International Journal of the Physical Sciences Vol. 7(2), pp. 306 - 316, 9 January, 2012
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.1428
ISSN 1992 - 1950 ©2012 Academic Journals

Full Length Research Paper

Capacitor bushing optimization via electrostatic finite element analysis

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Accepted 6 December, 2011

In high-voltage capacitor bushings, there is maximum field intensity at the edge of the aluminum foil and where foils overlap. Any technique decreasing much field intensity in those regions will significantly optimize the bushings' electrostatic characteristics. This paper presents the study of the effect of edge diversion in the overlapped region of an aluminum foil and of the shape of aluminum foil edge in improving the maximum field intensity of the overlapped region. Electrostatic analysis was used to minimize the field intensity. 2D and 3D simulations and analyses were run, respectively via finite element method magnetic (FEMM) and Vector Field Opera. Techniques improving field intensity distribution of capacitor bushing are presented. Results show that foils that are not folded and have the inner edge placed lower than the outer edge better distribute the field around the edges.

Key words: Capacitor bushing, cavities, electric field, electrostatic simulation, finite element analysis.

INTRODUCTION

As voltage increases, so does the importance of electrical insulation in high-voltage equipment (Guoqiang et al., 1999). The importance of insulation materials lies in their resistance against voltage or electric field intensity (Ueda et al., 1985). High voltage and high electric field intensity cause partial discharge, which, through the cavities formed during fabrication (Seghir et al., 2006; Ghourab and El-Makkawy, 1994; Hsu et al., 2011) leads to failure of insulation materials and deterioration and breakdown of dielectric insulation (Pompili and Mazzetti, 2002). Field analysis method allows analysis of electric field intensity in various parts of an insulator (Arora and Mosch, 2006). It allows calculation of maximum electric field and its distribution in all parts of a bushing and for various insulating materials. Various numerical techniques let designers solve problems insolvable by analytical methods (Faiz and Ojaghi, 2002). Finite element analysis is a powerful and precise method in complex geometrical modeling, providing solutions to many complicated problems in various fields of engineering (Monfared, 2011; Kumar Singh and Sharma, 2011; Jumaat and Ashraful Alam, 2011). Its capability in numerical solving also makes it the main analyzing method for calculation of the electric field in high-voltage bushing (Monga et al., 2006; Lesniewska, 2002).

Bushing is used in high-voltage equipment to insulate the high-voltage conductor from the external earthed body; 25 to 30% of large power transformer failures have been reported as due to bushing (Smith et al., 2010). At high voltage, aluminum plates uniformly distribute the high voltage potential between conductor and body. The plates, referred to as foils, make a series of cylindrical capacitors that uniformly distributes electric field. They are called capacitor bushings. In their core, typically, are thick papers that fill the distance between two capacitor plates that usually are conductors, semiconductor layers (graphite) or metallic (in which case they are mostly aluminum). The capacitor plates are placed as coaxial cylinders. The thick papers distancing the plates provide the required mechanical stability to the cylindrical capacitors. Figure 1 is a general view of a capacitor bushing (Ellis, 2004). When voltage increases, more aluminum foil

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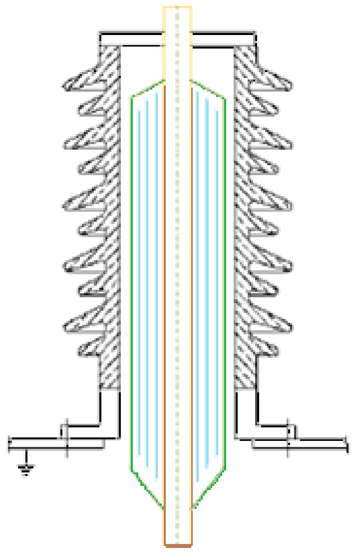


Figure 1. Typical configuration of a capacitor bushing.

is used, so, foil placement and the shape of the foil edge become crucial.

The part of a capacitive foil most sensitive to electric field intensity is its edge, which, when overlapping, increases the sensitivity. The electric field intensity is higher around that region than in the other regions. The relative position of two edges and their shape affect the field intensity of the surrounding and the overlapping regions, and so, partial discharges are expected to start there. This paper presents the calculation of the electric field intensity at the edges of a high-voltage bushing, and proposes a new technique and a new foil shape, both improving the field intensity of the affected regions. It first presents a mathematical model for the insulation system of a capacitive insulator, then compares the simulations of capacitor bushing electric field, via finite element method (FEM) software (2D simulation) and Vector Field Opera (3D simulation). Next it describes how folded and non-folded edges enhance electric field distribution of capacitive bushing, concluding with suggestions for improvement to electric field distribution.

THE MATHEMATICAL MODEL OF AN INSULATION SYSTEM

Considering the relation between electric potential and electric field intensity, the electric field in an insulation system is described by Laplace equation;

$$\nabla^2 V = o \quad (1)$$

The equation is described with Neuman and Dirichlet boundary conditions. Solving Laplace's equation with specific boundary conditions gives:

$$E = -\nabla V \quad (2)$$

To calculate the potential of capacitor plates and the cylindrical capacitor value between them, the capacitance dispersion between the plates should be considered. Capacitance dispersion is usually due to the foil's sharp edge. The value of each capacitor, even with a complex shape, can be derived by calculating the amount of electrical energy the field stores;

$$C = \frac{2W_e}{V^2} \quad (3)$$

The electrical energy of the electric field between the foils is:

$$W_e = \int \frac{D.E}{2} dv \quad (4)$$

How foil edge affects capacitor value can be calculated by finite element method (FEM). Cylindrical symmetry causes the electric field vector in the capacitor bushing to have two axial and radial components. In the region of two foil edges overlapping, the field intensity is higher owing to the resultant fields of the two edges' plates. Figure 2 shows the relative positions of foils 1, 2 and 3. The resultant field near the edges can be calculated.

