Volume 11, Issue 4
August 2022

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Comparison and Design Verification of Square and Circular Power Pad of Wireless Power Transfer for Hybrid Electric Vehicle

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ABSTRACT

Systems for contactless recharging have been developed to allow safe and flexible power transmission for electric automobiles. The anxiety associated with driving range may be considerably decreased by enhancing the viability of electric vehicle inductive charging systems as a whole. This study compares the features of round and square power pads for EV contactless charging systems. For the physical dimensions of these power pads, the Society of Automotive Engineers (SAE) suggested standard J2954. Parameters like as coupling coefficient as well as mutual inductance are analysed by imparting vertical and horizontal alignment to each kind of power pads. An interesting comparison has been presented by simulation of the power pads using ANSYS Electronics desktop and twin builder. In contrast, variable misalignment between two coils is has been utilised for analysis in dynamic computations of the coils' self and mutual inductance. This makes sweeping analysis easier and speeds up the computation. Impedance matching connections have been used on all three ports to tune the system at 51.3 kHz frequency for peak effectiveness. The greatest attainable efficiency for each coil prototype is calculated (through modelling and testing) and the results are compared. The importance of EMF software in designing a planar passive basis for WPT system has been explored. Overall, the suggested passive base coil approach has been shown to succeed in increasing the alignment between pads. It is also demonstrated that the mutual inductance reduces as misalignment increases, and vice versa.

Keywords: *Wireless Power Transfer, WPT, ANSYS, Maxwell, SAE.*

1. INTRODUCTION

Since wireless power transmission is anticipated to be more efficient than several traditional methods of power transfer, including cables, it has lately received a lot of attention from researchers [1]. This is because WPT has been the subject of research for many years. As technology advances, there will be a strong need for WPT-based applications. The dynamic modelling and analysis of a basic two-coil type wireless power transfer module are constructed in this article using ANSYS Electronics and Twin builder software, and the coefficient of mutual inductance coupling M, is dynamically determined over a wide range of distances. High-performance, effective tools like ANSYS Electronics and Twin builder were used to model, simulate, and test a product before developing it in real time.

To refuel EV's internal battery, majority of widely viable EVs, such as Hybrid Electric Vehicles (HEVs) and Plug-in Electric Vehicles (PHEVs), require a connector charging system [2-3]. Wireless charging for electric vehicles was created to address the disadvantages of previous charging systems. Wireless charging systems provide considerable advantages in terms of systems engineering, power transmission effectiveness, and easy implementation [4-6]. Academics and industry have both made major investments in power electronics and power pads in order to create improved wireless charging options. The majority of EV wireless charging systems rely on power pads. Diverse types of pads have been designed and are being researched to achieve the best possible power transfer performance. [7-9].

WPT power pads are fitted one on ground and another on vehicle's side. The grounded pad also known to be ground assembly (GA), and fitted on vehicle is as vehicle assembly (VA). Magnetic flux induced by high-frequency currents in GA is magnetically coupled to VA.

Power pads must have a high coupling coefficient ‘K’ (0 to 1) and has to be capable of transferring power in varieties of misalignment X, Y and Z planes [10]. The K value depends on system arrangement and misalignment between pads. Circular power pad architecture is the focus of SAE J2954, although square pads are viable solution as well. As a result, characteristics of both configurations are compared and analyzed in this research. The system standard defined in Society of Automotive Engineers (SAE) recommended standard J2954 [15] has been referred to design pads.

2. DESIGNING OF INDUCTANCE COIL

Both GA and VA coils resonates at same resonant frequency, which is the core pillar of wireless charging technology. To execute this purpose, a suitable resonant compensation capacitor is connected between the coils. From the transmitting and receiving endpoints and the WPT terminal connectivity relationship, the topological pattern of a system may be separated into series-series (S-S), series- parallel (S-P), parallel-parallel (P-P) and parallel-series (P-S). The fundamental structure, the series-series (S-S) resonates with the simplest wireless transmission.

