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تحية طيبة وبعد،،

برجاء التكرم بالموافقة على دعم فريق من الطلاب البحاثين لتمثيل قسم القوى الكهربية وكلية الهندسة جامعة المنصورة في المؤتمر العالمي لمنظمة IEEE المقام في مدينة أسوان بعنوان "*IEEE CONFERENCE ON POWER ELECTRONICS AND RENEWABLE ENERGY*" في الفترة من 23 الى 25 أكتوبر 2019، وذلك بعد قبول نشر البحث المقدم من الفريق بعنوان "*Wireless Power Transfer for Toys and Portable Devices*"، حيث أن نشر مثل هذا البحث لمجموعة من الطلاب - تحت التخرج – من شأنه تعزيز مكانة الكلية البحثية محليًا وعالميًا. إجمالي قيمة رسوم التسجيل للمؤتمر والإقامة ومصاريف السفر تقدر بـ 9500 (تسعة آلاف وخمسمائة جنيه مصري فقط)، كما نحيط علم سيادتكم أن حضور المؤتمر يعد شرطًا لاستكمال قبول نشر البحث وإلا سيتم استبعاد البحث من النشر. فيما يلي أسماء الطلبة المشاركين في البحث:

1- عبد الرحمن محمد العطار	الفرقة الرابعة – قسم القوى والآلات الكهربية
2- على مصطفى البيلى	الفرقة الرابعة – قسم القوى والآلات الكهربية
3- عبد الرحمن شريف الجزار	الفرقة الرابعة – قسم القوى والآلات الكهربية
4- إسلام نجيب عبد اللطيف	الفرقة الرابعة – قسم القوى والآلات الكهربية
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6- عبدالحميد سالم وفيق	الفرقة الرابعة – قسم القوى والآلات الكهربية

مرفق لحضرتكم نسخة مطبوعة من البحث، ونسخة من إيميل القبول.

تفضلوا بقبول وافر الشكر والتقدير،

عميد الكلية
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رئيس قسم القوى والآلات الكهربية
ا.د/ سحر صدقى

Wireless Power Transfer for Toys and Portable Devices

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Abstract—**Powering electronic toys by replacing chargeable batteries or using wires are common technique, although these techniques are unsecure for the children. Providing an alternative source to power the toys is a pressing demand for kid safety. Transferring power to toys/portable devices wirelessly is an attractive and desirable technique due to eliminating the risks of replacing batteries or using cords for the toys. In this paper, a wireless power transfer (WPT) system is designed and built, to deliver power from a stationary source (primary coil) to a moving toy/portable device (secondary coil) via magnetic resonant coupling. The moving toy/device must be able to move freely, a novel primary coil design is proposed to cover the required space for the toys. Three-dimensional finite element analysis COMSOL software is used to investigate the magnetic flux density distribution of three different primary coil designs. The simulation results show the novel design of the primary coil that distributes the electromagnetic field uniformly at any location for the moving toy (secondary coil). To improve the coupling between the primary and secondary coils, a *ferrite core* is used to significantly increase of flux through the coil. Three different secondary coils are proposed to provide the required power to the toys, which are *air core*, *ferrite toroid*, and PCB coils. Experiments are conducted to measure the received power by the secondary coil wirelessly from the novel primary coil. The Experimental results show the maximum efficiency achieved when the *ferrite toroid* secondary coil is used.**

Keywords—Wireless Power Transfer, Magnetic Resonance, Power Amplifier, Finite Element Analysis, Portable Devices.

I. INTRODUCTION

Wireless power transfer (WPT) refers to transferring electric power from a source to a load without using wires. WPT systems have been used in various industry applications such as portable devices, biomedical, and electric vehicles due to its advantages. The major benefit of WPT is eliminating electric cords that may cause shocks, sparks, and fires. Moreover, WPT systems reduce the risk of the possibility of infection by wires piercing the skin (for medical applications), wire breakage, and undesirable replacement and corrosion of embedded batteries. It is also cost effective for consumers and utility as no wires, mechanical connector nor maintenance needed. There are many other benefits such as high reliability, expandability power range and flexibility in charging devices [1-2].

