Journal of Engg. Research Vol. 11 No 3 pp.100-111 DOI:10.36909/jer.17631

Analysis of the Model Designed for Magnetic Resonance Based Wireless Power Transfer Using FEM

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Submitted : 03-03-2022

Revised : 05-09-2022

Accepted : 22-09-2022

ABSTRACT

Wireless Power Transfer (WPT) applications have been used to provide an efficient energy transfer. With the developing technology, WPT has started to be applied in many areas such as mobile phone charging, electric vehicle charging, lighting and control. The magnetic resonance method is highly preferred for WPT, especially at distances where the air gap is short, due to its features such as high efficiency and little negative impact on the environment. In WPT systems based on this method, a high-efficiency WPT transformer is used to increase system efficiency. In this study, the design and analysis of a WPT system was carried out using the magnetic resonance method. For this purpose, first of all, an original transformer was designed. The windings of the transformer are designed as litz conductors. In order to minimize the leakage fluxes that occur in the transformer, aluminum plates are used on the outer surfaces of the windings to keep the leakage magnetic flux between the windings. Magnetic analyzes of the transformer, modeled with ANSYS-Maxwell based on Finite Element Method (FEM), were carried out and the results obtained were verified with theoretical calculations. Using the results obtained from the magnetic field analysis, it has been seen that the WPT transformer performs power transfer with an efficiency of 95%. The results show that the designed transformer model can be used efficiently in WPT applications.

Keywords: AC Reactor; Wireless Power Transfer; Magnetic Resonance; Transformer; FEM.

INTRODUCTION

Frequency The use of electrical energy for different purposes in daily life has revealed the need for Wireless Power Transfer (WPT). Although WPT eliminates the disadvantages such as cable clutter caused by the increasing number of electrical devices, it also finds application areas for mobile phone charging and electric vehicle charging, which have become popular in recent years (**Shin J., at all, 2013**). The idea of WPT, whose foundations were laid by Nikola Tesla in the 19th century, constitutes the basis of these studies (**Takanashi H. and at all. 2012**). WPT is done by radiative and non-radiative methods. Magnetic resonance (MR) method from non-radiative methods; It attracts a lot of attention among researchers because it does not harm human health and has high efficiency. In a study, a 60 W lamp at a distance of 2 m was energized with an efficiency of around 40% using the MR coupling method **(Kurs at all., 2007).** At first, WPT applications were carried out at low power levels, but in recent years, applications that can reach 7-10 kW power levels at different transmission distances and have efficiency values between 80-95% have been observed (**Cederlöf M. 2012**).

MR coupled WPT systems consists of supply circuit, transformer circuit and load circuit. Transformer circuit includes transceiver coils and core structure. In this system, the resonance of the coils, the magnetic circuit (core) and the supply frequency of the transmitting coil play an important role in ensuring maximum energy transfer.

The operation of MR coupled WPT systems in resonance is important for efficiency **(Kurs at all., 2007).** Resonance proportionally increases the power transfer between source and load in WPT systems and thus increases system efficiency. However, in the realization of MR; the receiver and transmitter coils must be aligned, if the alignment cannot be achieved, the values of the resonant capacitors must be updated according to the new situation. In WPT systems, feeding the transmitter side with a source with a very high frequency compared to the network frequency is another factor that increases the system efficiency. For this reason, this situation should be taken into account in the design and feeding of the transfer coils.

One of the most important points affecting efficiency in WPT systems is to use transformers with low loss coupling. In a transformer, electrical energy transfer takes place by magnetic energy coupling between the primary and secondary coils. For an efficient transfer, maximum magnetic flux transfer should be provided between these coils. In WPT systems with air core transformers, the magnetic circuit is completely completed over air. This structure is preferred for energy transfer over long distances. Hybrid structures (air-magnetic core) are preferred for short-range energy transfers (**Ludvik S, at all. ,2015)**. The use of magnetic cores causes high core losses, especially in transformers operating at high frequencies. This is an important problem that negatively affects efficiency in WPT systems operating at high frequencies. In these systems, core geometries are modified to minimize core losses. In the studies, the use of segmented magnetic core structures, magnetic core structures taking into account the coil geometry, and flux-directed magnetic core structures have been studied by different researchers (**Fincan B and Üstün Ö 2015)**.

