Development of a wireless power transfer system for electric vehicle charging using an E-Class power amplifier

Ali Nasser Hussain[1], Sadik Kamel Gharghan[2], Rasha Majid Abd Al-nabe[3]
{alinasser1974@yahoo.com[1], sadik.gharghan@mtu.edu.iq[2], bcc0024@mtu.edu.iq[3]}

Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq[1, 3], Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq[2]

Abstract. Wireless transmission technology is considered one of the advanced and advanced technologies at present, through which complexity in electrical wiring is avoided, as well as its valuable use in difficult-to-reach places such as high places, roads, etc., in this research a wireless power transmission system was designed using electromagnetic induction technology to charge the battery of electric cars wirelessly and with a high transmission efficiency of up to 90% where an E-type power amplifier was used that includes an IRFP250 switch and a throttle coil of 325µH. The intrinsic is 67µH. and its internal resistance is 32mΩ. This system was implemented using the MATLAB program. As for the receiving side, a receiving coil was designed to be equal and equivalent to the transmitter coil with the size and inductive value, and the distance between the two coils was 20cm. After implementing the program, an excellent quality factor was obtained, high efficiency, and very little power loss.

Keywords: WPT, Class E, Electric Vehicle charger, Battery, inductive coupling.

1 Introduction

In recent years, interest in wireless transmission technology has begun to grow rapidly. The technology can be used for wireless charging of the mobile or any other electronic device. This method is important and useful when transmission by wires is not possible. Today, there is some vital and daily application that require Wireless Power Transfer (WPT). Wireless energy can be transmitted in various ways a technique such as resonant inductive coupling and capacitive coupling based on electromagnetic radiation, microwaves [1], [2]. One of the major challenges and difficulties facing researchers in this field is how to improve capturing the largest possible amount of energy using the techniques mentioned earlier. This process is known as energy harvesting. In 1891 Nikola Tesla made the wireless energy transmission using the resonant radio frequency transformer called Tessa's coils that produced high-frequency alternating currents, high voltage, and low output current [3]. After a short period, studies had shown that high-frequency currents can be used in medical applications because these high-frequency currents are not harmful to the human body and can pass through them without any danger [4]. Since the invention of wireless devices, this technology has evolved. In wet

IMDC-IST 2021, September 07-09, Sakarya, Turkey

DOI 10.4108/eai.7-9-2021.2314927

environments, wireless charging pads for devices such as electric razors and electric toothbrushes are utilized to reduce the risk of harmful electric shock. It has also been clarified when the turns of a coil are deployed and distributed inside its diameter, the coupling coefficient of flowing between the magnetically wrapped coils con be amplified and the situation is reversed when distributed at the circumference [5]. Using a strongly coupled system, the experimental results [6] showed that 60w were transferred with an efficiency of about 40% at a distance of 2m. That experimental model in its time was considered sufficient to interpret this technique. The helical transmitter and receiver used in that system were identical and had one copper ring with a radius of 25cm. The resonance frequency was 9.9 MHz Capacitors paralleled with a coil were used to achieve resonance between transmitter and receiver coils which in turn consisted of two large coils, each with a diameter of 30cm at a distance of 3.8 cm from each other [7]. The power was transferred up to 50% with a frequency of about 8.3 MHz showed that the efficiency and distance between transmitter and receiver could be enhanced in the WPT system by using an intermediate coil between the transmitting and receiving antennas [8]. The efficiency of that system was better and exceeded 90% at a resonance frequency of 1.25 MHz Various types and sizes of transmitter and receiver coils used at a frequency of 13.56 MHz were introduced [9]. The wireless power transfer and harvesting were obtained using magnetic resonance. The transmitter coil diameter was 60 and 20 cm apart from the receiver coil. The transmission efficiency was 80%. Next, the transmission efficiencies ranged from 40-75% at distances ranging from 20-50 cm were achieved keeping the size of the receiver like the size of the iPhone 4. The printed coil inductors were used at 13.56 MHz and implemented with implanted sensors [10]. The transmission of power was 15 mW at 6mm while at 17mm, the transmission of power had approached 1.17 mW. The wireless power transmission and harvesting system with Tesla’s resonators was introduced [11] To obtain an efficiency above 75% with a resonator’s frequency extending from (503-525) KHz, the resonators were arranged in a domino-like axis at a distance of 3m, 8W LEDs were used in that research. Eventually, it was concluded that the distances (spaces) between resonators are worse when they are not arranged. In a prototype introduced [12], the power transfer efficiency was enhanced to 64.2% at a separating distance of 15 cm, and the power transferred to load was also enhanced to 5.26 W with 10 V excitation voltage. In the systems introduced inductive magnetic resonance coupling was adopted to provide very high energy at short distances which can be used for wireless charging of electric such as cars and Handicapped vehicles [13] [14]. This paper begins with the WPT system and then proposes the inductive wireless power transfer technology and gives an overview of IWPT technology to solve the problem of power transfer with small distances and high efficiency, as well as concern for human safety by eliminating wire problems. The theory of WPT in electric vehicle applications has gained wide acceptance in the world. We hope that researchers will be interested in WPT theory because it contributes to the development of technology.