There are two main categories of WPT systems, radiative and non-radiative fields. The radiative fields also called electromagnetic radiation, in which power is transferred over long distances using laser or microwaves. In non-radiative fields power is transferred over medium and short distances such as capacitive coupling, inductive coupling, and magnetic resonance. The first prominent attempts in developing WPT systems were done by Nikola Tesla in 1890 [2-3].

Capacitive coupling transfers power between two electrodes using electric field, one of electrodes is connected to transmitter and the other is connected to the receiver. This capacitive technique is based on Maxwell's equations, and requires high voltage operation. WPT systems based on magnetic resonant coupling or inductive coupling can use two, three or four coils. After investigating the different techniques of the WPT systems, we decided to use a two coils system which is based on magnetic resonant coupling [2]. Inductive coupling and magnetic resonance techniques based on a two coils system transfer power form a transmitter/primary coil (L_P) to a receiver/secondary coil (L_S), where the power transfers via generated electromagnetic field from the primary coil. Both coils require a tight magnetic coupling between them, to overcome flux leakage, this technique is based on Ampere's and Faraday's laws [2-4]. Our application transfers power wirelessly to electric toys rather than batteries which would provide many merits such as; safety, weight, etc. Also, using the WPT system would be more flexible and useful for charging the electronic toys wirelessly in the future.

This paper is organized as follows. Section I provides the research motivation of using WPT system for toys. Section II describes the literature survey of using WPT systems for toys and portable devices. The methodology of our WPT system is described in Section III. Section IV describes the WPT theory. Simulation setup and results are reported in Section V. The experiment setup and results of our WPT are shown in Section VI. Finally, the conclusion is in Section VII.

II. LITERATURE REVIEW

There are many researchers developed WPT systems for portable devices and toys. In this section, a survey of WPT systems for toys/portable devices are described.

M. Fareq *et al.* designed and built a WPT system based on inductive coupling for charging mobile phone. Their DC supply was harvested from solar cells. They simulated the WPT system using NI Multisim software. The experiment results showed that the maximum induced voltage was 4.5 DCV, and the power was transferred up to 5 cm [5]. Their WPT system was not enough to charge mobile phone and the solar cells did not provide enough power to the WPT system. R. Lakshmanan *et al.* designed and built a WPT system integrated with a password security system. The induced voltage was rectified using a Cockroft Walton circuit. The experiments showed that the power transferred between two terminations across air medium and achieved an efficiency of 60% for no load and 36% for loaded [6]. S. Agrahari *et al.* designed a WPT system for charging a mobile phone from another mobile phone based on inductive coupling using bidirectional DC to DC converter. Their initial results showed that the developed WPT system can easily be made as a design in the backside of the mobile [1]. J. Youn *et al.* designed a WPT system to charge mobile and portable devices. Their WPT system was based on magnetic resonant coupling, which consists of four coils that are source, transmitter, receiver, and load coil. The transmitter and receiver coils were optimized for helical structure based on the simulation results using HFSS (High Frequency Structure Simulation) software. They used an impedance matching technique to compensate the change of the inductance and capacitance of the resonators. The experimental results showed that the maximum efficiency achieved was 73.8% [7]. Y. Roshan *et al.* designed a power electronic rectifier controller to increase the efficiency of transferred power in WPT system that was based on magnetic resonance coupling, their proposed system was simulated to investigate controlling/adjusting the impedance of the load for charging portable devices. They developed a modified incremental conductance algorithm to track the MPPT (maximum power point tracking). They modeled the system and analyzed it to ensure that the efficiency could be increased by adjusting the load resistance. The optimum resistance was calculated analytically and by simulation software PSIM [8]. C. Yang *et al.* designed a WPT system based on magnetic resonant coupling technique to charge portable devices on a desk, their system consisted of two helical antennas embedded into the monitor (transmitter) and the portable electronic devices (receiver). The structure of the two antennas were same, and the resonant frequency was 45.5 MHz. The experimental data showed that higher efficiency obtained when the two layers antennas and the impedance matching for the antennas were used [9]. P. Hao *et al.* proposed a technique to charge multiple devices (receivers) by using a priority technique in WPT system which based on magnetic resonance to improve the efficiency. They used Bluetooth to communicate between the devices and specify the priority that was function of the distance and the needed power. Their numeric results showed that the efficiency could be improved if the devices are charged in order based on priority [10]. M. A. Hassan *et al.* designed and built a WPT system for charging mobile phones based on the magnetic resonant coupling. Their model depended on series-series (SS) topology and the power was transferred at a frequency of 100 kHz in very short distance [11]. It is found that their system did not induce enough voltage because of the voltage, and they did not design/provide the charging system for the mobile phones. I. J. L. Paul *et al.* used a WPT system to design a charger system for any electronic devices which have batteries. The WPT and charger systems were simulated using ISIS simulation software. They developed a feedback system using a PIC microcontroller to control the input voltage [12]. Disney research team designed and built a WPT system inside a room 16×16 foot. Their system depended on quasistatic cavity resonance which involved induced current channeled through discrete capacitors in metalized walls, floor and ceiling to generate uniform magnetic fields in all places at the room [13].

