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Design of a WPT System Equipped with Three Receiving Coils for Power Harvesting Purposes

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Abstract: The transfer of power from one point to another without using any wire is one of the most efficient modern technologies. It satisfies the urgent need for the emergence operation of small mobile devices such as laptop, mobile, inaccessible sensors and others. Because of the short and limited lifetimes of batteries, the difficulty of their replacement and their inaccessible locations, charging them wirelessly reveals as an urgent need in this era. Wireless Power Transfer or transmission (WPT) now a days represents an effective technology to offer satisfactory solutions to the problems mentioned above. In this research, a proposed WPT system designed and tested on PSpice, Orcad 16.6 is introduced in addition to a review of previous works covering different technologies of WPT systems. The operating frequency of the proposed WPT system is 63.5 kHz and the DC supply Voltage is 12 V. The proposed system is driven by a class-E power amplifier having a planar spiral coil as transmitting antenna. The proposed WPT system comprises one planar spiral transmitting coil 150 cm apart from three parallel connected planar spiral receiving coils. The power harvesting capability of the receiving circuit of this system is 132 mW. It is verified that the power harvesting capability of any WPT increases with the decrease in the reactance of the receiving circuit, thus, parallel connection of power harvesting coils is recommended.

Key words: Wireless power transfer, power harvesting, wireless powering, class-E amplifier, batteries, reactance

INTRODUCTION

In recent years, interest in wireless transmission technology has begun to grow rapidly. The technology can be used to 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 are some vital and daily applications that require Wireless Power Transfer (WPT). Wireless energy can be transmitted in various ways and techniques such as resonant inductive coupling and capacitive coupling based on electromagnetic radiation, microwaves, lasers, etc., (Kim, 2012; Chen *et al*., 2013). One of the major challenges and difficulties facing the researchers in this field is how to improve capturing largest possible amount of energy using the techniques mentioned earlier. This process is known as energy harvesting. During 1891 Nikola Tesla made the beginning experiments in WPT and demonstrated the wireless energy transmission using the resonant radio frequency transformer called the Tessa's coils that produced high frequency alternating currents, high voltage and low output current. After a short period of time, 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 it without any danger (Nagoorkar, 2014). Since, the invention of wireless devices this technology has evolved. In wet environments, wireless charging pads for devices such as electric razors and electric tooth brushes are utilized to reduce the risk of harmful electric shock.

Zierhofer and Hochmair (1996) demonstrated that 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 reversed when distributed at the circumference. Using a strongly coupled system, the experimental results by Kurs *et al.* (2007) showed that 60 W were transferred with an efficiency of about 40% at a distance of 2 m. 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 25 cm. The resonance frequency was 9.9 MHz. Capacitors paralleled with a coil were used by Cannon *et al.* (2009) to achieve resonance between transmitter and receiver coils which in turn consisted of two large coils, each with a diameter of 30 cm at a distance of 3.8 cm from each other. The power was transferred up to 50% with a frequency of about 8.3 MHz. Kim *et al.* (2011) showed that the efficiency and distance between transmitter and receiver

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could be enhanced in the WPT system by using an intermediate coil between the transmitting and receiving antennas. 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 by Choi and Seo (2011). The wireless power transfer and harvesting was obtained using magnetic resonance. The transmitter coil diameter was 60 and 20 cm apart from 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 similar to the size of the iPhone 4. The printed coil inductors were used by Zhong *et al.* (2013) at 13.56 MHz and implemented with implanted sensors. The transmission of power was 15 mW at a distance of 6 mm while at 17 mm, the transmission of power had approached 1.17 mW. The wireless power transmission and harvesting system with Tesla's resonators was introduced by Olivo *et al.* (2013). In order to obtain an efficiency above 75% with a resonance frequency extending from (503-525) kHz, the resonators were arranged in a domino-like axis at a distance of 3 m, 8 W 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 by Ahn *et al.* (2014), 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 by Song *et al.* (2016), Luo and Wei (2018) inductive magnetic resonance coupling was adopted to provide very high energy at short distances which can be used for the purpose of wireless charging of electric vehicles such as cars and Handicapped vehicles.

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 three parallel connected power harvesting coils followed by a suitable rectifying circuit and driving a certain electrical load.

