

A Step Forward to Harmonise Wireless Charging after the European Law on a Single Standard for Charging Devices

Liang Lok Hang ¹, Wan Shui Ying ¹, Muhammad Umar Dad^{1,2*}

¹ Department of Physics, Guangdong Country Garden School, Shunde District, Foshan, 511419, China

² Institute of Materials Research (iMR), Tsinghua Shenzhen International Graduate School (TSIGS), Tsinghua University, Shenzhen, 518055, China

Abstract: This article will start off in the interest of the recent EU cable law and present a comprehensive study on the factors influencing short-range and long-range wireless power transmission (WPT) for efficient charging applications. The primary simulation tool employed will be COMSOL Multiphysics 6.1. In the context of short-range WPT, this research will analyse data on skin depth in relation to copper coil frequency and employ 2D plots to better visualise current density distribution in colour, this will also be aided by coil inductance and coil reactance values as frequency approaches infinity. Additionally, the impact of various frequency domains will be explored using 1D plot groups depicting current density and magnetic flux density. For the transmitter and receiver antenna networks, the study will consider factors such as rotation angle and air gap, which influence power transmission efficiency. To optimise the receiving antenna's position and minimise power loss, 3D plots of electric field distribution and S-parameters (including S11 and S21 parameters) will also be utilised. The investigation will also be extended to long-range WPT by comparing the characteristics of different antenna types. Lastly, the article will emphasise the importance of adhering to safety regulations for large-scale WPT applications, focusing on the specific absorption rate (SAR).

Keywords: Wireless power transmission (WPT), skin depth, current density, antenna, s-parameter and specific absorption rate (SAR)

*Corresponding Author

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Introduction

Rapid advances in communication technology have resulted in a number of issues, including electronic- waste (e-waste) and inconvenience due to the emergence of disparate charging standards. In order to alleviate these issues, the European Union (EU) recently enacted legislation mandating a single charging standard for electronic devices. This standardisation can save approximately 250 million annually on the purchase of redundant chargers and prevent 11,000 t of e-waste per year in the EU [1]. This article will investigate the possibility of an alternative charging method, specifically wireless power transmission (WPT) over long distances. As Dr. Neville of NASA states: "Receive power without cables, pipelines, or copper wires. We can send it like a cell phone call wherever, whenever, and in real time." [2].

Nikola Tesla laid the groundwork for the global wireless power transmission system in the late 1890s by testing with alternating surges of current and the Tesla Coil [3][4][5].

In the early 1900s (1901-1917), Tesla's Wardencliff Tower was meant for broadcasting and global wireless power distribution. Unfortunately, financial constraints kept the project from completion. However, the Tower was still a milestone in wireless power transmission. [2]

The interest in WPT wasn't brought back decades after the Second World War, high-power microwave tubes made it possible to transmit power beams over great distances in 1963 [6], and William C. Brown's ground-breaking microwave (wireless) power transmission (WPT) system validated this. Brown demonstrated his microwave-powered helicopter on CBS News the following year [7]. In 1975, Brown aimed to demonstrate the feasibility of application of MPT on space-based solar power systems in the NASA Goldstone experiments, also known as the Microwave Energy Transmission in Space (METS) project [8]. Finally, a major MPT experiment was conducted in 1975 at the Venus Site of the Goldstone facility, approximately 84% efficient direct current (dc) output (30 kW) was transmitted from a large transmitting antenna over a distance of 1.6 km (1 mile) to a receiving antenna (rectenna) that converted the microwave energy into electricity with an efficiency of about 84% [6]. This event marked the large-scale potential of safe and efficient MPT applications.

Space-based solar power (SBSP) is a concept proposed by Dr. Peter Glaser in 1968 that involved collecting solar energy in space and transmitting it wirelessly to Earth. His concept of the potential of long-distance WPT is explored mainly by NASA and the Japan Aerospace Exploration Agency (JAXA) [9][10][11]. This concept is illustrated by figure 1.

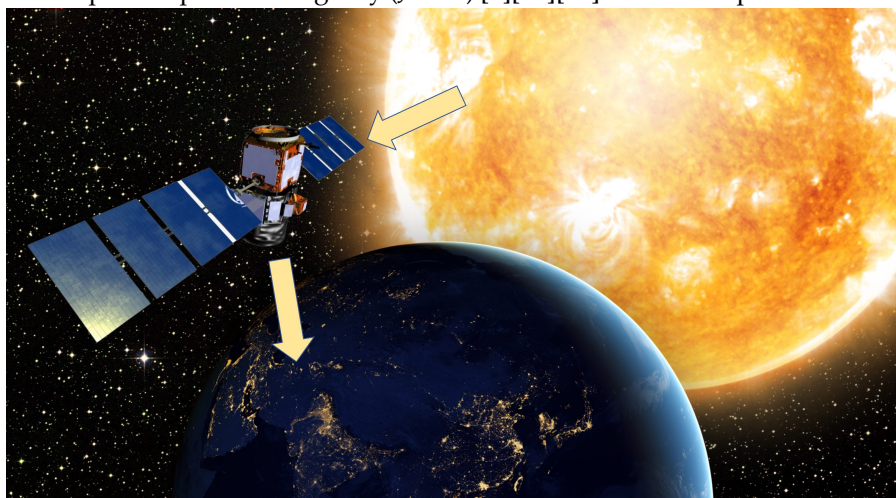


Fig. 1: Conceptual drawing of space-based solar power

In recent years, technology firms such as Ossia, Energen, and Powercast have been developing and refining Radio frequency (RF)-based WPT technologies, introducing Cota [12], WattUp [13], and P1110/P2110 Powerharvester receivers

[14]. These systems are designed to provide longer range and simultaneous charging for multiple devices (including but not limited to consumer electronics, Internet of Things (IoT) devices [15], and industrial sensors).