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Information Technology & Electrical Engineering

ISSN: - 2306-708X

Figure 1 describes simplified circuit of a series-series (SS) architecture WPT system. Voltage at high frequencies does have an advantage over rest is small size of compensating capacitor as well as coil. As a consequence, the low-frequency main voltage is converted to a high-frequency voltage and supplied to a primary circuit. This is similar to transformer action and leads to high frequency magnetic field. This field links with secondary coil, inducing a high frequency voltage across its winding terminals. This induced voltage is influenced by the coils' coupling coefficient. Finally, the alternating voltage in its secondary winding is mended before being delivered to the load.

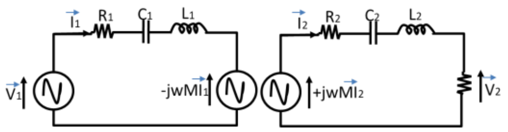

Fig.1 Simplified S-S compensated WPT system

S-S compensation arrangements is being used in electric vehicles since they have lower impedance at resonance, is appropriate power level and is least susceptible to misalignment. To evaluate the optimum capacitance and voltage level for the compensating circuits is very vital. At resonance the system becomes pure resistive and have best efficiency.

Low cost and high efficiency are its two advantages. The disadvantages are as follows: (1) the power level is limited to geometric coils; (2) the transfer of power is available in a short range; and (3) side and angular misalignment can reduce efficiency.

Hence, wireless power transfer necessitates the development of two inductive coils. The design of one such inductive coil, designated a transmitter (Tx), is presented, and the same analogy applies to the receiver coil (Rx). The modelling is done in the ANSYS Maxwell electromagnetic simulation model, with the time domain specification transient analysis used. We know that the inductance of the coils must be large in order to achieve superior mutual coupling, as shown by equation (1). As a result, the mutual coupling coefficient M, must be substantial in order for power transfer capabilities to be realized [3]. Figure 1 is transformer equivalent model of (S-S) resonant.

$$M = k\sqrt{L_1 L_2} \quad (1)$$

Here,
M – Mutual Inductance (Henrys)
K – Coefficient of coupling
L_1, L_2 Inductance of coils (Henrys)

$$C_1 = \frac{1}{w^2 L_1} \quad C_2 = \frac{1}{w^2 L_2} \quad (2)$$

Voltage equations for the voltages are

$$V_1 = Z_{T1} I_1 - jwMI_2 \quad (3)$$

$$Z_{T1} = Z_{C1} + Z_{R1} + Z_{L1} = \frac{1}{jwC_1} + R_1 + jwL_1 \quad (4)$$

$$Z_{T2} = Z_{C2} + Z_{R2} + Z_{L2} = \frac{1}{jwC_2} + R_2 + R_L + jwL_2 \quad (5)$$

At resonance,

$Z_{C1} + Z_{L1} = 0$ *and* $Z_{C2} + Z_{L2} = 0$;$V_1 = I_1 R_1 - jwI_2$
where,

$$I_2 = \frac{jwM}{R_1 + R_2} \times I_1,$$

Input power delivered

$$P_{in} = V_1 I_1 = \frac{R_1 \times (R_2 + R_L) + (wM)^2}{R_2 + R_L} \times {I_1}^2 \quad (6)$$

And output power

$$P_{out} = {I_2}^2 R_L = R_L \frac{w^2 M^2 {I_1}^2}{(R_2 + R_L)^2} \quad (7)$$

Power efficiency

$$\eta = \frac{P_{out}}{P_{in}} = \frac{R_L \times (wM)^2}{(R_2 + R_L) \times [R_1 \times (R_L + R_2) + (wM)^2]} \quad (8)$$

Neglecting R_2 as it is very less than R_L,

$$\eta \approx \frac{1}{\frac{R_1 R_L}{(wM)^2}} \quad (9)$$

3. DESIGN OF THE COIL PARAMETERS

Plane planner spiral coils having good coupling coefficient and quality factor, hence used for wireless power transfer.