The AC transmitting circuit consists of a class-E power amplifier driving a planar spiral transmitting coil R_X. The receiving coils T_{x1}-T_{X3} are also planar spiral coils located axially and perpendicularly with the transmitting coil on an axis passing through their center points as shown in Fig. 2. Each two adjacent receiving coils are 9.5 cm apart and the transmitting coil is 150 cm apart from the closest receiving coil R_{X1} (Fig. 3-5).

The coefficient of coupling k between two planar spiral coils located as shown in Fig. 2 is given by Lee (2003):

$$k = \frac{1}{\left(1+2^{\frac{2}{3}}\left(\frac{h}{\sqrt{r_t * r_r}}\right)^2\right)^{\frac{3}{2}}} \tag{1}$$

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 are given by Lee (2003):

$$L = \frac{(0.3937)\times(a\times N)^2}{(8\times a)+(11\times b)} \tag{2}$$

$$R_{low\ frequency} \approx \frac{1}{\sigma \Pi a^2}\left[1+\frac{1}{48}\times\left[\frac{a}{\delta}\right]^2\right] \tag{3}$$

Where:

N = Coil Number of turns

δ = Skin depth

σ = Conductor material conductivity

a, b and δ are given by:

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

$$b = r_0 - r_i \tag{5}$$

$$\delta = \frac{1}{\sqrt{\mu \pi \sigma f}} \tag{6}$$

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 19.05 mm and length of 14 m. Since, the adopted separation distance between each two adjacent turns is 2 mm, the outer and inner diameters become 660 and 130 mm, respectively as shown in Fig. 3. According to Eq. 2, the self-inductance L_1 of the transmitting coil T_X is 57.7 uH, the value of the self-inductance L_1 determined according to the analysis program (ANSYS electromagnetics Software 2016) is 42 uH and the experimentally measured value is 43 uH. The thickness of the copper tube used in implementing the transmitting coil is 0.81 mm. Using Eq. 3, the low frequency resistance R_1 of the transmitting coil is calculated as 0.011 Ω. Each receiving coil is wound of a copper wire having a Gauge of 14 (1.62824 mm of diameter) and length of 5 m. Using the same methodology

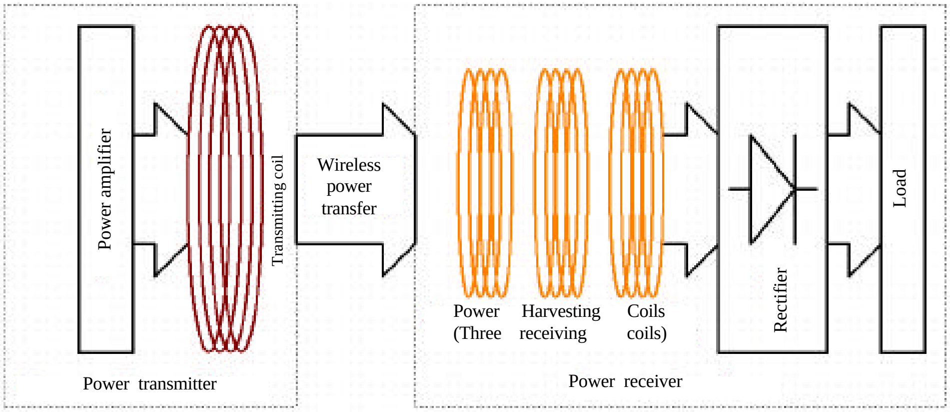

Fig. 1: The block diagram of a proposed power harvesting system having three parallel power harvesting coils

