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Wireless power transfer using relay resonators

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This paper presents an advanced design configuration of a wireless power transfer system using overlapping relay coil techniques for free loading position. The work undertaken investigates the tuning position of prototype relay coils in a horizontal configuration in order to evaluate power transfer efficiency versus increasing operating distance between the transmitter and receiver coils. A prototype relay coil system was evaluated to determine the optimum distance between the transmitter and receiver. Finite element magnetic simulation was used to appraise the magnetic field distribution and power transfer efficiency with respect to a strongly coupled magnetic resonance condition. Experimental and simulation results analysis suggest that the proposed design could achieve 85%–90% efficiency within a 4 cm operational distance. Finally, the experimental results were analyzed and compared with the simulation results. *Published by AIP Publishing.*
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Wireless Power Transfer (WPT) is now ubiquitous following on from developments at MIT (Massachusetts Institute of Technology), i.e., approximate 60 W of power was transferred between two 60 cm diameter coils which were separated by a distance of 2 m.[1] WPT systems are now used for powering electronic devices such as wireless charging, radio frequency identification devices (RFIDs), sensor networks, medical implanted devices (cardiac pacemakers), electric vehicles, maglev trains, and many more.[2–4]

WPT can be classified as non-radiative or radiative based on the system implemented in the power transfer process. The non-radiative type refers to near-field power transfer and it is applied in short or medium ranged applications where the operational distance is below the transmitted signal wavelength. Additionally, the transmitter-receiver distance of the short-ranged application is less or equal to the diameter of the transmitter coil. Capacitive and inductive coupling power transfer methods are forms of the short-ranged applications. The inductive coupling technique function on the principle of magnetic induction, i.e., a transmitting coil induces an EMF within the receiver coil via a magnetic field variation. The operational frequencies of a WPT system depend on the inductance and capacitance values of the coils. For capacitive coupling, energy is transferred through an electric field, the quantity of energy transferred being directly proportional to the frequency.[5,6] For medium range applications, the transmitter-receiver distance varies between one to ten times the diameter of the transmitter coil with an operational frequency range of 10 kHz–200 MHz. An inductively coupled system using multiple coils as advantages over other systems (non-multiple coils) by the extension of the power transfer distance between the transmitter to receiver. The coupled magnetic resonance system (CMRS) and inductive power transfer method are forms of the medium ranged applications.[5,6] The MIT research group described the detailed working principle of CMRS system.[7] This radiative type is known as far-field power transfer. However, the operational distance is two times higher than the transmitted signal wavelength. Its implementation is based on electromagnetic wave propagation in far field distance usually in the range of kilometers. Essentially, it exists in two forms: directive and non-directive. Currently, the directive form is used for remotely powering electric vehicles (evs), and the non-directive form is used in applications such as power transfer between omni-directional RF broadcast and portable devices, transfer of optical power through laser beams, and other applications.[6] There have been several studies over the last few years to enhance the efficiency of the WPT system for short, medium, and long distances using relay resonators between the transmitter and receiver coils.[5–24] For example, Choi and Lee[5] investigated the optimal position of relay coils from the tested measured results without verifying the experimental results with theory or simulation. In another paper, Ahn and Hong[3] demonstrated the WPT for multiple loads over various distances and verified the optimum conditions with measured results. Park *et al.*[8] discussed the magnetic field repeater concept for the maximum power transfer for the wireless system and provided the guidelines to select the optimum repeater positions and number between the transmitter and receiver. They verified their concept experimentally and found that this concept could double the coupling coefficient between the transmitter and receiver circuit. However, it was observed that the coupling was not considered for nonadjacent and adjacent cases. Zhang *et al.*[10] studied relay coupling but did not demonstrate the optimal power transfer efficiency at the resonance frequency due to the effect of nonadjacent coupling. Therefore, prior research in this field discusses the theoretical background and investigates the performance of a test prototype without magnetic simulation or verification of experimental results with simulation. An exception to this is the work of Zhang *et al.*[11] who simulated the magnetic WPT system using simple transmitter and receiver coils and verified the simulated results with measured results. However, Zhang *et al.*[11] did not use relay

