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An application of multi-magnetic circular planar spiral relay to improve the performance of wireless power transfer system

__Introduction.__ The system of delivering electricity without wires is known as wireless power transfer (WPT). The WPT system has been extensively used in a number of industries, health, telecommunications, and transportation. However, the distance between the transmitter and receiver coils has a significant impact on its efficiency. Lower power can be generated between coils the farther apart they are, and vice versa. __The novelty__ of the proposed work is innovative in that it develops a multi-magnetic circular planar spiral relay to improve the WPT system's performance and designs circular planar spiral coils to achieve an appropriate inductance value for the 5 kHz matching frequency. __The goal__ of paper is to create a circular planar spiral coil with an appropriate inductance value for the 5 kHz matching frequency. __Methods.__ The transmitter circuit, receiver circuit, and DC voltage source are parts of the WPT system. The inverter circuit uses the inductive coupling technique to transform the DC power source into AC voltage on the transmitter coil. The suggested coil is additionally employed as a multi-magnetic circular planar spiral relay in order to increase the mutual inductance between the receiver and transmitter coils. __Results.__ To monitor the power improvement that results from adding a multi-magnetic relay to the system, the transmitter coil, receiver coil, and multi-magnetic relay are positioned at specific distances from each other. With V_{dc} = 30 V and d_{tr} = 21 cm, the power received at the receiver coil can therefore be improved by up to 67 %. __Practical value.__ The multi-magnetic circular planar spiral relay applied in the WPT system has been investigated in an experimental study and it can be applied for DC load. References 26, table 1, figure 18.

Key words: **wireless power transfer, performance improvement, magnetic relay, multi-magnetic circular planer spiral relay.**

__Вступ__. Система доставки електроенергії без дротів відома як бездротова передача енергії (WPT). Система WPT широко використовується у ряді галузей промисловості, охорони здоров'я, телекомунікацій та транспорту. Однак відстань між передавальною та приймальною котушками істотно впливає на її ефективність. Чим далі котушки один від одного, тим нижча потужність, і навпаки. __Новизна__ запропонованої роботи полягає в розробці багатомагнітного круглого плаского спірального реле для покращення продуктивності системи WPT і в проєктуванні круглих пласких спіральних котушок для досягнення відповідного значення індуктивності для частоти узгодження 5 кГц. __Метою__ роботи є створення кругової плоскої спіральної котушки з відповідним значенням індуктивності для частоти узгодження 5 кГц. __Методи__. Схема передавача, схема приймача та джерело постійної напруги є частинами системи WPT. Схема інвертора використовує метод індуктивного зв'язку перетворення джерела постійного струму в змінну напругу на котушці передавача. Пропонована котушка додатково використовується як багатомагнітне кругле плоске спіральне реле для збільшення взаємної індуктивності між приймальною і передавальної котушками. __Результати__. Для контролю поліпшення потужності, яке відбувається в результаті додавання багатомагнітного реле в систему, котушка, що передає, приймальна котушка і багатомагнітне реле розташовуються на певних відстанях один від одного. При V_{dc} = 30 В і d_{tr} = 21 см потужність, яка приймається приймальною котушкою, може бути покращена до 67 %. __Практичне значення__. Багатомагнітне кругле плоске спіральне реле, що застосовується в системі WPT, було досліджено експериментально, і його можна застосовувати для постійного навантаження. Бібл. 26, табл. 1, рис. 18.

Ключові слова: **бездротова передача живлення, підвищення продуктивності, магнітне реле, багатомагнітне спіральне пласке реле.**

Introduction. Nowadays, there is a growing amount of work being done on the development and applications of wireless power transfer (WPT) in numerous fields. For instance, wireless power transmission has been effectively applied in a number of industries, including biomedicals [1, 2], battery chargers [3–6], the electrical industry, and even the transportation industry, including electric vehicles [7–9]. Activities are made simpler and more efficient by doing this. Additionally, it helps reduce the expense of using wires as a power conductor.

WPT system typically has three primary parts: the transmitter circuit, receiver circuit and DC voltage source [10, 11]. An inverter circuit and coil make up the transmitter circuit; the inverter circuit converts the primary DC power source to AC voltage [12, 13], which is then connected to the transmitter coil. AC power produced at the transmitter coil is then transferred to the receiver coil using the principle of inductive coupling. The transmitted AC power is determined by the quantity of magnetic flux that reaches the receiver coil, which in turn is determined by the magnetic field created by the transmitter coil. The transmitter coil diameter is the final factor that influences this [14].

Power transfer of inductive coupling occurs by conducting an alternating magnetic field on the transmitter coil [15, 16]. Consequently, in the receiver coil, the magnetic flux produced will be transformed into an electric current. The electric current that the transmitter coil delivers is always greater than the electric current that the receiver coil generates. The receiver coil receives less current the farther apart the two coils are [17–20]. The entire magnetic field that flows through the transmitter and receiver coil is measured as magnetic flux. The centre of the coils is where the flux is always focused. The distance between the transmitter and receiver coil impacts the amount of AC power that the receiver coil can receive; the greater the distance, the lower the AC power that can be obtained on the receiver coil [21, 22] and it can be classified in a low power electrical device and also as an electrical energy harvested [23]. To prevent the magnetic field from passing out of the centre between the transmitter and reception coils, the flux level can still be increased. To maximize the flux and raise the AC power on the reception coil, a multi-magnetic relay must be positioned between the transmitter and the receiver coil.

