Near Field WPT Charging a Smart Device Based on IoT Applications

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Abstract

Near-field wireless power transfers (WPTs) have seen major developments in recent years due to the increasing popularity and availability of smart devices for the Internet of Things (IoT) applications. To improve the power transfer energy (PTE) and transfer distance for charging smart mobile phones based on MRC by designing a copper wire coil to solve the air gap problem between the transmitter and receiver coils. As an energy-harvesting technique based on magnetic resonator coupling (MRC), WPT can charge batteries in smart devices, especially in mobile IoT devices where changing the batteries can be inconvenient. In this study, the multi-different copper wire coil (MDCWC) cover shield and double-receiver copper wire coil (DRCWC) systems were proposed to deliver power to devices with low-power consumption with a P-P topology using a Royer oscillator in one important scenario. The design scenario was implemented using the MDCWC in the transmitting and receiving circuits. However, three loads were used to test the performance metrics of the system, namely, 20, 50, and 100 Ω for home appliances. To achieve the aim, two near-field WPT techniques a DRCWC and MDCWC were designed and developed. An MDCWC having a covered copper wire coil design improved transfer power to 5.04 W and efficiency to 84% at 20 mm with a 100 Ω loaded systemin alignment condition. The results revealed that the coil geometry contributed to improving the performance metrics in terms of transfer power efficiency and transfer distance. The corresponding transfer power and efficiency values for the MDCWC were 5.04 W and 84% at 20 mm, 4.2 W and 70% at 60 mm, and 3.02 W and 50.37% at 150 mm, respectively, whereas the theoretical result of the transfer efficiency was 96%. However, the theoretical and experimental studies proved that the DRCWC prototype could be used to charge cell phones with a maximum air-gap range of 10 to 300 mm between the transmitter and receiver coils. Lastly, it should be noted that the proposed system can charge one device.

Keywords

Energy Efficiency, Internet of devices, MRC, Multi-different copper wire coil, PTE, WPT.

1. Introduction

Wireless power transmission (WPT) comprises different technologies used for the transmission of electromagnetic (EM) energy through a physical field, such as a wall, air, or water [1]. The need for charging of electronic devices keeps increasing as energy is a necessary component of our daily lives. Moreover, portable devices rely on battery for their long-term use and cannot work under power-saving conditions from conductive wires due to the high load transmission. Thus, copper cables are damaged and loosened over time, resulting in insecurity when charging devices [2, 3] Therefore, wireless charging autonomy is the preferred method of energy pooling over a short or medium range of devices, such as a mobile phone or a drone, after achieving close contact [4]. The object of study to improve the PTE and transfer distance for charging smart mobile phones based on MRC by designing a copper wire coil to solve the air gap problem between the transmitter and receiver coils. The subject of study Smart mobile charging based on the Qi standard based on IoD, which is specified by the Problems Wireless Power Consortium was released in [5] for power transmission via microwave communication [6]. The transfer distance and

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system efficiency are important concerns in inductive power transfer (IPT) systems. Several IPT tests have shown high-power transfer efficiencies that exceed 80% at distances of 10 to 100 mm [7]. The purpose of the work MDCWC described previously is to maximize PTE and distance without interfering with each wire, and to minimize coil diameter as much as possible to maintain a coil size that is compatible with mobile devices and Qi standard coil sizes.

2. Problem Statement

The magnetic field considers a factor that affects the amount of power transmitted between coils when charging device receivers interact. It represents not only a recipient's strength but also the power of the transmitters and other recipients. All other beneficiaries are affected by the addition, elimination, or movement of only one receiver inside the MRC of coil structure, which does not happen in RF systems. Failing to consider these interactions can result in significant magnetic field misalignment [8], which is linked to a high rate of electronic waste production [9]. Because of the short distance and low power transfer, accessories for electronic devices are not commonly used. Furthermore, WPT is highly directional, and its value decreases rapidly as transfer distance (range 0 - 400 mm) increases during wireless charging through the magnetic field. As a result, smart mobile chargers experience problems with distances of a few centimeters or less, which require the handset to be precisely aligned with the charging pad, and a short transfer distance is generally used for charging electronic devices, [10]. However, for tablet charging, solutions for extending the transfer distance beyond 5 cm have been proposed [11]. Phone chargers that operate at distances of tens of centimeters from the transmitter coil, that charge phones regardless of coupling direction, and that operate at a low operating frequency of 1 MHz are ideal. This eliminates the need to remove phones from this range in order to charge them. Furthermore, when a cell phone is charged, the design coils should be compared with the simulation results such as transfer efficiency, coupling coefficient, mutual inductance, and Q-factor to achieve the best distance and performance. However, the major restriction in the size or the diameter of receiver coils with Qi standards (range diameter = 0.9 - 4.4 cm) and without Qi standards, (range diameter = 4.8 – 40 cm) of outer diameter (dout). According to the pad size of the coil, the mobile coil size remained constant and remained small [12-16]. In addition, Qi standards of transfer efficiency was 95%, transfer power was 5 W, and the transfer distance range was 0–4 cm.

