iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: IV Month of publication: April 2025

DOI: https://doi.org/10.22214/ijraset.2025.68987

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IV Apr 2025- Available at www.ijraset.com

Design Proposals for Wireless Electrical Power Transmission

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Abstract: Wireless power transmission is defined as the ability to transmit electrical energy from a specific voltage source to an electrical load without the use of wires.
This study focuses on designing new coils for wireless power transmission, studying and understanding the properties of the magnetic. Additionally, it covers some important aspects of the design process after obtaining practical results and comparing them with theoretical results. After covering these aspects, a complete picture of how these innovative coils should be designed is formed, along with the possibility of modifying the design to improve the efficiency of wireless power transmission.
Keywords: Wireless, coil, transmit, power, Magnetic field

I. INTRODUCTION

Hertz was the first to explain the applications and analysis of radio signals [1]. Nikola Tesla was the first to think about transmitting electrical energy through air ions [2], where he designed an emitter coil connected in series with a capacitor to form what is known as a resonant frequency loop. The scientist Tesla stimulated the resonant loop (primary coil) as an energy transmitter and used it with another resonant loop (secondary coil) as an electrical energy receiver as shown in Figure 1.

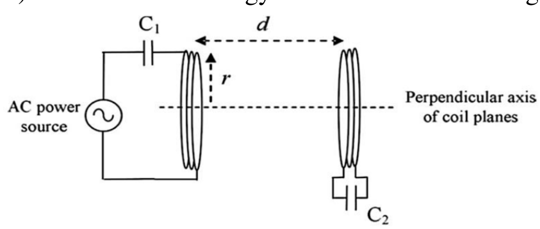

Fig 1: A model of Two Resonant Rings for Wireless Electrical Energy Transmission, Developed by Nikola Tesla [2].

Obtaining maximum power with high efficiency is a challenge in most wireless power transmission applications because the mutual inductance between the transmitting and receiving coils decreases as the distance between them increases, as shown in Figure 2.

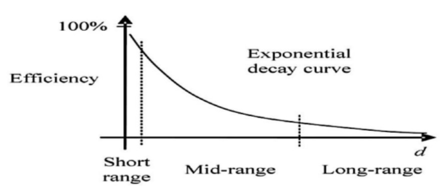

Fig 2: Mutual Inductance when the Distance between the Transmitter and Receiver Coil Increases

However, the transmission distance in electrical power transmission systems always needs to be increased to maximize the potential benefit from the transmitted waves. Several methods have been proven previously for extracting electrical energy stored at multiple locations. The scientist Tesla demonstrated that using Magnetic Field resonance of coils can achieve optimal transmission power [3]. Before 1391, there was little interest in the subject of wireless electrical power transmission due to the limited information available which made researchers realize the fact that the efficiency of transmitting electrical power from one point to another depends on the concentration of the magnetic at a particular point [4, 5]. Then, interest in wireless electrical power transmission systems increased recently after the publication of Soljak's research on wireless electrical power transmission using magnetic resonance [6, 7], and much of the research is based on coherent induction which is considered the basis of wireless power transmission systems.

In general, wireless power transmission systems can be classified into radiated and non-radiated power. The first type relies on high frequencies to stimulate the power source, as well as on the radiated power from the transmitting antenna to the receiving antenna through the transmission medium over long distances in the form of electromagnetic waves. The second type relies on the mutual induction of the electromagnetic coil near the transmitting loops or coils [8, 9]. In the past few years, many applications have been proven for the use of wireless power transmission systems, including cell phones [10, 11], laptops electric cars, as well as medical applications that contain batteries that need to be charged continuously, in addition to optical applications and televisions that need energy continuously, meaning they do not contain batteries.

A magnetic field is a magnetic force that is formed in the space surrounding a magnetic body; that is, an electric current passing through a wire produces a magnetic field due to that movement or passage; in other words, when an electric current flows through a wire, it actually produces a magnetic field, and as a result there will be a magnetic field intensity, and thus the intensity of the magnetic field depends on the amount of this coil [12, 13], that is, the electric current is the main factor for calculating the strength of the magnetic field on any type of conductor.

