Coil Parameter Analysis in Wireless Electric Vehicle Charging

KSHITIJ GHIMIRE
Master of Engineering
SRH Berlin University of Applied Sciences
Berlin
GERMANY

Abstract: - The hassle of using plug-in charging for electric vehicles (EVs) such as connecting charger to the port of vehicles, risk of getting electrocuted during rain, dirty and oily charging cable etc. can be eliminated using wireless/induction power transfer (IPT). It can be made smart and automated. Hence, IPT can be considered the future of EV charging. However, the technology is just emerging and there are a lot of limitations at present. The major problems are less efficiency caused by coil misalignment and air gap, and the electro-magnetic field generated around the coils which possesses greater risk for human health. These can be improved by selecting the types of coils and shields which produce maximum magnetic flux between the coils whereas reduce the flux outside the coils. In this research, the strength of magnetic fields produced by various types of coils (circular, square and hexagonal) were simulated in Ansys Maxwell 3D to understand their features and to know which coil is the best for high power transfer efficiency. Similarly, the effects of using ferrite and aluminum shields for leakage reduction, by varying their thickness, were studied. Finally, the leakage flux values were simulated at very high currents to understand their behavior in such conditions.

Key-Words: - electric vehicle (EV), induction power transfer (IPT), coupling coefficient (k), mutual inductance (M), magnetic flux density (B), leakage magnetic flux, airgap, coil misalignment.
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1 Introduction

For wireless charging of an EV, two coils are used at some air gap. The primary winding is positioned on the roadway which is connected to the public grid along with power electronics. The secondary winding is located within the car and is connected to the car's battery management system (BMS). When the charging process is started, the current flows through the primary coil, which creates a magnetic field around the coil because of which, current is induced in the secondary coil which recharges the battery in the vehicle. The working of wireless charging along with its parts are shown in the figure below:

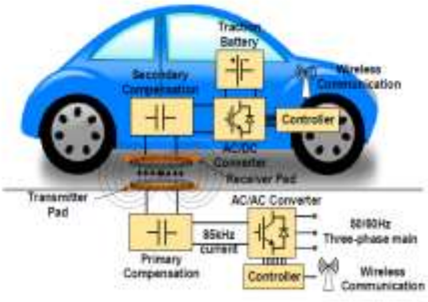


Fig. 1: Parts of a wireless EV charging system [1]

The charging process begins from the grid supply which can be from renewable or non-renewable sources. Since, the standard frequency for induction power transfer is 85kHz (recent standard) or 20kHz (old standard) [2], the supply of the grid must be converted before supplying it to the coils, which can be achieved by AC/AC frequency converter. It converts the frequency in two stages: first the input AC is converted to DC and again it is converted back to AC with high frequency using inverters.

After that, both the primary and secondary circuits need to be connected to compensating capacitors, so that the power transfer takes place at resonance, which ensures that the power is transferred with maximum efficiency at long air gaps. The compensating capacitors can be connected in various combinations of series and parallel to the primary and secondary circuits. Series-series is the simplest method and most used in EV charging. Various researchers have offered several other compensation topologies to combine beneficial aspects of the fundamental topologies because of the limitations and the load requirements of the basic ones. Researchers have even combined inductors in the compensation circuit to enhance the features [3].

The transmitting and receiving coils are kept in pad along with the shielding materials. The coils can be of various shapes, sizes and number of turns. Mostly the same shapes are used in both sides whereas the number of turns, and sizes can vary. Spiral coils are particularly of interest for electric vehicle charging applications because they can be made in a variety of shapes, both rectangular and circular windings, and because of their flexibility to optimize the coil shape [4]. Usually, the number of turns in transmitting sides are more than that in receiving sides because of the limitation of the space in vehicle chassis. The number of coils used can also be multiple which can increase the amount of power transfer since double power can be transferred using two sets of coils than when a single set of coils are used [5].

Now, the AC produced through secondary coils needs to be converted to DC to charge the battery by using full bridge rectifiers [2]. BMS monitors and protects the batteries by estimating its operational state and optimizing the performance.

The controllers, connected to both primary and secondary sides, perform the wireless communication between the vehicle and the charging station so that the charging process goes in a desired way smoothly. The information like charging requirements, power specifications, battery percentage etc. are transferred by the secondary controller to the primary controller, so that the primary side can act as required.

