Effect of Circular Coil Dimension on Resonant Coupling Wireless Power Transfer System

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***Abstract*—A wireless power transfer system based on the resonant inductive coupling circuit with an additional short-range distance detection was carried out. The hardware-implemented system can be divided into four components, namely the circular coils, transmitter and receiver circuits for power transmission and microcontroller-based distance detector for the monitoring system. As the resonating capacitor is constant (1 μF), different sets of inductive coils for the antenna of transmitter and receiver circuits depending on a number of turns (N) and diameter (D) were fabricated. The effect of circular loop resonant coil diameter was investigated on the output voltage and resonant frequency. The system is capable of transferring electrical energy with the maximum output voltage (V_{OUT}) at the receiver circuits is 27.3 V. The maximum gap distance between the transmitter and receiver coils is 10 cm, corresponding to the V_{OUT} of 4.4 V. Other than that, the maximum output power transfer (P_{MAX}) at the receiver circuit is 15.6 W. In addition, a short-range distance detection system using an Arduino MEGA microcontroller was built to automatically monitor the output voltage with respect to the air gap distance.**

***Index Terms*—Circular Loop; Resonant Coil; Microcontroller; Resonant Inductive Coupling; Wireless Power Transfer.**

I. Introduction

Recently, a wireless power transfer in the short-range distance has been comprehensively developed, especially for smartphone and tablet applications. However, as the innovative technologies and emerging solutions enabled by users are becoming integrated into every aspect of our daily lives, such wearable electronics with different sizes and forms require frequent charging with various standards in chargers. Eventually, this situation requires an innovative solution to ensure that the power supply works in a manner that is equally convenient as the electronic device itself.

Currently, most of the wearable electronics are using the power source to operate. The operation requires a physical connection for powering or charging from a power source. This device has a potential growth in the near future. Furthermore, wearable electronics connected to the internet of things (IoT) are expected to grow by ten times more than the human population over the next decade [1]. Thus, the wireless power transfer technology offers an energy transmission of electrical power from a source to a contactless load across an air gap to provide cable and connector-free solutions for charging wearable electronics.

This paper describes the electrical output parameters and the gap distance of the wireless power transfer system using different circular loop resonant inductive coil dimensions. Moreover, an automatic monitoring system using microcontroller has been developed to provide the output parameter with respect to the distance.

II. Background Study

In principle, the theoretical and technological aspects on wireless power transfer have been found from the beginning of the 20th century. However, the corresponding technology has become mature enough to be used in practice and to be commercialized. In particular, it has been reported that through strongly coupled magnetic resonance, the efficiency of transferring 60 W of power over a distance in excess of 2 m is as high as 40% of efficiency [2]. Furthermore, the improvement of wireless power transfer over a distance up to approximately 0.9 m was demonstrated with a similar output power of 60 W with 75% of efficiency [3].

Table 1
Wireless Power Transfer using Resonant Inductive Coils

Approach	Frequency (Hz)	Distance (cm)	Max. Power (W)
Resonant Inductive Multi-coil (4 coils) Wireless Charging System [7]	700 k	5.0	0.18
Resonant Inductive Coupling [8]	120 M	2.5	1.36 m
Resonant Inductive Multi-coil (3 coils) wireless Charging System [9]	2.5 M	5.0	1.2
Inductive Coupling with microfluidic coils [10]	4 M	1.5	130 m
Inductive Coupling with dipole coils [11]	20 k	0.7	11.1 m
Ultra Low Inductive Coupling [12]	62.5 k	1.0	0.6 m

The coupling coefficient is one of the important factors towards maximizing the efficiency of wirelessly transfer power and vitally influenced by the distance between the two coils. Therefore, the wireless energy cannot be carried over a distance longer than a few millimeters to obtain a high-efficiency output. Basically, the operating frequency of inductive coupling is in the kiloHertz (kHz) range. The high-quality factor helps to reduce the drastic decrease in coupling co-efficiency and charging efficiency with the increase of gap charging distance. As a result, extending the effective power transfer distance to meter range is possible.

