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An investigation on electric field emission in shielded capacitive coupler for wireless power transfer utilizing diverse materials

***Abstract**. This investigation proposes the utilization of diverse dielectric materials to reduce electric field emissions in shielded capacitive coupler for wireless power transfer. To identify the most influential dielectric materials in minimizing electric field emissions, Finite Element Analysis (FEA) was conducted. The dielectric materials incorporated in this proposed initiative encompass rubber, glass, FR4, halowax, air, mineral oil, and paper. These dielectrics served as separators between the coupler and the shielding plate. The work demonstrates the electric field emissions at various values in distinct locations of the exposure area, encompassing the top, bottom, and side of the coupler. The result shows the air is the most suitable insulator among all dielectric materials.*

***Abstract**. W tym badaniu zaproponowano wykorzystanie różnorodnych materiałów dielektrycznych w celu zmniejszenia emisji pola elektrycznego w ekranowanym sprzęgaczu pojemnościowym do bezprzewodowego przesyłania mocy. Aby zidentyfikować materiały dielektryczne, które najbardziej wpływają na minimalizację emisji pola elektrycznego, przeprowadzono analizę elementów skończonych (FEA). Materiały dielektryczne uwzględnione w proponowanej inicjatywie obejmują gumę, szkło, FR4, halowax, powietrze, olej mineralny i papier. Dielektryki te służyły jako separatory pomiędzy łącznikiem a płytą ekranującą. W pracy przedstawiono emisję pola elektrycznego o różnej wartości w różnych miejscach obszaru narażenia, obejmującego górę, dół i bok łącznika. Wynik pokazuje, że powietrze jest najbardziej odpowiednim izolatorem spośród wszystkich materiałów dielektrycznych. (**Badanie emisji pola elektrycznego w ekranowanym sprzęgaczu pojemnościowym do bezprzewodowego przesyłu mocy przy użyciu różnych materiałów**)*

Keywords: capacitive wireless power transfer, finite element analysis, dielectric material.
Słowa kluczowe:: pojemnościowy bezprzewodowy transfer mocy, analiza elementów skończonych, materiał dielektryczny.

Introduction

Wireless power transfer (WPT) has been a key scientific topic during the last century. Compared to wired techniques, the wireless power transfer technology can be more practical and safer. Many WPT methods, including inductive power transfer (IPT) [1]–[3], capacitive power transfer (CPT) and hybrid power transfer have been developed [4]–[6]. The hybrid power transfer is a combination of the IPT and CPT technology. Meanwhile, IPT and CPT are usually employed over shorter distances, but radio frequency (RF) and microwave are often given over longer ones. These WPT technology is widely used in electric vehicles charging system [4], [7]. The inductively coupled WPT system relies on the same basic principles of functioning as conventional transformers, employing weakly coupled coils named transmitting and receiving coils separated by an air gap. Furthermore, a comprehensive study investigates the impact of plane coil geometry on the efficiency of wireless power transfer systems [8], as well as comparing circular and square planar coil designs [9] ontributes to expanding the knowledge base in WPT systems by providing insights into various aspects. On the other hand, capacitive coupling-based WPT systems use the electrostatic field for power transmission. These systems feature a pair of parallel metallic plates—one operating as a transmitter and the other as a receiver—creating an equivalent capacitor that transfers energy in the form of static electricity [4].

Because of its low frequency and high power density need, IPT is currently preferred for short-distance , whereas CPT has historically been used for medium- distance power transfer [7]. In order to achieve wireless power transfer (WPT), capacitive power transfer (CPT) uses an electric field (EF) as the transfer medium [10] rather than a magnetic field. The CPT system presents notable advantages, featuring a lightweight design for enhanced portability, contactless operation for user convenience, and effective reduction of electromagnetic interference (EMI) for improved overall performance and reliability [11].

The CPT system has significantly increased transfer power, system efficiency, and transfer distance as a result of continuous research and discussion around the globe. Capacitive Power Transfer (CPT) has various applications across different industries due to its unique characteristics. Some applications including underwater applications [10], [12], [13], Electric Vehicles (EVs) [14], [15], Implantable Medical Devices [16]–[18], drones [19]–[21], Industrial Automation, Consumer Goods and others.

