DESIGN, TESTING AND COMMISSIONING OF A THROUGH-WALL AC AND DC BUSHING

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Abstract: The report describes the design of a through-wall bushing to be used to supply high voltage for the environmental chamber. The bushing is used to safely transmit 66 kV AC rms and 52 kV DC and will be exposed to the same environmental conditions for which the insulators under test are being exposed to. Research shows that under DC conditions, pollution accumulation on insulators is significantly higher than under AC conditions and the bushing is designed to withstand class 4 pollution under DC energization. Several bushing tests are done to ensure that the bushing designed is in accordance with the IEC and SANS standards. These test includes the power frequency test, partial discharge test, impulse test. The bushing designed in this report showed the presence of significant number of voids in epoxy resin as the measurements reading was 1.26 nC at 10 kV. This is because moulding of epoxy was not done using a vacuum chamber. Power frequency test was carried out up to 75 kV under dry conditions. Lightning impulse tests were carried out and the epoxy bushing survived a 335 kV impulse. These results indicated that the bushing could be used for application that require voltage up to 66 kV AC rms. DC tests done included the dry and even rain test and the bushing survived up to 52 kV. However, due to limitations in supply voltage no further tests were done and are left as future recommendation.

Key words: arc propagation, field inversion, space and surface charge, creepage and arcing distance

1. INTRODUCTION

The demand for uninterrupted electricity supply can be achieved if external insulation of systems can withstand the power frequency and switching surge voltages under different environmental conditions [1]. Pollution caused by pre-deposition of excrements and dust on insulators are other environmental conditions that can lead to failures on insulators. To reduce failures, insulators have to be tested to check if they can withstand these harsh conditions imposed by the environment. Environmental chambers are used to test insulator performances under different environmental conditions. Testing insulators involves supplying the environmental chamber with high voltage and a bushing is designed for this application. Transmitting high voltage through an earthed wall has to be carefully done as there are high electric fields at the interface between the bushing and the wall which may result in tracking or flashover.
It has also been found that pollution deposition on insulators or bushings used for DC applications is significantly higher due to static electric field. These pollution deposits reduce the effective electrical length that can result in violating the minimum distance required to avoid flashover.

The report is a documentation of the design, building and testing of a through-wall bushing that is able to transmit 66 kV AC rms and 52 kV DC. There are many factors that must be considered when designing a bushing that will be used for both AC and DC application. These factors include electric field distribution, pollution deposition on insulators, creepage distance and arcing distance. Research has shown that DC electric field is determined mainly by the conductivity of the insulators and that of AC is determined by the permittivities [2]. Conductivity is affected by temperature and hence the electric field distribution is non linear under DC energization [2].

2. BACKGROUND

2.1 Literature review

2.1.1 **Differences in pollution performance in AC and DC application:** The design of DC insulation is affected by many factors. These factors increases the accumulation of pollution on insulation. Pollution under AC conditions is primarily due to aerodynamic action and bird pollution. However under DC conditions, accumulation of dust particles is mainly due to static electric field [3].
Research on existing literature has shown that insulators have lower flashover voltage under DC than AC conditions [3]. It has also been shown that arc propagations under AC and DC are significantly different. Under AC condition the flashover tends to propagate along the surface of the insulator whereas that for DC is likely to leave the surface and propagate through air as shown in figure 1 [3].

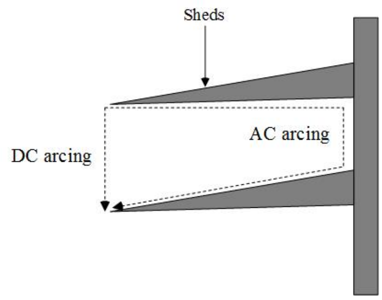

Figure 1 : Arc propagation in AC and DC [3]

2.1.2 **Electric field:** In AC applications, it has been shown that the electric field is dependant on the permittivities of the insulation being used. However in DC application the electric field is determined by the conductivities of the material [2]. These conductivities largely depends on the temperature. Temperature on the conductor is usually higher than that on the outside surface of the insulation [2]. This temperature gradient leads to the formation of charge in insulation and if the charge formed is sufficiently high, the electric field at the outer part of the bushing can be higher than that at the conductor i.e field inversion [4]. Research shows that a threshold electric field exist which if exceeded will lead to charge accumulation [4, 5]. This charge formed will reduce the effective creepage distance. Existing literature also shows that there is charge accumulation at the boundary between two insulating materials. If the quotient $\frac{\epsilon}{\sigma}$ is kept constant, there is no charge accumulation but due to the non linear nature of the conductivity the quotient cannot be constant [2].

Under cold conditions, the electric field distribution relationship given by equation 1 applies at a given point of the dielectric with radius r [6].

$$\frac{E_r}{E_0} = \frac{r_0}{r} \tag{1}$$

Where r_0 is the radius of the conductor.