The secondary coil can be tuned at the operating frequency to improve charging efficiency [4]. The maximum power transfer was achieved in the efficiency of 92.6% as demonstrated over the distance of 0.3 cm with an up-to-date prototype [5]. The magnetic resonant coupling was also applied between one transmitting resonators to many receiving resonators [6]. Table 1 summarizes the wireless power transfer approach using resonant inductive coils over resonant frequency, distance and output power.

III. COIL DIMENSION

The inductive coupling charging works by transferring the energy across a gap using an electromagnetic field, which is contactless with the electrical load. The basic principle of an inductively coupled power transfer system consists of transmitter and receiver coils [2]. There are several approaches to design coils for wireless power transfer, such as circular coils [13-14], rectangular coils [15] and spiral coils [16]. Two resonant coils are strongly coupled when both coils are operating at the same resonant frequency. The circular coils are most commonly used in wireless power transfer systems.

A. Transmitter Coil

Figure 1 shows the transmitter coil (TX) that uses a center tapped type with three pins. The center tap is a contact made to a point halfway along a winding of the coil. There are three coils with different types of number turns (N_1), which are 6, 10, and 18. The diameter of the transmitter coil (D_1) is set to 6.5 mm and 9.5 mm, respectively. Table 2 summarizes the three different dimensions of the transmitter coil. The total number of coil turn is the sum of LN_1 and LN_2.

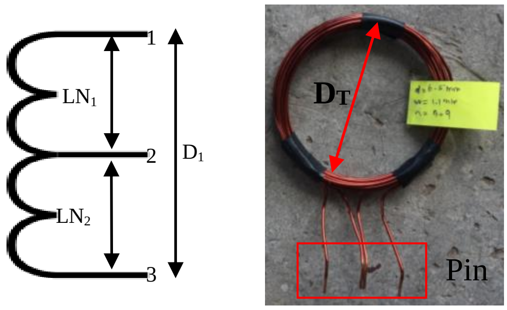

Figure 1: Transmitter coil (TX) dimension

Table 2
Specification of Transmitter Coil, TX (copper wire, diameter, d = 1.18 mm)

Coil Type	Number of turns, LN_1	Number of turns, LN_2	Total Number of turn, N_1
	D_{T1} = 6.5 mm		
TX1	3	3	6
TX2	5	5	10
TX3	9	9	18
	D_{T2} = 9.5 mm		
TX4	3	3	6
TX5	5	5	10
TX6	9	9	18

B. Receiver Coil

The receiver coil (RX) with two pins is designed by a number of coil turn (N_2) and diameter of the coil (D_2) as shown in Figure 2. The D_2 is set similar to that of transmitter coils (6.5 mm and 9.5 mm). Table 3 summarizes the three different dimensions of the receiver coil. The receiver coils are adjustable for the coil connection.

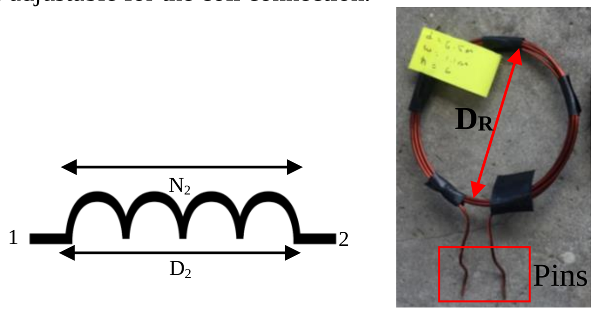

Figure 2: Receiver coil (RX) dimension

Table 3
Specification of Receiver Coil, RX (copper wire, diameter, d = 1.18 mm)

Coil Type	Total number of turn, N_2	Coil Type	Total number of turn, N_2
D_{R1} = 6.5 mm		D_{R2} = 9.5 mm	
RX1	3	RX5	3
RX2	6	RX6	6
RX3	9	RX7	9
RX4	15	RX8	15

IV. HARDWARE IMPLEMENTATION

Figure 3 shows a block diagram of circular loop-based wireless power transfer by resonant inductive coupling. Hardware implementation of the wireless power transfer system is divided into three components, namely the transmitter circuit, receiver circuit and microcontroller-based monitoring system. Previously, simulation and development of wireless power transfer system have been reported [17].

