2016

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Progress In Electromagnetics Research M, Vol. 50, 161–168, 2016

Electromagnetic Analysis of Different Geometry of Transmitting Coils for Wireless Power Transmission Applications

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Abstract—Inductive power transfer is recently a common method for transferring power. This technology is developing as the modern technologies need to get more efficient and updated. The power transfer efficiency has potential to get better. There are different ways to achieve a desirable efficiency. In this paper, a suitable geometry of a coil for transferring power as a transmitting coil is examined. In this work, three types of geometries are designed. Frequency analysis at frequency range (10 kHz–50 kHz) is done to investigate behaviour of various geometries. Magnetic field, electric field, magnetic flux density, and current density for various geometries are presented and compared. Magnetic flux density is measured via an experimental setup and is compared to simulated one to verify the validity of simulation results.

1. INTRODUCTION

Transferring power wirelessly is well known due to its reliability and related applications. The technology of wireless power transfer has been used for various applications in which power is transferred without any physical contact. This technology is popular among consumers [1]. There are various forms of wireless power transmission, including inductive, capacitive, laser, microwave power transfers, etc. Among the listed methods, inductive power transfer is very popular and has been used for various applications [2]. This method is well known and the has been well applied for decades [3]. The mentioned technology has been applied to charge electric vehicles, electric toothbrushes, mobile devices, and implanted devices applications [4, 5]. The advantages of inductive-based wireless power transfer are its safety and high efficiency at short distances. One disadvantage of this technology is that the transmitter and receiver need to be aligned [6]. An inductive system can include parts as coil, core, and coupling capacitances [7]. The operation of such a system can be compared to an air core transformer [8]. The transmitting coil, which is excited by means of an alternating current, generates an electromagnetic field which is dependent on dimensions of the coil, drive current and frequency [9]. There is an inductive coupling between transmitting and receiving coils [10]. Inductive wireless power transmission is dependent on different parameters such as air gap between the transmitter and receiver, frequency, and current excitation [11]. The power quality is dependent on geometry of the coil [12]. Many of the coils are designed based on the classic theories, and this method does not work for the complex shape of coils [13]. The objective of this paper is to present an obvious understanding of the various geometric forms of coils when being used as a transmitter. This objective is achieved by the analysis and comparison of various coils via electromagnetic results. This paper can provide a useful perspective for designing innovative coils. Different geometries of coils are accessible and reasonable. The diameter of a wire is standard as used in [14]. The designing process of coils and its dimensions are presented in detail. 2D-tools of COMSOL Multiphasic 5.1 software have been used to simulate

Received 5 July 2016, Accepted 14 September 2016, Scheduled 29 September 2016
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problems [15]. Magnetic field, electric field, magnetic flux density, and current density are presented and compared. The behavior of various geometries of coils versus changing frequency is illustrated. The experimental results are added to verify the validity of simulation results.

2. FUNDAMENTAL THEORY OF ELECTROMAGNETIC

According to Ampere's law, the integral of magnetic field intensity is proportional to current in the closed path.

$$\oint H \cdot ds = I \tag{1}$$

where H is magnetic field intensity, in Amperes per Meter (A/m). I and ds are electric current and the vector area of an infinitesimal element of surface S, respectively.

In practice, the relationship between magnetic flux density and magnetic field intensity can be expressed:

$$B = f(H) \tag{2}$$

where B is magnetic flux density in Tesla (T).

The following linear model states relationship between magnetic flux density and magnetic field intensity with the assumption that the magnetic field in the coil is homogeneous:

$$H = \frac{B}{\mu} \tag{3}$$

where μ is magnetic permeability, in Henries per Meter (H/m).

According to Faraday's law, the induced voltage is proportional to the changes of external magnetic field:

$$e = -N\frac{d\phi}{dt} \tag{4}$$

where N is the number of turns, and e and ϕ are induced voltage and magnetic flux, in Volt (V) and Weber (Wb), respectively.

Lenz's law states that induced current in the coil generates a magnetic field which tends to counteract the external magnetic field [16]. The similarity of magnetic flux to electric current is useful. As the electric resistant opposes electric current, the reluctance opposes magnetic flux [16].