1.1 Efficiency

The mutual inductance (M) and the magnetic coupling coefficient (k), which vary with the air gap and misalignment between primary and secondary coils, are the main factors influencing the efficiency of the power transfer. When the coils are misaligned or the gap between the coils is increased, the value of M will decrease and consequently k will also decrease. This leads to higher leakage of the inductances of coils and hence lower system efficiency [3]. The “k” can be calculated by the following equation:

$k = M/(\sqrt{L1+L2})$ (1)

where L1 and L2 are the self-inductances of the primary and secondary coils respectively. Only the flux induced in the receiver pad, "ϕtarget," is useful for EV charging. The leakage flux, "ϕleak" causes k to fall and consequently decreases M. The equation for “k” in this case is:

$k = \phi\text{target}/ (\phi\text{target}+ \phi\text{leak})$ (2)

This equation shows, the more the flux induced in the receiving coil, the more is the value of k and hence more efficiency. So, the charging coils must be designed in such a way that maximum flux is induced in the receiving coils and the minimum amount of the flux is leaked. The values of ϕtarget and ϕleak can be varied by varying the shape, size, and number of coils, and by adding shields which in turns varies the values of k.

1.2 Safety

Since, very high magnetic flux is leaked during the charging process, the leakage should be controlled within the safety limit. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has published the following limitations guidelines for the safety underexposed electromagnetic field (EMF) for the frequency range of 3kHz to 10 MHz:

Type	Electric field strength E (V/m)	Magnetic field strength H (A/m)	Magnetic flux density B (μT)
General Public	83	21	27
Occupational	170	80	100

Table 1: ICNIRP safety guidelines for exposed EMF [6]

Since, very high current is used for EV charging, the generated flux is also very high which is beyond the safe limit set by ICNIRP. This presents one of the major problems of IPT charging which is the risk of human exposure to high EMF. Hence, it is crucial to install the shield under the transmitter and above the receiver to reduce the leakage flux. If the magnetic field produced is not properly shielded, the magnetic field may also interfere with the devices or other objects, induce battery heating, and circulate current in metallic components of the vehicle. Shielding can be accomplished in two ways: by diverting the magnetic flux using high-permeability materials such as ferrite and by creating an opposing flux using aluminum [4]. Ferrite offers a low reluctance alternate path to the leakage flux and diverts the flux to the targeted locations. Eddy current is induced on the aluminum shield because of the high-frequency magnetic field generated by the transmitter and receiver pad, which produces its own magnetic field in opposite direction to minimize and cancel the magnetic field leakage [7].

2 Problem Formulation

2.1 Literature review

Wireless power transfer was experimented to run a laptop where the power consumption was of 12 Watts. The distance between the coils was 70cm and the efficiency of 50% was achieved [8]. A wireless charger was designed in MATLAB/Simulink to simulate the power transfer to find out the values of self-inductance and mutual inductance between the pads. The efficiency of approximately 95% was obtained at an air gap of 25cm. It was also found that the values of k and M increased with the decrease in air gap and vice versa [9]. Various topologies of coils including circular, rectangular, double D, double D quadrature and bipolar pad were studied to know their features, advantages and limitations [10]. The effects of non-ferromagnetic metal shielding on power transfer efficiency were studied by simulation and experiment. Double layered metal shielding by mixing ferromagnetic and non-ferromagnetic metals was found to improve the system's efficiency significantly [11]. A series-to-series WPT compensation topology was designed using MATLAB/Simulink for bidirectional power transfer at 3.7kW and 7.7kW operating at 40kHz and 85kHz resonating frequency and it was successfully experimented in the lab as well [12]. A team of scientists from the Massachusetts Institute of Technology (MIT) revived Tesla's theories and experiments between 2007 and 2013 to wirelessly transmit 60 W over a 2-meter distance with a 40% efficiency utilizing coils with a diameter of 0.6 meter [13]. Depending on the application and requirements, several coil shapes can be used to transfer power at desired levels. The shape and size of the primary coils has no limitations; however, the size of the secondary coils should be as compact as possible because it is kept in a confined space in EVs. Coil structures of square, rectangular, hexagonal, and circular shape are basic and frequently utilized for IPT applications. The effects of the parameters of square coils on k was studied and compared with the effects of using ferrite cores with square coils. It was found that if optimum parameters are used in the design, the value of k can be increased which optimizes the wireless charging system by increasing the efficiency of power transfer [14]. The M and k decreased vastly with the increase in the air gap. When the gap was maintained between 50 to 100 mm, reasonably high efficiency was possible. In addition, increasing the number of turns in primary or secondary coils, while keeping other factors the same, a high coupling coefficient was achieved which also helped to increase the misalignment tolerance [15]. Two identical double D coils were used in both the transmitting and receiving sides to find out that each coil transmitted power independently and simultaneously. The magnetic field of the coils did not interfere with each other. With the use of such multiple coils, high power transfer can be achieved without the losses that occur in a single coil topology [5]. A prototype was designed to transfer 10W at 86kHz power using solar power independently without grid connection with 75% efficiency where the number of turns in primary and secondary coils were 22 and 10 respectively [16]. An inductive wireless charging station prototype was successfully experimented in Thailand, which could achieve an efficiency of 90% with the use of Litz wire (a type of wire that has several strands of thinner wires) in both transmitting and receiving coils [17]. Wireless power transfer was simulated using Ansys for various coil geometries to calculate their efficiency, coupling coefficient and mutual inductance. Spiral and square coils of 120mm were used at 1A current to analyze at what distance their effects are harmful to human exposure [18]. Aluminum plates with small mesh holes were used for shielding in which its effects were studied by simulating in Ansys to find out that by making such holes the materials cost can be optimized without creating any harmful effects. The design was found to have made the coupling coefficient better with maintaining the leakage flux reduction too [19].

