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Safety-Oriented Design and Analysis of Dielectric Materials and Plate Geometry in Capacitive Wireless Power Transfer Systems

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Abstract: Capacitive wireless power transfer (CPT) technology is emerging as a promising alternative to inductive wireless power transfer (IPT) due to low cost, lightweight and electromagnetic compatibility advantages. CPT, however, has limitations in terms of the power transfer density and operation safety. The use of dielectric materials, both as transfer media and coatings, has an important role to overcome these limitations, making dielectric material selection as an important design approach. This paper presents a detailed safety-oriented design and analysis of CPT systems focusing on how dielectric materials influence the performance and safety of CPT systems. A four-plate coupler configuration was modeled using finite element analysis in ANSYS Maxwell to investigate a wide range of dielectric materials, coating strategies and thicknesses, and plate shapes across application scales ranging from low-power applications such as consumer electronics to high-power applications such as electric vehicles (EV). Particular emphasis is placed on overlooked safety hazards associated with localized electric field intensification caused by geometric discontinuities, fringing fields, dielectric permittivity mismatch, and triple-junction phenomena. In order to quantitatively assess breakdown risks in general CPT systems, two new safety metrics are introduced to CPT research. Simulation results demonstrate that circular plate geometries offer superior field uniformity and reduced risk of premature breakdown, improving the safety margin up to three times relative to square geometries. High-permittivity solid media improve both efficiency and safety in small-gap systems. By contrast, high-permittivity coatings can exacerbate edge-related breakdown risk, especially when they are applied to sharp-cornered plates in either small or large air gaps. However, coatings of moderate permittivity are shown to be effective in reducing field concentrations. In addition, the dangerous triple junction effects can be added or removed depending on the used coating strategy. The study findings provide useful design considerations for use in the different practical applications to realize safer, more reliable and high performance CPT systems.

Keywords: Capacitive wireless power transfer, Capacitive coupler, Electric-field coupling, Edge effects, Electric field enhancement.

Introduction

In recent decades, the explosive growth in the use of consumer electronics, electric vehicles (EVs), implantable medical devices, and autonomous robots has created the need to find efficient, safe, and reliable means of providing electrical energy to these power-hungry systems. Wireless power transfer (WPT) has become very transformative technology, which is able to provide contact-less or wire-less power transfer in various applications without the use of any physical cables or connectors, therefore offering benefits such as higher durability, rated safety, and even reduced maintenance over the traditional methods of power transfer (Shinohara et al., 2024; Ünal et al., 2024).

Inductive power transfer (IPT) is the most studied and popular technique of near-field wireless power transfer (WPT), where the electrical energy is transferred using magnetic fields between coupled coils (Atraqchi et al., 2021; Youssef & Ameen, 2023). An alternative to IPT in the near-field WPT is capacitive power transfer (CPT) which has attracted much research interests recently. CPT systems transmit electrical energy using high-frequency electric fields across simple, light-weight, low-cost metal plates. If its advantages are well utilized, CPT can be used to overcome IPT limitations in a variety of applications. For example, the low-cost metal plates are the ideal choice for the dynamic charging situation, where cost factor plays a more important role, compared to the costly coil materials. Besides, the lightweight and flat structure of CPT couplers has advantage over IPT on lightweight platforms, such as unmanned aerial vehicles (UAVs), where even a few grams can be significant. Furthermore, the expensive ferrite elements used in IPT to reduce electromagnetic interference (EMI) can be substituted in CPT by an extra pair of metal plates or low-cost insulating layers and thus improve EMI reduction capability while simultaneously improving safety in consumer and wearable electronics. While other benefits of CPT systems include better performance in misalignment scenarios and the ability to transfer power through metal barriers (Erel et al., 2022; Yang et al., 2025). Accordingly, CPT systems are being utilized in various applications and power levels, including EVs, electrical machines, robots, UAVs, consumer electronics, and biomedical implants (Behringer & Ludois, 2024; Etta et al., 2025; Hossain et al., 2022; Huang et al., 2024; Kodeeswaran et al., 2025; Liang et al., 2024; Rashid et al., 2023; Rong, Sun, Yang, et al., 2024).

The Basic structure of CPT systems is illustrated in Figure 1. The main components include a high-frequency inverter, which converts the DC or low-frequency voltage to high-frequency AC voltage fed to the primary-side compensation circuit that offers voltage gain and impedance matching. Then, the capacitive coupler transfers the power by electric field coupling to the secondary side through the dielectric transfer medium. At the receiver side, the secondary-side compensation circuit is in accordance with the primary-side circuit. Finally, a rectifier is used to change the voltage into an appropriate DC level to be used by the load (Erel et al., 2022).

CPT technology is still in the research and development stage, mainly because of its low power transfer density which is the main reason that limits its commercial widespread use. However, this limitation can be overcome with proper system design and parameter selection. Particularly, some experimental systems have achieved power transfer levels exceeding 10 kW over relatively large transfer distances (Etta et al., 2025; Tsurutani et al., 2023).

This performance is mostly dependent on the basic parameters of the system since the level of transferred power is proportional to coupling capacitance, operating frequency and applied plate voltages. The challenge is that the flexibility of the variation of these parameters is constrained by the fact that they interactively influence several system performance parameters (e.g. safety and power efficiency, spatial utilization). Increasing the coupling capacitance while keeping the transfer distance and medium unchanged requires an increase in the plate area, which does not conform to the miniaturization demand. Furthermore, certain safety considerations and standards limit raising the plate voltage level. Similarly, raising the operating frequency is limited by the power and frequency ratings of the available power electronic devices; in addition, it may introduce additional dielectric and magnetic losses (Mahdi et al., 2023; Maji et al., 2021; Wang & Yang, 2024).

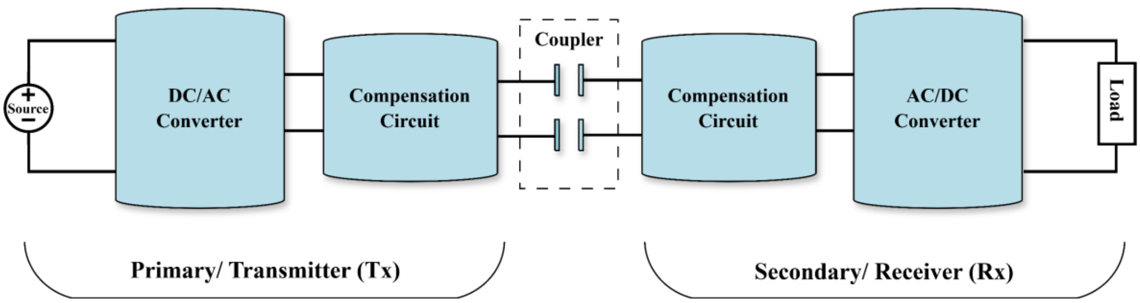


Figure 1. The basic structure of CPT systems

As a result, many studies have been conducted to address the CPT system limitations, focusing on power electronics devices, compensation circuit topologies, coupler design, and system-variation control techniques. Given the capacitive coupler as an essential and central system component, utilizing a solid dielectric material as a transfer medium is a practical approach to increase coupling capacitance. In addition to the use of a solid transfer medium, the dielectric coating or the insulation of coupler plates is of key importance for the efficient system design steps, which need to be studied carefully based on the system performance metrics and the suitable selection of dielectric material.

Although the use of dielectric materials in CPT systems is still understudied, existing studies have shown how dielectric materials affect system performance and research has covered a range of power levels and structural configurations. For instance, Ge et al. (2014) explored the ceramic dielectric coatings by applying titania (TiO_2) to different metal substrates. Their study included the evaluation of the breakdown voltage of the coated samples and testing the effect of coating thickness on the relative permittivity. In an efficient effort, Regensburger et al. (2018) suggested an optimised coupler design by covering the front and side surfaces of the plates with PTFE to minimise the arcing caused by the high electric field concentrations at the edges of the rectangular plates. Furthermore, the circular plate geometry was used to further reduce the edge effects resulting in better safety and power transfer density.

Of major importance, the dielectric coatings on the couplers for biomedical implants were investigated by Erfani et al. (2018), where the system response at frequency variations were compared with and without different coating materials. Zhang and Lu (2020) used polyamide material for underwater power transfer applications to propose a fully water-immersed insulated coupler design. Regarding the use of dielectric material instead of air as a transfer medium, Vincent and Williamson (2020) studied the use of multiple dielectric layers to enhance the power transfer capability while increasing the breakdown voltage limit of CPT systems. While Patidar et al. (2022) investigated the effect of hybrid medium structure that combines both dielectric materials and air on the overall performance of the CPT system. Similarly, the use of air as a filling dielectric and water as the primary transfer medium was investigated by Rong et al. (2024) in a six-plate coupler structure. To further expand the knowledge on the impact of solid dielectric media, Lecluyse et al. (2023) and Lecluyse et al. (2022), (2024) and Lecluyse et al. (2023) conducted extensive investigations into the characteristics of different types of materials and created models to assess leakage losses in CPT systems.

Despite these valuable efforts, it is observed that the majority of the studies in the literature have been mainly focused on the capacitance improvement, dielectric losses and insulation properties. However, important aspects related to material selection for achieving safety, especially under high electric field, are still not sufficiently addressed. In numerous studies, the simple idealized equation for the electric field strength, which is a linear function of the applied plate voltage divided by the transfer distance, is still used to determine the breakdown voltage value. This practice neglects the existence of strong edge effects, which locally intensify the electric field above its average value, which can cause partial discharges, surface flashovers, or full dielectric breakdown. In practice, it is the edge-enhanced electric field, rather than the idealized mean field, that determines the safe operating voltage of CPT systems (Bahl, 2022). This was experimentally confirmed by Lecluyse (2024) where edge effects caused a dielectric breakdown in a CPT experimental setup, even though Epratal, a high dielectric-strength material with a nominal breakdown voltage of 20 kV/mm, was used as the transfer medium.

Moreover, additional safety concerns such as the permittivity mismatch (Hosier et al., 2013; Taylor, 1977) and triple junction effects (Kawamoto et al., 2009; Kuffel & Kuffel, 2000), may be induced when using higher-permittivity materials as a hybrid medium combined with air or as a coating material. As a result, these conditions cause localized field enhancement and early breakdown possibilities, compromising safety and system reliability. Some studies still suggest the use of high-permittivity ceramics as insulating layers with sharp-cornered geometries, especially in high-power systems, to improve the power transfer efficiency (Lin et al., 2021), without a proper discussion of these important safety issues. Accordingly, it is necessary to investigate the CPT system behavior when using dielectric materials, mainly from the safety aspect as it should be considered as the first design rule before the high power-efficiency achieving objective. Therefore, it's necessary to know how do different dielectric materials influence electric field distribution and dielectric breakdown risks in CPT systems. Additionally, another question rises about the degree of ability of appropriate coating strategies to mitigate triple-junction effects.

This paper attempts to fill the above-mentioned research gaps, by conducting a comprehensive finite element method (FEM)-based simulations to investigate the impact of different dielectric materials, both as coating and transfer media, on the safety and key performance metrics of CPT systems. Thus, it will guide the appropriate selection steps of dielectric materials by focusing on the under-explored safety issues in the CPT literature. The analyses will be done across different dielectric material types, coating thicknesses, coating strategies, and plate geometries. The metrics of electric field enhancement, breakdown safety margins, dielectric losses, and coupling efficiency will be compared on each system setting that represents both low-power small air-gap (e.g., consumer electronics) and high-power large air-gap (e.g., EVs) charging conditions.

