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The modelling, simulation, and implementation of wireless power transfer for an electric vehicle charging station

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ABSTRACT
Recently, with the developing environmental awareness, electric vehicles are increasing even more. For this reason, different searches have emerged to solve the problems related to meeting the energy needs of electric vehicles and charging their batteries quickly and reliably. One of these ideas is wireless power transfer (WPT) battery charging systems, which researchers have focused on for the past two decades. In this study, a wireless charging station that can be used to charge the batteries of electric vehicles is designed and examined by applying it to a prototype vehicle. Also, it is examined that the designed system can be adapted with renewable energy sources (such as solar energy) independently of a local energy source. It is aimed with the WPT prototype to realize a more efficient system for the 10 W power level and 86 kHz. The electromagnetic modelling of WPT is designed using ANSYS-Electronics/Maxwell software. Ultimately, the power electronics circuit performance of this system was analyzed with ANSYS Electronics / Simplorer software for co-simulation.

1. INTRODUCTION

Wireless power transmission (WPT) has become a popular topic, especially in the last two decades. Many researchers study it with much greater interest. WPT based on the principle of transmitting electrical power with magnetic coupling (Kuzey, 2017; Tesla, 1900b). The emergence of WPT and the implementation of this principle has become possible after nearly two centuries (Fawwaz and Ulaby, 2015; Sun et al., 2018). At the end of this process, Nikola Tesla made some experiments on the wireless transmission of electrical energy in 1899 and received a patent on WPT on March 20, 1900 (Tesla, 1898, 1900a).

After the applicability of WPT in different fields was understood, it has started to be understood that the power transmission method could also take different forms. The first MASER (Microwave Amplification by Stimulated Emission of Radiation) oscillator, which was developed in 1954, is seen as the first example (Schawlow et al., 1960). This invention would later lead to the discovery of LASER (Light Amplification by Stimulated Emission of Radiation) in 1960 (Maiman, 1967).

The effects of WPT on medical electronics started with the use of implant devices. John Schuder proposed the transcutaneous WPT system to supply the energy needs of implant devices in 1961 (Mahmud, 2016; Schuder, 2002).

On the other hand, William Brown designed an antenna, which is called rectenna (rectifying antenna) in 1964. And he used the rectenna to canalize the microwaves to a model helicopter, which we can call a simple drone. This drone's energy was sourced from the microwave beam by using WPT. In his presentation,

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William C. Brown transferred 270 watts of power to a height of 50 ft (15.24 m) (Brown, 1965, 1969).

Also, Peter E. Glaser came up with the idea of SPS (Solar Energy System) or SBPS (Solar Based Power System) in 1973, where WPT systems could be applied. Thus, a diversity of resources is provided for WPT systems, which will lead to many different research and investigation areas in the future (Glaser, 1973).

Zhao *et al.* conducted studies on electromagnetic induction and WPT in 2012 (Zhang and Zhao, 2014). Although WPT was on the researcher's sights from time to time in the last century, it is not received the expected attention due to its inefficiency and difficulties in implementation. Nevertheless, in 2007, researchers at MIT (Massachusetts Institute of Technology) transmitted a 60 W power level to a distance of 2 meters with WPT (Kurs et al., 2007).

In the other studies conducted for the last 20 years, researchers focused on resonance magnetic coupling studies because of the low efficiency of magnetic induction and inductively coupled systems.

Thrimawithana *et al.* controlled the voltage induced in the primary coils with the control technique they performed on the primary side and provided inductive power transfer by regulating the primary current. Also, they transferred 150 W power to the secondary side at a frequency of 20kHz and compared the results of the experimental and the simulation results (Thrimawithana and Madawala, 2010).

Imura and Hori 2011 analyzed the relationship between the air gap and the efficiency by using the Neumann formula and equivalent circuit for magnetic resonance coupling.

