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Wireless power transfer systems and wireless charging design between electric vehicles

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ABSTRACT

The fundamentals of wireless power transmission began with Nikola Tesla, who used a Tesla coil to transmit energy wirelessly. These studies have paved the way for today's wireless power transmission technologies. In recent years, wireless power transmission has also garnered attention from phone companies and is now being considered for use in electric vehicles. One of the main reasons lithium-ion batteries are preferred in electric vehicles is the ease of charging. These batteries provide longer range compared to other types of batteries due to their high energy density, meaning they can store more energy relative to their size. Additionally, their faster charging capabilities are a major advantage for electric vehicle owners. As a result, charging technology is of great importance for electric vehicles. In this study, a design is presented that allows electric vehicles, which are becoming more common in daily life due to advancing technology, to wirelessly transfer charge to each other in emergency situations. In the design, the receiving coil is placed in the front hood of the vehicle, and the transmitting coil is placed in the rear hood, with the model being configured accordingly. The design also allows the location of the transmitting coil to be adjusted via distance sensors. When electric vehicles reach the optimum distance, the distance sensor gives an alert, allowing enough charge to be transferred for the vehicle to reach the nearest charging station. Additionally, the system can be designed to allow emergency vehicles (such as ambulances) to quickly receive energy from another vehicle in emergencies, due to the ease of sharing provided by the system. This system reduces the towing costs of electric and hybrid vehicles and offers drivers uninterrupted driving. Furthermore, the system provides numerous advantages such as eliminating cable clutter, offering ease of use, compatibility with all devices, multi-charging capability, and durability.

Keywords: Electric cars, wireless charging, transportation

INTRODUCTION

In recent years, the climate crisis and global warming have made the search for sustainable solutions even more critical. In response to the air pollution caused by fossil fuels, the importance of sustainable transportation has been steadily increasing. Under current conditions, electric vehicles have become one of the key components of transportation. Compared to internal combustion engine vehicles, electric cars offer an environmentally friendly and cost-effective energy alternative with a zero-emission principle. Based on the prediction that these electric vehicles will replace internal combustion engine vehicles worldwide and eventually dominate the market, the idea for this study emerged. In recent years, Turkiye has made remarkable strides, even envied globally, with the introduction of 100% electric TOGG vehicles and the establishment of a mass production facility in Gebze. Along with the production of 100% electric domestic and national vehicles, it is anticipated that vehicles with internal combustion engines currently in use will gradually be phased out. In other words, users purchasing a brand-new electric vehicle will likely put their internal combustion engine cars up for sale (İpek, 2022). This indicates a major transformation, where the demand for electric vehicle charging stations is growing daily. However, the significant increase in the number of electric vehicles charging stations may still not be sufficient, as users will need to charge their vehicles at the end of long trips. Currently, limiting factors for the widespread adoption of electric vehicles include parameters such as ion structures, anion/cation material structures, normal charging times, and fast-charging deformations. Despite these challenges, the number of electric vehicles is rapidly increasing, and these issues are being addressed through new technologies. One of the alternative methods proposed to address the issues of battery charging times or fast-charging problems is improving charging infrastructures. In this study, a different model for charging infrastructure has been developed, exploring the possibility of wireless charging between vehicles. Relevant studies in literature have been examined.

Literature Review

Contactless electric vehicle charging systems are a research area that has attracted great attention in recent years to meet the energy needs of electric vehicles. These systems allow vehicles to be charged wirelessly while in motion or parked. Wireless charging, especially while on the move, can solve the range problem of vehicles and reduce dependence on charging stations by continuously transferring energy along the road. Most of the work in this field is based on inductive power transfer (IPT) technology. IPT provides energy transfer from the primary coil to the secondary coil via a magnetic field. In vehicle charging systems, this technology is used between a series of primary coils (transmitter) placed under the road and a secondary coil (receiver) placed under the vehicle. It is very important to determine the correct inductance values for the coils to work effectively. At this point, correct calculation of inductance is a critical factor in terms of energy transfer efficiency and system performance.

Studies in literature generally focus on the following areas.