The major contributions of the research to the CPT systems field include:
(1) definition and quantification of the factor of the electric field enhancement caused by the various system configurations;

(2) comparison of the dielectric breakdown safety margin of the system by actual peak electric field as opposed to ideal or mean field assumption;
(3) a dedicated study of the phenomenon of permittivity mismatch and triple junction effects which are well-known causes of premature breakdown and flashovers in the high-voltage systems, but they have received limited attention in the CPT research;
(4) a comparative analysis of effect of the coating thicknesses and strategies on the safety and performance metrics; and
(5) practical guidelines for optimized dielectric materials use in the CPT systems.

The rest of this paper is structured in the following form: Section 2 presents the theoretical background associated with the study. In section 3, the methodology is provided. Section 4 contains the results and the discussion of the most important ones. Finally, the conclusion and the recommendations on further work are given in Section 5.

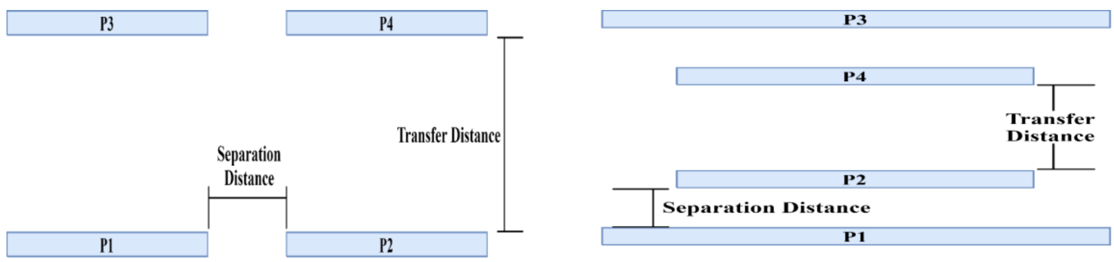
Theoretical Background

CPT System Architecture and Coupler Structures

The capacitive coupler is a core component in the CPT system as shown in Figure 1 and explained in the earlier section. Consequently, it should be designed with careful attention, as it regulates the behavior of electric fields, dielectric breakdown safety, and power transfer efficiency. Though the coupler is simple in structure, and is made of materials that are readily available, even minor changes in the structure of the coupler, such as plate number, plate shape, coating methodology, and dielectric material, can lead to significantly different outcomes in the coupling efficiency and system safety.

The capacitive coupler plates can be structured in many ways. Depending on the number of plates, the conventional structures are two-plate or single capacitive coupler (SCC) (Li et al., 2025), four-plate (Etta et al., 2025), six-plate (Rong, Sun, Qiao, et al., 2024), and electric field repeater (Minnaert & Monti, 2023). In addition, the number of coupler plates is not necessarily restricted to these conventional ones. Besides, the spatial structure can be in horizontal (parallel), vertical (stacked), rotating, or interleaved structures (Xia et al., 2022). The plates can have different geometric shapes, including rectangular, circular, ring, cylindrical, or disc, in addition to different application-dependent shapes.

The four-plate parallel coupler is the most widely used structure in CPT systems. It consists of two metal plate pairs, one forming the forward power transfer path and the other representing the power return path. Figure 2 illustrates the horizontal and vertical four-plate coupler structures; these structures have different electric field distributions, misalignment responses, capacitances, and total occupied space. P1 and P2 are the transmitter plates, while P3 and P4 are receiver plates. The separation distance separates adjacent plates on the same side, while the transfer distance or transfer gap separates the transmitter and receiver side plates.



(a) Parallel (b) Vertical
Figure 2. Four-plate coupler structures

Capacitive Coupler's Equivalent Model

The capacitance between any two parallel metal plates (neglecting fringing fields) can be calculated by Eq. (1).

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \tag{1}$$

Where:

- ε_0 is the permittivity of the free space (8.854 × 10-12 (F/m),
- ε_r is the relative permittivity of the dielectric medium between the plates; for air, its value is equal to 1,
- A is the effective plate area (m^2), and
- d is the gap between the plates (m).

To find the equivalent capacitances of the four-plate coupler, as illustrated in Figure 3(a), between each pair of plates, there is a coupling capacitance, resulting in six capacitances, namely, the main capacitances C_{13} and C_{24}, the cross-coupling capacitances C_{14} and C_{23}, and the leakage capacitances C_{12} and C_{34}. Using equations (2–4), the six-capacitance model can be further reduced to the π-equivalent model shown in Figure 3(b) (Lecluyse et al., 2021).

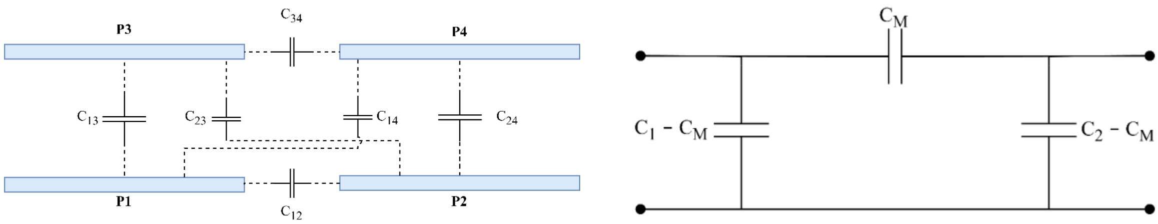
$$C_{1\,(Primary)} = C_{12} + \frac{(C_{13} + C_{14}).\ (C_{23} + C_{24})}{C_{13} + C_{23} + C_{14} + C_{24}} \tag{2}$$

$$C_{2\,(Secondary)} = C_{34} + \frac{(C_{13} + C_{23}).\ (C_{14} + C_{24})}{C_{13} + C_{23} + C_{14} + C_{24}} \tag{3}$$

$$C_M = \frac{C_{13}C_{24} - C_{14}C_{23}}{C_{13} + C_{23} + C_{14} + C_{24}} \tag{4}$$

C_1 and C_2 are the main or port capacitances at the transmitter and receiver sides, which are coupled by the mutual capacitance C_M. The capacitive coupling coefficient (k_c) determined by Eq. (5) represents an essential system parameter that quantifies the coupling efficiency between the two side plates.

$$k_c = \frac{C_M}{\sqrt{C_1 C_2}} \tag{5}$$



(a) Six-capacitance model (b) Equivalent π–model

Figure 3. Four-plate coupler's equivalent models

Fringing Fields and Edge Effects

The capacitance formula provided in Eq. (1) is valid under the ideal conditions in which the gap between plates is significantly smaller than their dimensions, yielding the electric field to be uniformly distributed. However, in practice, for relatively large gap distance as compared to finite plate dimension, the electric field lines bend outside the gap and get accumulated around the plate edges creating fringing electric fields which contribute to edge effects (Mahdi et al., 2022). The study of edge effects is fundamental in CPT systems because of its different consequences: Leakage capacitances increase due to the extension of field lines outside the overlap area, safety risks due to the field intensification at the plate edges, and power transfer efficiency may be reduced due to the reduced field strength at the inside of the gap edges.

The geometric shape of plates has a significant influence on the edge effects; the sharp edges are a favorable point of the field concentration. Thus, the rectangular or sharp-cornered plates have a higher risk of surface flashovers or dielectric breakdown, whereas the corner-free circular plates exhibit lower breakdown probabilities than other geometries (Bahl, 2022), but at a cost of increased spatial footprint to achieve the same capacitance. The peak electric field at the edges can be multiple times higher than the nominal electric field computed by Eq. (6), and this raises the likelihood of surface flashovers and formation of breakdown channels (Gehringer et al., 2022).

$$E = \frac{V}{d} \tag{6}$$

where E (V/m) represents the nominal or ideal average electric field between the plates, V is the applied plate voltage, and d is the gap distance. However, most CPT studies assess the system breakdown safety based solely on (6), overlooking the edge effects that cause peak field concentrations. While this oversight has practical implications, as reported by Lecluyse (2024), a breakdown occurred in an experimental CPT system despite employing high-dielectric strength material as a transfer medium. As a result, modeling and mitigating edge effects are critical for the safety and performance of CPT systems. For this reason, in addition to investigating the impact of dielectric materials in CPT systems, all case studies in this paper will also be conducted on square and circular plate geometries to examine how geometry interacts with dielectric materials utilization.

Dielectric Interface Phenomena

When multiple dielectric materials with different dielectric constants (relative permittivity, ε_r) are utilized in parallel plate capacitors – e.g., hybrid dielectric media or plates coated with solid dielectric material next to an air gap – a discontinuity in permittivity arises at the interface between adjacent dielectric materials, a condition known as permittivity mismatch. Maxwell's boundary conditions dictate that the normal component of the electric displacement field (D) is continuous across the dielectric interface. This causes a discontinuity in the electric field (E), inversely proportional to the permittivity values. This situation leads the electric field to be more concentrated in the lower ε_r material, typically air, resulting in dangerous localized field enhancement at the boundary, especially near geometrical discontinuities (i.e., sharp edges) (Kuffel & Kuffel, 2000). The following Eqs (7-8) define the governing relation:

$$\vec{D}_1 = \vec{D}_2 \rightarrow \varepsilon_1 E_1 = \varepsilon_2 E_2 \tag{7}$$

$$E_1 = \frac{\varepsilon_2}{\varepsilon_1} E_2 \tag{8}$$

The mismatch becomes critical when ε_2 (e.g. high permittivity ceramic) is significantly higher than ε_1 (e.g. air). Consequently, partial discharges may start from the field enhancement points (i.e. edges), causing the bulk breakdown of the dielectric under electric fields even much lower than those given by the bulk breakdown strength of the high ε_r material (Kuffel & Kuffel, 2000; Taylor, 1977). This phenomenon positions a major reliability risk in CPT systems employing high-ε_r coatings or hybrid dielectric media. For example, rectangular plates coated with a ceramic material that had a relative permittivity of 6000 were used in a study by Lin et al. (2021) in an attempt to enhance the capacitance and power transfer density for EV charging. Nonetheless, they did not account for the sharp change in permittivity between the coating layer and the air which could cause potential breakdown when worsened by sharp plate geometry, large air gap, and triple junction effect.

The triple junction effect (TJE) is the electric field behaviour at the intersection of three materials with different electrical properties: usually a high permittivity solid dielectric, a conductor, and a gas. This interface represents a local field enhancement location, and primarily in the lower permittivity material, because of conflicting boundary conditions. This phenomenon is well-studied in high-voltage insulation systems (Kawamoto et al., 2009; Naidu & Kumar, 2017; Tran Duy et al., 2008) but is rarely addressed in CPT systems, although it can occur in system configurations which involve high permittivity solid dielectric interfaces. The localized field enhancement at the lower-ε_r material (i.e. air) often is a preferred initiation site of partial discharges and leads to progressive insulation degradation and consequently to a dielectric breakdown. Therefore, it's important to avoid TJEs in capacitive coupler design, mainly at sharp edges and corners. As such, three coating strategies will be explored in the methodology section to assess and control TJEs in CPT systems.

