Role of Void Orientation and Shape on the Electric Field Distortion in High Voltage Cable

Raweya Moayed Tawfiq
raweyamoayed89@gmail.com

Dawood Najem Saleh
dnsaij@uomosul.edu.iq

Electrical Engineering Department, Collage of Engineering, University of Mosul

ABSTRACT

One of the problems that face the use of XLPE insulators is the appearance of defects. These defects appear during the manufacturing processes of the insulator, and one of these defects is air cavities or voids. The defects presence within the insulators of high voltage cables affects the distribution of the electric field within the cable layers. The distortion of the electric field due to the presence of air cavities is the main reason for the treeing appearance inside the insulator, which eventually leads to the emergence of partial discharges that reduce the life of the cable. In this study, the effect of the presence of an air cavity inside an XLPE insulator was studied by changing the dimensions of the cavity, that is, changing the ratio of the dimensions of the cavity parallel to the electric field and vertical to it and the effect of this on the value of the electric field in the center of the cavity. It was noted that the electric field in the cavity is higher than in the external electric field. The increase in the field in the cavity center does not depend on the cavity size, but rather on the ratio of the cavity dimensions parallel to the electric field to the vertical to it. The electric field enhancement factor was calculated based on the simulation results, which showed a reasonable agreement with the theoretical values.

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1. INTRODUCTION

Working at a high voltage level led to the emergence of insulation problems in the high voltage cables. For this reason, the manufacturing process of these cables should be achieved under high consideration so that defects such as cavities or air voids do not appear in the cable's layers, and that their products should be at a high-quality level in terms of the materials used [1].

The conducting research on the mechanism of the electric treeing found that they begin from wherever there are impurities, voids, or cavities containing gases or mechanical cracks in the layers of the insulating material of the cable, which leads to the occurrence of a high electric field concentration in a small area and finally lead to partial discharge. From this, it can be concluded that partial discharge is the cause and electrical treeing are the result [2]. Many studies have been focused on the effect of defects that occur in insulators, which may lead to a reduction the cable aging [3-7].

PS Patel et al. [8] studied the increase in the electric field in the cavity of the XLPE layer, which is one of the main reasons for the phenomenon of insulation failure. The researchers also studied the greatest electric field that occurs in the surface area of the cavity close to the side of the central conductor. They showed that when the radius of the cavity (its size) increases, this leads to an increase in the maximum electric field, and when the distance between the cavity and the central conductor increases, this leads to a decrease in the maximum electric field.

Adawy et al.[9] have represented the XLPE conductors by numerical analysis program (Finite Element Magnetics Methods software) (FEMM) and studied the electric field in the normal state and the case of a cavity in a capacitive insulator layer, They proved that the electric field increases in the center of the cavity because of its relative permittivity is less than the relative permittivity of the insulating layer. They studied the impact of cavity location on the electric field intensity. They

found as the cavity far from the center of the cable, the electric field inside the cavity decrease more.

K. Emna et al. [10], investigated the effect of the size and location of the void cavities on the shape and magnitude of the electric field formed inside the insulation layers using COMSOL Multiphysics. It has been observed that the generated electric field depends in form and value on the size and location of those cavities, as the larger the size of these cavities and approaching the central conductor, the greater the electric field generated program.

Zhu et al. [11], devoted to the study of electric field distribution in (DC) XLPE cables using the COMSOL Multiphysics program. The electric field distribution and its magnitude in the cable layers were studied in the presence or absence of defects in the cable-layers, and they found that the most severe of these effects on increasing the value of the electric field is the corona effect.

Algwari et al [12] and Gao et al [13] used a two-dimensional plasma model to simulate the impact of the presence of charged species inside the void on the distribution of the electric field on the inner surface of the void and the effect of this on the production of rough surfaces, which leads to the process of eroding the insulation and finally collapse.

Although there were many studies on the impacts of existence the void in high voltage cables on the electric field properties but there is no much details about the effect of varing the dimensions of the cavity inside the insulator, i.e., the ratio of changing the orientation of the cavity parallel to the electric field and perpendicular to it and the effect on the distortion of the electric field at the center of the cavity. Therefore, this paper will focus on studying the role of void orientation and shape on the electric field distortion in high voltage cable using the COMSOL Multiphysics program [14], which is based on the finite element method.