3. Review of the Literature

Waffenschmidt et al. [17] presented an IC WPT method to charge a mobile phone over a short distance; the researchers designed a power pad that involves an array of overlapping planar coils as a transmitter. The mobile device comprises a single planar coil as load or receiver that can receive a maximum power of 2 W. This study determined that the transfer efficiency of the IC method increases quickly when the air gap between the transmitter and receiver coils is changed, or axial misalignment occurs among the coils. The WPT system must consider these effects to preserve optimal efficiency.

Cao et al. [18] presented two separate qi standard coil shapes for a maximum power of 20 W WPTs based on loosely coupled inductive ties for high strength (transmitter: circular and receiver: square). However, a prototype circuit was designed and tested at a frequency of 150 kHz with a 2 cm airgap and a transfer efficiency of 65 %. [19] proposed a new topology that was supported by experimental verification and demonstrated excellent performance at both low (Qi and PMA standards) and high (A4WP standard) frequencies. They also presented a simple Enhancement-Mode Gallium Nitride field effect transistor (e-GaN FET)-based single amplifier topology, capable of operating in accordance with all mobile device wireless power standards at a frequency range of 100 kHz. The output powers of the three standards, namely, A4WP, Qi, and PMA, were compared to obtain the high and low frequencies with a low power transfer range of 1–70 W for A4WP, 5 and 10 W for Qi, and a maximum power of 5 W for PMA at a standard frequency of 6.78 MHz.

Worgan et al. [16] presented a PowerShake to transfer power between mobile devices. PowerShake preserves high power transfer by approximately 3.1 W, which is adequate to charge power-hungry devices such as mobile phones. As stipulated by the authors, the maximum power of 3.1 W (0.62 A at 5 V) and generated frequency of 97 KHz, of the transmitter, keeps the tissue of the human body safe from EM field effects. The design of their transmission and receiving circuits was subjected to Qi standards or specifications. Jadidian et al. [10] showed a mobile phone being charged remotely and working independently even though the phone is in the user's pocket, thereby benefiting from the idea of multiple-input multiple-output (MIMO) beamforming. Unlike beamforming in the wireless communication system, a non-radiated magnetic field was developed and directed toward the mobile phone and portable devices. The proposed MIMO system runs at a single frequency of 1 MHz and can charge a mobile phone at distances of roughly 0.5–40 cm with PTE equal to 89%.

The results show that the transfer efficiency of 90% was obtained at 5 cm with a high transmission power of 130W, which adequately meets the requirements of UAV wireless charging via WPT. Mobile charging [20] that requires 1400 mAh battery used small sized solar cells of 2W/83.33 mAh and the charging time was 16 h and 8 min with a resonance frequency of around 1.7 MHz. In addition, the limitation of solar charging systems is that they cannot use a battery externally to operate the transmitter circuit at night.

Park et al. [21] proposed a compact resonant reactive shielding coil topology for reducing EMF in NF WPT mobile device applications. The shielding coil utilizes closed-loop and matching capacitors and dramatically reduces the leakage in magnetic field of a WPT system. The shield coils were classified into four types according to the measured and simulated transfer efficiencies as follows: 1) Without shield, which had simulated and measured transfer efficiencies of 98.3% and 96.2%, respectively; 2) Active shield, which had simulated and measured transfer efficiencies of 79.3% and 75.1%, respectively; 3) Non-resonator shield, which had simulated and measured transfer efficiencies of 97.1% and 95%, respectively; and 4) Prop-resonator reactive shield, which had simulated and measured transfer efficiencies of 93.6% and 90.2%, respectively, under a 6.78-MHz frequency and 10- W input power. The results of their analytical solutions and simulations are consistent with those obtained by measurement.