The goal of this study is to create a circular planar spiral coil with an appropriate inductance value for the 5 kHz matching frequency. The usage of a higher frequency will result in a lower coil inductance since frequency and coil inductance have an inversely proportionate relationship. Conversely, the coil's inductance is directly correlated with its number of turns, meaning that an increase in turns will result in a larger coil inductance. To achieve the matching frequency of 5 kHz, a suitable type of coil and its inductance value are needed because the shape of the coil impacts the value of its inductance. With reference to [6], the receiver coil's AC power is always low, and the greater the distance between the transmitter and the coil, the lower the AC power is on the coil. Consequently, mutual inductance is needed to increase the induction between the transmitter and receiver coils in order to increase the power of 5 kHz WPT system. To obtain the mutual inductance in this instance, a multi-magnetic circular planar spiral relay is utilized. Because of this, the main focus of this study will be on enhancing the power of 5 kHz wireless power transmission through the use of mutual inductance to reinforce the magnetic field between the transmitter and receiver coils as well as multi-magnetic circular planar spiral relays.

Methodology. This section offers the design of a circular planar spiral coil for getting a sufficient inductance value for the matching frequency of 5 kHz. The construction of WPT system with inclusion of a multi-magnetic circular planar spiral relay is detailed in this part. This section also explains the assessment of the measurement findings of the WPT system's performances with and without the multi-magnetic circular planar spiral relay.

A block diagram of a proposed WPT system with a multi-magnetic relay is displayed in Fig. 1. The multi-magnetic planer spiral relay, receiver circuit, and transmitter circuit make up its three primary components. Circular planer spiral coils are the shapes of the magnetic planer spiral relay, transmitter coil, and receiver coil.

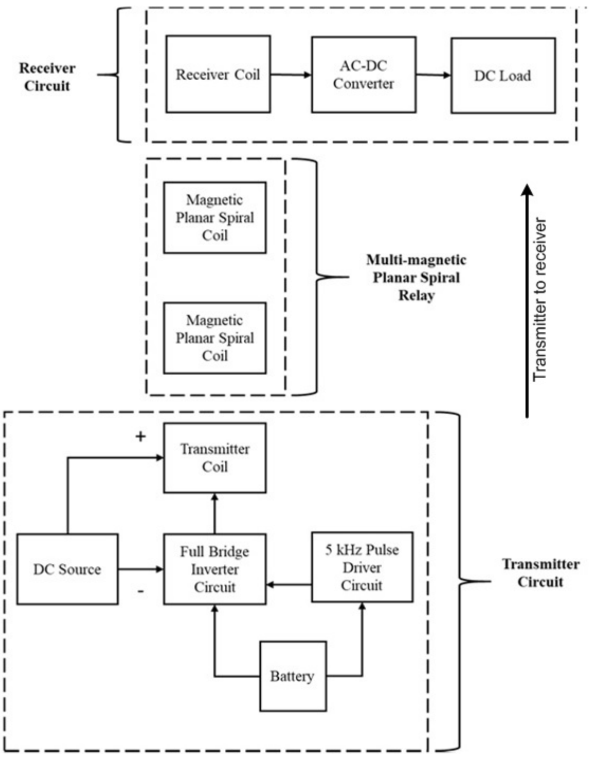


Fig. 1. Block diagram of proposed WPT system with multi-magnetic relay

The transmitter coil, full bridge inverter circuit, and 5 kHz pulse driver circuit make up the transmitter circuit. The PIC16F628A-I/P microcontroller, which powers the entire bridge inverter circuit, is responsible for creating the 5 kHz pulse wave and driving the MOSFETs' gate terminals. The primary purpose of the complete bridge inverter circuit is to change the DC voltage source into an AC voltage of 5 kHz for the transmitter coil.

The receiver coil, AC-DC converter, and DC load make up the receiver circuit. A 5 kHz AC voltage is applied to the receiver coil as a result of mutual magnetic flux leaking from the transmitter coil into the receiver coil. A rectifier (AC-DC converter) is needed when DC electrical is applied in the system [24, 25]. In this research, a rectifier rectifies 5 kHz AC voltage, which is then applied by the DC load.

Increasing the strength of the magnetic field between the transmitter and receiver coils is the primary purpose of a multi-magnetic relay. As a result, the receiver coil's AC voltage, current, and power can all be increased. This indicates that the WPT system performs better when using a multi-magnetic relay than when it does not.

Proposed design of circular planar spiral coil. The occurrence of an electromagnetic force in a conducting wire or coil as a result of variations in the magnetic force lines (magnetic flux) is known as electromagnetic induction. The fundamental idea of electromagnetic induction between transmitter and receiver coils is depicted in Fig. 2. Furthermore, Fig. 2 depicts the idea design of coils, including the wire diameter (d_w), the distance between turns (s), the inner diameter (d_{in}), and the outer diameter (d_{out}).

