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Effect of Electrode Protrusions on Properties of Polyethylene as a Dielectric for Capacitors

Parimal Sharma*, **C. Iyyappan and C. C. Reddy**

Indian Institute of Technology Ropar, Rupnagar - 140001, Punjab, India; parimal.22eez0001@iitrpr.ac.in

Abstract

The electric field distribution within capacitors and cables is predominantly influenced by the geometrical profile of the electrodes. It is important to consider the presence of protrusions on the electrode surface, as they can significantly impact the electric field intensity. These protrusions can intensify the electric field, potentially leading to premature breakdown of the dielectric material. Hence, the presence of protrusions on the surface of electrodes in high-voltage capacitors holds immense significance and should be carefully considered in the design and manufacturing processes. In this paper, a capacitor model with protrusions is simulated in FEM-based COMSOL Multiphysics software. Electric field distribution is obtained and the effect of protrusion geometry on peak electric field is analyzed.

Keywords: Capacitor, Electric Field, Protrusion

1. Introduction

Many industries, including High-Voltage (HV) pulsed power applications and High-Voltage Direct Current (HVDC) transmission systems, have been substantially upgraded by the use of capacitors. In these applications, capacitors are vital components that allow for the storage of electrical energy. Also, due to increasingly high power handling requirements, there has been a need for high energy density capacitors[1,2]. Over the years developments in capacitor technology have resulted in metalized polymeric films, particularly polypropylene films with enhanced material designs and properties like high dielectric strength, low dielectric losses, property of self-healing, and increased our knowledge on the effects of electrode surface on performance. Bi-axially Oriented Polypropylene (BOPP) film is currently the insulator of choice because of its remarkable physical characteristics[3]. BOPP is made by stretching highly isotactic polypropylene in both the transverse and processing assembly directions. This results in a highly crystalline structure with lesser conductivity than regular polypropylene. BOPP also improves thermal conductivity and dielectric strength.

The aging and failure mechanism observed in polypropylene films is believed to be electro-thermal in nature. Similar to cable insulation materials like Low-Density Polyethylene (LDPE), the conductivity in Bi-Axially Oriented Polypropylene (BOPP) exhibits a non-linear behavior dependent on both temperature and electric field[4]. The non-linearity of conductivity results in an interdependence between the electric field and temperature distribution within the insulation. Even a small increment in either parameter at a critical voltage can trigger an electro-thermal runaway, ultimately leading to a breakdown.

Practical dielectrics invariably have non-uniformities, which might be due to internal flaws such as impurities, metallic particles, or voids leading to because of processes like partial discharge and electrical treeing. Consequently, localized breakdowns due to such impurities lead to instability and result in the breakdown of BOPP insulation, as reported[5-7].

As a result, despite the structural differences between cable insulation (polyethylene) and capacitor insulation (BOPP), they share a lot in terms of their breakdown mechanisms and dielectric qualities. As a result, there is a correlation between the two results.

**Author for correspondence*

In this paper, the author investigates the effect of electrode protrusions on the electric field distribution in the dielectric. A COMSOL model was prepared to see the variation in the electric field due to different radii of curvature of electrode protrusions. The various results are then presented followed by discussion and inferences. These results are considered to be useful for capacitor manufacturers during the designing phase.

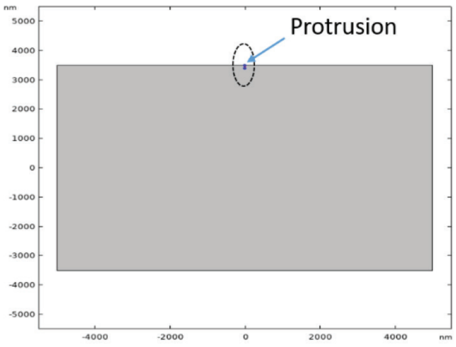
2. Simulation Model and Governing Equations