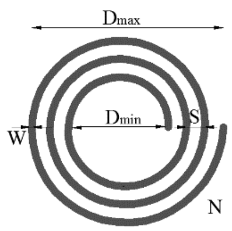

Fig.2 Circular coil

Here, D_{max} is the utmost outer diameter, D_{min} is the least inner diameter, N is coil turns, S is the distance among adjacent turns, and W is wire diameter.

$$D_{max} = D_{min} + (2N - 1)(S + W) + 2W \quad (10)$$

$$B = \frac{D_{max} - D_{min}}{D_{max} + D_{min}} \quad (11)$$

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Information Technology & Electrical Engineering
ISSN: - 2306-708X

$$D_{avg} = \frac{D_{max}+D_{min}}{2} \quad (12)$$

The distance between two turns should be calculated by considering following conditions.

$$S < S_{1max} = \frac{D_{lim} - 2W}{2N-1} - W$$
$$S < S_{2max} = \frac{2D_{lim} - (2W + 4r_{avg})}{2N-1} - W$$

Where, S_{1max} is allowable maximum coil internal spacing and S_{2max} is allowable maximum external spacing.

$$L = \mu_0 N^2 r_{avg}\left(ln\frac{2.46}{\beta} + 0.2\beta^2\right) \quad (13)$$

$$R = R_0 + R_a \quad (14)$$

$$R_a = 320\pi^4 N^2 \left(\frac{\pi r_{avg}{}^2}{\lambda^2}\right)^2 \quad (15)$$

$$R_0 = \left(\frac{\mu_0 w}{2\sigma}\right)^{\frac{1}{2}} \frac{N r_{avg}}{a} \quad (16)$$

$$Q = \frac{wL}{R} \quad (17)$$

Here,
L – spiral coil Inductance (Henrys)
R – equivalent resistance (Ohms)
R_0 – ohmic resistance (Ohms)
R_a – equivalent radiation resistance (Ohms)
Q – quality factor,
σ – conductivity of the wire,
β – filling rate,
a – radius of wire and
w – angular frequency

When two coil are coaxially coupled, its mutual inductance is calculated by

$$M = \frac{\mu_0 \pi N_1 N_2 r_{1avg}{}^2 r_{2avg}{}^2}{2\left(D^2 + r_{1avg}{}^2\right)^{1.5}} \quad (18)$$

The system working parameters are given in the following table:

V	f(kHz)	N	Zdist(mm)	P(W)	η(%)
230	51	20	15	3350	95.5

Table:1 System working parameters

The equation for calculating power product is as follows.

$$P_\eta = P.\eta = \frac{V^2 w^4 M^4 R_L{}^2}{Z_2(Z_1 Z_2 + w^2 M^2)^3} \quad (19)$$

The turns of coils are calculated from wire diameter and overall structure, being aware of the role of inter-turn voltage and wire insulation level for air breakdown.

It is suggested in this work that coils have a square form. It should be noted that square function is heavily reliant on the perimeter and only slightly depending on the loop area and wire radius. As a result, the inductance of intricate forms is sometimes well approximated by a simpler shape with the same parameters.

Grover et al. investigated a number of examples for polygons with side lengths and wire radius R. Using the following formula, we can simply determine inductance.

$$L = \frac{2\mu_0 s}{\pi}\left[ln\left(\frac{s}{R}\right) - 0.52401\right] \quad (20)$$

4. EFFICIENCY AND FREQUENCY

Figure:3 shows the output or power output against the receiver's success collected from the sender of the listed documents. It should be noted that efficiency increases with higher delivery power. However, performance varies and may be achieved by the same power delivered depending on system design.

The normative SAE J 2954 was created to standardize the battery charger for electric vehicles. This document describes all aesthetic qualities, including inductance, power, minimum efficiency, compatible topology, and the validation approach. SAE J 2954 specifies four power ranges for light duty EVs are presented in table:2.

The efficiency for circular and square pad have been plotted and compared with the help of ANSYS twin builder as shown in fig.4. It is clearly seen that the square pad is having much superior efficiency than circular pad, when all other parameters were kept similar.

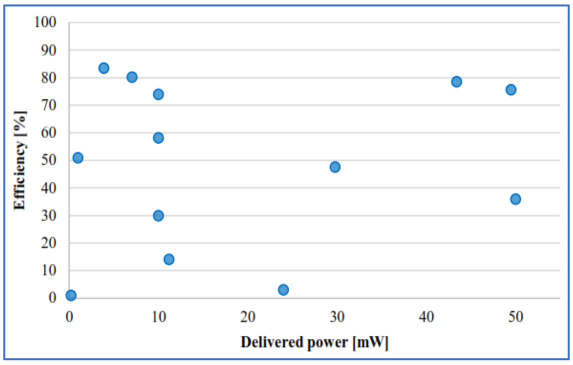

Fig.3 power v/s efficiency graph

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

Table:2 WPT & target efficiency

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Information Technology & Electrical Engineering
ISSN: - 2306-708X