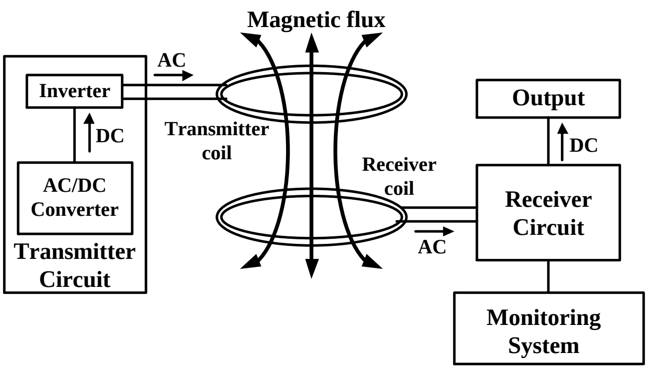

Figure 3: Block diagram of a wireless power transfer

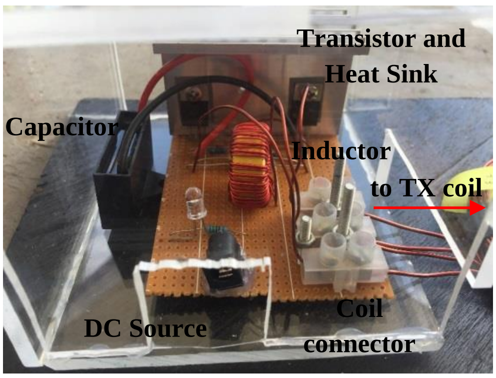

Figure 4: Hardware implementation of the transmitter circuit

A. *Transmitter Circuit*

Figure 4 shows a transmitter circuit, which is used to produce a voltage for wireless transmission. The circuit consists of the oscillator circuit and TX coil. The oscillator circuit was built up with two transistors to function as amplification of current as well as an electronic switch. A capacitor was connected in parallel to the inductor coil (TX coil) to produce a resonant frequency of the circuit.

B. *Receiver Circuit*

Figure 5 shows a receiver circuit, which is used to receive voltage wirelessly from the transmitter circuit. The receiver circuit consists of a receiver coil (RX coil), rectifier circuit and voltage regulator. Moreover, an inductor (7 μH) and capacitor (1 μF) were set-up for the RX coil as explained in Section III and connected to the receiver circuit. A total of eight sets of RX coils depend upon the number of turns and coil diameter, which could be attached to the receiver circuit.

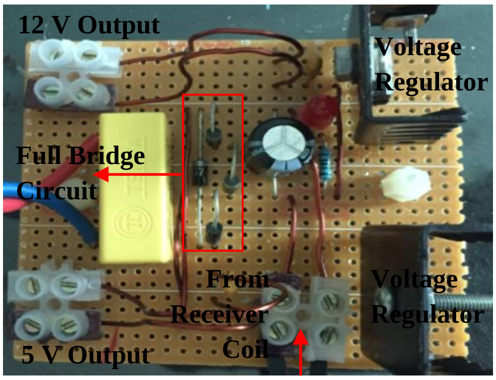

Figure 5: Hardware implementation of the receiver circuit

C. *Monitoring System*

Figure 6 shows a wireless power transfer system with a microcontroller-based monitoring system. The monitoring system was developed using an Arduino MEGA microcontroller with a distance sensor to monitor the output voltage automatically with respect to the air gap distance. Furthermore, a program was also developed to measure the output voltage from the receiver and calculate the distance between TX and RX coils. The output parameters were displayed on an LCD screen.