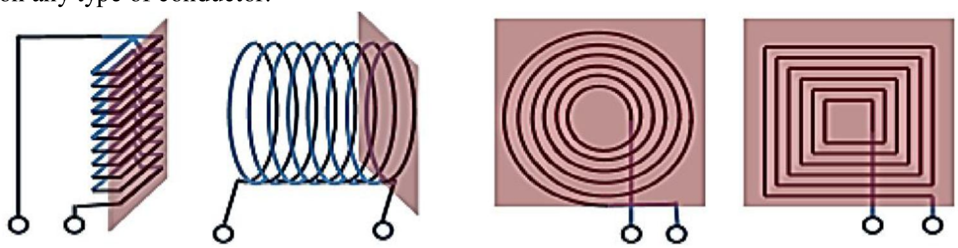

Fig 3: Some Types of Flat and Non-flat Spiral Coils

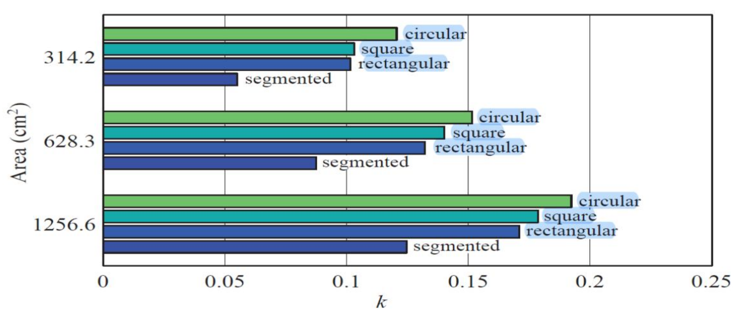

Fig 4: The Relationship of the Area of Each Coils Type with the Coupling Coefficient (K) [14]

In one of the scientific papers referred to in the reference about the relationship between the area of the geometric shape and the coupling coefficient, it was shown that the square shape and the rectangular shape give almost the same coupling coefficient at a certain area, but at the same area for the square and rectangular shape, the coupling coefficient for the circular shape is greater than the other two shapes; and this can be explained due to the distribution of the magnetic field at the corners of the shapes, as all geometric shapes except the circular shape contain corners that cause distortion of the magnetic field inside and outside the coil [15,]. The circular shape remains the best among these shapes, as it gives the best coupling coefficient while increasing the area of the geometric shape.

II. WIRELESS POWER TRANSMISSION SYSTEM CLASSIFICATION

A. Short-range Radiation

Short-range, mutually inductive wireless power transfer (WPT) transducers have been extensively studied over the past three decades as a concept for transmitting electrical power to devices implanted in biological tissues. Even if the transmitted power through these tissues is modulated, the maximum power that can be transmitted through biological tissues is limited to approximately 275 MW over a distance of 1 cm [16, 17]. The WPT system shown in [18] uses a rotating magnet to transmit the power; this rotating magnet, which relies on the transmitted power, can transmit 676 MW over a distance of 1 cm wirelessly.

B. Medium-range Radiation

There is growing interest in wirelessly transmitted electrical energy because it is used in many modern and important applications, whether they consume low power, such as medical applications, or high power, such as electric cars.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IV Apr 2025- Available at www.ijraset.com

For example, the team in [19, 20] used a harmonic impedance (IM) network to modify the resonant frequency of a pair of transmitters at a certain distance to approximately 13.56 MHz. Through experimentation and practical simulation, it was shown that using harmonic impedance changes the frequency, thus improving the transmission efficiency. The research team in [21] also demonstrated how to analyze and study an electrical energy transmission system consisting of two coils, one for transmission and the other for reception, in the medium range. The system demonstrated by the team operated with an efficiency of approximately 76% over a distance of 1 meter and with a transmission power of 40 W [22].

C. High Radiation Range

Electrical energy is transmitted over long distances in the form of electromagnetic waves, using a transmitting antenna, which has been proven to have very low efficiency during transmission [23].