Wireless charging technologies for electric vehicles (EVs) and unmanned aerial vehicles (UAV), which are more commonly known as drones, are the subject of some recent active research. WiTricity [16] and HEVO Power [17] are developing technologies that enable EVs to charge while parking or driving [18]. In the case of drones, researchers are investigating the feasibility of wireless power transmission from on-the-ground transmitter arrays or moving ground vehicles [19] to extend UAVs flying period [20][21].

However, most of the previous research and developments suffer from some critical limitations, including reduced efficiency and limited range due to energy loss during transmission, atmospheric attenuation, and alignment or focusing issues [22][2]. Additionally, the WPT has a biological impact [23]. Finally, the scalability and cost-effectiveness issues [24]. Here, we will analyse how to increase the efficiency that is one of the primary concerns in wireless power transfer. COMSOL is used to simulate and optimise the design of the coils, the distance between them, and the frequency of the power source to maximise efficiency. The range of wireless power transfer can be limited by factors such as coil size, power source, and interference from other sources. COMSOL is used to optimise the design of the coils and the frequency of the power source to extend the range of the system. Inductive wireless power transfer can create electromagnetic interference that can affect other electronic devices. From simulation we generated results, such as electromagnetic field strength and power transfer efficiency, as well as the level of mitigating electromagnetic interference generated by the system.

Despite the EU's significant efforts to achieve environmental sustainability by mandating a single charging cable for all daily electronic devices, the article wants to take a step forward by exploring the potential of harmonising all domestic charging networks with WPT, as shown in figure 2. By switching from traditional cable charging to longer-range WPT, we can substantially reduce the reliance on cables, ultimately achieving a more environmentally friendly approach for the EU cable law. Additionally, adopting WPT technology for charging electronic devices enhances users' convenience by allowing for greater device mobility while charging due to the lack of restriction from cable length. To investigate this, this article will conduct an extensive number of simulations and research into various aspects of WPT technology, from short-range to long-range WPT, including the factors affecting power transmission efficiency and the possible antennas for long-range applications.

This article begins with an introduction that provides essential background knowledge for the research conducted. The subsequent sections delve into the methodology, detailing the rigorous processes involved in data collection. Following the methodology, it presents the results and engages in a comprehensive discussion that analyses the trends and implications of the findings. Ultimately, the article concludes with a summary that encapsulates the key insights and takeaways from the research.



Fig. 2: Conceptual drawing of domestic wireless power transmission

Research Methodology

This section elucidates the modelling methodology employed within the COMSOL Multiphysics version 6.1. The software aids in the simulation and modelling of physical systems for magnetic fields in this article. The investigation delves into the impact of the skin effect on coil performance in addition to examining the occurrence of current dispersion in conductors across varying frequencies.

Within the scope of this article, the models are computed through the AC/DC module, which facilitates a sophisticated graphical user interface when executing AC/DC electromagnetic simulations, including static, quasistatic, and low-frequency scenarios. Regarding the primary emphasis in this article, magnetic fields (mf) shall serve as the fundamental physical interface under examination.

Parameters were set within the material content of a blank material, with copper being the primary material employed in this article. The parameters assigned for copper include: Relative permeability = 1, Electrical conductivity = 5.998×10^7 S/m, Relative permittivity = 1

For the investigation's meshing settings, an extra fine element size was utilised, and a boundary layer was applied throughout the entire geometry to mitigate the skin effect. Additionally, a coil was generated within the magnetic field (mf) using the model builder setting.

Throughout the investigation, the default dimension (length unit) employed was millimetre (mm). The investigated copper coil's size and shape consist of a circle with a 1.00 mm radius.

The skin effect is the tendency of a high frequency alternating electric current (AC) to get dispersed throughout a conductor so that the current density is greatest near the conductor's surface and diminishes exponentially with increasing depth. Current flows primarily through the "skin" of a conductor, in between the outer surface and a level known as the skin depth. This is being visualised on figure 3.

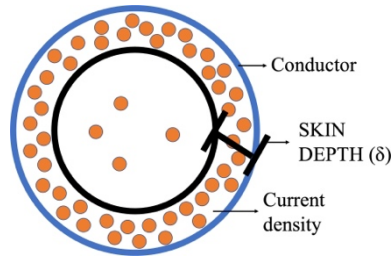


Fig. 3: Distribution of current flow in a cylindrical conductor in cross section

$$\delta = \sqrt{\frac{\rho}{(\pi f \mu_0 \mu_r)}}$$

(1)

δ = Skin depth;

ρ = Resistivity of the conductor ($1.678 \mu\Omega \text{ cm}$ for copper)

f = Frequency of the AC signal

$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$: The permeability of free space

μ_r = Relative magnetic permeability of the conductor (0.999991 for copper)

Furthermore, this article evaluates the effect on coil inductance and reactance by various frequencies.

Results and discussion

The frequency domains under consideration over the investigation include 1 Hz, 25 Hz, 50 Hz, 10k Hz, 50k Hz, 1M Hz, and 10M Hz. By modifying the frequency domains, various values of skin depths were obtained.

Frequency (Hz)	Skin depth (mm)
1	65.75
25	13.15
50	9.30
10k	0.66
50k	0.29
1M	0.07
10M	0.02

Table 1: Variation of skin depth with frequency

As shown in Table 1, the higher the frequency domain, the lower the skin depth, meaning larger inefficiencies in the transmission of electromagnetic waves through the material.

The frequency and reactance of an inductor are directly proportional. This suggests that an inductor will offer more oppositions to surges and fluctuations in current at high frequencies. Conversely, at low frequencies, the reactance of the inductor will be lower, permitting a higher amount of charge to flow through the inductor.