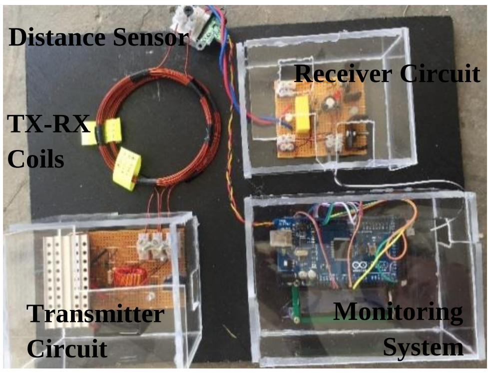

Figure 6: Wireless power transfer system with distance monitoring system

V. Measurement Results

A. *Output Voltage*

Figure 7 and 8 show the characteristics of the output voltage (V_{OUT}) for transmitter-receiver coil pair with a coil diameter of 6.5 mm and 9.5 mm, respectively. The results indicated that the output voltage has linearly increased as the number of turns of both transmitter and receiver coils increased. Moreover, overall results show that coils with a diameter of 9.5 mm produced better output voltage compared to that of 6.5 mm ($D_{T2} > D_{T1}$ and $D_{R2} > D_{R1}$) as a maximum output voltage (V_{OUT}) of 27.3 V obtained at the receiver circuits with a TX4-RX8 pair ($D_{T2} = D_{R2}$). The number of turns ratio between the TX coil and RX coil, i.e., N_1:N_2, where $N_1 < N_2$ has illustrated higher output voltages compared to that $N_1 > N_2$, but having lower turns ratio which would obviously reduce the amount of output voltage.

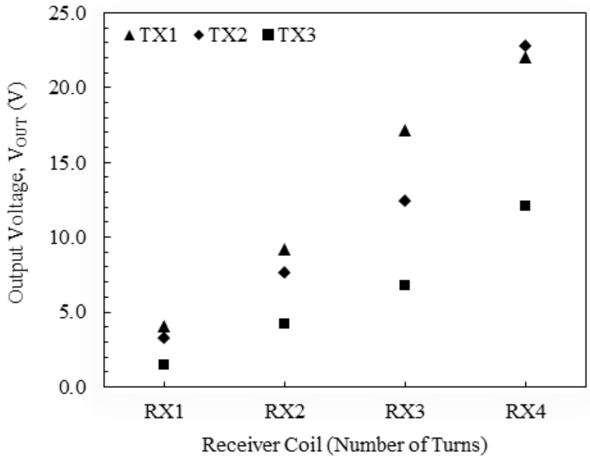

Figure 7: Characteristics of output voltage for transmitter-receiver coils pairs ($D_{T1} = D_{R1} = 6.5$ mm)

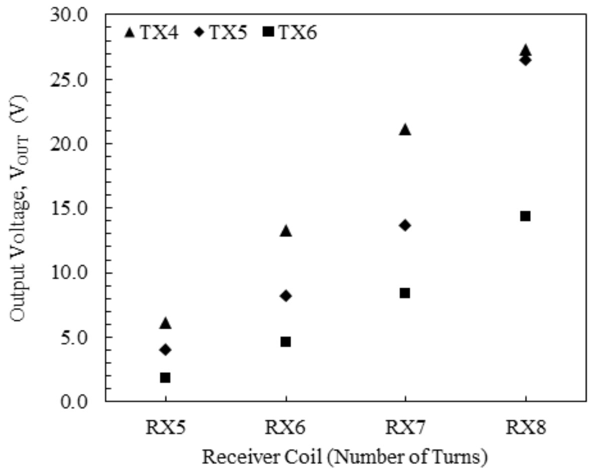

Figure 8: Characteristics of output voltage for transmitter-receiver coils pairs ($D_{T2} = D_{R2} = 9.5$ mm)