Assuming the fields due to the edge of the second foil in the overlap region to be E21 and E22, and the fields due to the adjacent foils to be E1 and E3, the combined field of the two edges of the second foil and the fields of the other adjacent foils (foils 1 and 3) will determine the field intensity in the overlap region of foil 2. The radial component of the field there equals:

$$E_r = E_{r21} + E_{r22} + E_{r1} + E_{r3} \quad (5)$$

Similarly, the axial component of the field equals:

$$E_a = E_{a21} + E_{a22} + E_{a1} + E_{a3} \quad (6)$$

The electric field intensity can be calculated through Equation 7:

$$E = \sqrt{(E_r^{\ 2} + E_a^2)} \quad (7)$$

Figure 3 shows in 3D the overlap region of the foil edges. Figure 4 is the resultant field in an overlap region of foil edges. It shows that owing to the position of both foils 1 and 3 relative to 2, the radial component of foil 1 is higher than its axial component, but the axial component in foil 3

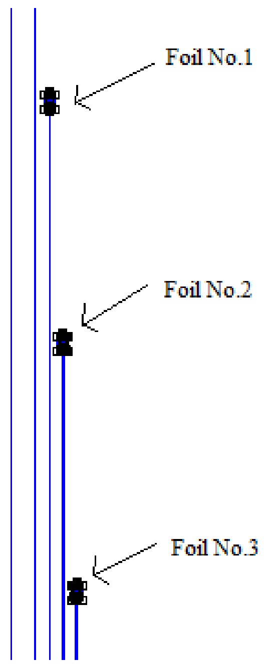


Figure 2. The proposed relative position of the foil edges.

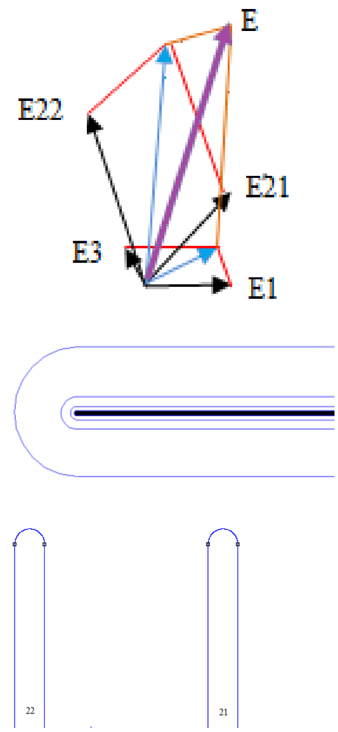


Figure 4. The resultant field in the overlap region of the foil edges.

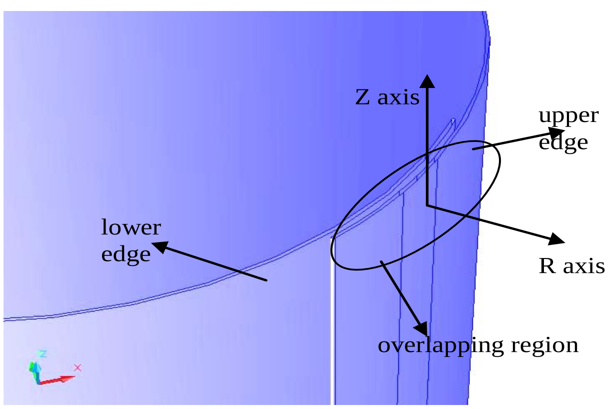


Figure 3. Position of a foil-edge in an overlap region.

is higher than its radial component.

SIMULATION

Finite element was used to investigate the electric field distribution of a capacitive bushing. All available finite element analysis (FEA) softwares were first compared before the one suitable for distribution was selected. FEA yielded the voltage for each foil of the selected test bushings. The field intensity of the overlap regions was obtained.

Electrostatic simulation

The cylindrical symmetry in capacitor bushing allows 2D simulations. The capabilities of three simulation softwares (Table 1) were compared; finite element method magnetic (FEMM) was chosen for 2D simulation and Vector Field Opera 14.0 for 3D simulation (Meeker, 2006).

HVB 1 to 145 kV capacitor bushing was selected for 2D simulation (Nirou Company, 2011). Its main insulator comprises several compressed layers of oil-impregnated paper. There are 47 foils, of which 23 are used in the air section of the bushing and 23 in the oil section (the resin part). The last foil is used as grounding foil, connected to ground through a flange, its potential zero. The oil-impregnated paper isolates the foils. Table 2 lists the bushing materials and their characteristics (Gremmel and Kopatsch, 2001; ABB company, 2011). Figure 5 is a 2D figure of the bushing.

SIMULATION RESULTS

Figure 6 is an auto-mesh generated on Vector Field Opera 14.0 software, a tetrahedral element with 6 nodes that fit foil-edge curvature. Figure 7 gives the simulation results of all parts of the bushing: good voltage distribution

Table 1. Comparing three simulation softwares.