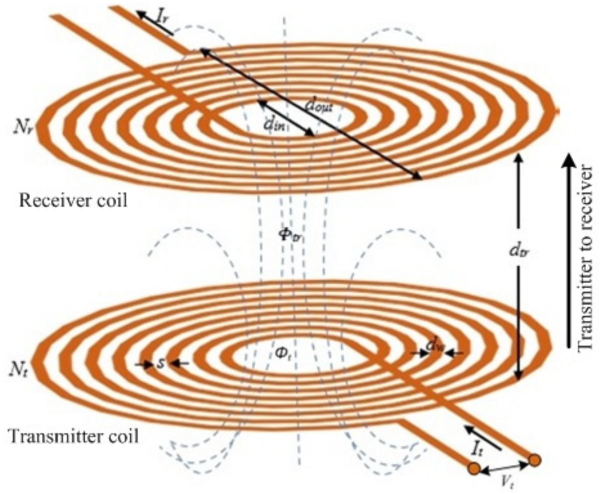


Fig. 2. The fundamental idea of transmitter and receiver coils

In this design, the turn numbers of the transmitter coil N_t and the receiver coil N_r are the same (N_t = N_r= N). The distance d_t separates the coils of the transmitter and receiver. Following (1) [18], the transmitter coil produces the magnetic flux Φ_t when an AC voltage V_t is supplied to it. This causes the AC current to pass through the transmitter coil.

$$V_t = -N_t \frac{\mathrm{d}\Phi_t}{\mathrm{d}t} . \quad (1)$$

The magnetic flux flows to the receiver coil through the air medium and produce the mutual magnetic flux Φ_{tr}. Thus, an induced voltage V_r is generated on the receiver coil and the current I_r flows through the receiver coil if it is a closed loop circuit.

In this setup, the circular planer spiral coil and a capacitor C are linked in parallel to yield a math frequency f of 5 kHz. Therefore, (2) can be used to compute the coil inductance L [17, 26]:

$$L = \frac{1}{4\pi^2 f^2 C}. \quad (2)$$

The specifications and computations of the parameter utilized in the following (2) must be understood before constructing the circular planer spiral coil design. Table 1 displays the characteristics of the circular planar spiral coil that was utilized in the experiment.

Table 1

Specification of the proposed circular planar spiral coils

Parameter	Value
Wire diameter d_w, mm	1.25
Inner diameter d_{in}, mm	20
Number of turns N	66
Spacing between turns s, mm	0.001
Outer diameter d_{out}, mm	185.131
Capacitance of capacitor C, µF	3
Inductance of coil L, µH	338

The circular planar spiral coil, which can be utilized as a multi-magnetic relay as well as a transmitter and receiver coil, is depicted in Fig. 3. Up to four circular planar spiral coils with the same inductance value L and number of turns N can be used in the WPT system created in this study. The coil was built using computations from the formulas given in this section and the design concept.

Fig. 3. Proposed circular planar spiral coil

Hardware construction of 5 kHz WPT system. A WPT system requires more than just the coils that are employed, circuit design and construction are essential for system application. It is important to build the circuits in a way that allows the WPT system to function correctly and in accordance with the intended mechanism. As a result, the construction of the circuits that are employed, such as the receiver side AC-DC converter and the transmitter side full bridge inverter is covered in this part.

Pulse driver circuit. The frequency of operation for the WPT system in this study is 5 kHz. The PIC16F628A-I/P microcontroller serves as the primary driver in the pulse driver circuit, which generates the frequency. The PIC compiler software's C language is used to program the PIC16F628A-I/P microcontroller to operate at a frequency of 5 kHz. Consequently, the complete bridge inverter is driven by the ensuing pulse wave.

A schematic representation of the pulse driver circuit employed in this study is presented in Fig. 4. The D1 1N4007 diode protects the battery's polarity and permits a current flow of 1 A before the 12 V voltage source from the battery enters the LM7805 voltage regulator. The LED, which serves as a voltage indication in the circuit, is connected in parallel to the LM7805 output terminal. On the other side of the connection, pins 4 and 14 are the positive 5 V terminal of the PIC16F628A-I/P microcontroller and pin 5, which is the negative terminal, where the 5 V output voltage that results from the regulation of the LM7805 is filtered by capacitors C1 and C2 to reduce noise. Conversely, pins 15 and 16 represent the oscillator terminals that are linked to the crystal, together with two parallel capacitors C3 and C4. With the use of a coding program, this oscillator determines the speed at which the processor will execute instructions to create two pulse waves at a frequency of 5 kHz, corresponding to pin numbers 11 and 12.

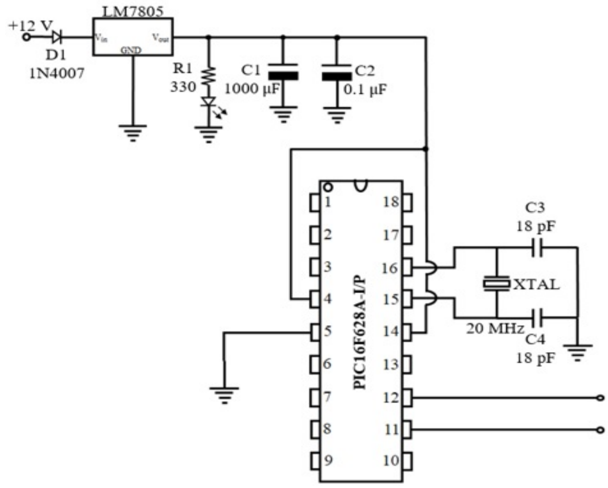


Fig. 4. Schematic diagram of pulse driver

Full bridge inverter circuit. As illustrated in Fig. 5, this study employs a full bridge inverter with four power MOSFET switches. Pins 11 and 12 of the pulse driver are connected to the input terminal of the full bridge inverter by terminals A and A'. The terminals B and B' link the full bridge inverter to the DC voltage source, enabling the nominal voltage to be set by the DC input provided at the transmitter side.

