International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I12P120

Volume 72 Issue 12, 227-234, December 2024

Original Article

Designing and Evaluating Circular and Square Coils for Tissue Monitoring using RF Wireless Power Transmission

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Received: 23 September 2024 Revised: 09 November 2024 Accepted: 09 December 2024 Published: 25 December 2024

Abstract - *Tissue engineering, a burgeoning multidisciplinary field, seeks to repair or replace damaged tissues and organs by leveraging engineering and biological principles. Central to the advancement of this field is the ability to monitor tissue growth in real-time. This necessitates the use of implantable devices, such as sensors, which need to be powered. Traditional power sources, like batteries, could impede tissue growth and tissue damage, making Wireless Power Transfer (WPT) an attractive alternative. This study delves into detail the design and evaluation of coil configurations for RF wireless power transmission applied to tissue monitoring. Specifically, the contrast of the performance metrics between two coil designs: one featuring four circular coils and another blending three square coils with one circular coil. The analyses revealed that while both configurations experience diminished performance as the distance between transmitter and receiver increases, the efficiency for four circular coils at a distance of 30 mm is 25%, and for three square coils and one circular coil is 45%, and their efficiencies vary distinctly. Circular coils showcased higher power transfer efficiency and biocompatibility, whereas a combination of square and circular coils extended the transmission distance. Our findings illuminate the interplay between coil design and WPT performance, offering invaluable insights for developing implantable devices tailored for real-time tissue growth monitoring. This study propels the design endeavors in WPT and positions itself as a pivotal reference for applications in wound healing, organ transplantation, and drug testing.*

Keywords - *Tissue engineering, Wireless Power Transmission, Coil design, Implantable devices, Circular coils, Square coils.*

1. Introduction

Tissue engineering is a rapidly growing multidisciplinary field combining engineering and biology principles to create functional tissues or organs in the laboratory [1, 2]. Tissue engineering aims to repair or substitute damaged or unhealthy tissues or organs by emerging novel treatments based on regenerative medication. This approach includes utilising cells, signalling molecules and biomaterials to form living structures that can be utilized in various medicinal applications involving organ transplantation, wound healing and drug testing [3, 4]. The growth monitoring of the engineered tissue in real-time is one of the main challenges in tissue engineering. Monitoring tissue growth is significant for evaluating the achievement of optimizing the growth conditions and tissue engineering process [5, 6]. A few techniques have been established for monitoring tissue growth, including Magnetic Resonance Imaging (MRI), optical imaging and Positron Emission Tomography (PET) [7, 8]. On the other hand, these methods have several limitations, such as their low spatial resolution, the need for contrast agents or radiation exposure, and high cost. To overcome these limitations, the using of (WPT) for monitoring tissue growth is a good solution. Wireless power transmission can be used to power bio-implantable devices, such as implantable microsystems and sensors that monitor tissue growth, without using wires that penetrate the tissue and cause infections and risk or batteries with limited lifetime [9]. The reason for using RF wireless power transmission in monitoring tissue growth is based on the capability of RF waves to transfer energy from a transmitter to a receiver wirelessly [10]. Several factors impact the efficiency of transmitter and receiver coil design, which affects the efficiency and effectiveness of RF wireless power transmission for tissue monitoring [11, 12]. The coil's shape, size, geometrics and number of turns can significantly impact the power transfer efficiency, biocompatibility, and transmission distance between the coils [13]. Researchers have made several attempts to design Wireless Power Transmission (WPT) systems using magnetically coupled resonators, where the design includes passive elements such as inductor, resistor and capacitor in each resonator. The receiver and load are connected in series or parallel [14]. It has been observed that a shorter transmission distance corresponds to critical coupling. Hence, multiple coils are used instead of two coils. As a special case, the structure of the three-coil design includes an additional component for the WPT system [15]. Laterally, an additional resonator is included with the transmitter or receiver and can be placed within the same plane as the receiver/transmitter coil [15-17]. Adding a coil to the transmitter will increase the input impedance, thus improving the overall power efficiency of the system. Higher transmission efficiency and lower sensitivity to load variation can be achieved with a three-coils system versus a two-coils system [17].