2.2 Coils design

There has been sufficient research in the sector of finding the mutual induction and coupling coefficient between the coils of various parameters and the results obtained from the experiment were excellent. However, achieving excellent values of M and k does not mean all the gaps in the research are fulfilled. The next most important question is if all the designs proposed and experimented are safe for human exposure. There is not enough research and knowledge in the field of generation of leakage magnetic flux and their shielding. This paper serves to answer those questions in detail and helps to understand the effects of various shielding techniques with their varying parameters.

For the analysis, simulations were carried out in Ansys Maxwell 3D which utilizes finite element methods for the analysis. Three coil shapes circular, square and hexagonal were taken with the same parameters of cross section 1mm*1mm, start of helix at distance of 100mm from the centre, number of turns of 5 and the distance between the consecutive turns of 10mm. The values of B were simulated at 35mm, 70mm and 105mm from the upper coils without ferrite and aluminium, with ferrite only and with both ferrite and aluminium. For ferrite, the thickness of 2mm, 5mm and 7mm were used and for aluminium, thickness of 1mm, 2mm and 5mm were used to find the optimum thickness. The dimensions of the ferrite cores were taken as 320mm*320m, and they were kept at the distance of 6mm above and below the coils. The dimensions of aluminium were 360mm*360mm and were placed 1mm above and below the ferrite cores. Also, ferrite and aluminium with holes at the centre were used to compare the effects. All these simulations were performed with current of 10 amperes and 20 amperes. Finally, very high currents of 100A and 200A were used to understand the leakage flux generation in high current condition. The designs of the coil setup drawn in Ansys are shown in the figure below:

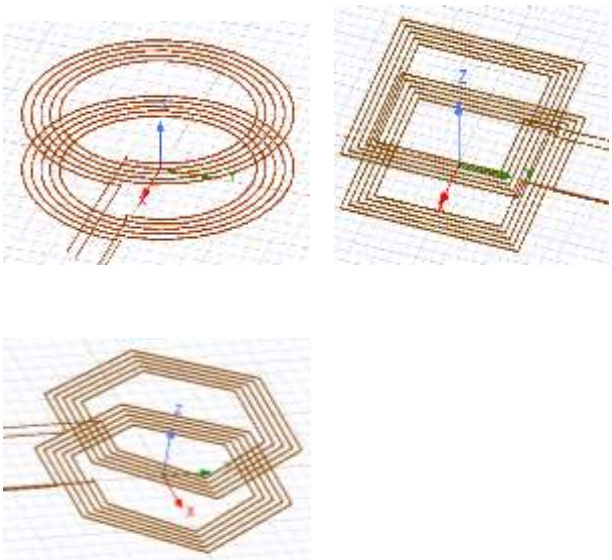
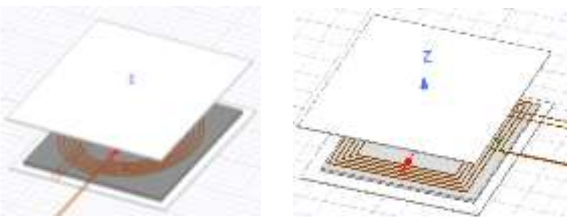