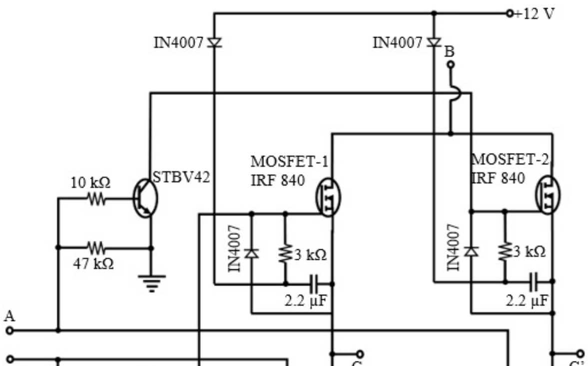


Fig. 5. Full bridge inverter schematic diagram

Four IRF 840 MOSFETs transform the DC input voltage into an AC voltage so that the inverter's output side (terminals C and C') can generate a full waveform output at a frequency of 5 kHz. In order to get a pure sinusoidal waveform, the outputs of the C and C' terminals can be routed to a 3 µF filter capacitor and a 100 µH inductor before being sent to the transmitter coil.

Receiver circuit. A DC waveform must be created by rectifying the 5 kHz AC voltage waveform that was received at the receiver coil on the receiving side. As a result, a device is required to change the waveform from AC to DC. As seen in Fig. 6, this study uses a full wave AC-DC converter with four diodes acting as switches.

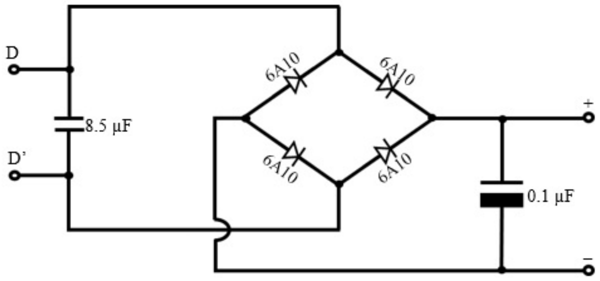


Fig. 6. Full bridge rectifier circuit

In accordance with the schematic diagram in Fig. 6, the connections at input terminals D and D' originate from the receiver coil. An 8.5 µF capacitor filters the input power that the receiver side of the circuit receives before it is sent to the full wave converter. A full wave AC-DC converter using four 6A10 diodes as switches rectifies AC-DC waveforms. Before connecting the DC load through the output terminals (+ and –), the AC-DC waveform's rectification results are filtered by a 0.1 µF capacitor to lessen noise.

Overall hardware and experimental setup of WPT system. The overall design and experimental configuration of the 5 kHz WPT system suggested in this study are described in this section. Figure 7 depicts the overall hardware of the suggested WPT system. As seen in Fig. 4, the battery may supply 5 V of DC voltage to the pulse driver circuit after the LM7805 reduces 12 V to 5 V. In Fig. 5 the battery supplies 12 V of DC voltage to the entire bridge circuit. As seen in Fig. 5, the DC voltage source (V_{dc} source) has the ability to supply the DC voltage source to the entire bridge inverter circuit at terminals B and B'.

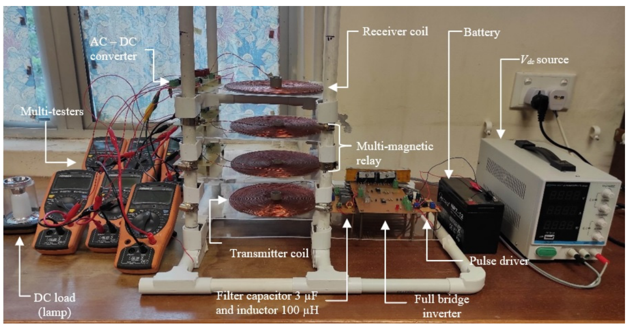


Fig. 7. Overall design of the proposed WPT system

The design of multiple experimental setups, ranging from the production of a 5 kHz pulse wave to the power transfer procedure utilizing the WPT system suggested in this study. In order to collect the required data, various settings were used in each experiment. This experiment involves setting a number of parameters, including the number of circular planar spiral coils utilized in the WPT system, variations in the DC voltage source (V_{dc} source), and variations in the distance between coils.

The waveform and frequency received on each coil must be verified to show that the proposed WPT system in this experiment operates at a frequency of 5 kHz in the form of a sine voltage waveform. Consequently, the system is set by connecting each coil to the oscilloscope as shown in Fig. 8. The multi-magnetic relay is connected to channels 2 and 3, respectively, and the transmitter coil is connected to oscilloscope channel 1. While the oscilloscope's channel 4 is linked to the receiver coil. In this experiment, the DC voltage is set to 15 V, and the coil spacing is adjusted to be 0 cm, 15 cm, 30 cm, and 45 cm. Verifying the waveform and frequency value that occur in each coil is the aim of this experiment.

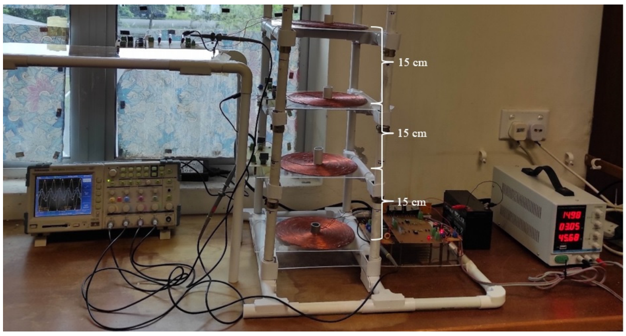


Fig. 8. Verification of waveform and frequency on all coils

There are just two coils (the transmitter coil and the receiver coil) used in the experiment shown in Fig. 9. The two coils are positioned vertically between three and thirty centimeters apart. Additionally, a voltage value ranging from 3 V to 30 V is supplied to the specified V_{dc} source. This arrangement allows findings on many parameters, including voltage, current, and power, to be obtained and shown graphically for the additional analysis.