The size of the coils is the main issue in the coils design, and it is still a challenge. To address this problem, multi-layers of coils were done on the transmitter side. Two approaches were suggested for designing the multi-layers. Firstly, a series-connected approach's geometric design is used to reduce these parasitic losses [18]. The second approach uses the Genetic Algorithm (GA) optimization technique to visualize double-layer, single-layer and multi-layer PSCs with variable width and minimal losses [19]. At present, recent research proposed the use of multilayer coils in serial connection has reported that there is a large inductance value in a limited area; though, there will also be an increase in the resistance value, which will generate heat as well as excessive power dissipation with respect to the coil, thus reducing the efficiency of wireless power transmission. The second approach is a parallel connection. Parallel connection can reduce the resistance and increase the Q value of the coil. This enhances the system's transmission efficiency. Although connecting coils in parallel enhances the transmission efficiency, the transmission power is still insufficient for long distances. The researchers designed four coils, two on the transmitter side as the source and transmitter coils and two on the receiver side as the receiver and load coils, to enable high transmission efficiency [20]. This method provides high efficiency while extending the transmission distance. Since the human body has limited space, placing multiple coils inside the human body, such as coronary artery sensors, is difficult. Therefore, the implanted coils must be very small.

Rectangular, circular and elliptical coils are generally used for tissue monitoring applications and other bio-implemented devices [21, 22]. This work will present and discuss a comparative study of two types of coils, circular and square, for tissue monitoring using RF wireless power transmission. The proposed coil's design and shapes will be investigated, as well as their effect on Power Transfer Efficiency (PTE), transmission distance and biocompatibility. The research aims to provide information on the effective coil design for monitoring tissues in RF wireless power transmission applications.

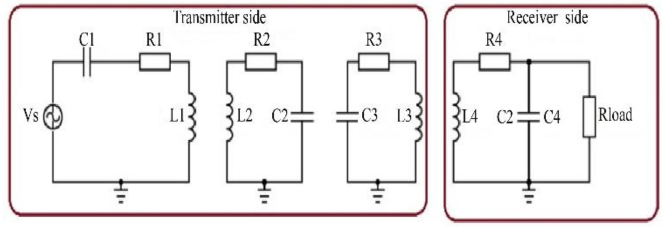

Fig. 1 The four RLC circuit configuration

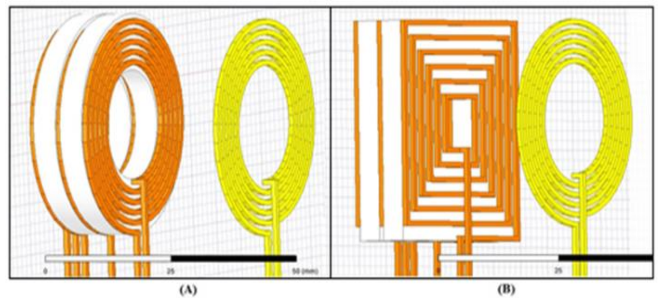

Fig. 2 The four coils design in (a) Circular coils, (b) Square coils

2. Methodology

The four RLC Circuit theories were implemented to assess its potential for Wireless Power Transfer (WPT) within the realm of monitoring tissue engineering treatments. This application was selected for its benefits, such as increasing effectiveness, enhancing patient comfort and minimizing intervention by reducing the need for multiple coils implanted in the body. The four coil circuit theory comprises two components: the transmitter, consisting of three RLC circuits and the receiver, incorporating an RLC circuit. The transmitter section consists of three coils: a source coil, an intermediate coil and a load coil. The source coil generates the field for transmitting power, which is then passed through the intermediate coil before being adjusted by the load coil to align with the resonance of the receiver coil. This setup boosts energy transfer efficiency and minimizes power loss. In the end, a coil is designed to capture the magnetic field and convert it into electrical energy. This energy can then be used to power implanted medical devices, such as sensors, which can monitor tissue health during tissue engineering monitoring.The receiving coil, implanted in the human body, is circularly shaped to provide maximum comfort and minimize the potential for harm due to the absence of sharp edges. Its shape is strategically selected to ensure the effective reception of power and safeguard against any internal injuries. We designed three coils utilizing circular and square geometries on the transmitter side, as depicted in Figure 2.