This relationship is true for both AC and DC. However, when there is a temperature gradient in the conductor the relationship is modified to equation 2 [6].

$$\frac{E_r}{E_0} = \frac{\rho_r}{\rho_0} \times \frac{r_0}{r} \tag{2}$$

Where ρ_0 = specific at the surface of the conductor and ρ_r is the resistance at position r in the insulation.

2.2 *Requirements and constraints*

2.2.1 **Requirements:** The following requirements forms the basis of the project:

- To design, build a suitable through-wall bushing that can safely transmit 66 kV AC and 52 kV DC.
- Perform high voltage bushing test such as the power frequency, impulse and partial discharge tests.
- Use justified simulation tools to model and analyse the design of the bushing

2.2.2 **Constraints:** The bushing is designed for the existing pollution chamber and following constraints exist:

- The length of the bushing inside the pollution chamber is limited to 1.7 m to avoid flashover between the bushing and grounded pollution chamber.
- The bushing must meet the requirements of the IEC standards i.e IEC 60060-1 and IEC 60137.
- The project must be completed in six weeks.
- The DC supply voltage available can go up to 52.1 kV maximum.
- Material expenses must be minimum.
- A vacuum chamber to accommodate a 3 m bushing was not available.

2.3 *Assumptions*

Several assumptions were made in the design of a through-wall bushing. These assumptions include:

- The current flowing in the conductor is very low and the conductor material was chosen entirely based on the strength.
- The is no temperature gradient between the conductor and outside of the insulation.
- The wall of the pollution chamber is assumed to a be earthed conducting sheet in all simulations.

2.4 *Success criteria*

The project is deemed successful if the bushing designed can safely transmit 66 kV AC rms and 52 kV DC through an earthed wall without any problems of tracking/flashover. IEC standards on high voltage bushing design and testing such as IEC60060, IEC60137 and IEC60815 must also be met.

2.5 *Existing solution*

The design of the bushing outlined in this documentation takes features for the existing through-wall bushing. These existing bushing includes the Paper Impregnated Condenser (POC) which is constructed using the method of capacitance grading where paper and conductive layers are wrapped around the conductor [7]. The use of paper as insulation require implementation of techniques to remove moisture inside the paper [7]. One technique to remove moisture is by drying the paper under heat and vacuum [7].

3. HIGH VOLTAGE BUSHING DESIGN

Carrying out pollution test involves the application of high voltage. This voltage is supplied from the transformer outside the chamber through the use of high voltage bushing. This bushing must conform to the IEC and SABS standards which mainly includes IEC 60137, IEC 60060, IEC 60507 and IEC 61245. Although there exist more standards to which the design must conform to, the above mentioned standards are essential.

3.1 *Design overview*

The design of a high voltage bushing can be divided into two main components i.e. the electric field control and dimensioning. In this project two bushings were designed and the other design is covered in [8]. The bushing design in this report was moulded using epoxy resin and the moulding process is shown in figure 9 in Appendix C. The final design for the epoxy bushing and epoxy-silicon bushing are shown in figure 10 in Appendix D and can safely transmit 66 kV AC rms and 52 kV DC. Epoxy used to mould these bushing is not hydrophobic and under wet conditions the effective creepage distance can be reduced. Silicon paint was used to make the bushing hydrophobic.

3.2 *Electric field control mechanism*

Research shows that there are high electric field when a high voltage conductor is passed through an earthed wall.

Several methods are used to control this electric field. From the preliminary simulations with conductor and epoxy, it was found that the electric field distribution was not uniform. These findings indicated that in the presents voids near the conductor, the electric field stress inside the void could be higher than the partial discharge inception voltage which would lead to partial discharge problems [7]. Using conductive layers leads to the formation of uniform electric field from the conductor to the grounded wall. Figure 2 shows the electric field distribution of the bushing with and without a wire mesh. These simulations also show that when a brass mesh is used, the electric field stress at the earthed wall is reduced from 6.8 kV/mm to 1.92 kV/mm which in the presents of voids in insulation would not cause many problems as it is below the breakdown of air.

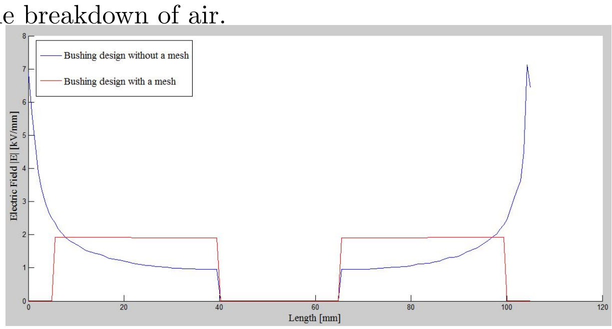

Figure 2 : Comparison between a design with and without a wire mesh.