2.1 Simulation Model

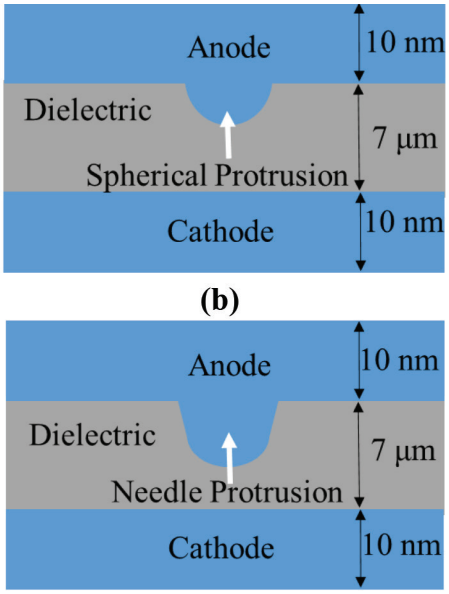
Thin film BOPP capacitors typically feature a dielectric film thickness of approximately 7 µm, while the electrode thickness is typically around 10 nm[8]. Figure 1(a) showcases a FEM COMSOL model of a capacitor with a plane-plane geometry, meticulously designed to accommodate an electrode protrusion. This model accurately considers the dimensions and voltage rating associated with thin film capacitors.

Figures 1(b) and 1(c) showcase the two types of protrusion configurations that were investigated to analyze the maximum electric field intensity at the tip. The thickness of electrodes is 10 nm which is very small compared to the thickness of dielectric film (approximately 7 µm) but for showing the protrusion, the metal parts are enlarged, and a model is shown in Figures 1(b) and 1(c).

Based on the geometry of a thin film capacitor and utilizing polyethylene (LDPE) as the dielectric material, an electric potential of 600V is applied. The permittivity of LDPE is considered to be 2.3 in this scenario. This setup allows for the evaluation and analysis of the capacitor's electrical characteristics and performance under these specific conditions.



(a)



(c)

Figure 1. Schematic figure used in simulation model **(a)** FEM model, **(b)** spherical protrusion **(c)** needle type protrusion.

2.2 Governing Equation

In order to obtain electric field distribution, Poisson's equation is solved for all regions.

$$\nabla . D = \rho_v \tag{1}$$

Assuming that the internal space charge is zero, the above equation reduces to

$$\nabla^2 V = 0 \tag{2}$$

current continuity equation for steady-state

$$\nabla . J = 0 \tag{3}$$

Where J is the current density.

The current density that relates conductivity and electric field (neglecting diffusion) is given by,

$$J = \sigma E \tag{5}$$

For needle-plane geometry, according to Mason's equation, the maximum field stress at the tip of protrusion is[9]

$$E_{tip} = \frac{2V}{r\ln\left(1+\frac{4d}{r}\right)} \tag{6}$$

The boundary condition used in this simulation is Dirichlet boundary condition.

3. Results and Discussion

This section showcases the outcomes derived from examining various geometrical configurations to estimate the electric field at the tip of a protrusion. Specifically, Section 3.1 focuses on the impact of the tip radius of a spherical protrusion, while Section 3.2 delves into the effect of the tip radius of a needle-shaped protrusion on the intensity of the electric field.

3.1 Spherical Protrusion

In the case of a tip radius of 1 nm, the maximum electric field intensity at the tip of the protrusion was measured to be 173.490 kV/mm. This value is approximately twice the intensity observed at the bulk of the material, as depicted in Figures 2(a) and 2(b). Figure 2(b) specifically presents a surface plot visualization of a spherical protrusion, providing a clearer representation of the electric field distribution and its intensified nature at the protrusion's tip.