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resonators or repeaters to extend the wireless power transfer distance between the transmitter and receiver. Magnetic simulation for a magnetic WPT system is necessary to be able to appreciate the optimum size and flux linkage of the transmitter and receiver resonators as the magnetic coupling and the resonance condition are the main factors in achieving the maximum power transfer. This paper presents the design concept of an overlapping relay resonator structure in horizontal configuration for WPT as opposed to the previous nonoverlapping technique of vertical and horizontal relay resonators. This design is particularly beneficial for low power medical applications and also for free loading mobile charging applications. In development, this design concept was simulated using the FEA magnetic simulation software package to aid understanding of the flux linkage and magnetic coupling factor of the structure. An experimental circuit prototype was built and tested using off-shelf components in order to acquire experimental data relating to the performance and operational wireless power transfer distance limit. The simulated power transfer efficiency with the variation of distance was compared and verified. Finally, the efficiency comparison between this study and other prior studies are discussed with conclusions

$$R_{TX} = R_{tx} + R_s \quad R_{RX} = R_{rx} + R_L.$$

A typical induction coupling WPT consists of a transmitter and a receiver circuit, as shown in Fig. 1. The circuit generates and transfers electrical energy between two resonant coils through varying magnetic fields. Since both coils are closely coupled and operate at the same resonant frequency, high energy transfer can be achieved with small leakage. This magnetic resonance coupling can be applied between one transmitting coil and many receiving coils for concurrent charging the multiple devices.[7] The resonant frequency of the system can be calculated from $f_0 = \frac{1}{2\pi\sqrt{LC}}$, where L and C represent the inductive and capacitive quantities of the circuit. $\boldsymbol{k}$ is the coupling coefficient between the transmitter circuit and receiver circuit. $\boldsymbol{V_s}$ is the source of power for the transmitter circuit, $\boldsymbol{R_s}$ is the resistance of the source, $\boldsymbol{R_{tx}}$ is the resistance in the transmitter circuit, $\boldsymbol{R_{rx}}$ is the resistance in the receiver circuit, $\boldsymbol{R_L}$ is the load, $\boldsymbol{C_1}$ is the series connected transmitter capacitance, $\boldsymbol{C_2}$ is the series connected receiver capacitance, $\boldsymbol{L_{TX}}$ is the inductance in the transmitter circuit, and $\boldsymbol{L_{RX}}$ is the inductance in the receiver circuit. The system's mutual inductance, i.e., where the magnetic field generated by a coil causes voltage induction in the coil adjacent, is found via[12]

$$M = k\sqrt{L_{TX}L_{RX}}, \tag{1}$$

where the coupling coefficient, k, between the adjacent coils has been defined as[18]

$$k = \frac{1}{\left|1 + 1.6\left(\frac{h^2}{r_t * r_r}\right)\right|^{\frac{3}{2}}}, \tag{2}$$

where $\boldsymbol{h}$ is the center to center distance between adjacent coils, $\boldsymbol{r_t}$ is the transmitter coil radius, and $\boldsymbol{r_r}$ is the receiver coil radius. It is necessary to match the load impedance with the source impedance to transfer maximum power at the load end. Since both the magnetic field strength and coupling factor gradually decrease with the distance, the power transfer distance of a magnetically coupled WPT system will depend on the size and properties of the magnetic material and the coil dimensions. High Q-factor transmitter and receiver coils could compensate the low magnetic coupling to increase the power transfer distance to a certain degree. However, an excessive Q-factor could represent excessive reactance for each load resulting in an increase of the existing magnetic field which could pose a risk to body tissue. The relay coils implementation as shown in Fig. 2 could be a suitable option, i.e., to improve the magnetic coupling over a longer distance which will increase the power transfer distance from the transmitter to the receiver end.

It can be seen from the schematic circuit in Fig. 2 that the typical relay coil WPT comprises of basic transmitter and receiver circuit with n number of resonators.