A micro-aerial vehicle (MAV) inductive resonant WPT system was designed, modeled, analyzed, and experimentally validated by [22]. A Crazyflie 2.0 drone consisted of a receiver coil (seven turns) carried by the MAV and a transmitting coil (two turns) that can either be fixed to the ground or placed on a mobile platform. An AC-DC rectifier, DC-DC regulator, and RF power supply of the system were tested using two-coil WPT. A power loaded model (maximum power 12.5 W) was developed for the two-coil system. The model was used to select suitable coil geometries to maximize the power received by the MAV for hovering within a distance of 20 cm and efficiency of >90% was achieved. The model was validated using experimental results, and the proof-of-model was demonstrated by successful power, which enabled the MAV drone to hover. Grabham et al. [23] designed two coils using a circular and square shape; the study used a Litz wire for the Qi standard for charging mobile applications with a resonance frequency of 1 MHz. Therefore, the DC-DC transfer power efficiency was 35% at 5 mm for the output power of 2.06 W for the circular coil and was 33.3% at the same transfer distance for the a maximum power of 2.05 W for the square coil. The coil design consists of screen-printed coils fabricated with a silver-polymer ink on the printed interface layer. The embroidered coils were fabricated using a variety of conductive threads formed by coating textile fibers and using copper fibers.

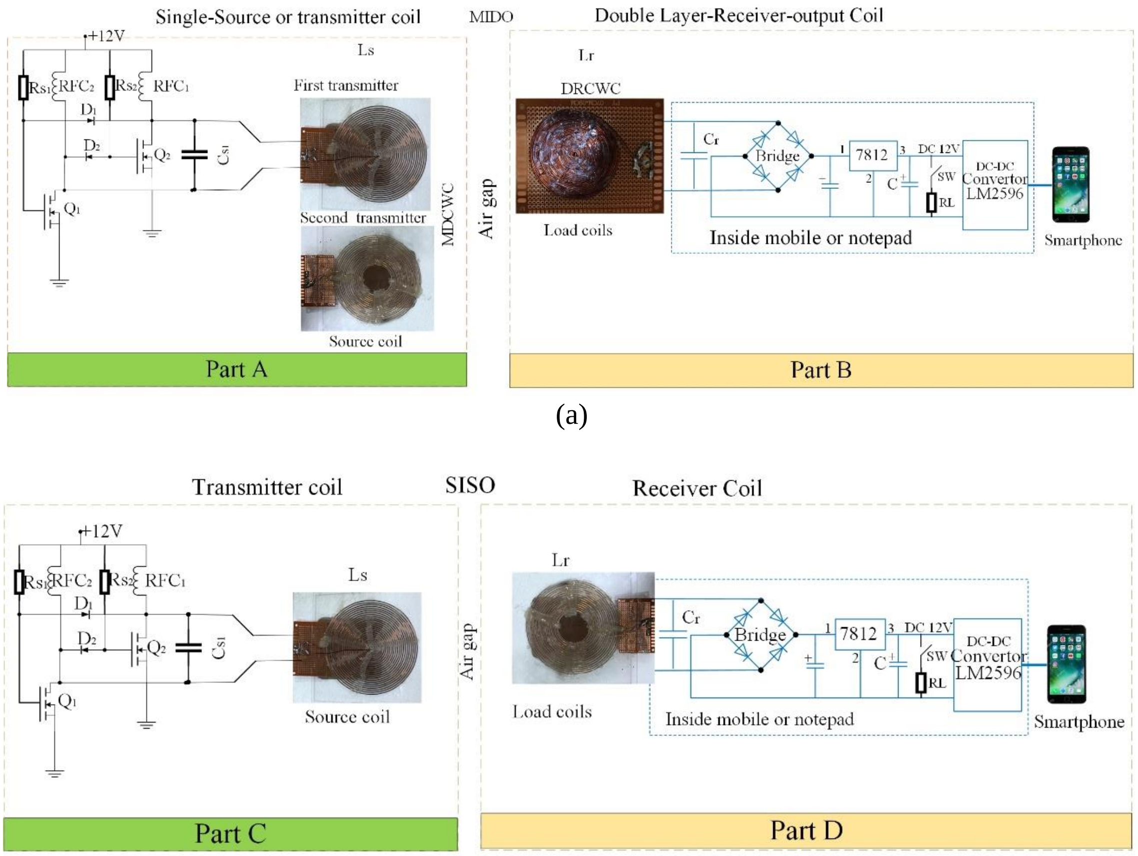
4. Materials and Methods

The proposed system consists of one source (transmitter) of two sizes of wire coils and double receiver coils (same wire size) as shown in Fig. 1. The transmitter includes two transmitter copper wire coils, while the receiver is a DRCWC (Figure 1). Fig. 1 (a) Part A illustrates the testing of the first MDCW coil; the second MDCW coil test is presented from the transmitter and the receiver side in Fig. 1 (a) Part B. The designs differ in the diameter, the number of turns, and types of wire used in the coils; they were evaluated for transfer efficiency because the receiver coil has a limited diameter and normally smaller sized than the transmitter coil; hence, it is incorporated into the mobile. In this work, a small sized receiver and a fewer number of turns (until a maximum of 27 turns) has been proposed to improve the transfer efficiency. Finally, the design of two coils on the transmitter side as a receiver was presented in Fig. 1 (b) Parts C and D. A frame pad for various wire coil sizes was built using a Glass Plastic Board that was cut by laser to provide a shield; a glue Veroboard was used between the two receiver coils.

