016316834
105	0.163085578	0.003007173
130	0.114945914	0
155	0.081905697	0
180	0.05897233	0
200	0.045662554	0

Table 4-9 Misalignment and k for square & circular pad

The coupling coefficient drops to 0.045662554 and 0 for square and circular pads respectively, whenever the vertical misalignment is 200 mm. The values droop as vertical misalignment between the transmitting and receiving power pads increases, in both types of coils.

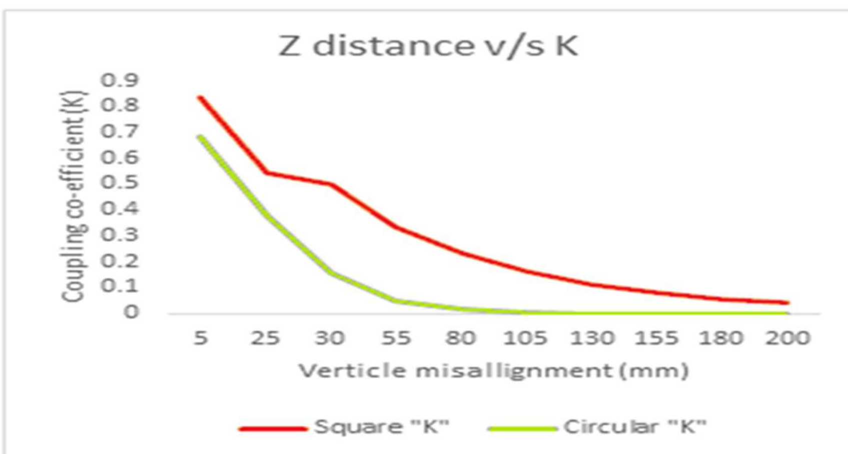

Figure 4-34 Ccomparative graph between ZDist vs Coupling coefficient.

The coupling coefficient of square power pads is greater than that of circular power pads, and the difference is more obvious for larger vertical displacements. Comparative relationship between square and circular coils in terms of coupling coefficient (k) values are presented here in tabular form in Table 4-9 Misalignment and k for square & circular pad. These values have been taken at 25 mm interval of vertical misalignment.

4.5 Simulation with ANSYS Twin Builder:

The values for L_1, L_2, k, B, and H are included in the imported ANSYS Electronics Desktop model of the sub circuit.

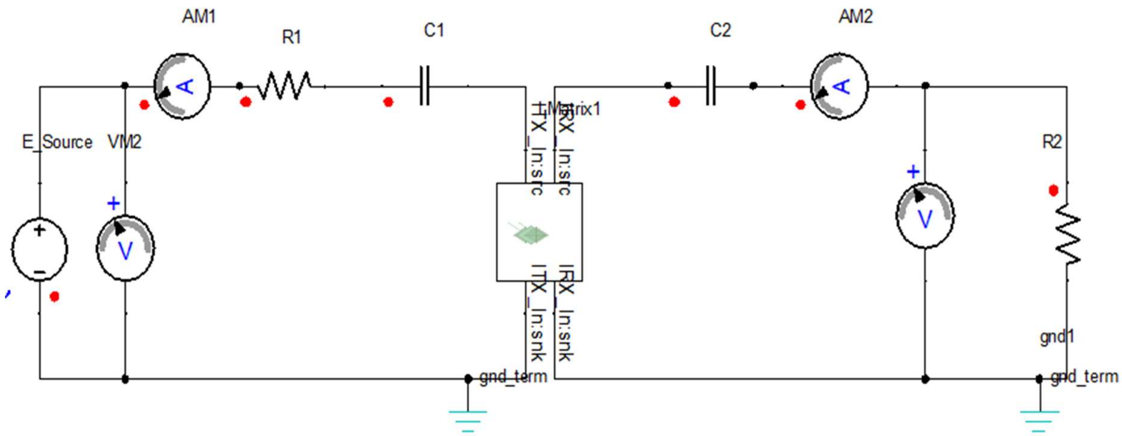

Figure 4-35 ANSYS Twin Builder simulation model.

These data are currently used in the ANSYS Twin Builder circuit model. The only variables in this simulation are ZDist (vertical misalignment) and frequency (f), which yield a variety of results such as power, efficiency, and resonance frequency. Figure 4-35 shows the ANSYS Twin Builder circuit simulation model with imported sub circuit model of square coil pads. Simulation parameters for this circuit are L is equal to 3.9 mH and C_1 and C_2 are 5.1 micro F and others are given in Table 4-10.. It is difficult to vary capacitance with inductance due to misalignment, so ZDist variation was not considered.