III. METHODOLOGY

The main purpose of this work is to power toys wirelessly via magnetic resonant coupling. Our WPT system is based on a two coils system that are primary coil (stationary) and secondary coil (moving). A novel primary coil is designed and compared with two traditional transmitter coil designs. Finite element analysis (FEA) COMSOL software is used to simulate the generated electromagnetic field distribution of the three primary coil designs. Section V illustrates the comparison of the primary coils and using a *ferrite core* to improve the coupling between the primary and the secondary coils.

A power amplifier is designed to generate a high sinusoidal current go through the primary coil and generates electromagnetic field. The oscillating electromagnetic field will be captured by the receiver/secondary coil which moves freely around the perimeter of the primary coil. Experiments are conducted to measure the transferred power wirelessly, as shown in Section VI.

IV. THEORY

Our WPT systems is based on magnetic resonant coupling system. The power transfers wirelessly via electromagnetic field that is generated by an alternating current through a primary coil. This electromagnetic field induces voltage into a secondary coil. This induced voltage (V_{ind}) in the secondary coil can be expressed in terms of the primary current (I_P) as [14]:

$$V_{ind} = -\frac{N_p N_s \mu_0 \mu_r A_s a_p^2}{2(\sqrt{a_p^2 + r^2})^3} . j\omega I_p \qquad (1)$$

where, N_P is the number of primary turns, N_s is the number of secondary turns, μ_r is the relative permeability of a specific medium, μ_0 is the permeability of free space, A_S is the loop area of the secondary coil, a_P is the primary coil radius, and I_P is the current applied to the primary.

There are four topologies for achieving magnetic resonant coupling between the primary and secondary coils. The topologies are SS, SP, PP, and PS, where S means series compensation primary or secondary winding and P means parallel compensation primary or secondary winding. We found that the SP topology is suitable for our WPT system, as described in [2]. Fig.1 shows the wiring diagram of the SP topology.

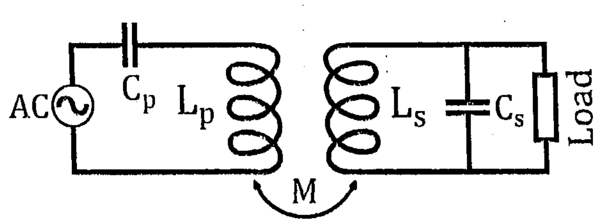


Fig.1: SP topology for our WPT system

The load impedance of the secondary resonator is calculated as a lumped impedance Z_S whose value depends on the secondary parallel compensation as given by [2, 15]:

$$Z_S = j\omega L_s + \frac{1}{j\omega C_S + (1/R_L)} \quad (2)$$

where, L_S is the inductance of the secondary side, C_s is the capacitance of the secondary side, and R_L is the load.