Coil design and geometry: The inductance value depends on factors such as the size and shape of the coils, the number of turns, the distance between them and the use of magnetic cores. That's why coil design is important for energy efficiency.

Some studies provide optimized designs by analyzing how coil geometry affects inductance. For example, planar chokes and ferrite core chokes have been widely studied to improve efficiency.

Inductance calculation methods: There are various studies in which inductance is calculated using analytical, numerical and experimental methods. FEM (finite element method) is commonly used as a tool for these calculations.

Calculations based on electromagnetic principles such as Maxwell's equations and Ampere's law allow accurately model the magnetic field and inductance behavior of coils.

Energy transfer efficiency: In contactless charging systems, studies on resonance frequencies are important to reduce energy loss and increase efficiency. Inductive charging systems with magnetic resonance are used to optimize energy transfer.

Dynamic charging technologies: Charging the vehicle while it is in motion contributes to the expansion of the electric vehicle infrastructure by reducing the number of charging stations. The literature in this field is particularly focused on dynamic charging systems.

In addition to this literature survey, current advances in wireless charging systems along the way include new materials, electronic circuit designs, and more advanced control algorithms to increase the broad applicability of the systems.

With the increasing use of electronic devices, especially mobile devices, wireless charging methods have been developed to eliminate the disadvantages of wired charging systems. Thanks to wireless power transmission, people have become more mobile, and cable dependency has been removed, replacing the need for fixed positions and wiring. The simplicity and durability of wireless energy transfer offer much more effective solutions in such cases. Furthermore, wireless energy transfer is provided with high efficiency (Karakaya, 2007). Wireless power transfer refers to the transmission of electrical energy from a power source to a target without any physical connection. The idea of wireless energy generation was introduced by Tesla at the beginning of the 1900s, and experimental studies were conducted to achieve this energy transfer. However, since the direction of the energy could not be controlled, the efficiency remained low (Arslan & Erkan, 2022). Today, despite the availability of different techniques, the most common wireless power transfer methods are magnetic resonance coupling, inductive coupling, and microwave power transfer techniques (Imura et al., 2009). In a study aimed at designing a wireless electric vehicle charging system, a wireless power transfer system with hexagonal coils of 1 kW was established, achieving an 85% charging efficiency performance in 10 cm of atmospheric air (Aydın & Aydemir, 2021). Kızıldağ and Yılmaz have researched and examined studies on wireless power transfer systems. They simulated the circuit in Matlab/Simulink and analyzed the advantages of power transfer methods during charging. At the end of their study, they concluded that inductive power transfer technology is efficient and reliable for transmitting electric power wirelessly (Kızıldağ & Yılmaz, 2021). In their studies, Yugendra Rao (2015), calculated the mutual inductance between a pair of coils for wireless power transfer applications using Ansys Maxwell, assigning the distance between the two coils as a variable. Tel & Kuşdoğan (2019), worked on charging electric vehicles using wireless power transmission with ansys maxwell simplorer. This study included the analysis results of the parameters on which the inductance between the coils depends, and the optimal coil selection was made.

In this study, based on the long-distance requirements of the vehicles, the design of the energy transfer between them for instantaneous vehicle charging is analytically designed. The study also investigates the possible ways to improve the energy efficiency of electron transfer during charging.

METHODS

In this study, the design of the coils that enable wireless power transfer is very important. To increase the efficiency of the system, the coils are designed by considering parameters such as material, thickness, length and distance of the terminals, number of turns, geometry and dimensions of the coils. In wireless energy transfer, whether the transmitter and receiver coils are spatially and angularly aligned also affects efficiency. If the coils are aligned, they can operate with higher efficiency in higher air gaps than angular and spatially unaligned coils (Ağçal & Doğan, 2021). When designing a wireless charger, features such as inductance, cross-section, number of windings and copper length should be considered in the selection of a suitable coil, and coil dimensions should also be considered. Reducing the size of the coils for the same number of turns decreases the inductance value of the coils. The size of the coils will therefore be optimally adjusted to suit all vehicles. The average air gap distance between the coils varies between 150-300 mm, in this study it is assumed that the distance difference is within this range. Once the design criteria have been determined, the prototype of the system has the potential to be applied to model vehicles.