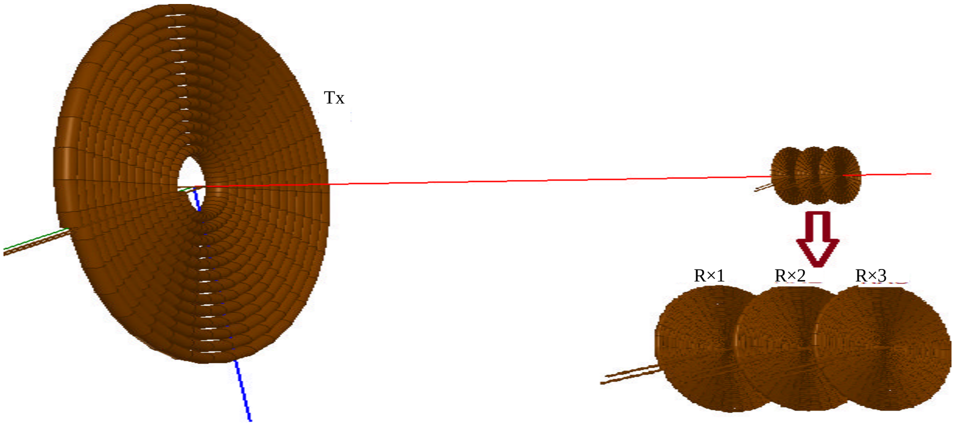

Fig. 2: The orientation of the power transmitting coil and power harvesting coils in the proposed WPT system

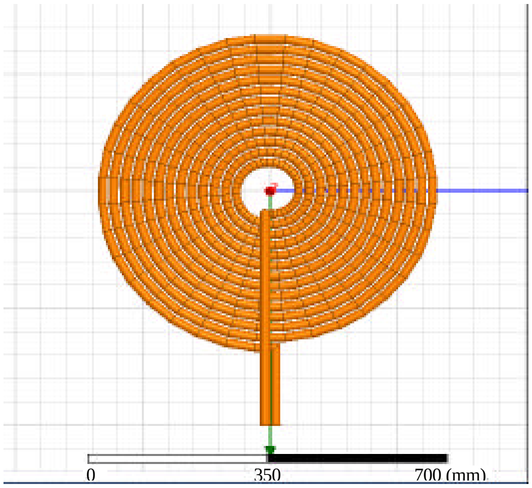

Fig. 3: The designed transmitting coil

for inductance and resistance calculations, the self and resistances of receiving coils are listed in Table 1. In this table, L_2 and R_2, L_3 and R_3 and L_4 and R_4 are corresponding to receiving coils, R_{X1}-R_{X3}, respectively.

Table 1: Calculated and measured parameters of transmitting and receiving coils

Parameters	Inductance (uH)	Resistance (Ω)	r_i (mm)	r_0 (mm)	No. of turns
L_1 of T_X	43	0.011	65	330	13
L_2 of R_{X1}	40	0.023	1	65	30
L_3 of R_{X2}	40	0.023	1	65	30
L_4 of R_{X3}	40	0.023	1	65	30

Table 2: Coupling coefficients between transmitting and receiving coils

K_{12}	K_{13}	K_{14}	K_{23}	K_{34}	K_{24}
0.00046	0.00039	0.00033	0.1087	0.1087	0.0180

In Table 1, the measured inductances are listed. Using Eq. 1 and the parameters of the designed transmitting and receiving coils, the inductive coupling coefficients between coils are summarized in Table 2. In this table, K_{12} represents the inductive coupling coefficient between the transmitting coil T_X and the first receiving coil R_{X1} and K_{23} represents the coupling