The rationale behind incorporating two distinctive shapes lies in our intent to scrutinize their comparative performance. Examining their efficiency in power transmission and alignment with the receiver coil aims to discern which geometry is most effective for this specific application in tissue monitoring.

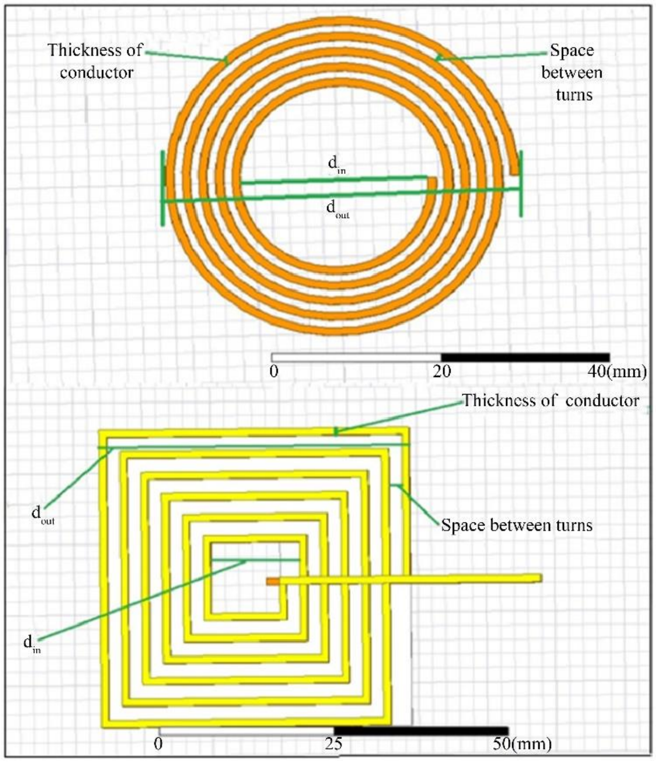

Fig. 3 The circular and square coil's dimension

Table 1. Parameters of coils design

parameter	Circular	square coil
Size	5cm2	5cm2
din	22.6mm	10.06mm
dout	54.6mm	48.06mm
Thickness	1mm	1mm
space	2mm	2mm
davg	38.6mm	29.06mm
$\boldsymbol{\phi}$	0.41	0.65
Number of turns (n)	5	5

The specific characteristics of each coil, including parameters such as diameter, coil thickness, coil distance, material, and number of turns, as shown in Figure 3, are detailed in Table 1. The outer diameter geometric for the circular coil is 54.6 mm and the inner diameter geometric is 22.6 mm; for square coil, the outer dimeter is 48.06 mm; the inner diameter is 10.06 (1-3). This table provides a comprehensive overview of the design specifications for each coil used in this study, providing the groundwork for replicating and expanding upon this research.

In the methodology given in this study, the operated frequency is 6.78 MHz ISM band to avoid tissue damage [22], and the supplied current is 1 mA. The copper material is used for both circular and square coils on the transmitter side. In contrast, gold makes the receiver coil compatible with the human body. Both coils were tested in the air environmental conditions. The fill factor $\boldsymbol{\phi}$ is an important parameter in coil design. It is defined as a dimensionless parameter that ranges from 0 to 1 and is used to quantify how much of the cross-sectional area of the coil is filled with wire [12]. This factor is essentially impacts the inductance of the coil and is a critical parameter to the efficiency and functionality of the (WPT) system calculated from Equation (1)

$$\emptyset = \frac{d_{out}-d_{in}}{d_{out}+d_{in}} \quad (1)$$

Hence, regarding the values given in Table 1 and Equation (1), the value $\boldsymbol{\phi}$ = 0.421, which is considered ideal as it balances between the coil size, power handling capabilities and performance. To calculate the inductance values for both square and circular coil shapes, the equations (2) and (3) are applied respectively. The mathematical calculation of the models considers important parameters such as coil geometry, number of turns, coil material, fill factor and operation frequency. Therefore, this will enable a comprehensive understanding of the proposed coil's characteristics and its insinuations on the overall system's performance.