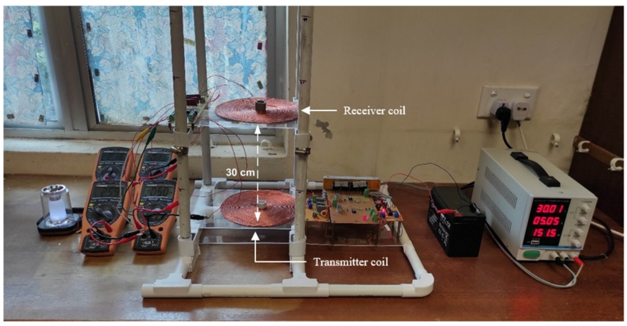


Fig. 9. WPT system without multi-magnetic relay

As illustrated in Fig. 10, this experiment is similar to the setup discussed previously, but it adds a multi-magnetic relay consisting of two circular planer spiral coils positioned between the transmitter and receiver coils. The four coils that are being used are separated by 7 cm due to the multi-magnetic relay's positioning between 7 and 14 cm. The transmitter side's input voltage (V_{dc} = 30 V) and the reception coil's distance (d_{tr} = 21 cm) are both fixed at the DC voltage source. This setup makes use of the output obtained on the receiver side to determine how adding a multi-magnetic relay affects the created WPT system's performance.

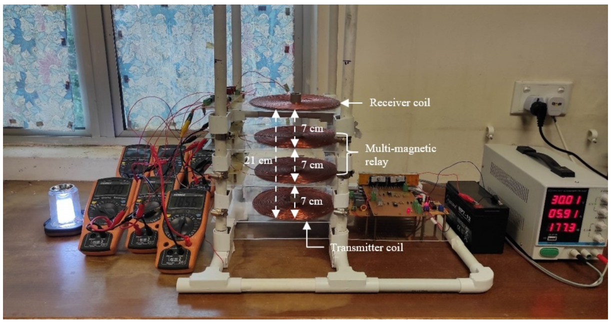


Fig. 10. WPT system with multi-magnetic relay

Results. The study findings are covered in this section, beginning with the development of a 5 kHz frequency in the pulse driver circuit using the microcontroller PIC16F628A-I/P. Additionally, the hardware produced in this research has been used in studies to convert DC to AC as the result waveform on full bridge inverters. Above all, the analysis results of the power development tests are provided by this section, which examines the power output data from the transmitter, receiver, and multi-magnetic relay sides.

Generation of 5 kHz pulse wave. The pulse driver circuit, which has the microcontroller PIC16F628A-I/P as its primary component, produces the 5 kHz frequency. In order to achieve a frequency of 5 kHz, this pulse driver circuit applies frequency through the MOSFETs' gate terminals. Four MOSFETs make up the entire bridge inverter circuit utilized in the driver circuit.

The configuration of the four MOSFETs allows for continuous operation. Simultaneous driving of MOSFET-1, MOSFET-4, MOSFET-2 and MOSFET-3 is observed. In order to provide the transmitter coil with an AC voltage, this is done to reverse the direction of current flow through the coil. This is a result of MOSFET-1 and MOSFET-4 having identical phase angles, ranging from 0° to 180°, configured. In contrast, the phase angles of MOSFET-2 and MOSFET-3 are arranged from 180° to 360°. Stated otherwise, MOSFET-2 and MOSFET-3 are «OFF» when MOSFET-1 and MOSFET-4 are «ON». Conversely, MOSFET-1 and MOSFET-4 are «OFF» when MOSFET-2 and MOSFET-3 are «ON». Thus, Fig. 11 displays the result of the coordination of these four MOSFETs as an output of the hardware that was constructed.

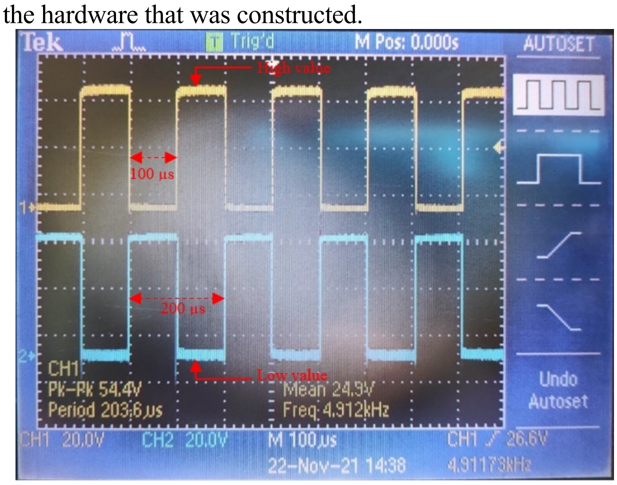


Fig. 11. 5 kHz pulse wave generations

AC voltage waveform and magnetic flux generated on the transmitter coil. The four MOSFETs' rectification produced an AC voltage on the transmitter coil, but it is still not entirely functional. Consequently, in order to change the square waveform into a sinusoidal waveform, a filter is required. Here, the wave filters are a 3 µF capacitor and a 100 µH inductor. Furthermore, when an inductor has electricity flowing through it, it can also produce a magnetic field. The entire magnetic field that flows through the transmitter and receiving coil is measured as magnetic flux. As a result, it is important to choose an inductor value that will produce the intended result. When an excessively big inductor is used, the transmitter coil experiences a lower voltage but a better waveform (sinusoidal waveform). On the other hand, even though the voltage that results is larger, an inductor that is too small cannot provide a perfect sinusoidal waveform.