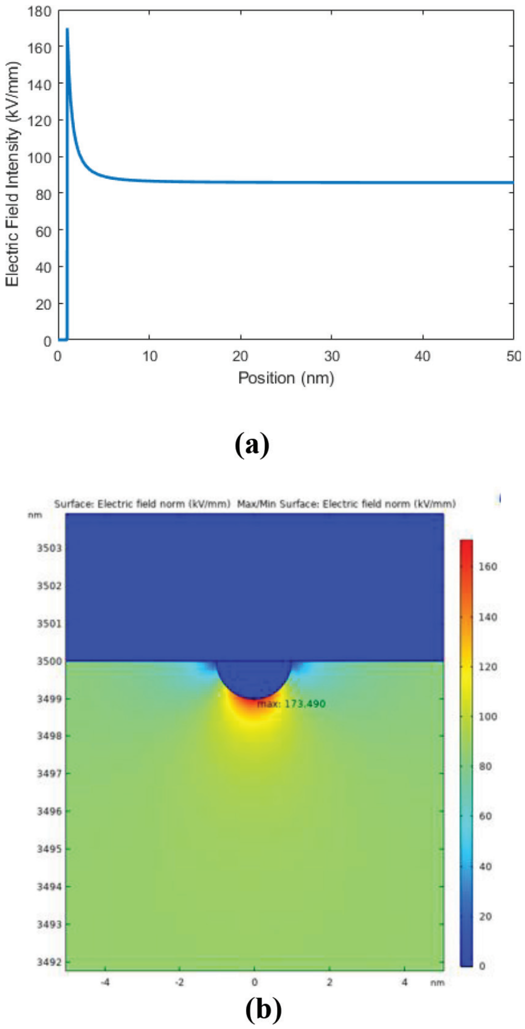


Figure 2. **(a)** Electric field distribution line graph. **(b)** surface plot of electric field distribution for spherical protrusion.

The maximum electric field at the tip of spherical protrusion for tip radii of 1 nm, 5 nm,10 nm,15 nm is shown in Figure 3. It can be observed that as the radius of curvature of a spherical protrusion decrease, the maximum electric field at the tip of the protrusion increases exponentially. This phenomenon indicates that smaller radii of curvature lead to significantly intensified electric fields at the tip of the protrusion[9], which can also be validated from Equation (6). This exponential increase highlights the critical role that the radius of curvature plays in determining the electric field distribution and intensity within the capacitor system.

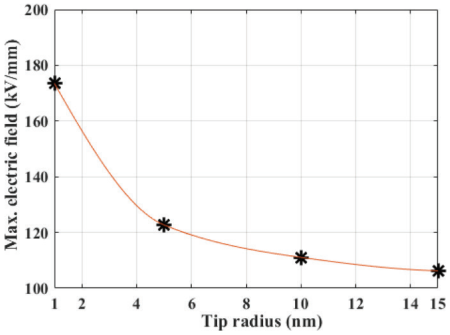
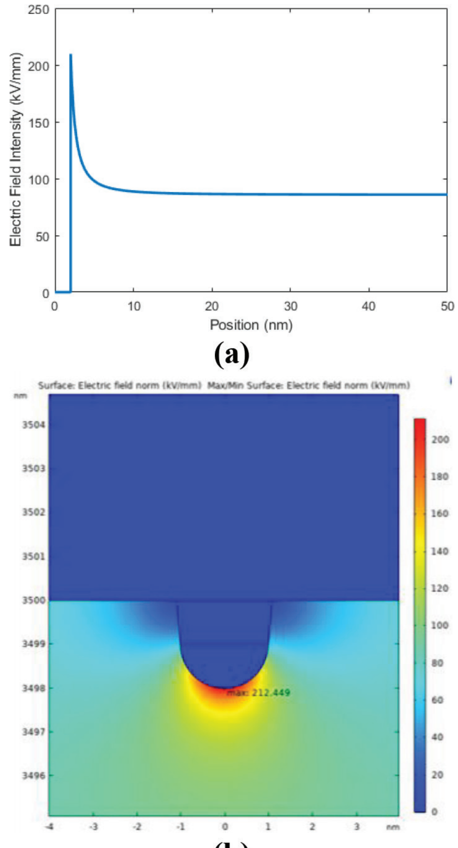


Figure 3. Electric field with tip radius of spherical protrusion.

3.2 Needle-Shaped Protrusion

The needle-type protrusion is considered 1nm inside the dielectric of capacitors as per[9]. In the case of a tip radius of 1 nm, the maximum electric field intensity at the tip of the protrusion was measured to be 212.449 kV/mm. This value is more than twice the intensity observed at the bulk of the material, as depicted in Figures 4(a) and 4(b). Figure 4(b) specifically presents a surface plot visualization of a needle protrusion, providing a clearer representation of the electric field distribution and its intensified nature at the protrusion's tip. In contrast to spherical protrusions, it has been found that the maximum electric field in needle-type protrusions is more than twice the field observed in the bulk material. This difference indicates a more significant enhancement of the electric field intensity at the tip of needle-type protrusions. Unlike the spherical protrusions where the field was below twice the bulk value, the needle-type protrusions exhibit a greater amplification of the electric field, emphasizing their impact on the overall field distribution within the capacitor system.