$$L = \frac{C_1\mu_0 N^2 d_{avg}}{2}\left[l_n\left(\frac{C_2}{\varphi}\right)+C_3\varphi+C_4\varphi^2\right] \quad (2)$$

Where L is the inductance of circular coil, C refers to the coefficient of the circular coil layout based on the values as C1 = 1.00, C2 = 2.46, C3 = 0.00, C4 = 0.20, μ0 is the permeability of free space (4π × 10-7 H/m), N is the number of turns in the coil, davg is the average coil diameter, where dout is the outer diameter and din is the inner diameter of the coil.

$$L = \frac{1.27\mu N_{square}^2 d_{avg}}{2}\left[ln\left(\frac{2.07}{\emptyset}+0.18\emptyset+0.13\emptyset^2\right)\right] \quad (3)$$

Where L is the inductance of square coil, μ is the permeability of free space (4π × 10-7 H/m), N is the number of turns in the coil, davg is the average diameter of the coil, ∅ is the fill factor, defined as a dimensionless parameter that ranges from 0 to 1 and is used to quantify how much of the cross-sectional area of the coil is filled with wire. It is commonly used in inductance calculations for multiple layers or turn coils. When applying the theory of the four RLC circuits to the proposed coil design, the proposed methodology's basic components should be considered. To calculate the mutual inductance between each pair of coils, the mutual inductance is a critical parameter in the proposed design of the four-circuit RLC model because it determines the amount to which a change in current in one circuit induces a voltage in another circuit. Understanding this relationship allows for more accurate system performance prediction and coil design optimisation.

For mathematical calculations, the mutual inductance between each pair of circuits on the transmitting side, consisting of three coils, is determined. Then, the mutual inductance between the overall transmitter system and the receiver coil is calculated. These calculations provided key insights into how the different parts of the system interacted and how effectively power could be transferred from the transmitter to the receiver. Equations used to calculate the mutual inductance, considering factors such as coil geometry, separation distance, and relative positioning, are detailed in the subsequent section of this paper. These equations provide a theoretical foundation crucial in understanding and predicting the interactions within the coil system.

$$M_{T.R} \cong \frac{\mu_0 N_T d_{out.T}^2 N_R d_{out.R}^2 \pi}{2\sqrt{\left(d_{out.R}^2 + X^2\right)^3}} \quad (4)$$

Where the NT and NR are the number of turns of the transmitter and receiver coils.

The calculation of mutual inductance between a square and a circular coil is more complex than the calculation for two similar shapes due to differences in their geometries. It is a relatively specific scenario that does not have a common, simple, direct formula because the magnetic field produced by a square coil does not couple perfectly with a circular coil and vice versa. Typically, one would use numerical methods to calculate mutual inductance between two dissimilar geometries, like a square and a circular coil. The most common method would be to break down the coils into small differential elements and then integrate the mutual inductance between these elements over the entire volume of the coils. Tools that use numerical methods, such as Finite Element Analysis (FEA) software, could help calculate the mutual inductance between a square and a circular coil. These tools numerically solve Maxwell's equations for complex geometries without a closed-form solution.

It was important to determine the Power Transfer Efficiency (PTE) from the transmitter to the receiver for both coils to evaluate the performance of both proposed circular and square coil configurations design. n general, PTE is defined as the proportion of power received by the load compared to the power provided by the source. A formula that considers design factors, like power source, coil inductance, mutual inductance, resistance, capacitance and operating frequency, must be included to assess this efficiency. These formulas are utilized to gauge and contrast the efficiency of circular and square coil designs with precision since the resulting efficiency values establish a benchmark for assessing and contrasting the performance of the proposed designs. Furthermore, they help interpret our findings and contribute to our recommendations for coil design in applications involving tissue monitoring using RF Wireless Power Transmission.

$$\eta = \frac{K_{12}^2 K_{23}^2 K_{34}^2 Q_1 Q_2^2 Q_3^2 Q_p}{\left(1+K_{34}^2 Q_3 Q_p + K_{23}^2 Q_2 Q_3\right)\left(1+K_{34}^2 Q_3 Q_p + K_{23}^2 Q_2 Q_3 + K_{12}^2 Q_1 Q_2 + K_{12}^2 K_{34}^2 Q_1 Q_2 Q_3 Q_p\right)} \times \frac{R_{load}}{R_{load}+R_4} \quad (5)$$

In the power transfer system, η represents efficiency, while K12, K23 and K34 denote the coupling coefficients of coil pairs. Q1, Q2, Q3 and Qp stand for the quality factors of the coils and power transfer link. Rload signifies the load resistance. R4 is a parameter for resistance. The system's resonance frequency, which is the frequency at which the power transfer efficiency is maximized, is another critical parameter evaluated. Achieving resonance between the four coils - three on the transmitting side and one on the receiving side - is crucial for optimizing the efficiency of WPT.