Equations (5) and (6) are presented to evaluate the stored magnetic and electric energies in free space, respectively:

$$W_E = \iiint \frac{1}{2}\varepsilon_0 |E|^2 dv \tag{5}$$

$$W_H = \iiint \frac{1}{2}\mu_0 |H|^2 dv \tag{6}$$

where W_E and W_H are the stored electric and magnetic energies in free space. E, H, ε_0 and μ_0 are electric field intensity, magnetic field intensity, vacuum permittivity and magnetic permeability of free space, respectively [17].

3. MODELLING OF A DIFFERENT GEOMETRY OF COILS FOR FINITE ELEMENT ANALYSIS

Finite element method (FEM) can be used to solve different physical problems. This method makes differential equations solvable. This method approaches the problem by reducing errors [18]. FEM is used in different researches for various purposes such as modeling and parameter identification [19–25]. An acceptable solution from Maxwells equations for most practical cases is neither possible nor accurate. Thus FEM is often used to calculate physics quantities [26]. 2D-tools of COMSOL Multiphysics 5.1 software have been used to solve problems via finite element method. In this work, diameter of a wire is considered as used in [14]. New geometries of coils are designed. These models are shown in Fig. 1. Design values of the proposed coils are presented in Table 1.

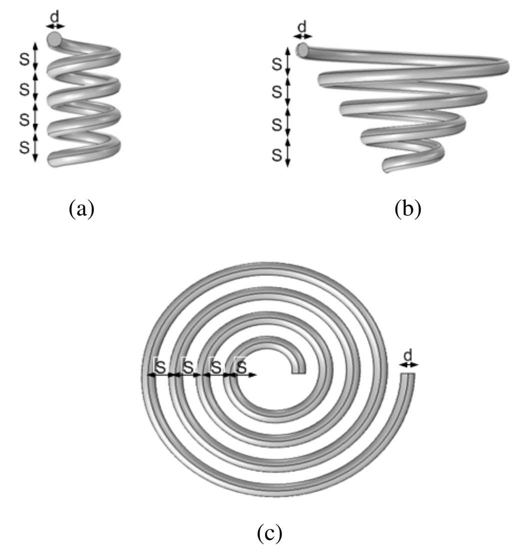

Figure 1. Geometry of coils. (a) Helical. (b) Conical. (c) Circular.

Table 1. Design values of proposed coils.

Parameter	Value
Diameter (d)	2 (mm)
Space (S)	5 (mm)
Turns	4
Voltage source (p-p)	20 (V)

4. ASSESSMENT OF SIMULATION AND EXPERIMENTAL RESULTS

4.1. Simulation Results

For all types of coils 4 turns are considered. The coils are connected to a signal generator as shown in Fig. 2.

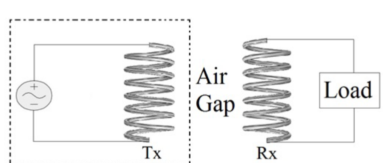

Figure 2. Inductive coupling system.

To analyse the behavior of the coils, a transmitting coil connected to a source is assumed. Figs. 3–6 illustrate magnetic field, electric field, magnetic flux density, and current density at frequency 10 kHz, respectively.

In most models, the effect of high frequency is ignored while this effect is an important source of losses [27].