The transformer coupling principle proposes that the product of capacitance and inductance in circuit must be the same to have a resonant circuit[10]

$$f_{TX} = f_1 = f_2 = f_3 = f_4 = f_5 = f_6 = f_7 = f_{RX}, \tag{3}$$

$$L_{TX} \times C_1 = L_A \times C_3 = L_A \times C_3 = \ldots\ldots\ldots\ldots L_{RX} \times C_2. \tag{4}$$

The wireless system power transfer efficiency is described as the ratio of the power dissipated at the load to the power input to the transmitter and is derived by summing the total dissipated power in the coils and the load.[12]

Applying Kirchhoff's voltage law to solve the circuit, the power transfer efficiency is given by[9]

$$\eta = \frac{P_L}{P_{in}}, \tag{5}$$

$$= \frac{\frac{1}{2}R_L|I_n|^2}{\frac{1}{2}R_{tx}|I_{tx}|^2 + \frac{1}{2}R_a|I_1|^2 + \cdots + \frac{1}{2}R_{n-1}|I_{n-1}|^2 + \frac{1}{2}(R_L + R_n)|I_n|^2},$$

$$= \frac{R_L}{R_{tx}\left|\frac{I_{tx}}{I_n}\right|^2 + R_a\left|\frac{I_1}{I_n}\right|^2 + \cdots + R_{n-1}\left|\frac{I_{n-1}}{I_n}\right|^2 + (R_L + R_n)}. \tag{6}$$

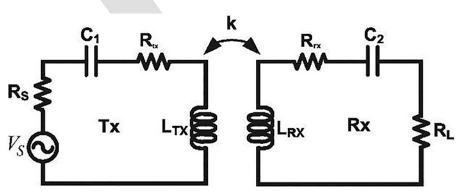

FIG. 1. Equivalent circuit model of the transmitter-receiver WPT system.

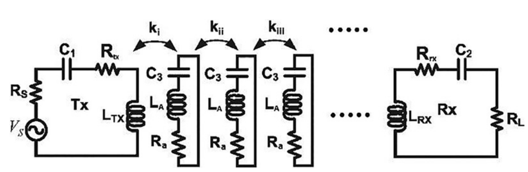

FIG. 2. Equivalent circuit model of the WPT system with n resonators.

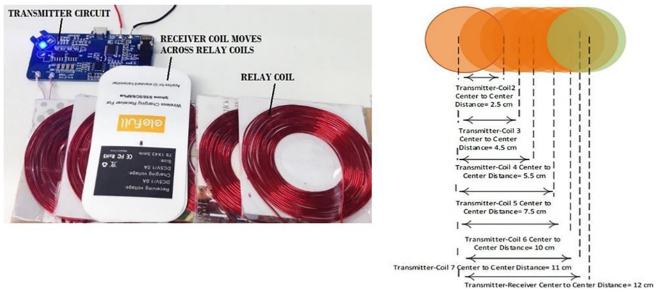

FIG. 3. Practical setup of the horizontal design for wireless power transfer.

The current ratio $\frac{I_{tx}}{I_n}\dots\frac{I_{n-1}}{I_n}$ can be realized using inverse matrix on the resolved matrix form of the circuit. Therefore, $\boldsymbol{\eta = f(C_3, \dots, C_2, R_L)}$. It should be noted that $\boldsymbol{C_1}$ **and** $\boldsymbol{R_s}$ are related to impedance matching and not the power transfer efficiency. So, for maximum power transfer analysis, realization of $\boldsymbol{C_3, \dots, C_2, R_L}$ are critical.

Figure 3 shows the prototype of the relay coils WPT system which was built using off-shelf components and characterized experimentally. The design is implemented using seven overlapping relay coils alternatingly placed at approximately center to center distances as shown.

Essentially, 3-D FEA magnetic transient simulation using Infolytica package was carried out to determine the flux linkage and power transfer efficiency over the distance. Finally, the measured results were analyzed and discussed with the simulation results.