Field Enhancement and Safety Factors

Analyzing the behavior of electric field is important to avoid possible partial discharges and premature breakdowns caused by local field enhancements (Takuma & Techaumnat, 2010). The field enhancement factor (FEF) (Kuffel & Kuffel, 2000) is the ratio of the peak electric field (E_{peak}) caused by edge effects and dielectric interfaces to the nominal or average field (E_{ideal}) estimated by Eq. (6). It is possible to express this factor as follows:

$$FEF = \frac{E_{peak}}{E_{ideal}} \tag{9}$$

Evaluating FEF in CPT systems is critical to be able to compare different configurations and select the optimum system design. A higher FEF, which is affected by many factors such as fringing fields and dielectric interface phenomena, implies higher system failure risks. Complementary to FEF, the breakdown safety margin (or the electric field safety margin) of the system assesses the safety margin of the system from breakdown occurrence.

This factor can be calculated as the ratio of (E_{BD}) the system's dielectric strength or breakdown voltage to its actual peak field (E_{peak}), mathematically determined by:

$$Safety\ Margin = \frac{E_{BD}}{E_{peak}} \tag{10}$$

For a safe system design, the E_{peak} should be kept substantially lower than E_{BD}. Consequently, the surface breakdown due to the sharp edges and surrounding environmental conditions sets the maximum applied plate voltages rather than the nominal or average field between the plates (Bahl, 2022). Therefore, the system design should begin by initially determining the maximum permissible plate voltages, which should guarantee an adequate safety margin. Given that as a result of environmental conditions, such as humidity and surface contamination, the breakdown can occur even below E_{BD}. Moreover, the partial discharges can initiate at lower field values, especially in AC systems, thus degrading materials and causing eventual failure.

Furthermore, it is worth mentioning that the system's dielectric breakdown voltage is governed by the weakest link in the system, which is the material with the lowest dielectric strength, typically air, acting as a main transfer medium or as a surrounding region if the coupler is not fully sealed. Thus, coating plates separated by an air gap with high E_{BD} material does not improve the breakdown voltage of the system; in contrast, this may worsen the case and stress the air more due to permittivity mismatch and TJEs where present (Kuffel & Kuffel, 2000). As a result, the appropriate safety margin selection in CPT systems should carefully consider the lowest dielectric strength material, transfer distance, environmental conditions, and insulation aging over time.

In this study, both FEF and breakdown safety margin factors are evaluated for system configurations with different plate geometries, dielectric media, and coating types to identify optimal system designs for enhanced safety and reliability. Although illustrated here using specific scenarios, these factors are broadly applicable to all CPT systems with other configurations and represent essential tools to evaluate the system safety in terms of breakdown and field enhancements.

Role of Dielectric Materials in CPT Systems

Dielectric materials in CPT systems can be used as insulating coating layers on the coupler plates and/or as a transfer medium between them. Incorporating dielectrics in the coupler design serves distinct roles and affects the system's coupling capacitance, electric field distribution, breakdown limits, and power losses. The capacitance of parallel plates filled with a dielectric medium instead of air can be computed by substituting the material's relative permittivity into Eq. (1). Similarly, to evaluate the total capacitance between parallel plates with the presence of dielectric materials as a coating and/or transfer medium, the total capacitance can be regarded as a series-connected multiple capacitors, which can be calculated using Equations (11)–(13) as follows:

$$\frac{1}{C_{Total}} = \frac{1}{C_{coating1}} + \frac{1}{C_{medium}} + \frac{1}{C_{coating2}} \tag{11}$$

$$\frac{1}{C_{Total}} = \frac{d_{c1}}{A\ .\ \varepsilon_{rc}\ .\ \varepsilon_0} + \frac{d_m}{A\ .\ \varepsilon_{rm}\ .\ \varepsilon_0} + \frac{d_{c2}}{A\ .\ \varepsilon_{rc}\ .\ \varepsilon_0} \tag{12}$$

$$C_{Total} = \frac{A\ .\ \varepsilon_0}{\frac{d_{c1} + d_{c2}}{\varepsilon_{rc}} + \frac{d_m}{\varepsilon_{rm}}} \tag{13}$$

Where:

- $C_{coating1}$ and $C_{coating2}$ are the capacitances due to the coating layers on each plate.
- d_{c1} and d_{c2} refer to the thickness of each coating layer.
- d_m is the actual thickness of the transfer medium (i.e., transfer distance minus the total thickness of coatings).
- ε_{rc} and ε_{rm} represent the relative permittivity of the coating and medium materials, respectively.

Equation (13) demonstrates that the total equivalent capacitance of parallel plates separated by a composite series-dielectric medium or coated with dielectric layers is less than the smallest individual capacitance connected in series. In typical CPT systems, this capacitance is usually dominated by the material filling the main transfer distance (i.e., the air in common CPT configurations). As a result, for large air gaps or transfer distances, the increase in capacitance is minimal when employing coating layers or hybrid transfer medium layers with a dominating air gap (Vincent & Williamson, 2020). However, the situation differs for small transfer distances, as the capacitance can increase significantly depending on the adopted material's relative permittivity. Therefore, this point has to be considered carefully for accurate design calculations.

Dielectric Coatings

Coating capacitive coupler plates with an insulating layer is an important aspect of the design and careful selection of coating material, strategy and thickness is required. The most important advantages of plate coating can be determined as follows:

- Electrical insulation, by protecting humans and animals from accidentally direct contact with energized plates.
- Galvanic isolation, by avoiding undesired ohmic contact between transmitter and receiver plates in the case of misalignment or foreign object intrusion, particularly in tiny air-gap systems (< 1 mm), as in rotary applications (Ge et al., 2014).
- Electric field confinement, by reducing electric field emissions around the plates.
- Flashover suppression, by distributing the field lines uniformly inside the insulating layer (Regensburger et al., 2018). However, because of high permittivity mismatch and TJEs, undesired results may be obtained if special attention is not paid to the design of the dielectric interface.
- Mechanical and environmental protection, by guarding the plates from corrosion, mechanical wear, contamination, moisture, and oxidation due to chemical reactions.

The actual usage of these benefits is relative to the correct selection of the coating material based on a number of factors, such as electrical properties (relative permittivity ε_r, dielectric strength, tan δ), mechanical durability, cost, weight, and environmental stability.

Dielectric Transfer Media

The use of solid dielectric materials as transfer medium in CPT systems significantly improves the coupling capacitance. This enhancement can be useful in increasing the power transfer density and system miniaturization, which is the case for small gap systems. Another advantage in the context of the safety aspect is the mitigation of fringing fields by having the electric fields confined more uniformly in the dielectric medium.

The beneficial use of solid media as opposed to air depends on several factors, including gap distance, operating frequency, type of application, and properties of the materials. Although theoretically possible, it is largely impractical to use a solid dielectric medium with a thickness of 150 mm - typical road clearance for most EVs. This is because the resulting disadvantages of inefficient power transfer caused by higher dielectric losses, increased cost, and bulky volumes can not be overcome by increased capacitance.

On the contrary, the usage of a solid medium is of high significance for small transfer distances, especially for low-power applications such as consumer electronics and wearable devices, in addition to high-power rotary machines (Behringer & Ludois, 2024). In some cases, such as in wireless charging pads or stands, non-contact wireless charging becomes impractical because of physical constraints and sensitivity to misalignment. In such cases, CPT contact charging is a more feasible method, in which the solid dielectric medium allows for efficient and stable power transfer. In this context some might wonder about the usefulness of wireless contact charging as opposed to wired charging, one of the main advantages is the elimination of direct ohmic contact problems between transmitter and receiver, leading to improved durability and reliability (Mishra et al., 2016).

The most common dielectric materials used in CPT systems can be classified into the three major types of dielectrics: polymers, ceramics and composite dielectrics. Each group has different properties to serve different application requirements such as flexibility, conformability, mechanical robustness, thermal stability, permittivity and loss tangent. Accordingly, this study evaluates a representative set of materials from these groups to be used as coating and transfer media in CPT systems.

Methodology

Simulation Framework and Model Setup

This study employs a simulation-based approach using finite element analysis (FEA) in ANSYS Maxwell 3D to evaluate the impact of dielectric materials as coatings and transfer media on the performance and safety of CPT systems. The main focus will be on the analysis of internal field behavior within CPT couplers, in addition to dielectric losses and coupling efficiency. The adaptive meshing strategy is used along with the AC conduction solution type. Accordingly, the convergence criteria are based on using identical analysis settings and percent error ratio of 0.1% across all simulation cases to ensure a fair comparison base.

Plate Geometries and Configurations

The parallel four-plate capacitive coupler structure described in section 2.2 has been used in this study with four aluminum plates as illustrated in figure 4(a). To isolate the geometric-based field enhancements (edge effects due to sharp edges and corners) from the dielectric-interface-related field enhancements, two main plate geometries were investigated:

- Square plates of side length L.
- Circular plates of diameter D equal to 1.1284 L (to provide equivalent area and capacitance).

The study's main focus is on the low-power small air gap applications plate scale for both coating and media simulations across varying transfer distance ranges. Furthermore, to evaluate the effect of coating materials and thicknesses in high-power scenarios, a scaled-up coupler targeting the large air gap applications with a fixed transfer distance value was used in the coating simulations. The plate scale details are as listed in Table 1.

Table 1. Simulated coupler plate scales

Parameter	Low-power scale (mm)	High-power scale (mm)
Plate side length (L)	100	610
Plate thickness (h)	1	1
Separation distance (d_{sep})	10	50
Transfer distance (d)	1-10 by 1 mm	120
Circular plate diameter (D)	113	688.4

Dielectric Materials and Configurations

Four major dielectric-materials-related simulation cases were conducted as described in the following sections. All coating and transfer medium materials were modeled as perfectly conformal with no porosity, voids, or bubbles in order to evaluate the intrinsic material behavior and avoid field enhancements caused by manufacturing defects. The used materials for both coatings and media are listed along with their electrical characteristics in Tables 2 and 3, respectively.

Table 2. Dielectric medium materials

Material	Dielectric constant (ε_r)	Dielectric strength (kV/mm)	Loss tangent (tan δ)
Air	1	3	≈ 0
PTFE	2.1	20–60	0.001
Silicone Rubber	3	20–30	0.003
Kapton (Polyimide)	3.5	100–300	0.008
FR4	4.4	18–40	0.02

Table 3. Dielectric coating materials

Material	Dielectric constant (ε_r)	Dielectric strength (kV/mm)	Loss tangent (tan δ)
PTFE	2.1	20–60	0.001
Parylene-C	2.95	220–275	0.013
Kapton (Polyimide)	3.5	100–300	0.008
Alumina	9.4	9–18	0.006
TiO_2	85	4–8	0.0005

Transfer Medium Study

The air gap between low-power scale uncoated plates is filled with dielectric materials (air (baseline), PTFE, silicone rubber, Kapton, and FR4) as listed in Table 2. The selection of dielectric materials is based on different permittivity, loss tangent, and dielectric strength to suit diverse CPT application requirements. Each medium was analyzed at:

- 1 MHz and 13.56 MHz operating frequencies to evaluate frequency-based dielectric losses at higher frequencies. The chosen frequencies belong to the standard ISM-band (industrial, scientific, and medical) frequencies that reflect common industrial CPT applications, enabling compatibility and minimizing EMI concerns.
- 1–10 mm transfer distances (material thickness).
- Square and circular geometries.