Efficient power transfer between the transmitter and receiver via an ungrounded metal barrier is one of the main advantages of CPT [3]. Additionally, the ongoing evolution of the CPT system has captivated research teams globally, driven by its uncomplicated structure, lightweight design, and cost-effectiveness[22]. Researchers globally are actively investigating its potential applications and advancements. Moreover, this capability allows CPT couplers to be smaller, catering to applications with smaller gaps. The ongoing research and discourse worldwide have led to significant enhancements in transfer power, system efficiency, and transfer distance within the CPT system.

Coupler structure in CWPT

Multiple metal plates work together to create an electric field that facilitates the flow of electricity in a capacitive coupler as in Fig.1. There are coupling capacitances in every pair of plates, and every type of capacitive coupler construction has a unique coupling model including two-port model and π-shaped model [10]. In addition, coupling capacitances are used to calculate the power transfer efficiency. In recent developments, coupler structures have evolved into two-plate [23], four-plate [24], [25], and six-plate configurations [26]–[28]. These variations offer diverse solutions, catering to specific needs in terms of efficiency and functionality.

A capacitive coupler in a Capacitive Power Transfer (CPT) system, specifically focusing on a two-plate structure as in Fig.1, also known as a unipolar structure. In this configuration, one metal plate acts as a power transmitter on the primary side, while the other serves as a power receiver on the secondary side. The current flows through a ground path and parasitic capacitance, with the earth ground acting as the returning path and mutual capacitance serving as the forward path for the current.

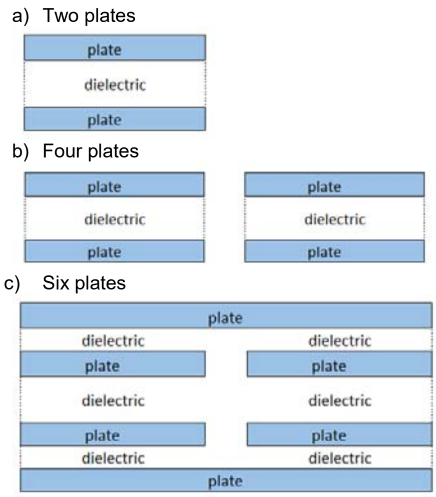


Fig.1.The coupler structure.

Compared to a conventional four-plate coupler (Fig.1), the two plates coupler offers cost savings and improvements in misalignment and coupling tolerances. It is particularly beneficial for applications requiring only a few watts of power. However, the text notes limitations when used in higher power practical applications due to low efficiency. The four plates parallel structure, also known as bipolar, creates two pairs of coupling capacitors as in Fig.1. It gets its name because the plates are typically found in the both horizontal and vertical oriented pairs to create direct and return current pathways for transferring power [29]. The separation of two pairs will reduce the amount of capacitance caused by cross coupling.

A six plates coupler in capacitive wireless power transfer refers to a specific configuration used in Capacitive Power Transfer (CPT) systems. In this setup, six metal plates are employed to facilitate the transmission of power wirelessly as shown as in Fig.1. he arrangement of plates in the wireless power transfer system is carefully structured for optimal efficiency. The two additional plates, sufficiently large to envelop the internal four plates, serve multiple purposes. The additional plates not only function as coupling capacitors to streamline the compensation circuit but also serve as electric field shields, effectively minimizing field emissions [26].

Electric field emission in capacitive wireless power transfer involves the generation and utilization of an electric field between transmitter and receiver plates. As power is transferred wirelessly, the electric field facilitates energy transmission without direct physical contact. This process relies on the capacitive coupling between the plates, allowing for efficient power transfer.

Modelling of the coupler structure

The S-CPT coupler component configuration with six plates in Fig.2 where the capacitance represents a plate structure comprised of six coupling elements with voltage input V_{in} and load resistance R_L. Only the parasitic capacitance between the coupler and the shielding plate and the primary coupler to the secondary coupler is used to represent the capacitance of the S-CPT structure.