Fig. 2: Three basic types of coils (circular, square and hexagonal)



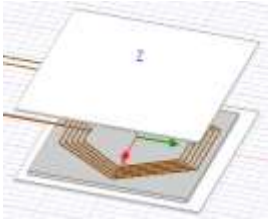


Fig. 3: Coils setup with ferrite and aluminum

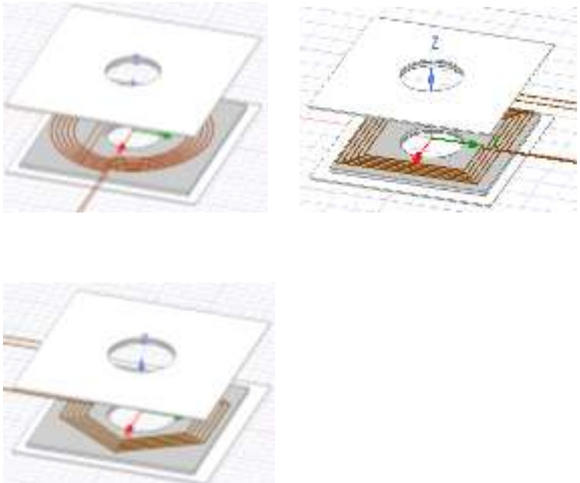
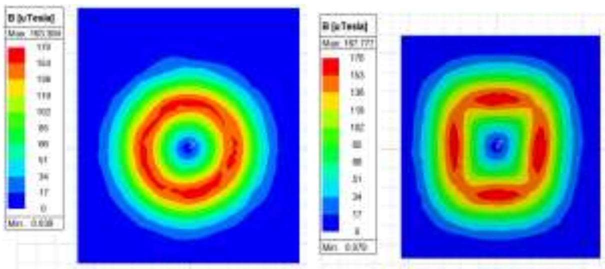


Fig. 4: Coils setup with holes in ferrite and aluminum

3 Problem Solution

Various plots were obtained by simulating the above coils setup with the current of 10A and 20A. The plots of B at 70mm from the upper coils, without using ferrite or aluminum, when 10A current was supplied are given in the figure below:



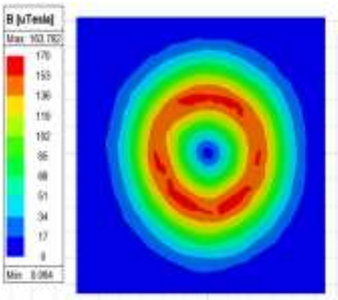


Fig. 5: Plots of B for circular, square and hexagonal coils respectively

3.1 Effects of ferrite

The maximum values of B at various distance with and without using ferrite for 10A current are given in the tables below:

Circular coils	Without Ferrite	Thickness of ferrite		
Distance of plot		2mm	5mm	7mm
35mm	384	78.4	73.2	71.8
70mm	163.4	26.23	21.09	20.8
105mm	88	12.4	10.7	10.5
Between the coils	431.4	653	701	713

Table 2: Maximum values of B for circular coils

Square coils	Without Ferrite	Thickness of ferrite		
Distance of plot		2mm	5mm	7mm
35mm	382	112.5	105.6	105.2
70mm	167.77	44.8	39.6	39.2
105mm	88	23.35	21.5	21.1
Between the coils	439,5	636	670	675

Table 3: Maximum values of B for square coils

Hexagonal coils	Without ferrite	Thickness of ferrite		
Distance of plot		2mm	5mm	7mm
35mm	384	82.12	76.2	75.8
70mm	163.78	30.4	26.07	24.7
105mm	90	14.5	13.3	13.1
Between the coils	398.5	662	683	685

Table 4: Maximum values of B for hexagonal coils

The values of B for various coils at various distances are shown in the above tables with various thickness of ferrite. The maximum value of B produced between the coils is the highest in square shaped coils with the value of 439µT. After that, the circular coils have the maximum value of 431.4µT. The hexagonal coils have the least value of B which is 398.5µT. Whereas, outside the coils at 35mm, 70mm and 105mm, the values of B are almost the same in all cases. After using ferrite, the leakage flux is best reduced outside the coils and the flux generated is best increased between the coils in case of circular coils. When the values of B were compared for various thickness of ferrite, we can see that from 2mm to 5mm there is significant improvement whereas from 5mm to 7mm there is only slight change. Hence, it can be concluded that 5mm is the optimum value of thickness for ferrite. Also, we can see that although use of ferrite has limited the flux significantly in circular and hexagonal coils, the reduction is the least in case of square coils.