In this study, mobile phone charging, electric vehicle charging etc. In this paper, it is aimed to design a high efficiency WPT system based on 10 cm air gap MR that can be used in power transfer applications. For this purpose, a WPT transformer was designed to minimize core losses. The designed transformer was used for the first time in the literature in this study. Magnetic analyzes of the designed transformer were made using Finite Element Method (FEM) using ANSYS-Maxwell and the system efficiency was calculated and verified.

MATERIALS AND METHODS

Due WPT systems; supply circuit, transformer WPT systems; It consists of 3 main components: supply circuit, transformer and load system. Figure 1 shows the block diagram of a basic WPT system.

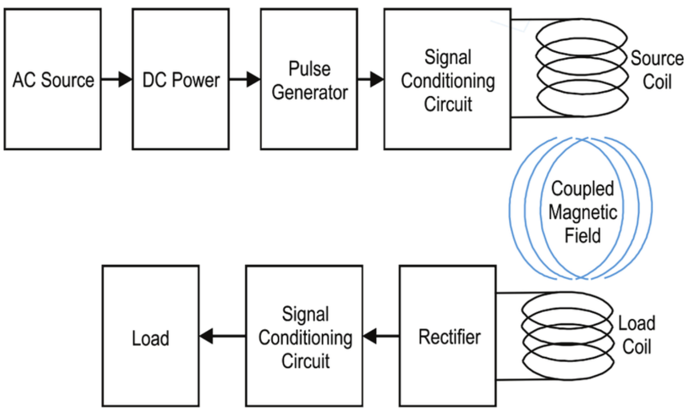


Figure 1. Shows the block diagram of a basic WPT system

The supply circuit is the section where the transformer input voltage is conditioned. The electrical energy transferred from the primary side to the secondary side in a transformer depends on the frequency of the supply source, the magnetic core structure and the number of primary and secondary circuit windings. While maximum flux transition can be achieved at low frequency levels in iron core transformers, the same process can be performed with high frequency in air core and hybrid core transformer structures. Therefore, in industrial applications of WPT systems, the supply circuit is in the structure of a high frequency inverter (HFI). In WPT system transformers, mostly spiral circular geometric structures are preferred for transmit coil (Tx) and receive coil (Rx) (**Tezcan Y,.at all. 2016)**. Figure 2 shows the geometry of the spiral circular coil.

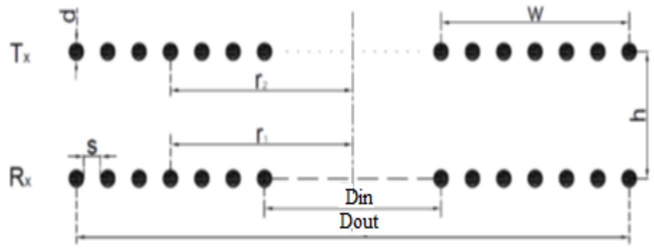


Figure 2. The geometry of the spiral circular coil.

Coils show self-inductance values according to the geometric structure and magnetic environments in which they are formed. Although various methods are used in the self-inductance calculation of the coils, the Wheeler method is one of the most preferred methods because it can be used in the inductance calculations of both single-layer and multi-layer coils and has a low margin of error. The self-inductance of a spiral circular coil made of solid round wire is calculated according to Wheeler's method as follows.

$$L = \frac{31.33\mu_0 N^2 r^2}{8r+11\omega} \quad ...(1)$$

Where, N is the number of turns of the coil, r is the average radius of the coil, w is the thickness of the coil. In the calculation of the common inductance of the coils, Neumann's formula is an accepted formula. The common inductance calculation of circular spiral coils is solved by numerical analysis approaches (**Sample A-P,. at all .2010**). According to these approaches, the common inductance M of the circular spiral coils is expressed by equation (2).