Source Voltage V (Volts)	**Operating frequency f (kHz)**	**Primary resistance R1 (mΩ)**	**Secondary resistance R2 (mΩ)**	**Power P (W)**	**Efficiency η (%)**
230	53.1	19.9	100	3350	95.5

Table 4-10 Simulation parameters and results for square coils.

Since it would be exceedingly challenging to show the entire set of findings in a table, Figure 4-36 is given instead. A graph between frequency and output power is shown in Figure 4-36. Peak of power is achieved at a frequency of 53.1 kHz.

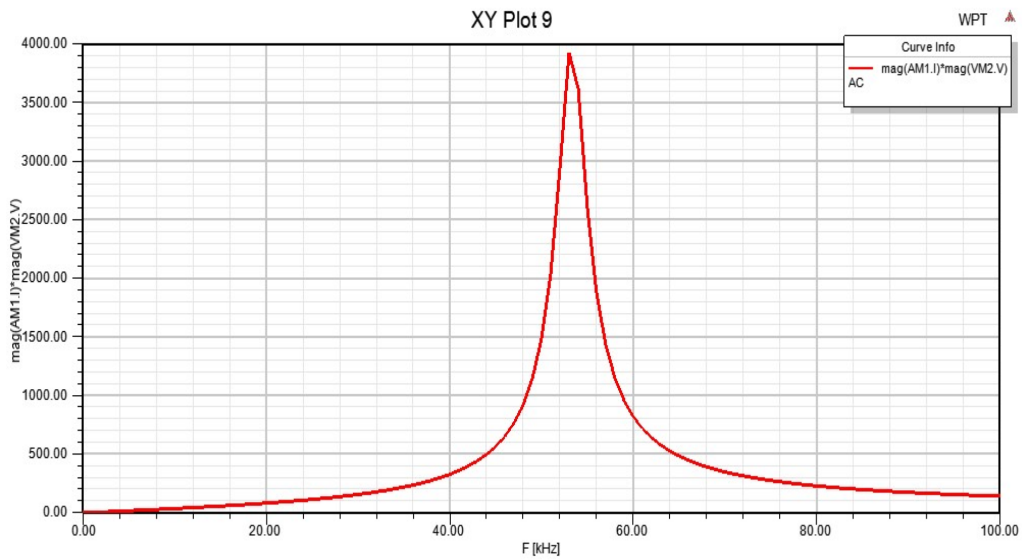

Figure 4-36 Power plot.

From Figure 4-36, it can be seen that the resonance occurs at 53.1 kHz. After calculation of the output power and input power, we find the efficiency, which was around 95.5%. This range is well above SAE J2954 standard (85.5 %).

ANSYS Twin Builder has been used to assess the simulation of wireless power transmission utilising circular pad geometry and the system characteristics listed in Table 4-11. Figure 4-37 and Figure 4-38 depicts the power flow from the transmitter pad to the receiving pad. 3023 watts of electricity are transferred at their highest during the system frequency of 53.1 kHz. The resonant angular frequencies of the system are defined as ω_{n1} and ω_{n2}, and further normalized as $\omega_{n1}\omega_{n1}/\omega_1$ and $\omega_{n2}\omega_{n2}/\omega_2$, respectively.

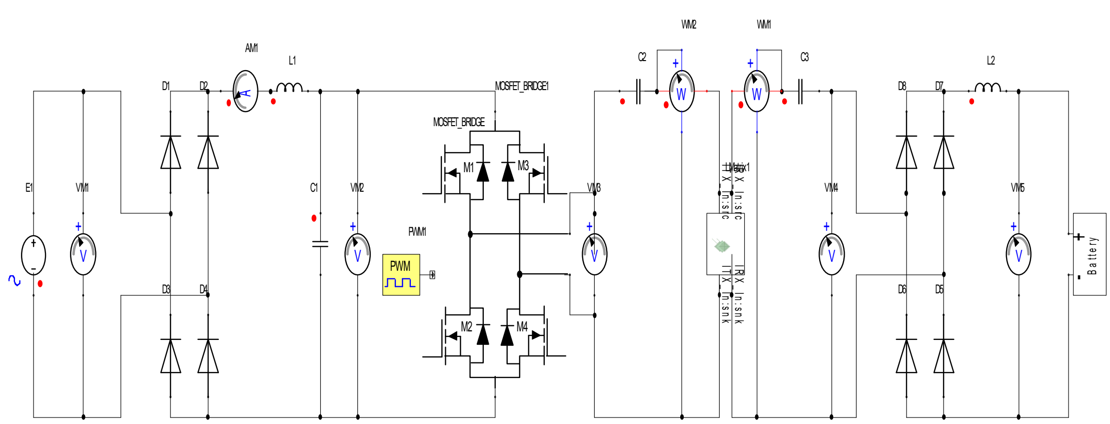

Figure 4-37 ANSYS Twin Builder circuit for circular geometry.