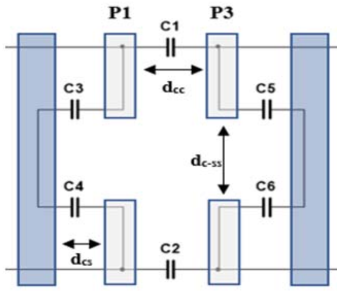


Fig.2.The capacitance in the coupler structure

As a result, C1 and C2 which are a capacitance between the coupler plate at both primary and secondary sides is present in Fig.2 as the capacitance model. The capacitance between the coupler and shielding plate represents the parasitic capacitance at the primary and secondary side which are labelled as C3, C4, C5 and C6. Based on the circuit in Fig.2, the capacitance value, C can be obtained by using the formula stated below:

(1) $$C = \frac{\varepsilon_o \varepsilon A}{d}$$

where: ε_o – electric constant ($\varepsilon_0 \approx 8.854 \times 10{-}12 F \cdot m{-}1$), ε – dielectric material constant, A – plate area, d –distance between the plates.

The geometric model is portrayed in Fig.3 with l_1 representing the conducting plate length, l_2 representing the shield plate length, d_1 representing the distance between two coupler plates, d_2 representing the distance between coupler and shield plate, ε1 representing the relative permittivity of the dielectric media placed between the plates, and ε2 representing the relative permittivity of the dielectric material surrounding the system which is air. Aside from that, the permittivity value of the dielectric material placed between the coupler and shielding plate can be varied according to Table I.

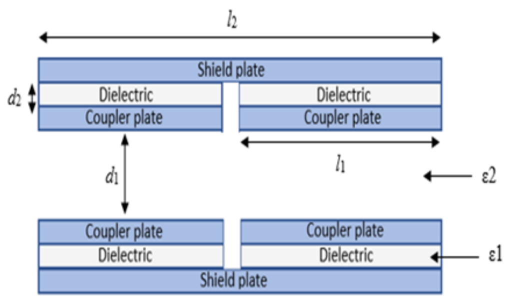


Fig.3.The capacitance in the six plates coupler structure

Table 1. Permittivity value of dielectric materials.

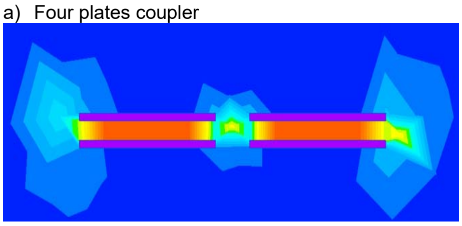
Dielectric Materials	Permittivity Value
Air	1.00
Mineral Oil	2.23
Paper	3.50
FR4	4.20
Halowax	5.20
Rubber	7.00
Glass	10.00

The Table 1 provides permittivity values for various dielectric materials, showcasing their respective electrical properties. Air has the lowest permittivity at 1.00, followed by mineral oil (2.23), paper (3.50), FR4 (4.20), Halowax (5.20), rubber (7.00), and glass with the highest permittivity at 10.00. These values indicate the materials' capacity to influence electric field behavior, with lower permittivity materials having less impact on electric fields and higher permittivity materials having a more pronounced effect.

Result

To analyse the influence of different dielectric materials towards electric field emission, experimental setup utilizing QuickField software. In initial stage, the electric field comparison was done between the four plates coupler and six plates coupler as in Fig. 4 using air as the dielectric material.

a) Four plates coupler



b) Six plates coupler

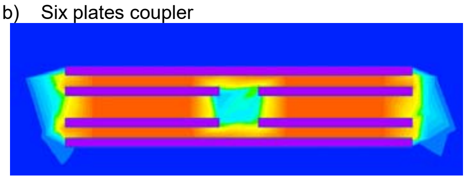


Fig.4.The electric field in the four plates and six plates structure.

Fig. 4 shows the electric field in the both four plates and six plates structure. As the result, size plates structure show no electric field emission for top and bottom structure. However, in four plates structure, there are emission for top and bottom structure. As the resultant, the six plates structure give more safety benefits in term electric field emission.

Continuity to the simulation, the measurement, all the dielectric materials were simulated using the material as in Table 1 and filed measurements were done. The electric field measurement at the edge point (top, bottom, beside the coupler) was taken approximately 100mm long starting from the edge of the coupler at both x and y axes as shown in Fig.5.

