# Design of Innovative Conical Coil Transmitter for Efficient Delivery of Wireless Power in Inductive Communication Systems

Nagi F Ali Mohamed[1], Salim Habeeb Salim Al Tabouni[2], Mohammed Houseen Abdulsalam3
Department of Electrical Engineering, College of Engineering Technology, Houn, Libya
n.mohamed@ceh.edu.ly [1], attabouni3837@gmail.com [2], mohamedhseen432@gmail.com [3]

***Abstract:*** **This paper reports on the study and design of innovative conical coil transmitter for precise delivery of flux in inductive communication systems. The obtuse angle of the conical frame plays the major part of delivers the flux effectively. The loops are wound in conical shape to deliver larger amount of power wirelessly from the larger radius of the coil. By controlling obtuse angle of the coil, different flux pattern can be governed. In this manner, the flux pattern control has been recognized and proposed. The resultant flux pattern is stronger and more pointed than the flux produced by conventional coils. The magnetic field is found to be higher and wider at the larger radius of the conical coil and advantageous for applications such as biomedical implant devices where wireless power transfer needs to be directed and concentrated. The magnetic field obtained from the smaller radius of the conical design is low and narrow. This allows us to prevent the wireless power transfer to useless areas in applications such as mobile devices recharge. This paper proves that the conical coil used in wireless powering is more efficient than the simple circular coils.**

***Index Terms:*** **conical coil, obtuse angle, flux control, top and bottom radius, flux pattern, power efficiency, wireless power transfer**

## I. Introduction

An ideal wireless powering system has been known as transferring power from one end to another without any intermediate coil in between. In contrast, a relay coil system with the same resonant frequency between transmitter and receiver resonators can extend the distance of wireless power transmission and improve the powering efficiency [1]. As the distance is extended, number of repeater antennas will increase [2]. Hence, cross coupling between repeaters and receivers will take a place. Coupling coefficient between transceivers and quality factor are important aspects to consider for large field inductive and highly performance [3],[9]. These two parameters can significantly impact the transmission efficiency by changing either the size or geometry of coils [4]. Analysis and optimal coils size for wireless power transfer have been introduced in [3],[4]. The team in [5] has achieved a high performance and strong coupling over long range using planar spiral resonators. The team has explained the impact of the geometrical parameters such as thickness and width of coil on coupling between transceivers, but they have not been exploring the flux principle. In [6] the highest magnitude has been obtained from the central area of the spiral coil because of the non-linear flux that is produced. Hence, the objects in [7] can only receive high wireless energy when they placed in a specific location. Compared with simple coils, printed spiral coils are widely used because of its convenience. Adjusting its geometric parameters to give better performance can optimize this type of coils [8],[10]. Wireless power efficiency in most cases of designing robust implants is a critical factor. Thus, the wireless power efficiency must be designed very carefully to avoid skin tissue damage [11]. This factor requires a high wireless power delivery with safety biological tissue. Therefore, those challenges could be overcome by designing efficient coils to deliver large amount of safer power radiation. Regarding to the coil design, planar spiral coil again offers controllable design that impact on the output power transmission. Some researchers [12], [13], [14] are improving these issues by employing multi-layer and hybrid multi-layer coils with higher efficiency. They deliver power of about 80mW wirelessly to the load with skin temperature less then 1C$^{o}$.The main goal of this work is to achieve an optimal geometry for the transmitter coils, which would eventually increase the power transfer efficiency for a given receiver. Furthermore, the proposed transmitters determine a controllable mechanism to point the electromagnetic field. To reach this target, a newly designed inductor is built to describe the electromagnetic flux properties. In this paper a conical model of inductors with respect to the obtuse angle has been studied and proposed. In this paper, we proposed a novel wireless power transfer system transmitter for many application including biomedical implant devices to deliver the wireless power efficiently. The system uses new type of coils (conical coil) that has been developed to obtain higher efficiency than using the simple coils (circular coil). The rest of the paper is organized as follows. Section II reviews the design description of the conical coil including the calculation method of its inductance and some principles of the coil structure. Section III describes the transmitter magnetic field pattern of conical and circular coils. Also discusses the comparison between the conical and circular design through experimental results, including the wireless voltage received, the magnetic field pattern, and the efficiency. Finally, Section IV presents the paper conclusion.