The results of the transmitter coil voltage pulse waveform in the simulation can be seen in the form of a sine voltage waveform with a half cycle formed in 100 µs and one cycle formed in 200 µs. On the other hand, the pulse waveform generated in the experiment is also a sine wave with a frequency of 4.9 kHz where it is very close to get 5 kHz. Figure 12 shows the rectification result of the square waveform into a sine waveform that occurs in the full bridge inverter and filtering by 3 µF capacitors and 100 µH inductors. Based on the oscilloscope's scale, this is clear. One cycle sine wave's length is composed of two divisions, each taking 100 µs of time. Afterwards, 200 µs is needed to generate one cycle of the AC sine voltage waveform. This indicates that the AC sine voltage waveform has 5000 cycles in a second.

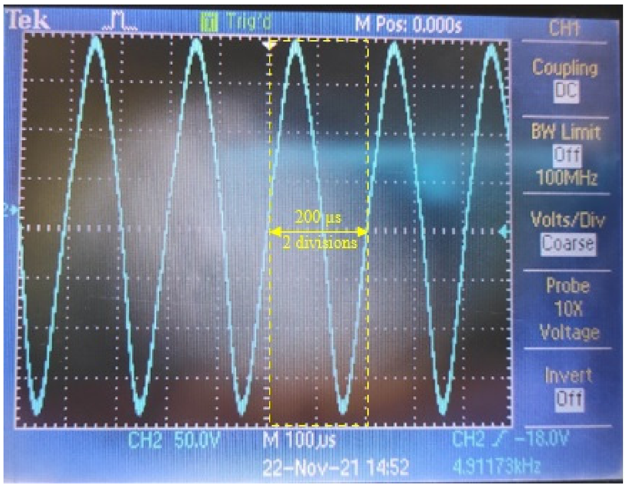
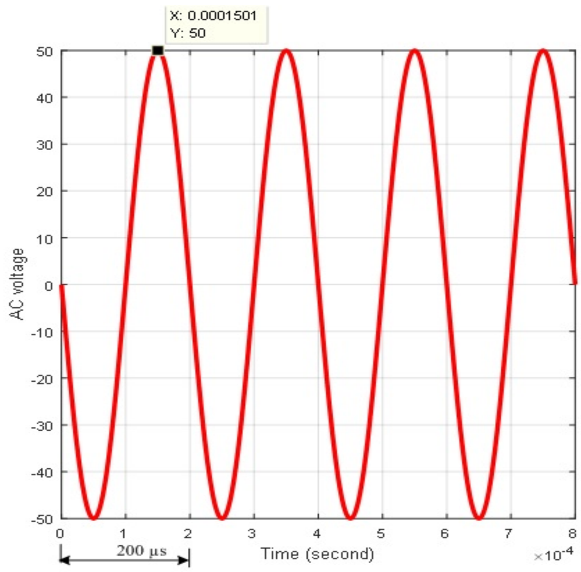


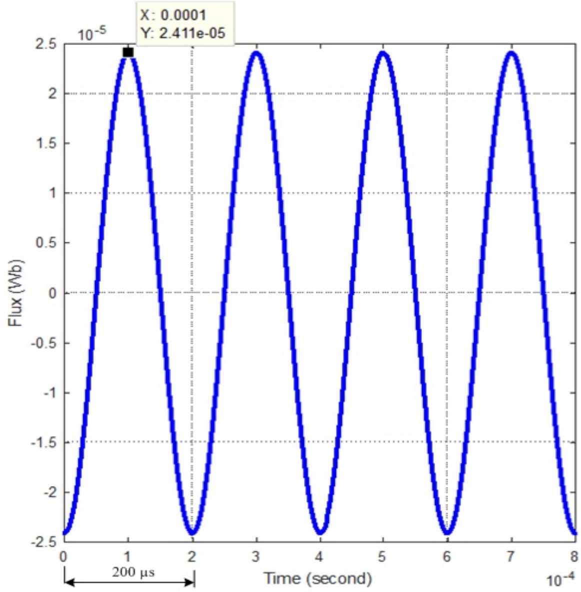
Fig. 12. 5 kHz sine voltage waveform of transmitter coil

In order to generate the magnetic flux (Fig. 13,*b*) following (1), the sine voltage waveform in Fig. 12 is formed (Fig. 13,*a*) with a peak voltage of 50 V. The link between the coil's number of turns and the integral of the voltage on the transmitter coil side is represented by the magnetic flux. The waveform and frequency broadcast in the system are identical to the sine voltage waveform that forms at a frequency of 5 kHz in the transmitter coil.