Simulations with a void present at 66 kV were done for two different mesh lengths and results are shown in figure 3. These results showed that careful consideration must be done on the length of the brass mesh. These results showed that as the length of the mesh increased, the electric field decreased to a value below the partial discharge inception voltage. Simulations diagrams are shown in Appendix E. However when the voltage is increased, multilayer conductive plates must be considered i.e capacitive bushing design.

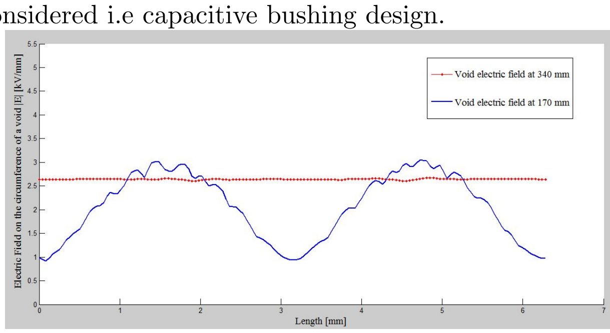

Figure 3 : Effects of increasing mesh length on air bubbles.

3.3 Dimensioning

3.3.1 Determining aluminium wall thickness:

When designing a horizontal bushing, one of the challenges is to design a bushing that is strong enough to withstand its own weight. It was assumed that the bushing must be able to handle 100 N cantilever strength.

Equation 3 was then used to determine the wall thickness required on an aluminium hollow rod [9]. This equation assumes that all the load is applied at one end of the rod but in reality, the weight is distributed along the length of the rod and hence the deflection obtained is the worst case. Wall thickness of 3 mm was found to be enough to handle 100 N cantilever without any significant deflection.

$$d = \sqrt[4]{D^4 - \frac{6.79 \times F \times L^3}{E_y \times x}} \tag{3}$$

Where x is the allowed deflection due to loading, F is the cantilever load, E_y is the young modulus of Aluminium, D is the outer diameter and d is the inner diameter.

3.3.2 Determining epoxy thickness:

Determining the thickness of epoxy is done by modelling the bushing as a coaxial cable and using equation 4.

$$r_2 = r_1 e^{\frac{V}{E \times r_1}} \tag{4}$$

where r_2 is the radius of the dielectric material, r_1 is the radius of the conductor, V is the applied voltage and E is the electric field stress.
Although the electric field stress of epoxy is 20 kV/mm, the design will assume that the electric field is 80 % of 20 kV/mm. This is because these breakdown voltages are statistical and insulation may break before 20 kV/mm is achieved. The thickness of epoxy is found to be 6 mm however due to the irregularities in moulding, it was decided that thickness of 11 mm would be used.

3.3.3 Creepage distance:

Table 1 shows various recommended creepage distance for various pollution class. The bushing in this report was designed for pollution class 4. For the bushing to meet class 4

Table 1 : Recommended creepage distances for various pollution severity for both AC and DC [10]

Pollution severity class		Minimum specific creepage distance (mm/kV) AC phase to ground	DC
1	Light	28	20
2	Medium	35	24
3	Heavy	43	31
4	Very Heavy	54	38

requirements inside the pollution chamber, the overall creepage distance required was calculated to be 3544.2 mm and outside the pollution it was calculated to be 1848 mm. Calculating the outer creepage dimensions was done after assuming the following:

- Shed spacing = 80 mm.
- Shed thickness was 10 mm.
- All sheds were of the same dimensions.
- The inner and outer diameter of the sheds was 46 mm and 140 mm respectively.

The number of sheds required was then calculated to be 19 inside the pollution chamber and 13 outside. The IEC standards specify some of the shed requirements to avoid sheds that a closely spaced [10] as this may cause problems especially under DC energization. The parameters that control the spacing between sheds are the spacing to projection ratio (S/P), creepage factor (CF) and profile factor (PF) [10]. These parameters limits are specified in IEC60815 and values are shown in Table 2. The parameters CF,PF and S/P for the epoxy bushing

Table 2 : Sheds profile parameter limits

S/P	$\geq$	0.65
CF	$\leq$	4 for pollution class 5
PF	$\geq$	0.7

designed in this report are calculated to be 2.14, 1 and 1.7 respectively and these values meet the requirements of the IEC60815. The final design dimensions are shown in figure 4.

4. HIGH VOLTAGE BUSHING TESTING AND RESULTS

Several tests were done to check if the bushings were complying with the IEC60137 standards [11]. These tests include: Dry and wet power-frequency voltage withstand test, Dry lightning impulse voltage withstand test (BIL) and Partial discharge test. These tests were done for both AC and DC on two bushings, one designed in this report and the other one designed in [8].