	Software	Vector field	ANSYS	FEMM
Pre-Processing	Possibility of 3D simulation	No	Yes	Yes
	Geometry problem definition	Easy	Difficult	Partly difficult
	Possibility of importing files from AutoCAD and other softwares	Yes	Yes	No
	2D mesh classification	Easy	Partly easy	-
	3D mesh classification	-	Difficult for huge amount of meshes	Difficult
	Solution for speed	Good	Low	Good
Post-Processing	Possibility of displaying the electric field	Yes	Yes	Yes
	Possibility of displaying the field components	Yes	Yes	Yes
	Display of the equipotential lines	Yes	No	Yes
	Possibility of displaying the fields in 3D	No	Yes	Yes
	Possibility of displaying quantities in specific pages	-	Yes	Yes
	Possibility of using software's output for other processing softwares	Yes	Yes	Yes

Table 2. Material properties of the bushing components (ABB).

Material	Relative permittivity	Conductivity σ
Oil impregnated paper	2.3	6.3×10^{-11}
Mineral oil	2.2	1×10^{-10}
Porcelain	6	1.9×10^{-9}
Resin	4.2	2.2×10^{-9}
Air	1	8.0×10^{-15}

distribution throughout the bushing and non-uniform distribution in the distal region. Next described is the simulation performed to optimize foil-edge field. Table 3 lists the numeric voltage of each foil. Figures 8 and 9 give the voltage value of each side of the bushing.

Simulations of the overlap region

Simulations were performed for various situations of foil edges in overlap regions, and the maximum field value was determined for the regions around the edges. Figure 10 is a visual presentation of a 2D simulation of two overlapping foil edges, showing the equipotential lines. The maximum field values in the specified interval around the edges were achieved by changing the relative locations of the foil edges. Figure 11 is a contour of the field showing the equipotential lines where the inner edges are moved in Z-axis direction and displaced lower. Parameter "M" indicates the displacement of the inner edge from the outer edge. Figure 12 compares the maximum intensities of various situations.

The horizontal axis represents the deviation of the inner edge (the left edge in Figure 10) from the outer edge. Units are in millimeter. Field value clearly varies with changes to the position of the inner edge. Table 4 lists the results for when the edges are far from each other. The negative sign shows the inner edge is lower than the outer edge.

Figure 12 shows maximum voltage intensity

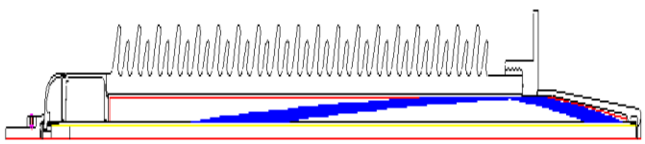


Figure 5. 2D view of the HVB 1 to 145 kV capacitor bushing selected for simulation.

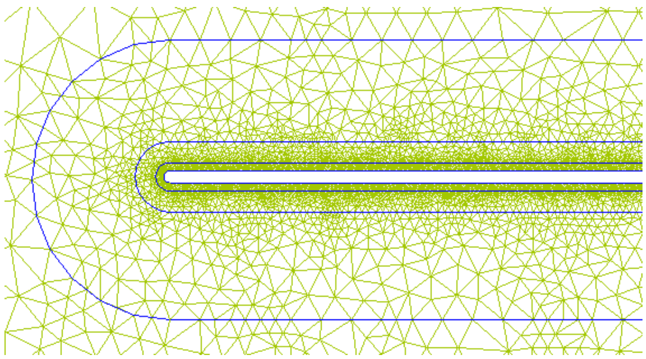
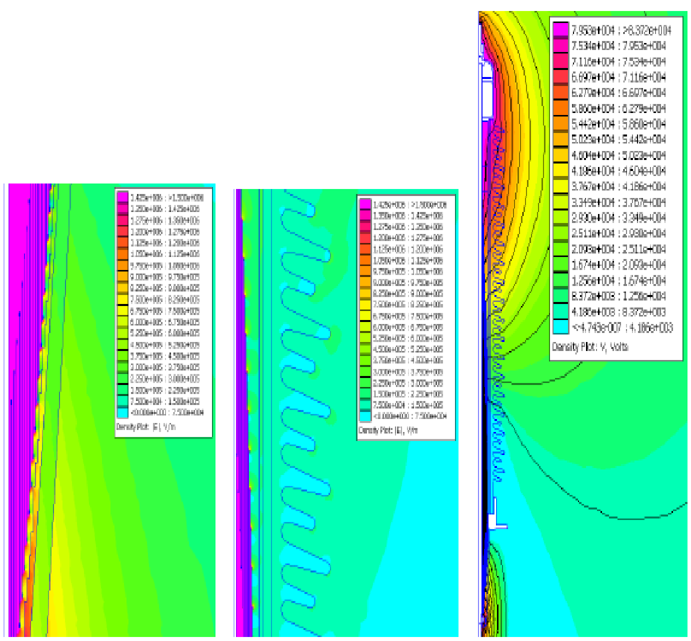


Figure 6. 3D auto-mesh generation in Vector Field Opera 14.0 (Opera Version 14.0 User Guide, 2011).



a b c

Figure 7. (a) Field intensity on oil-side of bushing; (b) Field intensity on air-side of bushing; (c) Voltage contours in various regions of bushing.

varying with movement of the edges relative to each other. The positive value of the X-axis shows that the outer edge is higher than the inner edge.