The loading effect of the secondary coil back onto the primary circuit causes a reflected impedance (Z_r) in primary circuit. It depends on the coupling factor and operating frequency, and it can be written as [15]:

$$Z_r = \omega M/Z_s, M = K\sqrt{L_S L_P} \quad (3)$$

where, M is the mutual inductance between the primary and secondary coils, and k is the coupling coefficient (value between 0 and 1). Our WPT system is considered loose coupling system because of the low coupling factor [1]. Substituting (1) into (2), the reflected impedance is obtained as:

$$Z_r = \frac{\omega^2 M^2 R_L}{{R_L}^2(\omega^2 C_S L_S - 1) + \omega^2 {L_S}^2} + j\frac{-\omega^3 M^2[{R_L}^2 C_S(\omega^2 C_S L_S - 1) + L_S]}{{R_L}^2(\omega^2 C_S L_S - 1) + \omega^2 {L_S}^2} \quad (4)$$

Our WPT system is based on magnetic resonant coupling,.and the operating frequency is the secondary resonant frequency (w_O), which is given by:

$$\omega_0 = \frac{1}{\sqrt{L_S C_S}} \quad (5)$$

The reflected impedance at the resonant frequency can be calculated from (3) and (4) [15]:

$$Z_{r_0} = \frac{M^2 R_L}{L_S^2} + j\frac{-\omega_0 M^2}{L_S} \quad (6)$$

The primary capacitance used for SP topology can be obtained by [2, 15]:

$$C_P = \frac{1}{\omega_0^2(L_P - {M^2}/{L_S})} \quad (7)$$

The literature shows that the transferred the power depends on the quality factor of the primary or secondary coils ($Q_{S,P}$), which can be obtained by:

$$Q_{S,P} = \frac{R}{\omega_0 L_{S,P}} \quad (8)$$

The transferred real power (P_O) via the magnetic resonant coupling is defined as [14]:

$$P_O = \frac{{V_{ind}}^2}{R_L} \quad (9)$$

V. SIMULATION SETUP AND RESULTS

In this paper, we designed a novel design of the primary coil (L_P). Three primary coil designs are proposed and simulated to find the best candidate design of the primary coils. We used FEA COMSOL software to simulate the generated electromagnetic field of the three primary coil designs. The first is a rectangular coil shape (Fig.2 (a)) and the second is a figure 8 shape coil (Fig.2 (b)). The outer dimensions of each coil are 50x29x1 cm^3. Each coil consisted of 7 turns and were wrapped under a piece of wood. We used *Tetrahedral* meshing setting, the total number of meshing points were 56477 and 73971 for the rectangular coil and figure 8 shape coil, respectively. A sphere was used which mimics the surrounding area (*air core*). A *Frequency Study* was used to simulate the magnetic field distribution, the *Edge Current* constraint was set to 4 A to go through the primary coils.

Fig. 2 shows the magnetic flux density distribution in the x-y plane at 1.7 cm of z-axis for the rectangular and figure 8 shape coils. The maximum flux density was about 4 µT. The magnetic flux density distribution of the figure 8 shape coil is better than the rectangular coil, where there is a significant increase in the magnetic flux density at the middle/center of the coil. Fig. 3 illustrates the arrow flux lines in z-y axes. The both coils show same profile of the flux path at the edges, although the arrow flux at the center of the figure 8 shape coil is denser than the rectangular coil. However, the figure 8 shape coil shows less magnetic flux distribution at the middle edges than the rectangular coil, so the both shapes do not cover the magnetic field uniformly for the moving secondary coil.