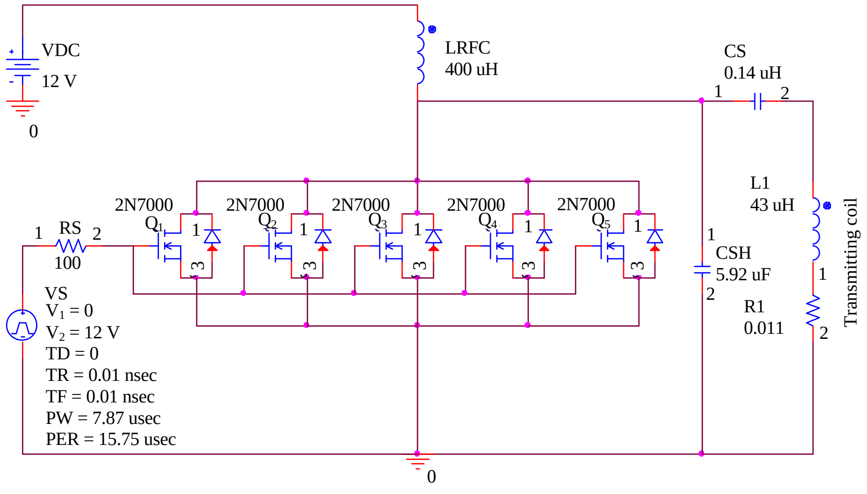

Fig. 4: The proposed class-E power amplifier

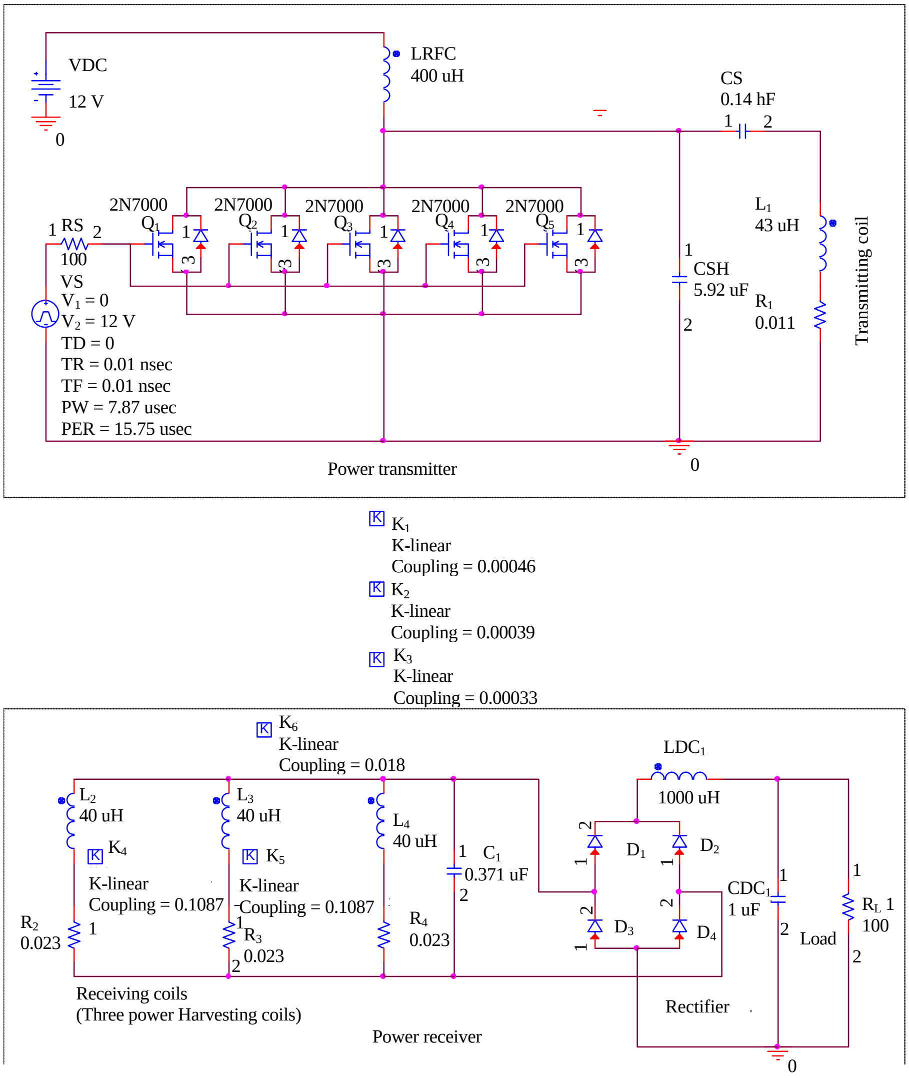

Fig. 5: The circuit design of a proposed WPT system

coefficient between the receiving coils R_{X1} and R_{X2}. Since, the distance between the transmitting coil and the closest receiving coil R_{X1} is very much greater the separation distances between the coils of the transmitting circuit, the inductive coupling coefficient K_{13} between the transmitting coil T_X and the second receiving coil R_{X3} is approximately equal to the inductive coupling coefficient K_{12} between the transmitting coil T_X and the first receiving coil R_{X1}. To some extent, the inductive coupling coefficient K_{14} between the transmitting coil T_X and the third receiving coil R_{X3} is approximately equal to the inductive coupling coefficient K_{13} between the transmitting coil T_X and the second receiving coil R_{X2}.