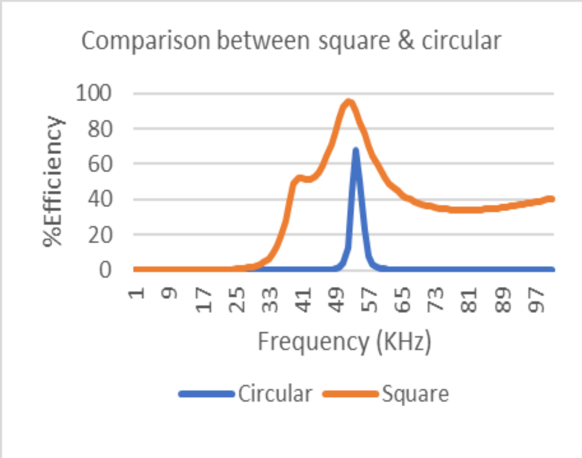

Fig.4 Frequency v/s efficiency comparison

5. MODELLING AND SIMULATION OF PADS

Figure:5 shows how coefficient of coupling varies with vertical misalignment ranges from 5 to 200 mm between GA and VA. Magnitude of coefficient of coupling reflects flux linkage between the pads. A greater coupling values indicate stronger connection between both the power pads, which is vital for EV charging systems.

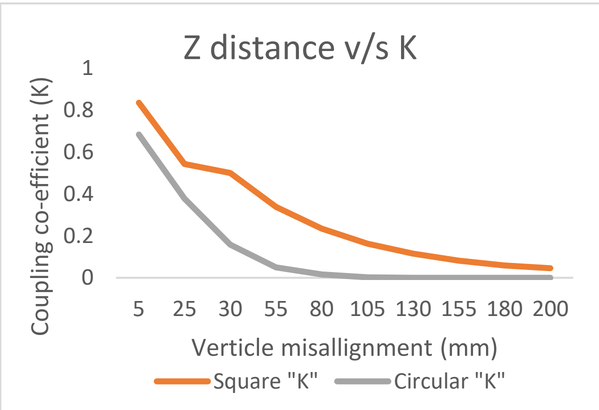

Fig.5 vertical misalignment v/s K

When the vertical misalignment is 5 mm between power pads, the coupling coefficient is maximum and equal to 0.683323243 & 0.834986118 for circular and square pads respectively. With increasing vertical displacement, the coupling coefficient steadily diminishes. The coupling coefficient drops to 0.045662554 and 0 for square and circular pads respectively. The values drops when distance between GA and VA increases, similar in both geometries. The coupling coefficient of square pads is greater than that of circular pads and the difference is more significant for larger misalignments.

Table:3 Misalignment and K for square & circular pad

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

Figure:6 depicts the variability of self & mutual inductance for square power pads with a vertical misalignment between the pads from 5 mm to 200 mm. The mutual inductance values for different misalignment have been given in table 4.

Table:4 Distance v/s self & mutual inductance

ZDistt [mm]	Matrix1.L(IRX_In,ITX_In) [uH] - Ir='10A'	Matrix1.L(ITX_In,ITX_In) [uH] - Ir='10A'
5	6.17137788	9.032130905
15	3.25674543	9.032101
25	1.86735467	9.03209087
30	1.432625206	9.032063973
35	1.112534467	9.032087
45	0.693645478	9.032063973
55	0.440771607	9.03361665
65	0.284673648	9.032063973
75	0.182435647	9.032063973
80	0.144431852	9.033990677
85	0.112345468	9.031700902
95	0.060965746	9.032824864
100	0.039512714	9.028852367
105	0.019373635	9.029584207
130	0	9.027948659
155	0	9.026987
180	0	9.0256748
200	0	9.0251324