Techniques to improve field intensity in overlap areas

The best way to find the optimum configuration improving field intensity in overlap region of foil edges is 3D simulation (the non-symmetrical edges make 2D simulation impossible). Vector Field Opera 14.0 3D was used to simulate the electric field in the region of edges (Opera Version 14.0 User Guide 2011).

To simplify simulation, the cylindrical edges are considered curvature-less, so modeling them becomes easy. This study simulated various conditions of the edges: their relative positions and their shapes. It also compared the field values of the regions near the edges. Simulation results of the conditions are plotted in field contours. The overall results for the conditions are compared, and solutions for optimization were presented.

Folded edge

Folded edge is rectangular, so is sharp. Field intensity in sharp regions is high, so the shape of an edge should be changed. The foil edge is thus folded onto itself. Figure 13 shows the inner edge folded. Its field contour, for a plane near the edge overlap, is as shown in Figure 14.

Non-folded edges

The foil edges were, for this simulation, considered non-folded. Their corners are as shown in Figure 15. Figure 16 is the simulation results for a plated contour.

Non-folded and displaced

The edges were not folded and the inner edge was lower than the outer edge. The placing of the top of the inner edge at a level lower than the top of the outer edge is based on the 2D simulation described previously. Figure 17 shows edge positions and Figure 18 their field contours. Table 5 lists the maximum electric field for folded, non-folded and non-folded and displaced-low edges.

CONCLUSION AND SUGGESTION

The present study has been a finite-element analysis of the electric field of an HVB 1 to 145 kV capacitor bushing. The electric field in various regions of the bushing was calculated through a numeric solution of Laplace's equation with Neumann and Dirichlet boundary conditions. The high field-intensity at the edges of the aluminum foil and where the foils overlap motivated the technique for making it uniform at that point. Simulation results show that placing the inner edge at a position

Table 3. Voltage of each foil.

Foil number	Voltage (V)	Foil number	Voltage (V)	Foil number	Voltage (V)
1	79532.5	17	22680.7	33	43228.7
2	75720.3	18	19329.9	34	39967.2
3	71790.7	19	15862	35	36642.4
4	68147.1	20	12775.2	36	33250.4
5	64546.5	21	9561.2	37	29786.9
6	60991	22	6039.04	38	26515.8
7	57471.7	23	3172.94	39	23301.8
8	53869.7	24	78648	40	20004.4
9	50413.5	25	74125.8	41	16933.1
10	46972.7	26	69579.3	42	13763.2
11	43675.7	27	65476	43	11005.6
12	40271	28	61505	44	8182.66
13	36756.4	29	57670.8	45	5132.29
14	33129.6	30	53951.4	46	2681.35
15	29661.2	31	50214.2	-	-
16	26229.2	32	46683.5	-	-

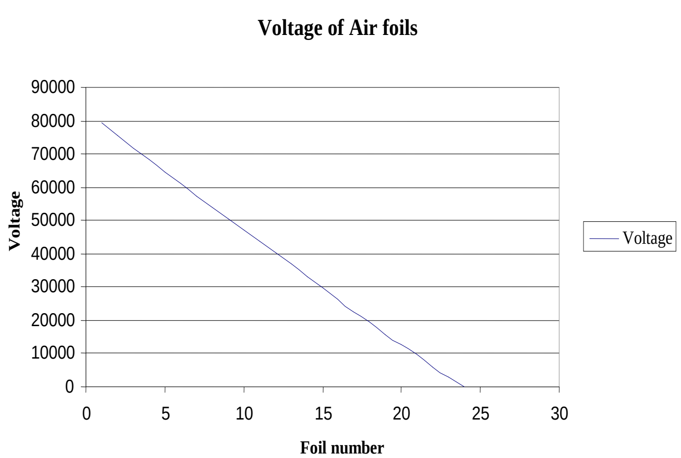


Figure 8. Voltage on air-side of bushing.

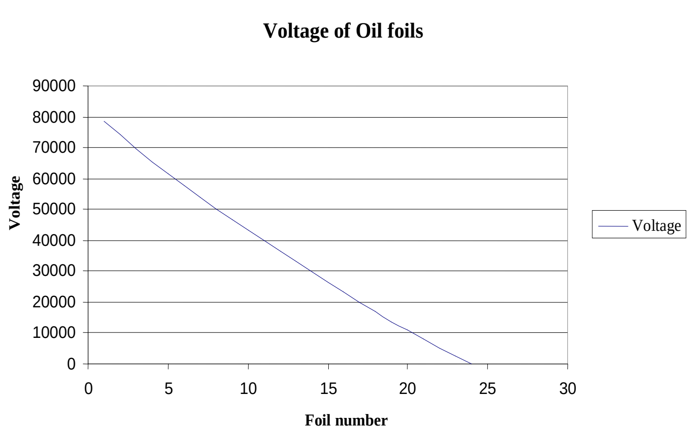


Figure 9. Voltage on oil-side of bushing.