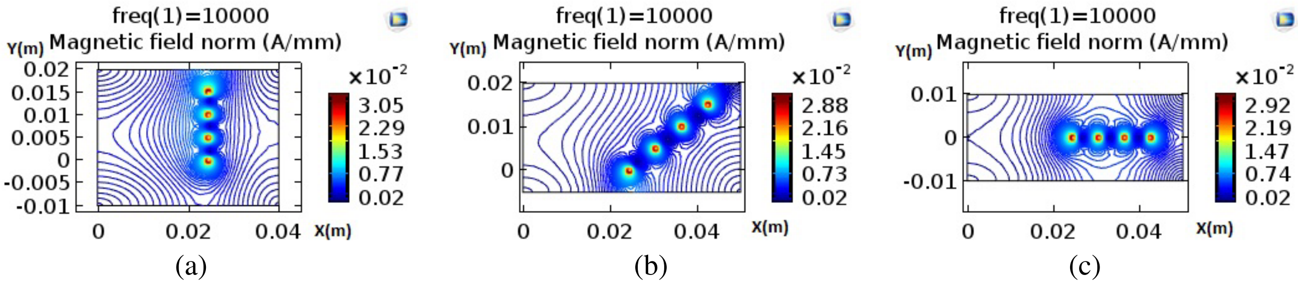

Figure 3. Magnetic field norm at 10 kHz (A/mm) in (a) Helical. (b) Conical. (c) Circular.

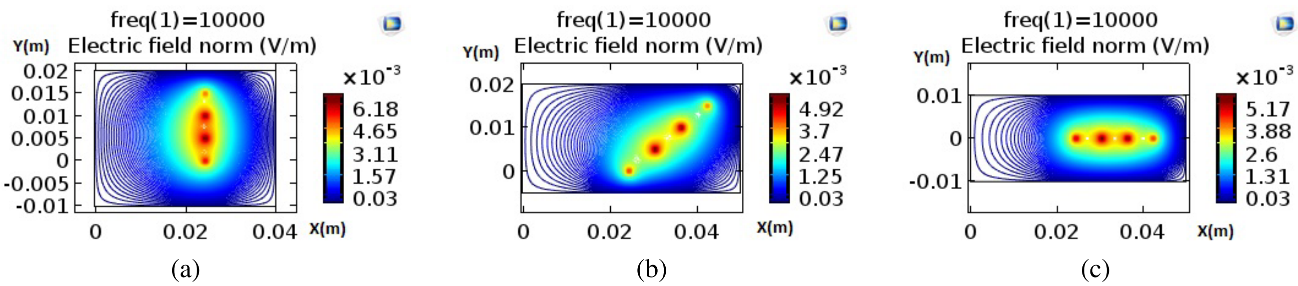

Figure 4. Electric field norm at 10 kHz (V/m) in (a) Helical. (b) Conical. (c) Circular.

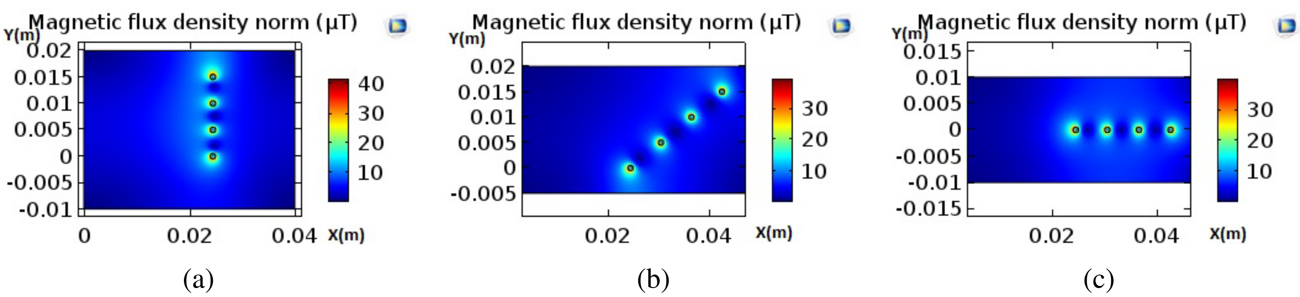

Figure 5. Magnetic flux density norm at 10 kHz (μT) in (a) Helical. (b) Conical. (c) Circular.