III.STEERING

Coil orientation is key to designing a wireless power transmission system using magnetic induction. Mutual inductance depends primarily on the shape of the transmitter and receiver coils, as well as the orientation of the coils. [24, 25] The orientation of the transmitter and receiver coils has a significant impact on mutual inductance. The further the magnetic field is from the transmitter coil due to changing the orientation of the transmitter or receiver coil, the lower the mutual inductance between the two coils, thus reducing transmission efficiency. In practical applications, coil drift is a normal thing, and one of the common problems that occur in wireless power transmission systems; for example, when charging electric cars, the orientation of the coils must be as best as possible to obtain the maximum mutual inductance to charge the car; where we can obtain the best mutual inductance and correlation coefficient (K) when the transmitter and receiver coils are in one direction, that is, when the coils are at the best orientation; The transmitted wireless energy and the amount of this energy lost change with the change in the form of diffraction of these coils; there are several forms of diffraction:

A. Lateral Misalignment.
B. Angular Misalignment.
C. Angular Elevation Misalignment.
D. Angular Azimuth Misalignment.
E. Rotational misalignment.
F. Incorporated misalignment.

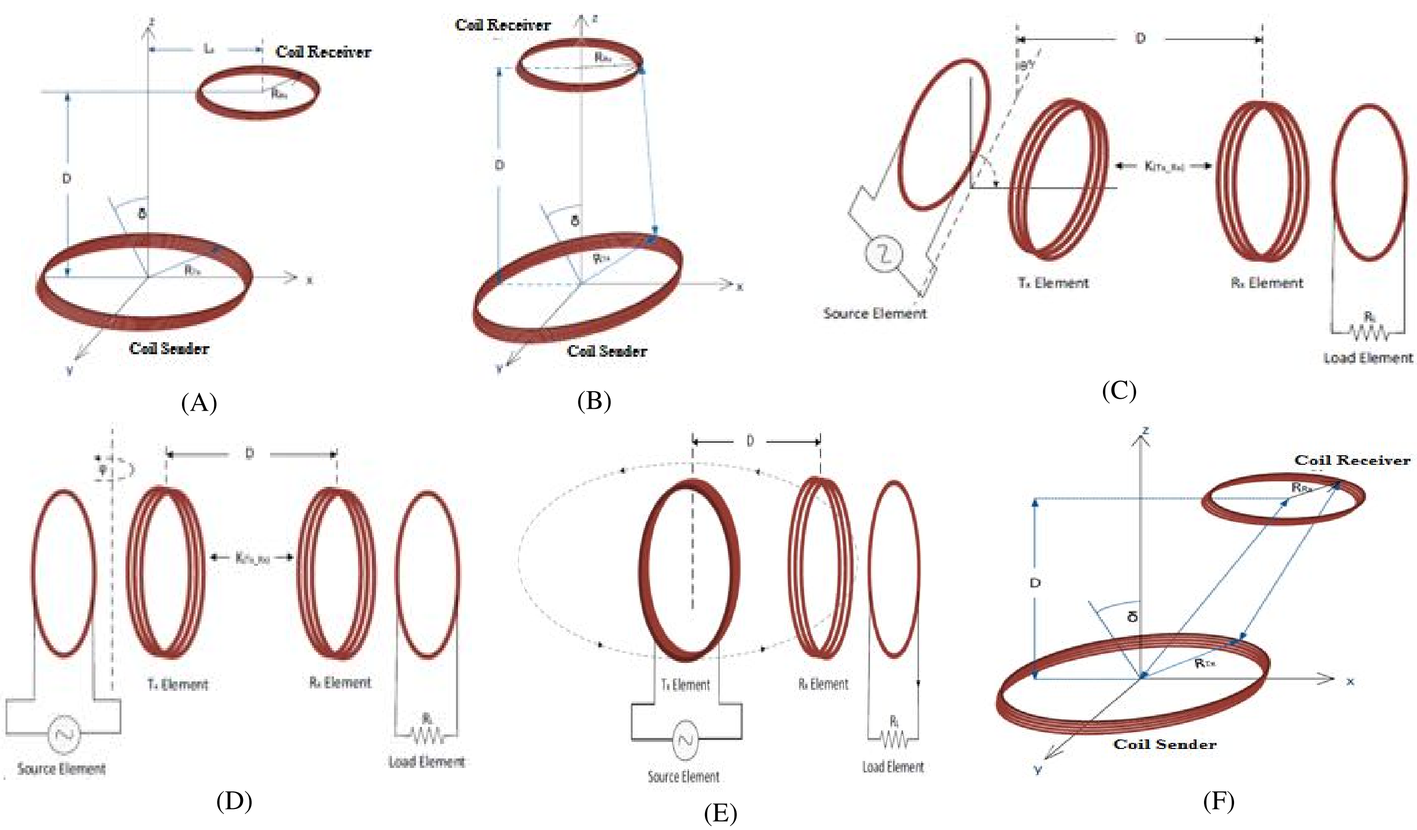

Fig 5: Coil Deviation

IV. THE PRACTICAL SIDE

This section includes testing some of the proposed coils for their transmission and reception efficiency, calculating the inductance value for each one practically, and then comparing these conventional coils with the proposed design. Additionally, the magnetic field profile of each coil was drawn. It is worth noting that the designed coils have uncoordinated specifications due to the unavailability of some of the materials required for coil design.

A. Inductance

There are many mathematical formulas for calculating inductance, some of which depend on the type of coil and others on the size of the coil, so it was necessary to use the most common laws to ensure reaching more accurate results. To achieve this, two laws were used to calculate inductance, which are as follows [26]:

$$L1 = N^2 4\pi 10 - r^7 \ln(2r/d) \quad (1)$$

$$L2 = N^2 4\pi 10 - r^7 \ln((8r/d) - 2) \quad (2)$$

Where:

L1: The First Law

L2: The Second Law