AC voltage waveform on the transmitter coil, multi-magnetic relay and receiver coil. Verification of the waveform on the multi-magnetic relay and receiver coil has also been done in order to confirm the waveform created in the transmitter coil. Figure 14 displays the verification outcomes for each coil's frequency and waveform.



a) sine voltage



b) magnetic flux

Fig. 13. 5 kHz sine voltage (*a*) and magnetic flux (*b*) waveform on the transmitter coil following (1)

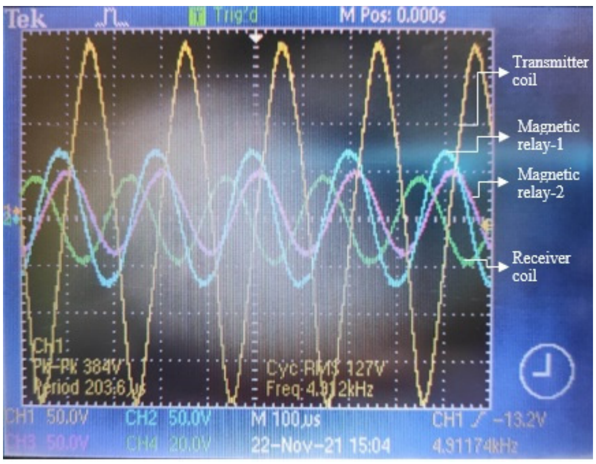


Fig. 14. Waveform and frequency on all coils

The output of the transmitter coil is represented by channel 1 of the oscilloscope, the multi-magnetic relay is represented by channels 2 and 3, and the waveform produced in the reception coil is represented by channel 4.

The output waveform and frequency reported in Fig. 14 reveals almost 5 kHz. It is shown that the WPT system and all coils are working properly and the experiment is ready to proceed in the data gathering and analysis stage.

Performance improvement of 5 kHz WPT system. The impact of incorporating a multi-magnetic relay on the designed WPT system's performance is covered in this subsection. This part also covers the performance comparison between the WPT system with and without multi-magnetic relays based on the output produced in the experiment. The transmitter and receiver coil distances, the constant V_{dc} at 30 V, and the d_{tr} constant at a distance of 21 cm are the settings for the tests conducted in this section. This is done to monitor the performance and determine the best spacing between multi-magnetic relays.

WPT performance with the addition of one magnetic relay. This configuration is done to see how adding a magnetic relay affects the output voltage, current, and power in the receiver side of the developed WPT system. The experiment is set up with the DC voltage source V_{dc} = 30 V, and the distance between the transmitter and receiver coil d_{tr} = 21 cm. Additionally, one magnetic relay is placed between the transmitter and receiver coils with distances set at 3 cm, 6 cm and 9 cm. As a result, a graph of the receiver side output comparison based on the system configuration with a magnetic relay added is displayed in Fig. 15. In contrast, Fig. 16 illustrates the percentage improvement of the WPT system with a magnetic relay added when compared to the WPT system without one.

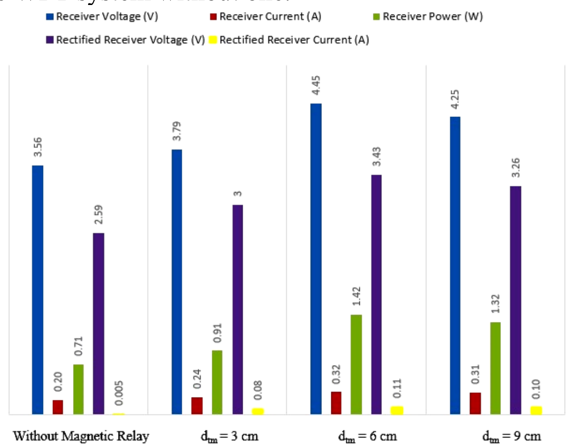


Fig. 15. WPT performance with the addition of one magnetic relay

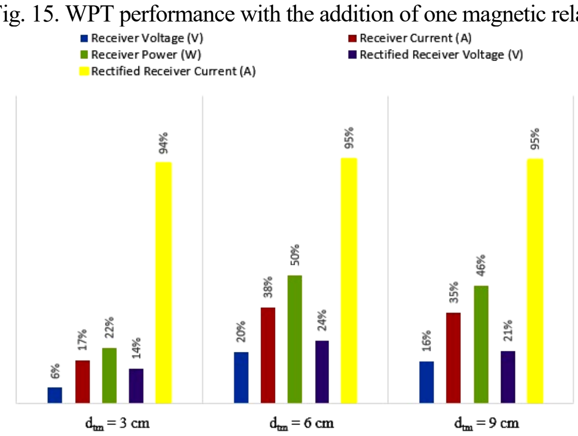


Fig. 16. Improvement of WPT by addition of one magnetic relay in percent (%)

The output of the receiver coil produced from the experiment without a magnetic relay is 3.56 V and 0.2 A with a power of 0.71 W. However, after adding a magnetic relay, the observed parameters have increased. The power achieved at the magnetic relay point (d_{tm} = 3 cm) is 0.91 W at 3.79 V of voltage and 0.24 A of current. When the magnetic relay is positioned at d_{tm} = 3 cm (Fig. 16) the receiver coil's output improves by 22 % in power, 6 % in voltage, and 17 % in current. Conversely, however, there was also improvement at d_{tm} = 6 and 9 cm. The resulting output experiences a 20 % voltage rise, a 38 % current increase, and a 50 % power gain at d_{tm} = 6 cm. At d_{tm} = 9 cm, there is a 16 % increase in voltage, a 35 % increase in current, and a 46 % increase in power.