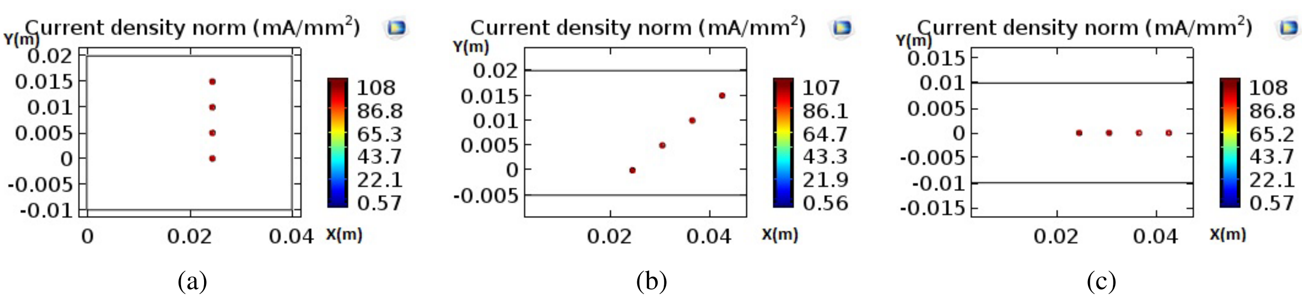

Figure 6. Current density norm at 10 kHz (mA/mm^2) in (a) Helical. (b) Conical. (c) Circular.

4.2. Skin Effect at High Frequencies

Behavior of the coil changes at high frequencies. The skin and proximity effects lead to reduction of coil inductance. The parasitic capacitors are not negligible at high frequencies [28]. The skin effect leads to an internal magnetic field in a conductive wire. This internal field pushes electric current to external surface of conductor. There is an expression to calculate skin depth (δ) [29]:

$$\delta = \frac{1}{\sqrt{\pi \sigma \mu f}} \tag{7}$$

In the above equation, (σ) is the medium conductivity and (μ) the permeability. The skin effect is illustrated in Fig. 7.

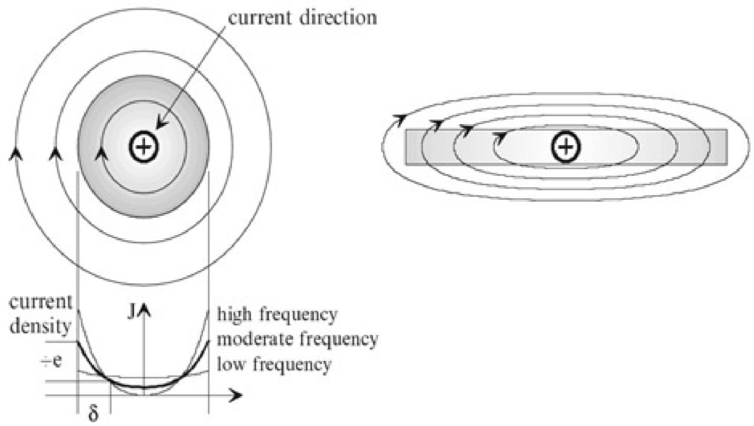

Figure 7. Skin effect [29].

4.3. Verification of Simulation Results

To verify the validity of simulation results, magnetic flux density is measured practically and compared to simulated values. Experimental setup is shown in Fig. 8.

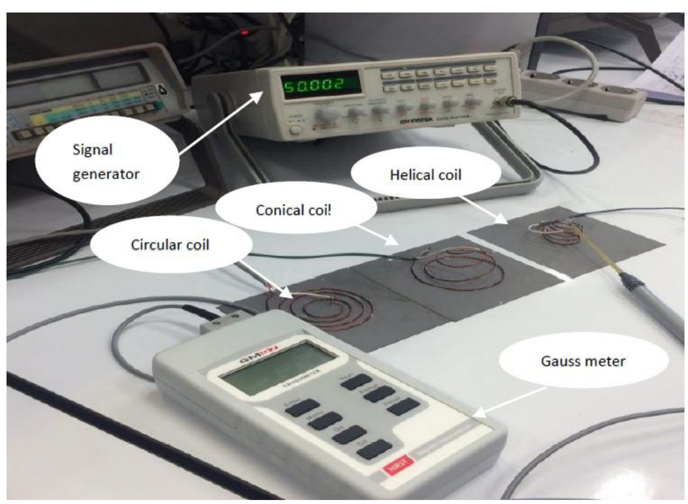

Figure 8. Experimental setup.

Figure 9 presents comparison of experimental and simulated magnetic flux densities. This figure illustrates magnetic flux density versus changing frequency from 5 kHz to 15 kHz.