## II. The Design Describtion

The design has been built based on the idea of wave reflection that can be seen in many applications such as microphones, satellite and light reflectors. Figure 1 shows the basic design of the conical coil. The $r_1$ indicates the larger radius and $r_2$ indicates the smaller radius of the conical. The obtuse angle q

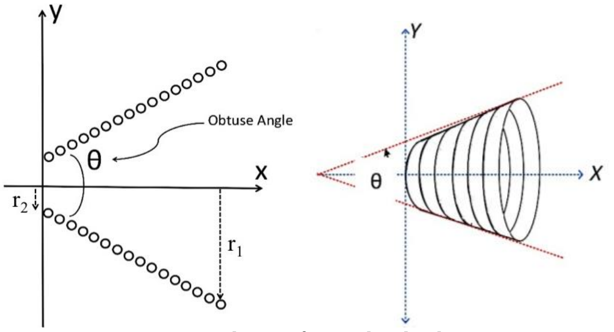



Figure 1: A design of conical coil inductor

### *A. The Inductance*

The conical coil resonator in the system is modeled as a horn shape, as depicted in figure 1. The inductance of the proposed coil is calculated in the following manner. The inductance of the conical coil is divided into several parts depending on the number of turns. Then, the total inductance is the sum of the self-inductance of each part of the divided loops. The self-inductance of each divided loop is calculated using equation (1).

$$L = N^2 4\pi \times 10^{-7} r \ln\left(\frac{2r}{d}\right) \quad (1)$$

Where (d) is the diameter of the wire, (r) is the radius of the coil and N is the number of turns.
This equation has been used based on the assumption that the flux produced by each divided loop is uniform along the centerline of the loop. Indeed, the single loops of the conical coil are not identical and are differ from each other in size. The overall inductance of the completed model of the conical coil is practically found to be the sum of all divided loops. This method is not very accurate but it converges the inductance to its actual values. More accurate formula of the conical coil inductance is still being developed. Once the total inductance of the conical coil is calculated, it can then be employed for transmitting or receiving the power wirelessly. When the number of turns of the coil is changed, the total inductance of the new divided loops needs to be recalculated.

### *B. The Coil Structure*

In order to assess the potential of using the conical coil for wireless power transfer system in principle, several adjustments need to be defined:

1- Wireless powering efficiency in respect to the distance.
2- The ability to control the power transferred level.
3- The ability to adapt to different obtuse angle of the coil configurations.
4- The possibility to control and direct flux according to these configurations.

The conical coil can impose further requirements related to size and type of its wire on the wireless power transfer system. The first assessment focuses more on increasing the wireless powering distance. Then comes the ability to control the flux pattern by adjusting the obtuse angle, and therefore changes the power transfer level.
For these assessments, three conical coils of 0.85mm thickness have been designed. The coils radiuses are different from one another. Then, coils are assumed to have different self-inductance. The inductance of each coil was calculated using the described method in section a. With these in mind, we can introduce the three coils that are used in the proposed system as listed in table 1.

TABLE 1. Parameters of The Designed Conical Coils

| Specifications | Coil 1 | Coil 2 | Coil 3 |
|---|---|---|---|
| Number of turns | 60 turns | 60 turns | 97 turns |
| The bottom radius | 2.6 cm | 2.7 cm | 3 cm |
| The top radius | 4.6 cm | 6 cm | 5 cm |
| The wire thickness | 0.85 mm | 0.85 mm | 0.85 mm |
| The obtuse angle | 22.5° | 40° | 20° |

### *C. Self-inductance Calculation*

The basic structure of the conical coil is as shown in (figure 2 a and b). It consists of a number of divided conducting loops and each loop has a different radius. The sum of these loops as connected together in series to achieve the total self-inductance of the complete design. The number of divided loops is implemented on each coil in respect to its length (or number of turns) to approximate the total inductance value. It is suggested that as the number of turns increases, the divided loops increases; therefore, this will produce more accurate results. Based on the measured data in the previous section, Table 2 lists the approximated optimal inductance for 10 different types of divided loops assuming average radius for each.