The formula to demonstrate this phenomenon is:

$$X = 2\pi fL \quad (2)$$

X = reactance of the inductor (in ohms Ω)

$\pi \approx 3.14159$

f = frequency of the AC signal (in hertz Hz)

L = L is the inductance of the inductor (in henrys H)

Table 2: This table shows the variation of coil inductance and coil reactance with frequency

Frequency (Hz)	Coil inductance (μ H)	Coil reactance (m Ω)
1	0.050	0.00031
25	0.050	0.0079
50	0.050	0.016
10k	0.047	2.97
50k	0.029	9.07
1M	0.0065	40.80
10M	0.0021	130.62

This phenomenon is quantified in Table 2. As the frequency of an AC signal increases towards infinity, the reactance of the inductor also increases, and so does its impedance. This makes the inductor behave like an open circuit. Power transmission systems with higher reactance are less efficient. Higher reactance may result in transmission line voltage drops and power losses, reducing load voltage and power.

A series of visual simulations of 2D colour table plot groups of current density for a copper conductor are shown in figure 4 to figure 9. Currents are becoming increasingly concentrated along the copper conductor's upper surface when the frequency domain rises. As frequency approaches infinity, current takes up a decreasing proportion of the copper conductor's cross-sectional area.

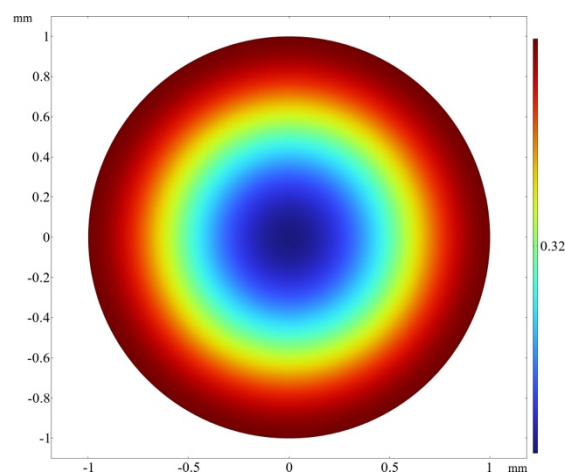


Fig. 4: freq(1)=1 Hz Current density (A/mm²)

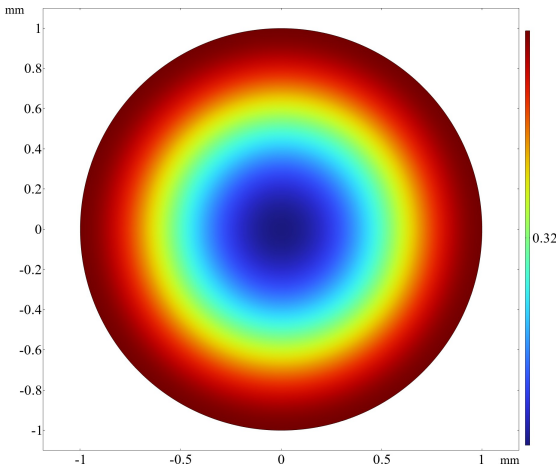


Fig. 5: freq(2)=25 Hz Current density (A/mm²)

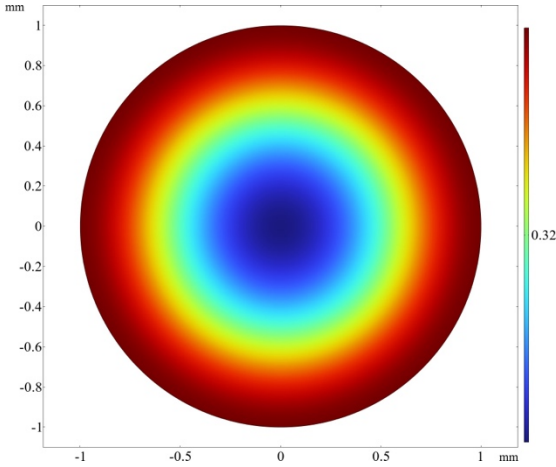


Fig. 6: freq(3)=50 Hz Current density (A/mm²)

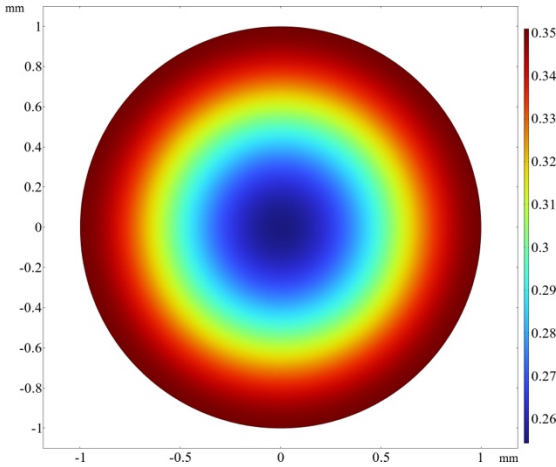
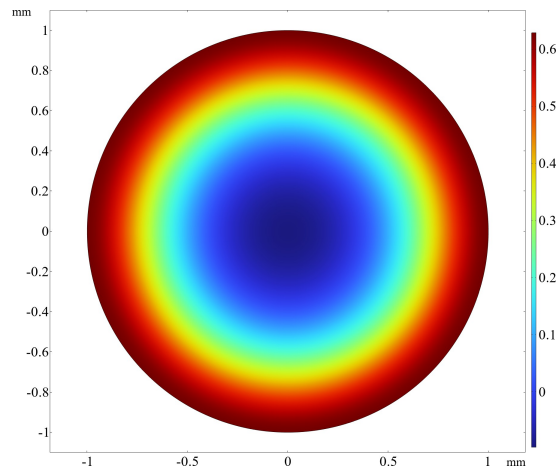
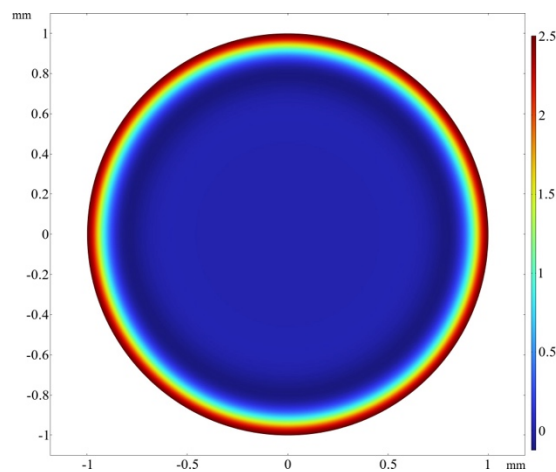
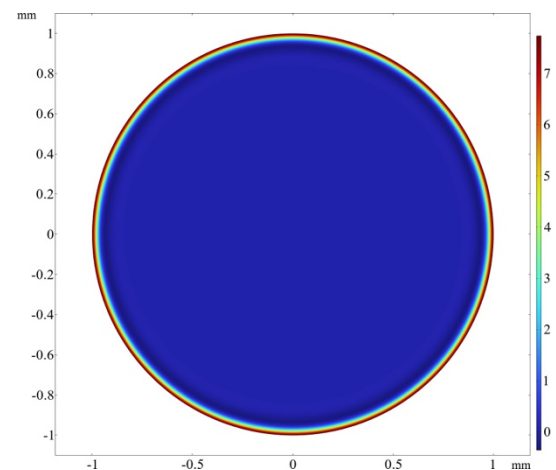