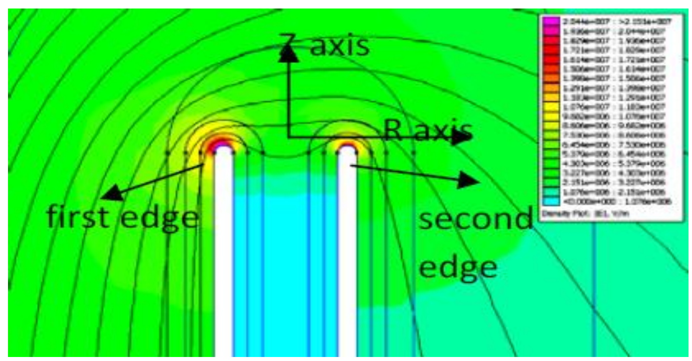


Figure 10. Voltage contour and equipotential lines in the overlap region.

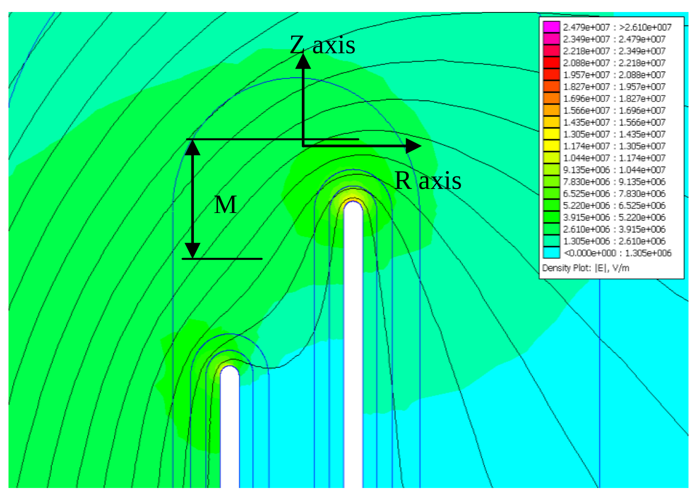


Figure 11. Field contour and the displacement value of the inner edge from the outer edge.

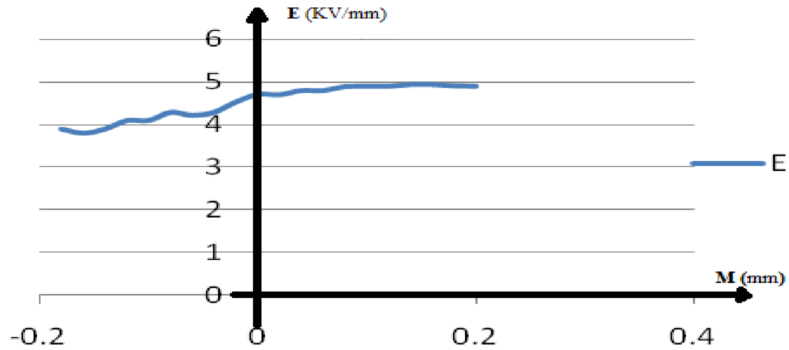


Figure 12. Variation of the maximum field intensity around edge against edge position.

Table 4. Electric field values with increased distance between edges.

M (distance between inner edge and outer edge) (mm)	E_{max} (kV/mm)
-1.12	2.9
1.0	4.74

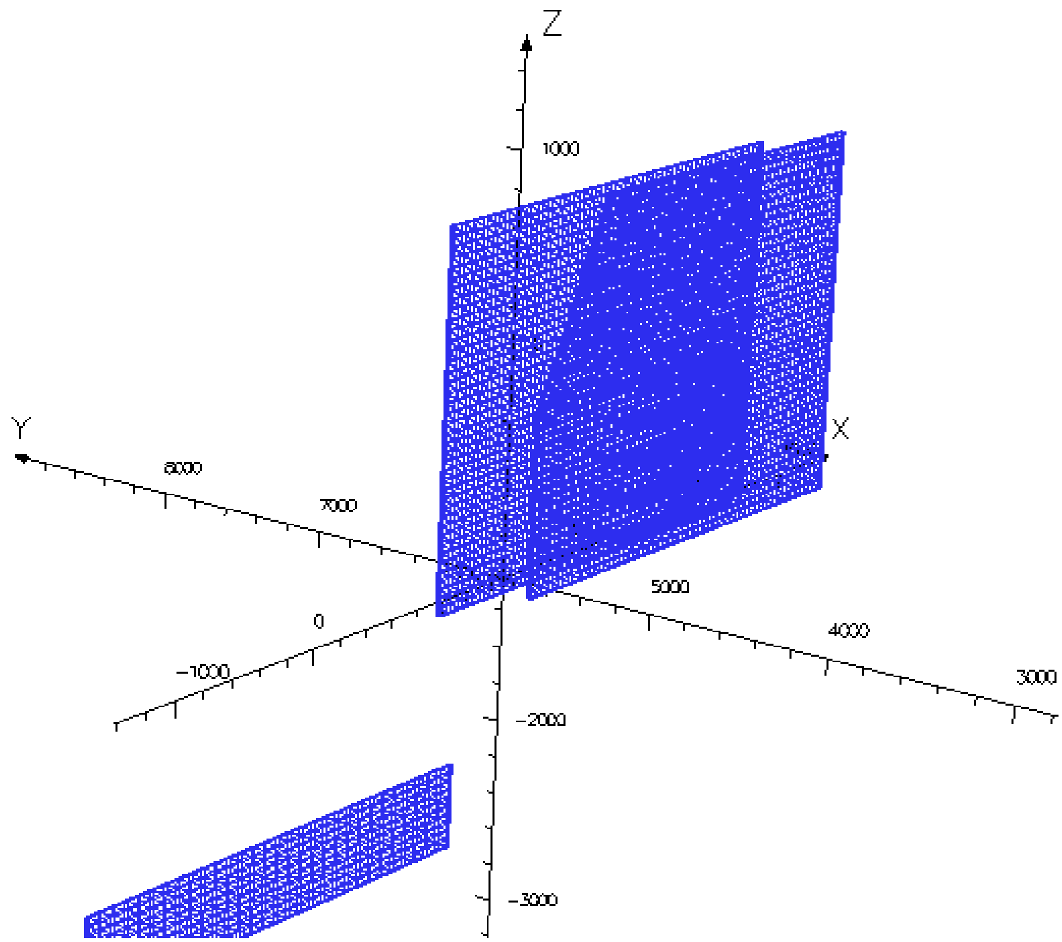


Figure 13. Position of edge against each other (folded edges).