In Fig.5, the measurement setting for electric emission is illustrated, depicting the experimental conditions applied to various materials. The parameters are represented by three axes: X, Y1, and Y2, corresponding to the beside, top, and bottom sides, respectively. Each axis signifies a specific aspect of the electric emission measurement setup. The arrangement of these axes allows for a comprehensive analysis of the emissions from different orientations and surfaces of the materials under investigation. This configuration facilitates a thorough examination of the electric emission characteristics, enabling a nuanced understanding of how the materials perform in terms of electric emissions across different spatial dimensions. The measurement results are presented in the Fig.6 –Fig.9.

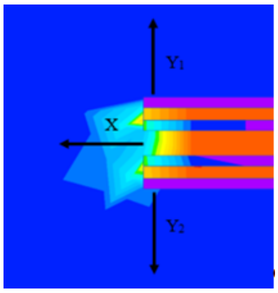


Fig.5. Electric field measurement at the edge of the coupler

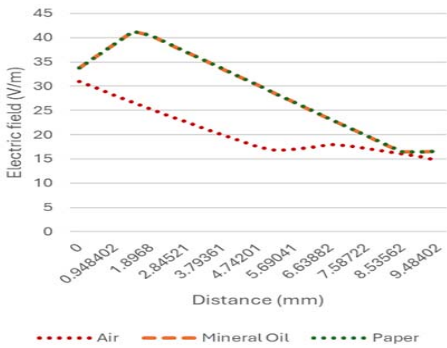


Fig.6. Electric field emission at the top structure for air, mineral oil and paper

In Fig. 6 and Fig.7, the electric field emissions at the top of the structure are presented for various materials, including air, mineral oil, paper, F, Halowax, rubber, and glass. Interestingly, the results highlight a distinct disparity in the air emission values compared to other materials. In contrast, the emissions from the remaining materials exhibit a consistent pattern and value on the graph. It is noteworthy that the maximum electric field emission is recorded at 41 V/m, indicating the highest intensity observed in the study

However, in the electric field emission beside the coupling interface as in Fig.8, the air material shows a huge difference in compared to others material., where the maximum value near the coupler plate is quite high which is 4500 V/m compared to the maximum value of other dielectric materials which is just 550 V/m. According to ICNIRP standards, the electric field emission with 6.78 MHz frequency to the general public for 6 minutes or longer is 200 V/m and 90 V/m for both local and whole-body exposure.

Fig. 9 shows the electric field emission for the bottom structure. The air material shows the lower value in EF emission in compare to others material. However, all the materials give the under value of EF in term in ICNIRP standard. However, in terms of electric field strength, it can be seen that different permittivity values of dielectric materials did not influence the electric field's strength and emission at all except for the area around the edge mentioned previously.

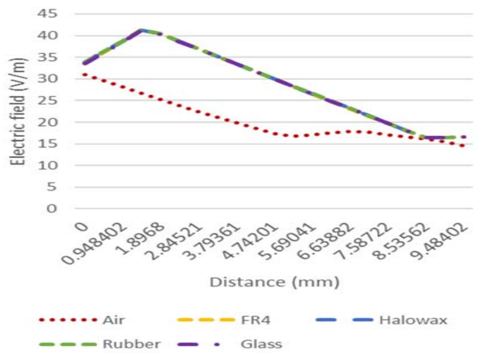


Fig.7 Electric field emission at the top structure for air, mineral oil and paper