4.1 AC Tests

4.1.1 **Partial discharge test:** The test is done to find failures due to internal discharge in the insulation of the bushing [12] and the IEC60137 standards recommends that the measurements be made after the dry power frequency test [11].
According to standards, the designs are supposed to have partial discharge measurement of 5 pC at 44 kV [11]. Figure 5 and Figure 6 shows the results of the partial discharge for epoxy and epoxy-silicon bushing respectively and these results shows that the values are higher than the recommended. This is because when epoxy is being used as insulation strict measures to remove bubbles must be implemented. These measures includes the use of vacuum chamber and temperature and pressure controlled systems. These techniques were however unavailable for these designs due to the length of the bushing.

4.1.2 **Wet and Dry power frequency test:** This test involves testing the bushing at a voltage of at least 10 % above the rated value. This test must be done or repeated after impulse voltage withstand test. The values are supposed to be taken under certain environmental conditions and hence the voltage measurements must be standardized by dividing with a correction factor calculated in Appendix F. Results from this test showed that under both dry and wet tests, flashover occurred at

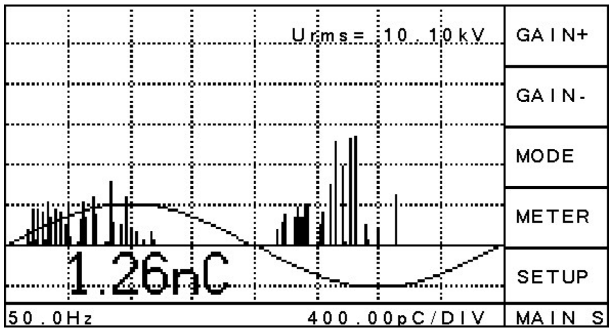

Figure 5 : Inception voltage for the epoxy bushing.

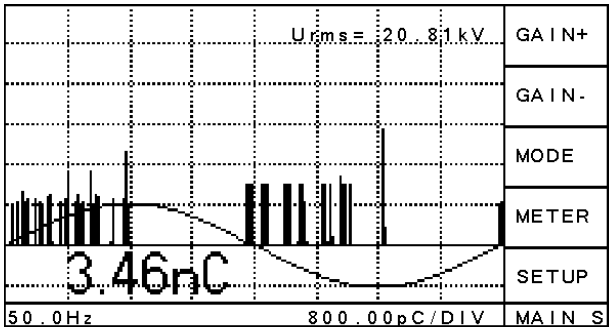

Figure 6 : Inception voltage for the epoxy-silicon bushing.

values in table 3 for both designs. These values were above 72.6 kV recommended by the standards. However there was intense corona close to the earthing point. Corona camera was then used to identify the position the corona was coming from and the figure 7 shows the location of corona on epoxy bushing. It is believed that the earthed brass mesh was close to the surface of the bushing and sharp edges were causing enhancement of electric field which led to surface discharge (corona). These corona effects were not intense at 66 kV on the epoxy-silicon bushing designed in [8] with a mesh which is 16 mm away from the surface. This results supports suggestion stated above that intense corona on the epoxy bushing is due to sharp mesh ends.

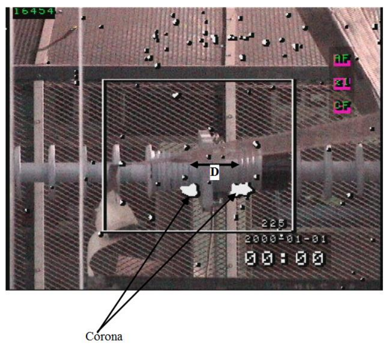

Figure 7 : Picture taken to find the location of corona heard during the power frequency test for the epoxy bushing.

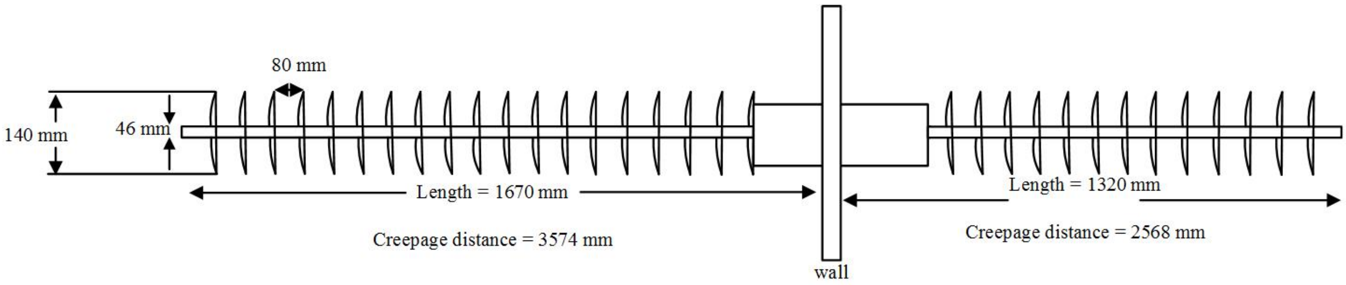

Figure 4 : Epoxy bushing design.