$$\mathrm{M} = \frac{\mu_0 N_1 N_2}{4\pi\pi} \iint \frac{r_1 r_2 \cos(\varphi-\varphi')d\varphi\varphi'}{\sqrt{r_1^2+r_2^2+h^2-2r_1r_2\cos(\varphi-\varphi')}} \quad ...(2)$$

Where, $r_1$and r_2 mean radii of the transmit and receive coils, the number of turns are N_1 and N_2. h is the distance between the coils. The expressions in Equation (1) and Equation (2) are valid for air core coils. If a magnetic core is used, the equation μ=$\mu_0\mu_r$ should be used instead of μ_0 for the magnetic permeability of the gap in the equations. In this equation, μr is the magnetic permeability of the material.

The self-inductance and common inductance of the receiver and transmitter coils cause a certain phase shift with respect to the input signal. In order to eliminate this phase shift, capacitors are connected to the circuit and the system is put into resonance. In WPT systems, resonance is an important parameter that plays a key role on efficiency (**Doğan Z**. **at all. 2019**). In a circuit with inductance L and capacitance C, the resonance frequency can be calculated by the expression in Equation (3).

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad ...(3)$$

In these systems, circuit topologies are named Series-Serial topology (SS), Serial-Parallel topology, Parallel-Serial topology, and Parallel-Parallel topology according to the connection of the capacitors that will provide the resonance operation to the circuit **(Navid R. at all., 2022; Feng L. at all., 2022)**.

In the SS topology, the emitter side acts as a current source and tends to give a constant output current. Moreover, the SS topology has a higher efficiency than other topologies over a wide range of load resistances. Because of these advantages, the SS topology seen in Figure 3 is frequently used.

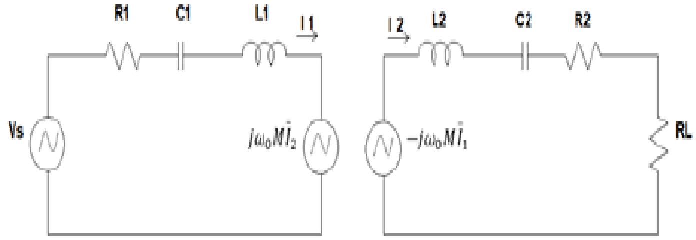


Figure 3. Serial-to-serial topology [16]

This circuit is powered by a high frequency AC voltage source (V_s). In the circuit, R_1, L_1, C_1 show the equivalent ohmic resistance, inductance and capacitance value of the donor side, respectively. R_2, L_2, C_2, R_L represent the equivalent ohmic resistance inductance, capacitance value and load resistance of the receiving side, respectively. In this circuit, the voltage equations of the receiver and transmitter side can be written as given in Equation (4).

$$\begin{cases} \bar{V}_s = \dot{Z}_1\bar{I}_1 + j\omega_0 M\bar{I}_2 \\ -j\omega_0 M\bar{I}_1 = \dot{Z}_2\bar{I}_2 \end{cases} \quad ...(4)$$

Where $\dot{Z}_1$ and $\dot{Z}_2$are the equivalent impedances of the transmit and receiving side, respectively, and the angular frequency at the resonant frequency ω_0. The currents flowing from the transmitter and receiver coils are given in Equations (5-6).

$$\bar{I}_1 = \frac{\dot{Z}_2}{\dot{Z}_1\dot{Z}_2+\omega_0^2 M^2}\bar{V}_s \quad ...(5)$$

$$\bar{I}_2 = -\frac{j\omega M}{\dot{Z}_1\dot{Z}_2+\omega_0^2 M^2}\bar{V}_s \quad ...(6)$$

The values of the circuit resonant capacitors are as in Equations (7) and (8).