Kuzey, in his thesis in 2017, designed a WPT system that can be used in charging electric vehicle batteries. He cross-examined the 20 cm and 30 cm air-gapped WPT topologies for two models for 15 kW and 45 kW power levels. He found the maximum efficiency of the system in the ideal condition of 15 kW power to be 75.38% (Kuzey, 2017; Kuzey et al., 2017). On the other hand, Lee examined in his study in 2019 that WPT systems can be adapted in different sizes in places where it is difficult to reach. Also, he transferred 47 W power with 52% efficiency with WPT at a distance of 60 cm which is the approach distance of the high voltage lines (Lee et al., 2019).

In 2020, Ustun *et al.* 2020 developed a simulation model by using an artificial bee colony algorithm to predict the variables of the inductively coupled WPT system designed for electric vehicles. In their study, they determined that the analysis of the WPT circuits related to the charging efficiency can be easily calculated with the proposed model without considering long time simulation and complex equations.

WPT can also be used as a new charging technique for Unmanned Aerial Vehicles (UAVs). Le et al. 2020 analyzed different WPT charging technique for UAVs. they searched WPT near-field techniques capacitive, inductive, and resonant inductive coupling methods for UAVs in their study. They addressed possible ways to apply these techniques for UAVs.

Frechter and Kuperman 2020 presented the analytical investigation and design of a WPT system for a through-glass AC power transfer system in their study.

Recent technological advances are also showed us that there are some other new ways to produce a WPT system. Kim et al tried to secure sustainable electrical power in human bodies by using an active photonic WPT approach in their study. They designed an active photonic WPT which is consists of a pair of the skin-attachable photon source patch and the photovoltaic device array integrated into a flexible medical implant (Kim et al., 2020).

Despite all studies, WPT efficiency is still a disadvantage of this system. Yan *et al.* designed and analyzed a multi-transmitter system for greater WPT efficiency. This system also aimed more efficiency under lateral-misalignment conditions (Yan et al., 2020). Assawaworrarit *and Fan 2020.* searched for the increase of WPT's efficiency by using a switch-mode implementation.

The energy harvesting system is also a different type of WPT. Kim *et al*. 2020 used this idea to design a WPT system. They tested WPT efficiency at different modulation types and at different waveforms. Shen *et al.* 2021, designed a closed-loop WPT with adaptive waveform and beamforming.

The alignment of the receiver and the transmitter is also an important variable for WPT's efficiency. Liu *et al.* 2021 examined the electrical parameters of a compensation inductance and the transmitter to determine the receiver position.

WPT has some other application areas such as insulation from environmental conditions. Wang *et al.* examined a single-phase shaded-pole induction motor system with WPT. They achieved a WPT's efficiency of 77% with a 20 mm transfer distance (Wang et al., 2021).

At WPT systems, the design and the shape of receiver and transmitter coils are very significant factors for efficiency. Yakala *et al.* 2021 studied the circular transmitter and receiver coils design for WPT system in battery charging applications of electrical vehicles. They designed a power pad for WPT. It can transfer the power of 3.7 kW for a distance of 100 mm, at a vertical offset of 150 mm (Yakala et al., 2021) .

Today, the awareness of human health and the environment is very developed, so one of the first questions that come to mind regarding this technology is the effects of WPT on human health and the environment. Although researches which are about WPT effect on humans health is still ongoing, they show that the magnetic field in WPT technology is within the international boundaries for human health (Baikova et al., 2018; Christ et al., 2013; Kuzey et al., 2017; Sun et al., 2018).

In this study, the charging system of electric vehicles, which is one of the application and research areas of WPT, is designed as a prototype. Also, it is examined the energy-storing obtained from the alternative energy source (Solar energy). So that the designed system can be kept ready for use independent of the grid. In the designed WPT system, it is aimed to achieve optimum efficient power transfer with minimum air gap and low coupling coefficient. For a 10 W model with a 1.5-2 cm parametric distance value, the WPT in power transmission is examined. First of all, the variables of the designed WPT system are calculated. Then, with these variables, coils are designed in ANSYS Electronics/Maxwell software and the magnetic model simulation of WPT is examined. The performance of the model is analyzed by simulating the designed and simulated transceiver (transmitter and receiver) coils simultaneously with the WPT electrical equivalent circuit model created in ANSYS Electronics/Simplorer software. Then, the designed and simulated system is applied and finally, the simulation results are compared with the application results.