A specific equation that considers parameters such as inductance, mutual inductance, and capacitance is employed to determine the resonance frequency for the coil configurations. These equations, detailed in the following section, allowed us to model and predict the system's resonance frequency mathematically. Through this analytical process, we could ascertain the conditions under which the system would operate at peak efficiency. Furthermore, these theoretical predictions of resonance frequency were verified through experimental testing, allowing the accuracy of the mathematical models to be validated.

Table 2. The parameter used in the design of the circuit with three circular coils on the transmitter side and one circular coil on the receiver side

Parameter	Value
$L_1=L_2=L_3=L_4$	11.69 µH
C_1	47.13 PF
C_2	65.63 PF
C_3	85.06PF
C_4	25.67 PF
$Q_1=Q_2=Q_3$	132.97
Q_L	0.498
Q_p	2.0154
$R_1=R_2=R_3=R_4$	3.7 Ω
R_{load}	1000 Ω
f	6.78 MHz

Table 3. The parameter used in designing the circuit with three square coils on the transmitter side and one circular coil on the receiver side

Parameter	Value
$L_1=L_2=L_3$	701.99 µH
L_4	11.69 µH
C_1	0.784 PF
C_2	1.093 PF
C_3	1.43PF
C_4	25.67 PF
$Q_1=Q_2=Q_3$	220.21
Q_L	0.497
Q_p	2.0155
$R_1=R_2=R_3$	135.8Ω
R_4	3.7 Ω
R_{load}	1000 Ω
f	6.78MHz

3. Result and Discussion

Using Equations (2) and (3), the inductance values for the circular and square coils were calculated. For the circular coil, the inductance was 11.69 µH, and for the square coil, it was 701.99 µH. The slightly different values indicate the inherent differences in the geometries of the coils. The parameters of the two circuit designs can be seen in Tables 2 and 3, which are calculated based on the equations from our previous study.

For the system with three circular coils on the transmitter side and one circular coil on the receiver side, as the distance between the transmitter and receiver side increases from 5 to 30 mm, the coupling coefficient seems to decrease slightly, dropping from 0.156 to 0.0209. For the system with three square coils on the transmitter side and one circular coil on the receiver side, the measurements are provided over distances from 5 to 30 mm. The mutual inductance decreases as distance increases, but the values are generally higher than those of the purely circular coil setup. The mutual inductance reduces from 0.376 to 0.036 as the distance goes from 5 to 30 mm, as shown in Figure 4.

The system with three square coils and one circular coil consistently demonstrates higher coupling values than the all-circular coil system over comparable distances. This suggests that the square coil configuration might more effectively transfer power to a circular receiver coil under these specific conditions. The design characteristics and orientation of square coils might produce a more concentrated or consistent magnetic field, which enhances the coupling with the circular receiver coil. The geometry of the transmitter and receiver coils and the distance between them greatly affect the efficiency.

For the four-circle coils, the relationship is inverse between distance and efficiency, with the efficiency decreasing abruptly with increasing distance. For example, at a distance of 5 cm between the transmitter and receiver coils, the efficiency is comparatively high at 74.77%, but it drops to 5.06% at a distance of 30 cm. The average efficiency of this design is 32.93%, with a standard deviation of 27.70%, indicating a large variation. The 95% confidence interval for the average efficiency ranges from 3.86% to 62.00%, reflecting the rapid decline in performance over distance.