The values of both the inductance of the coil derived using the first and second laws were compared with the experimental value, and then the law closest to the experimental results was derived and adopted in the rest of the calculations, using the law shown in Equation (3), and the value of the capacitor was calculated after assuming that the resonant frequency is 900 kHz. This frequency was imposed because all the designed coils have a resonant frequency ranging between $1.3MHZ \leftarrow 600KHZ$ and also because the voltage source used is limited.

$$C = 1/(4\pi^2 Fr^2 L) \quad (3)$$

The results in Table 1 show the theoretical calculations for some of the typical types of coils that were designed, and a comparison of the inductance results for each of them according to the law used.

TABLE I
THEORETICAL CALCULATIONS FOR SOME TYPES OF REGULAR COILS

r (cm)	d (mm)	N (turnc)	Fr (k HZ)	L1 (µH)	C1 (F)	L2 (µH)	C2 (F)
2.50	0.95	16	900	31.886	982.5p	42.90	72.90 p
2.50	0.95	08	900	7.97	3.92 n	10.73	2.90 n
6.25	1.30	10	900	35.86	872 p	46.68	672 p
10.5	1.30	21	900	295.72	105.86 p	376.169	83.20
3.40	0.80	21	900	82.52	379.30 p	108.51	288 p
1.75	0.50	08	900	5.979	5.23 n	7.90	3.90 n
1.70	0.70	08	900	5.30	5.90 n	7.18	4.36 n
1.70	0.70	07	900	4.06	7.70 n	5.50	5.689 n
1.25	0.50	08	900	3.9328	7.9516 n	5.3136	5.891 n
1.70	0.20	20	900	43.886	712.57 p	35.78	874.8 p
1.70	0.20	08	900	7.018	4.460 n	8.90	3.50 n

TABLE II:
APPROXIMATE VALUES OF INDUCTANCE IN PRACTICE

r (cm)	**d (mm)**	**N (turnc)**	**Fr (k HZ)**	**L (μH)**	**C (F)**
2.50	0.95	16	1.25 M	16.227	01 n
2.50	0.95	08	888 K	8.70	3.69 n
6.25	1.30	10	963 K	31.212	876 p
10.5	1.30	21	1.3 M	140	106.8 p
3.40	0.80	21	1.2 M	46	382 p
1.75	0.50	08	01 M	4.6055	5.5 n
1.70	0.70	08	1.1 M	3.80	5.7 n
1.70	0.70	07	1.1 M	2.70	7.7 n
1.25	0.50	08	01 M	3.16	08 n
1.70	0.20	20	950 K	28	01 n
1.70	0.20	08	1.16 M	4.18	4.5 n

After examining the results shown in Tables 1 and 2, it is noted that when the number of coil turns is less than 10, the theoretical inductance value must be divided by 2 to obtain an approximate value for the practical inductance. This is due to the irregularity of the magnetic field, as mentioned above. However, when the number of turns is greater than or equal to 10, the theoretical inductance value is very close to the practical value, and the division process is not performed.
The obtained results can be reinforced by examining the shape of the curves, which indicate that the first law for calculating inductance is closest to the values obtained theoretically.