2. THEORY
2.1. The electric field in the presence of a cavity.

It is possible to study the behavior of the electric field when there is a cavity having a relative permittivity ε_{r1} less than the relative permittivity of the material of the insulator layer ε_r. Therefore, the electric field inside that cavity, symbolized by E_{x1} volts/meter, increases compared to the electric field in the insulator layer, symbolized by E_x as follows [15]:

$$E_{x1} = \frac{3\,E_x\,\varepsilon_r}{(\varepsilon_{r1}+2\,\varepsilon_r)} \qquad (1)$$

If the relative permittivity of the insulator is much greater than the relative permittivity of the cavity, the equation for the electric field inside the cavity can be reduced to:

$$E_{x1} = 1.5\,E_x \qquad (2)$$

As for the equation of the electric field in the region outside or around the cavity affected by the occurrence of the cavity, it is denoted by E_{x2} as follows:
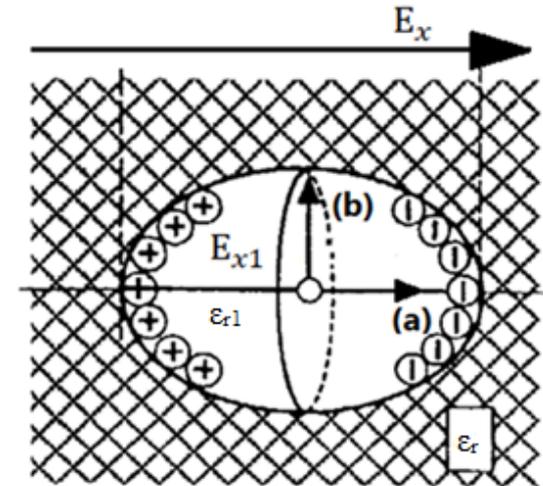

Figure 1 Schematic diagram of the ellipsoidal cavity inside the insulator

$$E_{x2} = \frac{3\,E_x\,\varepsilon_{r1}}{(\varepsilon_{r1}+2\,\varepsilon_r)} \qquad (3)$$

These equations lead to the following conclusion, which is that inside the cavity is subject to a higher electric field than the field on the insulator surrounding the void [15].

2.2. Impact of the shape and size of the cavity.

The cavity inside the insulator can be represented as an ellipsoid as shown in Fig. 1 [16]. The presence of a cavity in the insulator layer of the cable works to enhance the electric field inside that cavity as mentioned earlier, and it is possible to calculate the value of this enhanced electric field, which could lead to the presence of partial discharges inside the cavity from the following equation [17]:

$$E_{x1} = f\,E_x \qquad (4)$$

where f is the electric field enhancement factor and is affected by the value of the axis ratio (a/b) and the dielectric constant ε_r of the insulator. It is possible to represent the shape of this cavity in the a-axis, which is the axis parallel to the direction of

the applied electric field, and the b-axis, which is the axis vertical to the direction of the applied electric field. The variation of the axes ratio function K(a/b) to the ellipsoidal void axis ratio can be deduced graphically from Fig. 2, then it is possible to find the value of the electric field enhancement factor from the following empirical relation [17]:

$$f = \frac{k\left(\frac{a}{b}\right) \in_r}{1 + \left[k\left(\frac{a}{b}\right) - 1\right] \in_r} \qquad (5)$$

For the spherical cavity, meaning that a = b (a/b=1) of the Fig. 2, k(a/b) =3 and the value of f is:

$$f = \frac{3 \in_r}{1 + 2 \in_r} = 1.232 \qquad (6)$$

For the vertical ellipsoidal void was (a/b) = 0.5, then k (a/b) =2 and the value of f is:

$$f = \frac{2 \in_r}{1 + \in_r} = 1.3939 \qquad (7)$$

While for the parallel ellipsoidal void was (a/b) =2, then k(a/b) =6 and the value of f is:

$$f = \frac{6 \in_r}{1 + 5 \in_r} = 1.104 \qquad (8)$$

Therefore, the greatest field occurs in the center of the ellipsoidal cavity perpendicular to the direction of the field, and less than it in the spherical cavity and the least in the case of the ellipsoidal cavity parallel to the field.
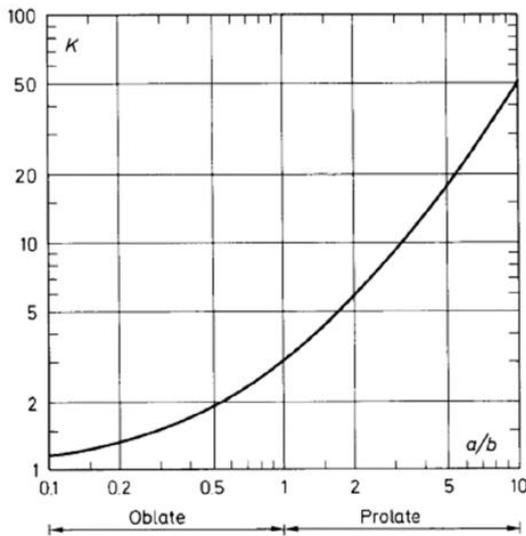

Figure 2 Variation of K(a/b) with the ellipsoidal axis ratio

3. MODEL DESCRIPTION

3.1. Cable model
The cable model that was under simulation is an XLPE single-phase cable, operating at medium voltage 33 kV 50Hz AC voltage, consisting of seven layers, starting from the center of the cable with the central conductor, the inner

semiconductor sheath, the XLPE insulator, the outer semiconductor sheath, the metal tape, the lead tape, and the outer sheath. Each layer has a thickness and relative permittivity as shown in Table 1 [15].

Table 1 Cable layers features [15].

Layer no.	Material Copper	Thick. (mm)	Radius (mm)	Relative permittivity
1	Copper		11.12	1
2	Graphite screen	1.8	12.92	1
3	XLPE	23	35.92	2.3
4	Graphite screen	1.5	37.42	1
5	Copper screen	1.7	39.12	1
6	Pb-Lead	3	42.12	1
7	PVC	5	47.12	2.9
8	Air void		variable	1

The location of the void is in the middle of the XLPE insulation layer and it is ellipsoidal so that its radii change to form a spherical void once and again an ellipsoidal void transverse to the electric field lines and finally an ellipsoidal void that is along the field lines.

A fixed reference point has been taken to compare the electric field values when changing the shapes and dimensions of the void. It is located in the center of the voids in all its shapes and on the horizontal axis and is 24.5 mm away from the center of the cable. Fig. 3a shows the void position and its center while fig. 3b shows the mesh distribution in the cable-layers.
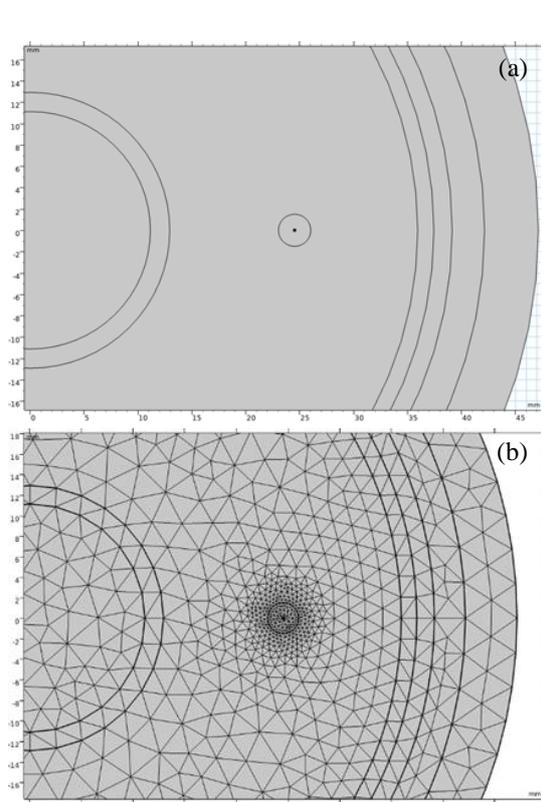
Figure 3 the void position and its center (a), the mesh distribution in the cable-layers (b).

3.2. Boundary Conditions

Boundary conditions mean the conditions under which an electric field travels between two different mediums. These conditions differ according to the type of media that the field will move between, as follows:

1- Insulator-insulator: When an electric field is transmitted between two mediums that are both insulators, but there is a difference in their properties, the equations of boundary conditions become as follows:

$$E_{1t} = E_{2t} \qquad (9)$$

$$D_{1n} - D_{2n} = \rho_s \qquad (10)$$

E_{1t} The component of the electric field tangent to the surface of the first insulator, while
E_{2t} The component of the electric field tangent to the surface of the second insulator.
D_{1n} is the vertical component of the electric field density in the first insulating medium, while
D_{2n} is the vertical component of the electric field density in the second insulating medium, and ρ_s is the surface charge density in coulombs/m².