In contrast, the design of three square coils as transmitter and one circular coil as receiver shows superior efficiency over different distances. For example, at 5 cm, it achieves an efficiency of 96.30%, which remains relatively high even at 15 cm to achieve an efficiency of (80.98%) and drops to 16.58% at 30 cm. This design has an average efficiency of 63.16%, with a standard deviation of 32.10%, showing a large variation but better performance than the circular coil design. The 95% confidence interval for the efficiency of this design ranges from 29.47% to 96.84%, confirming its superior efficiency over a different range of distances.

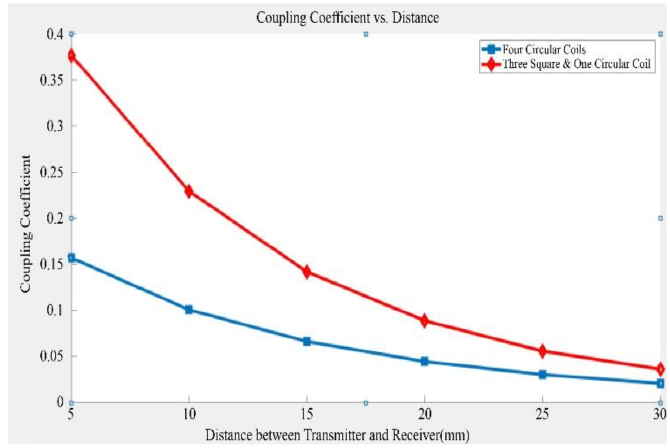

Fig. 4 The relation between the coupling coefficient and distance for two circuit design

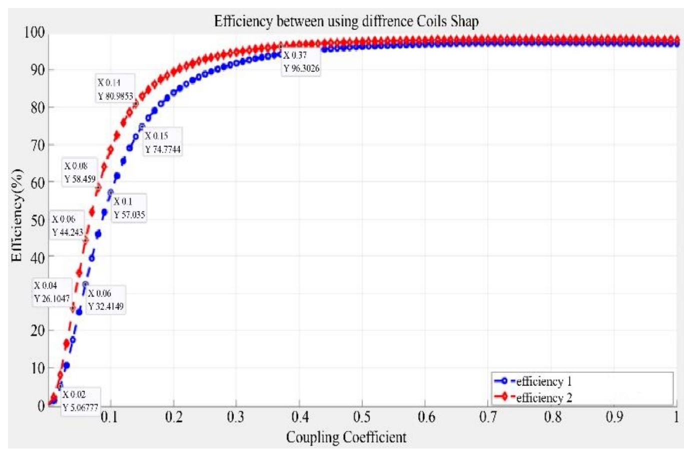

Fig. 5 The relation between the efficiency and coupling coefficient for both circuit design

While the coupling coefficient does decrease with distance in both configurations, it is notable that the rate of decline is not rapid. This implies that coil placement might be flexible without substantially compromising efficiency, which is valuable information for practical applications, especially in tissue engineering treatment monitoring. The mixed geometry of square and circular coils offers particular advantages in mutual inductance over the all-circular setup. This can be leveraged in designing more efficient power transfer systems, as shown in Figure 5, especially when balancing other factors like patient comfort and safety.

For four circular coils designed at a distance of 5 mm, the efficiency is at its highest, with a value of 74.77%. The efficiency steadily drops as the distance between the transmitter and receiver increases. It is noted that when the distance reaches to 30 units, the efficiency has radically decreased to 5.06%. Figure 6 shows the magnetic field distribution, a critical aspect of this study on RF wireless power transmission and tissue monitoring. The figure observes that circular and square coil designs generate different magnetic field patterns.

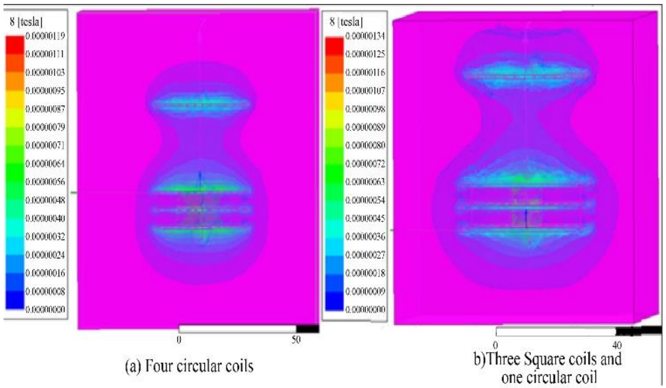

Fig. 6. shows the magnetic field distribution in (a) Four circular coils, (b) Three Square coils and one circular coil.