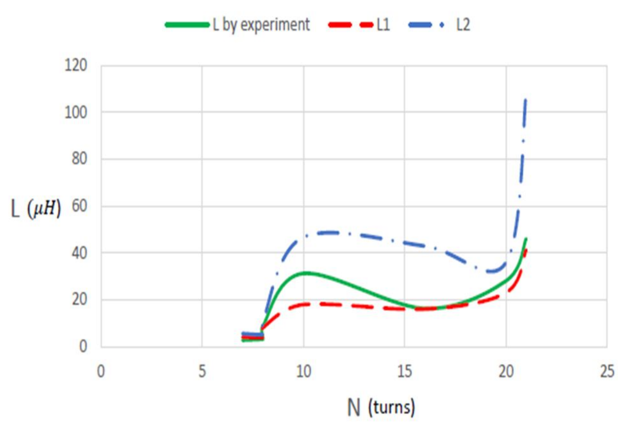

Fig 6: The Difference between Theoretical and Practical Inductance Values

B. Receiving and Transmitting

The process of transmitting electrical energy wirelessly from the source (transmitter coil) to the consumer (receiver coil) relies on a magnetic field. Based on this principle, electrical energy is transmitted from the transmitter to the receiver in the form of magnetic waves resulting from the passage of alternating current within the coil. For communication to occur, resonance must occur between these coils, which lead to mutual induction and a significant increase in flux lines.
Practical experiments were conducted to transmit and receive electrical energy using a number of coils to study the characteristics and efficiency of the transmitting and receiving coils. The goal was to select the most efficient coils in terms of wireless transmission efficiency. These efficient coils were then compared with the coils proposed for this study.

TABLE III:
SPECIFICATIONS OF ALL DESIGNED COILS

Coil	r (cm)	d (mm)	N (turnc)	∂^0
1	2.5	0.95	16	0
2	2.5	0.95	08	0
3	6.25	1.30	10	0
4	10.5	1.30	21	0
5	3.4	0.80	21	0
6	1.75	0.50	08	0
7	1.7	0.70	08	0
8	1.7	0.70	07	0
9	1.25	0.50	08	0
10	1.7	0.20	20	0
11	1.7	0.20	08	0
12	5.25	0.85	107	0
13	2.6 , 4.6	0.85	60	22.5
14	2.7, 6	0.85	60	40
15	2.9 , 5.1	0.85	105	20

Fig 7: Images of Some of the Mentioned Coils

The basic idea of the experiment is based on connecting one of the coils to the alternating source, which is the transmitting coil, or another to the load, which is the receiving coil, at different distances, at which the value of the receiver voltage is measured.
The following tables (4, 5, 6 and 7) show the readings for the circular coil with wires arranged for transmission and reception operations with the change in the distance between the transmitter and receiver coils for several coils that differ from each other in terms of diameters and number of turns.

TABLE IV:
FUTURE COIL EFFORT FOR DIFFERENT DISTANCES

d= 0.95 mm r= 2.5 cm N= 16 turns		
V_{TX} (volts)	V_{RX} (volts)	D (cm)
1.2	1.17	1
1.2	1.10	2
1.2	0.60	3
1.2	0.30	4

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ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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TABLE V:
RECEIVER AND TRANSMITTER COIL SPECIFICATIONS AND RECEIVER COIL VOLTAGE FOR DIFFERENT DISTANCES

T_X Coil			R_X Coil			
d= 1.30 mm	r= 10.5 cm	N= 21 turns	d= 1.30 mm	r= 6.25 cm	N= 10 turns	
V_{TX} (volts)			V_{RX} (volts)			D (cm)
20			2.2			15
20			1.2			30
20			0.32			35
20			0.06			80