Coating Strategies Study

A comparative evaluation of the three below-listed coating strategies as illustrated in Figures 4(b – d) by using a representative high relative permittivity material (alumina with 100 µm thickness) is conducted to visualize the effect of triple junction effects at each coating method:

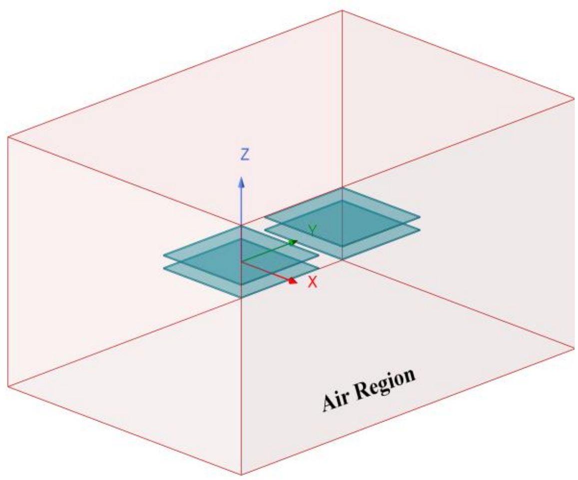
- Inner-face coating (only the inner gap-side face of each plate is coated).
- Inner-face rimmed-edge coating (inner face and edges are coated with a rim of 1 mm at the outer face).
- Fully coated (the plate is completely enveloped with coating material).

Simulations were done at a 1 MHz operating frequency for both square and circular plate geometries at low-power scale plates with an air transfer medium.

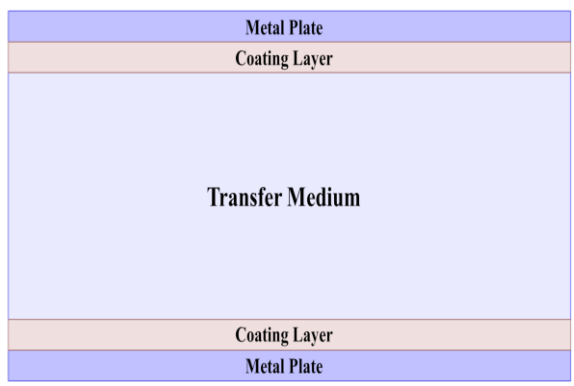
Coating Materials Study

An investigation was done on five dielectric coating materials (PTFE, Parylene-C, Kapton, Alumina, and Titanium Dioxide TiO_2), each applied as a full conformal coating with 100 µm thickness, with air as the transfer medium. Simulations were performed under 1 MHz frequency for both square and circular plates at low- and high-power application scenarios, with previously mentioned details. This study aims to evaluate how different dielectric materials combined with plate geometries affect the electric field enhancement and power transfer performance.

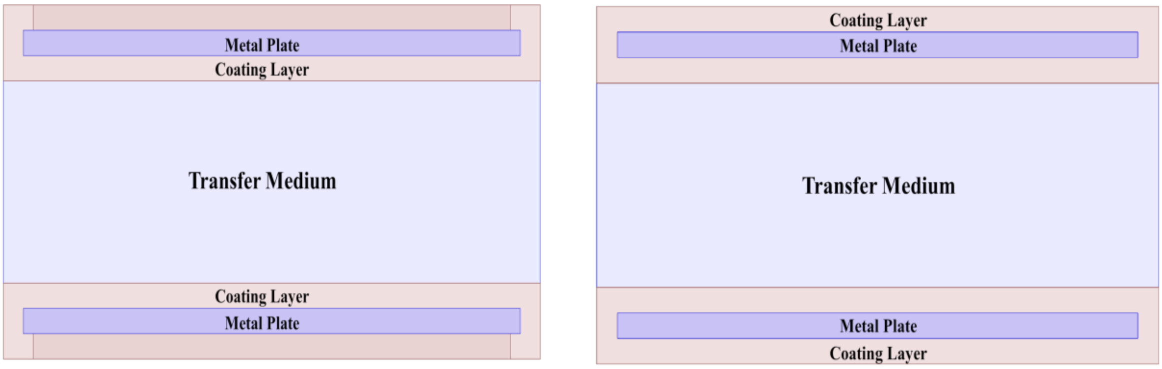
Coating Thickness Study



(a) Simulation setup



(b) Inner-face Coating



(c) Inner-face, rimmed-edge coating (c) Full-coating

Figure 4. Simulation setup and simulated coating strategies

To evaluate the effect of coating thickness on the electric field enhancement and power transfer efficiency, fully PTFE-coated plates with varying coating thicknesses from 50 µm to 250 µm in 50 µm increments were tested. The simulations were done at 1 MHz frequency for square and circular plates with the following details:

- Low-power case: at 5 mm air gap.
- High-power case: at 120 mm air gap.

Excitation Conditions and Extracted Parameters

A representative balanced excitation voltage of 500 V (low-power) and 5 kV (high-power) was applied between the transmitter and receiver sides of the low- and high-power scale plates, respectively. Accordingly, the ideal (average) electric field value (E_{ideal}) is calculated for each transfer distance using Eq. (6). A sufficiently large air solution region is used for all simulation cases to ensure the accuracy of captured electric field values.

The following parameters were extracted from each simulation setup:

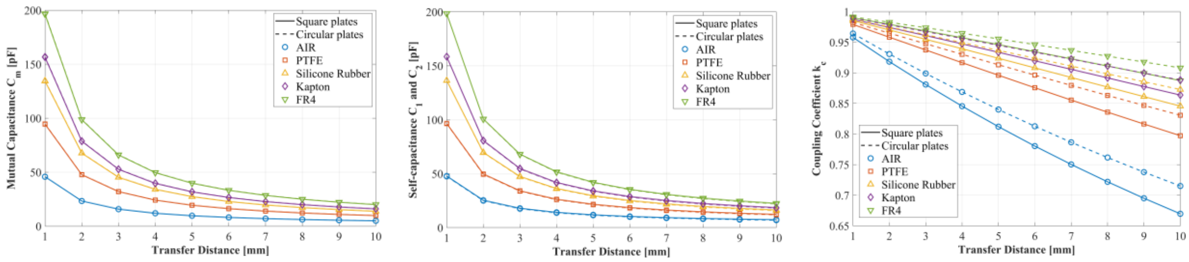
- Coupling parameters (C_m, C_1, C_2, k_c).
- Dielectric losses.
- Peak electric field (E_{peak}) within transfer media, coating layers, and surrounding air.
- Field enhancement factor (FEF).
- Breakdown safety margin.

Results and Discussion

Solid Transfer Media Effects

Coupling Efficiency Analysis

Figure 5(a-c) shows the variation of coupling parameters (C_m, C_1, C_2, k_c) as a function of transfer distance for different dielectric transfer medium materials for both square and circular plate geometries. Since the coupler is symmetrical in structure at the transmitter and receiver sides, the self-capacitances C_1 and C_2 are almost equal.



(a) Mutual capacitance C_m (b) Self-capacitances C_1 and C_2 (c) Coupling coefficient k_c

Figure 5. Coupling parameters variation with transfer distance for different medium materials

All coupling metrics for all materials exhibit the same trend by decreasing with increasing transfer distance. The dielectric medium selection dominates the values of C_m, C_1, and C_2 at small gaps, while at larger distances, the gap itself becomes the controlling parameter. This confirms that using a high-ε_r solid medium is advantageous mainly in the small-gap applications. The coupling coefficient, k_c, also follows a similar pattern by increasing proportionally to the ε_r of the dielectric medium. Materials with higher ε_r help preserve higher k_c even as the gap increases, in contrast to the capacitances, which degrade with increasing distance. Among the studied materials, FR4 and Kapton have the highest k_c values, making them particularly suitable for misalignment-tolerant applications.

The impact of the geometric shape on the coupling parameters is minimal since equivalent-area plates are used. However, the differences originate from the mitigated edge effects in circular plates, which enhance the coupling efficiency and electric field uniformity.

Dielectric Losses

Figure 6 illustrates the variation of dielectric losses for all studied dielectric materials against transfer distance at two operating frequencies: 1 MHz (solid line) and 13.56 MHz (dashed line). The losses are almost identical for both geometries, so only the square geometry's results are presented.

Consistent with theoretical expectations, dielectric losses decrease with increasing transfer distance over all frequencies and materials. Keeping the applied voltage constant while increasing the distance yields a weaker electric field, which reduces dissipated energy in the dielectric medium. Although the high permittivity of FR4 material provides the highest capacitance among the studied materials, it has a large loss tangent that makes it the most dissipative material at the same time. This becomes more pronounced at higher frequencies as the dielectric losses increase linearly with frequency; these observations align well with the theoretical expression of dielectric losses demonstrated in Eq. (14):

$$P_{loss} = \omega \, C \, V^2 \tan \delta \tag{14}$$

Where:

- P_{loss} (W) is the dissipated power in the dielectric material.
- $\omega = 2\pi f$ (rad/sec) is the angular frequency.
- C (F) is the mutual capacitance.
- V (v) is the applied voltage across the dielectric.
- $\tan \delta$ is the material's dielectric loss tangent.

Therefore, at higher operating frequencies, low loss tangent materials should be selected even at the expense of the permittivity.

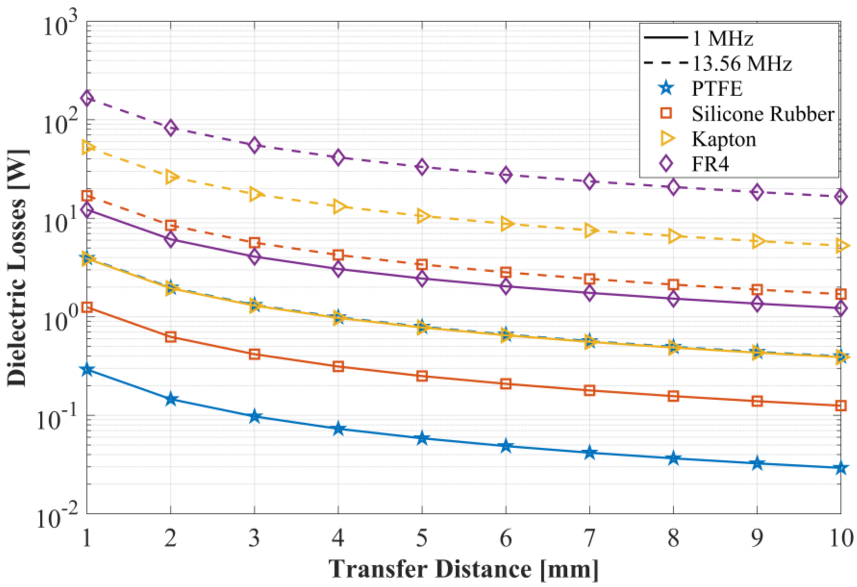
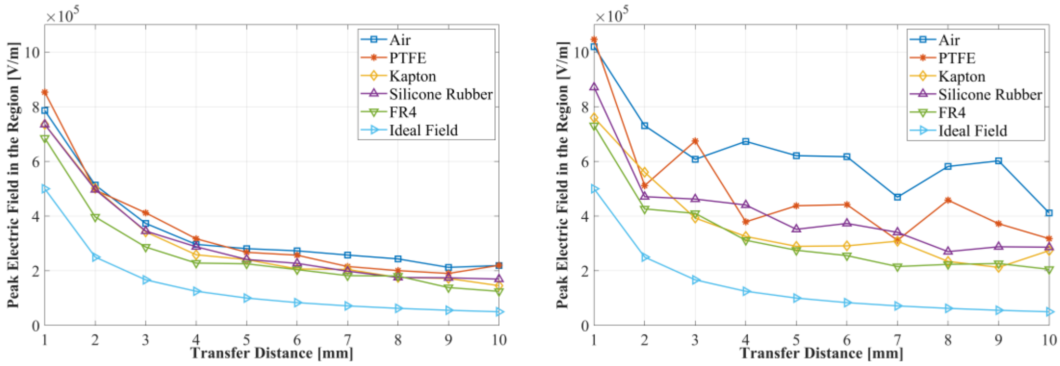


Figure 6. Dielectric medium losses vs. transfer distance for different materials and frequencies

Electric Field Analysis

Figures 7(a) and 7(b) show the peak electric field plots in the surrounding air region for circular and square plate geometries as a function of transfer distance for all tested medium materials. The ideal electric field, E_{ideal}, is calculated according to Eq. (6) across all transfer distances and plotted as a baseline reference. To facilitate the comparison, a consistent scale is applied to all plots. The examined parameter represents the localized electric field peaks in the air regions surrounding the plates. This field, originating from edge effects, triple junction effects, and permittivity mismatch, is not useful for power transfer. On the contrary, it creates partial discharge and premature breakdown risks. Therefore, the proper design objective is to keep this field as low as possible.