Table 3 : Dry and Wet power frequency tests results

Bushing type	Dry withstand	Wet withstand
Epoxy	75 kV	73 kV
Epoxy-silicon	89 kV	86 kV

4.1.3 **Dry lightning impulse test:** The bushing's ability to withstand impulse voltages was also tested. This test involves applying 15 positive and 15 negative impulses to the bushing and if two flashovers occur at either polarity, the bushing is considered to have failed the test. For a 72.5 kV bushing, an impulse of 325 kV must be applied. This impulse voltage are measured at standard atmospheric conditions and correction factor must be used to convert the impulse voltage measured at given test conditions. This correction factor is calculated in Appendix F. Results obtained from the negative and positive lightning impulse tests on the epoxy bushing and epoxy-silicon bushing are shown in table 4. However, epoxy-silicon bushing had a puncture after 11 positive impulses and due to time constraints there was no time for repairing and re-testing of the bushing.

*NB F represents a flashover and P represents a puncture

Table 4 : Positive and negative lightning Impulse test results

Impulse number	Bushing type		
	Epoxy		Epoxy-silicon
	positive (kV)	negative (kV)	positive (kV)
1	295	-373	331
2	324	-375	326
3	314	-368	337
4	337	-374	321
5	337	-378	347
6	337	-370	342
7	316	-375	342
8	324	-365	347
9	326	-368	334
10	334	-375	342 (F*)
11	337	-370	233 (P*)
12	324	-381	
13	324	-374	
14	334	-374	
15	319	-378	

and figure 8 shows the punctured epoxy-silicon bushing.

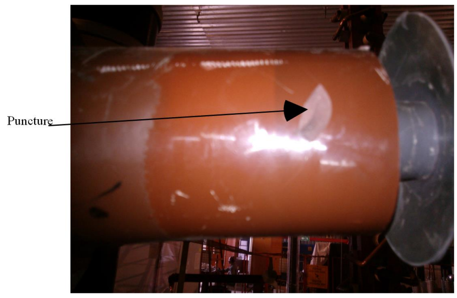

Figure 8 : epoxy-silicon bushing punctures during the positive dry lightning impulse test.

4.2 DC Tests

The tests were carried out in accordance to the IEEE standard C57 [14]. The test done includes the low frequency dry power frequency test and the even rain test. The voltage was increased to 52 kV for both tests and only a slight corona was heard. The DC generator available could only supply voltage up to 52.1 kV and no further tests for higher voltages were done due to this limitation. It was decided that the bushing be rated at the maximum voltage available but this voltage rating can be higher than 52.1 kV.

5. CRITICAL ANALYSIS AND DESIGN EVALUATION

The bushing designed in this project had problems with corona and it is believed that the sharp ends of the brass mesh may have caused enhancement of electric field on both designs. Possible solution to this problem is to use mesh with no sharp ends. Epoxy bushing sheds are not the same and hence the creepage distance from the actual bushing is less than that calculated in theory. The major problems that was supposed to be rectified from the previous pollution chamber bushing was high electric field stress at the wall and the sagging of the bushing. These problems were addressed through the use of aluminium rod to increase strength and epoxy for electric field control. However, the epoxy bushing designed in this report was heavier than expected

6. FUTURE IMPROVEMENTS AND RECOMMENDATIONS

Important improvements and recommendations that may improve the bushing performance include:

- Performing pollution tests such as clean and salt fog tests and solid layer tests.
- Use of vacuum chamber is recommended if the bushing is to be used constantly at its rated voltage to improve the bushing lifetime.
- The through-wall bushing donated by EMC was rated at 15 kV and this may have caused problems with surface discharge. It is recommended that a 66 kV must be designed.
- The voltage rating can be increased by reducing the shed spacing to projection ratio and hence increasing the creepage distance.
- Testing DC above 52.1 kV using the Cockroft Walton generator.
- Designing and building of a mould that can make construction of a bushing more easier.

7. CONCLUSION

The design and commissioning of a through-wall bushing has been presented. Tests to access the performance of the bushing under different environmental conditions have been performed. Results from the power frequency test shows that the bushing can safely transmit 66 kV into the pollution chamber without problem. Lightning impulse voltage test were also performed and the epoxy bushing was able to survive a 325 kV positive and negative impulse. However, the epoxy-silicon bushing had a puncture and it is suspected that the insulation thickness may have been too small to handle a 325 kV. Results from the partial discharge showed the presence of bubbles in epoxy as the discharge quantity was above the recommended value at 10 kV for the epoxy bushing. The main cause for bubbles in insulation was mainly because of the moulding conditions. A vacuum chamber is usually used to minimize bubbles but because of the length of the bushing designed the chamber was not available.