TABLE VI:
RECEIVER COIL VOLTAGE FOR DIFFERENT DISTANCES

d_{RX}= 0.95 mm	r_{RX}= 2.5 cm	N_{RX}= 16 turns
V_{TX} (volts)	V_{RX} (volts)	D (cm)
20	0.4	10
20	0.2	20
20	0.078	30
20	0.01	50

TABLE VII:
THE SENDER'S COIL HAS DIFFERENT SPECIFICATIONS THAN THE RECEIVER'S COIL

T_X Coil			R_X Coil			
d= 0.85 mm	r= 5.25 cm	N= 107 turns	d= 0.80 mm	r= 3.40 cm	N= 21 turns	
V_{TX} (volts)			V_{RX} (volts)			D (cm)
20			10.0			5
20			4.20			10
20			2.00			15
20			1.25			20
20			0.85			25
20			0.63			30
20			0.50			35
20			0.40			40
20			0.30			45
20			0.23			50

C. *Loading Effect at P_{RX}*

All previous experiments demonstrate the transfer of electrical voltage without connecting a load to the receiving coil. Note that the relationship between voltage and current is inversely related. There fore, when the current decreases with increasing resistance, the voltage across the resistance increases.

In this experiment, a variable resistor with a range of 1Ω to 10Ω was used, connected in parallel with the receiving coil.

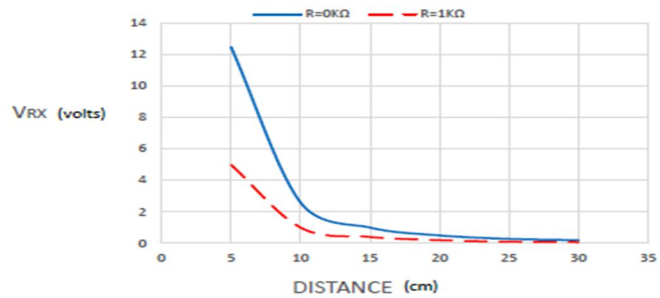

Fig 8: Table 8: Effect of Voltage on Distance When Resistance Value is 0Ω and 1Ω

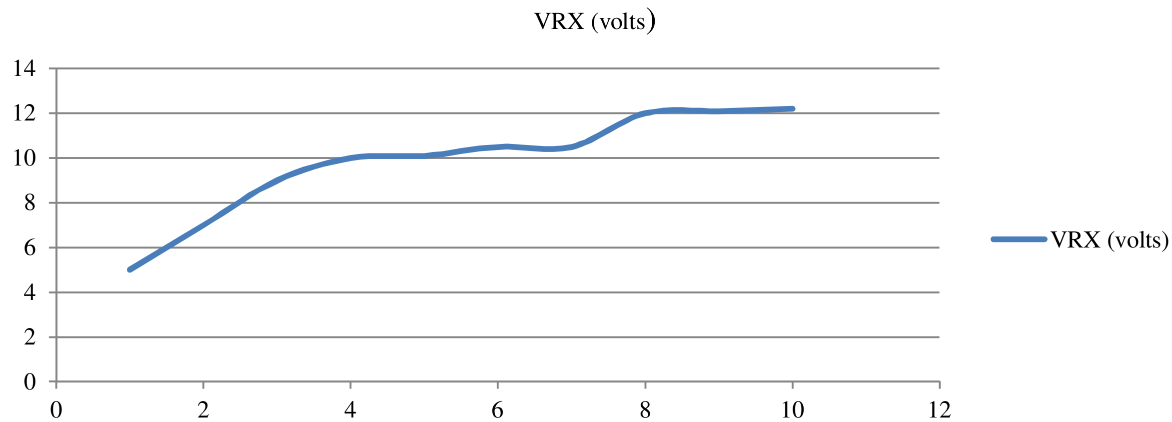

Fig 9: Effect of Voltage on A variable Load Resistance When the Distance is Constant (D= 5cm)

From Figure 9, it can be seen that as the load resistance value increases, the voltage value increases, and consequently, the current value decreases due to the inverse relationship between voltage and current. This can have an impact on the power capacity of the coil receiving the energy. In all cases, this impact must be taken into account, depending on the type of application being used.