f (kHz)	% η	f (kHz)	% η	f (kHz)	% η	f (kHz)	% η
1.00	0.0000	26.00	1.0759	51.00	95.5019	76.00	34.3710
2.00	0.0000	27.00	1.4343	52.00	94.6825	77.00	34.2324
3.00	0.0000	28.00	1.9171	53.00	90.2862	78.00	34.1448
4.00	0.0000	29.00	2.5740	54.00	83.9000	79.00	34.1043
5.00	0.0001	30.00	3.4792	55.00	77.0216	80.00	34.1077
6.00	0.0003	31.00	4.7464	56.00	70.5381	81.00	34.1519
7.00	0.0006	32.00	6.5543	57.00	64.8097	82.00	34.2345
8.00	0.0012	33.00	9.1915	58.00	59.9018	83.00	34.3532
9.00	0.0023	34.00	13.1259	59.00	55.7522	84.00	34.5061
10.00	0.0039	35.00	19.0768	60.00	52.2586	85.00	34.6916
11.00	0.0065	36.00	27.8584	61.00	49.3167	86.00	34.9081
12.00	0.0103	37.00	39.0965	62.00	46.8336	87.00	35.1542
13.00	0.0158	38.00	48.7325	63.00	44.7313	88.00	35.4288
14.00	0.0237	39.00	52.4555	64.00	42.9462	89.00	35.7307
15.00	0.0347	40.00	52.2060	65.00	41.4265	90.00	36.0589
16.00	0.0499	41.00	51.4110	66.00	40.1306	91.00	36.4124
17.00	0.0706	42.00	51.4996	67.00	39.0246	92.00	36.7901
18.00	0.0985	43.00	52.8061	68.00	38.0811	93.00	37.1912
19.00	0.1358	44.00	55.3808	69.00	37.2779	94.00	37.6147
20.00	0.1855	45.00	59.2437	70.00	36.5963	95.00	38.0595
21.00	0.2515	46.00	64.4141	71.00	36.0215	96.00	38.5246
22.00	0.3387	47.00	70.8426	72.00	35.5406	97.00	39.0088
23.00	0.4539	48.00	78.2470	73.00	35.1433	98.00	39.5108
24.00	0.6061	49.00	85.8539	74.00	34.8207	99.00	40.0292
25.00	0.8078	50.00	92.2070	75.00	34.5654	100.00	40.5619
η=(mag(AM2.I)*mag(VM1.V))/(mag(AM1.I)*mag(VM2.V))*100 []							

Table 4-11 Variation of efficiency for square coils.

For the typical dual resonance, the differences between the two resonance angular frequencies are specified as $\Delta\omega_{0n12} = \omega_{0n1} - \omega_{0n2}$ and $\Delta\omega_{n12} = \omega_{n1} - \omega_{n2}$ for the suggested system, respectively. The resonance differences under varied conditions are shown in Figure 4-38. The intrinsic angular frequencies of the resonator are the only factors that affect and determine the resonant frequencies of the proposed system. The resonant resonances of the classical system are tightly coupled nonlinearly. While the two resonant frequencies of the average system are somewhat close to one another, and it is difficult to realize in practice.

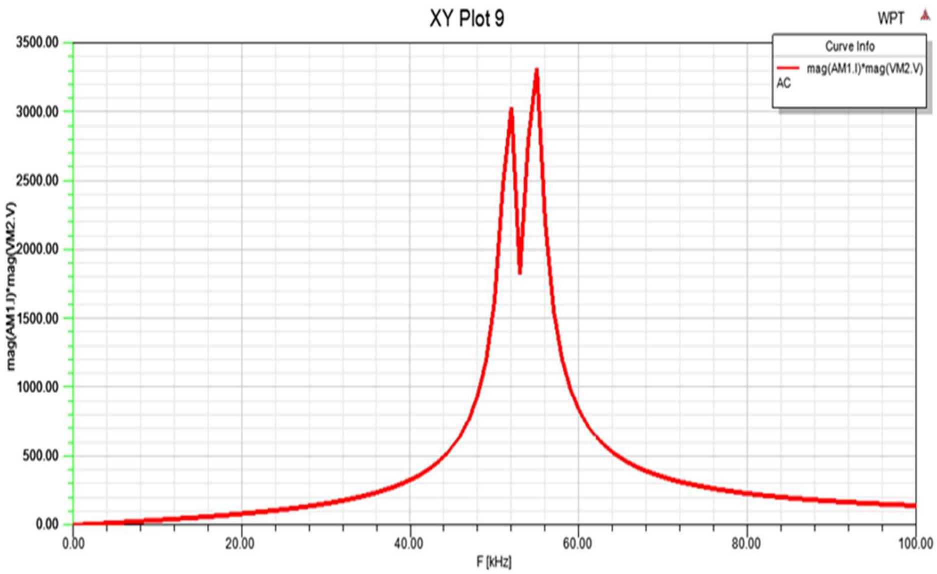

Figure 4-38 Power plot for square coils.