3.2 Effects of Aluminum

The plots of B were obtained for the coil designs without and using various thickness of aluminum along with 5mm thick ferrite. The obtained data are given in the tables below:

Circular coils	Without Aluminum	Thickness of Aluminum		
Distance of plot		1mm	2mm	5mm
35mm	73.2	61.56	58.2	57.9
70mm	21.09	19.9	18.5	18.3
105mm	10.7	9.7	9.1	9

Table 5: Maximum values of B for circular coils

Square coils	Without Aluminum	Thickness of Aluminum		
Distance of plot		1mm	2mm	5mm
35mm	105.6	102.9	100.8	100.2
70mm	39.6	39.5	39.4	39.4
105mm	21.5	21.5	21.4	21.4

Table 6: Maximum values of B for square coils

Hexagonal coils	Without Aluminum	Thickness of Aluminum		
Distance of plot		1mm	2mm	5mm
35mm	76.2	70.8	65	64.7
70mm	26.07	25.2	23.5	22.8
105mm	13.3	12.9	12.5	12.1

Table 7: Maximum values of B for hexagonal coils

Aluminum was used with ferrite to study its effects. As we can see in the above table, aluminum helps to reduce the leakage further. Changing the thickness from 1mm to 2mm, we can see significant improvement whereas from 2mm to 5mm the change is not so significant. Hence, 2mm thickness is considered optimum. Also, we can see that in square coils, using aluminum does not have any significance as other coils which again proves this type is the hardest to limit leakage flux.

3.3 Effects at 20A current

Simulations were performed to see the effects at 20A current with 5mm ferrite and 2mm aluminum. The values obtained are given in the table below:

Types of coils	Distance of plot	only coils	coils with ferrite	coils with ferrite and aluminum
circular	35mm	733	146.5	116.4
	70mm	323	42.8	37.07
	105mm	176	21.46	19.35
square	35mm	763	211	201
	70mm	339	77	76
	105mm	176	43	42.8
hexagonal	35mm	742.6	152.5	129.8
	70mm	323	48.2	46.2
	105mm	180	26.6	25.2

Table 8: Maximum values of B at 20A current

When these values are compared with the values at 10A, these are approximately doubled in each case. This proves that B is directly proportional to the current supplied to the coils.

3.4 Effects of holes in ferrite and aluminum

The maximum values of leakage B without and with using holes in ferrite and aluminum at 10A current at various distances are given in the table below:

Types of coils	without hole		
	35mm	70mm	105mm
circular	58.2	18.5	9.1
square	100.8	39.4	21.4
hexagonal	65	23.5	12.5
	with hole		
	35mm	70mm	105mm
circular	61.8	20	10.5
square	103.5	40.6	22.2
hexagonal	65.4	24.8	13.6

Table 9: Maximum values of B without and with holes in ferrite and aluminum

Since, in all the plots of B, there was a zone of very weak flux at the center because of the space in the coils in the center, coil setups were designed with 100mm holes in ferrite and aluminum to observe their effects. The data in the above table show that with holes the leakage only increases slightly which are insignificant.

3.5 Effects at high current

The final set of simulations were performed with the supplied currents 100A and 200A, where both ferrite cores and aluminum shields were used with holes. The data obtained are shown in the table below:

100A	Types of coils		
distance	circular	square	hexagonal
300mm	9.984	21.12	16.052
500mm	1.727	2.919	3.745
700mm	0.414	0.801	1.234
200A	Types of coils		
distance	circular	square	hexagonal
300mm	19.458	42.424	32.126
500mm	3.554	3.015	7.438
700mm	0.826	1.624	2.385

Table 10: Maximum values of B at high current

The obtained values were compared to see if they are within the limit guidelines set by ICNIRP. The value of leakage B produced by circular coils is the lowest of all in the case of circular coils whereas the values are the highest in square coils. The values of hexagonal coils are in between circular and square coils. For 100A all the values are within the same limit set by ICNIRP which is 27μT whereas at 200A, only the leakage B generated by circular coils are within the limit.