Power amplifier design: In 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, five parallel connected MOSFET of the type 2N7000 are chosen as main switching device of the class-E power amplifier. The series Capacitor C_S and L_1 are tuned to a resonance frequency slightly less than the proposed WPT frequency which is 63.5 kHz. The shunt or parallel Capacitor C_{SH} is determined such that the parallel combination constituted by L_1C_S and C_{SH} resonates at 63.5 kHz which complies with the MOSFET transition frequency specified in its datasheet. The inductance of the radio frequency choke L_{RFC} is chosen to be very much $>L_1$. The MOSFET is liable to be triggered by a square wave of positive level in the range of 7-12 V. The amplifier DC Voltage is 12 V. Figure 4 shows the complete circuit diagram of class-E power amplifier which is designed on PSpice of Orcad 16.6.

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 three parallel connected planar spiral power harvesting coils followed by a rectifying circuit driving a certain load as receiving circuit. The proposed system is designed on PSpice as shown in Fig. 5. The three parallel power harvesting coils are tuned to resonate at a frequency of 63.5 kHz by the Capacitor C_1, which is set to 0.371uF. The coupling coefficients in the PSpice design designated by K_1-K_6 are representing K_{12}, K_{13}, K_{14}, K_{23}, K_{34} and K_{24} in Table 2, respectively. The class-E power is the same as that specified in Fig. 4 and is driven by a 12 V DC supply and triggered by square wave of positive level of 12 V and having a frequency of 63.5 kHz.

RESULTS AND DISCUSSION

The performance of the power amplifier proposed in Fig. 4 was tested on PSpice. The triggering Voltage V_S to the switching device is shown in Fig. 5 and 6. The figure shows a square wave of frequency of 63.5 kHz and DC positive voltage level of 12 V. The switching MOSFET drain voltage and the DC supply voltage is shown in Fig. 7.

The DC current I_{DC} drawn by the power amplifier and the AC current i_{TX} flowing in the transmitting coil is shown in Fig. 8. The AC voltage V_{TX} across the terminals of transmitting coil is shown Fig. 9. It is obvious that the amplitude of the AC voltage across the terminals of the transmitting coil is about 823 V. The DC current I_{DC} drawn by the amplifier is about 8 A.

The performance of the proposed WPT system shown in Fig. 5 was tested on PSpice. The AC and DC voltage outputs of the receiving circuit for a load resistance of 100 Ω are shown in Fig. 10. The figure shows an AC voltage amplitude of 5.7 V and DC voltage level of about 3.2 V. The AC and DC voltage outputs of the receiving circuit for a load resistance of 200 Ω are shown

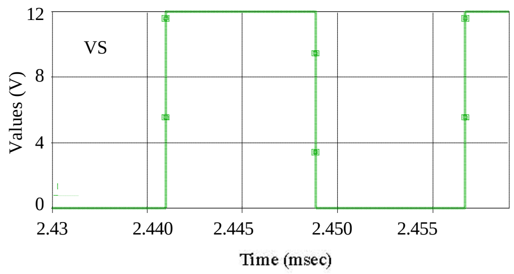

Fig. 6: The proposed class-E power amplifier triggering voltage; V(VS: +)

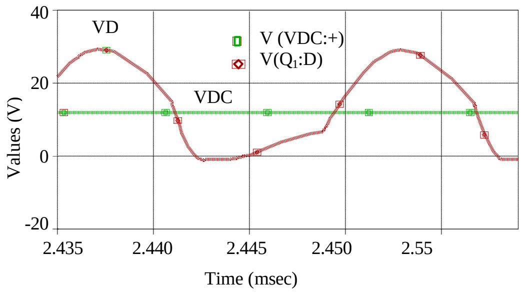

Fig. 7: The DC supply voltage and MOSFET drain voltage of class-E power amplifier

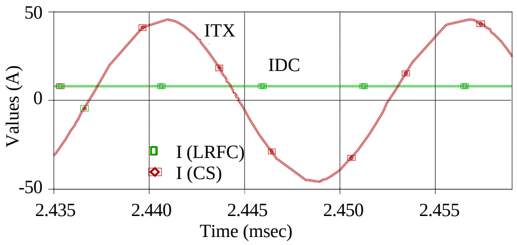

Fig. 8: The DC current and transmitting coil AC current of class-E power amplifier