The efficiency for circular and square pad have been plotted with the help of ANSYS Twin Builder as shown in Figure 4-39. It is obvious that the square pad is having much superior efficiency than circular pad, when all other parameters kept similar.

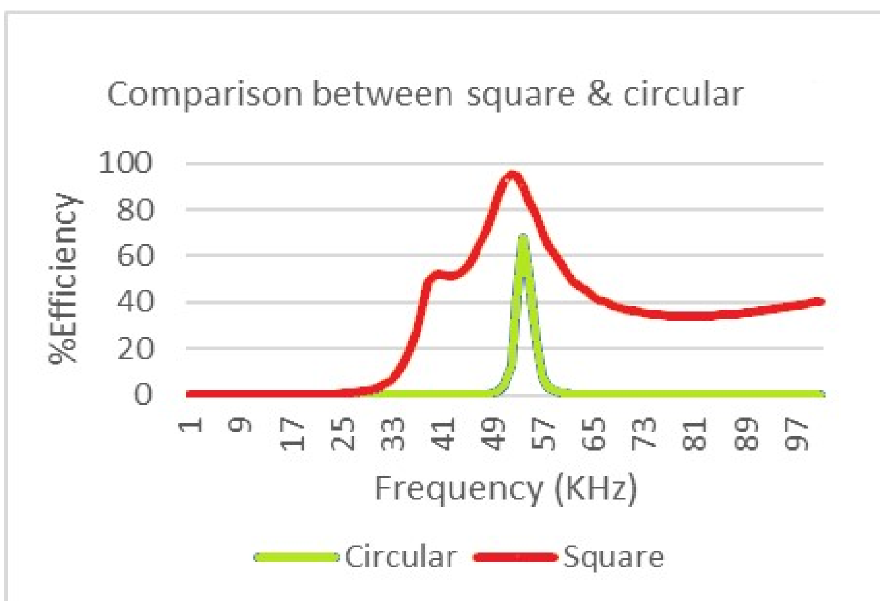

Figure 4-39 Comparison of efficiencies for square and circular coils.

4.6 Correlation of Efficiency with Frequency:

The SAEJ2954 standard was developed to standardize the battery charger for electric cars. This document describes all design characteristics, namely inductance, power, required efficiency, compatible topology, and the validation procedure. SAEJ2954 specifies four power ranges for light duty EVs: WPT1 (3.7 KVA), WPT2 (7.7 KVA), WPT3 (11.1 KVA), and WPT4 (22 KVA). The minimal efficiency for each class is shown in Table 4-12.

Min. Input Power	WPT1 3.7KVA	WPT2 7.7KVA	WPT3 11.1KVA	WPT4 22KVA
Min. Target efficiency	>85%	>85%	>85%	>85%
Min. Target efficiency at offset position	>80%	>80%	>80%	>80%

Table 4-12 WPT & target efficiency.

The results are giving an idea about placements of coils for higher efficient charging at parking/ garages. The outcome of flux density distribution analysis, particularly in the context of assessing the importance of tight coupling between coils for effective power transfer, plays a crucial role in WPT system development and efficiency improvement. Here's how this analysis outcome is utilized:

Optimizing Coil Alignment: The analysis results help in determining the optimal alignment conditions between the transmitter and receiver coils for achieving tight coupling. By understanding how misalignment affects flux density distribution and consequently power transfer efficiency, engineers can devise alignment mechanisms, such as dynamic or adaptive alignment systems, to maintain tight coupling even in dynamic or changing environments.

In this research, a comparative study of square and circular power pads for EV's wireless power transfer systems is presented. ANSYS Electronics Desktop and Twin Builder has been used to make 3D models for both types of power pads that are based on the SAE J2954 recommended physical dimensions. Vertical and y-axis misalignment between the transmitting and receiving sides ranges between 5 mm and 200 mm for each type of power pads have been taken into consideration. For both types of power pads, parameters such as coupling coefficient, mutual inductance, magnetic field strength, and magnetic flux density are investigated, plotted and presented in graphical forms. According to the simulation results, it has been concluded that square power pads have a great potential for application in EV wireless charging systems.