2. MATERIAL AND METHOD

2.1. Examination of the Basic Circuit Block Diagram of the Designed WPT System

The block diagram showing the basic circuit structure of the designed WPT system is shown in Figure1. On the block diagram, the supply of the system is modelled from both the renewable energy source and the network. A high frequency switched DC / AC inverter is designed for the charging station. Then, transmitter coil design and calculations are made. After the charging station is completed, a receiver coil, AC / DC rectifier and battery measurement and monitoring system are placed on the vehicle to feed the vehicle battery.

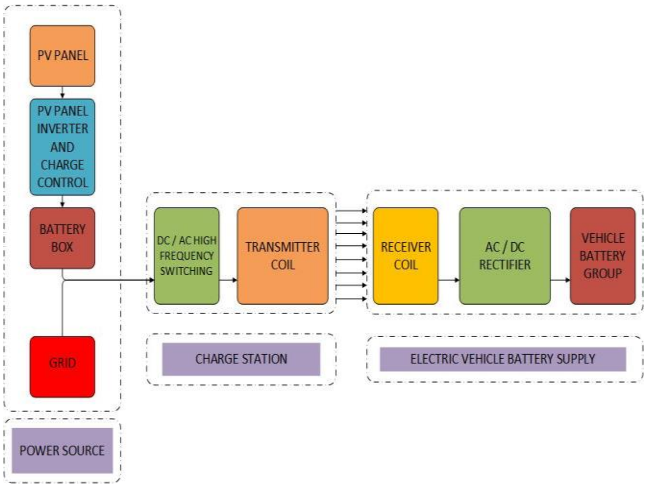

Figure 1. The block diagram of proposed WPT system

2.2. Determination of the Resonance Frequency for Designed WPT System

In this study, the "Tank Circuit", which is based on the electromagnetic resonance circuit (RLC circuit) and can store very large energies with ideally infinite oscillation, is used to provide resonance. However, due to the absolute existing resistance and physical limitations, the resonance frequency has to be calculated at a certain value. There are two common types of resonant-tank circuits. The first one is the series tank circuit which is given in Figure 2, and the other one is the parallel tank circuit which is given in Figure 3.

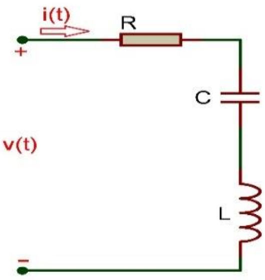

Figure 2. Series RLC circuit

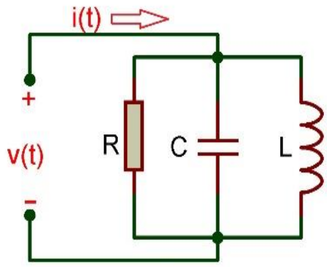

Figure 3. Parallel RLC circuit

For a given frequency value, the inductance (L) and capacitance (C) become equal for the maximum current to flow through the circuit in the resonance state. First of all, the transmitter and the receiver coils are calculated and designed. The inductance value (L) of the coils is calculated by Equation 1 (Chapman, 2012; Cheng, 1983).

$$L = \frac{\mu_0 . N^2 . A}{l} \tag{1}$$

Where, μ_0 permeability of the vacuum, N is the number of turns, l is the length of the coil, and A is the diameter of the coil wire. In this case, the resonance frequency (ω_0) is calculated by Equation 2.

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{2}$$

The resonance frequency is calculated for the designed WPT system in this study which is aimed at 10 W power transmission at 86 kHz.

2.3. Simulation Studies

The variables determined in the system designing and modelling are used in the ANSYS Electronics/Maxwell software to create the magnetic model of the coils.

The designed model in the Maxwell is shown in Figure 4. In this model, the grey-coloured coil is the primary coil with 22 turns which is the transmitter and the green-coloured coil is the secondary coil with 10 turns which is the receiver coil.

The inductance values of the designed coils are also examined in the simulation studies. Mutual inductance and self inductances of the coils are shown in Figure 5.