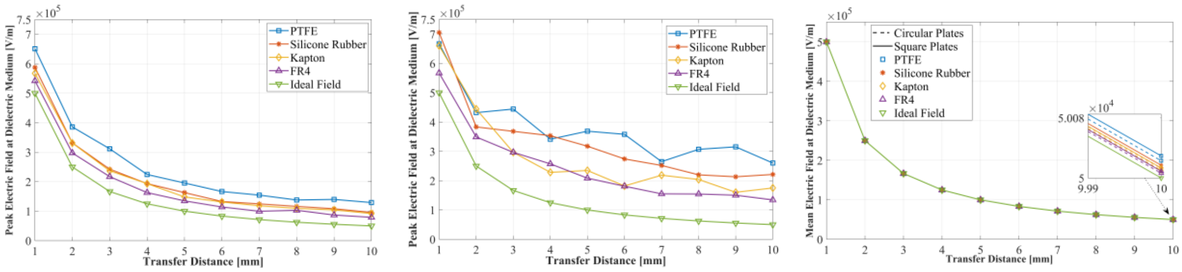
The comparison based on geometrical shapes shows that circular plates have the lowest localized peak field values compared to the square plates. The absence of sharp corners yields fewer field enhancement points, although they are still present, albeit to a reduced extent. In contrast, the square plate geometry exhibits the highest localized peak fields due to sharp edges and corners. Moreover, the peak field reduction rate with the increasing distance is slower than in the circular plates case. At the dielectric material level, this parameter is inversely proportional to the material's relative permittivity. The stored energy within the dielectric medium increases proportionally to capacitance; hence, the fringing outside the medium decreases.



(a) Circular plates (b) Square plates

Figure 7. Peak electric field in the surrounding air region for different transfer medium materials

Figures 8(a) and 8(b) illustrate the peak electric field within solid dielectric media versus transfer medium for circular and square geometries. The same analysis determined above applies here as well. In addition, the effect of the dielectric interface phenomena is less pronounced in the case of solid media employment, since the junction area is quite large, which makes the enhancement weaker. As a result, adopting high-permittivity materials is an efficient design approach to mitigate fringing fields. Figure 8(c) shows the mean field value within the dielectric media, which matches the ideal field plot. The tiny deviation (the highest for PTFE and the lowest for FR4) shown in the zoomed-in view is mainly due to the effects of fringing fields.

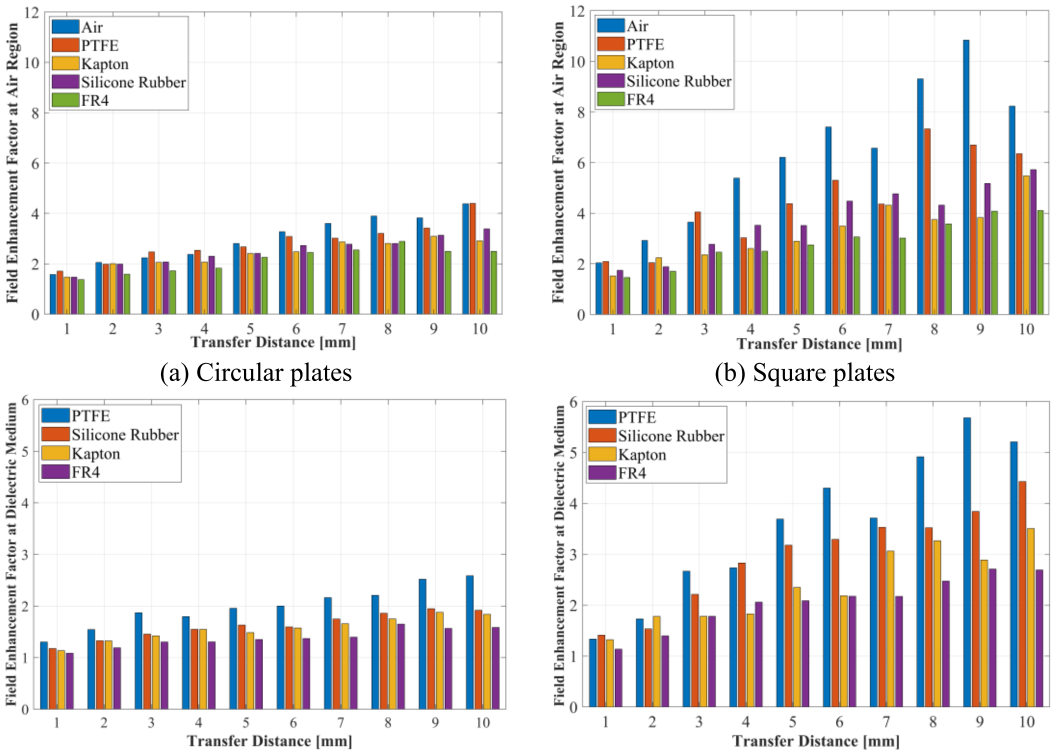


(a) Circular plates (b) Square plates (c) Mean electric field

Figure 8. Peak and mean electric field in the solid dielectric medium for different materials

Field Enhancement Factor

To better visualize the field enhancement effect at each geometry and material case, the field enhancement factor, FEF, is computed at the surrounding air region and solid dielectric media, as shown in Figures 9(a-d). This parameter in the air region is almost twice its value in the dielectric medium. The air medium with the square geometry presents the worst enhancement case. Meanwhile, the FR4 outperforms other materials in both geometries.



(a) Circular plates (b) Square plates

(c) Circular plates (d) Square plates

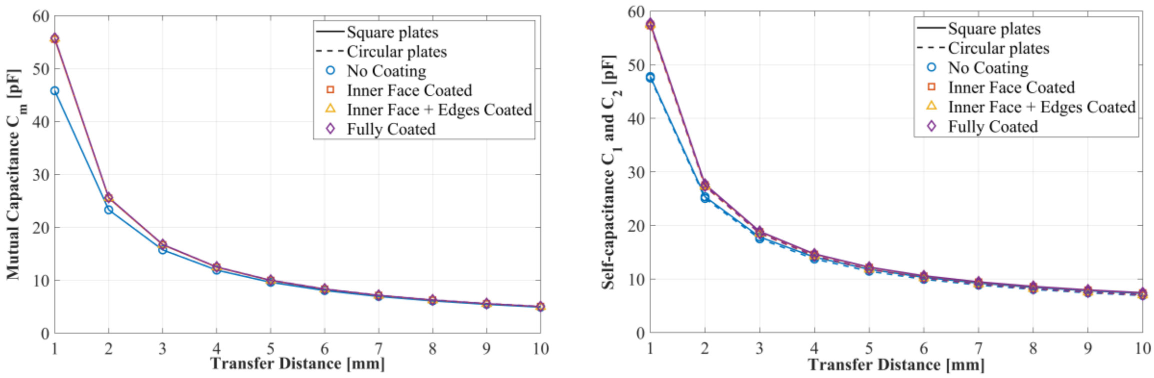
Figure 9. Field enhancement factor at (a-b) surrounding air region and (c-d) transfer media

To avoid underestimating the utilization of solid dielectric media, the safety margin parameter computation is not included in this section. This parameter depends on the lowest dielectric strength material incorporated in the coupler design, which may be air or any other material sealing the coupler.

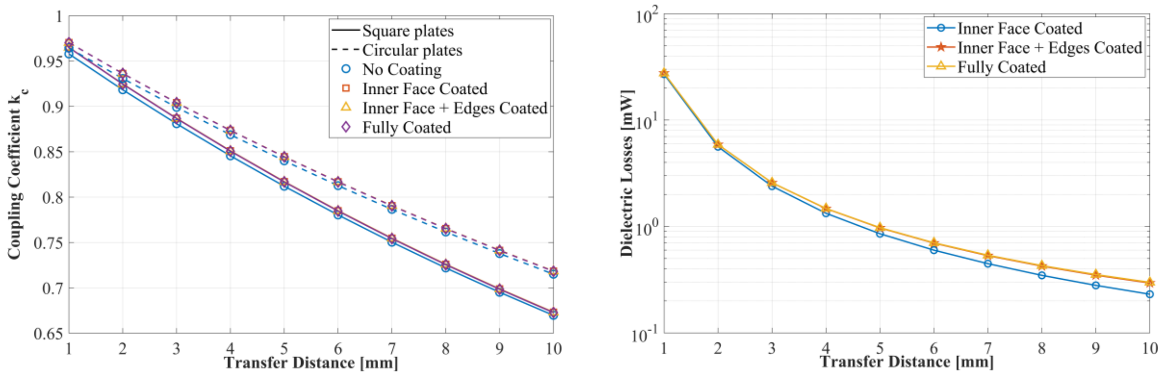
Coating Strategies Comparison

Coupling Efficiency and Dielectric Losses Analysis

The effect of simulated coating strategies on the coupling parameters and the dielectric losses is shown in Figures 10(a-d). As observed from plots, the differences in these parameters are minimal for all strategies. Therefore, the evaluation will be based on the safety perspective as in the following sections.