$$C_1 = \frac{1}{\omega_0^2 L_1} \quad ...(7)$$

$$C_2 = \frac{1}{\omega_0^2 L_2} \quad ...(8)$$

In case of resonance, the total efficiency of the whole system including the load and the source η can be given as in Equation (9).

$$\eta = \frac{\omega_0^2 M^2 R_L}{(R_R+R_L)^2 R_S + M^2\omega_0^2(R_R+R_L)} \quad ...(9)$$

Where, the resistance R_S is the source and switching circuit equivalent resistance. The common inductance value between the coils can be calculated with the connection factor (k), which is one of the most important parameters for WPT. In order to maximize the power transferred from the primary to the secondary, the coupling factor should be as close to 1 as possible. The formula in Equation (10) is used to calculate the coupling factor of concentric coils.

$$\mathrm{k} = \frac{\mathrm{M}}{\sqrt{\mathrm{L_1 L_2}}} \quad ...(10)$$

The choice of magnetic core material in transformers is important in terms of coupling. While iron cores are used in conventional transformers ferrite cores are preferred since high-frequency operations are in question in WPT systems. In WPT, the distribution of the magnetic flux between the transmitting and receiving coils and not escaping to an area other than this area is also an important condition that affects the efficiency. In order to prevent stray fluxes, supporting the outer surface of the ferrite core with aluminum will increase the system efficiency.

Design of WPT System with Ansys-Maxwell

In this paper, while creating the WPT system, first of all, transformer design was made. Then, a simulation circuit was designed to obtain the electrical data of the transformer, which was created by putting forward a unique core structure.

Designed WPT Transformer

The most important part of MR-based WPT system designs is transformer design. The main goal in these designs is to make high efficiency transformers. The WPT transformer structure designed in this study consists of transmitter and receiver coils, magnetic core and aluminum sheets. WPT transformer design was made in 3D with ANSYS Maxwell based on FEM. The cross-sectional view of the realized design is shown in Figure 4. The dimensions of the WPT transformer are given in Figure 5, and the properties of the materials used in the design of the transformer are given in Table 1.

Table 1. The properties of the materials used in the design of the WPT transformer.

Magnetic Core	**Winding Coil**	**Shield Plate**
Material: Forced Ferrite Core (B_s =0.53T, μ_i=2400)	Litz wire : 0.25φ×384 parallel turns	Aluminum
	Conductivity : 5.8x10^7[S/m]	
	Primary : 10 turns	
	Secondary : 5 turns	