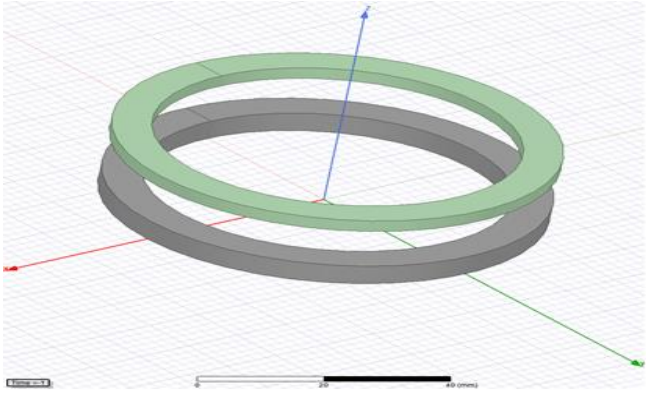

Figure 4. Designed coils with Ansys-Maxwell

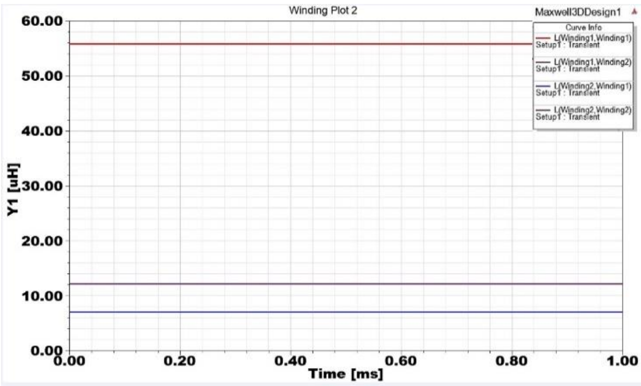

Figure 5. The mutual and self inductances of coils

In this modelling, magnetic flux distribution and coupling effect are also examined. Magnetic flux distribution and coupling effect are shown in Figure 6.

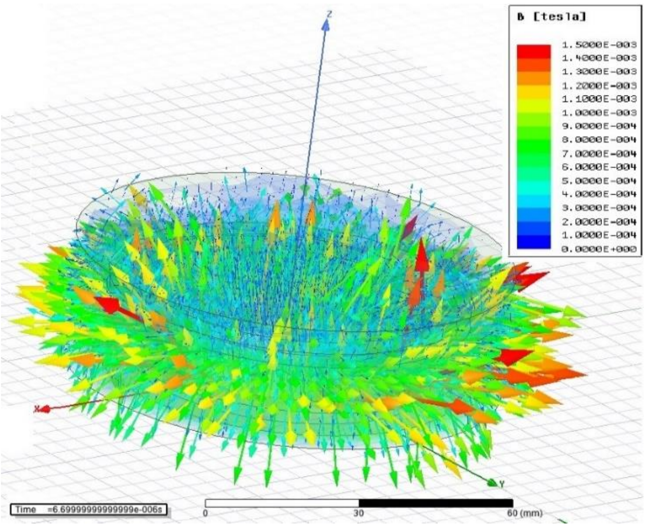

Figure 6. Magnetic flux distribution and coupling effect

An electrical equivalent circuit model for the designed WPT system is designed in the ANSYS Electronics/Simplorer program. Afterwards, the ANSYS Electronics/Simplorer program is simulated simultaneously with realized transceiver coil models in the Maxwell. The performance of the whole of the designed system is analyzed. The Simplorer circuit model of the designed WPT system is shown in Figure 7.

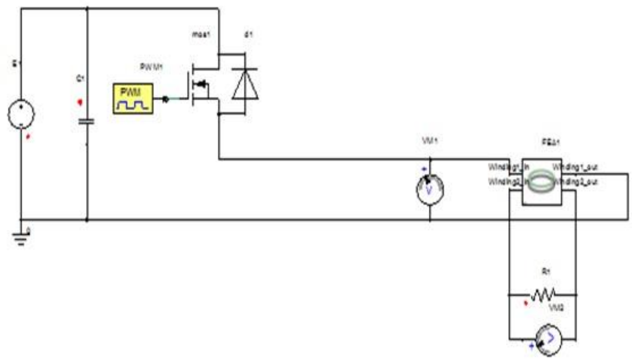

Figure 7. Ansys - Simlporer circuit model

The design of the receiver circuit to be placed on the model vehicle is also made along with the simulation studies of the receiver and transmitter coils. A real-time voltmeter is added to the design on the receiver circuit. The voltmeter shows the voltage level to be obtained from the receiver coil. Thus, it is aimed that this measurement is not affected by the current battery of the model vehicle with the D1 diode. The designed receiver coil measurement circuit and AC / DC rectifier circuit diagram are shown in Figure 8.