(a) (b)

Figure 2: The structure of the conical coil, (a) the divided loops, (b)

total self-inductance of the complete design

TABLE 2. THE CALCULATION OF THE TOTAL INDUCTANCE OF CONICAL COILS

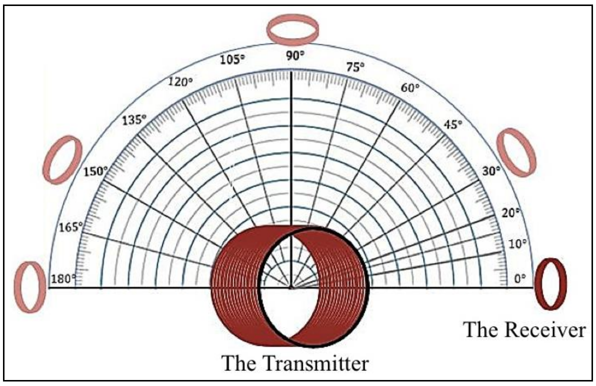
| Coil 1 | Loop 1 | Loop 2 | Loop 3 | |
|---|---|---|---|---|
| Number of turns | 20 turns | 20 turns | 20 turns | |
| The average radius | 3.03 cm | 3.7 cm | 4.4 cm | |
| The Calculated inductance | 29.92µH | 40.26µH | 102.66µH | |
| The total self-inductance of the complete conical coil | 172.84µH | | | |
| Coil 2 | Loop 1 | Loop 2 | Loop 3 | |
| Number of turns | 20 turns | 20 turns | 20 turns | |
| The average radius | 6.6 cm | 8.8 cm | 10.25 cm | |
| The Calculated inductance | 167.4µH | 235.9µH | 255.07µH | |
| The total self-inductance of the complete conical coil | 657.47µH | | | |
| Coil 3 | Loop 1 | Loop 2 | Loop 3 | Loop 4 |
| Number of turns | 25 turns | 25 turns | 24 turns | 23 turns |
| The average radius | 3.25 cm | 3.73 cm | 4.25 cm | 4.75 cm |
| The Calculated inductance | 110.7 µH | 131.94 µH | 141.667 µH | 148.93 µH |
| The total self-inductance of the complete conical coil | 533.237µH | | | |

The approach described in the previous part is approximate and can be applied to different conical coil configuration, such as different number of turns and different obtuse angle.

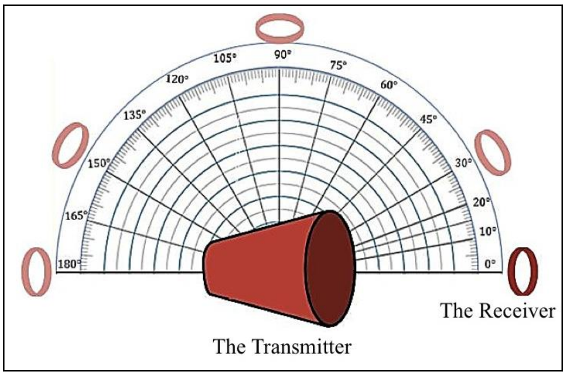
## III. DISTRIBUTION OF TRANSMITTER MAGNETIC FIELD

The amount of wireless power transfer to a receiver device is proportional to the transmitter's magnetic flux density. It has been learned that to increase and control the flux delivered from the conical coil to any type of receivers, the conical obtuse angle is used. This is a method, which is developed by adjusting (increasing or decreasing) obtuse angle of the conical coil so as to distribute the flux widely in a pointed shape. To illustrate this, we start from 0 obtuse angle (circular coil) and add a desired degree to form the conical coil shape. The conical coil can be then called the flux concentrator. Its function is to concentrate and wider distribute the magnetic field transferred to the receiver side. It's noted that the amount and the shape of the magnetic field distributed wirelessly is larger and wider from the top radius of the conical coil if the obtuse angle is larger. In order to draw the magnetic field pattern of conical coils, the following steps should be considered [15].

1- The receiver moves around the transmitter in a dome.
2- The voltage recorded at the receiver side must be fixed to 1 volt each time the receiver moves around the transmitter by increase or decrease the distance between them.
3- Considering that the magnetic field of a normal circular coil is symmetrical from its both sides, as for the conical, the magnetic field is not symmetrical due to its geometric shape as will be described later.
4- Based on step 3, the amount of the flux delivered can be measured by the circular coil transmitter as the receiver moves around from 0° to 90° and then circulate these values to the rest of angles. As for the conical coil, the amount of the flux delivered can be measured by the transmitter as the receiver moves around from 0° to 180° and then circulate these values to the rest of the angles see figure 3 (a) and (b).