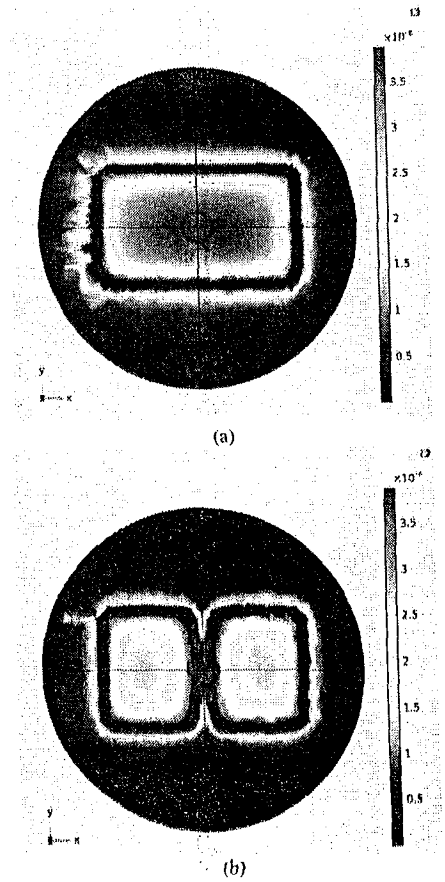
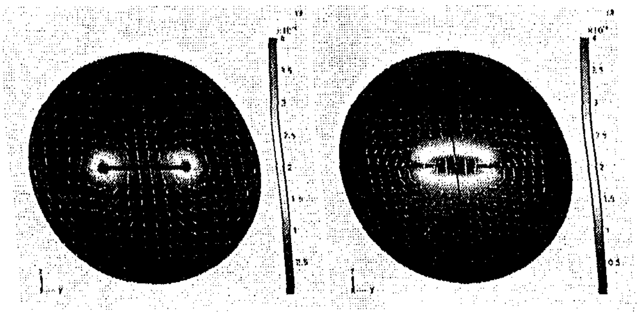
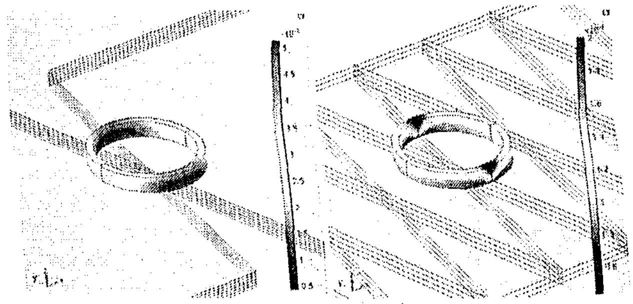


Fig. 2: Magnetic field density in x-y plane at 1.7 cm of; (a) rectangular shape coil, and (b) figure 8 shape coil



(a) (b)

Fig. 3: Arrow flux lines distribution in the z-y axes; (a) rectangular shape coil, and (b) figure 8 shape coil



(a) (b)

Fig. 5: 3D magnetic field volume of *ferrite core*; (a) rectangular shape coil, and (b) hybrid coil

To overcome the problem of covering the generated magnetic field of the figure 8 shape and rectangular coils, a new coil design is proposed. This novel primary coil is a hybrid of the two coils, as shown in Fig. 4. This coil is denoted as hybrid coil, which consisted of 4 turns rectangular and 3 turns cross-winding turn alternately. In the cross-winding turn, the current direction was taken into consideration to avoid the magnetic field cancelation. The total *Tetrahedral* meshing points are 51942. Fig. 4 shows the magnetic field distribution at x-y plane of the novel coil design at the same height (z=1.7 cm) in comparison with Fig. 2.

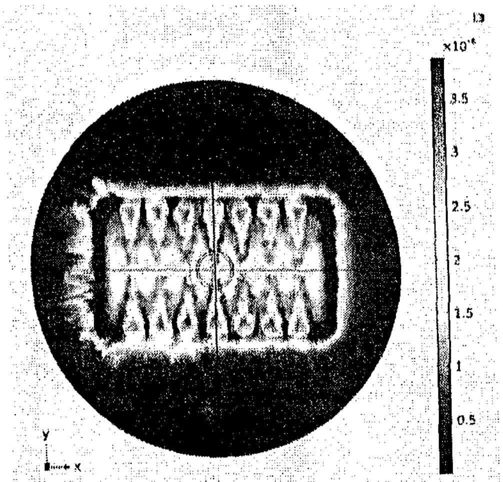


Fig. 4: Magnetic field distribution at x-y plane of the novel coil

The previous simulation results used *air core*. To improve the coupling between the primary and secondary coils, a piece of *toroid ferrite* is used as a receiver core. The toroid has a radius of 4 cm, height of 1.2 cm, and thickness of 0.5 cm. The air gap between the toroid bottom surface and the upper turn of the coil is set to be 0.5 cm in the z-axis. The *Tetrahedral* meshing setting was used also for the ferrite toroid. Fig. 5 shows the 3D magnetic field volume of the *ferrite toroid* at the middle/center of the figure 8 shape and the hybrid primary coil designs. The simulation results that the hybrid coil design is the best option for our application, where the generated electromagnetic field covers the required space area for the toys uniformly.