Fig. 7: freq(4)=10 kHz Current density (A/mm²)

Fig. 8: freq(5)=50 kHz Current density (A/mm²)Fig. 9: freq(6)= 1 MHz Current density (A/mm²)Fig. 10: freq(7)=10 MHz Current density (A/mm²)

From 1 Hz to 10 kHz, the current density distribution is very similar, notable changes weren't observed until the jump from 10 kHz to 50 kHz.

Figure 12 to figure 17 illustrates the current density (A/mm²) over the radius (otherwise known as arc length) and magnetic flux density (μ T) over the radius of the copper conductor. Magnetic flux density is a measurement of the magnetic

field strength in a specified region of space. It has a symbol of B and is defined as the ratio of force per unit current per length of cable on a wire conductor perpendicular to the magnetic field.

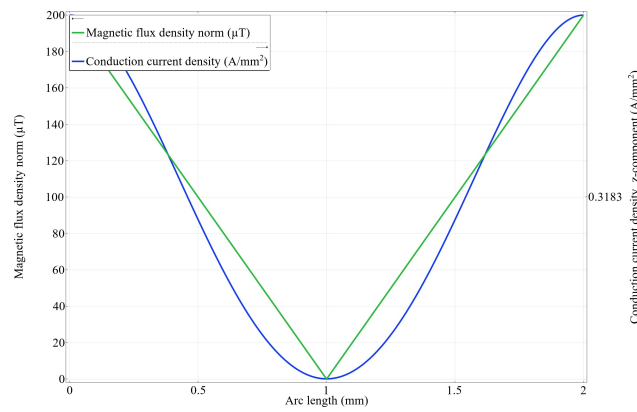


Fig. 11: freq(1)=1 Hz current density (A/mm²) and magnetic flux density (μT)

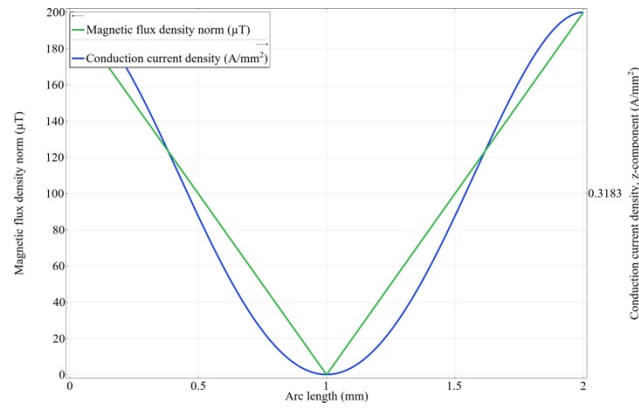


Fig. 12: freq(2)=25 Hz current density (A/mm²) and magnetic flux density(μT)

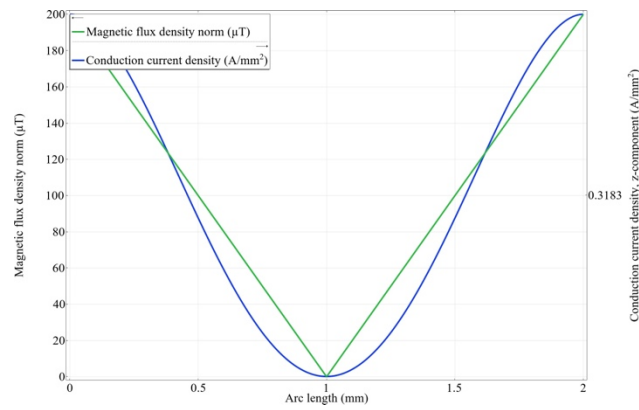


Fig. 13: freq(3)=50 Hz current density (A/mm²) and magnetic flux density(μT)