D. Coils Design

Many coils have been designed for circular coils with varying numbers and specifications of wires. Different types of wires exist, distinguished by their degree of conductivity, size, and type. Their diameters range from 1.7 to 10.5 cm and the number of turns ranges from 7 to 107, depending on transmission efficiency and the limitations of the AC voltage source.

E. Magnetic Field

After studying and determining the direction of the magnetic field using the right-hand rule, the shape of the magnetic field of the coils used was practically determined. This was accomplished by fixing the transmitter coil and sequentially moving the receiving coil around the transmitter in a circular motion, maintaining a constant receive voltage value at the receiving coil throughout the motion. This was accomplished by following these steps:

- To determine the shape of the coil, the receive voltage value must be maintained constant.
- The movement of the receiving coil around the transmitter is circular, starting at 0° and ending at 360°.
- It should be noted that the shape of the magnetic field produced by a normal circular coil is symmetrical about both the vertical and horizontal axes.

F. The Magnetic Field of the Circular Coil

The magnetic field of the circular coil was drawn by fixing the receiver voltage at a certain value from the transmitting coil and rotating around the transmitting coil as explained in the previous paragraph, and taking the distance values for all angles, taking into account that the value of the receiver coil voltage is constant as shown in the figure below.

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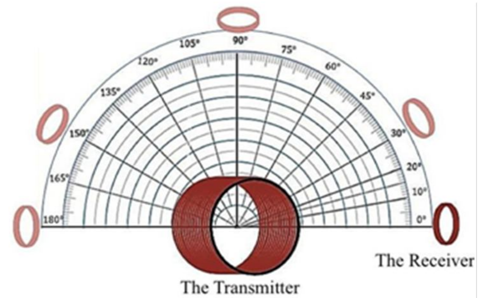

Fig 10: Magnetic Field Diagram of A circular Coil with A fixed Receiver Voltage

The values were taken at all angles, taking into account the stability of the transmitter coil on the horizontal axis.
By changing the distance between the transmitter and receiver coil of the circular coil, the practical results of the shape of the magnetic field were obtained.

Specifications
N= 16 turns
d= 0.95 mm
r= 2.50 cm

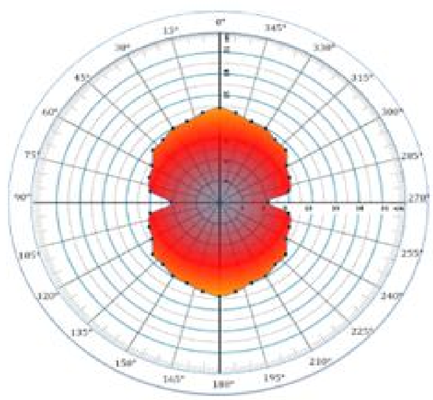

Fig 11: Shape of the Magnetic Field with Changing Distance Relative to the Angle of Rotation of the Receiving Coil 1

Specifications
N= 08 turns
d= 0.50 mm
r= 1.75 cm

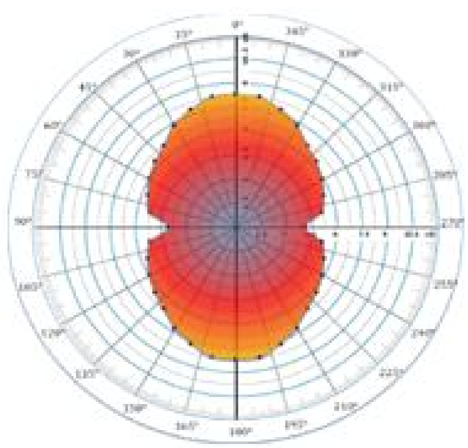

Fig 12: Shape of the Magnetic Field with changing Distance Relative to the Angle of Rotation of the Receiving Coil 2

From Figures 11 and 12, it is noted that the magnetic field of a circular coil with tightly packed wires has a uniform shape (meaning that the resulting magnetic field reaches its maximum value equally from both ends of the coil, on the open side).

V. RESULTS

From the results obtained from the tables, it can be noted that there are factors that have a direct impact and increase the amount of wireless energy transmitted between the two coils (transmitter and receiver): increasing the diameter of the coil wire and the number of turns. A circular coil can transmit electrical energy equally in two different directions. The magnetic field generated by the coil reaches a shorter distance than the magnetic field generated by the open ends, due to the different density of the magnetic spectrum lines. It can also be noted that the shape of the field is very similar to the magnetic field of the radio waves transmitted by the dipole antenna used in cellular communication systems.