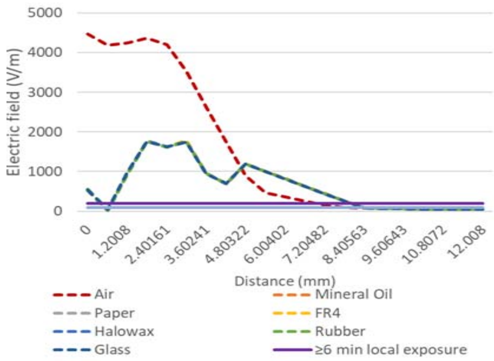


Fig.8 Electric field emission at the beside structure

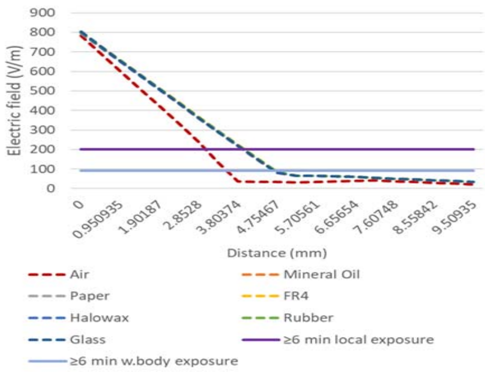


Fig.9 Electric field emission at the bottom structure

As shown in Fig. 9 where all of the dielectric materials produced almost a similar value of electric field emission with maximum value 800 V/m. While in contrast, less electric field emission can be seen behind the shield plates as the plates themselves act as safety feature and serve the purpose of helping to block the electric field from spreading. Thus, it can be concluded that air is the most suitable insulator among all-dielectric materials presented in this experiment due to the minimum differences of electric field emission made by other dielectric materials compared to air. Moreover, air has a high dielectric strength and lower permittivity value which gives a better insulation system. In addition, an S-CPT system which uses air as a medium require less cost and easier to fabricate.

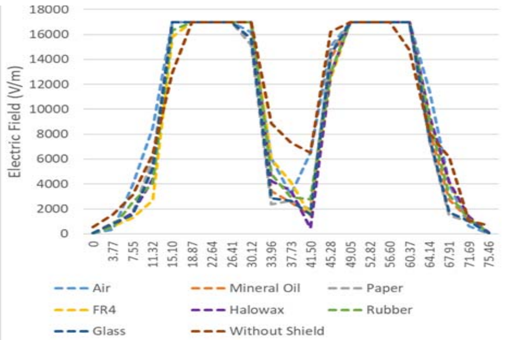


Fig. 10. Electric field emission of S-CPT across the gap between two coupler plates.

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Fig. 10 shows that the highest electric field value is focusing on the area between two coupler plates and the area between coupler and shield plates which were over 1600 V/m and 1700 V/m respectively. While in contrast, less electric field emission can be seen behind the shield plates as the plates themselves act as safety feature and serve the purpose of helping to block the electric field from spreading. In addition, there was approximately 1700 V/m up until 10200 V/m of electric field emission around the edge-to-edge coupler with a distance of 62.5mm.

The results of this measurement are shown in Fig.6-10, which confirms that the dielectric material between the coupler and shield plates did reduce the electric field emission. However, different permittivity values of dielectric materials used in this experiment did not affect the electric field's strength and radiation at all. This can be proven by looking at figures (paper-glass) where the safe distance from electric field exposure was plotted on average at 10.56 mm for public and 11.27 mm for whole-body exposure while the safe distance of the figure (air) is plotted at 7.75 mm and 8.45 mm for both public and whole-body exposure, respectively. This is because, in a real system, adding an insulation layer can lower the maximum value of the electric field that one individual can encounter. Moreover, air is the most suitable insulator among all-dielectric materials presented in this experiment due to its high dielectric strength and lower permittivity value which gives a better insulation system. Thus, insulation with lower permittivity and higher dielectric strength should be one of the main criteria in selecting materials to reduce the electric field emission.

Conclusion

This paper compiles and evaluates the most recent advancements and improvements in CPT technology. It also studied the impact of various dielectric materials used in the CPT system. It aims to analyze the influence of dielectric materials on the effectiveness of those materials in reducing electric fields emission to surroundings. QuickField software were utilized to perform the FEA analysis of this project. Seven types of dielectric material have been chosen: air, mineral oil, paper, FR4, halowax, rubber and glass. Based on the results obtained, it can be summarized that all of the materials used in these experiments produced the same results except for air.

When compared closely, air seems to have the strongest electric field emission among others, thus proven the strength of electric field emission to the coupling interface and its surrounding is not affected by different permittivity value used yet due to the presence of the dielectric materials itself. As for the hardware, only S-CPT that uses air as a medium is implemented in this project as in consequence of cost limitation to fabricate the hardware.

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