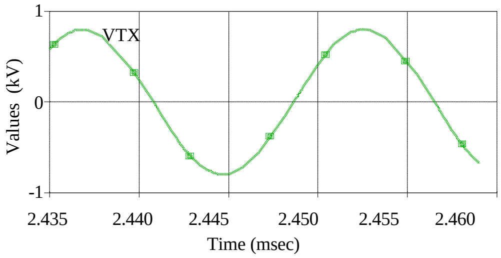

Fig. 9: The AC voltage of the transmitting coil of class-E power amplifier; V(L_1: 1, L_1: 2)

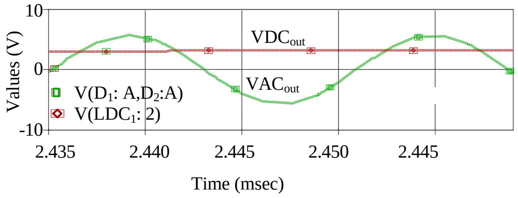

Fig. 10: The AC and DC output voltages of the WPT system having three parallel connected spiral power harvesting coils for RL = 100 Ω

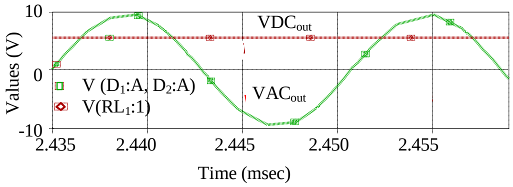

Fig. 11: The AC and DC output voltages of the WPT system having three parallel connected spiral power harvesting coils for RL = 200 Ω

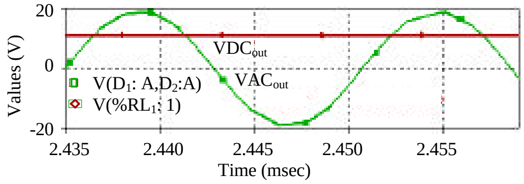

Fig. 12: The AC and DC output voltages of the WPT system having three parallel connected spiral power harvesting coils for RL = 1000 Ω

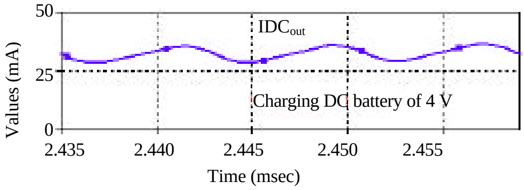

Fig. 13: The DC charging current of 4V DC battery in the WPT system having three parallel connected spiral power harvesting coils; I(V_1)

in Fig. 11 which shows an AC voltage amplitude of 9.5 V and DC voltage level of about 5.65 V. The AC and DC voltage outputs of the receiving circuit for a load resistance of 1000 Ω are shown in Fig. 12 which shows an AC voltage amplitude of 16 V and DC voltage level of 10 V.

It is obvious that DC and AC output voltages increase with the increase of the load resistance. The load resistance R_{L1} in Fig. 5 was replaced by a chargeable DC battery of 4 V. Figure 13 shows the charging current of this battery. The charging currentis about 33 mA.

The simulation results of the proposed WPT system reveals a power harvesting capability of 132 mW (33 mA×4V) which represents the charging capability of this proposed system to a chargeable battery of 4 V. Low resistance in parallel with an LC circuit is reflected in series RLC having significant resistance which in turn reduces the series resonance current determining the amount of harvested power. The power consumed by class-E power amplifier driving the planar spiral transmitting coil of 43 uH is 96W (8A×12 V). The efficiency of a WPT is measured by how much power it is capable to harvest from a certain transmitting source.

CONCLUSION

The proposed WPT system comprising three parallel connected planar spiral coils as power harvesting coils is designed and tested on PSpice. The capability of power harvesting of this system is 132 mW which represents a considerable amount of power harvested at a distance of 150 cm from the power source. The data of the power harvested by the receiving circuit of this system reveal that the low reactance coil harvests more power than that having high reactance or inductance. Consequently, parallel connection of power harvesting coils are recommended and series connection is not preferable. Even though, the transmitted power is high and the harvested power is low, powering inaccessible nodes like sensors embedded in human body is very much valuable and the efficiency of the WPT system in such cases is measured by how much power it can harvest from a certain power transmitter.

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