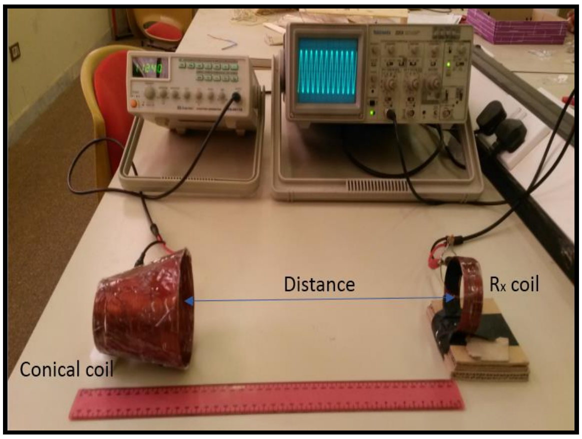
(a)



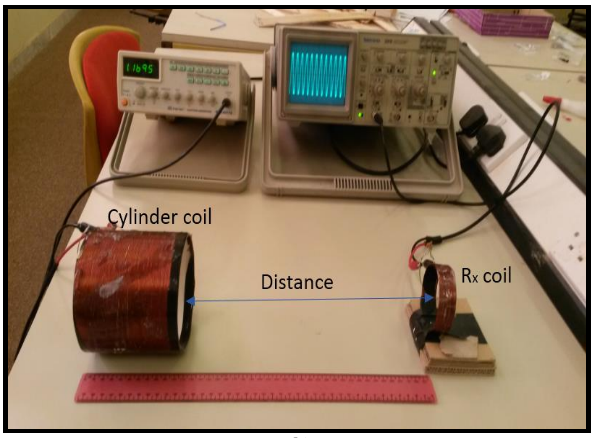
(b)

Fig 3 (a) The flux measurement method of circular coil, (b) The flux measurement method of conical coil.

Through these steps, the magnetic field pattern of any type of coils can be drown. The objective of this setup is to assess flux distribution around the conical transmitter. Two shapes were examined (a) when the transmitter is circular and (b) when the transmitter is conical as in Fig4 (a) and (b). Since we focus on the design of the transmitter part of the system, the receiver side could be in any shape. In this paper, the receiver used is in a circular shape.




(a)




(b)

Fig4 (a) The transmitter is circular, (b) The transmitter is conical.

## IV. Results and Discussion

### *A. Comparison between circular and conical coils*

The main differences between circular and conical coils are related to the geometry of the coil and radiation pattern. The changes in the geometry of coils cause changes in the radiation pattern. As shown in Fig 5 the measured voltage is plotted as a function of receiver position along each angle and the distance between receiver and transmitter [16]. From the figure, it is learned that the magnetic flux pattern of the circular coil is symmetric. Thus, the magnetic field of this type of coils reaches the maximum wireless power transfer in both sides along the horizontal axis. The radiation pattern obtained from the circular coil is similar to the radiation pattern of the Dipole antenna that used in radio frequency field. It is useful in applications where maximum wireless power needs to be transferred in two directions.