VI. Experiment Works

This section describes the experiment setup and results of our WPT system. The block diagram of our WPT system is shown in Fig. 6, where a DC source powers the WPT system. A power amplifier (Class-E) is used to convert the DC power to AC power and generate sinusoidal current (I_P). This sinusoidal current flows through the primary coil windings and generates sinusoidal electromagnetic field. The secondary coil (L_S) captures the generated magnetic field and induces voltage. A resonant tank and the Class-E power amplifier are configured to achieve the magnetic resonant coupling of the SP topology.

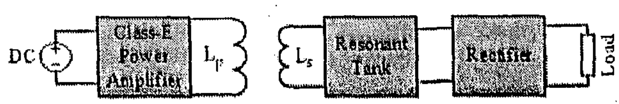


Fig. 6: block diagram of WPT system

A. Power Amplifier

Fig. 7 depicts the schematic diagram of series resonance Class-E power amplifier. It consists of a DC supply (V_{DD}), a DC-feed inductor (L_{choke}), a switch (MOSFET), the ESR of the windings of the primary coil (R_P), a parallel capacitor (C_{par}) with the MOSFET, and a series resonant circuit (L_P &C_{ser}). The power losses of the amplifier are minimized at the operating frequency (resonant frequency). The efficiency is maximized by minimizing power dissipation of the Class-E power amplifier. This is achieved when the MOSFET voltage (V_{DD}) or the voltage across the capacitor (C_{par}) is zero, and its derivative should be zero at switch closure. Otherwise there will be power losses due to the simultaneous large current through and voltage across the MOSFET. The output current in the (L_{coil}) and (C_{ser}) is sinusoidal with a frequency equal to the frequency of the MOSFET drive (V_G) [2, 16].

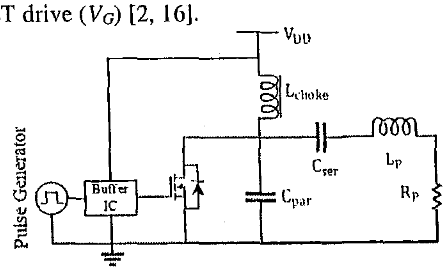


Fig. 7: Class-E power amplifier

Class-E power amplifiers have many parameters and variables that affect the performance of the WPT systems. The derivations of design equations are carried out for achieving the Class-E operation, which are described in [2, 16]. The inductance and the quality factor of the hybrid primary coil are measured using an LCR meter at 55 kHz, which are 73 μH and 21, respectively. The C_{ser} and C_{par} are calculated [2]:

$$C_{par} = \frac{1}{2\pi f \, R_p 5.447} \quad (10)$$

$$C_{ser} = \left(\frac{1}{(2\pi f)^2 L_p}\right)\left(1 + \frac{1.42}{Q_P - 2.08}\right) \quad (11)$$

The numerical values of the (C_{ser}) and (C_{par}) are 123 nF and 443 nF, respectively. LTspic software is used to simulate the Class-E power amplifier. Fig. 8 shows the simulation results of the output voltage of the amplifier (blue line) and the V_{DS} voltage (red line). The output RMS voltage and current of the Class-E are 122.7 V and 5.3 A, respectively, when the V_{DD} is set to 12 V, as shown in Fig. 9.