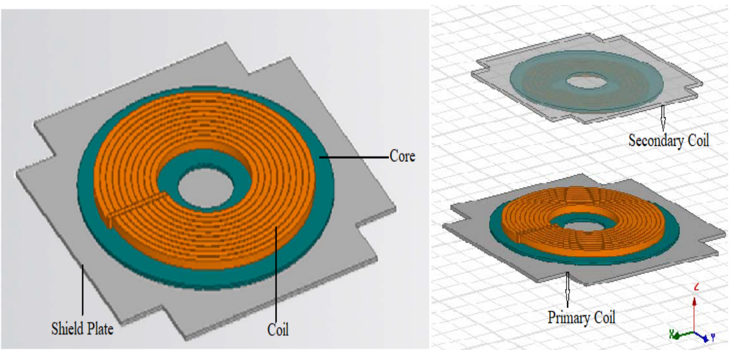


Figure 4. The designed WPT transformer

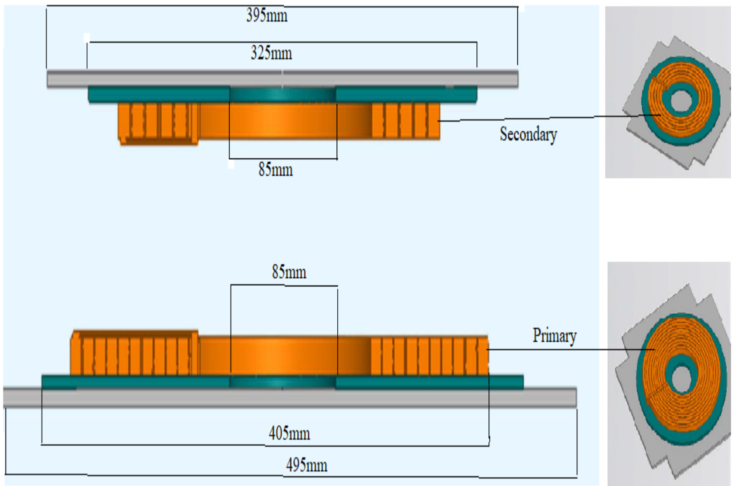


Figure 5. Dimensions of the WPT transformer.

In this transformer, the transmit and receive coils are identical. In coils operating at high frequency, losses occur due to the skin effect. To eliminate this effect, the coil wires are made multi-core. However, in a multi-core wire, magnetic fluxes generated by the current passing through the wires placed side by side in parallel with each other create another loss in the wire called the proximity effect. Multi-core wires are twisted to eliminate the proximity effect. In the WPT transformer designed in this study, multi-core twisted litz wire was used in order to prevent the high-frequency skin and proximity effects of the coils. In order to obtain high efficiency in transformers, it is imperative to provide a lossless magnetic coupling between the transmit and receive coils. In transformers used in industry, almost lossless magnetic flux transitions can be obtained by winding the transceiver coils on a single iron core. In WPT transformers, on the other hand, it is not possible to use the receiving and transmitting coils on a single core. For this reason, air and split core are used together in WPT transformers designed for short distances. Circular, circular-bar, square, rectangular, T-core, U-core, E-core, Double-U, and bar-core structures used in previous studies are shown in Figure 6. Different fragmented core structures have been used in studies carried out so far.

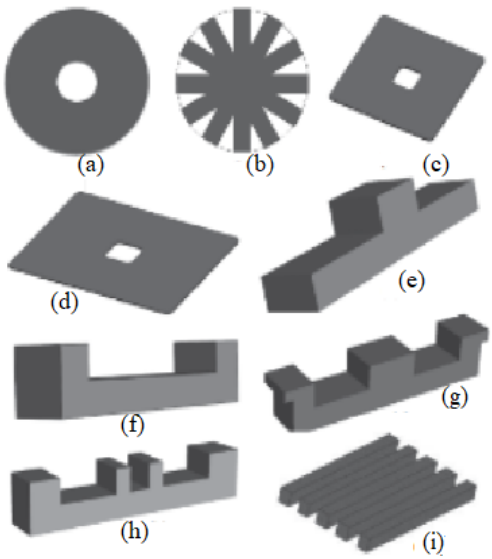


Figure 6. (a) Circular, (b) Circular-Bar, (c) Square, (d) Rectangle, (e) T- Core, (f) U- Core, (g) E-Core, (h) Double U, (i) Bar.

In the modeled transformer, it is aimed to make the magnetic flux directing correctly by keeping the magnetic flux path between the transmitter and receiver coils as much as possible. Ferrite material is used in the core of the transformer due to its high frequency operation compatibility. In the WPT transformer design, an aluminum plate is placed on the outer surfaces of the core for the coil in order to reduce the losses by minimizing the leakage flux. Thus, the flux was forced to stay in the region between the coils.

WPT Circuit

WPT circuit was created by using the designed WPT transformer model in a circuit with SS topology in ANSYS Simplorer environment. In this circuit shown in Figure 7, a WPT transformer is fed from a sinusoidal source and power is transferred onto a constant R_L load.