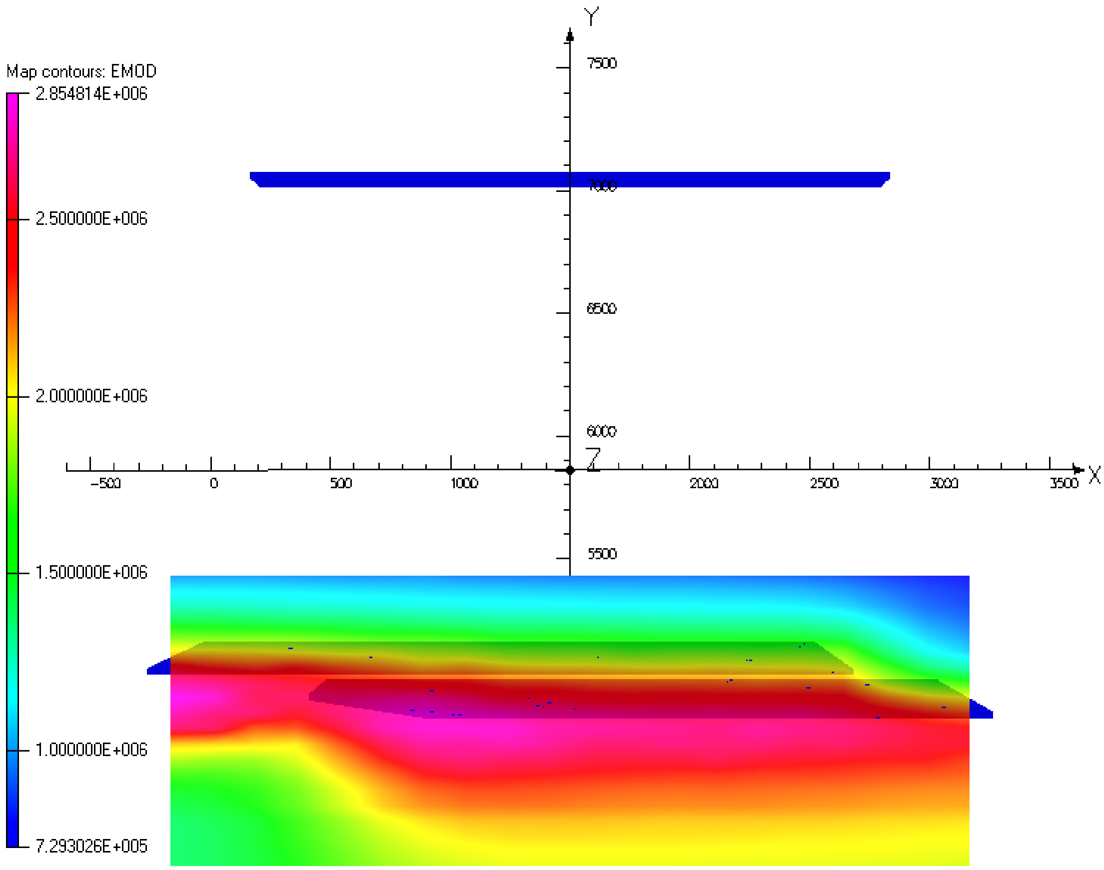


Figure 14. Electric field contour (folded edges).

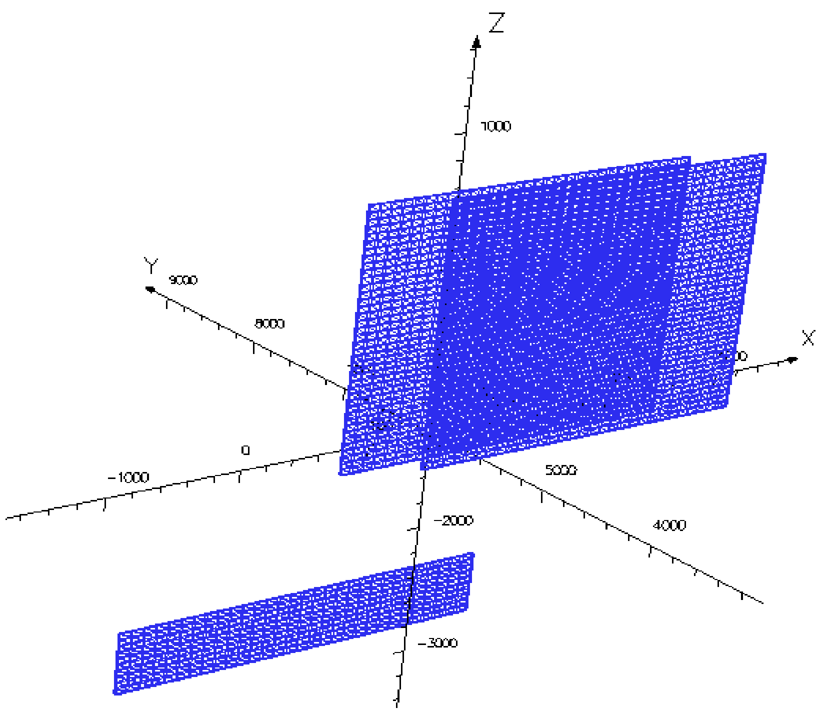


Figure 15. Position of edge against each other (non-folded edges).