The magnetic relay placed 6 cm away from the transmitter coil produced the maximum output that was measured. Stated otherwise, this is the best position relative to other positions. The amount of flux that the magnetic relay can capture can be large at the distance between the transmitter and the magnetic relay, d_{tm} = 3 cm, but the flux cannot completely reach the receiver coil due to the distance between the magnetic relay and the receiving coil being relatively far. Conversely, the output obtained is marginally less than the distance d_{tm} = 6 cm at d_{tm} = 9 cm or higher. This is due to the transmitter coil's action, which is where the flux is initially generated. As a result, the magnetic coil acts to retain the flux in the magnetic field between coils before it escapes. Because of this, the flux received at d_{tm} = 6 cm is more than at d_{tm} = 9 cm or higher, but it is still capable of reaching the receiver coil with magnetic flux. As is well known, mutual induction involves a magnetic coil in addition to the transmitter and receiver coils in this experiment.

This experiment involves rectifying the waveform from AC to DC in addition to the process of power transfer between the coils. Rectifiers or AC-DC converters are used in the rectification process. Because the created WPT system operates at a frequency of 5 kHz and prevents it from being delivered directly to the load, this rectification procedure is necessary. The trend of the observed DC voltage and the AC parameters in the receiver coil are consistent (Fig. 15, 16). But the outcome of the rectification is marginally less than the input, which in this instance is the receiver coil. This results from a decrease brought on by the rectifier circuit's kind of diodes' threshold voltage value.

WPT performance with the addition of multi-magnetic relay. This experiment is comparable to the one discussed previously, but it adds a multi-magnetic relay (two coils). The distance between the transmitter and receiver coils, d_{tr} = 21 cm, and the DC voltage source, which serves as the transmitter side's DC input voltage, are both fixed at V_{dc} = 30 V. The multi-magnetic relay is positioned at a distance of 7 and 14 cm from the transmitter and receiving coils, respectively. By using the output received on the receiver side, this setup is done to observe how adding a multi-magnetic relay affects the created WPT system's performance. Consequently, a comparison graph of the WPT system's performance that was enhanced by the addition of a multi-magnetic relay is displayed in Fig. 17. Furthermore, a comparison of the percentage improvement that happens when the system uses a multi-magnetic relay is shown in Fig. 18.

The performance of the WPT system with a multi-magnetic relay is compared to the experiment without a magnetic relay and with the addition of one magnetic relay (one coil) in Fig. 17. Using one magnetic relay at d_{tm} = 6 cm, the maximum receiver power in the experiment is utilized as a comparison, with reference to Fig. 17, 18. As a result, with a voltage gain of 0.58 V (12 %) and a current improvement of 0.11 A (26 %), the receiver power received at the receiver coil by 0.74 W, or 34 %. Concurrently, the experiment's receiver power increased by roughly 1.45 W, or 67 %, from the system without a magnetic relay to the one with a multi-magnetic relay added. The system also had a higher voltage difference of 1.47 V, or 29 % higher, and a higher current difference of 0.12 A, or 53 % higher, than the system without a multi-magnetic relay.

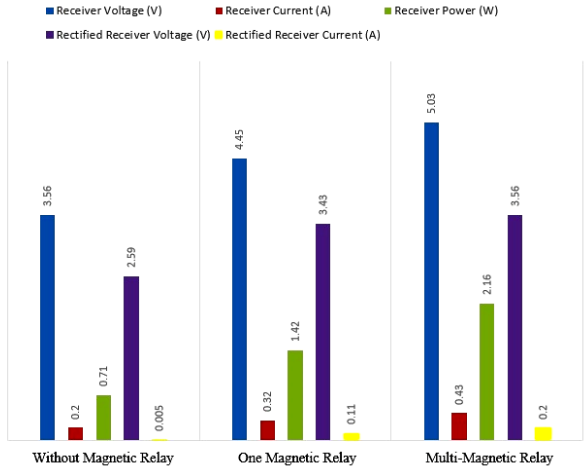


Fig. 17. WPT performance with the addition of multi-magnetic relay

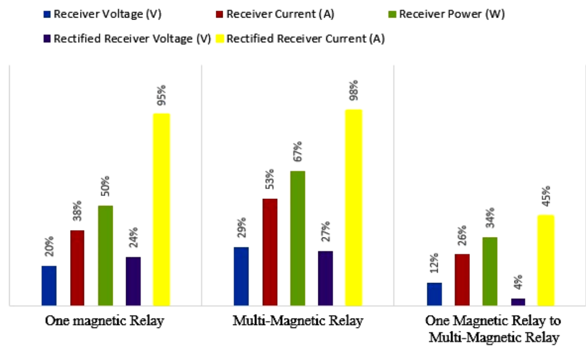


Fig. 18. Improvement of WPT by addition of multi-magnetic relay in percent (%)

Conclusions. The purpose of this research is to create a circular planar spiral coil with an appropriate inductance value for the 5 kHz matching frequency. The following conclusions can be been conducted.

1. A circular planar spiral coil is developed by designing and calculating a number of parameters, including the number of turns, inner and outer diameter, wire diameter and the spacing between turns. According to the findings, 338 μH is the proper circular planar spiral coil inductance value for the 5 kHz WPT system.

2. System performance is improved when a multi-magnetic circular planar spiral relay is incorporated into the WPT system. Consequently, there was a 67 % improvement in the power received at the receiver coil, going from 0.71 W to 2.16 W.

3. The percentage error between simulation and experiment is still less than 10 %, according to the validation data. This indicates that the WPT system hardware created for this investigation is dependable and matches the simulation.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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