The first coil design adopted 18 American wire gauge (AWG) (1.02 mm) copper wire; the second one used 24 AWG (0.51 mm) copper wire coil. The receiver also used 18 AWG (1.02 mm) to charge home appliances. Two receiver charging circuits were considered: the DRCWC and MDCWC, which are useful in charging device batteries that require 5.09 W. The mobile charging requirement is based on the power needed to charge the smartphone, such as an iPhone 7 and Samsung note 5 mobile phones, as well as the DRCWC receiver which can charge home appliances (such as headphones, shavers, and toothbrushes).

The final part of the transmitter and receiver coil test (Fig. 1 (c) Parts E and F) investigated the transfer efficiency; this involved selecting the highest-performing coil combinations from the preceding three tests (a, b and c) in order to propose a model for improved MRC WPT transfer efficiency. The design structure of the coil was comprised of two different mobile coils, such as MDCWC and DRCWC. The first coil, MDCWC (consisting of TCWC and RCWC), is constructed of fiberglass and features a cover with a 0.2 mm depth, and a 2 mm line space between each turn. MDCWC coil design built of a square piece of square piece of plastic with a transparent fiber material that resembles glass. The wire type of litz is placed inside the plastic disk-shaped piece to keep the electromagnet between the two coils. To save energy during transmission, an appropriate depth is used. Moreover, the design makes use of a less sophisticated machine that cuts the cover off like a Compact Disc (CD) and glues the wire inside. Additionally, this cover design (MDCWC) was used to boost transmission power and reduce the EMF generated during charging. The second coil, the DRCWC, is identical to the Qi standard coil in that it uses a two-coil vertical arrangement. This configuration is distinguished from the first by the absence of a cover shield and a small line space (*S*) between the wires (line space: S1 equals 2 mm for MDCWC and S2 equals zero for DRCWC). The purpose of the MDCWC described previously is to maximize PTE and distance without interfering with each wire, and to minimize coil diameter as much as possible to maintain a coil size that is compatible with mobile devices and Qi standard coil sizes.

This work proposed DRCWC, a planar resonant reactive shield for use in smartphone applications involving WPT systems. The shielding or cover coil is a closed-loop coil with a matched magnetic field that is wrapped around the WPT source coil's periphery. The shielding coil produces a canceling magnetic field that transmitting circuit includes an oscillator circuit that generates 1 MHz.



(a)

(b)

Figure 1: The proposed Royer circuit (a) SIDO coils and (b) SISO coils

This circuit generates oscillation with two MOSFET transistors (three types: IRFP250N, IRFP510N and IRFP460LC), two general-purpose diodes (type BYS26-45), a parallel coupling capacitor and two resistors. The load coils (i.e., two multi-turn spiral coils) pass the energy to the load through bridge rectifiers and voltage regulators, enabling the battery to be used as a load for various applications. Usually, the resonant wireless power transfer systems use over 1 MHz frequency to get higher efficiency, and it is very complicated to implement such a high frequency because of many losses in high frequency alternating current supply [24]. Therefore, a frequency of 1 MHz is used in the designed model.

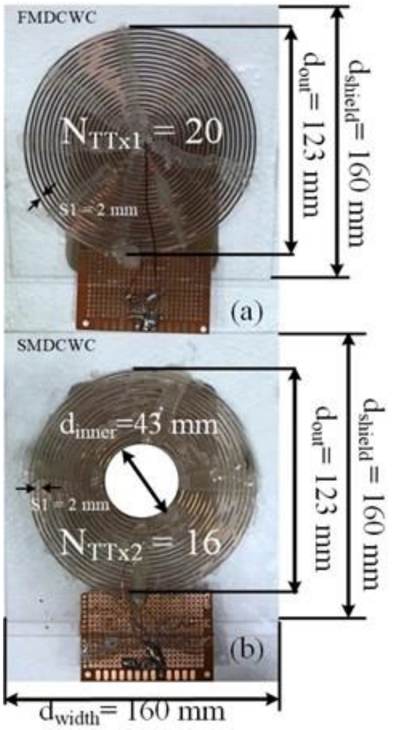


Figure 2: Example of coil designs: (a) the first transmitter coil (FMDCWC) and (b) the second coil (SMDCWC) were used twice, first on the transmitter side and then on the receiver side