The circular coil generates a well-defined and concentrated magnetic field around its core, with field lines extending outward from the coil. This firm, focused magnetic field is important for efficient energy transfer to the target tissue. On the other hand, the square coil exhibits a different magnetic field pattern, with field lines forming a distinct square shape. The square coil's magnetic field distribution is characterized by symmetry and evenness. These results show the importance of coil geometry in shaping the magnetic field and its penetration depth into the tissue layers. The choice between circular and square coils should be selected based on the specific requirements of tissue monitoring applications, considering the distinct field patterns generated by each coil type.

The Four Circular Coils configuration results clearly indicate a rapidly diminishing efficiency with increasing distance. This suggests that for applications using this design, keeping the transmitter and receiver as close as possible is essential to maintain optimal performance. Such a design could be suitable for applications where the distance between the coils remains relatively small, such as in specific medical implant scenarios. For three Square and One Circular Coil, at a distance of 5 mm, the coupling coefficient is impressively high at 96.30%. A similar trend is observed in this configuration as with the four circular coils: as the distance increases, the coupling coefficient decreases. By 30 mm, it has significantly reduced to 16.58%.

The coupling coefficient is an essential parameter as it reflects the efficiency with which energy is transferred between the coils. A high coupling coefficient suggests efficient energy transfer. However, the sharp decline in the coupling coefficient with increased distance between the transmitter and the receiver suggests that this coil combination, like the four circular coils, is more suitable for applications with minimal separation between the coils. Both configurations exhibit a decline in performance (efficiency or coupling coefficient) with increased distance between the transmitter and receiver. However, the rate of decline seems steeper for the four circular coil configurations when considering efficiency. The three square and one circular coil configuration starts with a very high coupling coefficient at short distances, indicating a potentially stronger initial magnetic field interaction than the four circular coil configurations.

However, it is crucial to note that while coupling coefficient and efficiency are related, they are not directly comparable. Compared to state-of-the-art techniques, this coil design, particularly the hybrid configuration of three square and one circular coil, achieved superior performance in short- and mid-range wireless power transfer applications. The combination of optimized geometry, alignment resilience, high-frequency operation, and material selection enhanced efficiency and demonstrated robust performance under real-world conditions. The results of tissue engineering treatment monitoring suggest that one might achieve better power transfer (and hence, device performance) using a system with three square coils and one circular coil. However, patient comfort, device implantation procedure, and safety might influence the final choice of coil geometry.

4. Conclusion

This paper extensively investigates the performance metrics of two distinct coil configurations used for Wireless Power Transfer (WPT) – one with four circular coils and another with three square coils combined with one circular coil. The primary performance indicators under scrutiny were efficiency and the coupling coefficient. A fundamental observation from this study is that as the distance between the transmitter and receiver increased, there was a discernible drop in performance for both configurations. The decline in efficiency was notable for the four circular coil configurations, beginning at 74.77% at a 5 mm distance and plummeting to 5.06% at a 30 mm distance. Similarly, while exhibiting a robust coupling coefficient of 96.30% at a 5 mm distance, the three square and one circular coil setup witnessed a considerable reduction to 16.58% at a distance of 30 mm.

These observations underscore the proximity between coils in WPT applications, especially when high efficiency or coupling is critical. The study also brought to light the relative strengths of the configurations. The three square and one circular coil setup demonstrated superior initial performance at shorter distances, suggesting its potential advantage in applications demanding robust wireless power transfer over minimal distances.

The findings from this study serve as a pivotal guide for engineers and researchers in the realm of WPT. Deciding on the optimal coil configuration hinges on the specific demands of the intended application. As WPT continues to be an area of intense research and application, especially in fields like medical implants and tissue engineering treatment monitoring, understanding the nuances of coil design and arrangement will be crucial. Future research could delve deeper into coil shape variations, sizes, materials, and orientations to discern their impact on efficiency and coupling coefficient. This will pave the way for even more optimized and efficient WPT systems tailored for a plethora of applications.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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