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ISSN: - 2306-708X

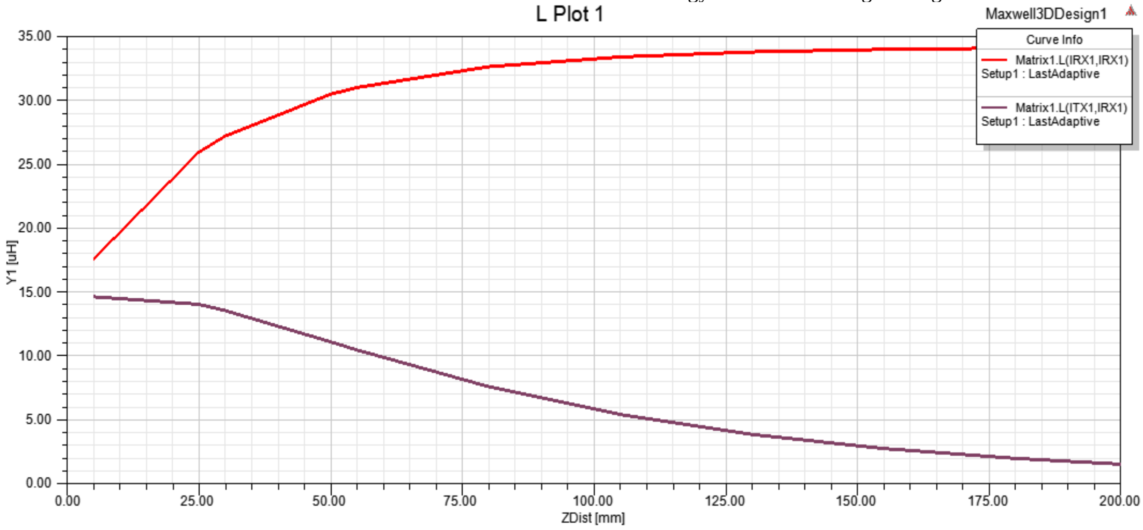

Fig.6 Distance v/s self & mutual inductance for square pad

When both vertical and horizontal misalignments have been used, the self and mutual inductance of square & circular power pads at 10 Ampere and 0 Ampere are seen in Figure:8.

Figure 7 shows flux density (B) in magnitude and in vector forms for square power pads for vertical misalignment of 30 mm. As pads are more misaligned, both magnetic field intensity and flux density decrease, and both are least at greatest misalignment (200 mm) of the research.

The simulations in this work are being done without considering shielding effect of ferrite bars. The coefficient (K) and mutual inductance (M) of square power pads demonstrate higher misalignment tolerance when compared to circular power pads.

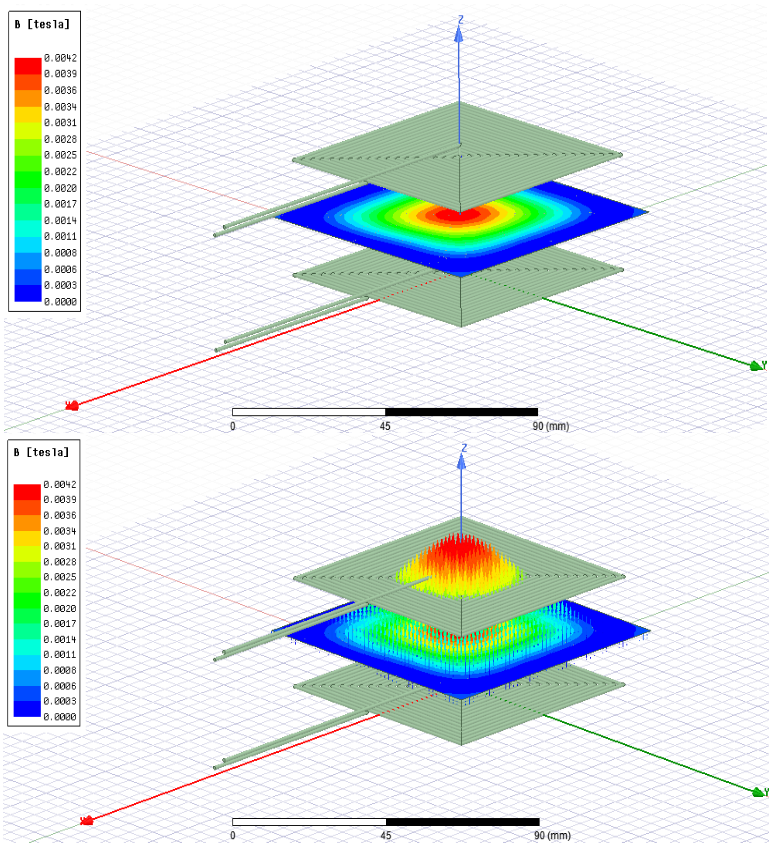

Fig.8 Flux density and vectors at 30mm.