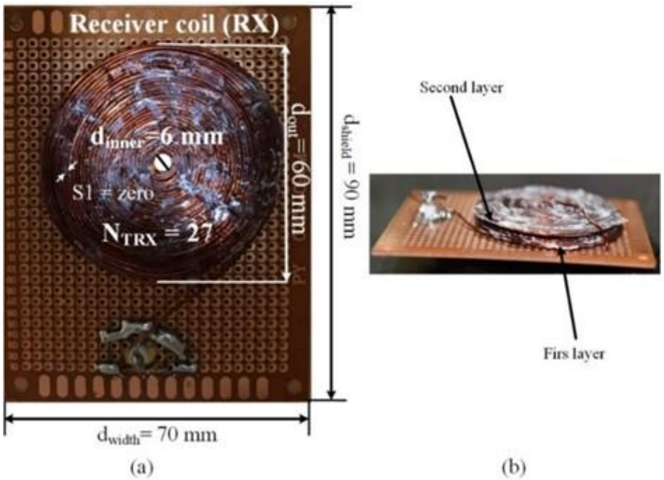


Figure 3: Example of DRCWC receiver coils: (a) a diameter coil, and (b) a double layer coil

The parameters adopted for the source and load circuits are illustrated in Tables 1 and 2 for the MDCWC system and DRCWC receiver system, respectively. The method in the current work is expected to yield improved transfer distance and efficiency between the source and load coils than those in previous studies that utilized other topologies (i.e., P-P and S-P). Several coils were tested in terms of the design diameter of the wire and tube, as well as the geometry of the coil when the N_T, line space, and line width of the coils were increased and decreased. The output of coil geometry, on the other hand, had an effect on the constructed coil. When charging a mobile phone, a wire coil is better than a tube coil because a small coil size is needed to fit the small size of the phone (L: 138.3 mm, W: 67.1 mm, and D: 7.1 mm for iPhone 7) and a higher N_T improves the transfer power and efficiency, while a tube coil cannot be small in size or have a high N_T because of the large line space. Therefore, wire and tube diameter different from coil geometry design when charging the mobile. As a result, when charging the phone, the Litz-wire required a small diameter to improve the coil geometry design. Furthermore, a copper wire coil is used for mobiles because a small wire diameter requires more energy, more room, and a smaller mobile. However, because of the large size of the drone and the energy of the battery, an aluminum tube coil is used for the drone, and a large line width of the coil diameter is used, increasing the battery charging level. In this work, the coupling type is a magnet coupling between the transmitter and receiver coils.

Table 1
The parameters of Royer oscillator circuit transmitter

Parameters	Value
Input voltage DC (E/Volt)	12
Input current DC (Amp)	0.5
Operating frequency (f/MHz)	1
Inductance of transmitter coil (RFC1/μH)	100
Inductance of transmitter coil (RFC2/μH)	100
Compensating capacitor of source coil (Cs1/pf)	150
Resistances (Rs1/ Ω)	50
Resistances (Rs2/ Ω)	50

Table 2
Parameters of circuit receiver

Parameters	Value
DC output voltage (E/Volt)	22.08
Output current DC (Amp)	0.23
Operating frequency (f/MHz)	1
Transfer distance (mm)	20
Compensating capacitor of receiver coil (Cr/pf)	200
Load resistance (RL/Ω)	20, 50, 100

5. Experiments

The proposed system is intended for charging low-power-consumption home appliances, such as smartphones, shavers, and toothbrushes. However, as DRCWC has a cover shielding to reduce magnetic field leakage [21], the proposed MDCWC-based topology can be expected to generate more magnetic field leakages than a DRCWC design. The circuit designs of the first coil of the transmitter side and of the MDCWC of the receiver side, are shown in Fig. 4 (a) at 20 mm; the circuit designs used a Royer transmitter oscillator circuit at 1 MHz frequency. Fig. 4 (b) showed the first coil on the transmitter side and the second coil on the receiver side (i.e., DRCWC); both were set with 20 mm air gaps to measure the transfer distance, power, and efficiency when the system was loaded. However, the type of coupling is magnetic and tightly coupling.