Error occurs when comparing the experimental results of magnetic flux density with simulated ones. It increases as the frequency goes high due to the measuring instrument. Fig. 10 shows comparison of measured current and voltage versus changing frequency from 10 kHz to 50 kHz for a various geometries of coils.

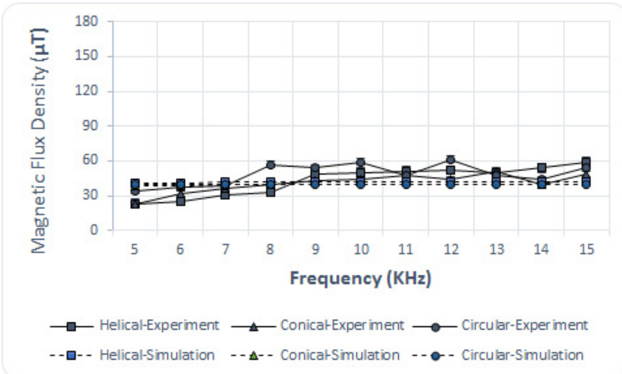

Figure 9. Comparison of experimental and simulated magnetic flux densities.

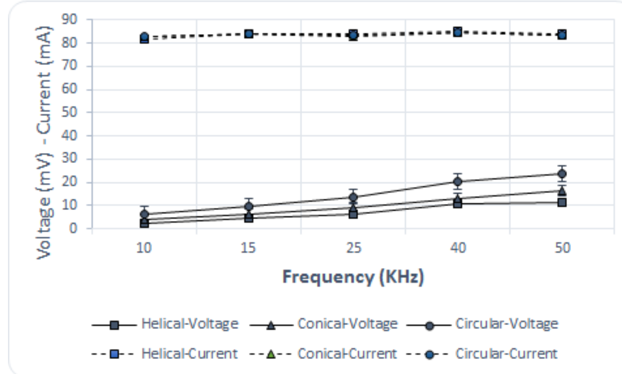

Figure 10. Comparison of measured voltage and current.

To calculate the current density practically, it is assumed that the electric current is distributed within the cross section uniformly. The comparison of simulation via calculated values is presented in Table 2.

Table 2. Comparison of simulation via calculated values.

Current density (J)		
Type	Maximum point-Simulation (mA/mm^2) at 10 kHz	Uniform-Measured (mA/mm^2) at 10 kHz
Helical	108	103.95
Conical	107	105.61
Circular	108	105.73

About 3% error occurs at frequency 10 kHz when comparing the experimental results of current density with simulated ones. The design of inductive power transfer systems is based on an accurate understanding of spatial distribution of magnetic field that is produced by a certain geometry of coil [26].

Table 3. Comparison of maximum electromagnetic characteristics at 10 kHz.

Type	Magnetic Field (A/mm)	Magnetic Energy Density (J/m^3)	Electric Field (V/m)	Electric Energy Density (J/m^3)
Helical	3.05×10^{-2}	3.24×10^{-4}	6.18×10^{-3}	1.05×10^{-16}
Circular	2.92×10^{-2}	2.92×10^{-4}	5.17×10^{-3}	7.36×10^{-17}
Conical	2.88×10^{-2}	2.87×10^{-4}	4.92×10^{-3}	6.67×10^{-17}

Magnetic and electric fields are compared to evaluate the stored magnetic and electric energies produced by the coils. According to Eqs. (5) and (6) and assuming an equal volume around each coil, the one with higher magnetic and electric fields has larger magnetic and electric energies [17]. According to the values presented in Table 3, the stored electric energy is negligible compared to the stored magnetic energy. Storing the most magnetic energy is an important factor in all wireless transfer systems based on inductive technique because storing more magnetic energy leads to higher power transmission efficiency. The above table shows that helical coil can be recognized as an efficient geometry among proposed coils, based on storing magnetic energy.

5. CONCLUSION

In this paper, various geometries of coils for inductive power transfer applications are analysed. A set of simulation results: magnetic field, electric field, magnetic flux density, and current density are presented. The COMSOL multiphasic software has been used to simulate results. The simulations have been verified with empirical results. This work presents an efficient perspective to coil designers.

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