In this study, the inductance value between the coils was first calculated analytically and then analyzed with Ansys

Maxwell. When designing a wireless charger, inductance, cross-section, number of windings and copper length should be considered in addition to coil dimensions. Reducing the coil dimensions for the same number of windings will decrease the inductance value of the coils. For this reason, the size of the coils is optimally adjusted to fit all vehicles.

The calculation of the circuit element values in the wireless power system is done with the following equations. In Equation 1, the values of the circuit elements, i.e. resistance elements, were calculated (Tang et al., 2012).

$$R = \frac{1}{S*\sigma} \quad (1)$$

In Equation 2 and Equation 3, the values of system elements such as capacitance were calculated.

Primary Coil:

$$R_1 = 1.7 \times 10^{-8} * \frac{25}{49*10^{-6}} = 0.0087\ \Omega \quad (2)$$

Secondary Coil:

$$R_2 = 1.7 \times 10^{-8} \frac{25}{49*10^{-6}} = 0.0087\ \Omega \quad (3)$$

In addition, the square coil cross-sectional area is 49 mm^2, and the resistivity of copper is 1.7×10-8 Ωm.

Inductance values of the designed system are given below.

For distance 60 mm:

LTx (L1)=119.86 μH, LRx(L2)=134.75 μH and k=0.3781.

The coil dimensions are determined as 400*400, and the thickness of the wire is 7 mm in the system.

$$\omega 0=2*\pi*f0 \text{ (angular frequency)}=2*\pi*10*103=62.83*103 \quad (4)$$

$$C_p = \frac{1}{\omega_0{}^2*L2} = \frac{1}{(62.83*10\wedge3)^2*(134.75*10\wedge-6)} = 1.87\ \mu F \quad (5)$$

$$C_s \frac{1}{\omega_0*(1-k^2)L1^2} \frac{1}{(62.83*10\wedge3)^2*(1-0.3781^2)*(119.86*10\wedge-6)} = 2.3\ \mu F \quad (6)$$

Finally, the calculations showed that the system is efficient when the source frequency is above 10 kHz.

According to this data, the efficiency was calculated as in Equation 7.

$$\text{Efficiency(n)}=\frac{P_{out}}{P_{input}} x100 = \frac{15.1250}{19.2129} x100 = 78.72\% \quad (7)$$

In the design, the voltage at the receiver coil is calculated as vout (Rms)= 194.4544 V and the current value at the output is calculated as I (Rms)= 77.7817 A and according to these values, the receiver coil power is calculated in Equation 8. Power equation taken from (Croft, Terrell; Summers, Wilford I. 1987)

$$P_2 = I*V = 77.7817*194.4544 = 15124.99\ W = 15.125\ kW \quad (8)$$

Parameters Affecting the Analysis of Designed Coils

Analysis studies on the coils whose dimensions were determined were carried out on two different coil geometries: circular and square. According to the studies conducted by (Mahesh et al., 2021), it was determined that the effects of misalignment were less in square-sized coils and rectangular geometry was studied in the analysis. Coil sizes are determined by what the Maxwell student version can decipher. At the prototype stage, size selection appropriate to reality will be made. Analysis was carried out in two different geometries and improvement efforts were directed according to the analysis results. In improvement works; Parameters such as coil geometry, number of windings, dimensions, materials used, structure of the core, and cross-section selection were studied. As a result of the analysis, the data was examined, and the most efficient coil distance was determined to be 50 mm in the selected dimensions. As the distance increases, the connection factor and inductance value decrease. For this purpose, the optimum distance should be selected in the preferred coil design. These parameters were considered in the study to reduce losses and increase system efficiency. The simulation of the selected coil structure of the design under specified conditions was solved in Ansys Maxwell and Ansys Maxwell simplorer programs.