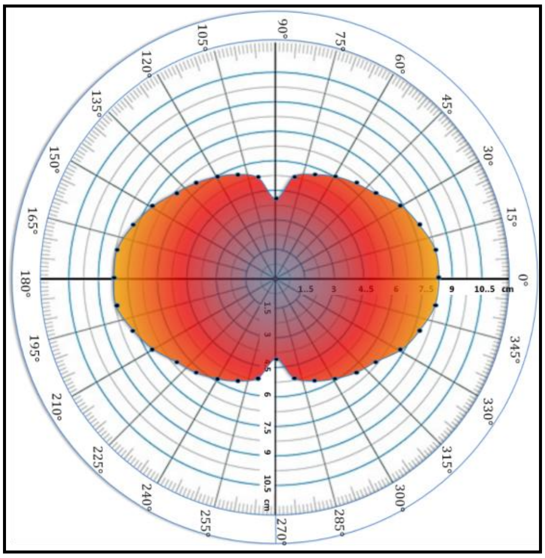


Figure 5: The magnetic field pattern of circular coil

Similarly, the approach used in the previous part can be applied for the conical coil system, where obtuse angle of the coil is 40°. The electromagnetic field pattern obtained by this type of coils is larger from the top radius and small from the bottom. The maximum amount of the electromagnetic field pattern of the circular coil is bounded within a range of about 30°. In contrast, the maximum amount of the electromagnetic field pattern of the conical coil is bounded within a range of about 120°. This achievement again strengthens the statement that the amount and the shape of the magnetic field distributed wirelessly is larger and wider from the top radius of the conical coil. It is important to design a transmitter that produces a higher degree of accuracy, when more receiver combinations placed around that transmitter in some applications such as medical implant devices. Therefore, obtuse angle does affect the system performance and the power transfer efficiency.

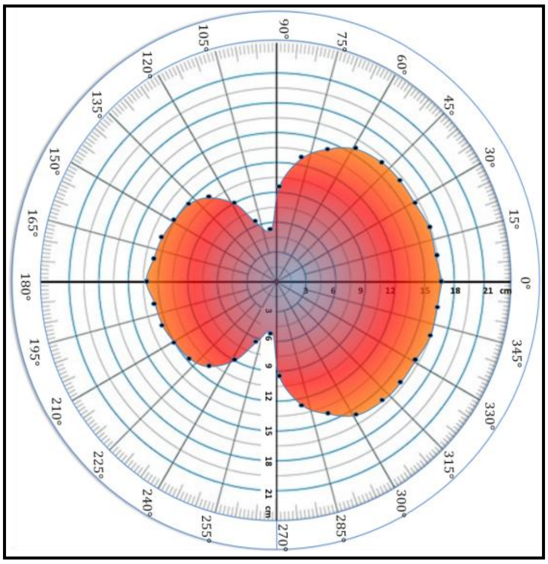


Figure 6: The magnetic field pattern of conical coil with obtuse angle 40°.

The obtuse angle of the conical coil has been modified to be 20° to study the affect of the angle changes. The results obtained in Fig 7 close to the one achieved in the previous section for the system with 40° obtuse angle. From this figure, it is learned that the system performance is affected by the adjustments of the obtuse angle.

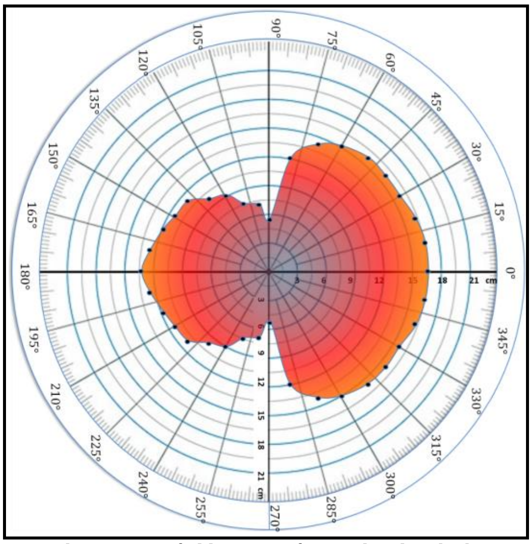



Figure 7: The magnetic field pattern of conical coil with obtuse angle 20°.

It is seen in Figs 6 and 7 that the radiation pattern of conical coils varied and controlled by changing the obtuse angle. The maximum amount of the electromagnetic field pattern of the circular coil is bounded at a range of about 140, which is wider, and more directive than the previous type of the conical coil. Meanwhile, the back lobe is diminish. This can be approved by using Biot-Savart law which indicates the magnetic field at a distance x along the center line of a coil of radius r carrying a current I. The law is described by

$$B_x = \frac{\mu_0}{4\pi}\frac{2\pi r^2 I}{(x^2 + r^2)^{3/2}} \qquad (2)$$

From this expression, it is approved that in order to maximize the magnetic field of such coil at a given distance, the radius needs to be maximized. According to this evident, the larger radius of the conical coil produced a maximum amount of magnetic field than the smaller radius. Indeed, the radiation pattern obtained from the conical coils is similar to the radiation pattern of the Directive antenna in radio frequency field. For verification of the comparative method, two self-resonators were created as shown in figures 4 (a) and (b). The resonant frequency, f was 1.13MHz. In the first case, the transmitter side resonator was a circular type (r=10.5cm, N= 107 turns, a=0.85mm). In the second case, the transmitter side resonator was a conical type (r1=5cm, r2=3cm, N= 97 turns, a=0.85mm). Both of the coils were resonate with circular receiver type (r= 10.5cm, N= 107 turns, a=0.85mm) in separated experiments. The target resonant frequency of each case with the receiver was adjusted.