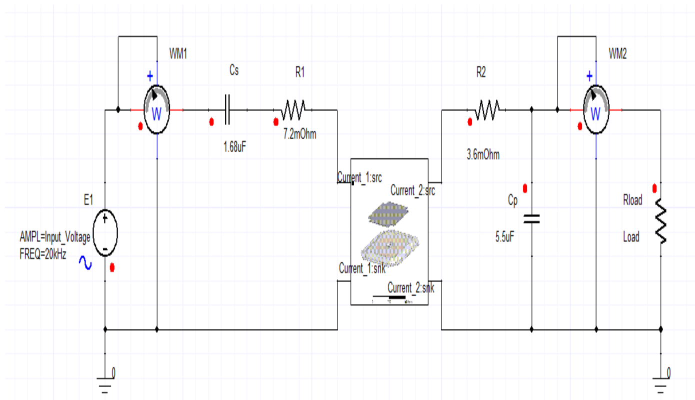


Figure 7. Sinusoidal source fed WPT system with constant load

The purpose of this circuit is to determine the maximum efficiency of the WPT transformer in the ideal supply condition. In this circuit, there is an ideal operating situation as the load is stable and the supply source is a sinusoidal source with a constant 400 V voltage and a frequency of 20 kHz. These ideal operating conditions are important for calculating the rated values and efficiency of the designed transformer system. The value of the R_L load in the circuit was calculated as 10.2 Ω by using the Genetic Algorithm optimization method in ANSYS Maxwell, taking into account the maximum power transfer.

RESULTS AND DISCUSSION

In this paper, inductance, common inductance, coupling factor values as well as resistance value of each coil, core and winding losses were obtained from the magnetic analyzes based on FEM of a low loss coupling transformer proposed in this study. In magnetic analysis, 3D model analyzes of the WPT system were made. Then, using these analysis results in the simulation circuits in Figure 6, the WPT system efficiency was calculated. Tetrahedron mesh structure was used in 3D magnetic analysis based on FEM in ANSYS Maxwell. This structure gives reliable results especially in three-dimensional magnetic field calculations.

Magnetic Analysis Results

In these analyzes, 3D FEM analyzes were performed at the resonant frequency of the designed WPT transformer. The distribution of magnetic flux density (B) in air obtained from these analyzes is given in Figure 8.

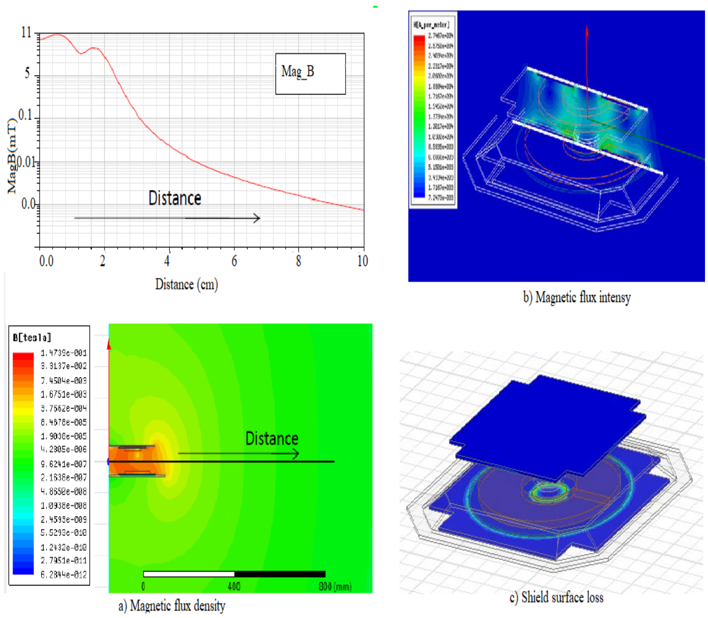


Figure 8. B distributions of the transformer in air: (a) 3D model B scalar distribution (b) Magnetic flux intensy (c) Surface loss

These plates placed at the top and bottom of the coils have been successful in directing the magnetic flux. In the lateral regions, B is low, and leakage fluxes are seen to exist, albeit slightly. Figure 9 shows the B distributions on the cores.