4 Conclusion

Using ferrite and aluminum the leakage flux can be significantly reduced to limit it within the safe value. To find the dimension of ferrite and aluminum, the system can be simulated in Ansys to the zone of high flux at certain distance. The length and breadth should be decided based on the plot obtained. Ferrite should cover the zone of maximum B whereas aluminum can be taken slightly larger than ferrite which could be 20-25% bigger than ferrite so that the setup can limit the extra leakage which ferrite only cannot prevent. If the coils have space in the center, the ferrite cores and the aluminum shields also can be made with holes in the center without increasing any harmful effects of magnetic field. This can reduce the material required and hence minimize the cost. To find the dimension of the hole, simulations can be carried out to see the zone of very weak magnetic flux. In general, as seen in the simulated plots of B in various conditions in this research, the holes can be made with the dimension half of the space in the coils. With considering the safety factors, circular types of coils are the best among all. In case when square coils and hexagonal coils are used at high current, extra shielding must be used which can be thicker and bigger ferrite cores or aluminum shields. Similarly, if anyone must go near the coils, it is recommended to use shielding clothes. The conclusion about the types of coils as obtained from this research is given below:

	Types of Coils		
Features	Circular	Square	Hexagonal
Power Transfer Efficiency	high	highest	moderate
Field Distribution	uniform	non-uniform	uniform
Leakage Reduction by Shielding	highest	lowest	moderate
Field Strength	high	highest	moderate
Safety at High Current	highest	lowest	moderate

Table 11: Features of various types of coils

4.1 Future considerations

There are other complex types of coils which need to be researched well to find out their properties if those are better than simpler coils. Analysis can be done by varying the number of turns in the coils, cross-sectional area of the coils, air gap between the coils etc. for finding out the best option. Similarly, use of multiple coils in transmitting and receiving sides must be researched which can make the charging process faster. Composite materials must be studied if they match the required properties for less cost than ferrite. For better shielding at very high currents, powered shielding such as active and reactive shielding should be considered, in which the shields are powered such that it produces a magnetic field in opposite direction of the leakage flux which cancels out the leakage flux. The materials which can produce maximum shielding effects with minimum extra power must be found out. Similarly, the shielding effects of such shields can be controlled by varying its parameters such as voltage, current, frequency etc. to produce an exact amount of shielding effect. Future research must focus on the process and ideas to eliminate misalignment and air gap so that power transfer with high efficiency is possible. One of the ways to eliminate this problem is by making movable transmitting or receiving pad with the help of sensors and actuators, so that the coils align themselves to maintain proper alignment and air gap needed for power transfer with high efficiency.

References:

[1] Sarwat, A. I., Sundararajan, A., Parvez, I., Moghaddami, M., & Moghadasi, A. (2018). Towards a Smart City of Interdependent Critical Infrastructure Networks. In M. H. Amini, K. G. Boroojeni, S. S. Iyengar, P. M. Pardalos, F. Blaabjerg, & A. M. Madni (Eds.), Sustainable Interdependent Networks (Vol. 145, pp. 21–45). Springer International Publishing. https://doi.org/10.1007/978-3-319-74412-4_3

[2] Aydin, E., Aydemir, M. T., Aksoz, A., El Baghdadi, M., & Hegazy, O. (2022). Inductive Power Transfer for Electric Vehicle Charging Applications: A Comprehensive Review. Energies, 15 (14), 4962. https://doi.org/10.3390/en15144962

[3] Al-Saadi, M., Al-Omari, A., Al-Chlaihawi, S., & Al-Gizi, A. (2018). Inductive Power Transfer for Charging the Electric Vehicle Batteries. 11.