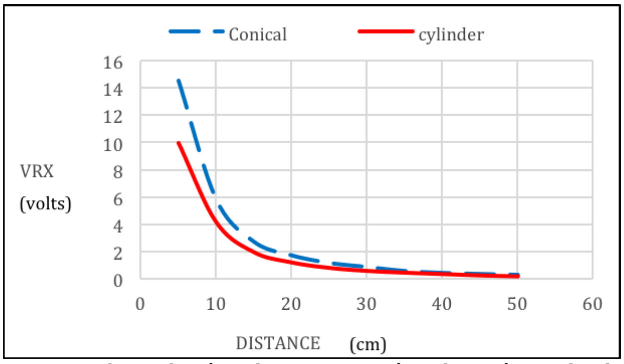



Figure 9: The results of wireless power transfer voltage of conical and circular coils.

Figure 9 shows the experimental voltage (V) received according to the distance (D) between the two indicated self-resonators. It can be observed that the voltage received from the conical coil case is higher than that for the circular coil case. In the circular coil case the maximum voltage is received at distance of 5cm (50% efficiency) and the maximum distance to receive an acceptable value of voltage is 30cm with efficiency reducing to 3%. In contrast, the voltage efficiency of the conical coil case at the same distance of 5cm is about 75% and the maximum distance to receive an acceptable value of voltage is about 30cm with reduced efficiency of 5%. Therefore, the conical coil design has improved the system efficiency at 5cm (from 50% to 75%). At 30cm the efficiency factor is also improved (from 3% to 5%). The improvement is very small due to the limitation of the source. Compared with the circular coil case, the received voltages at equivalent distance have increased by using the conical coil. The conical coil system also provides extended range. For instant, at a distance of 8cm the receiver voltage is equal to 8V. This is the same voltage received at distance of 5cm with the circular coil system.

## V. Conclusion

We have proposed a conical coil wireless power transfer design to provide an effective magnetic field signal accurately in wider and directive path. The design provides the ability to control the shape of the flux pattern. High efficiency can be achieved with the conical coil system. The short and long-range performances of wireless power transfer systems can be improved by using conical design. The design of the conical coil system can be used in applications where wireless power needs to be concentrated in one direction such as biomedical and portable devices charge. Future work may include further investigation into other possible experiments such as adjusting the obtuse angle of the conical coil transmitter to get the desired pattern while maintaining the receiver coil at a constant distance.

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## BIOGRAPHIES

Nagi F Ali Mohamed received the Engineer degree in Electrical and Electronics Engineering from University of Garyounis, Benghazi, Libya, in 2006, and the Masters degree of Telecommunication and Network Engineering from La Trobe University, Melbourne, Australia, where his work of Wireless Energy Transfer and Broadcasting (WETB) recognized as the Best Masters Project at the Hooper Memorial Student Project Presentation, in 2012. From 2007 to 2009, he was demonstrator in the Department of Electrical Engineering, Faculty of Houn, Libya, where he is currently assistant lecturer. Engineering Technology, His current research interests include antennas design, telecommunication network design, the analysis and developments of RF and wireless power transfer systems.

Mohammed Houseen Abdulsalam was born in , Wadan, Libya, on March 1, 1993. He received Bsc degree in Electrical Engineering from the College of Engineering Technology, Houn, Libya in 2016. His main research interests include wireless power transfer system and design, wireless communication transceivers and power electronics field.

Salim Habeeb Salim Al Tabouni was born in Misurata, Libya, on April 23, 1993. He received Bsc degree in Electrical Engineering from the College of Engineering Technology, Houn, Libya in 2016. His most recent work is on wireless power transfer design. He is also working on power system design and home networking.