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Appendix

A APPENDIX A

A1 Reflection on group work

The project requires a lot of work and achieving the target is done by subdividing tasks amongst group members. Both members of the group have to take the project serious from the beginning. Although hard-working members are usually the major requirement for success, it is also advisable to establish good relationship amongst yourselves. More often there are conflicts in ideas but learning to converge unanimously on a certain solution is very helpful.When working in a lab where other students are working, it is also advisable to communicate especially if groups are sharing resources. Lab projects are projects that require ordering materials outside the University and these acquisition have to be made before the beginning of the project as they may delay the completion of the project.

I am happy to say even though our ideas crossed with Cedric Banda at some point we were able to resolve and continue with the hard work. He is a person who is open to new ideas and willing to take risks. The design of the bushing using lunch boxes was a high risk idea but it was a risk which he was willing to take and that makes him a perfect project partner.

Its always good to come out victors in project like these and we are happy with the two design we built during these two weeks. Although the are some few issues with bubbles, I believe we can achieve even more given the time and resources. All in all I think I have had a great time with my group member and I gained more information and ideas on how to tackle problems. I have also learnt that simple things like lunch boxes can actually build a bushing as big a 3 m.

B APPENDIX B

C APPENDIX C

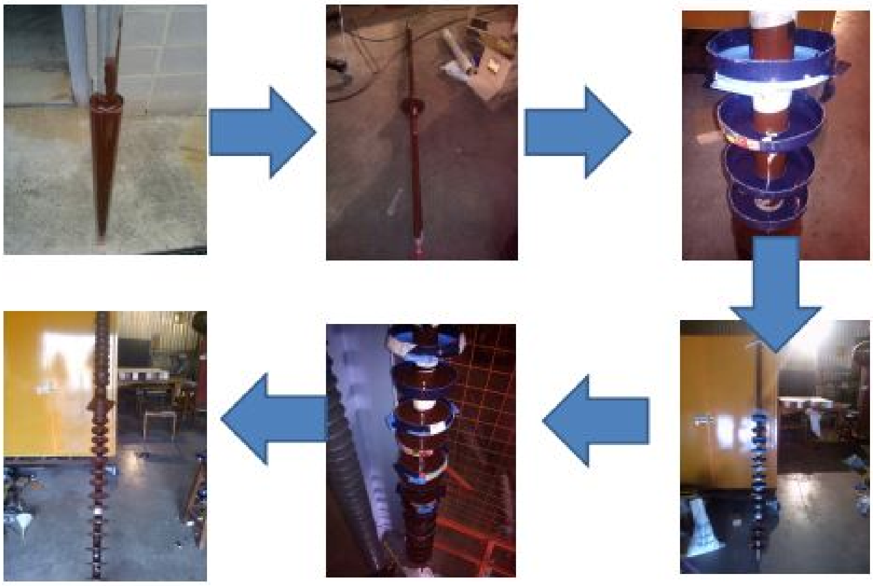

Figure 9 : building process of the epoxy bushing.

D APPENDIX D

Figure 10 : Final design for the epoxy bushing (left) and epoxy-silicon bushing (right).