2- Conductor-insulator: When the electric field is transmitted between two mediums, one of them is a conductor and the other is an insulator, the
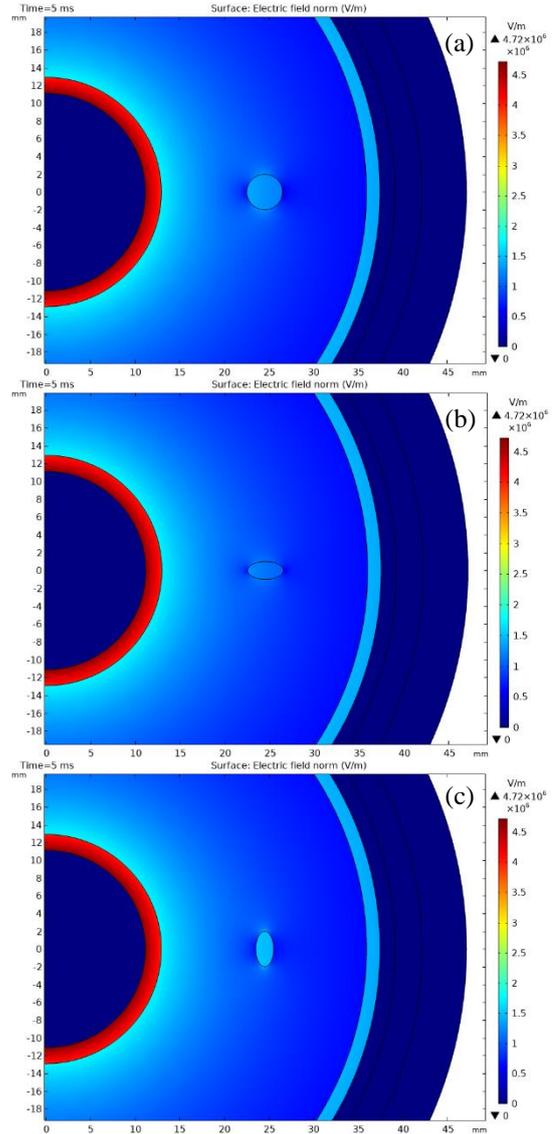

Figure 4 type of the voids, spherical(a), elliptical void transverse to the field direction (b) and elliptical void along the field direction(c).

equations of boundary conditions become as follows:

$$E_{1t} = E_{2t} = 0 \qquad (11)$$

$$D_{2n} = \rho_s \qquad (12)$$

3- Applied voltage: The alternating voltage is applied to the central conductor of the conductor while the outer metal layers of the conductor are grounded.

4. SIMULATION RESULTS AND DISCUSSIONS

4.1. Electric field distribution in the presence of a cavity

The interpretation of the change of the electric field at the reference point depends on the capacitive effect of the void and the number of charges accumulated on its surfaces, or in other words, depends on the applied voltage and the dimensions of the void. As for the applied voltage, the change is slight or non-existent when changing the dimensions of the void, which is small if compared to the dimensions of the insulator surrounding the void, so this effect can be neglected and only the effect of the dimensions can be maintained.

The capacitive effect of the void can be approximated to the simplest form, which is produced by two parallel plates by taking the effective area of the surface as well as the effective distance between the surfaces on which the charges are collected, as in Fig. 1 where it can be assumed that the effective area is perpendicular to the direction of the electric field while the effective distance in the same direction.

Since the capacitive effect increases with the increasing area and decreases with increasing distance, three types of voids can be distinguished which are spherical, elliptical void transverse to the field direction, and elliptical void along the field direction as shown in Fig. 4.

Case 1: the effect is equal for both the effective area and the effective distance, and this is clear if the void is in the form of spherical with different radii, as shown in Fig. 5, where the electric field at the reference point located in the center of the voids is the same in all cases, despite the change of radii of the voids which is about 1.28MV/m, but the field value remains the highest with the voids than without void which equal to 0.921MV/m [9][18].

The amount of distortion in the electric field at the reference point has reached 140% of the field value in the absence of an air void at the same point. The shape of the field distortion depends on the void radius. The electric field value is higher at the inner surface of the void which is close to the center of the cable.