2 Materials and Methods

The proposed power harvesting system: The proposed WPT system is shown in Fig. 1. It represents a resonant inductive WPT system built of a transmitting circuit which includes an AC power transmitting coil driven by a power amplifier and a receiving circuit consisting of receiving coil connected power harvesting coil followed by a suitable rectifying circuit and driving a certain electrical load.

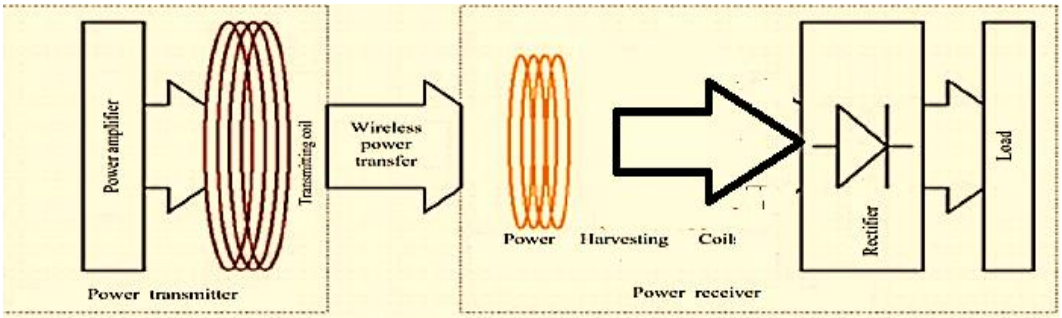

Fig. 1. The block diagram of a proposed power harvesting system having one transmitting antenna and one receiving antenna.

The AC transmitting circuit consists of a Class-E power amplifier driving a planar spiral transmitting coil T_x. The receiving coil R_x is also a planar spiral coil located axially and perpendicularly with the transmitting coil on an axis passing through their centre points as shown in Figs 2 to 4.

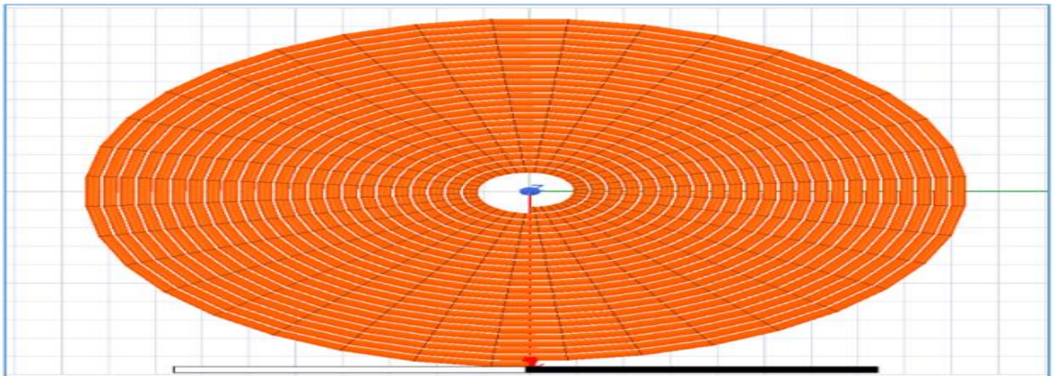

Fig. 2. The power transmitting coil in the proposed WPT system.