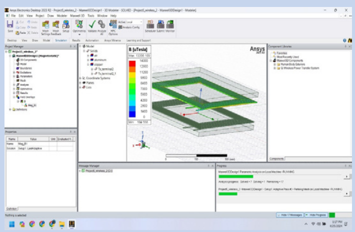
Characterization of Materials

Experiments were carried out on the materials of the coils: copper, steel 4300, steel 4340 and copper-coated silver. Analysis showed that copper has high electrical conductivity but low magnetic field. Steel was found to have a higher magnetic field and lower conductivity than copper. Material selection was based on criteria such as low cost, long life, high efficiency, conductivity and magnetic field generated. In recent years, efforts to increase efficiency on the coil and core have been ongoing. The analysis was performed at room temperature and in the air. As a result of the analysis, inductance values, coupling factor, efficiency and magnetic field value of the coils were calculated using ansys maxwell.

Analysis of Aluminum Core Coil in Square Dimensions

The properties of the sized aluminum core coil are shown in Table 1. Since aluminum is a paramagnetic material, it is a material with a relative permeability slightly greater than 1. When placed in a magnetic field, they are weakly magnetized in the direction of the field. Ferrite is a ferromagnetic material. They are substances with a relative magnetic permeability much greater than 1. When placed in a magnetic field, they magnetize very strongly in the direction of the field (Jackson & John; 1998 and Jiles & David; 1998). For this reason, the inductance value obtained from the coils we obtained using aluminum core was lower. Here material selection is a good way to increase efficiency.

Table 1. Analysis results of square aluminum core coil

Features of the transmitter coil		Features of the receiver coil	
Widht=7 mm	NTx=14	Height=7 mm	NRx=14
Distance between windings =1 mm (2*poligon radius=radius change)			
Geometry of Square Aluminum core coil and core 400*400 mm Core thickness= 20 mm, Distance = 60 mm 			
LTx =67.2204 μH		LRx = 72.6084 μH	
k=0.2357			

The analysis results of the aluminum core coil, the dimensions of which were determined, are shown in Figure 1. Looking at the results in Figure 1, the inductance value obtained for 70 mm is maximum. In addition, it was determined because of the analysis that the ferrite core coil used in the same dimensions is more efficient than the aluminum core coil.

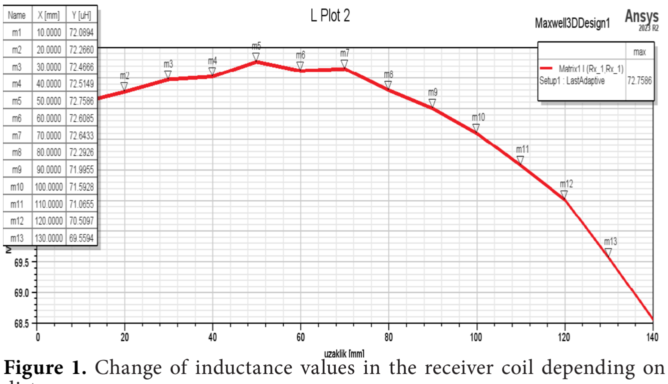
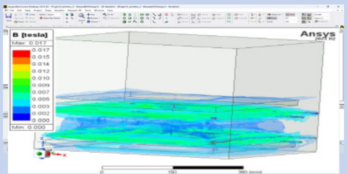


Figure 1. Change of inductance values in the receiver coil depending on distance

Analysis of Ferrite Core Coils with Square Dimensions

The properties of the ferrite core coil, the dimensions of which were determined, are shown in Table 2. The disadvantage of the ferrite core is that it has corrosion, and the way to prevent this is by coating the ferrite core. Or another alternative is to use an aluminum core over a ferrite core, which would be a design to reduce corrosion.

Table 2. Analysis results of the ferrite core coil in square dimensions

Features of the transmitter coil		Features of the receiver coil	
Widht = 7 mm	NTx = 14	Height = 7 mm	NRx = 14
Distance between windings = 1 mm (2*poligon radius=radius change)			
Geometry of the quadratic ferrite core coil and core = 400*400 mm Core thickness 20 mm, Distance = 60 mm, Magnetic field = 0.017 T 			
LTx = 119.8622 µH		LRx = 134.7552 µH	
k = 0.3781		M = 47.874 µH	

The analysis results of the ferrite core coil, whose dimensions were determined, are shown in Figure 2, 3. As can be seen from the analysis, when ferrite material was used as the core, inductance values increased more than aluminum. The reason for this is that ferrite material has a better magnetic permeability than aluminum material.