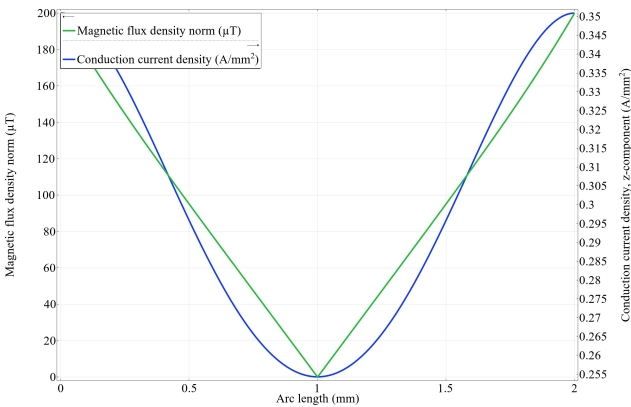


Fig. 14: freq(4)=10 kHz current density (A/mm^2) and magnetic flux density(μT)

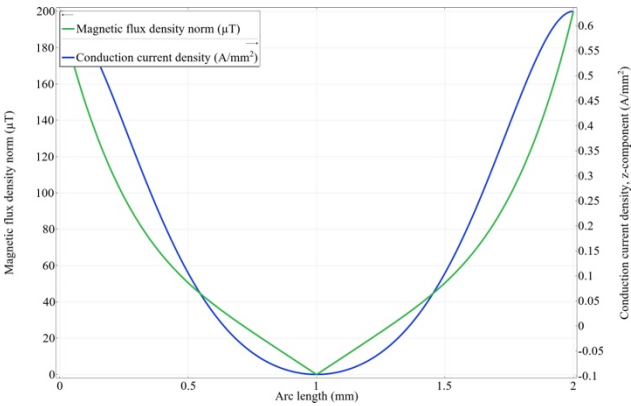


Fig. 15: freq(5)=50 kHz current density (A/mm^2) and magnetic flux density(μT)

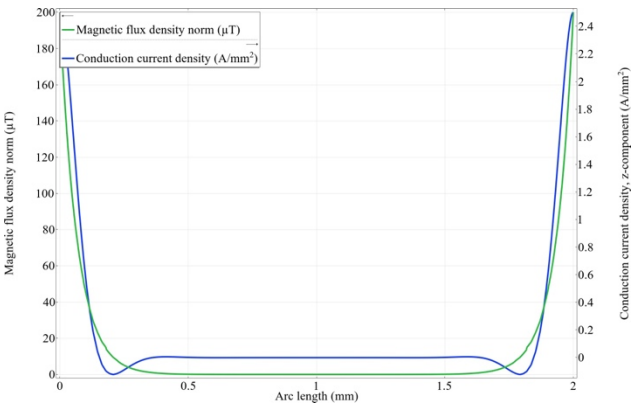


Fig. 16: freq(6)=1 MHz current density (A/mm^2) and magnetic flux density(μT)

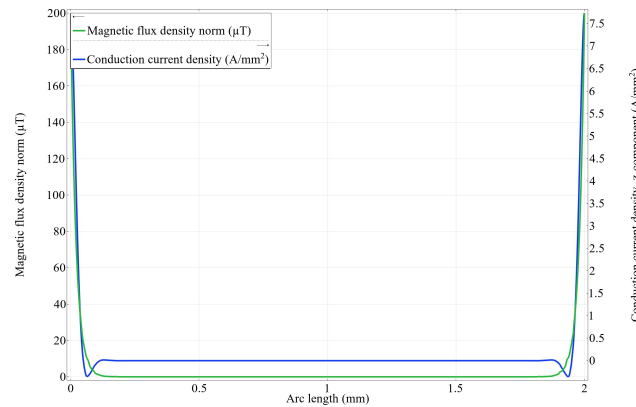


Fig. 17: $\text{freq}(7)=10$ MHz current density (A/mm^2) and magnetic flux density(μT)

As shown in the figure 12 to 17, as the frequency goes up, the magnetic flux and current density are greatest at the surface of the conductor and decrease as they move toward the core conductor. (The higher the arc length, the closer it is to the surface)

3.1. Short-range wireless power transfer

In the context of RF (radio frequency) systems and devices, S-parameters, also known as scattering parameters, are essential coefficients utilised to characterise the electromagnetic behaviour of coils in wireless power transfer systems, especially at high frequencies. By examining properties such as reflection, transmission, and coupling, these parameters serve to analyse the performance of the involved electrical networks. Understanding S-parameters is necessary for maximising the effectiveness and efficiency of wireless power charging systems.

S11 parameter in a wireless power transmission system represents the reflection coefficient of port 1 in the transmitting antenna, and receiver antenna's port 2 transmission coefficient is denoted by S21 [25]. In general, the greater the magnitude of an S-parameter, the more powerful the transmitted or reflected signal.

By using COMSOL to model a coil with the following dimensions: outer diameter of 36 mm and an inner diameter of 33 mm, I am able to collect several sets of data pertaining to the orientation angle (in this case, a parametric sweep of 0° , 15° , 30° , 45° , 60° , 75° , 90°), air gap (in this case, 50 mm, 100 mm, 300 mm), and S-parameter of the lumped port of the transmitting and receiving antenna.

The frequency of the AC current excited in this simulation is 915 MHz. For the transmitting and receiving antennas, the coil material used is copper [26].

The figures below illustrate the distribution of the electric field strength on the xy-plane and a visualisation of the power flow (arrows) from the transmitting antenna as the receiving antenna is rotated. In addition, plots of the S-parameter as a function of the receiving antenna rotation angle for different air gap domains.