B. *Matching Resonant Frequency*

Figure 9 and 10 show the characteristics of resonant frequency (f) against the number of turns of transmitter-receiver coil pair ($D_T = D_R = 6.5$ mm and 9.5 mm), respectively. The results indicated that the value of frequency has dropped when the number of coil turns for both transmitter and receiver were increased. The number of turns ratio, i.e. N_1:N_2, has a significant effect on the resonant frequency as when the $N_1 < N_2$, both diameters for the coils exhibited similar resonant frequency ranging from 20 to 40 kHz for all transmitters paired with receiver RX8, which then validates the higher output voltages at the receiver circuit. In the principle of magnetic resonant coupling for wireless power transfer, resonant frequency has a vital influence output voltage and power transfer rate. A greater efficiency for energy exchange in wireless power transfer could be achieved, when a couple of circular loop resonant coils are tuned in the similar frequency.

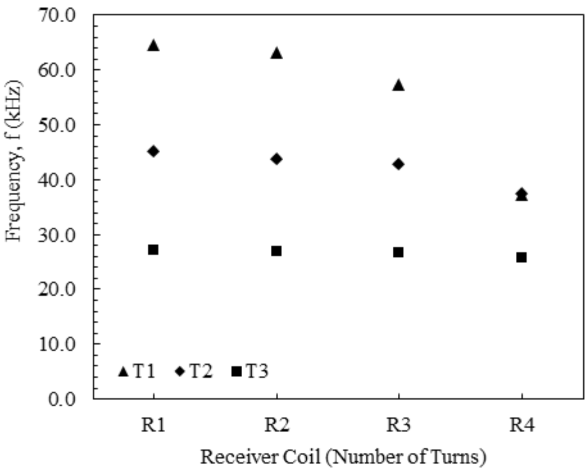

Figure 9: Characteristics of resonant frequency for transmitter-receiver coils pairs ($D_{T1} = D_{R1} = 6.5$ mm)

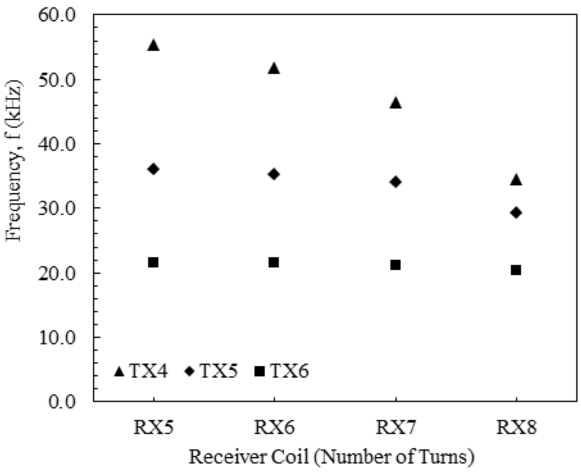

Figure 10: Characteristics of resonant frequency for transmitter-receiver coils pairs ($D_{T2} = D_{R2} = 9.5$ mm)

C. Output Power Transfer over Distance

Figure 11, 12 and 13 show the output power performance of the transmitter and receiver coils at same diameter dimension (9.5 mm) over a range of separation distances up to 10.0 cm for each of three transmitter coils (TX1, TX2 and TX3). Output power and transfer distance are plotted for different transmitter-receiver (TX-RX) pairs depending on a number of turns at a constant diameter. The results indicated that the output power was decreased with increasing distance, having distance and output power inversely proportional, especially for the TX3 type. The output power was decreased by over 70-80% up to 4.0 cm and almost zero by 6.0 cm. The system is capable transferring electrical energy with the maximum gap distance between transmitter and receiver coils of 10 cm, corresponding to the V_{OUT} of 4.4 V. Moreover, the TX2-RX8 pair exhibited the maximum output power transfer (P_{MAX}) of 15.6 W among the three of transmitter coils.