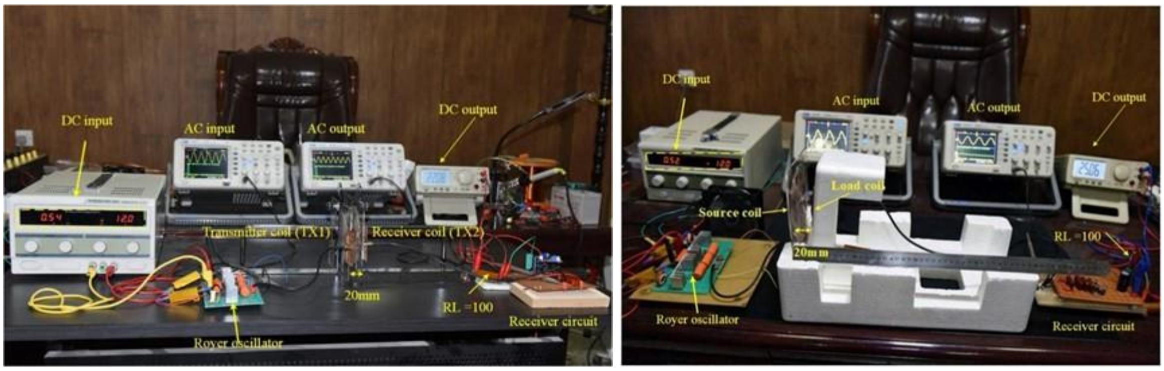
The transfer power and efficiency were recorded relative to the transfer distance. Measurements were recorded from the source and receiving coils with a digital multi-meter (DT9205, Dowdon, Shenzhen, China), an oscilloscope (MCP lab electronics/DQ7042C, Shanghai MCP Corp., Shanghai, China), a digital multi-meter (MCP lab electronics/MT8045, Shanghai MCP Corp., Shanghai, China) and a traditional distance meter (0–400mm). Load resistances of 20, 50, and 100 Ω were used to test the power delivery capabilities at the receiver circuit. A DC power supply of 30V/10A (QJ-5010S, QJE, China) supplied the source circuit. Specifications of the source and receiver coils of the first and second proposed MDCWC systems are shown in Table 3 and Table 4, respectively.

Table 3
Parameters of the first transmitter coil

Specification	First transmitter (FMDCWC)
N_{TS} for first transmitter	20
Line tracking width (*W1*) (mm)	1.02
Line space (*S1*) for first transmitters (mm)	2
Outer diameter (d_{out1}) of the coil (mm)	123
Transfer distance (mm)	1–300

Table 4
Parameters of the second coil

Specification	Second coil while using in transmitter and receiver side (SMDCWC)
N_{TS} for second transmitter	16
Line tracking width (W1) (mm)	0.51
Line space (*S1*) for second transmitters (mm)	2
Outer diameter (d_{out1}) of the coil (mm)	123
Inner diameter (d_{inner1}) of the coil (mm)	43
Air gap between (mm)	1–300



(a) (b)

Figure 4: Example Comparison of experiment topologies with a load and transfer distance of 20 mm with a Royer oscillator transmitter used 1 MHz between (a) DRCWC coils and (b) FMDCWC, SMDCWC

6. Results and Discussion

This paper outlined an iterative design procedure that starts with the design constraints and initial values that will apply to the closed-form expressions referred to in section 5. MATLAB software was used to find the optimal inductive link power transmission efficiency by sweeping all the parameters included in the previous equations [14]. The procedure ended with the optimal geometric values for pair PSC. The results and values suggested by theoretical calculations were verified using the Electromagnetic field coils in theoretical and measurements. To miniaturize the receiver size, there are two techniques proposed for the receiver (MDCWC and DRCWC) in the mobile application WPT system; these are the single layer shield coil MDCWC (123 × 123 mm^2) and the double layer receiver coil (60 × 60 mm^2). In the first case, the cover shield and wood were used as the dielectric medium in both the theoretical estimates and calculations and in the second case, the air is the dielectric medium between the transmitter and receiver coils. The current chapter evaluated the proposed methodology by presenting MDCWC and DRCWC WPT results in the first stage. The results were validated in terms of the challenges to battery life during low-power home appliance operations of MRC. The MRC coil design was first tested in theoretical and measurements before being tested in the laboratory. The transfer power, efficiency, and distance for charging mobile devices on the basis of the two proposed systems (MDCWC and DRCWC) were investigated.

Fig. 5 showed the relationship between M and k (initial values = 0.95, 0.68, 0.587, 0.44, 0.35, 0.25, 0.21, 0.15, 0.11, 0.09 ≥ 1) as M is the condition on which to calculate k according to transfer distance. Fig. 6 presented a comparison of the theoretical and experimental results of transfer power and efficiency obtained from MDCWC as explained in section 5. The potential reasons may include the following: First, practical self-tuning capacitances and inductances are impossible to exactly match the theoretic values due to their precision errors. Second, the impedance of the mobile is assumed to range from 7 to 100 Ω [25]; it will change with its temperatures when working in the lab. Finally, energy dissipation inevitably happens on high-frequency amplifier circuits and power matching circuits; this is ignored in theoretical calculations [26]. After calculating the M, the transfer efficiency theory can be applied [14] thus, the results indicate an improvement transfer efficiency of 96 percent and 25 W of the transmitted power coil receiver.