Fig. 2 shows the number of turns of the coil, the inner diameter of the coil, and the outer diameter of the coil. The coefficient of coupling k=0.02194 between two planar spiral coils located as shown in fig.6 is given [15]:

$$K=\frac{1}{[1+\sqrt[3]{4}\left[\frac{h}{\sqrt{r_t * r_r}}\right]^2]^{\frac{3}{2}}} \quad (1)$$

Where:
r_t and r_r : Radii of transmitter and receiver coils.
h: Distance between the centers of the two coils.
The inductance and low-frequency resistance of the planar spiral coil is given [15] :

$$L=\frac{(0\cdot 3937)\times(a\times N)^2}{(8\times a)+(11\times b)} \quad (2)$$

$$R_{low\ frequency} \approx \frac{1}{\sigma\pi a^2}[1+\frac{1}{48}\times[\frac{a}{\delta}]^2] \quad (3)$$

Where:
N: Coil Number of turns
δ: Skin depth
σ : Conductor material conductivity
At operating frequency 100kHz.
a, b and $\delta$are given by:

$$a = \frac{r_0+r_i}{2} \quad (4)$$

$$b = r_0 - r_i \quad (5)$$

$$\delta = \frac{1}{\sqrt{\mu\pi\sigma f}} \quad (6)$$

Where:
$r_i$and r_0: Inner and outer radii of the spiral coil
$\mu=\mu_{0.}\ \mu_r$= Permeability
f = WPT system operating frequency
The transmitting coil is designed and implemented using a copper tube of diameter of 6.35 mm and length of 15 m. the outer and inner diameters are 360 and 60 mm, respectively as shown in Fig 2, according to Eq. 2, the self-inductance L_T of the transmitting coil Tx is 67 uH, the value of the self-inductance L_T determined according to the analysis program (ANSYS electromagnetics Software 2016) is 67 uH. Using Eq. 3, the low-frequency resistance R_1 of the transmitting coil is calculated as 0.032 **Ω**. Each receiving coil is wound of a copper tube of a diameter of 6.35 mm and length of 15 m. Using the same methodology for inductance and resistance calculations, the self and resistances of receiving coils are listed in Table 1.

Table 1. Calculated parameters of transmitting and receiving coils.

Parameter	Inductance	Resistance	r_i	r_o	N
L_t	67 uH	0.032 Ohm	30 mm	180 mm	23
L_r	67 uH	0.032 Ohm	30 mm	180 mm	23

In this table, transmitter coils L_t and R_t are corresponding to receiving coils, L_r and R_r respectively. In Table 1, the inductances are listed. Using Eq. 2 and the parameters of the designed transmitting and receiving coils.

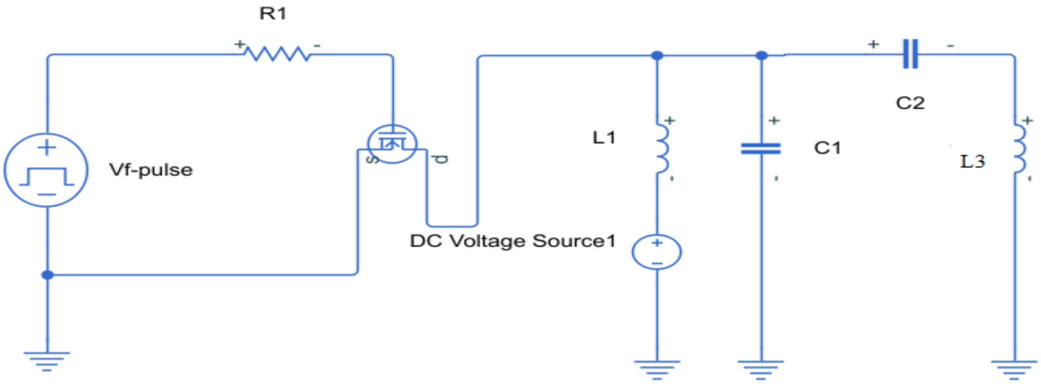

Fig. 3. The proposed Class-E power amplifier.

Fig 3 shows the circuit design of a Class-E power amplifier, DC voltage source, and Vf-pulse at the operating frequency.

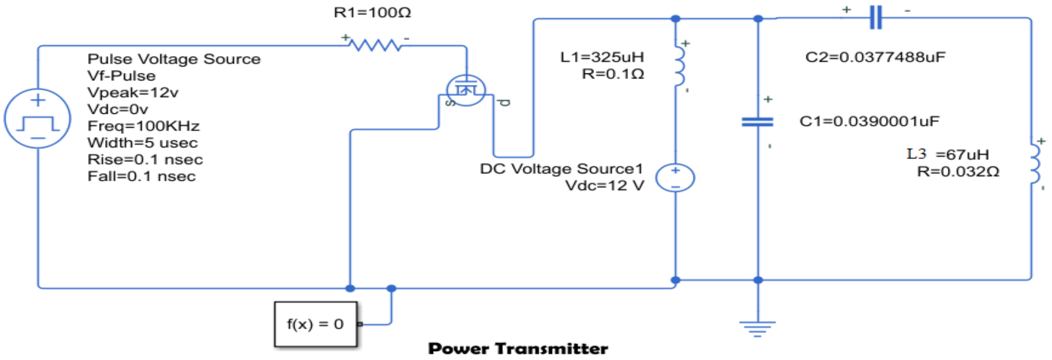

Fig. 4. The circuit design power transmitter of a proposed WPT system.