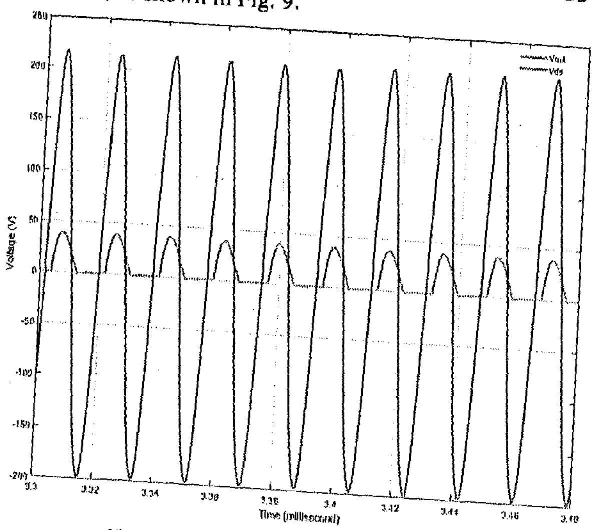


Fig. 8: Simulation results of power amplifier

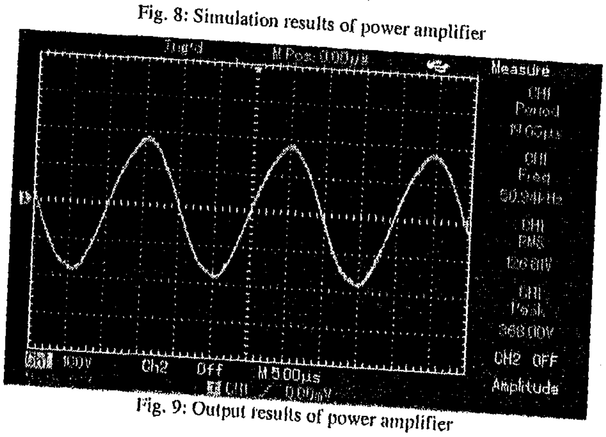


Fig. 9: Output results of power amplifier

B. Experiment Setup

Fig. 10 illustrates the experiment setup of our WPT system. Three different secondary coils are used, which are *air core*, *ferrite toroid core*, and PCB coil (two layers). The secondary coil is mounted in the bottom of the car toy, as shown in Fig. 10 (*air core*). Table I lists the main parameters of these secondary coil prototypes. For the *ferrite toroid* prototype, two identical coils are connected in series, so the total inductance 29.5 mH. The induced voltage by the secondary coil powers the electronic circuits of the car toys. The following subsection illustrates the experimental results

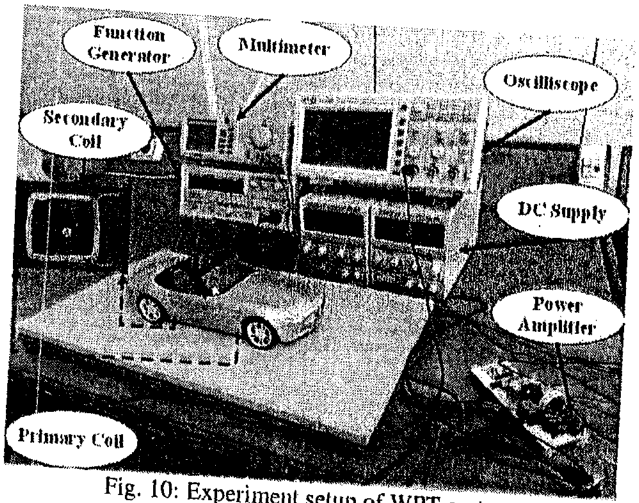


Fig. 10: Experiment setup of WPT system

TABLE I. PARAMETERS OF SECONDARY COILS

Coil Type	Dimension (cm)	Number of Turns	Inductance (mH)
Air Core	6×6.5	5	0.01
Ferrite Toroid	4×1.2×0.5	40	14.75
PCB Coil	XX	XX	XX

C. Experimental Results

This section shows the experimental results of our WPT system. Experiments with the three prototype secondary coils are conducted to measure the power transfer between the primary and secondary circuits. The experiments varied two independent parameters: the position of the secondary coil with respect to the primary coil and the current (I_p) applied to the primary coil (0.5, 1, 1.5, and 2 A RMS). The resulting voltage induced in the secondary circuit is measured by a voltage probe across the load (R_L), where a twisted cable is used to connect between the output of rectifier and R_L. The twisted cable is used to eliminate the EMI and noise signals [17]. The received power is calculated as shown in equation (9), where the used R_L is 10 kΩ.