Table 5

Comparison between MDCWC and DRCWC and previous works on Qi standard

Ref.	Frequency (MHz)	Transfer distance (mm)	P_{in} (W)	P_{out} (W) (With load)	η (%) (With load)	*Q-factor*	Type of coils
(Jadidian et al. 2014) [10]	1	5, 20, 50, 100	6	3	89 @ 5 mm 87 @ 20 mm 74 @ 50 mm 53 @ 100 mm	N/A	Mobile phone (iPhone 4s)
(Cao et al. 2018) [27]	6.78	50	6	5	86	2	MIMO (Qi standard)
(Zhu et al. 2019) [28]	1	N/A	7	5	71	N/A	Mobile phone (Qi standard)
(Feng et al. 2019) [29]	6.78	N/A	6	5	68-80	N/A	Mobile phone
This work of MRC (measurements)	1	10, 20,60, 100 and 150	6	5.09@ 10mm 5.04@ 20mm 4.2@ 60mm 3.51@100mm 3.19@150mm	84.83@ 10mm 84@ 20mm 70@ 60mm 58.54@ 100mm 50.37@ 150mm	0.0478 and 0.066	MDCWC (iPhone 7)
This work of MRC (measurements)	1	20,60 and 150	6	2.87 @ 20mm 2.51 @ 60mm 1.40@150mm	47.86@ 20mm 41.94@ 60mm 23.47@ 150mm	0.065 (single) and 0.032 (double)	DRCWC (iPhone 7)

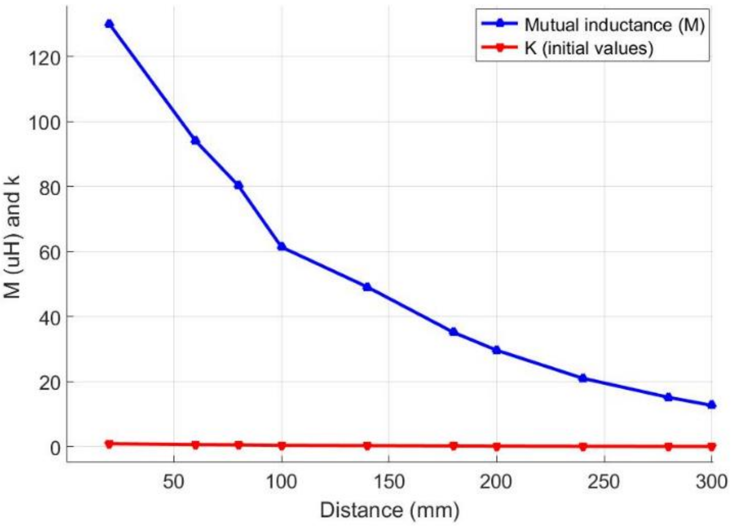


Figure 5: The relationship between *M* and *k* (initial values) with transfer distance

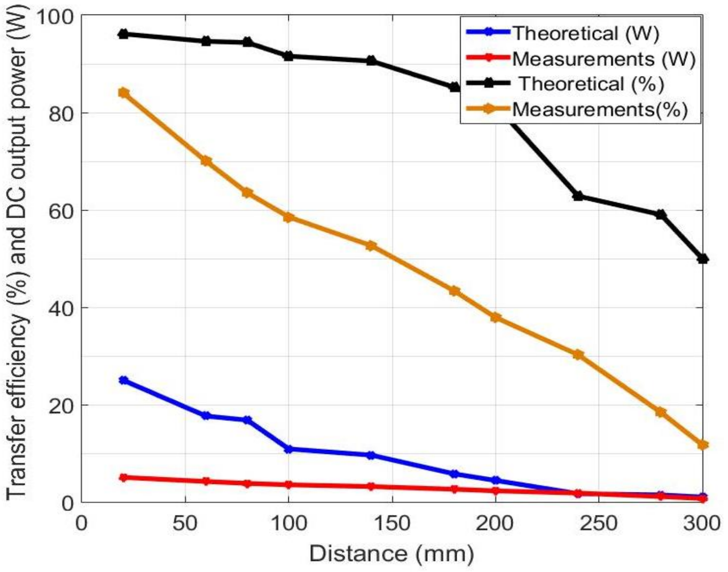


Figure 6: The comparison of theoretical and experimental results for transfer power and transfer efficiency of MDCWC