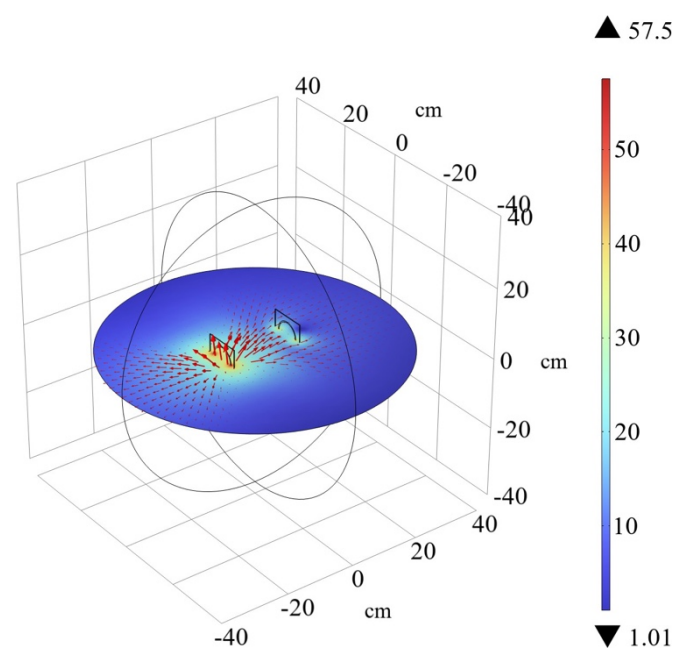


Fig. 18: Electric field distribution for rotation angle of 0 degrees with 100 mm air gap

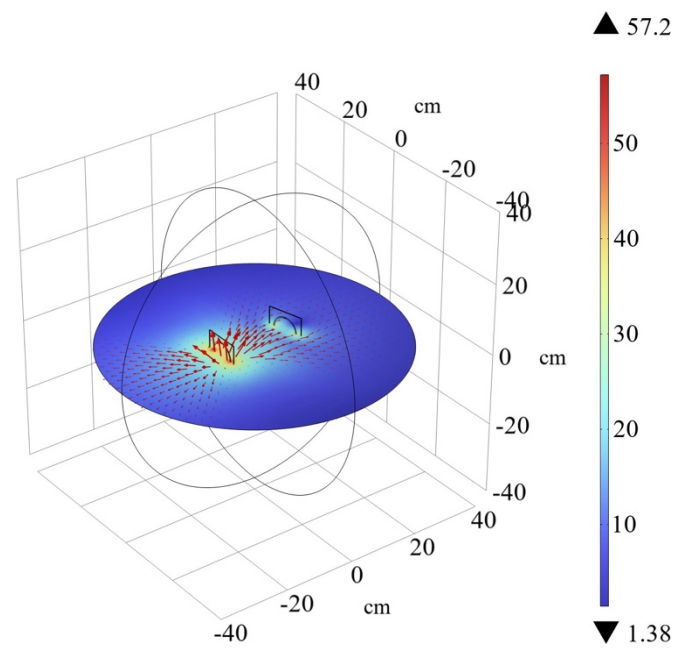


Fig. 19: Electric field distribution for rotation angle of 15 degrees with 100 mm air gap

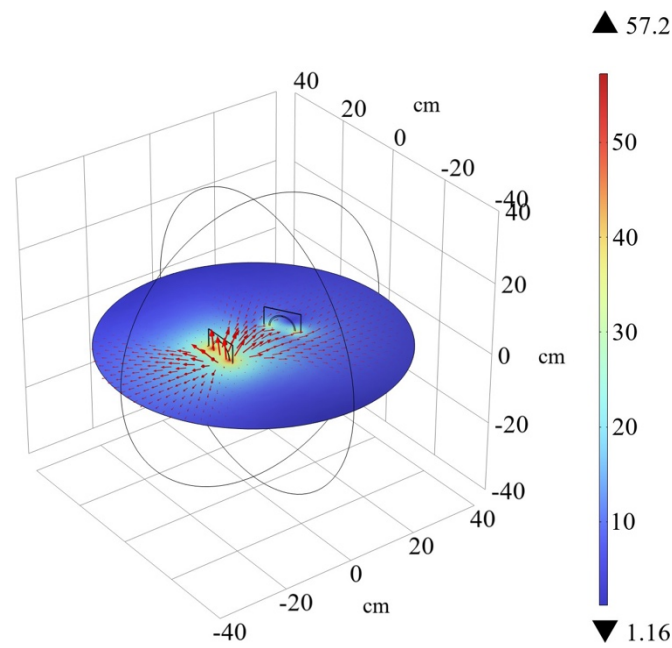


Fig. 20: Electric field distribution for rotation angle of 30 degrees with 100 mm air gap

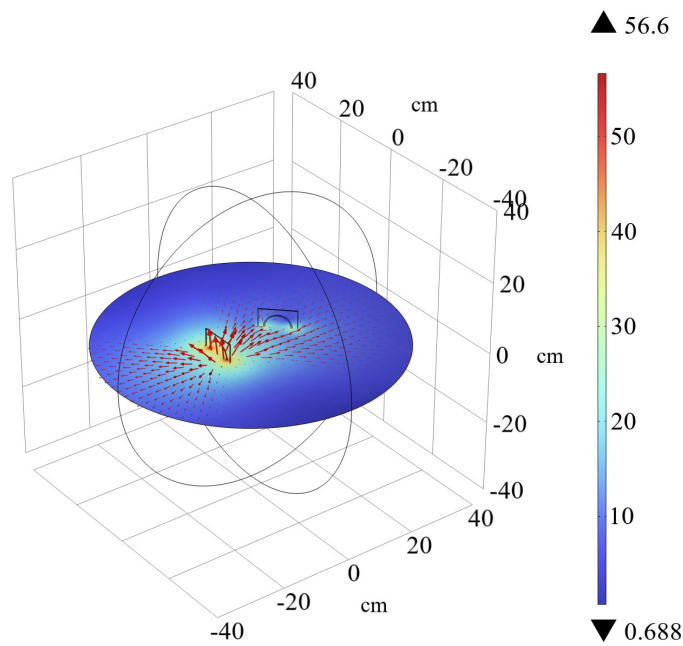


Fig. 21: Electric field distribution for rotation angle of 45 degrees with 100 mm air gap