The components used to implement the WPT system include commercial Qi transmitter and receiver. The transmitter circuit consists of an inverter circuit integrated with a ferromagnetic transmitter coil. The maximum input voltage of the transmitter circuit is 5 V (dc) recommended by the manufacturer, and the output of the inverter will provide 50 mV (rms) sinusoidal voltage to the transmitter coil for magnetic induction.[13] The receiver comprises of a copper coil, a ferromagnetic layer, and the rectifier circuit;[13–15] relay coils are made of copper having 20 number of turns which have been tuned at a resonance frequency to maximize the power transfer. The operation of wireless power transfer system at the resonant frequency is necessary to achieve the maximum output power and efficiency. The resonant frequency of the transmitter and receiver circuit is 220 kHz, and the relay coils are tuned with this frequency to achieve the maximum efficiency. The distance of the each relay coil from the transmitter circuit, as shown in Fig. 3, is the

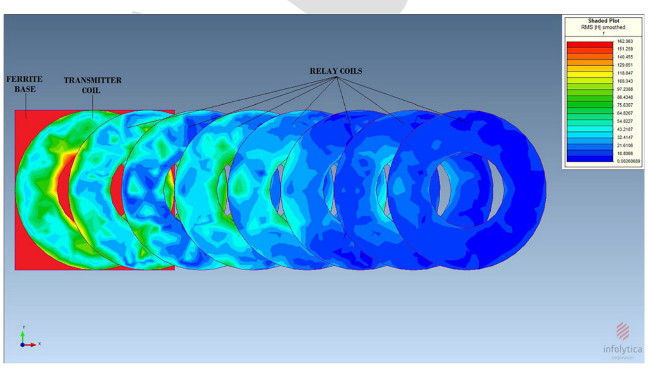

FIG. 4. 3-D transient simulation model of the WPT system.

TABLE I. Coil parameters used in simulation.

	No. of turns	Resistance (mΩ)	Inductance (μH)	Inner radius (cm)	Outer radius (cm)
Transmitter coil	10	180	24	1.2	2.3
Relay coils	20	232	24	1.5	3
Receiver coil	35	135	8	1.1	2.2

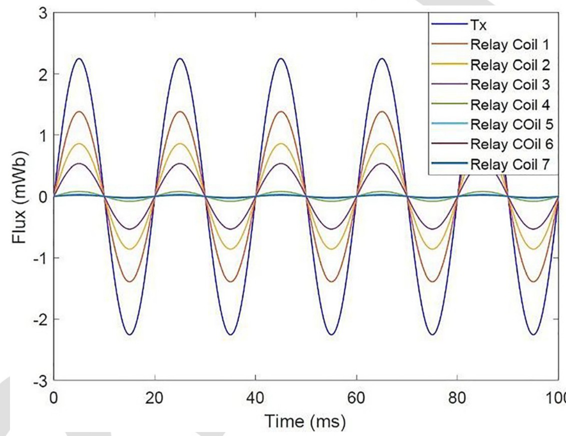

FIG. 5. Effective flux linkage for all the coils.

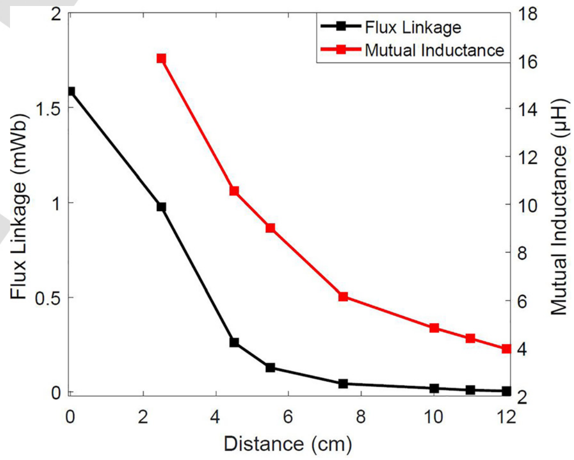

FIG. 6. Flux linkage and calculated mutual inductance over operational distance of the relay resonators.