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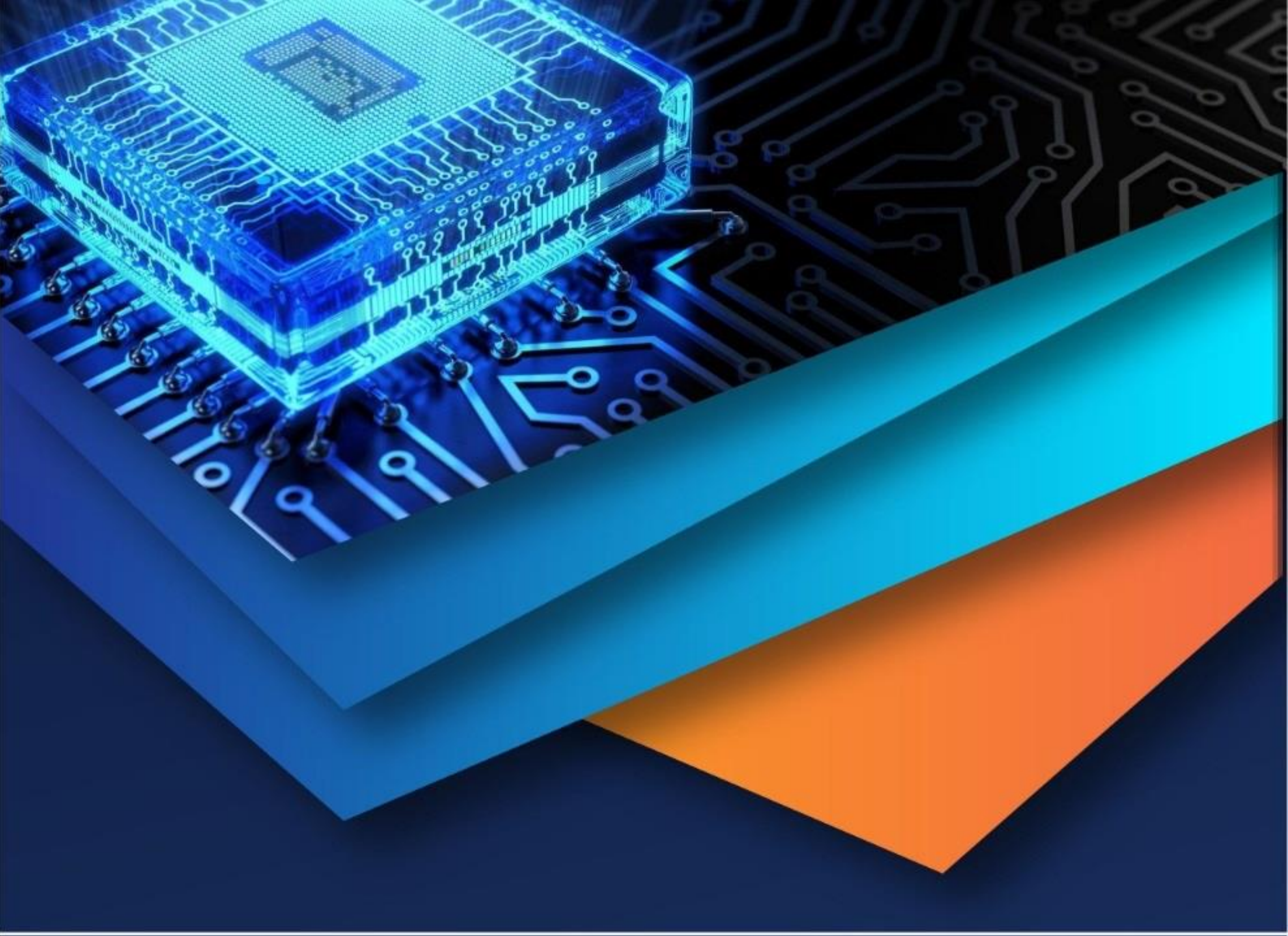

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