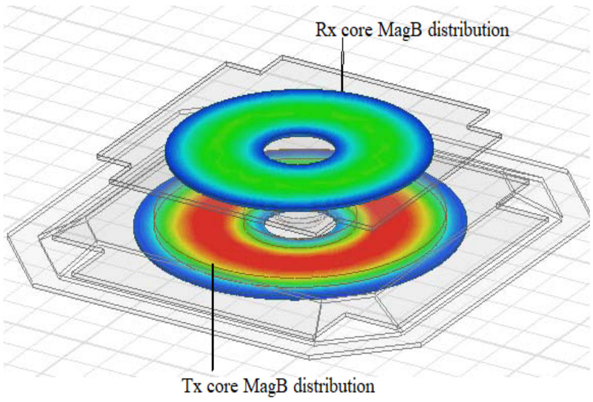


Figure 9. B distributions on cores (a) Tx core B distribution

(b) Rx core B distribution

At the resonance frequency, the results obtained from the 3D magnetic analyzes and the results obtained from the analytical calculations are given in Table 2. As can be seen from Table 2, analytical results and simulation results are approximately in agreement. The coupling factor is 0.56 for the designed core, which is a good value for such cores.

Table 2. Inductance value and k factor at resonant frequency

	Ansys-Maxwell Conclusion	**Theoretical Conclusion**
LTx (μH)	50.485	51
LRx (μH)	12.891	13
k	0.5621	0.56

Circuit Analysis Results

In the analysis of the WPT circuit, the circuit shown in Figure 6 was simulated. These analyzes are obtained by running the magnetic analysis results by embedding them in the simulation circuit. As a result of the analysis, the current, voltage and power results of the circuit were obtained. Figure 10 shows the currents graphs of the transmitter-receiver sides. A current of 39.2 A is drawn from the transmitter side from a 400 V sinusoidal supply-source with a frequency of 20 kHz.

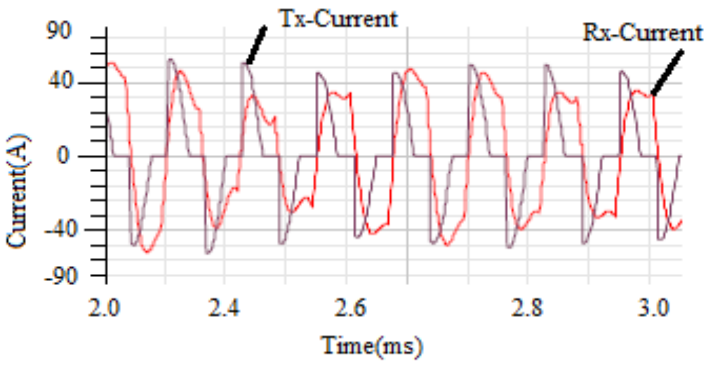


Figure 10. Transmitter-Receiver current graphs

Figure 11 shows the voltages graphs of the transmitter-receiver sides. The voltage transferred to the receiver side of the system is a sinusoidal voltage of 390 V. 10.2 Ω R_L load drew 39.2 A current.

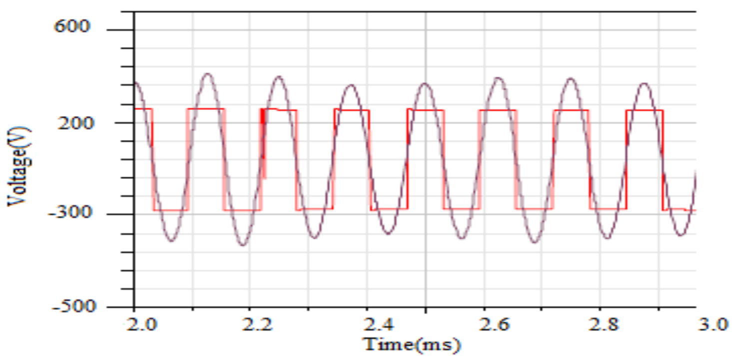
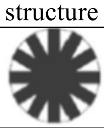


Figure 11. Transmitter-Receiver voltage graphs

The absence of phase differences between the current and voltage of the receiving and transmitting sides and the fact that the powers do not take negative values confirm that the system is in resonance. In terms of a general evaluation, the methods used in the studies on the WPT system of the model proposed in this study and the WPT systems in the literature with different geometries and core structures and the yield results are given in Table 3. The WPT system with 20 kHz resonance frequency Series-Series circuit structure proposed in this study, on the other hand, performed power transfer from a sinusoidal source to a constant load with 95% efficiency in the 10 cm air gap.