The MDCWC and DRCWC MRC WPT coils were calculated and implemented to charge a smart device and to increase the transfer power, distance, and efficiency of the device. The optimal value that can charge the battery of a mobile phone was presented using theoretical MDCWC results, which improved transfer efficiency and power at 100 lbs of load with transfer distances of 20, 60, and 150 mm of MRC WPT. However, the results of calculations (i.e., theoretical) were presented, with transfer efficiency, strength, and distance of 96 %, 25 W, and 20 mm, respectively. The results indicated that the MDCWC system can improve transfer efficiencies of 88.75%, 79.38%, and 54.38% without a load, and at distances of 20, 60, and 150 mm, respectively. When the system is loaded with 100 Ω at the corresponding distances, the transfer efficiencies reduced to 84%, 70%, and 50.37%. In addition, the DRCWC was tested in a practical application; a Li-ion-battery was charged with total system efficiencies of 90.84%, 77.3%, and 60.23% without a load at the same distances of 20, 60, and 150 mm, respectively. When the system was loaded with 100Ω at the corresponding distances, the transfer efficiencies drastically reduced to 47.86%, 41.94%, and 23.47%, respectively.

The optimization problem that was used in this paper is described in (Section. 2). Most WPT applications demand that coils be built to fit within a physical size constraint. In many applications, such as the Qi standard, the Rx coil must be miniaturized in particular. As a result, transmitter and receiver coil sizes are limited to 200 mm and 50 mm, respectively. The nominal transfer distance is set to 50 mm, with various misalignment profiles ranging from 50 to 200 mm. The wire's radius is set to 1 mm, and the operating frequency is set to 1 MHz. Depending on the application specifications, these design criteria may be modified.

Previous Fig.5 and Fig. 6, the voltage value was sufficient to charge the mobile phone; however, both MDCWC and DRCWC methods have certain limitations in terms of improving the key metric parameters (i.e., transfer power, efficiency, *M*, *k*, and distance). First, the transfer power always varies when charging mobile devices due to misalignment; thus, transfer efficiency is not always constant and may decrease. The energy collected is therefore only suitable for supplying low-power devices or sensors and cannot be used for high-power applications. Second, energy transfer can be raised by increasing the power of the source coil; however, in medical applications, power and operating frequency cannot be increased when transferring the maximum power to a load device owing to the effect of increased power and frequency on human tissues. The same test with transfer distances ranging from 20 to 300 mm produced theoretical results indicating a 96 percent and 25 W increase in transfer efficiency and power, respectively. To prevent exposing a human body to EM waves, the permissible exposure amount should be observed.

Contrasting results were observed between the proposed MDCWC and DRCWC methods owing to misalignments between the transmitters and receiver coils. The MDCWC differs in diameter to DRCWC; the output power of the proposed system can charge the latest smartphone on the market, with generated output powers of 5.09W (MDCWC) and 3W (DRCWC) at a 10 mm distance. Comparison of the results with previous work highlighted a higher transfer efficiency of MDCWC (with a load and without a load) as opposed to DRCWC (with a load and a without load) with the same transfer power and distance value. A comparative analysis of the results of the present study against the works of other researchers in this field for the last decade showed that the current research offered a smaller size and more efficient power transfer. MDCWC was also subjected to theoretical and experimental transfer tests. DRCWC, on the other hand, was not theoretically tested and was only used in experiments due to its low transfer power performance. In metal cover smartphone applications, the distances between the coils are relatively short, necessitating the consideration of all two coils' mutual inductances. Additionally, due to the metal cover's low-quality factor, the resistances of the three coils design cannot be ignored during circuit analysis.

7. Conclusions

This study provided the measurements design, and implementation of NF WPT based on MRC that can be used for charging home appliances. The MRC was implemented practically using MDCWC and DRCWC coils. Several coil designs were considered for charging the batteries of cell phones and drones, and to solve misalignment conditions. In this study, the MDCWC (cover shield) and DRCWC systems were proposed to deliver power to devices with low-power consumption with a P-P topology using a Royer oscillator in one important scenario. The design scenario was implemented using the MDCWC coil in the transmitting and receiving circuits. However, three loads were used to test the performance metrics of the system, namely, 20, 50, and 100 Ω for home appliances. The transfer power and efficiency were investigated at 20, 60, and 150 mm for all loads. The transfer power and efficiency were observed to be optimal at a 100 Ω resistive load. The corresponding transfer power and efficiency values for the MDCWC were 5.04 W and 84% at 20 mm, 4.2 W and 70% at 60 mm, and 3.02 W and 50.37% at 150 mm, respectively, whereas the theoretical result of the transfer efficiency was 96%. However, the theoretical and experimental studies proved that the DRCWC prototype could be used to charge cell phones with a maximum air-gap range of 10 to 300 mm between the transmitter and receiver coils. Lastly, it should be noted that the proposed system can charge one device.

8. Acknowledgements

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