(a) C_m (b) C_1 and C_2

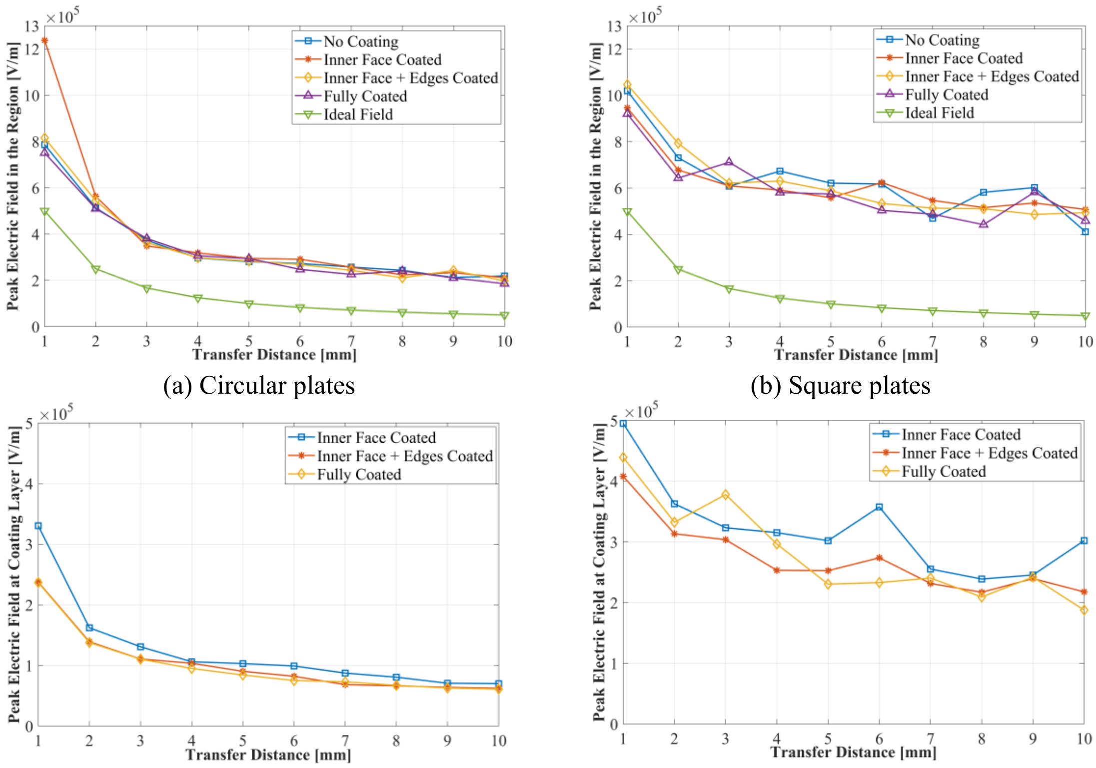


(c) k_c (d) dielectric losses

Figure 10. Coupling parameters and dielectric losses for simulated coating strategies

Electric Field Analysis

The peak electric field in the air medium and region, as well as in the dielectric coating layers, is illustrated in Figures 11(a-c) for both geometries. The full coating strategy offers lower field concentrations, among other strategies. The following section will focus on the field enhancement causes for each case.



(a) Circular plates (b) Square plates

(c) Circular plates (d) Square plates

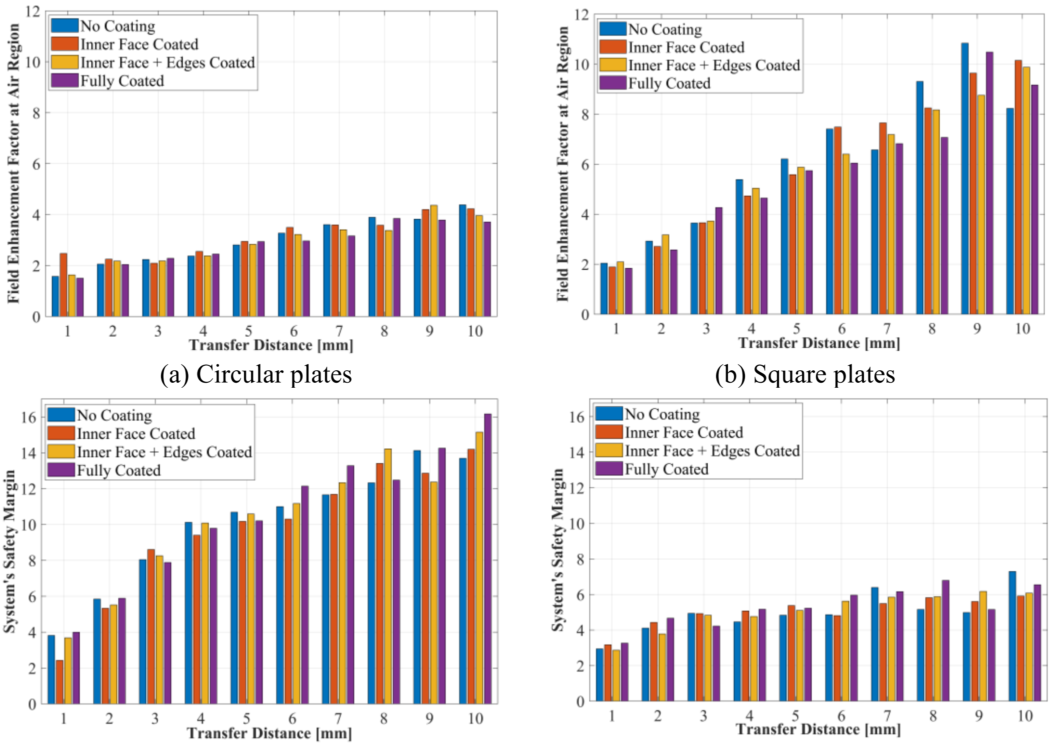
Figure 11. Peak electric field at (a–b) surrounding air region and (c–d) coating layers, for simulated coating strategies

Field Enhancement Factor and Safety Margin

The FEF is computed and plotted for the tested coating methods, as shown in Figures 12(a) and 12(b). Meanwhile, the breakdown safety margin is evaluated and illustrated in Figures 12(c) and 12(d). The fully coated method provides the lowest FEF and, consequently, the highest safety margin. In comparison, the single-face and single-face rimmed-edges coated plates have a higher FEF and lower safety margins due to the presence of triple junction effects, which are eliminated by the full coating method. However, perfect manufacturing quality is required to avoid coating imperfections that cause hazardous internal triple junction points. As a moderate field mitigation strategy, the inner face rimmed-edges coating method shifts the triple junction points away from the critical sharp corners and edges toward the plate's outer surface. Table 4 briefly compares the field enhancement factors for each coating method.

Table 4. FEF-based comparison of simulated coating strategies

Material	Field enhancement causes	FEF
No coating	Fringing fields	High (no insulation)
Inner face only	Fringing fields, permittivity mismatch, critical TJEs	Highest
Inner face and edges rimmed	Fringing fields, permittivity mismatch, moderate TJEs	Moderate (depends on the rim width)
Fully coated	Fringing fields, permittivity mismatch	Lowest



(a) Circular plates (b) Square plates

(c) Circular plates (d) Square plates

Figure 12. (a–b) FEF and (c–d) breakdown safety margin for simulated coating strategies

Coating Material Effects

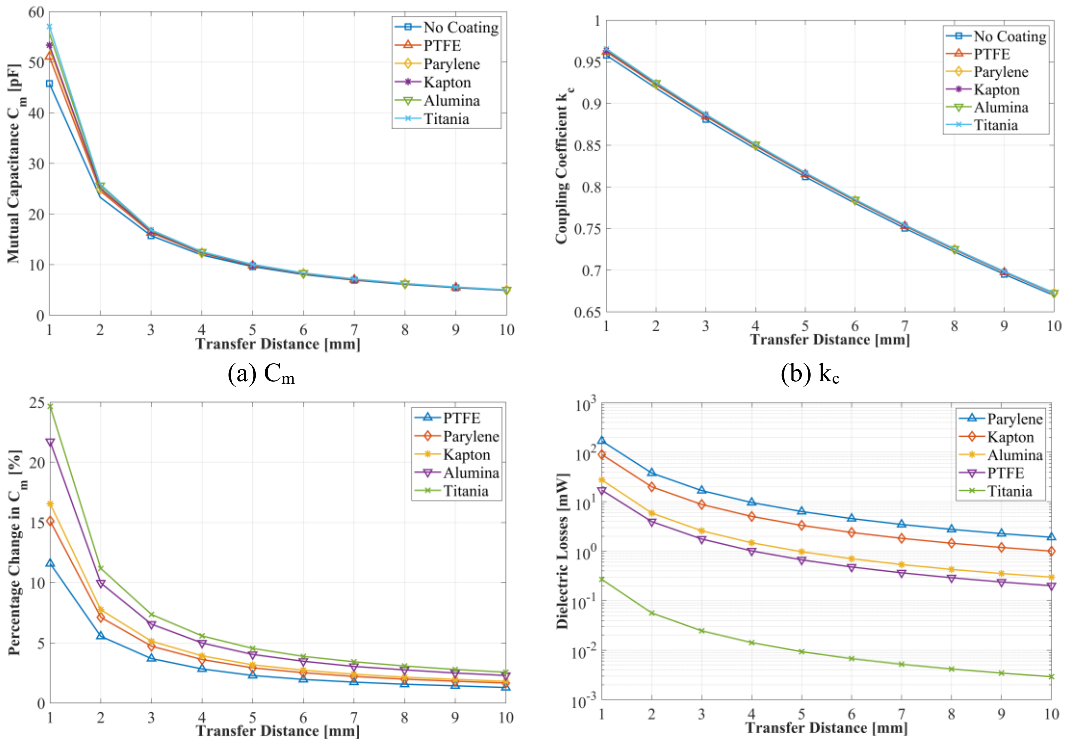
Low-Power Plate Scale

Coupling Efficiency and Dielectric Losses Analysis

Based on the findings from the previous section, the fully coated method, using different materials as listed in Table 3, is applied to the two scales of plates to enable comparison between the materials. For the low-power application scale, Figures 13(a) and 13(b) outline the variation of the coupling parameters C_m and k_c as a function of transfer distance for the tested coating materials. The variation in C_m is significant and proportional to the material's permittivity at smaller distances but diminishes as the gap increases. To reflect this trend, Figure 13(c) captures the change ratio in C_m relative to the uncoated case. The same analysis applies to self-capacitance variations, which are not included to avoid crowding. In contrast, the variation in k_c remains minimal for the simulated materials. Nevertheless, a precise design should account for any changes in the coupling parameters to avoid resonance detuning. The dielectric losses at 1 MHz frequency are shown in Figure 13(d). Although the losses are small due to the employed thin coating layer (i.e., 100 µm), they can change due to the affecting parameters defined in Eq. (14).

Electric Field Analysis

Figures 14(a) and 14(b) present the peak electric field in the surrounding air region when using different coating materials. Despite having relatively different peak field values, the plots for both geometries consistently highlight titania (TiO_2) as the highest localized field enhancement-inducing material, followed by the uncoated case and alumina. Conversely, PTFE exhibits the lowest localized peak field values among observed materials. These findings align well with the theoretical knowledge stating that the severity of permittivity mismatch increases in proportion to the insulating material's relative permittivity.