Case 2: The effect of the effective area is greater than the effect of the effective distance, and this occurs when the elliptical void is perpendicular to the field lines so that the values of the axis perpendicular to the field (b) change while the axis parallel to the field (a) remains constant. At that time, the field values will increase with the increase in the values of the vertical axis, as shown

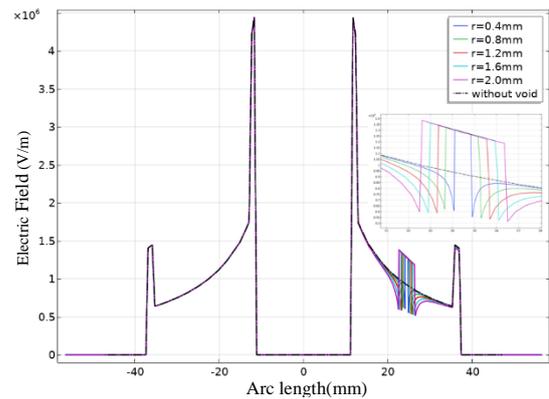in Fig.6. The maximum field is about 1.73MV/m

Figure 5 spherical void with different radii.

and is occurred when the vertical axis (b) is equal to 2.0mm and the (a) axis is 0.4mm.

In this case, the field distortion at the reference point is the greatest value, especially when the vertical axis (a) is equal to two 2.0 mm, while the (b) axis is equal to 0.4 mm, where the amount of distortion is within the limits of 187%.

Case 3: When the effect of the effective distance is greater than the effect of the effective area, the values of the electric field at the reference point decrease with the increase in the length of the (a) axis, and the (b) axis remains constant, as shown in Fig. 7 [17]. The maximum field is about 1.284MV/m and occurs when the vertical axis (b) is equal to the parallel axis (a) and is 0.4 mm so that the void is spherical. While the lowest value of the field is about 1.016MV/m and it occurs when the vertical axis (b) is equal to the lowest value of 0.4 mm and the parallel axis (a) with the highest value of 2.0 mm. The amount of field distortion for this position of the void is the least value and is in the range of 110%.
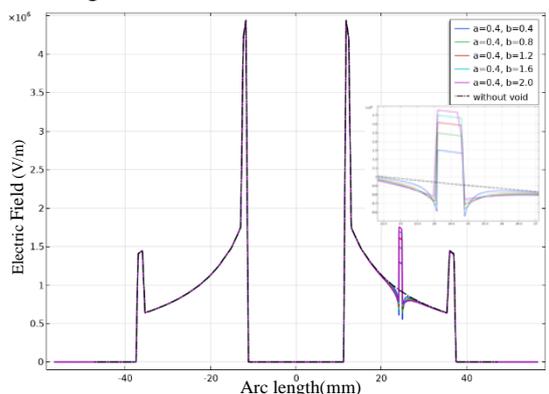

Figure 6 elliptical void perpendicular to the field lines, a=0.4mm and b=0.4, 0.8, 1.2, 1.6 and 2.0mm respectively.

4.2. The electric field enhancement factor

To clearly show the difference in the field values at the reference point for the three aforementioned cases, can refer to Fig. 8, where the field values are fixed when the radii of the spherical void change, while the field values increase in the case of the transverse voids with the increase of the vertical axis and the horizontal axis constant and vice versa in the case of horizontal gaps.
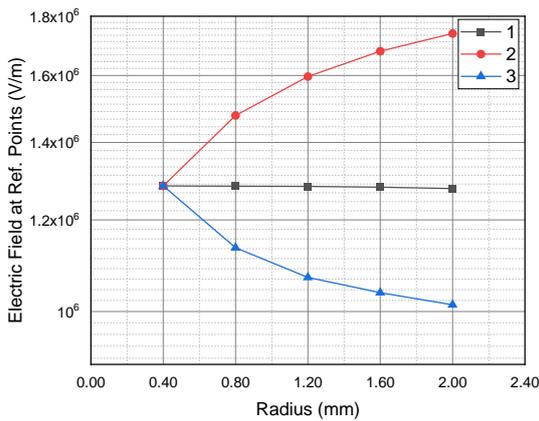

Figure 8 the electric field at the reference point, for spherical void (1), vertical elliptical void (2) and parallel elliptical void (3).