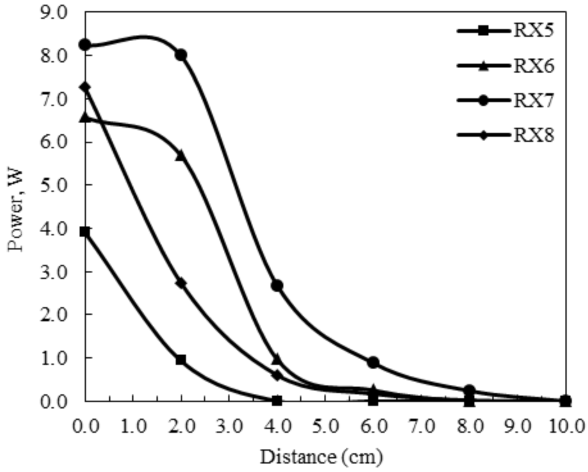

Figure 11: Output power over distance using TX1 ($D_{T2} = D_{R2} = 9.5$ mm).

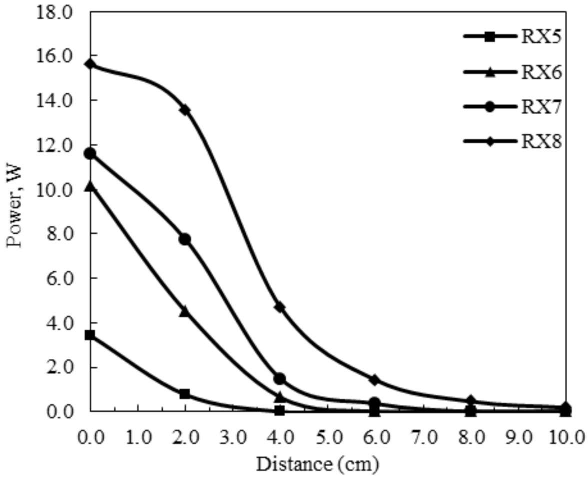

Figure 12: Output power over distance using TX2 ($D_{T2} = D_{R2} = 9.5$ mm).

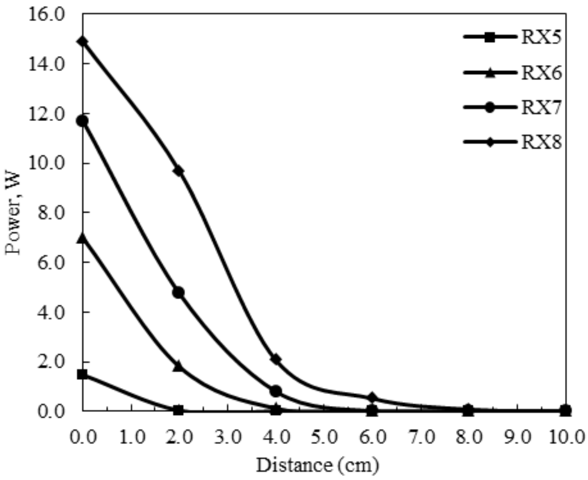

Figure 13: Output power over distance using TX3 ($D_{T2} = D_{R2} = 9.5$ mm).

The output power at receiver was measured at the receiver circuit with similar resonant frequency. The frequency matching is important so that the energy efficiency could be maximized. The frequency depends on the number of turns of the coil and the diameter size. The higher number of turns of the receiver coil is the further distance the power can transfer between the transmitter and receiver coils. Furthermore, both coils are also important to achieve a good power transfer rate. The wireless power transfer rate is affected by the specification of transmitter and receiver coils as well as air gap distance. Thus, the nearest distance of both coils exhibited the highest power transfer rate.

VI. CONCLUSION

This wireless power transfer, using a resonant inductive coupling, was developed by circular loop coils. Depending on the dimension of transmitter and receiver coils, i.e., diameter and number of turns of the coils, higher output voltages were achieved in the range of resonant frequency from 20.3 to 37.1 kHz. Furthermore, the power transfer occurred up to an air gap distance of 10 cm with the highest output power of 15.6 W. In addition, a monitoring system using an Arduino MEGA was connected to the wireless power transfer to measure the output voltage with respect to the air gap distance. Thus, the developed wireless power transfer is suitable to charge wearable and medical devices as well as in IoT applications to provide a cable-free solution and an easier charging terminal.

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