Table 3. Comparison of the results of the WPT system according to the studies in the literature and the core structure

Core Shape				
WPT Method	MR	MR	MR	MR

System Efficiency	95 %	90 % (**Wu H-H at all. 2012)**	90 % (**Takanashi H. at all. 2012)**	80 % (**Shin J. at all. 2013)**
Air-Gap	10 cm	26.5 cm	20 cm	26 cm
Resonant Frequency	20 kHz	20 kHz	50 kHz	20 kHz

Experimental Analysis

In this part of the study, the experimental analysis of the WPT transformer, which was designed using Ansys-Maxwell, which realized a solution based on the finite element method, was carried out. The experimental set and the materials used are given in Figure 12.

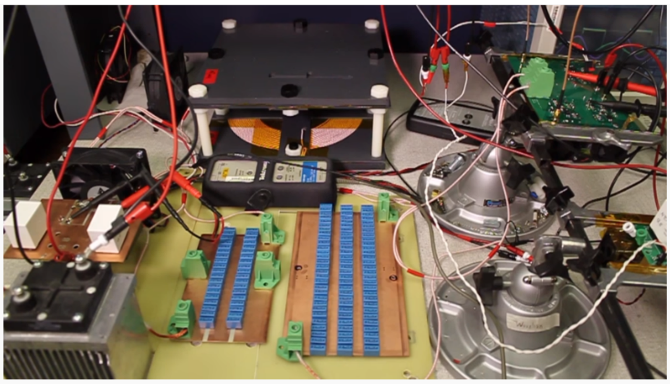


Figure 12. Experimental analysis elements.

Experimental analysis was done by energizing a rectifier-powered DC-DC converter. The output of the full-bridge converter energizes the primary coil of the transformer. The output of the smaller diameter secondary coil of the transformer is used to feed the bridge rectifier. The experimental results obtained were compared with the simulation results and presented in Table 4. The results show that there is sufficient supply voltage when using a larger coil as the primary. It has been observed that the amount of energy transferred decreases as the distance between the coils of the designed WPT transformer increases. At the same time, it was seen how good the efficiency of the designed core was.

Table 4. Comparison of the results of experimental and simulation

	Simulation (FEM) Results	**Experimental Results**
System Efficiency (η)	95 %	94.3%

This study was carried out jointly for a vehicle manufacturing factory. The desired data were analyzed theoretically, simulation and experimentally and the results were obtained.

CONCLUSION

In this paper, mobile phone charging, electric vehicle charging etc. In order to be used in short distance power transfer applications, a 10 cm air gap magnetic resonance coupling WPT system has been designed. First of all, a unique WPT transformer with low loss coupling was designed. The coil structure of the transformer is made of copper litz wire to prevent high frequency skin and proximity effects. Ferrite material is used in the magnetic core structure of the transformer, and the air core between the receiver and transmitter coils is 10 cm long. In order to prevent leakage fluxes in the transformer, the magnetic flux is forced to stay between the windings, thereby minimizing energy losses. The results of the magnetic analysis of the transformer with FEM were verified by calculating numerically. The designed WPT transformer has been tested with the SS resonance topology with the help of a simulation circuit. In this circuit, in order to determine the maximum efficiency of the transformer under ideal conditions, a transformer is fed from a sinusoidal source with a frequency of 20 kHz, and power transfer is realized on a constant ohmic (R_L) load with an efficiency of 95 %. When this yield value is compared with the studies in the literature, it has been seen that it is an important result. These results showed that the proposed WPT transformer can be used successfully in applications. It has also been observed that the experimental results obtained are compatible with the simulation results.

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