To verify the results, the values of the electric field enhancement factor *f*, which were obtained from the simulation results and after applying Eq. (4), were compared with the results obtained from the empirical Eq. (5), as shown in Table 2, where acceptable matching appears, especially when the ratio is large. The value of the electric field at the reference point does not change when the ratio is constant, even though the values of the axes (a) and (b) change as in the case of the spherical void.

Table 2 The electric field enhancement factor f.

a/b	E_{x1}(MV/m)	E_x (MV/m)	$f = E_{x1}/E_x$	f from eqs.5
0.5	1.474	0.921	1.6	1.393
1.0	1.278	0.921	1.394	1.232
2	1.132	0.921	1.229	1.104

5. CONCLUSION

In this work, the effect of the void shape and orientation on the amount of distortion that occurs in the electric field in the XLPE insulator was studied using the COMSOL Multiphysics program. It has been obtained that the electric field in the void region is increased due to the
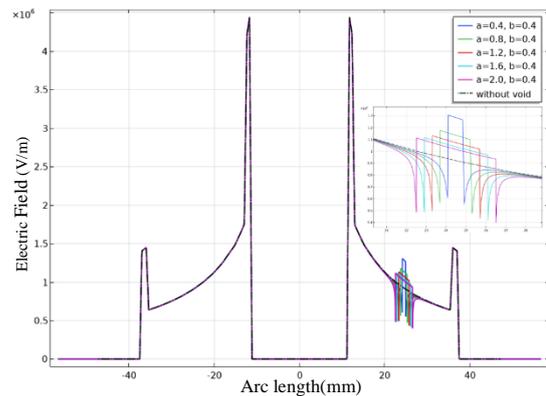
differences in the relative permittivity of the XLPE

Figure 7 elliptical void parallel to the field lines, b=0.4mm and a=0.4, 0.8, 1.2, 1.6 and 2.0mm respectively.

insulator and the air void. It is also observed that the electric field at the reference point is strongly depend on the geometry of the void (a/b ratio). From the simulation results, it was noted that the maximum electric field and hence the maximum enhancement factor is obtained when the ratio of a/b is less than one and the minimum value of the electric field and the enhancement factor when the ratio of a/b is more than unity. The field value is constant and is not affected by the change in the size of the void when the ratio is equal to unity and this makes the enhancement factor equal to one.

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دور اتجاه وشكل الفجوة في تشويه المجال الكهربائي في قابلوات الجهد العالي

داود نجم صالح   راوية مؤيد توفيق

dnsaij@uomosul.edu.iq   raweyamoayed89@gmail.com

جامعة الموصل ـ كلية الهندسة ـ قسم الهندسة الكهربائية

الملخص

من المشاكل التي تواجه استخدام عوازل XLPE هي ظهور العيوب في هذه العوازل .حيث تظهر هذه العيوب أثناء عمليات تصنيع العازل ، ومن هذه العيوب تجاويف الهواء أو الفجوات. يؤثر وجود العيوب في عوازل القابلوات ذات الجهد العالي على توزيع المجال الكهربائي داخل طبقات القابلوات. يعد تشوه المجال الكهربائي بسبب وجود تجاويف هوائية هو السبب الرئيسي لظهور التشجر داخل العازل ، مما يؤدي في النهاية إلى ظهور تفريغات جزئية تقلل من عمر القابلو. في هذه الدراسة ، تمت دراسة تأثير وجود تجويف هوائي داخل عازل XLPE من خلال تغيير أبعاد التجويف ، أي تغيير نسبة أبعاد التجويف الموازية للمجال الكهربائي والعمودية عليه و تأثير هذا على قيمة المجال الكهربائي في مركز التجويف .حيث لوحظ أن المجال الكهربائي في التجويف أعلى من المجال الكهربائي الخارجي. لا تعتمد الزيادة في المجال في مركز التجويف على حجم التجويف ، بل تعتمد على نسبة أبعاد التجويف الموازية للمجال الكهربائي إلى الابعاد العمودية عليه. تم حساب معامل تعزيز المجال الكهربائي بناءً على نتائج المحاكاة التي أظهرت توافقًا معقولاً مع القيم النظرية.

الكلمات الداله :

المجال الكهربائي ، الفجوة ، تجويف الهواء ، تحليل العناصر المحدودة ، قابلو الجهد العالي ، عازل XLPE..