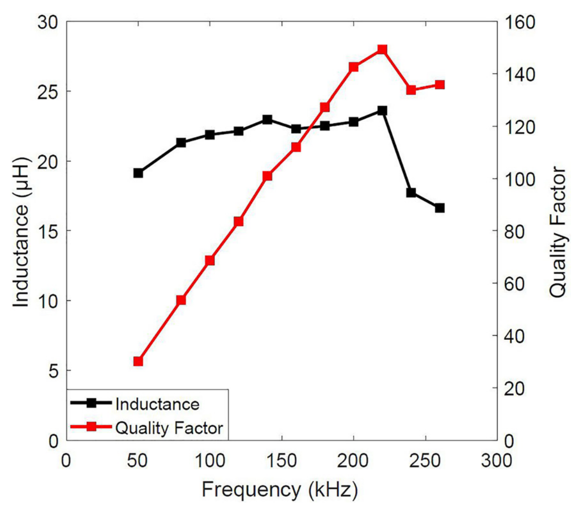

FIG. 7. Relay coil inductance values and quality factor with the variation of frequency.

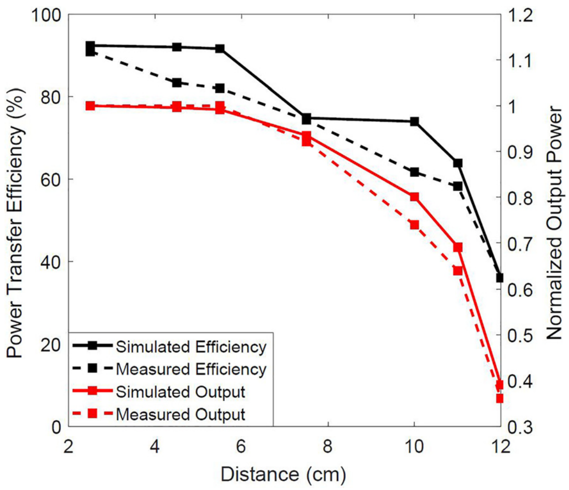

FIG. 8. Measured and simulated output power and efficiency of the relay coils.

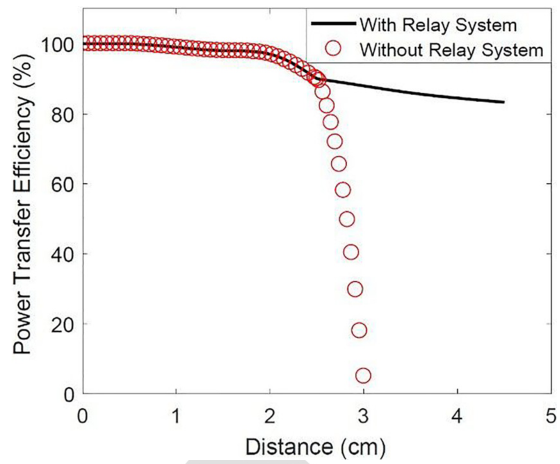

FIG. 9. Measured and simulated output power.

optimum distance for this configuration, i.e., that would allow connectivity and transmission to subsequent coils.

Figure 4 presents the descriptive model of WPT system with relay coils which has been used in the finite element magnetic simulation. The first coil integrated with the ferrite material is the transmitter coil, and the subsequent coils are the relay coils. Table I shows the coil parameters used in the simulation. The transmitter coil is driven by a sinusoidal voltage source with the magnitude of 50 mV (rms) at 50 Hz frequency. Figure 5 shows the sinusoidal flux variation over the time period of the WPT system for individual coils. In order to understand the flux linkage over the operational distance, the rms values of the flux linkages were plotted, as shown in Fig. 6. The distance between the center of the transmitter and receiver coils varied due to the change in position of the receiver coil across the relay coils resonator. The distances represent the points where the different relay coils are placed. It can be seen from the graph that the flux linkage decreases near exponentially over distance with the flux linkage dropping by 65% at the 4th coil from the transmitter, at the 7th coil, and beyond power transfer is not achievable as the flux linkage reduction is 92%. Initially, the inductance and the quality factor (Q) of the relay coils were measured with the variation of frequencies. Figure 7 shows the measured inductance and the calculated Q factor for 20 turn coils. The quality factor, Q, is determined using the formula $Q = \frac{\omega L}{R}$ from the measured inductance and resistance values.