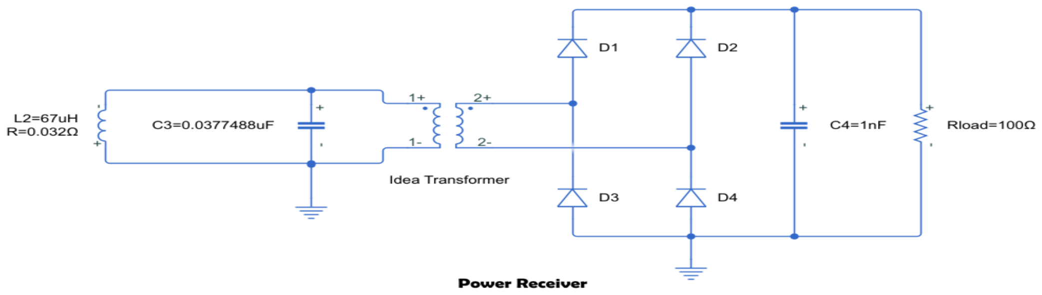

Fig. 5. The circuit design power receiver of a proposed WPT system.

Fig.5 shows the design of the receiver circuit containing the full-wave rectifier circuit.

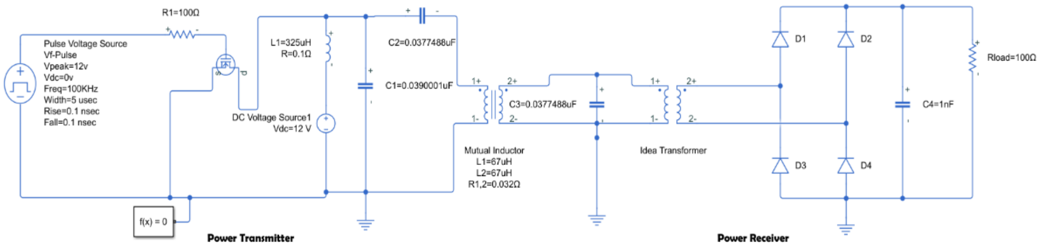

Fig. 6. The circuit design of a proposed WPT system.

2.1 Power amplifier design

In the WPT system, several techniques are used in the transmitter to increase the amount of transmitted energy and thus increase the spreading of magnetic flux in the area to be covered. The most efficient of these technologies is the Class-E power amplifier which is a switch-mode amplifier having high efficiency and high output power, thus, it is suitable to be used in the WPT system to enhance the power transmission efficiency. To increase the power output of the transmitter, connected MOSFET of the type IRFP250 are chosen as the main switching device of the Class-E power amplifier. The series Capacitor C_2 and transmitter inductance L_3 are tuned to a resonance frequency slightly less than the proposed WPT frequency which is 100 kHz. The shunt or parallel Capacitor C_1 is determined such that the parallel combination constituted by L_3 and C_1 resonates at 100 kHz which complies with the MOSFET transition frequency specified in its datasheet. The inductance of the radio frequency choke LRFC is chosen to be very much >L_3. The amplifier DC Voltage is 12 V. Figure 3 shows the complete circuit diagram of the Class-E power amplifier which is designed on the MATLAB program.

2.2 Circuit design of the proposed WPT system

This system is built of a Class-E power amplifier with a planar spiral coil as a transmitting circuit and receiving coil connected planar spiral power harvesting coil followed by a rectifying circuit driving a certain load as receiving circuit. The proposed system is designed on MATLAB program as shown in Fig. 4, Fig. 5, Fig. 6. The receiving coil power harvesting coil is tuned to resonate at a frequency of 100 kHz by the Capacitor C_2, which is set to 0.0377 uF, and C_1, which is set to 0.039 uF. The Class-E power is the same as that specified in Fig. 3 and is driven by a 12 V DC supply and triggered by a square wave of a positive level of 12 V and having a frequency of 100 kHz.