[4] Naik Mude, K. (2015). Wireless Power Transfer for Electric Vehicle. https://www.research.unipd.it/retrieve/e14fb26f-a1e5-3de1-e053-1705fe0ac030/Kishore_Mude_Thesis.pdf

[5] Prosen, N., Domajnko, J., & Milanovič, M. (2021). Wireless Power Transfer Using Double DD Coils. Electronics, 10(20), 2528. https://doi.org/10.3390/electronics10202528

[6] GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC AND MAGNETIC FIELDS (1 Hz TO 100 kHz). (2010). Health Physics, 99(6), 818–836. https://doi.org/10.1097/HP.0b013e3181f06c86

[7] Asa, E., Mohammad, M., Onar, O. C., Pries, J., Galigekere, V., & Su, G.-J. (2020). Review of Safety and Exposure Limits of Electromagnetic Fields (EMF) in Wireless Electric Vehicle Charging (WEVC) Applications. 2020 IEEE Transportation Electrification Conference & Expo (ITEC), 17–24. https://doi.org/10.1109/ITEC48692.2020.9161597

[8] Sample, A. P., Meyer, D. A., & Smith, J. R. (2011). Analysis, Experimental Results, and Range Adaptation of Magnetically Coupled Resonators for Wireless Power Transfer. IEEE Transactions on Industrial Electronics, 58(2), 544–554. https://doi.org/10.1109/TIE.2010.2046002

[9] Ruhul Amin, Md., & Roy, R. B. (2014). Design and simulation of wireless stationary charging system for hybrid electric vehicle using inductive power pad in parking garage. The 8th International Conference on Software, Knowledge, Information Management and Applications (SKIMA 2014), 1–5. https://doi.org/10.1109/SKIMA.2014.7083516

[10] Liu, C., Jiang, C., & Qiu, C. (2017). Overview of coil designs for wireless charging of electric vehicle. 2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), 1–6. https://doi.org/10.1109/WoW.2017.7959389

[11] Li, J., Huang, X., Chen, C., Tan, L., Wang, W., & Guo, J. (2017). Effect of metal shielding on a wireless power transfer system. AIP Advances, 7(5), 056675. https://doi.org/10.1063/1.4978463

[12] Yang, Y., El Baghdadi, M., Lan, Y., Benomar, Y., Van Mierlo, J., & Hegazy, O. (2018). Design Methodology, Modeling, and Comparative Study of Wireless Power Transfer Systems for Electric Vehicles. Energies, 11(7), 1716. https://doi.org/10.3390/en11071716

[13] Mohamed, A. A. S., Shaier, A. A., Metwally, H., & Selem, S. I. (2020). A comprehensive overview of inductive pad in electric vehicles stationary charging. Applied Energy, 262, 114584. https://doi.org/10.1016/j.apenergy.2020.114584

[14] Yang, Y., Cui, J., & Cui, X. (2020). Design and Analysis of Magnetic Coils for Optimizing the Coupling Coefficient in an Electric Vehicle Wireless Power Transfer System. Energies, 13(16), 4143. https://doi.org/10.3390/en13164143

[15] Bouanou, T., El Fadil, H., Lassioui, A., Assaddiki, O., & Njili, S. (2021). Analysis of Coil Parameters and Comparison of Circular, Rectangular, and Hexagonal Coils Used in WPT System for Electric Vehicle Charging. World Electric Vehicle Journal, 12(1), 45. https://doi.org/10.3390/wevj12010045

[16] ÇiÇek, M., Gençtürk, M., Balci, S., & Sabanci, K. (2021). The Modelling, Simulation, and Implementation of Wireless Power Transfer for an Electric Vehicle Charging Station. Turkish Journal of Engineering. https://doi.org/10.31127/tuje.930933

[17] Thongpron, J., Tammawan, W., Somsak, T., Tippachon, W., Oranpiroj, K., Chaidee, E., & Namin, A. (2022). 10 kW Inductive Wireless Power Transfer Prototype for EV Charging in Thailand. ECTI Transactions on Electrical Engineering, Electronics, and Communications, 20(1), 83–95. https://doi.org/10.37936/ecti-eec.2022201.246108

[18] El-Shahat, A., Danjuma, J., Abdelaziz, A. Y., & Abdel Aleem, S. H. E. (2022). Human Exposure Influence Analysis for Wireless Electric Vehicle Battery Charging. Clean Technologies, 4(3), 785–805. https://doi.org/10.3390/cleantechnol4030048
[19] Wang, K., Zuo, Z., Sang, L., & Zhu, X. (2022). Comprehensive Analysis for Electromagnetic Shielding Method Based on Mesh Aluminium Plate for Electric Vehicle Wireless Charging Systems. Energies, 15(4), 1546. https://doi.org/10.3390/en15041546

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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