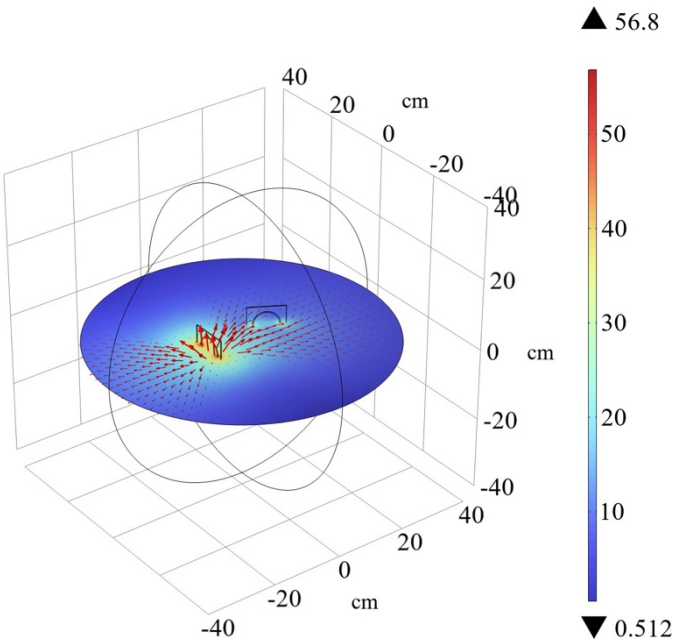


Fig. 22: Electric field distribution for rotation angle of 60 degrees with 100 mm air gap

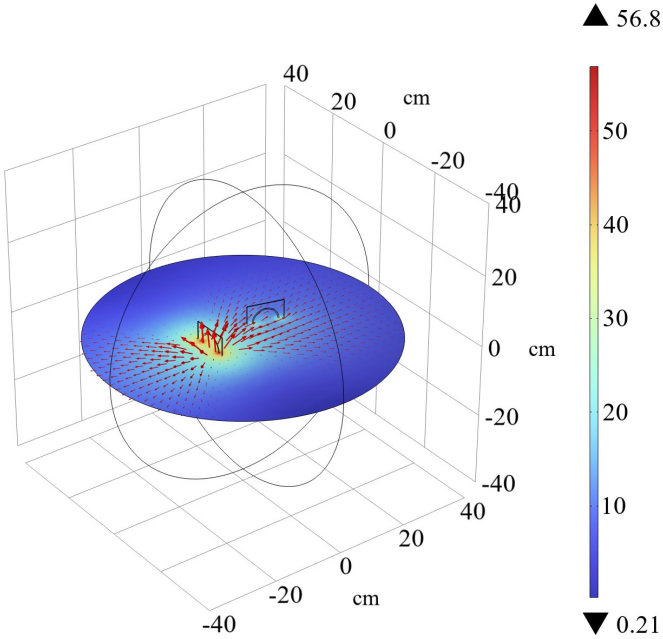


Fig. 23: Electric field distribution for rotation angle of 75 degrees with 100 mm air gap

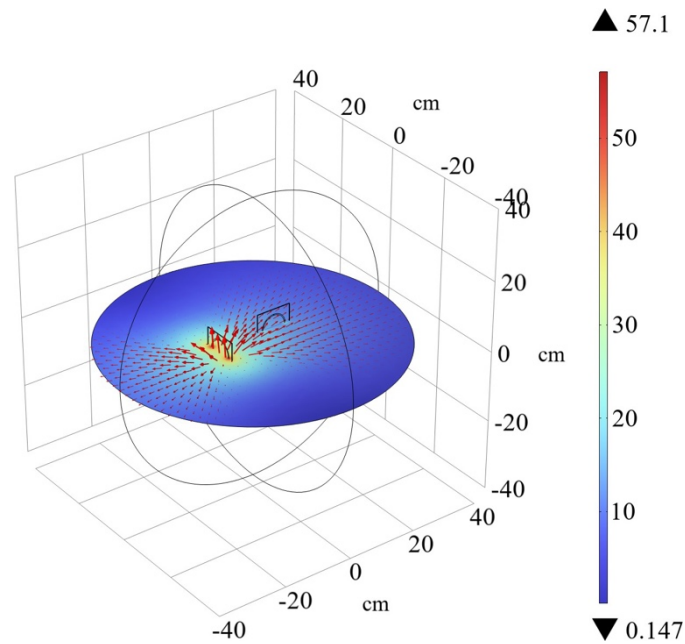


Fig. 24: Electric field distribution for rotation angle of 90 degrees with 100 mm air gap

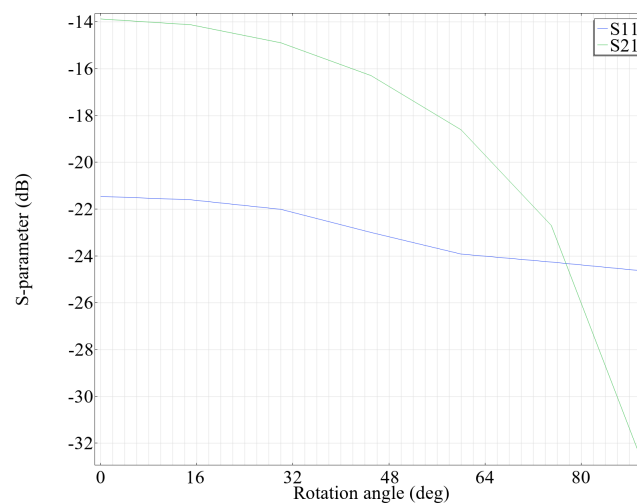


Fig. 25: S-parameter and rotation angle plots

In general, when the receiving antenna is facing directly towards the transmitting antenna (0 degrees), a maximum value at the S-parameter (demonstrated in figure 18 to 25) and a larger hot area indicate strong coupling between the antennas. As the receiving antenna is rotated, the S-parameter begins to decrease, indicating a decrease in power transfer between the two antennas. At a rotation angle of 90 degrees, the S-parameter reaches its minimum value, indicating no significant coupling between the antennas. As shown in all the S-parameter plots, regardless of the orientation of the receiving antenna, the transmitting antenna has an S11 computed input matching characteristic that is below -20 dB.