3 Results and Discussion

The performance of the power amplifier proposed in Fig. 3 was tested on the MATLAB program. The triggering voltage Vs to the switching device is shown in Fig. 6. The DC supply voltage level of 12 V is shown in Fig. 7 and the switching MOSFET drain voltage is shown in Fig.8. The DC I_{Dc} is drawn by the power amplifier shown in Fig. 9 and the AC I_t is flowing in the transmitting coil is shown in Fig. 10.

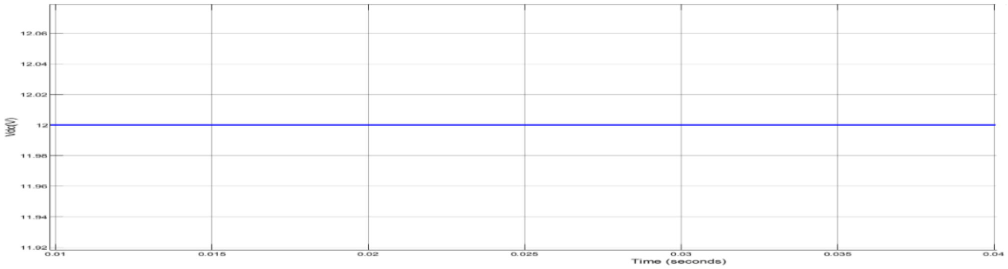

Fig. 7. The DC supply voltage.

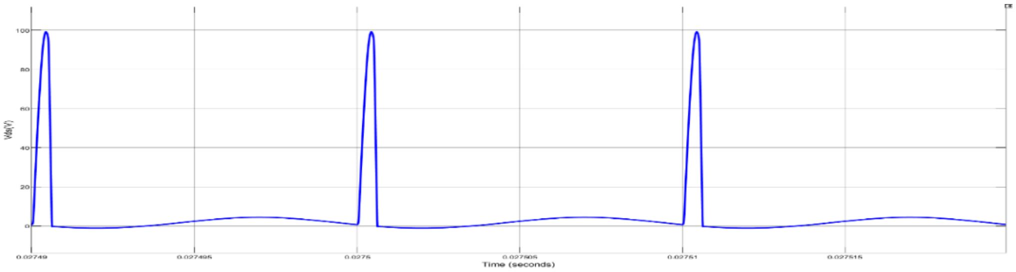

Fig. 8. The DC voltage MOSFET drain voltage of the Class-E power amplifier.

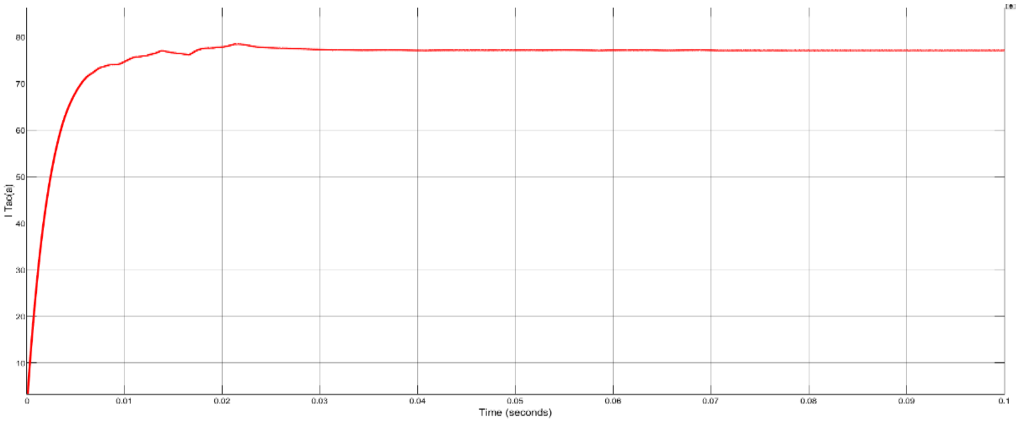

Fig. 9. The DC of the Class-E power amplifier.