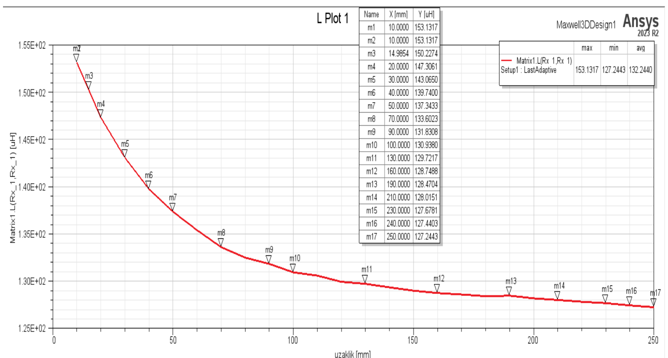


Figure 2. Change of inductance values in the receiver coil depending on distance for the ferrite core coil

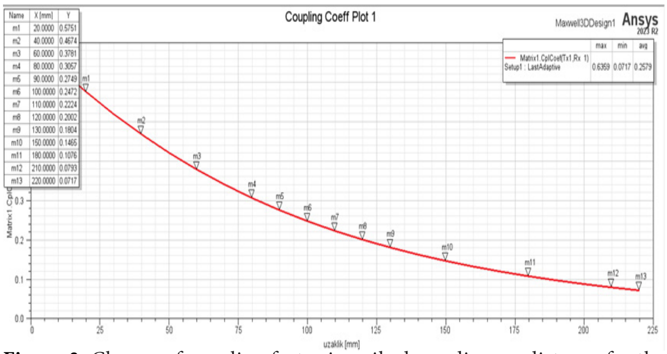


Figure 3. Change of coupling factor in coils depending on distance for the ferrite core coil

RESULTS

In this study, a design is presented that enables electric vehicles, which are becoming more and more widespread in daily life with the developing technology, to transfer their loads to each other in emergency situations in a contactless way. The 3D models are transferred to simplorer file and the efficiency of the system is calculated. The simplified structure of the system will be prepared in Ansys Maxwell simplorer and the circuit structure of the system is prepared by making numerical calculations according to the inductance values obtained from the coils. As a result of the analysis, a sinzoidal graph was obtained and the efficiency of the system in the charging state was found to be 78.72%. Simplorer circuit results for these values are as follows. The geometry we created in ansys maxwell 3D and transferred to the simplified wireless power transmission system is shown in Figure 4.

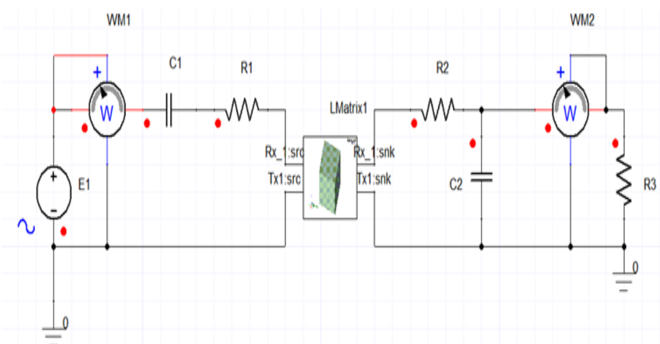


Figure 4. Importing Ansys Maxwell 3D component to simplorer file

The simulation results obtained by transferring the geometry created in Ansys Maxwell 3D to the simplified wireless power transmission system are shown in Figure 5.