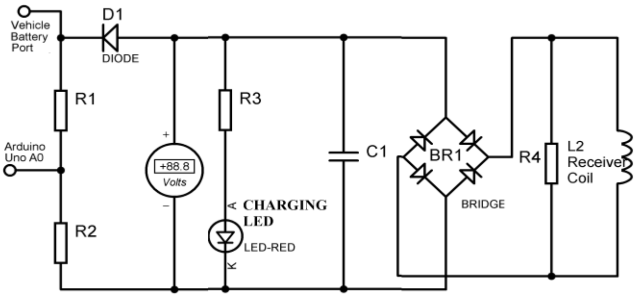

Figure 8. The circuit of the vehicle side

2.4. Realization of The Designed Model

The model which was designed and simulated, manufactured as a prototype. The list of used materials is shown in Table 1.

Table 1. The technical specifications of WPT circuit

Materials	Function
Arduino Uno	The control unit at the model vehicle
Arduino Nano	The control unit of PWM
Mosfet (Driver Module of IRF520 MOSFET)	The switching unit at the WPT system
The Designed Coils: 0.60 mm² 10 Turns-Reciver Coil 0.60 mm² 22 Turns – Transmitter Coil	The components which are used for energy transfer at the WPT system
LCD	The element used to see the voltage and distance values on the model vehicle
Ultrasonic Distance Sensor (HC-SR04)	The element used to prevent misaligned problems
PV Module	Power Source of the WPT system

The receiver circuit of the designed model is assembled to the model vehicle. The assembly of the receiver coil and the rectifier circuit is shown in Figure 9.

Figure 9. The assembly of the receiver circuit

A charging station has also made for the electric vehicle. Theoretical, the energy which is obtained by the PV module is stored at the battery cell. Afterwards, the energy is switched by the designed WPT system at 86 kHz frequency. The designed charging station is shown in Figure 10.

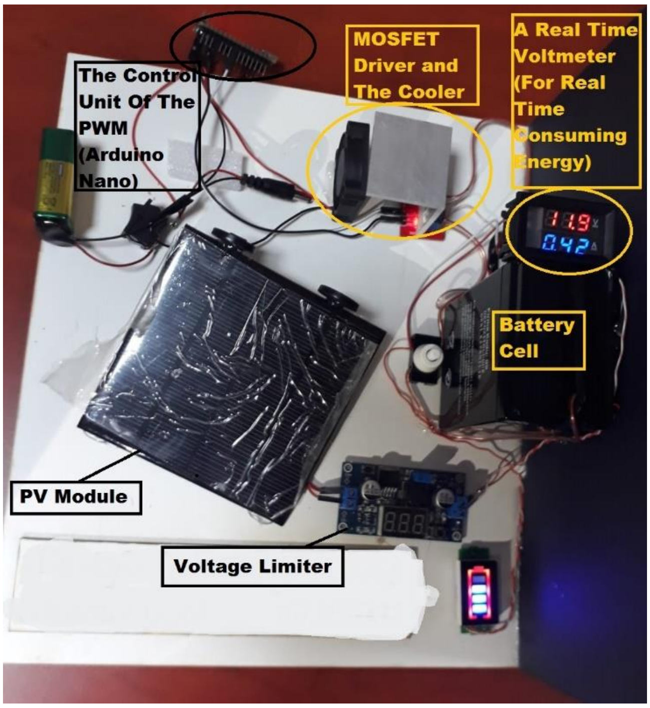

Figure 10. The PV panel and the WPT system

The charging station and the WPT system are designed as a whole system which is combined with the vehicle and the station. After that, all components are assembled and the designed system is manufactured. The final situation of the manufactured system is shown in Figure 11.