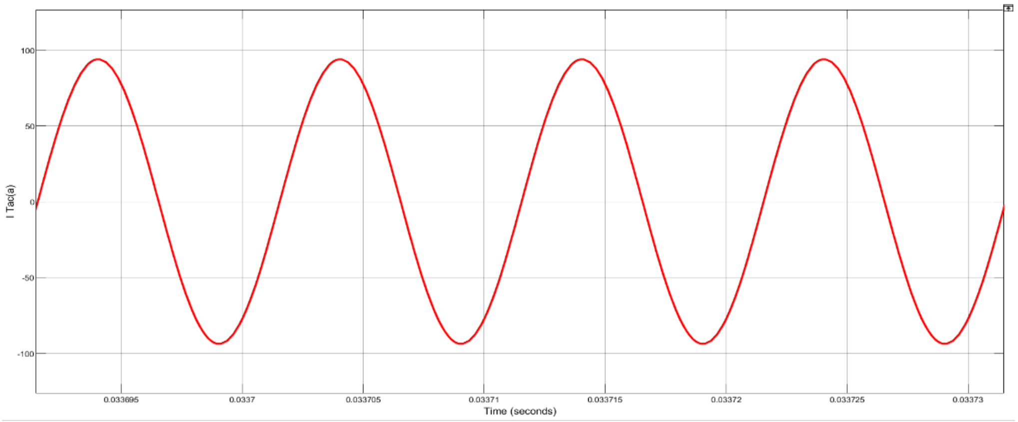

Fig. 10. The AC transmitting coil current of Class-E power amplifier.

The AC voltage V_t across the terminals of the transmitting coil is in shown Fig. 11. The amplitude of the AC voltage across the terminals of the transmitting coil is about 3Kv.

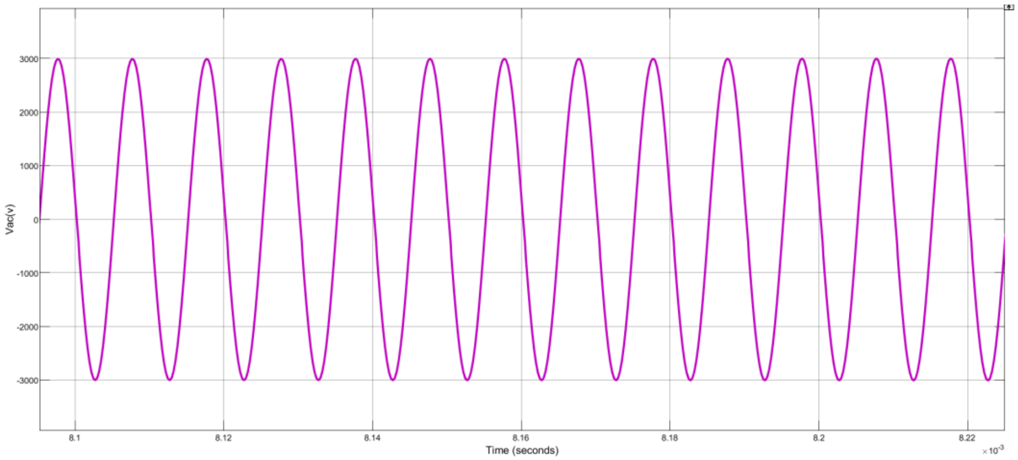

Fig. 11. The AC voltage transmitting coil of Class-E power amplifier.

The performance of the proposed WPT system shown in Fig. 6 was tested on the MATLAB program. The AC and DC voltage outputs of the receiving circuit for a load resistance of 100 Ω are shown in Fig. 12, Fig.13.

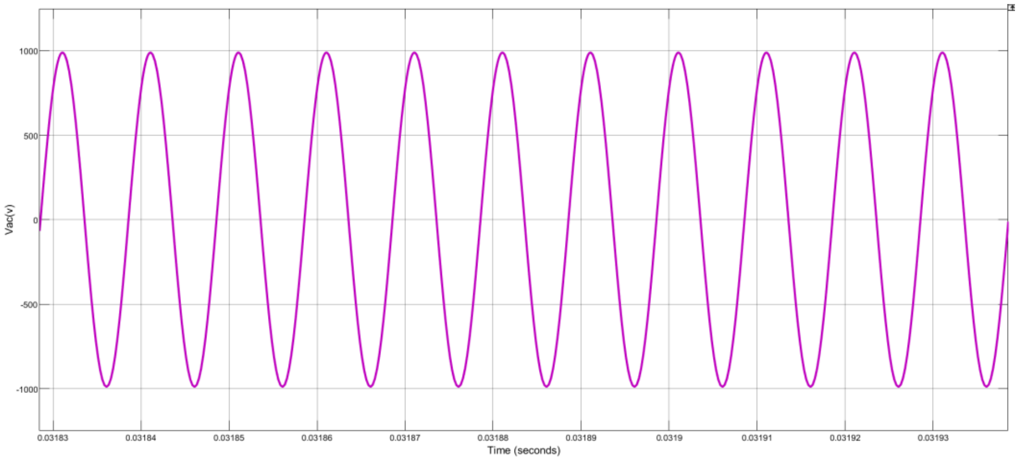

Fig. 12. The AC output voltages of the WPT system receiving a spiral power harvesting coil.