(a)

(b)

Figure 4. (**a**) Electric field. (**b**) surface plot, in case of needle-shaped protrusion.

The maximum electric field at the tip of needle protrusion for tip radii of 1 nm, 5 nm,10 nm, and 15 nm is shown in Figure 5. Similar to spherical protrusion, needle protrusion also shows the same trend with tip of the radius of protrusion. i.e., as the radius of curvature of a spherical protrusion decrease, the maximum electric field at the tip of the protrusion increases exponentially.

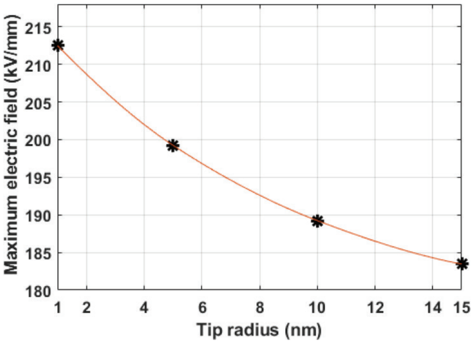


Figure 5. Maximum electric field with increase in tip radius of needle protrusion.

The presence of a high electric field at the tip of a protrusion leads to an increase in local conductivity[10,11]. This phenomenon causes the dielectric material near the protrusion tip to transition from its insulating state to a resistive state. Consequently, partial discharge events begin to occur in this region, posing a risk to the overall breakdown strength of the capacitor.

Partial discharge refers to localized electrical discharges within the dielectric material, which can lead to its degradation and compromise its insulating properties. As a result, the breakdown strength of the capacitor gradually decreases over time. This decrease signifies an increased vulnerability to electrical breakdown and potential failure when subjected to high voltage conditions.

4. Conclusion

Among several reasons responsible for protrusion formation in high voltage film capacitors, the major reasons are manufacturing defects, electro-thermal aging of capacitors, or uneven adhesion of metalized PP film. The uneven deposition of metalized film on the dielectric or uneven dielectric surface may result in the formation of protrusion, which over aging may increase the surface roughness of dielectric film, resulting in the high electric field at the tips[12].

Certainly, the high electric field concentration at the tip of a protrusion can result in an increase in local conductivity. This elevated conductivity can further contribute to an unexpected field distribution within the capacitor system. It can lead to the formation of local hotspots, areas where the electric field is excessively concentrated, and can cause localized heating.

These local hotspots and uneven field distributions pose a potential risk to the performance and reliability of the capacitor. The excessive heat generated in these regions can adversely affect the dielectric material, leading to its degradation or even breakdown. If many electrode protrusions are present at the interface, can result in reduced capacitor lifespan, decreased efficiency, and potentially catastrophic failures, as it is observed in cables that small protrusions or any defects may start growing under the influence of high electric field and get converted to electric treeing resulting in failure of cables. Since cable geometry resembles cylindrical capacitors, therefore, it is crucial to carefully consider the design and geometry of this high-voltage capacitor, including the presence of protrusions, to mitigate the formation of local hotspots and ensure a uniform and reliable electric field distribution throughout the system.

Indeed, the results presented above provide valuable insights, but further studies are necessary to validate and expand upon these findings. The research conducted so far can be viewed as an initial attempt to investigate the impact of nano-sized defects in capacitors, particularly focusing on the behavior of protrusions and their effects on the electric field distribution.

Among several reasons responsible for protrusion formation in high voltage film capacitors, the major reasons are manufacturing defects, electro-thermal aging of capacitors, or uneven adhesion of metalized PP film. The uneven deposition of metalized film on a dielectric or uneven dielectric surface may result in the formation of protrusion, which over aging may increase the surface roughness of dielectric film resulting in electrical treeing or carbonization of dielectric material finally leading to puncture in the dielectric.

As protrusion may lead to failure of the capacitor, so care must be taken while manufacturing that the deposition of a metalized film on polypropylene is done uniformly.

As can be observed from the simulation, that as the length of protrusion increases the electric field at the tip also increases, so it should be kept under a certain range according to the thickness of the electrode. Moreover, the polypropylene film roughness should be kept as minimum as possible as it will hinder the adhesion of metalized film.

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