In a two-port wireless power transfer network, the air gap is the proximity or distance between the transmitter and receiver antennas. As the air gap widens, or the rotation angle increases from 0° to 90°, the power induced in the receiver antenna decreases.

Anticipated trend (in theory):

Impedance is the ability to oppose electrical flow [27], an impedance mismatch happens when there is an incongruity between the input and output impedance of a signal source. Signal reflection or inefficiency may occur as a consequence.

The concept of the S11 parameter is a qualitative measure of the quantity of power reflected from the receiver back to the transmitter due to the presence of an impedance mismatch between the antennas. As air gaps increase, the significance of impedance mismatch also increases, resulting in more power reflection, therefore, what is anticipated is that S11 will fall due to a larger air gap or angle ($> 90^\circ$)

Actual trend:

Nonetheless, it is possible that a decrease in efficiency due to a larger air gap or rotation angle ($> 90^\circ$) may, in consequence, lead to a lower value of S11, which is presented in the above figures. This is because less power is transmitted to the receiver due to larger air gaps, which reduce the quantity of power reflected back to the transmitter antenna.

The S21 parameter is a measure of the amount of power transmitted from the transmitter antenna to the receiver antenna. The wider the air gap or the larger the rotation angle ($> 90^\circ$), the poorer the performance in transmitting power, as most of the electric fields would already have dissipated before reaching the receiver antenna.

Overall, the S-parameter over rotational angle plot provides a quantitative measure of the power transfer between the two antennas and helps us to optimise the performance of wireless communication systems. By analysing these plots, we can identify the optimal orientation of the receiving antenna to maximise the signal strength and minimise interference.

3.2. Long-range wireless power transfer

Circular corrugated horn antennas and parabolic reflectors are suitable for two main purposes, including communication: microwave and millimetre-wave transmissions, radar systems, and satellite transmissions; and the transmission of power over long distances wirelessly.

In some cases, corrugated circular horn antennas may be preferred due to their specific characteristics: Lower sidelobe levels: reduce interference and minimise energy waste, which could contribute to higher overall system efficiency. Wide bandwidth: operates over a broad range of frequencies, making it suitable for various applications. Robust performance: more consistent performance across their operating bandwidth, ensuring reliable power transmission over long distances. On the other hand, parabolic reflector antennas have their advantages: Higher gain: better focusing of the transmitted or received signal. Scalability: easily scaled up to achieve higher gains Customisable radiation patterns: The radiation pattern can be modified by adjusting the shape of the reflector or by using additional elements such as sub reflectors[28][29][30][31][32]

3.3. Safety

It is of the utmost importance to maintain its safe operation in the event that long-distance wireless power transmission is adopted by the general public. The Federal Communications Commission (FCC) along with the Institute of Electrical and Electronics Engineers (IEEE) have implemented a few sets of safety standards. Threshold limit values (TLVs) of an electric field strength of 614 V/m and a magnetic flux density of 205 μ T across a frequency spectrum of 30-100 kHz [33]. The third safety metric is Specific Absorption Rate (SAR), which quantifies the rate of radiofrequency (RF) energy absorption by a biological tissue [34], indicating a source's ER exposure properties (measured in watt per kilogram).

$$SAR = \frac{\sigma \times E^2}{\rho \times 2} \quad (3)$$

σ = conductivity of the tissue being exposed to RF radiation (in siemens per meter or S/m)

E = electric field strength (in volts per meter or V/m)

ρ = density of the tissue being exposed to RF radiation (in kilograms per cubic meter or kg/m³)

In a recent experiment, a group of researchers investigated the safe transmission of power using SAR analysis. They used a 3D model of an adult male and a simulated environment to determine the safe maximum current, which was found to be 140 amps. Their findings indicated that it is possible to safely transmit 1.9 kilowatts of power at a 90% efficiency level, which is sufficient to charge up to 320 USB devices. The whole-body average SAR value was approximately 0.06 W/kg, staying below the established safety limit of 0.08 W/kg. However, the researchers also noted that the maximum permissible power level is dependent on transfer efficiency, and additional safety measures such as intrusion detection or protective barriers may be necessary for distances closer to the pole (source)[35].

Summary

In the relationship between the frequency domain of the current on the coil and its skin depth, results demonstrated that as frequency increases, skin depth decreases, indicating a greater transmission inefficiency. The skin depth was supported by a series of 2D current density plots, revealing the hot area of current density over the cross-sectional area of the coil that continued to decline as frequency rose. Obtaining coil inductances due to different frequencies and using a formula to calculate the coil reactance further proved the inefficiency phenomenon at higher frequencies by establishing a positive correlation between frequency and the inductor's reactance, which suggests greater voltage drops..

In the investigation of transmitter and receiver antennas, three-dimensional plots of electric field distribution were created. First, when the air gap between the two ports was fixed and the rotation angle was the independent variable, the hot area of the electric field decreased from 0 degrees (horizontal) to 90 degrees (perpendicular); second, when the air gap was increased while the rotation angle remained constant, less power was transmitted to the receiver antenna. These results suggested that the WPT performance degrades with increasing rotation angle (when kept between 0 and 90 degrees) and air gap.

The primary antennas highlighted for long-distance wireless power transmission were corrugated circular horn antennas and parabolic reflectors due to their low sidelobe levels and high gain.

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Conflicts of Interest: The authors declare no conflict of interest.

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