E APPENDIX E

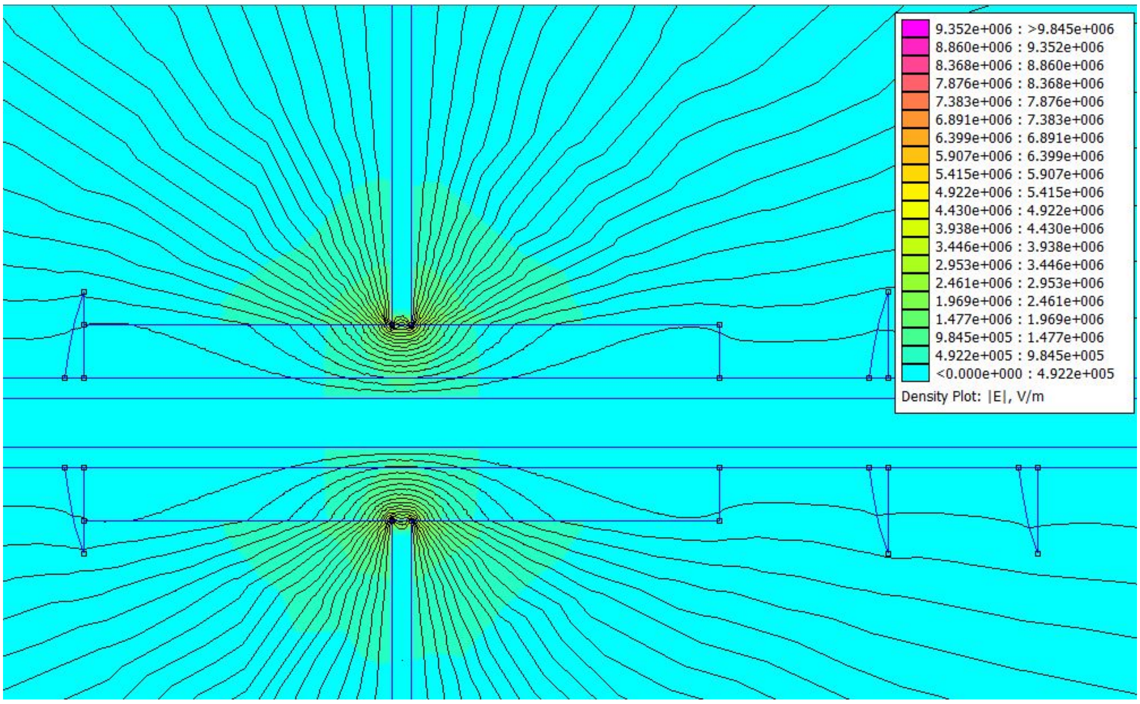

Figure 11 : Electric field distribution without a mesh at the earthing point.

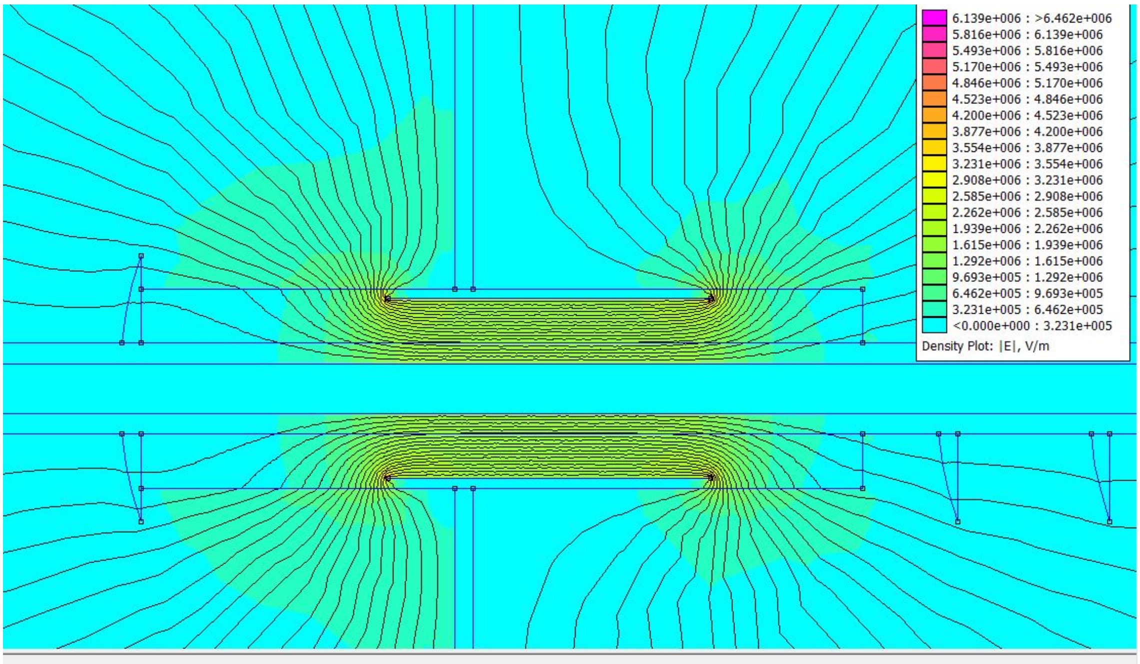

Figure 12 : Electric field distribution with a mesh at the earthing point.

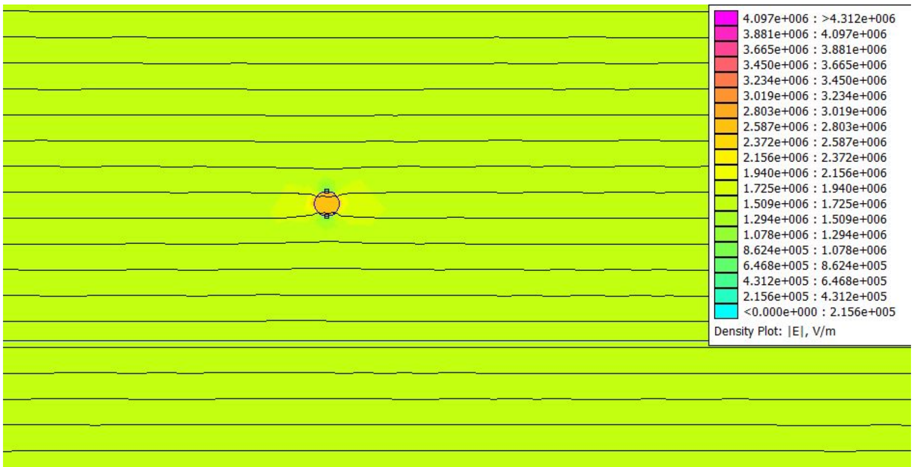

Figure 13 : Electric field distribution inside a void with wire mesh length of 340 mm.