An LCR meter was used to measure the inductance and resistance of the coils at different frequencies. The coil exhibits a maximum quality factor 150 at 220 kHz frequency. Several relay coils with different number of turns were used in the experiment to evaluate the quality factor variation with frequency.

The experimental results suggest that the coil performance is critically affected by the number of turns and the wire gap of the coil. The coupling factor (k) and the mutual inductance of the WPT system have been evaluated using Eqs. (2) and (1), respectively, to evaluate how they affect the performance of power and efficiency over the distance across the relay coils between 2 cm and 12 cm. It can be seen from Fig. 6 that the mutual inductance is significantly reduced over the operational distance.

The transmitter circuit is supplied by a 5 V DC source, and the input/output voltage and power of the WPT system have been measured to characterize the prototype. The measured output power for 2.5 cm and 12 cm distance are 2.5 W and 0.9 W, respectively. Figure 9 shows the measured and simulated normalized output power and power transfer efficiency against the different distances/position of the receiver coil across the relay resonators. Measured and simulated output powers were normalized based on the maximum simulated output power.

TABLE II. Comparison with previous works.

Reference	Coil dimension: r_t, and r_r (mm)	Operating frequency (MHz)	Efficiency without relay coils (%)	Efficiency with relay coils (%)	Operational distance (mm)
Rakhyani *et al.*[25]	32, 11	0.70	28	77%, 2 relay coils	30
Rashid[26]	130, 130	38.15	4.5	25%, 1 relay coil 75%, 2 relay coils	1000
Zhang *et al.*[10]	81, 81	8	10	46%, 2 relay coils	300
Bhutada *et al.*[27]	…	4–12	40	93%, 2 relay coils	500
Zhu *et al.*[28]	23, 22	0.25	15.9	36.3%, 2 relay coils	20
Wang *et al.*[20]	8.5, 6	200	…	30%, 2 relay coils	7
This work	23, 22	0.22	35	85%–90%, 7 overlapping relay coils	27

Figure 8 shows the comparison between measured and simulated power transfer efficiency for the relay coil system. It can be seen that the simulated results are closely matched with the measured results and that the efficiency drops from 90% to 35% over a 10 cm distance. The receiver output power was also measured without a relay coil to evaluate the operational distance and efficiency with and without a relay coil.

Figure 9 clearly indicates that without a relay coil the efficiency will drop from 85% to 0% within very short operational distance of between 2 cm and 3 cm.

Both mutual inductance and the power transferred both decrease with increasing the distance between the transmitter and receiver coils. It can be seen that high power transfer can be achieved with a low source impedance which will provide the low I^2R_s loss in the system.

This study has investigated the tuning position of prototype overlapping relay coils in a horizontal design for distance extension of WPT and evaluated power transfer efficiency with the increase in operating distance between the transmitter and receiver coils.

Table II summarizes the comparison between this study and previous research[20–23] with and without relay coils and demonstrated that the relay coil WPT system will increase the efficiency significantly compared to a system without a relay coil. However, the efficiency and the operational distance depend on the coil dimension and magnetic material of the transmitter and receiver coils. It can be seen from Table II that the overlapping relay resonators show the highest WPT efficiency compared to the previous findings. Additionally, the overlapping relay coils design of the WPT system would enhance a wide range of applications such as implantable medical devices, i.e., cardiac pacemaker, nerve simulator, and retinal prosthesis with other applications such as wireless charging and wearable sensing devices.[16]

The design configuration is simulated using the FEA magnetic software, and the simulated results have been analyzed and compared with the measured results. The measured results suggest that the prototype is capable of achieving 85%–90% efficiency within a 4 cm distance from the transmitter coil. The relay coil resonators have been built and tested for the purpose of extending power transfer. This is particularly beneficial in health and medical applications and also in mobile charging applications due to small power requirements. These areas are undergoing further study. The eventual goal is to optimize the relay coils and transmitter/receiver coils using the magnetic simulation software with the horizontal array configuration. Furthermore, this horizontal configuration is compared with the vertical array configuration to optimize the design.

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