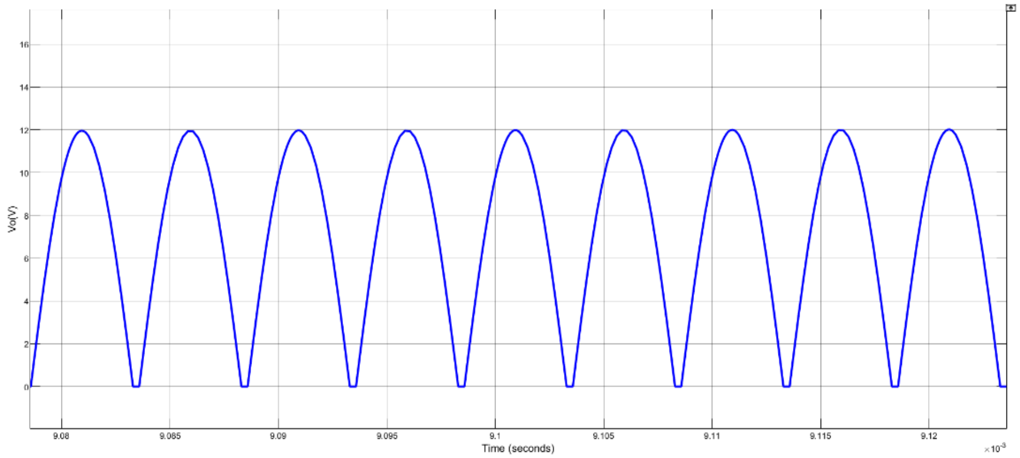

Fig. 13. The DC output voltages of the WPT system having connected spiral power harvesting coil RL=100Ω.

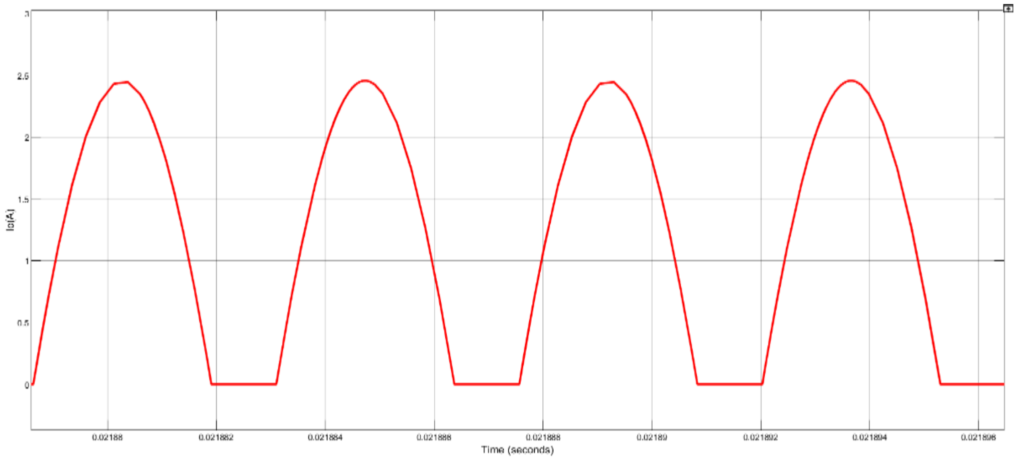

Fig. 14. The DC charging current of the 12V DC battery in the WPT system having connected spiral power harvesting coils.

Fig. 14 shows a DC charging the battery with a value of 2.5 Amps. The power consumed by the Class-E power amplifier driving the planar spiral transmitting coil of 67 uH is 29.4w (2.45A×12 V). The efficiency of a WPT is measured by how much power it is capable to harvest from a certain transmitting Source.

Table 2. Comparison between the WPT system and previous works.