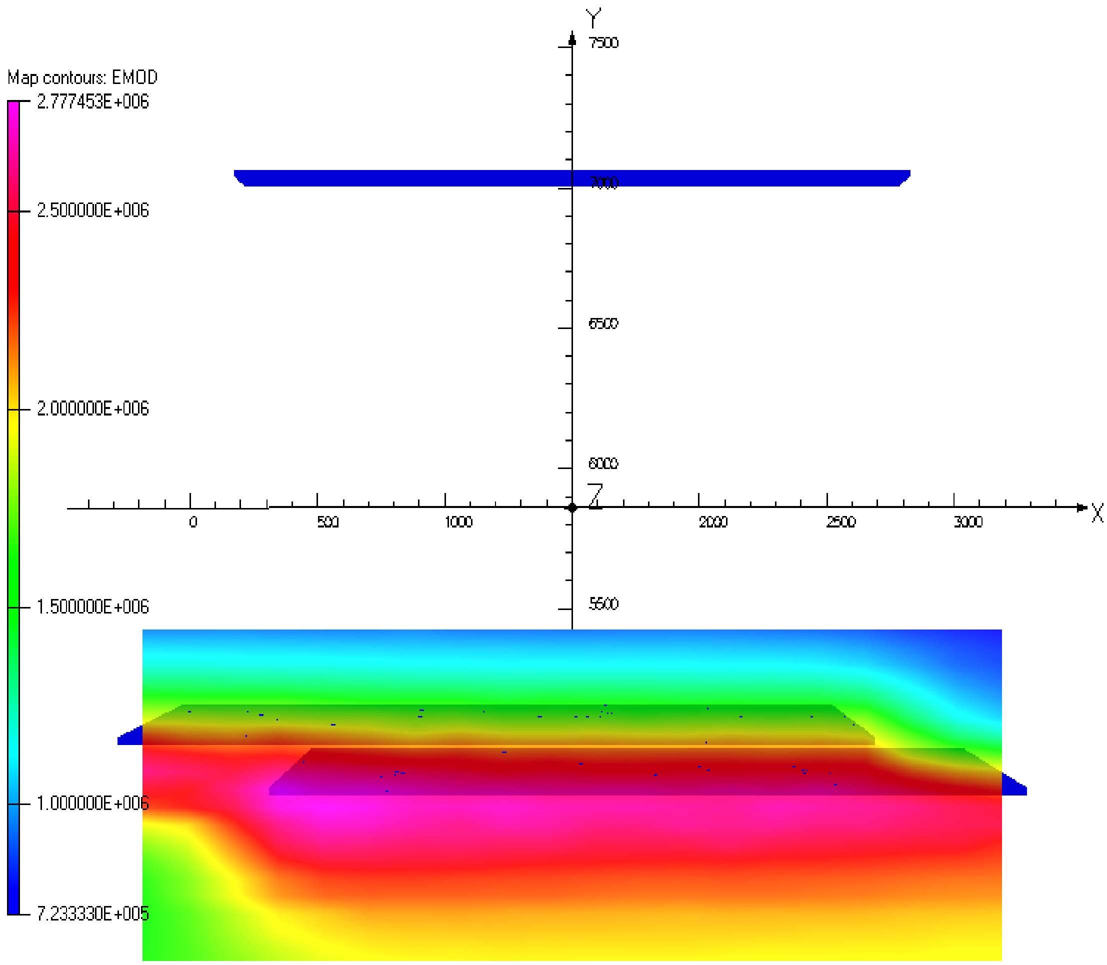


Figure 16. Electric field contour (non-folded edges).