(a) C_m (b) k_c

(c) C_m change ratio (d) dielectric losses

Figure 13. Coupling parameters and dielectric losses for different coating materials

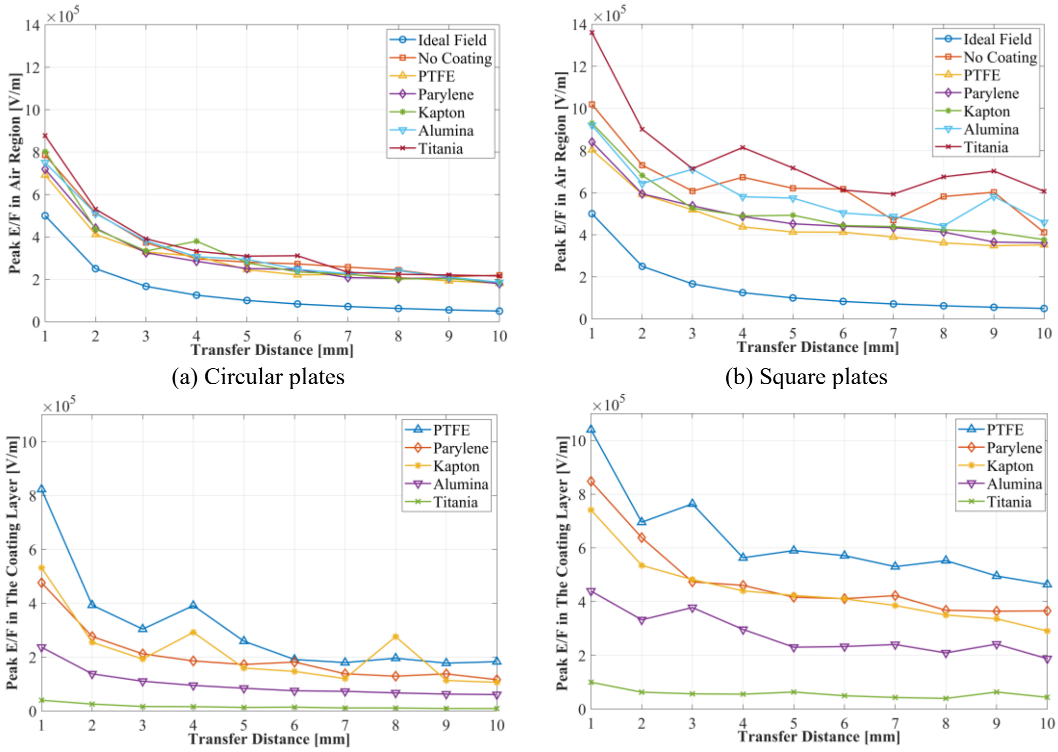
In contrast to the surrounding air region, the peak electric field within the coating layer demonstrates an opposite ranking trend across the studied materials. This opposition, caused by the discontinuity in the electric field at the dielectric–air interface as previously defined by Eq. (8), is highlighted in Figures 14(c) and 14(d) for the circular and square plate geometries.

Field Enhancement Factor and Safety Margin

To enable direct comparison across different coating materials and to assess each material's contribution to the localized field intensification, Figures 15(a) and 15(b) present the FEF in the surrounding air region versus the transfer distance. The FEF for all materials increases with increasing distance, moderately in the circular geometry and sharply in the square one. This enhancement is proportional to the relative permittivity of each material, as discussed in the previous section.

Figures 15(c) and 15(d) illustrate the system's breakdown safety margin across all materials as a function of the transfer distance. Owing to its lower FEF, the circular plate geometry offers a significantly increasing safety margin for all materials in proportion to the distance. Conversely to the square geometry, which presents a moderate increment in the safety margin across the same materials.

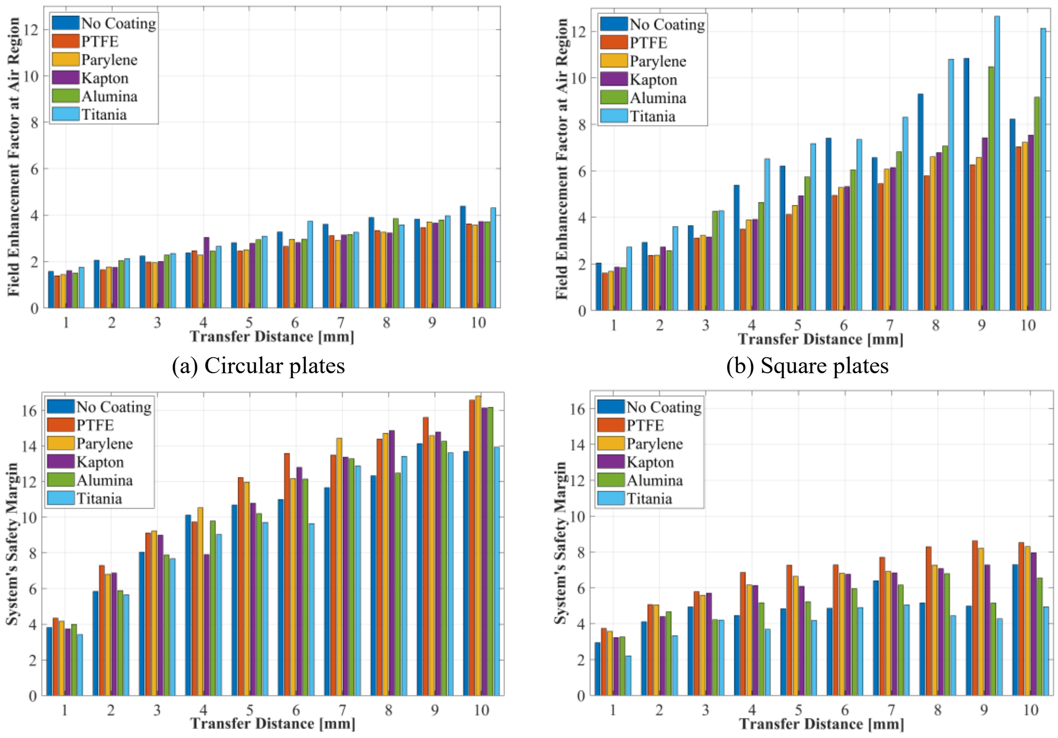
Compared at the material level, the critical safety margin values belong to Titania (i.e., equal 2.2 for square and 3.4 for circular plates at 1 mm air gap) at a relatively low applied plate voltage (i.e., 500 V_{peak}). The breakdown voltage of the dry air equals 3 kV/mm, while this threshold can be reduced under certain environmental conditions to lower levels. Given that the misalignment cases alter and elevate the peak field between and around the plates. Therefore, a minimum safety margin of 3 is necessary to prevent the initiation of partial discharges and premature breakdowns.



(a) Circular plates (b) Square plates

(c) Circular plates (d) Square plates

Figure 14. Peak electric field in (a–b) air region and (c–d) coating layers, for different coating materials



(a) Circular plates (b) Square plates

(c) Circular plates (d) Square plates

Figure 15. (a–b) FEF and (c–d) breakdown safety margin for simulated coating materials

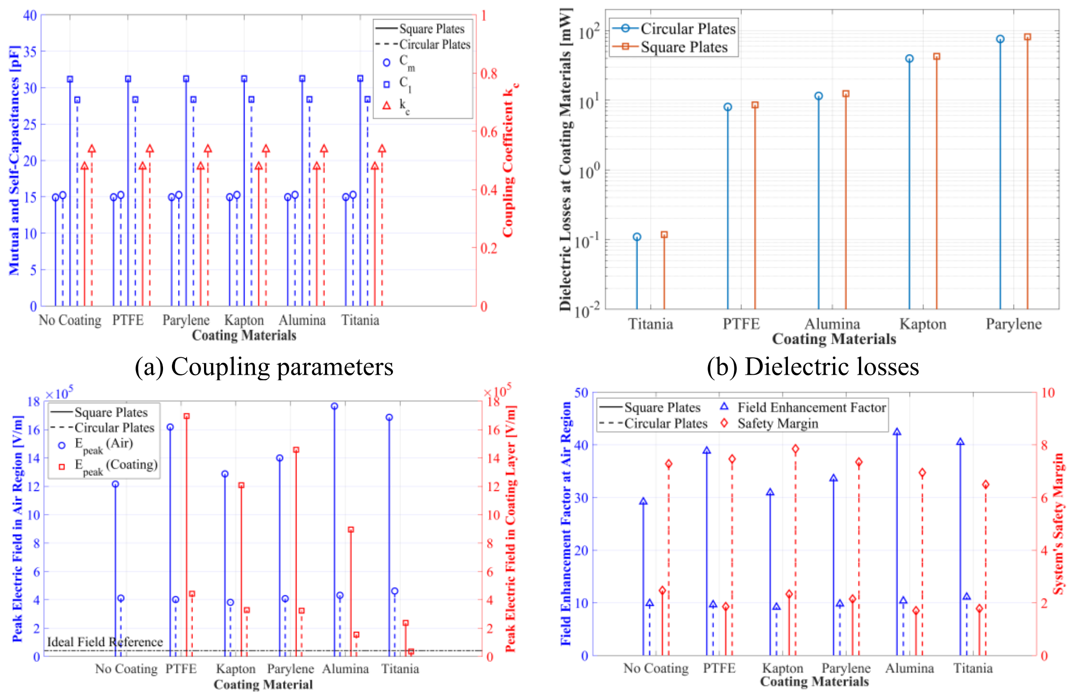
Scaled-up High-Power System Representation Analysis

For the high-power case study, representative of EV charging coupler scale, a transfer distance of 120 mm and 5 kV applied plate voltages are considered. The coupling parameters of each coating material are shown in Figure

16(a). It is found that these parameters are nearly the same for all materials, which indicates that the effect of coating on the capacitance becomes negligible at large air gaps. However, the increasing self-capacitance values for the square plate coupler are more pronounced than for the circular plate one and this is because of more pronounced fringing fields. This increment in C_1 and C_2 affects the coupling coefficient for the square plates, according to Eq. (5), to be smaller than that of circular plates.

Figure 16(b) shows the dielectric losses for each material, highlighting a relatively low dissipated power due to the large air gap despite the applied high voltages. Figure 16(c) shows the peak electric field in surrounding air regions and in the coating layer for all materials. The results are of the same nature as in the low power scale case but with much more localized peak fields compared to the ideal field, as a consequence of stronger fringing fields at large separations. The field enhancement factor and breakdown safety margins of all materials are indicated in Figure 16(d). Results show a significant field enhancement especially at the square plate geometry. This large field amplification shows how the geometry worsens the permittivity mismatch. In contrast, in the circular plate geometry, the FEF because of permittivity mismatch is moderate for the same system configuration.

Consequently, the breakdown safety margin is reduced to critical levels at the square plate geometry. These values indicate that all studied configurations operate near the critical air breakdown threshold, despite applying relatively moderate plate voltages (i.e., 5 kV). However, the circular plates exhibit improved FEF and safety margins across all materials, thereby increasing robustness, but at a cost of increased spatial requirements.



(a) Coupling parameters (b) Dielectric losses

(c) Peak electric field (d) FEF and safety margin

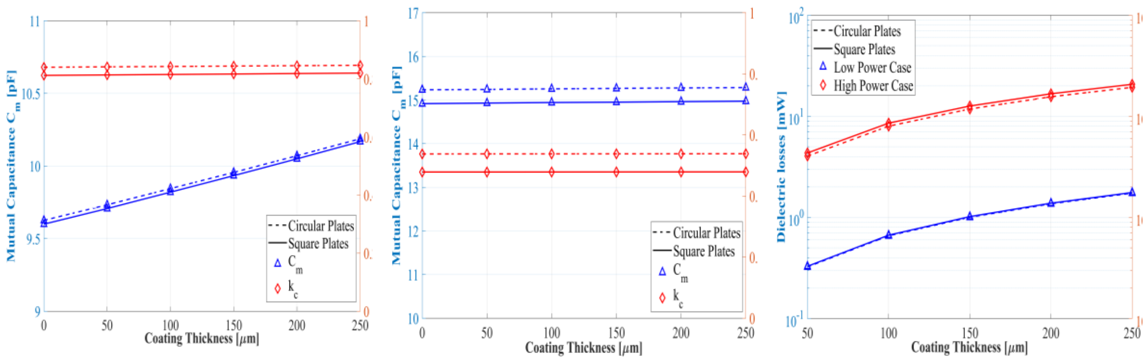
Figure 16. Scaled-up high-power system simulation results for different coating materials

Coating Thickness Effect

Coupling Efficiency and Dielectric Losses Analysis

To observe the effect of coating layer thickness on the performance and safety metrics, PTFE-coated plates with varying coating thicknesses from 50 to 250 µm are simulated. Figures 17(a-c) show the effect of increasing coating thickness on the coupling parameters and dielectric losses for low- and high-power coupler designs. In the low power case, the coupling coefficient is almost constant, and the mutual capacitance shows a small proportional relationship with the increased coating thickness. By contrast, at the high-power scale, all coupling parameters are essentially constant across the varying coating thickness range, indicating the prevalence of the large air gap over the varying thickness. Meanwhile, the dielectric losses of both scales are increasing with the thickness, and the effect is more remarkable in the high-power case because of higher applied voltages.