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August 2022

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The power of the square coil is measured by simulation of the square coil pad at various lateral misalignment. The simulation have been carried out using ANSYS twin Builder. Figure:10 shows the circuit diagram of the equivalent circuit.

Simulation of the wireless power transfer using square pad topology, using the system parameters given in table:1 has been analyzed using ANSYS Twin Builder. The power transfer from transmitter pad to receiver pad has been shown in Figure: 11. Highest power transfer 3350 Watts occurs during system frequency of 51.3KHz.

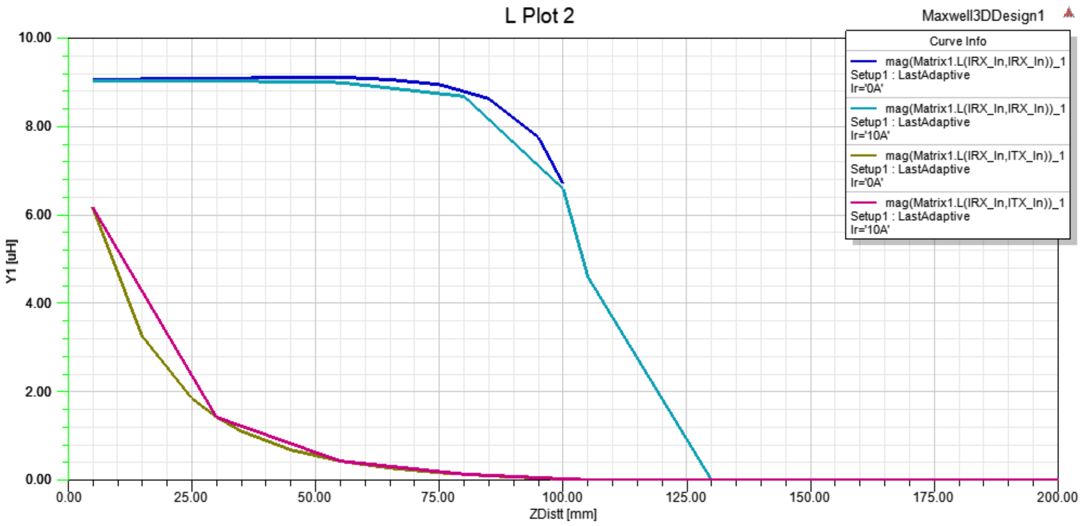

Fig.8 Distance v/s self and mutual inductance for square pad at 10 Ampere & 0 Ampere

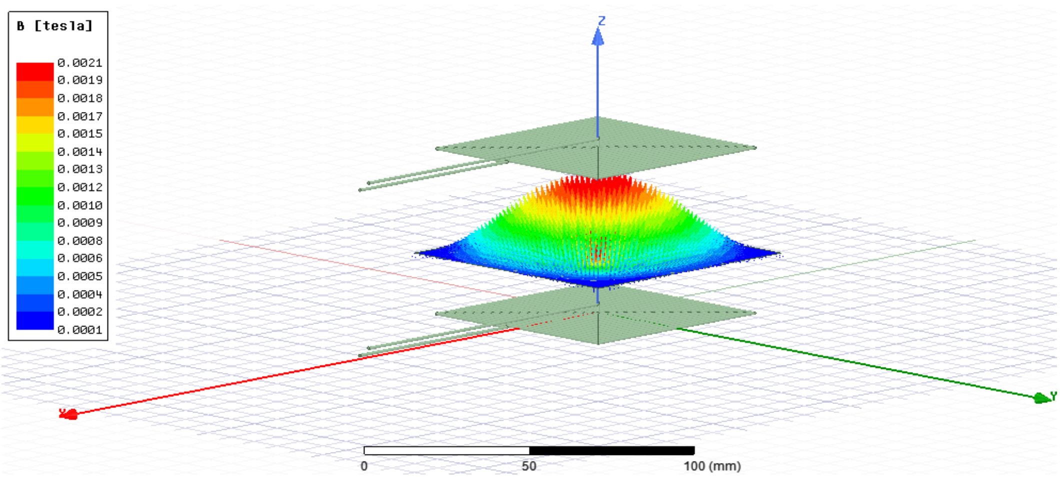

Fig.9 Flux density distribution at Zdist 55mm & plate at 20mm.