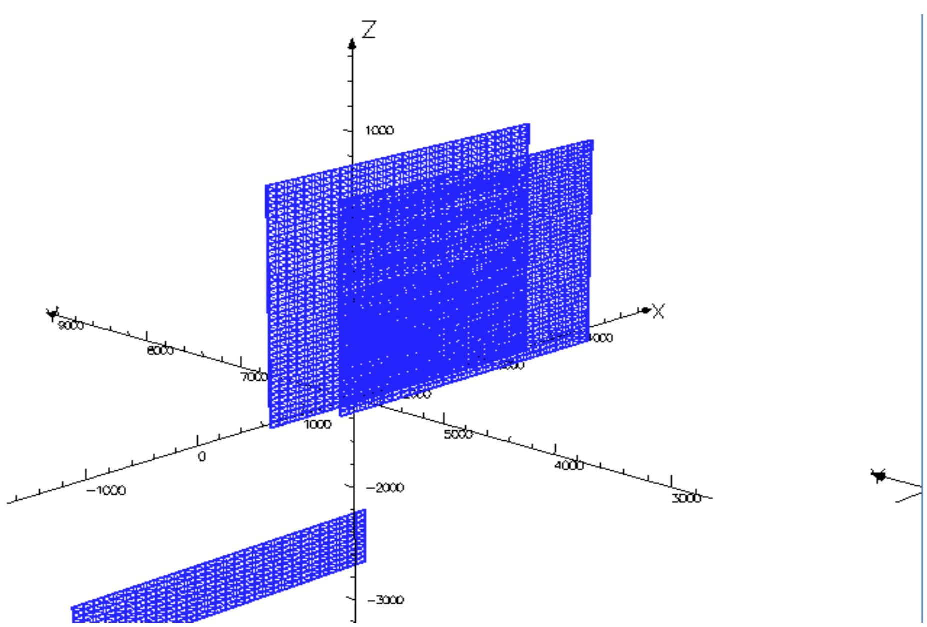


Figure 17. Relative positions of the non-folded and displaced edges.

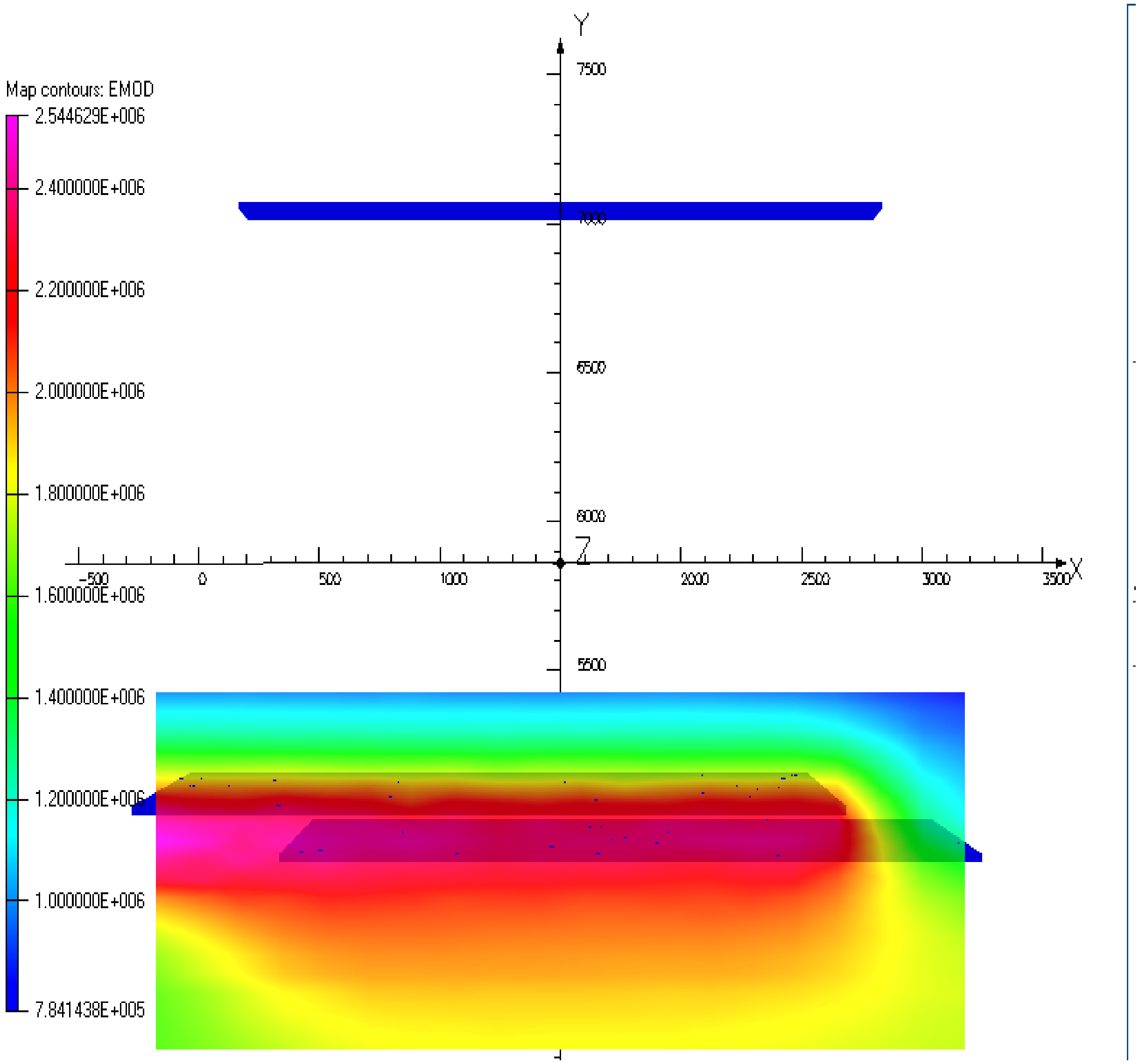


Figure 18. Electric field contour of non-folded and displaced edges.

Table 5. Maximum electric field values.

	E_{max}	E_{zmax}	E_{rmax}
Folded	2.85	-2.43	2.48
Non-folded	2.77	-2.36	2.13
Non- folded and displaced	-2.4	-2.17	2

lower than the outer edge better distributes the field around those edges. Contrarily, placing the inner edge at a position higher than the outer edge makes for the worst field distribution around the edges. Also, the folding of a foil edge affects the field intensity. Non-folded foil edge and the placing of the inner edge at a position lower than the outer edge greatly affect optimization of field intensity.

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