THE REMAINING CONTETS OF EXPERIMENTAL RESULTS (SECONDARY COILS, RECEIVED POWER AND ANALYSIS) WILL BE ADDED

VII. CONCLUSIONS

THIS INFORMATION OF THIS SECTION WILL BE PROVIDED.

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Fwd: [CPERE 2019] Your paper #1570549268 ('Wireless Power Transfer for Toys and Portable Devices')

1 message

Abdulrahman Al-Attar <ab.attar.g@gmail.com> Mon, Jul 15, 2019 at 1:47 PM
To: khalouda2991@gmail.com

---------- Forwarded message ---------
From: **(orabi@ieee.org)** <orabi=ieee.org@edas.info>
Date: Mon, Jul 8, 2019, 9:13 PM
Subject: [CPERE 2019] Your paper #1570549268 ('Wireless Power Transfer for Toys and Portable Devices')
To: Abdulrahman Al-Attar <Ab.Attar.g@gmail.com>, Ali Al-Bialy <e.Ali.bialy@gmail.com>, Abdulrhman S. Al-Gazar <a.shalgazar96@gmail.com>, Eslam Abdelatif <eslamnageb01182@gmail.com>, Sabry Attia <sabryattia2025@gmail.com>, Abdelhamid Salem <abdelhameedsalem@gmail.com>, Basem Badr <bbadr@uvic.ca>
Cc: M. Hamad <mostafahamad1177@gmail.com>, Mostafa Marei <mostafamarei@ieee.org>, <orabi@ieee.org>

Dear Mr. Abdulrahman Al-Attar:

Congratulations! Your paper No#1570549268 entitled ('Wireless Power Transfer for Toys and Portable Devices'), has been **accepted** for the 2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE), to be held in Movenpick Resort, Aswan, Egypt from October 23-25, 2019. We look forward to your participation and presentation at CPERE2019.

You will receive another email soon for the decision about the session title and paper type (Oral/Poster).

The full Conference schedule will be available on the CPERE 2019 web site very soon. Be sure to check the conference web site (http://www.ieee-cpere.org/) often as important information is posted regularly on this site. If there are additional co-authors for this paper, please make sure to inform them of this decision.

The reviewers' comments are included below or can be found at https://edas.info/showPaper.php?m=1570549268 for your information, to assist you in improving your paper prior to final submission. The Technical Program Committee cannot give any further clarification and you do not need to explicitly respond to them.

Registration Payment:

In order to guarantee inclusion in the conference program one author must be registered by July 31, 2019, the author deadline. Register details will be send soon

Conference registration is REQUIRED in order to receive an invitation letter.

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3. Your full paper in PDF format must be submitted no later than July 31, 2019 at this web site: https://edas.info/showPaper.php?m=1570549268. Your paper must comply with the specifications outlined on the web site.

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Presentation Information

1. Presentation template & guidelines will be provided sometime in August.

Please accept our thanks for submitting your paper to CPERE 2019. We look forward to seeing you in Aswan, for an interesting and exciting Conference.

Sincerely, Mohamed Orabi, IEEE Senior Member
Conference Chair

======= REVIEW 1 =======

*** Readability: Readability Barely Acceptable (3)

*** Originality: Originality Barely Acceptable (3)

*** Significance: Significance Barely Acceptable (3)

*** Relevance: Relevance Barely Acceptable (3)

*** Overall: Overall Barely Acceptable (3)

*** Recommend: Do you recommend this paper as a candidate of the best paper award? [yes, no, maybe]

*** Comment for author: Comment for author

Conclusion is missing? Figures need to be plotted in more professional way Please follow IEEE format

======= REVIEW 2 =======

*** Readability: Readability Acceptable (4)

*** Originality: Originality Acceptable (4)

*** Significance: Significance Barely Acceptable (3)

*** Relevance: Relevance Barely Acceptable (3)

*** Overall: Overall Acceptable (4)

*** Recommend: Do you recommend this paper as a candidate of the best paper award? [yes, no, maybe]

no

*** Comment for author: Comment for author

The missing section should be completed. The sections captions should be more descriptive. Words like "We" and "Our" are note recommended.