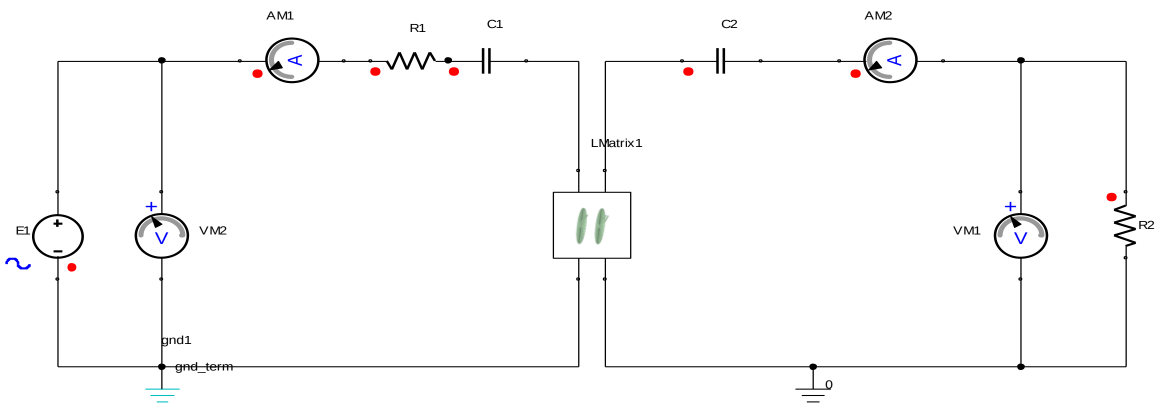

Fig.10 ANSYS Twin Builder equivalent circuit.

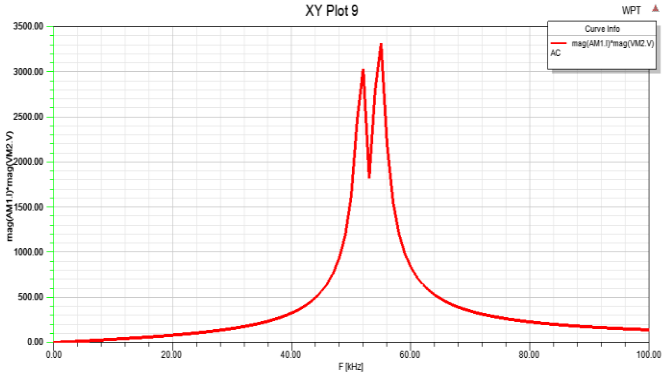

Fig.11 Frequency v/s power.

6. CONCLUSIONS

A comprehensive and comparative analysis of square and circular pads for EV WPT systems has been presented in this research. 3D models for both geometries of power pads were designed using ANSYS Electronics and Twin Builder which is based on the SAE J2954 physical dimensions. For every pad, vertical misalignment between 5 mm and 200 mm has been chosen and results has been presented. Important aspects like coupling coefficient (K), mutual inductance (M), magnetic field strength (B), and magnetic flux density (h) were explored for both geometries. Modelling and results demonstrate that square power pads have a great potentiality for use in EV wireless charging systems.

REFERENCES

[1] Yui Hou,Yuan Jhou, Jian Wu, Huihui Song, Yanbin Qu, “A New Type of Curved Coupling Coil for Wireless Power Transmission,”22nd International Conference on Electrical Machines and Systems (ICEMS), pp. 19-25, Aug. 2019.

[2] Tasnime Bouanou, Hassan El Fadil, Abdellah Lassioui, “Analysis and Design of Circular Coil Transformer in a Wireless Power Transfer System for Electric Vehicle Charging Application,” Proc IEEE 4th International Conference on Electrical and Information Technologies ICEIT’2020, 13-17 June, 2020.