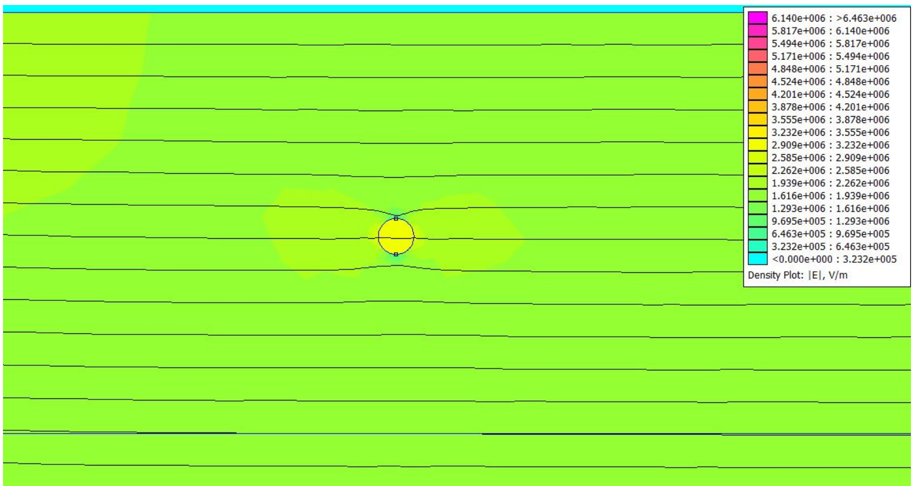

Figure 14 : Electric field distribution inside a void with wire mesh length of 170 mm.

F APPENDIX F

F1 Atmospheric correction factor

The values recommended by the standards are values obtained under standards conditions. These conditions are:
Temperature $t_0 = 20\ ^\circ c$.
Absolute pressure $p_0 = 1013\ mbar$.
Absolute humidity $h_0 = 11\ g/m^3$.

It is shown in IEC60060-1 that, the disruptive discharge voltage are corrected to the standards atmospheric conditions using equation 5.

$$U_0 = \frac{U}{k} \tag{5}$$

Where k is the correction factor which is calculated using equation 6.

$$k = k_1 \times k_2 \tag{6}$$

Air density correction factor $k_1 = \delta^m$. Where

$$\delta = \frac{p}{p_0} \times \frac{273 + t_0}{273 + t} \tag{7}$$

Using the atmospheric conditions below, δ was calculated to be 0.806 for dry and wet power frequency tests and DC tests and 0.769 for impulse test.

Temperature $t = 26\ ^\circ c$.
pressure $p = 833\ mbar$.
humidity $R = 27\ \%$.

Atmospheric conditions for impulse test are shown below.

Temperature $t = 28\ ^\circ c$.
pressure $p = 800\ mbar$.
humidity $R = 25\ \%$.

Humidity correction factor $k_2 = k^w$ and k is determined by the type of test being performed. Table 5 shows the values of k. h is also obtained using equation 8.

$$h = \frac{6.11 \times R \times e^{\frac{17.6 \times t}{243 + t}}}{0.4615 \times (273 + t)} \tag{8}$$

Where h is the absolute humidity, R is the relative humidity and t is the ambient temperature. The value of h for AC and DC is calculated to be 6.55 g/m^3 and for impulse 6.78 g/m^3.
Exponents w and m are obtained by first obtaining the value of g using equation below.

Table 5 : Values of k calculated for AC, DC and impulse test

Test type	k value
AC	0.966
DC	0.958
Impulse	0.978

$$g = \frac{U_{50}}{500 L \delta k} \tag{9}$$

where U_{50} is 1.1 times test voltage, L is the shortest arcing distance to earth.
g for AC case is calculated to be 0.156, for DC g is 0.114 and for impulse $g = 0.77$.
The values of m and w are then obtained from table 1 in [13]. For AC and DC tests, the values of g are less that 0.2 and hence m and w are both zero. However for impulse test, the values of m and w are found to be 0.54 and 0.54 respectively.
The correction factor for AC and DC is found to be 1 and that for impulse test it was 0.86.

G APPENDIX G

The conductor material is chosen entirely on the strength. Copper is more conductive than aluminium but the weight of epoxy may cause deflections that are not acceptable. Due to low current flowing in the conductor a hollow aluminium rod is chosen. The wall thickness is determined using the cantilever beam deflection equation in equation 10

$$x = \frac{F}{E_y I}\left(\frac{L^3}{3}\right) \tag{10}$$