Figure 11. Prototype imaging of the designed wireless charging station

3. RESULTS

In this study, a WPT system that is operated at 86 kHz frequency is designed, simulated, and implemented. The maximum efficiency of WPT is obtained 75% at the ideal condition for a 10 W power value. The output signals of the designed system are also performed simulation and experimental tests at the 95% power level. Thus, the output signals obtained as a result of these tests are shown in Figures 12 and 13, respectively.

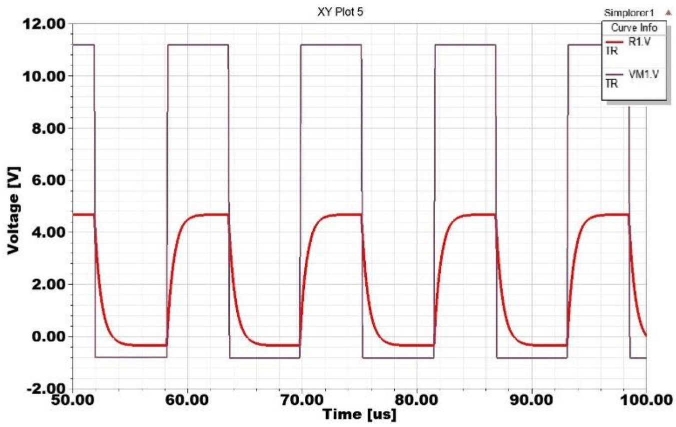

Figure 12. The output signal with simulation reports

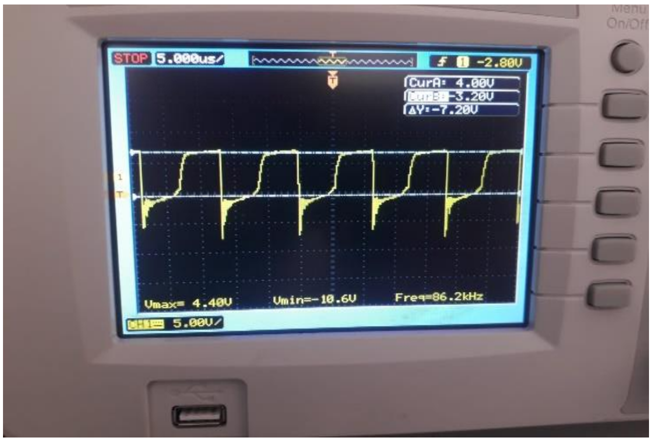

Figure 13. The output signal with scope image reports

4. CONCLUSION

This paper presents a charging station for electric vehicles based on WPT. The proposed WPT system is designed, simulated and implemented. The designed system shows that WPT charging systems can be realized independently from the grid by using alternative energy sources. In addition, the designed WPT system is derived from the flyback converter topology. Firstly, the power electronics circuit of the WPT system was simulated with the Ansys-Simplorer software. The optimum distance value between the coils is determined. Then the prototype of the WPT system is built and experimental studies are carried out at 86 kHz and 10 W. According to the experimental studies, the maximum efficiency of the WPT system was found to be 75% in the ideal state of the topology. The results obtained in the study showed that a similar application can be applied to real vehicles with real high power level.

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Author contributions

Mehmet Çiçek: Conceptualization, Design, Writing draft preparation, Literature review, Software (ANSYS Electronics), Visualization, Design of the electronic circuits, Investigation, Critical review. **Mustafa Gençtürk:** Conceptualization, Design, Writing draft preparation, Literature review, Software (Arduino), Visualization, Design of the electronic circuits, Investigation, Critical review. **Selami Balcı:** Conceptualization, Methodology, Design, Software (ANSYS Electronics), Data collection and/or processing, Analysis and interpretation, Critical review, Inspection. **Kadir Sabancı:** Conceptualization, Methodology, Software (Arduino), Data collection and/or processing, Analysis and interpretation, Design of the electronic circuits, Critical review, Inspection

Conflicts of interest

The authors declare no conflicts of interest.

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