[3] Linlin Gao, Xingming Fan, Chao Wang, Yuanming Tan, Xin Zhang, “Coil Design of EVs Wireless Charging System Based on MCR-WPT,” 2018 11th International Symposium on Computational Intelligence and Design, pp. 169-172, 2018.

[4] Maryam Salama Mohamed, Mohamed Abdul Raouf Shafei, Doaa Khalil Ibrahim, Ahmed Ali Mansour, “Coils Design and Parallel Resonant H-bridge Inverter for Inductive Power Transfer of Low-power portable devices,” 21st International Middle East Power Systems Conference (MEPCON), Tanta University, Egypt, pp.621-626, June, 2019.

[5] K. Aditya and S. S. Williamson, "Comparative study of Series-Series and Series-Parallel compensation topologies for electric vehicle charging," IEEE 23rd International Symposium on Industrial Electronics (ISIE), Istanbul, 2014, pp. 426-430.

[6] Sallan J., Villa J. L., Llombart A., ve Sanz J. F., “Optimal design of ICPT systems applied to electric vehicle battery charge,” in IEEE Trans. on Industrial Electronics, vol. 56, no. 6, pp. 2140-2149, June 2009.

[7] Wang C.S., Covic G. A., ve Stielau O. H., “General stability criterions for zero phase angle controlled loosely coupled inductive power transfer systems,” in Proc. IEEE Annual Conf. of the Industrial Electronics Society, Denver, CO, vol. 2, Nov. 2001, pp. 1049-1054.

[8] Wang C. S., Covic G. A., ve Stielau O. H., ‘‘Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems,’’ IEEE Transaction on Industrial Electronics, vol.51, no. 1, pp. 148–157, Feb. 2004.

[9] Society of Automotive Engineers SAE J1772-2001 electric vehicle conductive charge coupler[S] USA2001.

[10] Zhang Xian, Yang Qingxin, Cui Yulong, et al. “Design Optimization and Verification on the Power Transmitting Coil in the High-Power Wireless Power Transmission System,” Transactions of China Electrotechnical Society, vol. 28, Oct. 2013, pp. 12-18.

[11] Cove S R Ordonez M Shafiei N et al. Improving Wireless Power Transfer Efficiency Using Hollow Windings with Track-Width Ratio[J]. IEEE Transactions on Power Electronics, 2015.

[12] Meng W Jing F Yanyan S et al. Demagnetization Weakening and Magnetic Field Concentration with Ferrite Core Characterization for Efficient Wireless Power Transfer[J]. IEEE Transactions on Industrial Electronics, 2018,66(3):1842-1851.

[13] Ha-Van N, Seo C. Analytical and Experimental Investigations of Omnidirectional Wireless Power Transfer using a Cubic Transmitter[J]. IEEE Transactions on Industrial Electronics, 2017:1-1.

[14] M. Budhia, J.T. Boys, G.A. Covic and C.–Y. Huang, “Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems,” IEEE Transactions on Industrial Electronics, vol. 60. No. 1, pp. 318-328, January 2013, DOI: 10.1109/ IE.2011.2179274.

[15] S. Chopra and P. Bauer, “Driving range extension of EV with on road contactless power transfer – a case study,” IEEE Trans. Ind. Electron., vol. 60, no. 1, pp. 329–338, Jan. 2013, DOI: 10.1109/

TIE.2011.2182015.

[16] G.A. Covic and J.T. Boys, “Modern trends in inductive power transfer for transportation applications,” IEEE J. Emerging Sel. Topics Power Electron., vol. 1, no. 1, pp. 28–41, Mar. 2013, DOI:10.1109/JESTPE. 2013. 2264473.

[17] N.Y. Kim, K. Y. Kim, J. Choi, and C.-W. Kim, “Adaptive frequency with power-level tracking system for efficient magnetic resonance wireless power transfer,” Electronics Letters, vol. 48, no. 8, pp. 452454, April 2012.

[18] J.M. Miller, C.P. White, O.C. Onar, and P.M. Ryan, “Grid side regulation of wireless power charging for plug-in electric vehicles,” in Proc., IEEE Energy Conversion Congress and Exposition (ECCE’12), pp. 261-268, September 2012, Raleigh, NC, DOI:10.1109/ECCE.2012. 6342814.

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