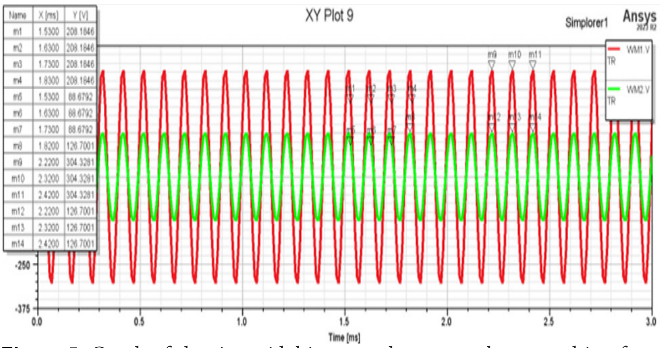


Figure 5. Graph of the sinusoidal input and output voltage resulting from the analysis

The resonant circuit shown in Figure 6 is made to avoid losses that may occur during the transfer of the Maxwell file. The result of the analysis of the resonant circuit model is shown in

Figure 7. The simplified resonant circuit model is taken from (Aditya, 2016).

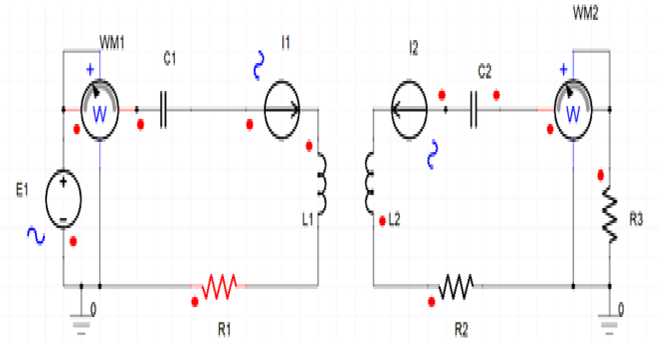


Figure 6. Creating the resonance circuit model in simplorer

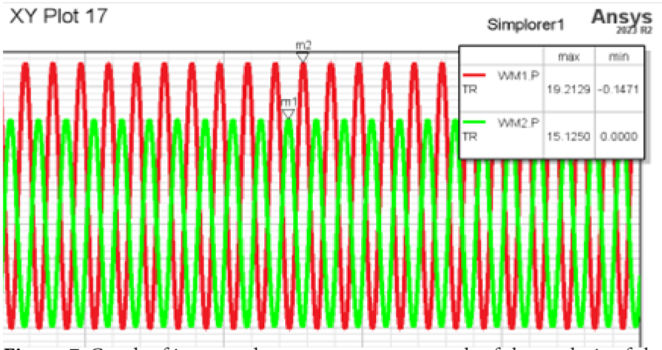


Figure 7. Graph of input and output power as a result of the analysis of the resonance circuit model

Limitations

The analyzes used in the study could not be supported by experimental studies. The system has limitations such as charging speed, heating problems, distance restriction and misalignment. These limitations may decrease as studies progress. Studies that can be done in the future; the expected performance can be achieved with studies such as advanced cooling systems, moving alignment and material improvements.

CONCLUSION

In short, in this study; vehicles will be able to charge enough to reach the charging station via wireless power transmission. In this way, drivers will be able to control the process in emergency situations without panicking. When designing the wireless charger, inductance, cross-section, number of windings, copper length, as well as coil dimensions should be taken into consideration when selecting the appropriate coil. Decreasing the coil dimensions for the same number of windings reduces the inductance value of the coils. Therefore, the size of the coils will be optimally adjusted to be compatible with all vehicles. The magnetic field formed in ferrite-core copper coils is below 0.02 Tesla, meaning that the system alone is not at a level that can affect human health. ICNIRP (ICNIRP, 1998) and IEEE standards were taken as reference to examine the harms of the wireless power transmission system to human health IEEE, (2019). The magnetic field emitted by the system is below these reference values. However, we continue to work on the magnetic field that will occur if more than one user activates the system in heavy traffic. Protective shield works to protect against magnetic fields will be concentrated in the future. If we compare it with the article by (Tel & Kuşdoğan; 2019), trial studies have been carried out on different materials. It can reduce the disadvantage of other materials, which causes an increase in the power drawn from the source due to their low conductivity, by charging the battery with renewable energy or by coating the coils. This study has the following limitations.

ETHICAL DECLARATIONS

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

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Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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