These results show that varying coating thickness has a limited effect on coupling parameters but noticeably affects dielectric losses. Therefore, the safety-based assessment is important in selecting the suitable coating thickness.

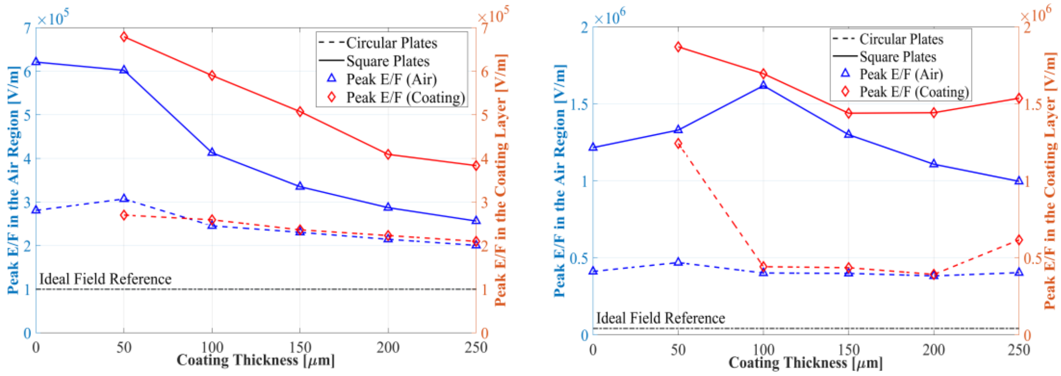


(a) Low-power system (b) High-power system (c) Dielectric losses

Figure 17. Coupling parameters and dielectric losses vs. coating thickness

Electric Field Analysis

Figures 18(a) and 18(b) illustrate the effect of coating thickness variation on the peak electric field in the surrounding air medium and the coating layer for both plate geometries and power levels. For the low-power case, the peak electric field in both the air region and the coating layer reduces with increasing coating thickness. The reduction in peak electric field is moderate in the circular plate geometry but is most significant in the square plate geometry. This indicates that thicker coatings effectively suppress the fringing fields, which are substantial in the square geometry, in both the coating and the medium. For the high-power scale, the same analysis applies but with a less uniform electric field behavior, particularly in the coating layer, due to the strong fringing fields at larger air gaps.

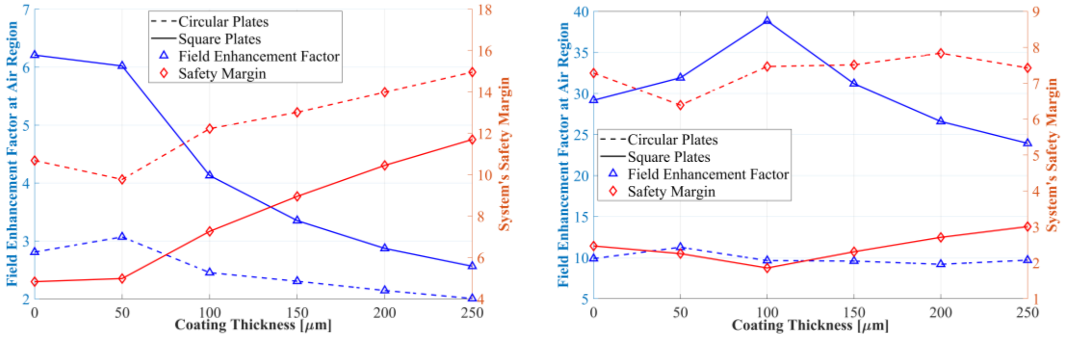


(a) Low-power system (b) High-power system

Figure 18. Peak electric field vs. coating thickness

Field Enhancement Factor and Safety Margin

Figures 19(a) and 19(b) show the effect of the variation of coating thickness on the field enhancement factor and the breakdown safety margin of two power-level simulations. In the low-power scale, the FEF is decreasing with increasing coating thickness for both geometries; At the same time the breakdown safety margin is increasing in relation to the increasing coating thickness, specifically in square plate geometry. The high-power scale's response to the coating thickness variation is similar but more moderate. This has been experimentally confirmed by Regensburger et al. (2018), in which PTFE having a thickness of 254 µm was applied on the square and circular plates and the transferred power density improved effectively. These results show the importance of proper coating thickness selection, especially in sharp edged geometries. However, there are a number of factors influence the selection, including: electrical and mechanical characteristics of the coating material, manufacturing complexity and cost.



(a) Low-power system (b) High-power system

Figure 19. FEF and breakdown safety margin vs. coating thickness

Key Findings and Recommendations

The detailed investigations done in this study highlight important considerations and give further insight regarding the effects and results of using dielectric materials in CPT systems in various roles and configurations:

- *Plate Geometry Selection:*

The circular plate geometry was found to perform relatively better than the square plate geometry in all simulated study cases by showing relatively suppressed edge effects and slightly higher coupling efficiency. Nevertheless, this performance improvement comes with a penalty of needing a larger spatial footprint to obtain the same capacitance. The following design factors should be taken into consideration in determining the trade-off between the two geometries. If circular plates with a diameter equal to the side length of a square plate are used, then they will result in a reduction in the value of the capacitance by 21.5% due to the inherent reduction of the area (π/4). However, this decrease in capacitance can be adequately compensated for by a slight increase in plate voltages.

Since the transferred power by the CPT system is proportional to the square of voltage, to compensate for the 21.5% loss in capacitance, a factor of 13% increase in voltage must be provided to give the same power. In regard to the advantage of lesser edge effects, less field enhancement factors, and larger breakdown safety margins of circular plates, such an increase in voltage can be extended safely. However, the applied voltage is not only restricted by the dielectric breakdown voltage, but also by the permissible electric field emission around the coupler, which is determined in international standards, such as IEEE C95.1 (2019). Thus, these trade-off parameters should be taken into account when choosing the plate geometry.

- *Dielectric Material Selection:*

The properties of dielectric materials have a great influence on the performance and safety of CPT systems. Therefore, correct material selection is important and is based on trade-offs between different material characteristics such as relative permittivity, loss tangent, dielectric strength, thermal stability, mechanical strength, environmental durability, weight, and cost. The most important ones are the relative permittivity and loss tangent.

While relative permittivity is usually related to capacitance enhancement in the CPT literature, in this study we point out its direct role in the safety of CPT systems. The use of high permittivity materials as a transfer medium improves the safety and performance of the system to a great extent. In contrast to this, high-permittivity coatings typically do not have this advantage as electric field enhancements due to permittivity mismatch can be very severe. In particular, if combined with sharp-edged geometries, the breakdown safety margin will be significantly lowered. Hence, if the design requires the use of a material, which will create a high permittivity mismatch, then proper field management tools and strategies should be considered. In addition, the trade-off between dielectric material loss tangent and operating frequency is also important.

- *Coating Strategy and Thickness:*

Three coating methods are modelled and compared. While they do not affect coupling parameters and dielectric losses very much, they affect system safety by adding or removing the dielectric interface phenomena (i.e., TJE). The inner-face coating strategy is introducing TJEs and must be avoided for safe system designs, especially in the case of sharp-edged plates. The rimmed-edges coating method moves the triple junction points from the critical edges to the outside face of the plate and offers moderate field control as a function of the width of the rim. In contrast, full-coating strategy completely removes TJEs if perfectly manufactured and it protects the plates from environmental effects. However, the manufacturing complexity and costs need to be taken into account during design trade-off considerations.

Similarly, although the coating thickness marginally impacts the coupling parameters, it noticeably impacts the system safety, particularly at sharp-edged plate geometries and small air gap systems. The optimal thickness selection depends on the coating material properties and should balance electrical insulation, mechanical durability, and manufacturing costs.

- *Breakdown Safety Margin Limit:*

The safe systems design should account for different dielectric breakdown-causing factors, including environmental conditions that lower dielectric breakdown voltage threshold and field enhancement factors that increase localized peak electric field, such as geometric effects, fringing fields, dielectric interface phenomena, and misalignment scenarios. Therefore, an adequate breakdown safety margin should be selected as a first system design step. Moreover, the breakdown safety margin should be computed based on the lowest dielectric-strength material incorporated in the coupler design, as well as the localized peak electric field instead of the mean or ideal electric field.

Conclusion

In this study, FEM modeling was used extensively to test the effects of dielectric media (both as transfer media and surface coating) on the performance and safety of CPT systems. The results show the impacts of dielectric materials, coating methods and thicknesses, operating frequencies and plate geometries on the electric field distribution, the breakdown safety margins, the dielectric losses and the coupling efficiency for both low- and high-power applications. The findings show that successful implementation of CPT systems in practical applications not only relies on obtaining higher capacitances but also on reduction of the localized high electric field concentrations which are of considerable safety concern.

Whereas high relative permittivity is usually linked together with high coupling efficiency in CPT literature, here it is highlighted for its crucial impact on system safety. High-permittivity materials are used as a medium in small-gap applications where performance and safety are improved, but dielectric breakdown risks might be increased if used as a coating, especially on sharp edged geometries. On the other hand, the moderate-permittivity materials, such as PTFE, Kapton, and Parylene-C, show great promise as coatings in reducing edge effects. Therefore, the choice of plate geometry must be dependent on the dielectric materials that are used in the system design, either as a media or as a coating. Circular plate geometry gives minimal field enhancement factors and maximum breakdown safety margins, thus offering more favorable edge effects mitigation and localized field enhancement reduction. On the other hand, the square and sharp-edged geometries exhibit the highest FEFs and lowest breakdown safety margins for all considered dielectric structures relative to the circular plates, but with a benefit of good spatial utilization.

Coating strategies, as well, have an impact on safety through introducing triple junction effects at the interface between conductor, coating and air. Applying partial coatings will create severe mismatches in the permittivity and local field intensification at sharp edge contact points. So depending upon application requirements the entire plate or at least one face and edges coating is recommended. Additionally, the coating thickness can be increased to decrease peak electric fields, but with an increase of additional dielectric losses. Therefore, it is important during the design process to optimize coating thickness according to trade-off between safety and performance. Overall, the conducted simulation study offers useful design guidelines for understanding and avoiding dielectric breakdown in CPT systems and can be applicable beyond the specific materials studied here.

Future work can include circuit level efficiency analysis with optimized dielectric structures, design of field grading methods that are dependent on the plate geometry and coating material, use of advanced dielectric materials, and experimental testing of the design guidelines.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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