Ref.	**Frequency (KHz)**	**Distance (mm)**	**Efficiency (%)**
[16]	40	300	85
[17]	100	300	81
[18]	60	200	82
[19]	20	160	80
[20]	31.6	200	74.8
This work	100	200	90

4 Conclusion

The wireless power transmitting system that uses electromagnetic induction technology to charge the electric vehicle battery has two coils, the first is transmitter coil and the second is the receiver coil, both of which have the same value of 67 μH and internal resistance of 32 mohm. A Class-E power amplifier type was used on an IRFP 250 switch and a 325 μF throttle switch. Implementation of this system using MATLAB program. The distance between the two coils was 20 cm. After implementing the program, an excellent quality factor was obtained, high efficiency up to 90%, and very little power loss.

Parameters

L= Inductance
N=Number of Turns of coil
C = Capacitance
R= Resistance
F = Operating frequency
P= Power
Q= Quality Factor
K= Coupling Factor

r_o= outer Radius of coil
r_i= inner Radius of coil
L_1= Inductance chock LRFC
T_X= Transmitting coil
R_X= Receiving coil
V_O= Output voltage/ Secondary coil voltage
Io = Output current/ Secondary coil current

References

[1] Kim, K.Y., Wireless power transfer-principles and engineering explorations. 2012.

[2] Chen, W.-T., et al., A 36 W wireless power transfer system with 82% efficiency for LED lighting applications. 2013. **6**(1): p. 32-37.

[3] Valenta, C.R. and G.D.J.I.M.M. Durgin, Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems. 2014. **15**(4): p. 108-120.

[4] Nagoorkar, V., Midrange Magnetically-Coupled Resonant Circuit Wireless Power Transfer. 2014.

[5] Zierhofer, C.M. and E.S.J.I.t.o.B.E. Hochmair, Geometric approach for coupling enhancement of magnetically coupled coils. 1996. **43**(7): p. 708-714.

[6] Kurs, A., et al., Wireless power transfer via strongly coupled magnetic resonances. 2007. **317**(5834): p. 83-86.

[7] Cannon, B.L., et al., Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers. 2009. **24**(7): p. 1819-1825.

[8] Kim, J., et al., Efficiency analysis of magnetic resonance wireless power transfer with intermediate resonant coil. 2011. **10**: p. 389-392.

[9] Choi, J., J.-K. Cho, and C. Seo. Analysis on Transmission efficiency of wireless energy transmission resonator based on magnetic resonance. in 2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications. 2011. IEEE.

[10] Zhong, W., C.K. Lee, and S.R.J.I.t.o.i.e. Hui, General analysis on the use of Tesla's resonators in domino forms for wireless power transfer. 2011. **60**(1): p. 261-270.

[11] Olivo, J., et al., A study of multi-layer spiral inductors for remote powering of implantable sensors. 2013. **7**(4): p. 536-547.

[12] Ahn, D., M. Kiani, and M.J.I.t.o.m. Ghovanloo, Enhanced wireless power transmission using strong paramagnetic response. 2013. **50**(3): p. 96-103.

[13] Song, C., et al., Low EMF and EMI design of a tightly coupled handheld resonant magnetic field (HH-RMF) charger for automotive battery charging. 2016. **58**(4): p. 1194-1206.

[14] Luo, Z. and X.J.I.T.o.I.E. Wei, Analysis of square and circular planar spiral coils in wireless power transfer system for electric vehicles. 2017. **65**(1): p. 331-341.

[15] Lee, Y.J.A., Microchip Technology Inc, Antenna circuit design for RFID applications. 2003.

[16] Covic, G.A., J.T.J.I.J.o.E. Boys, and S.t.i.p. electronics, Modern trends in inductive power transfer for transportation applications. 2013. **1**(1): p. 28-41.

[17] Dai, Z., et al., A witricity-based high-power device for wireless charging of electric vehicles. 2017. **10**(3): p. 323.

[18] Zeng, H., S. Yang, and F.Z.J.I.T.o.P.E. Peng, Design consideration and comparison of wireless power transfer via harmonic current for PHEV and EV wireless charging. 2016. **32**(8): p. 5943-5952.

[19] Gao, Y., et al. Misalignment effect on efficiency of wireless power transfer for electric vehicles. in 2016 IEEE Applied Power Electronics Conference and Exposition (APEC). 2016. IEEE.

[20] Nayak, P.S.R. and D. Kishan. Design and analysis of SS resonant IPT system with computed mutual inductance through FEM model. in 2018 International Conference on Power, Instrumentation, Control and Computing (PICC). 2018. IEEE.